

# ECE367 Cheatsheet

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### 1 QA

**Intuition: Optional” problems:** Optional problems provide extra practice or introduce interesting connections or extensions.

- They need not be turned in. We will not grade them, but we will assume you have reviewed and understood the solutions to the optional problems when designing the exams.

## 2 Vectors, Norms, Inner Products (Ch. 2.1-2.2)

### 2.1 Linear transformation

**Definition:**  $T : X \rightarrow Y$  that satisfies

1. **Additivity:**  $T(x_1 + x_2) = T(x_1) + T(x_2)$
  2. **Homogeneity:**  $T(\alpha x) = \alpha T(x)$
- **Note:** Linear algebra is the study of linear transformations over vector spaces.

#### 2.1.1 Matrix representation of a linear transformation

**Definition:** Let  $\mathcal{V}$  and  $\mathcal{W}$  be vector spaces. Let  $T : \mathcal{V} \rightarrow \mathcal{W}$  be a linear transformation. When  $\mathcal{V} = \mathbb{R}^n$  (or  $\mathbb{C}^n$ ) and  $\mathcal{W} = \mathbb{R}^m$  (or  $\mathbb{C}^m$ ), then  $T$  can be uniquely represented as a matrix  $A \in \mathbb{R}^{m \times n}$  such that:

$$T(\mathbf{x}) = A\mathbf{x}$$

where

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

- **Key:** Any linear transformation is a matrix multiplication. Any matrix multiplication is a linear transformation.

## 2.2 Vectors

**Definition:** Ordered collection of numbers, where  $x_i \in \mathbb{R}$  or  $\mathbb{C}$

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad \mathbf{x}^T = [x_1 \quad x_2 \quad \cdots \quad x_n].$$

- $n$ : Dimension of  $\mathbf{x}$
- $\mathbf{x}$ : Column vector
- $\mathbf{x}^T$ : Transpose of  $\mathbf{x}$  (row vector)
- $T$ : Transpose
- $x_i$ :  $i$ -th element of  $\mathbf{x}$ .

## 2.3 Vector spaces

**Definition:** A vector space over a field  $\mathbb{F}$  (e.g.  $\mathbb{R}/\mathbb{C}$ ) consists of:

1. A set of vectors  $\mathcal{V}$
  2. A vector addition operator  $+$ :  $\mathcal{V} \times \mathcal{V} \rightarrow \mathcal{V}$  s.t.  $\forall x, y \in \mathcal{V} \rightarrow x + y \in \mathcal{V}$  (i.e. closed under VA)
  3. A scalar multiplication operator  $\cdot$ :  $\mathbb{F} \times \mathcal{V} \rightarrow \mathcal{V}$  s.t.  $\forall \alpha \in \mathbb{F}, \forall x \in \mathcal{V} \rightarrow \alpha x \in \mathcal{V}$  (i.e. closed under SM)
- $\times$  is not scalar multiplication.

For  $\mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathcal{V}$  and  $\alpha, \beta \in \mathbb{F}$ . The following properties are satisfied:

- **Vector addition** satisfies (i.e., Abelian group):
  1. **Commutativity:**  $\mathbf{x} + \mathbf{y} = \mathbf{y} + \mathbf{x}$ .
  2. **Associativity:**  $\mathbf{x} + (\mathbf{y} + \mathbf{z}) = (\mathbf{x} + \mathbf{y}) + \mathbf{z}$ .
  3. **Additive identity:**  $\exists \mathbf{0} \in \mathcal{V}$  s.t.  $\mathbf{x} + \mathbf{0} = \mathbf{0} + \mathbf{x} = \mathbf{x}$ .
  4. **Additive inverse:**  $\forall \mathbf{x}, \exists \mathbf{y}$  s.t.  $\mathbf{x} + \mathbf{y} = \mathbf{0}$  (i.e.  $\mathbf{y} = -\mathbf{x}$ ).
- **Scalar multiplication** satisfies:
  1. **Associativity:**  $\alpha \cdot (\beta \cdot \mathbf{x}) = (\alpha \cdot \beta) \cdot \mathbf{x}$ .
  2. **Multiplicative Identity:**  $\exists 1 \in \mathbb{F}$  s.t.  $1 \cdot \mathbf{x} = \mathbf{x}$ .
  3. **Right Distributivity:**  $\alpha \cdot (\mathbf{x} + \mathbf{y}) = \alpha \cdot \mathbf{x} + \alpha \cdot \mathbf{y}$ .
  4. **Left Distributivity:**  $(\alpha + \beta) \cdot \mathbf{x} = \alpha \cdot \mathbf{x} + \beta \cdot \mathbf{x}$ .

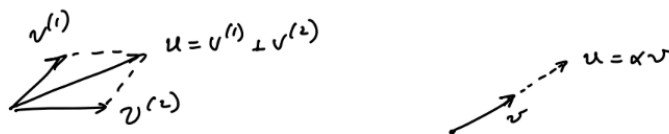


Figure 1: Vector addition and scalar multiplication.

### 2.3.1 How to prove or disprove a vector space?

#### Process:

##### Prove:

1. Prove that  $\mathcal{V}$  is closed under VA and SM.
2. Prove all the properties under VA and SM.

##### Disprove:

1. Disprove one of the properties or that it isn't closed under VA and SM.

**Warning:** If standard addition and multiplication then, closed under VA and SM properties is enough to prove it's a vector space.

#### Example:

- Let  $\mathcal{V} = \mathbb{R}^n$  and  $\mathbb{F} = \mathbb{R}$ : This represents vectors of dimension  $n$  where each element belongs to  $\mathbb{R}$ .

$$\mathcal{V} = \mathbb{R}^n = \left\{ \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} : x_i \in \mathbb{R} \right\}$$

For  $\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^n$  and  $\mathbf{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} \in \mathbb{R}^n$ :

$$\mathbf{x} + \mathbf{y} = \begin{bmatrix} x_1 + y_1 \\ \vdots \\ x_n + y_n \end{bmatrix}$$

For  $\alpha, \beta \in \mathbb{R}$ :

$$\alpha \cdot \mathbf{x} = \begin{bmatrix} \alpha x_1 \\ \vdots \\ \alpha x_n \end{bmatrix}$$

- Let  $\mathcal{V} = \mathbb{C}^n$  and  $\mathbb{F} = \mathbb{C}$ : This represents vectors of dimension  $n$  with complex components.

$$\mathcal{V} = \left\{ \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} : x_i \in \mathbb{C} \right\}$$

$\mathcal{V}$  is a vector space over  $\mathbb{C}$  under element-wise addition and scalar multiplication.

- Let  $\mathcal{V} = \{\text{set of all continuous functions } f : \mathbb{R} \rightarrow \mathbb{R}^n\}$  and  $\mathbb{F} = \mathbb{R}$ :

Let  $f_1, f_2 \in \mathcal{V}$ , and for  $t \in \mathbb{R}$ :

$$(f_1 + f_2)(t) = f_1(t) + f_2(t) \Rightarrow f_1 + f_2 \in \mathcal{V}$$

For  $\alpha \in \mathbb{R}$ :

$$(\alpha f)(t) = \alpha f(t) \Rightarrow \alpha f \in \mathcal{V}$$

–  $f$  is the vector,  $\mathbb{R} \rightarrow \mathbb{R}^n$  is the input-output relationship. For 2D,  $f(x) = [x_1, x_2]^T$ , where  $x$  is the input, the vector is the output in 2D, and the vector is  $f$ .

- Let  $\mathcal{V} = \mathcal{P}_n$ , the set of all polynomials with real coefficients and degree  $\leq n$ :

$$\mathcal{V} = \mathcal{P}_n = \{p(x) = a_0 + a_1x + a_2x^2 + \dots + a_nx^n : a_0, a_1, \dots, a_n \in \mathbb{R}\}$$

$\mathcal{V}$  is a vector space over  $\mathbb{R}$  under standard addition and scalar multiplication.

## 2.4 Subspace

**Definition:** A **subspace** is a subset of a vector space  $\mathcal{V}$  that is a vector space by itself.

- **Test:** To check whether a subset is a subspace, check that it is closed under VA & SM.

**Example:**

- Let  $\mathcal{V} = \mathbb{R}^3$ , and consider the set:

$$S = \left\{ \begin{bmatrix} x_1 \\ x_2 \\ 0 \end{bmatrix} : x_1, x_2 \in \mathbb{R} \right\}$$

This set  $S$  is a subspace of  $\mathbb{R}^3$ .

- Let  $\mathcal{V} = \mathbb{R}^3$ , and consider the set:

$$S = \left\{ \begin{bmatrix} x_1 \\ x_2 \\ 1 \end{bmatrix} : x_1, x_2 \in \mathbb{R} \right\}$$

This set  $S$  is **not** a subspace of  $\mathbb{R}^3$  because adding two vectors will make the last component 2.

- Let  $\mathcal{V} = \mathbb{R}^n$ , and consider the set:

$$S = \{\mathbf{0}\}$$

This set  $S$  is a subspace of  $\mathbb{R}^n$ .

## 2.5 Span

**Definition:** Given a finite set of vectors  $S = \{\mathbf{v}_1, \dots, \mathbf{v}_k\}$  in the same vector space  $\mathcal{V}$  over some field  $\mathbb{F}$  then,

$$\text{Span}(S) = \left\{ \sum_{i=1}^m \alpha_i \mathbf{v}_i \mid \alpha_i \in \mathbb{F} \right\}$$

- **Note:**  $\text{Span}(S)$  is always a subspace of  $V$ .

### 2.5.1 How to draw the span?

**Process:**

1. Identify the vectors.
2. Plot the vectors: Plot each vector on a coordinate plane starting at the origin.
3. Draw the span: Extend the vectors in both directions to show the line or plane formed by their span. If they span the entire plane, draw dashed lines extending their direction.

**Example:**

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

$$\text{span}(S) = \left\{ \begin{bmatrix} x_1 \\ x_2 \\ 0 \end{bmatrix} : x_1, x_2 \in \mathbb{R} \right\}$$

This set  $\text{span}(S)$  forms a plane in  $\mathbb{R}^3$ . The vectors span the xy-plane with the z-coordinate fixed at zero.

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

$$\text{span}(S) = \left\{ x \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} : x \in \mathbb{R} \right\}$$

In this case,  $\text{span}(S)$  is a line in  $\mathbb{R}^3$  along the x-axis with y and z coordinates fixed at zero.

## 2.6 Linear independent (LI) set

**Definition:** A set of vectors  $S = \{\mathbf{v}_1, \dots, \mathbf{v}_k\}$  is LI if no vector in  $S$  can be written as a LC of other vectors in  $S$ .

In other words, the only  $\alpha_i$ 's that makes  $\sum_{i=1}^m \alpha_i \mathbf{v}_i = \mathbf{0}$  is  $\alpha_i = 0, \forall i$ .

- If  $S = \{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k\}$  is LI, then  $\forall \mathbf{u} \in \text{span}(S)$ , there is a **unique** set of  $\alpha_i$ 's s.t.  $\mathbf{u} = \sum_{i=1}^k \alpha_i \mathbf{v}_i$  (i.e. there is no redundancies in representation)
  - **Coordinates:**  $\{\alpha_1, \alpha_2, \dots, \alpha_k\}$  of  $\mathbf{u}$  w.r.t.  $S$ .
- If  $S$  is linearly dependent, then one of the vectors can be written as a LC of the other vectors. In this case, we can remove that vector and continue this process until the remaining set is LI.
  - **Note:** Such an irreducible linearly independent set is called a **basis** of  $\text{span}(S)$ .

### 2.6.1 How to determine if a set is linearly independent

**Process:**

1. Write a linear combination with coefficients  $\alpha_1, \dots, \alpha_k$ .
2. Set the linear combination equal to 0.
3. Solve for  $\alpha_1, \dots, \alpha_k$  by solving the set of equations (i.e. each component is one equation).
4. If  $\alpha_1 = \dots = \alpha_k = 0$ , then it is linearly independent.
5. Else, linearly dependent by finding a counter example, where the linear combination is 0 for  $\alpha_1, \dots, \alpha_k$  not all equal to 0.

## 2.7 Basis

**Definition:** A set of vectors  $B$  is a basis of a vector space  $\mathcal{V}$  if

- $B$  is LI
- $\text{Span}(B) = \mathcal{V}$

**Example:** What is the standard basis for  $\mathcal{V} = \mathbb{R}^n$ ?

$$\mathbf{e}^{(1)} = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad \mathbf{e}^{(2)} = \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{bmatrix}, \quad \dots, \quad \mathbf{e}^{(n)} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix} \quad \text{for } \mathbb{R}^n$$

If  $\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^n$ , then:

$$\mathbf{x} = x_1 \mathbf{e}_1 + x_2 \mathbf{e}_2 + \dots + x_n \mathbf{e}_n$$

### 2.7.1 Dimension

**Definition:** The dimension is the number of basis vectors.

- **Note:** Basis is not unique. But  $\dim(\mathcal{V})$  is well-defined.

**Example:**

- $\dim \left( \text{span} \left( \left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\} \right) \right) = 2$
- $\dim \left( \text{span} \left( \left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right\} \right) \right) = 1$



- $\dim(\{\mathbf{0}\}) = 0$
- The dimension for  $\mathcal{V} = \mathbb{R}^n$  of the standard basis is  $n$

**Process:**

1. Given a set of vectors,  $S$
2. If l.i. and  $\text{span}(S) = \mathcal{V}$ , then it's a basis.
3. If for each pair of vectors, the inner product is 0, then it's orthogonal basis.
4. If unit norm, then it's orthonormal basis.

## 2.8 Norms (Notion of distance)

**Definition:** Let  $\mathcal{V}$  be a vector space over  $\mathbb{R}$  or  $\mathbb{C}$ . A norm is a function  $\|\cdot\|: \mathcal{V} \rightarrow \mathbb{R}$  that satisfies

1. **Non-negativity:**  $\|\mathbf{x}\| \geq 0$ ,  $\forall \mathbf{x} \in \mathcal{V}$ , and  $\|\mathbf{x}\| = 0$  iff  $\mathbf{x} = \mathbf{0}$
2. **Homogeneity:**  $\|\alpha \mathbf{x}\| = |\alpha| \|\mathbf{x}\| \forall \mathbf{x} \in \mathcal{V}, \alpha \in \mathbb{F}$
3. **Triangle inequality:**  $\|\mathbf{x} + \mathbf{y}\| \leq \|\mathbf{x}\| + \|\mathbf{y}\|, \forall \mathbf{x}, \mathbf{y} \in \mathcal{V}$  (triangular inequality)

**Example:**  $\ell_p$  norms:

$$\|\mathbf{x}\|_p \equiv \left( \sum_{k=1}^n |x_k|^p \right)^{1/p}, \quad 1 \leq p < \infty.$$

- **Note:** For  $p < 1$ , triangular inequality doesn't hold.

1. **Sum-of-absolute-values length**  $p = 1$ :  $\|\mathbf{x}\|_1 \equiv \sum_{k=1}^n |x_k|$

2. **Euclidean length**  $p = 2$ :  $\|\mathbf{x}\|_2 \equiv \sqrt{\sum_{k=1}^n x_k^2}$

3. **Max absolute value norm**  $p = \infty$ :  $\|\mathbf{x}\|_\infty \equiv \max_{k=1, \dots, n} |x_k|$

- Largest term will dominate as if we common factor out the largest term, each of the other terms will go to 0 as noted in the lp norm.

4. **Cardinality**  $p = 0$ : The number of non-zero vectors in  $x$  is

$$\|\mathbf{x}\|_0 = \text{card}(\mathbf{x}) \equiv \sum_{k=1}^n \mathbb{I}(x_k \neq 0), \quad \text{where} \quad \mathbb{I}(x_k \neq 0) \equiv \begin{cases} 1 & \text{if } x_k \neq 0 \\ 0 & \text{otherwise.} \end{cases}$$

- **Key:** Not a norm since  $\|\alpha \mathbf{x}\|_0 = \|\mathbf{x}\|_0 \neq |\alpha| \cdot \|\mathbf{x}\|_0$  (e.g. if  $\alpha = 2$  then this would double the count of number of non-zero vectors for the RS)

### 2.8.1 Norm balls

**Definition:** The set of all vectors with  $\ell_p$  norm less than or equal to one,

$$B_p = \{\mathbf{x} : \|\mathbf{x}\|_p \leq 1\} \quad (1)$$

**Example:** For 2D, the norm balls are as follows:

- $\ell_2$ :  $B_2 = \left\{ \mathbf{x} \mid \sqrt{x_1^2 + x_2^2} \leq 1 \right\}$
- $\ell_1$ :  $B_1 = \{ \mathbf{x} \mid |x_1| + |x_2| \leq 1 \}$
- $\ell_\infty$ :  $B_\infty = \{ \mathbf{x} \mid \max |x_i| \leq 1 \text{ or } |x_1| \leq 1, |x_2| \leq 1 \}$
- $\ell_0$ :  $B_0 = \{ \mathbf{x} \mid \text{card}(\mathbf{x}) \leq 1 \}$

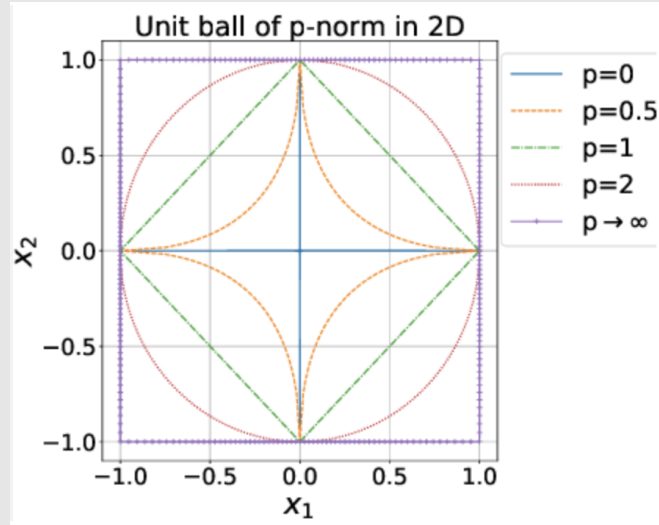


Figure 2: Norm balls of different p values.

### 2.8.2 Motivation for Norms

**Example:** In optimization problems, different norms are used to achieve various goals. Suppose we are trying to solve an optimal control problem, where  $x = (x_1, \dots, x_n)$  are some action variables.

- $\min \|x\|_2^2 = x_1^2 + \dots + x_n^2$  (i.e. minimizing the total energy (power) in  $x$ )
- $\min \|x\|_\infty$  (i.e. minimizing the peak energy in  $x$ ).
- $\min \|x\|_1$  (i.e. minimizing the sum of action variables).
- $\min \|x\|_0$  (i.e. find sparse solution)

### 2.8.3 Distance metric

**Definition:** A norm induces a distance metric between two vectors  $x$  and  $y$  in  $\mathbb{V}$  as

$$d(x, y) = \|x - y\|$$

- **Note:** The  $\ell_2$ -norm induces the Euclidean distance

$$\|x - y\|_2 = \sqrt{\sum_{i=1}^n (x_i - y_i)^2}$$

## 2.9 Inner product (Notion of angle)

**Definition:** An inner product on a vector space  $\mathcal{V}$  is a function  $\langle \cdot, \cdot \rangle : \mathcal{V} \times \mathcal{V} \rightarrow \mathcal{F}$  such that:

1. **Positive definiteness:**  $\langle x, x \rangle \geq 0 \forall x \in \mathcal{V}$  and  $\langle x, x \rangle = 0$  iff  $x = 0$
2. **Conjugate Symmetry:**  $\langle x, y \rangle = \overline{\langle y, x \rangle}$ 
  - $\langle x, y \rangle = \langle y, x \rangle$  in  $\mathbb{R}^n$
  - $\langle x, y \rangle = \overline{\langle y, x \rangle}$  in  $\mathbb{C}^n$ .
3. **Linearity in first argument:**  $\langle \alpha x + y, z \rangle = \alpha \langle x, z \rangle + \langle y, z \rangle \quad \forall x, y, z \in \mathcal{V}, \alpha \in \mathbb{F}$

**Example:** How to use the properties of inner products?

$$\begin{aligned}
 \langle x, \alpha y + z \rangle &\stackrel{(2)}{=} \overline{\langle \alpha y + z, x \rangle} \\
 &\stackrel{(3)}{=} \overline{\alpha \langle y, x \rangle + \langle z, x \rangle} \quad \text{also by conjugate prop.} \\
 &\stackrel{(2)}{=} \overline{\alpha} \overline{\langle y, x \rangle} + \overline{\langle z, x \rangle} \\
 &\stackrel{(2)}{=} \overline{\alpha} \langle x, y \rangle + \langle x, z \rangle
 \end{aligned}$$

### 2.9.1 Examples of inner products

**Example:**

- In  $\mathbb{R}^n$  (Dot product):  $\langle \mathbf{x}, \mathbf{y} \rangle = \sum_{i=1}^n x_i y_i = \mathbf{x}^\top \mathbf{y} = \mathbf{y}^\top \mathbf{x}$ 
  - Key:**  $\langle \mathbf{x}, \mathbf{x} \rangle = \sum_{i=1}^n x_i^2 = \mathbf{x}^\top \mathbf{x} = \|\mathbf{x}\|_2^2$
- In  $\mathbb{C}^n$ :  $\langle \mathbf{x}, \mathbf{y} \rangle = \sum_{i=1}^n \overline{x_i} y_i = \mathbf{y}^H \mathbf{x} = \overline{\mathbf{x}^H \mathbf{y}}$ 
  - $\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$      $\mathbf{x}^H = [\overline{x_1} \quad \cdots \quad \overline{x_n}]$
- $\mathcal{V} = \left\{ f : \mathbb{R} \rightarrow \mathbb{R}; \int_{-\infty}^{+\infty} f^2(t) dt < \infty \right\}$  (i.e. the set of square integrable functions)
 
$$\langle f, g \rangle = \int_{-\infty}^{+\infty} f(t)g(t) dt$$

### 2.9.2 Connection of inner product to angle

In  $\mathbb{R}^n$ , the notion of inner product has a geometric interpretation, and is closely related to the notion of angle between vectors.

**Definition:**

$$\cos \theta = \frac{\langle \mathbf{x}, \mathbf{y} \rangle}{\|\mathbf{x}\|_2 \|\mathbf{y}\|_2} = \left\langle \frac{\mathbf{x}}{\|\mathbf{x}\|_2}, \frac{\mathbf{y}}{\|\mathbf{y}\|_2} \right\rangle \quad (2)$$

- $\langle \mathbf{x}, \mathbf{y} \rangle = 0 \Rightarrow \cos \theta = 0 \Rightarrow \theta = \frac{\pi}{2}$  (i.e. perpendicular)
- $\langle \mathbf{x}, \mathbf{y} \rangle = \|\mathbf{x}\|_2 \|\mathbf{y}\|_2 \Rightarrow \cos \theta = 1 \Rightarrow \theta = 0$  (i.e.  $\mathbf{x}$  and  $\mathbf{y}$  are aligned)
- $\langle \mathbf{x}, \mathbf{y} \rangle = -\|\mathbf{x}\|_2 \|\mathbf{y}\|_2 \Rightarrow \cos \theta = -1 \Rightarrow \theta = \pi$  (i.e.  $\mathbf{x}$  and  $\mathbf{y}$  are in opposite directions)
- $\langle \mathbf{x}, \mathbf{y} \rangle > 0 \Rightarrow \cos \theta > 0 \Rightarrow$  angle is acute
- $\langle \mathbf{x}, \mathbf{y} \rangle < 0 \Rightarrow \cos \theta < 0 \Rightarrow$  angle is obtuse

**Derivation:** L3: Inner products and orthogonality.

### 2.9.3 Cauchy-Schwartz inequality and its generalization

**Definition:**

$$|\langle \mathbf{x}, \mathbf{y} \rangle| \leq \|\mathbf{x}\|_2 \|\mathbf{y}\|_2 \quad (3)$$

**Hölder's Inequality (generalization):**

$$|\langle \mathbf{x}, \mathbf{y} \rangle| \leq \|\mathbf{x}\|_p \|\mathbf{y}\|_q \quad \text{where } 1 \leq p, q < \infty \text{ and } \frac{1}{p} + \frac{1}{q} = 1 \quad (4)$$

**Example:** For  $p = 1$  and  $q = \infty$ , we have:

$$|\langle \mathbf{x}, \mathbf{y} \rangle| \leq \|\mathbf{x}\|_1 \cdot \|\mathbf{y}\|_\infty$$

$$|\langle \mathbf{x}, \mathbf{y} \rangle| \leq \left( \sum_{i=1}^n |x_i| \right) \cdot \max_i |y_i|$$

## 2.9.4 Inner product induces a norm

**Definition:** Any inner product induces a norm, but not all norms are induced by an inner product.

- **Key:** If given an inner product, take the square root of the inner product to get the norm.
  - e.g.  $\|\mathbf{x}\|_2 = \sqrt{\langle \mathbf{x}, \mathbf{x} \rangle}$ , which holds for  $\mathbb{R}^n$  and  $\mathbb{C}^n$



Figure 3: Ordering of the vector spaces.

**Warning:** A norm doesn't induce an inner product (e.g.  $l_1$  or  $l_\infty$ )

## 2.10 Orthogonal decomposition

### 2.10.1 Mutually orthogonal

**Definition:** A set of non-zero vectors  $S = \{\mathbf{v}^{(1)}, \mathbf{v}^{(2)}, \dots, \mathbf{v}^{(d)}\}$  is **mutually orthogonal** if  $\langle \mathbf{v}^{(i)}, \mathbf{v}^{(j)} \rangle = 0 \forall i \neq j$ .

- **Fact:** Orthogonal set of vectors  $S = \{\mathbf{v}^{(1)}, \mathbf{v}^{(2)}, \dots, \mathbf{v}^{(d)}\}$  is linearly independent.
  - **Proof:** In L3.

### 2.10.2 Orthonormal basis

**Definition:** Set of orthogonal basis vectors that have unit norm.

If  $S = \{\mathbf{v}^{(1)}, \mathbf{v}^{(2)}, \dots, \mathbf{v}^{(d)}\}$  is a set of mutually orthogonal vectors, then  $\left\{ \frac{\mathbf{v}_1}{\|\mathbf{v}_1\|}, \dots, \frac{\mathbf{v}_d}{\|\mathbf{v}_d\|} \right\}$  is an orthonormal basis for  $\text{span}(S)$

**Example:** Standard basis is an orthonormal basis for  $\mathbb{R}^n$

### 2.10.3 Orthogonal

**Definition:** Consider  $\mathbf{x} \in \mathcal{V}$ , and let  $S$  be a subspace of  $\mathcal{V}$ . We say  $\mathbf{x}$  is orthogonal to  $S$  if:

$$\langle \mathbf{x}, \mathbf{v} \rangle = 0 \quad \forall \mathbf{v} \in S.$$

We write:  $\mathbf{x} \perp S$ .

### 2.10.4 Orthogonal complement

**Definition:** The **orthogonal complement** of  $S$ , denoted  $S^\perp$ , is the set of all orthogonal vectors to  $S$ :

$$S^\perp = \{\mathbf{x} \in \mathcal{V} : \mathbf{x} \perp S\}$$

- $S^\perp$  is a subspace. (Closed under addition and scalar multiplication)
- $S \cap S^\perp = \{\mathbf{0}\}$
- **Orthogonal decomposition:** Any  $\mathbf{x} \in \mathcal{V}$  can be uniquely written as:  $\mathbf{x} = \mathbf{x}_S + \mathbf{x}_{S^\perp}$  where  $\mathbf{x}_S \in S$  and  $\mathbf{x}_{S^\perp} \in S^\perp$

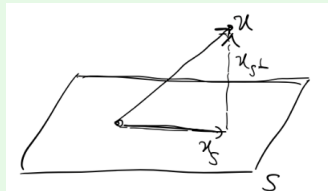


Figure 4: Drawing any  $\mathbf{x}$ .

- $\mathcal{V} = S + S^\perp = \{\mathbf{u} + \mathbf{v} : \mathbf{u} \in S, \mathbf{v} \in S^\perp\}$

### 3 Orthogonal Decomposition, Projecting onto Subspaces, Gram-Schmidt, QR Decomposition, Projection onto Affine Sets, Hyperplanes and Half-Spaces (Ch. 2.2-2.3)

#### 3.1 Projection onto subspaces

**Definition:**

$$x^* = \text{Proj}_S(x) = \arg \min_{y \in S} \|x - y\|_2 \quad (5)$$

If  $\{v^{(1)}, \dots, v^{(d)}\}$  is an orthonormal basis of  $S$  then

$$x^* = \sum_{i=1}^d \langle x, v^{(i)} \rangle v^{(i)} \quad (6)$$

- The error vector should be orthogonal to each vector in the subspace.

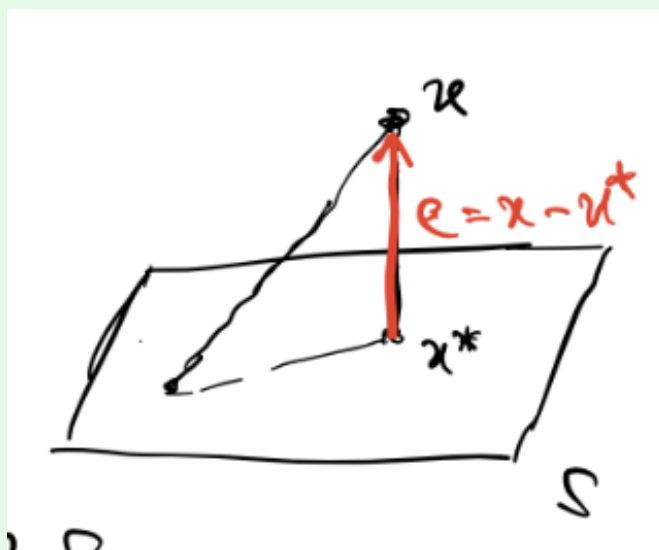


Figure 5: Error vector being perp. to  $S$ .

**Example:** For  $v = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$

The  $i$ th component can be extracted by doing the inner product with the  $i$ th standard basis:

$$\begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = v_1$$

$$\begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = v_2$$

$$\begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = v_3$$

Therefore, analogous to  $\mathbf{x}^*$ , we can write them as the sum of the inner product times the standard basis.

$$v = v_1 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + v_2 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} + v_3 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

### 3.1.1 Basic problem

**Intuition:** Given  $x \in \mathcal{V}$  and a subspace  $S$ . Find the closest point (in norm) in  $S$  to  $x$ :

$$\text{Proj}_S(x) = \arg \min_{y \in S} \|y - x\| \quad (7)$$

- $\|y - x\|$ : Some norm.
- **Subspace:**  $S$  doesn't have to be a subspace.
- **arg min:** Vector  $y$  that minimizes  $\|x - y\|$

### 3.1.2 Projection onto a 1D subspace

**Derivation:** Projection onto a 1-dimensional subspace.

Let  $S = \text{span}(\mathbf{v})$ , and we denote the projection of  $\mathbf{x}$  onto  $S$  as:

$$\text{Proj}_S(\mathbf{x}) = \mathbf{x}^*$$

Under the Euclidean norm (i.e.  $\ell_2$  norm), we have nice geometry: we should have

$$\langle \mathbf{x} - \mathbf{x}^*, \mathbf{v} \rangle = 0$$

Since  $\mathbf{x}^* \in S$ ,  $\mathbf{x}^* = \alpha \mathbf{v}$  for some scalar  $\alpha$ .

We need to find  $\alpha$ .

So,

$$\begin{aligned} \langle \mathbf{x} - \alpha \mathbf{v}, \mathbf{v} \rangle &= 0 \\ \Rightarrow \langle \mathbf{x}, \mathbf{v} \rangle - \alpha \langle \mathbf{v}, \mathbf{v} \rangle &= 0 \\ \Rightarrow \alpha &= \frac{\langle \mathbf{x}, \mathbf{v} \rangle}{\langle \mathbf{v}, \mathbf{v} \rangle} \end{aligned}$$

Thus,

$$\mathbf{x}^* = \alpha \mathbf{v} = \frac{\langle \mathbf{x}, \mathbf{v} \rangle}{\langle \mathbf{v}, \mathbf{v} \rangle} \mathbf{v}$$

which simplifies to:

$$\mathbf{x}^* = \frac{\mathbf{x}^\top \mathbf{v}}{\|\mathbf{v}\|_2^2} \mathbf{v} = \left\langle \mathbf{x}, \frac{\mathbf{v}}{\|\mathbf{v}\|_2} \right\rangle \frac{\mathbf{v}}{\|\mathbf{v}\|_2}$$

- **Orthonormal Basis for S:**  $\left\{ \frac{\mathbf{v}}{\|\mathbf{v}\|_2} \right\}$  since  $\left\| \frac{\mathbf{v}}{\|\mathbf{v}\|_2} \right\|_2 = 1$
- **Projection Coefficient:**  $\left\langle \mathbf{x}, \frac{\mathbf{v}}{\|\mathbf{v}\|_2} \right\rangle$
- **Note:**  $\mathbf{x}^*$  is the point we are looking for in the projection problem.

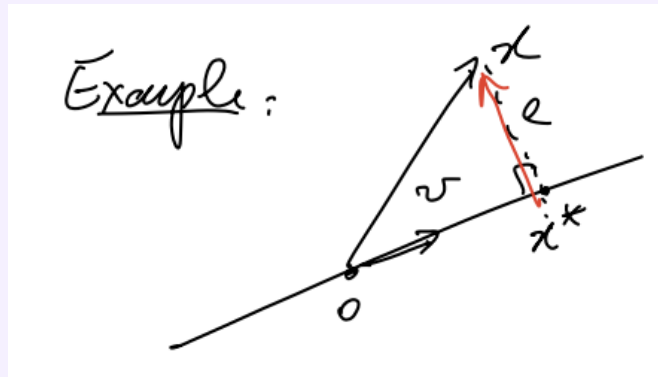


Figure 6: Visual representation of the projection problem.

### 3.1.3 Projection onto an n dimensional space

**Derivation:** Let  $S$  be a subspace of  $\mathcal{V}$ , and let  $\{\mathbf{v}_1, \dots, \mathbf{v}_d\}$  be an orthonormal basis of  $S$ .

#### 1. Problem setup

$$\mathbf{x}^* = \sum_{i=1}^d \alpha_i \mathbf{v}_i$$

**Goal:** Find  $\alpha_1, \dots, \alpha_d$  so as to minimize the norm  $\|\mathbf{x} - \mathbf{x}^*\|_2$ .

#### 2. Derivation: By geometry, we require that

$$\langle \mathbf{e}, \mathbf{v}_j \rangle = 0 \quad \forall j = 1, \dots, d$$

which implies:

$$\begin{aligned} \langle \mathbf{x} - \mathbf{x}^*, \mathbf{v}_j \rangle &= 0 \quad \forall j \\ \Rightarrow \langle \mathbf{x} - \sum_{i=1}^d \alpha_i \mathbf{v}_i, \mathbf{v}_j \rangle &= 0 \quad \forall j \end{aligned}$$

Using linearity of the inner product:

$$\Rightarrow \langle \mathbf{x}, \mathbf{v}_j \rangle = \sum_{i=1}^d \alpha_i \langle \mathbf{v}_i, \mathbf{v}_j \rangle$$

Since  $\langle \mathbf{v}_i, \mathbf{v}_j \rangle = 0$  if  $i \neq j$  and 1 if  $i = j$ , this simplifies to:

$$\alpha_j = \langle \mathbf{x}, \mathbf{v}_j \rangle \quad \text{b/c only the } i=j \text{ term survives}$$

Thus,

$$\mathbf{x}^* = \sum_{i=1}^d \alpha_i \mathbf{v}_i = \sum_{i=1}^d \langle \mathbf{x}, \mathbf{v}_i \rangle \mathbf{v}_i$$

#### 3. Solution:

$$= \sum_{i=1}^d (\mathbf{x}^\top \mathbf{v}_i) \mathbf{v}_i$$

- $\mathbf{v}_i \in \mathbb{R}^n$ .
- **Projection Coefficients:**  $\mathbf{x}^\top \mathbf{v}_i$

#### 4. Example of Orthogonal Decomposition:

$$\mathbf{e} = \mathbf{x} - \mathbf{x}^* \in S^\perp, \quad \mathbf{x}^* \in S$$

So,

$$\mathbf{x} = \mathbf{x}^* + \mathbf{e}, \quad \text{where } \mathbf{x}^* \in S, \quad \mathbf{e} \in S^\perp$$



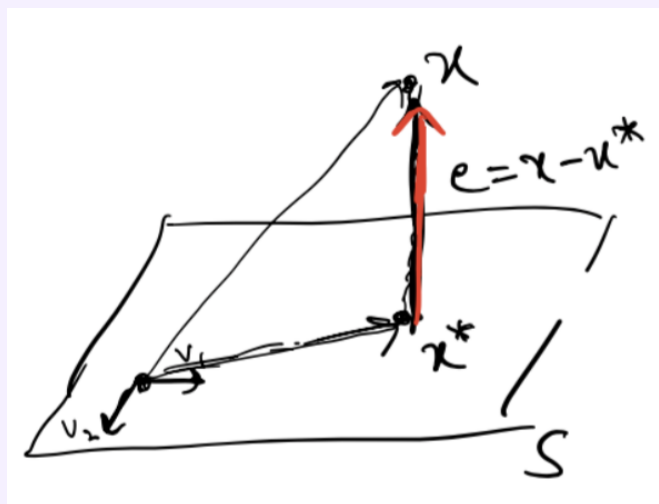


Figure 7: Generalization of projection.

### 3.1.4 Application of projections: Fourier series

#### Example: Fourier series:

1. Suppose we have a periodic function  $x(t)$  with period  $T_0$ .

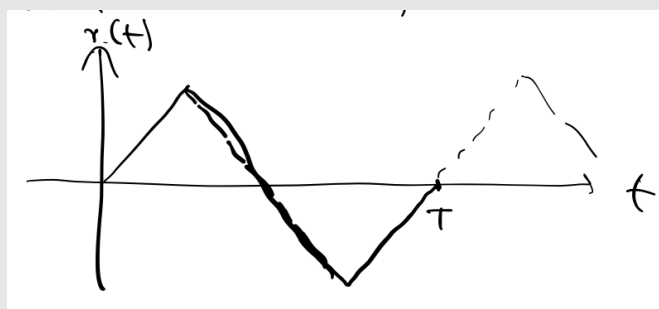


Figure 8: Periodic triangle function.

2. **Inner product for time domain (complex version):**  $a_k = \langle x(t), y(t) \rangle = \frac{1}{T} \int_T x(t) \overline{y(t)} dt$

- **Note:** Real version is without the conjugate.

3. **Projection (i.e. one component of the sum):**  $\text{Proj}_{\underline{v}_i}(\underline{x}) = \langle \underline{x}, \underline{v}_i \rangle \underline{v}_i$

4. **Goal:** Express  $x(t)$  (i.e. any periodic function) as a sum of complex exponentials:

$$x^*(t) = \sum_{k=-\infty}^{\infty} a_k e^{jk\omega_0 t}$$

- **Projection:**  $\text{Proj}_{e^{jk\omega_0 t}}(x(t)) = \langle x(t), \exp(jk\omega_0 t) \rangle e^{jk\omega_0 t} = a_k e^{jk\omega_0 t}$  for a certain value of  $k$ .

- **Projection coefficient:**  $a_k = \langle x(t), e^{jk\omega_0 t} \rangle = \frac{1}{T_0} \int_0^T x(t) e^{-jk\omega_0 t} dt$

- **Fundamental frequency:**  $\omega_0 = \frac{2\pi}{T_0}$ .

5. **Prove orthonormal basis for the complex exponentials:** To prove it's an orthonormal basis, must prove it has unit norm 1 and each pair of vectors are orthogonal (i.e. inner product is 0).

- (a) **Magnitude of exp:**  $|e^{j\theta}| = 1$ . Therefore, it has unit norm.

(b) **Orthogonality:**

$$\langle e^{ji\omega_0 t}, e^{jl\omega_0 t} \rangle = \begin{cases} 1, & i = l \\ 0, & i \neq l \end{cases}$$

Therefore, for each pair of basis vectors, they are orthogonal.

• **Conjugate of exp:**  $(e^{j\theta}) = e^{-j\theta}$

6. **Conclusion:** Fourier series is a projection of a function onto the set of orthonormal basis functions  $\exp(jk\omega_0 t)$ , where  $k$  is an integer.

• **Optimal:** This projection is optimal as it minimizes the approximation error  $\|x(t) - x^*(t)\|$ , i.e.

$$\frac{1}{T} \int_0^T (x(t) - x^*(t))^2 dt$$

As the number of terms in the summation increases to infinity, the error goes to 0.

## 3.2 Gram-Schmidt and QR decomposition

### 3.2.1 What if the set of basis vectors is not orthonormal?

**Derivation:** Let  $\{u^{(1)}, \dots, u^{(d)}\}$  be a set of basis vectors for a subspace  $S$  (not necessarily orthonormal)

We can still use the orthogonality principle, i.e.,

$$e = x - x^* \perp S$$

Therefore,

$$\langle x - x^*, u^{(j)} \rangle = 0 \quad \forall j = 1, \dots, d$$

Also,  $x^* \in S$  so  $x^*$  can be written as a linear combination of basis vectors, so  $x^* = \sum_{i=1}^d \alpha_i u^{(i)}$

Need to find  $\alpha_1, \dots, \alpha_d$  s.t.

$$\begin{aligned} \langle x - \sum_{i=1}^d \alpha_i u^{(i)}, u^{(j)} \rangle &= 0 \quad \forall j = 1, \dots, d \\ \Rightarrow \langle x, u^{(j)} \rangle &= \sum_{i=1}^d \alpha_i \langle u^{(i)}, u^{(j)} \rangle \quad \forall j = 1, \dots, d \end{aligned}$$

$$\begin{bmatrix} \langle u^{(1)}, u^{(1)} \rangle & \langle u^{(2)}, u^{(1)} \rangle & \dots & \langle u^{(d)}, u^{(1)} \rangle \\ \langle u^{(1)}, u^{(2)} \rangle & \langle u^{(2)}, u^{(2)} \rangle & \dots & \langle u^{(d)}, u^{(2)} \rangle \\ \vdots & \vdots & \ddots & \vdots \\ \langle u^{(1)}, u^{(d)} \rangle & \langle u^{(2)}, u^{(d)} \rangle & \dots & \langle u^{(d)}, u^{(d)} \rangle \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_d \end{bmatrix} = \begin{bmatrix} \langle x, u^{(1)} \rangle \\ \langle x, u^{(2)} \rangle \\ \vdots \\ \langle x, u^{(d)} \rangle \end{bmatrix}$$

Solve for  $\alpha_1, \dots, \alpha_d$ , Then, we get  $x^* = \sum_{i=1}^d \alpha_i u^{(i)}$

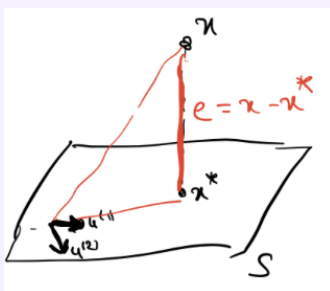


Figure 9: Not orthogonal, but similar to projection with orthonormal basis.

- **Note:** If  $\{u^{(1)}, \dots, u^{(d)}\}$  is an orthonormal basis, then the matrix is the identity matrix, and we get  $\alpha_j = \langle x, u^{(j)} \rangle$  as before.

**Example: Function approximation.** Let  $B$  be the set of basis functions that is not orthonormal:

$$\mathcal{B} = \{1, t, \dots, t^d\}$$

Let  $x(t)$  be a function over  $[0, 1]$ .

- **1st Goal** Approximate  $x(t)$  by  $x^*(t) = \sum_{n=0}^d \alpha_n t^n$
- To find  $\alpha_0, \alpha_1, \dots, \alpha_d$ , need to solve the  $Ax = b$ .
- **2nd Goal:** Minimize the approximation error  $\|x(t) - x^*(t)\|_2 = \left( \int_0^1 (x(t) - x^*(t))^2 dt \right)^{1/2}$

**Recall: Taylor series expansion**

$$x(t) \approx x(0) + x'(0)t + \frac{x''(0)}{2}t^2 + \dots$$

- Taylor series expansion is completely different from the projection method, and the reason is that Taylor series expansion is a local approximation.

### 3.2.2 Gram-Schmidt Procedure

**Motivation:** This is to get an orthonormal basis, so we can use the easier projection method.

**Intuition:** Another way to find the projection of  $x$  onto  $S = \text{span}\{u^{(1)}, \dots, u^{(d)}\}$  is to first find an orthonormal basis of  $S$ , and then the projection problem becomes easier.

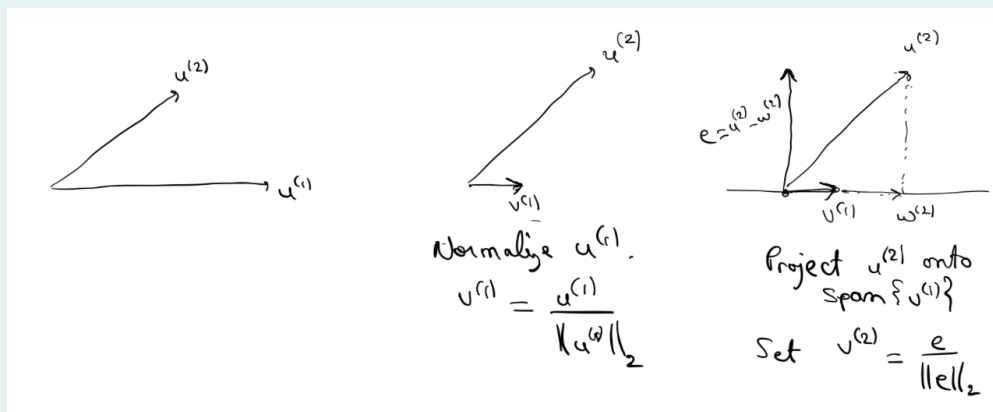


Figure 10: Gram-Schmidt Process for 2D.

1. Normalize  $u^{(1)}$
2. Find the error vector by projecting  $u^{(2)}$  onto the subspace  $v^{(1)}$ .
3. Normalize the error vector.
4. Now you have two vectors that form an orthonormal basis in 2D.

**Definition:** Turns any set of basis vectors of a subspace into an **orthonormal** set of basis vectors.

**Process:**

1. Normalize  $u^{(1)}$  to get  $v^{(1)}$ :

$$v^{(1)} = \frac{u^{(1)}}{\|u^{(1)}\|_2}$$

2. (a) Project  $u^{(2)}$  onto  $S = \text{span}\{v^{(1)}\}$  to get:

$$w^{(2)} = \langle u^{(2)}, v^{(1)} \rangle v^{(1)}$$

(b) Set:

$$v^{(2)} = \frac{u^{(2)} - w^{(2)}}{\|u^{(2)} - w^{(2)}\|_2}$$

3. Continue similarly:

(a) Project  $u^{(3)}$  onto  $S = \text{span}\{v^{(1)}, v^{(2)}\}$  to get:

$$w^{(3)} = \langle u^{(3)}, v^{(1)} \rangle v^{(1)} + \langle u^{(3)}, v^{(2)} \rangle v^{(2)}$$

(b) Set:

$$v^{(3)} = \frac{u^{(3)} - w^{(3)}}{\|u^{(3)} - w^{(3)}\|_2}$$

4. Continue this process for higher dimensions. Therefore,  $\{v^{(1)}, \dots, v^{(d)}\}$  is an orthonormal basis for  $\text{span}\{u^{(1)}, \dots, u^{(d)}\}$ .

**Intuition:**

- Create the Gram matrix by making an orthonormal basis.
- Then this terms the matrix into the identity.

**Warning:** Not every set of vectors in  $\mathbb{R}^n$  turns into the standard basis. It depends on how you apply the Gram-Schmidt.

- For example if you have the vectors  $(1, 0)$  and  $(1, 1)$ .
- If you apply Gram-Schmidt starting with  $(1, 0)$ , then you will get the standard basis.
- But if you apply Gram-Schmidt starting with  $(1, 1)$ , then you will get  $(1/\sqrt{2}, 1/\sqrt{2}), (1/\sqrt{2}, 1/\sqrt{2})$ .

### 3.2.3 QR decomposition

Another way to see Gram-Schmidt procedure is through matrix multiplication.

**Definition:** Stack all  $u^{(i)}$  vectors as columns of a matrix

$$\begin{aligned} [u^{(1)} \quad \dots \quad u^{(d)}] &= QR \\ [u^{(1)} \quad \dots \quad u^{(d)}] &= [v^{(1)} \quad \dots \quad v^{(d)}] \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1d} \\ 0 & r_{22} & \dots & r_{2d} \\ \vdots & & \ddots & \vdots \\ 0 & \dots & 0 & r_{dd} \end{bmatrix} \\ &= [r_{11}v^{(1)} \quad r_{12}v^{(1)} + r_{22}v^{(2)} \quad \dots] \end{aligned}$$

- $Q$ : Orthonormal matrix (i.e., its columns are orthogonal to each other and have unit norm)
  - $Q$  has zero columns when  $A$  is linearly dependent because it's impossible to construct orthogonal vectors for linearly dependent directions of  $A$ .
- $R$ : Upper triangular.

**Intuition:** For  $Ax = b$ , therefore,

$$QRx = b$$

- Since  $Q$  has columns of orthonormal basis, then it has an inverse, which is  $Q^{-1} = Q^T$ .

Then,

$$Rx = Q^T b$$

**Example:**

$$\{1, t, t^2, \dots, t^d\}$$

is *not an orthonormal basis*, which as an example is defined from  $[0, 1]$

The  $L^2$ -norm for this example is given by

$$\|f\|_2 = \left( \int_0^1 f^2(t) dt \right)^{\frac{1}{2}}.$$

The inner product between two functions  $f(t)$  and  $g(t)$  is defined as:

$$\langle f, g \rangle = \int_0^1 f(t)g(t) dt.$$

1. Start with  $u^{(1)} = 1$ , which is equivalent to  $v^{(1)}$  because it's unit norm.
2. For  $u^{(2)}$ , calculate the projection:

$$\omega^{(2)} = \text{Proj}_{\text{span}\{v^{(1)}\}} u^{(2)} = \langle u^{(2)}, v^{(1)} \rangle = \int_0^1 t \cdot 1 dt = \frac{1}{2}.$$

So, the projection of  $u^{(2)}$  onto  $u^{(1)}$  is:

$$\frac{1}{2}v^{(1)}.$$

3. Now subtract the projection from  $u^{(2)}$  and normalize:

$$v^{(2)} = \frac{u^{(2)} - \omega^{(2)}}{\|u^{(2)} - \omega^{(2)}\|_2} = \frac{t - \frac{1}{2}}{\left( \int_0^1 \left(t - \frac{1}{2}\right)^2 dt \right)^{\frac{1}{2}}}.$$

### 3.3 Projection of a subspace defined by its orthogonal vectors

#### 3.3.1 Subspace defined by its orthogonal vectors

**Intuition:**

1. So far, we have defined a subspace by its basis vectors:

$$S = \text{span}\{v^{(1)}, \dots, v^{(d)}\}.$$

2. But, in many cases, we can define  $S$  in terms of the set of vectors that are orthogonal to it.

**Definition:**

$$S = \left\{ x \mid \left( a^{(i)} \right)^T x = 0, i = 1, \dots, m \right\}$$

then the vectors  $a^{(1)}, \dots, a^{(m)}$  are orthogonal to all vectors in  $S$  (i.e. the inner products are 0 for all vectors  $x$  with  $a^{(i)}$ ). Therefore,  $S^\perp = \text{span}\{a^{(1)}, \dots, a^{(m)}\}$ .

**3.3.2 Projection****Derivation:**

1. Projecting a vector  $x$  onto a subspace  $S$  spanned by the vectors  $\{a^{(1)}, \dots, a^{(m)}\}$ . The projection  $x^*$  is given by:

$$x^* = \text{Proj}_S(x) = \arg \min_{y \in S} \|x - y\|_2$$

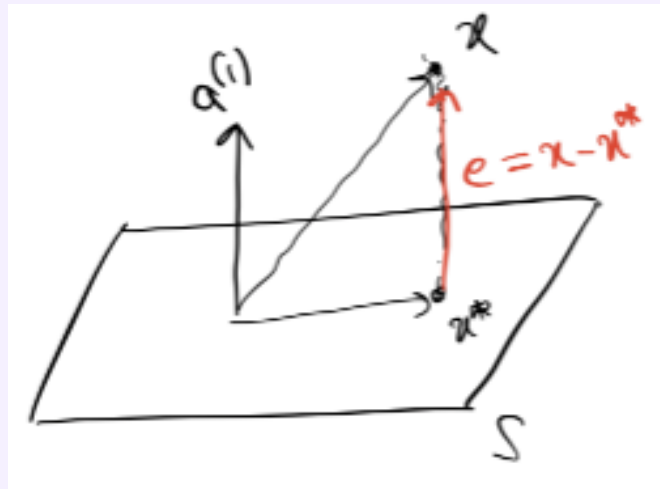


Figure 11: Projection onto a subspace defined by its orthogonal vectors

2. Using the orthogonality principle, the error  $e = x - x^*$  must be orthogonal to the subspace  $S$ , i.e.,

$$e \perp S$$

This implies that:

$$e \in \text{span}\{a^{(1)}, \dots, a^{(m)}\}$$

3. The error can be written as a linear combination of the basis vectors:

$$e = x - x^* = \sum_{i=1}^m \beta_i a^{(i)}$$

We need to find the coefficients  $\beta_1, \dots, \beta_m$ .

4. Since  $x^* \in S$ , we have the condition:

$$\langle x^*, a^{(j)} \rangle = 0 \quad \forall j = 1, \dots, m$$

which leads to the following equation:

$$(a^{(j)})^T x^* = 0 \quad \forall j = 1, \dots, m$$

5. Substituting  $x^* = x - \sum_{i=1}^m \beta_i a^{(i)}$  into the above equation, we get:

$$(a^{(j)})^T \left( x - \sum_{i=1}^m \beta_i a^{(i)} \right) = 0 \quad \forall j$$

6. Expanding the terms using linearity in the first argument for inner products:

$$(a^{(j)})^T x = \sum_{i=1}^m \beta_i (a^{(j)})^T a^{(i)}$$

This system of equations can be written in matrix form as:

$$\begin{bmatrix} (a^{(1)})^T a^{(1)} & \dots & (a^{(1)})^T a^{(m)} \\ \vdots & \ddots & \vdots \\ (a^{(m)})^T a^{(1)} & \dots & (a^{(m)})^T a^{(m)} \end{bmatrix} \begin{bmatrix} \beta_1 \\ \vdots \\ \beta_m \end{bmatrix} = \begin{bmatrix} (a^{(1)})^T x \\ \vdots \\ (a^{(m)})^T x \end{bmatrix}$$

We can solve this system of linear equations to obtain the values of  $\beta_1, \dots, \beta_m$ .

7. Once we have the values of  $\beta_i$ , we can compute the projection as:

$$x^* = x - \sum_{i=1}^m \beta_i a^{(i)}$$

8. **Note:** If the set  $\{a^{(i)}\}$  is orthonormal, the matrix on the left-hand side becomes the identity matrix  $I$ , and the coefficients simplify to:

$$\beta_j = (a^{(j)})^T x = \langle x, a^{(j)} \rangle$$

### 3.4 Projection onto affine sets

#### 3.4.1 Affine spaces

**Definition:** An affine space (or affine set) is a translation (or shift) of a subspace  $S$ .

**Example:** Consider a vector  $x^{(0)}$  (not necessarily in  $S$ ). The affine space  $\mathcal{A}$  is defined as:

$$\mathcal{A} = \{u + x^{(0)} \mid u \in S\}$$

where  $x^{(0)}$  is the shifting vector and  $S$  is the original subspace. This represents a shifted version of the subspace  $S$ .

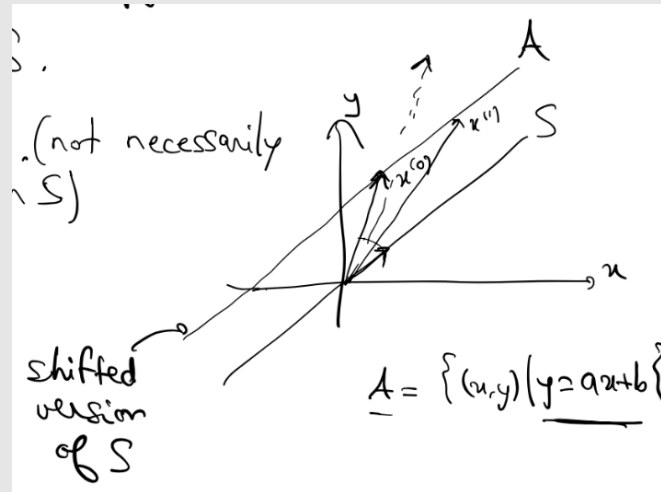


Figure 12: Affine space of a 2D space, where the  $x^{(0)}$  is the constant (i.e. shifting origin to the Affine set) that we are adding to shift all the vectors to the affine space.

### 3.4.2 Projection of Affine space defined in terms of basis vectors of corresponding subspace



**Derivation:**

1. The affine space is described by:

$$\mathcal{A} = \left\{ x \mid x = \sum_{i=1}^d \alpha_i v^{(i)} + c \right\}$$

- $\{v^{(1)}, \dots, v^{(d)}\}$ : Basis vectors of the subspace  $S$
- $c$ : Vector (i.e. shift).

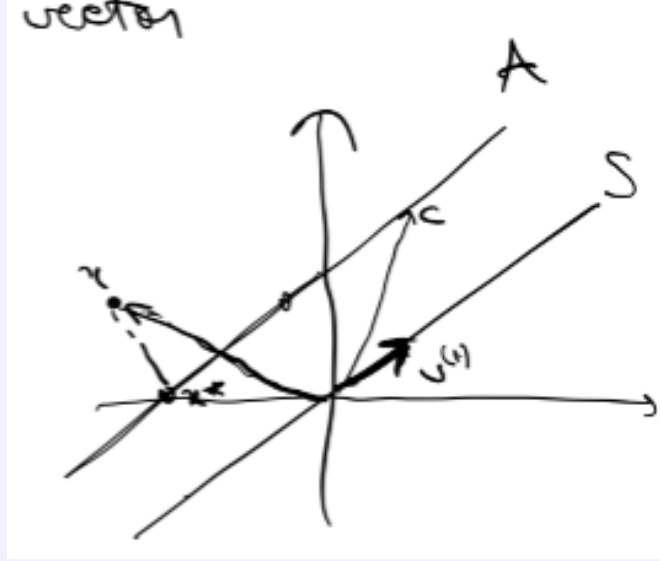


Figure 13: Projection problem visualization, where we are projecting the vector onto the Affine space.

2. Using the orthogonality principle, we must have:

$$\langle x - x^*, v^{(j)} \rangle = 0 \quad \forall j = 1, \dots, d$$

where  $x^* \in \mathcal{A}$ . Therefore:

$$x^* = \sum_{i=1}^d \alpha_i v^{(i)} + c$$

3. This leads to the condition:

$$\left\langle x - \sum_{i=1}^d \alpha_i v^{(i)} - c, v^{(j)} \right\rangle = 0 \quad \forall j = 1, \dots, d$$

4. Simplifying this expression using the linearity in first argument for inner product, we obtain:

$$\langle x - c, v^{(j)} \rangle = \sum_{i=1}^d \alpha_i \langle v^{(i)}, v^{(j)} \rangle \quad \forall j = 1, \dots, d$$

5. To solve for  $\alpha_1, \dots, \alpha_d$ , we set up the following system of linear equations in matrix form:

$$\begin{bmatrix} \langle v^{(1)}, v^{(1)} \rangle & \dots & \langle v^{(1)}, v^{(d)} \rangle \\ \vdots & \ddots & \vdots \\ \langle v^{(d)}, v^{(1)} \rangle & \dots & \langle v^{(d)}, v^{(d)} \rangle \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_d \end{bmatrix} = \begin{bmatrix} \langle x - c, v^{(1)} \rangle \\ \vdots \\ \langle x - c, v^{(d)} \rangle \end{bmatrix}$$

- **Note:** We are projecting onto  $x - c$ , which we can see on the RS, which is the subspace.

6. Solving this system gives us the values for  $\alpha_1, \dots, \alpha_d$ . Finally, the projection  $x^*$  onto the affine space  $\mathcal{A}$  is:

$$x^* = \sum_{i=1}^d \alpha_i v^{(i)} + c$$

**Note:** We are projecting onto  $x - c$  (i.e. subspace), then adding the shift into the end to be back on the Affine set.

### 3.4.3 Projection of Affine space defined in terms of orthogonal vectors to corresponding subspace

#### Derivation:

1. The affine set  $\mathcal{A}$  is defined as:

$$\mathcal{A} = \{x \mid \langle x, a^{(i)} \rangle = d_i, i = 1, \dots, m\}$$

- $d_i$ : Scalars
- $\{a^{(1)}, \dots, a^{(m)}\}$ : A set of vectors spanning the affine space. (Check why this is equivalent to the previous definition of an affine set.)

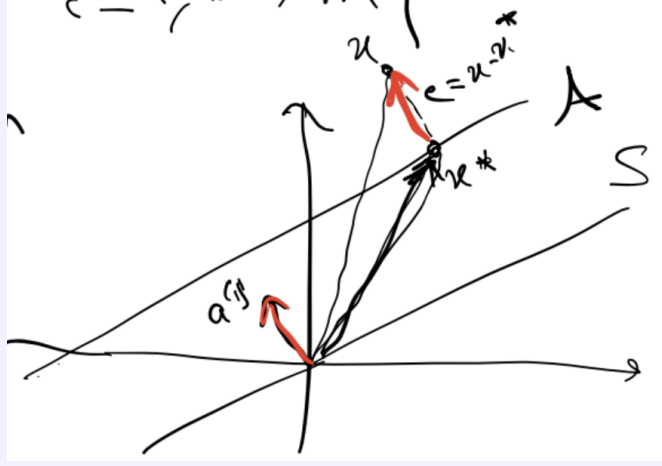


Figure 14: Projection problem visualization, where we are projecting the vector onto the affine space, which is in line with the orthogonal vectors.

2. Since  $x - x^*$  lies in the span of  $\{a^{(1)}, \dots, a^{(m)}\}$ :

$$x - x^* = \sum_{i=1}^m \beta_i a^{(i)}$$

where  $\beta_1, \dots, \beta_m$  are the coefficients to be determined.

3. Since  $x^* \in \mathcal{A}$ , we also have:

$$\langle x^*, a^{(j)} \rangle = d_j \quad \forall j = 1, \dots, m$$

This implies the orthogonality condition for the projection:

$$\langle x - \sum_{i=1}^m \beta_i a^{(i)}, a^{(j)} \rangle = d_j \quad \forall j = 1, \dots, m$$

4. Expanding the above expression using the linearity in first argument for inner product, we get:

$$\langle x, a^{(j)} \rangle - \sum_{i=1}^m \beta_i \langle a^{(i)}, a^{(j)} \rangle = d_j \quad \forall j = 1, \dots, m$$

5. This leads to the system of linear equations:

$$\langle x, a^{(j)} \rangle - d_j = \sum_{i=1}^m \beta_i \langle a^{(i)}, a^{(j)} \rangle \quad \forall j$$

6. We now solve this system of linear equations for the coefficients  $\beta_1, \dots, \beta_m$ . The system can be written in matrix form as:

$$\begin{bmatrix} \langle a^{(1)}, a^{(1)} \rangle & \dots & \langle a^{(1)}, a^{(m)} \rangle \\ \vdots & \ddots & \vdots \\ \langle a^{(m)}, a^{(1)} \rangle & \dots & \langle a^{(m)}, a^{(m)} \rangle \end{bmatrix} \begin{bmatrix} \beta_1 \\ \vdots \\ \beta_m \end{bmatrix} = \begin{bmatrix} \langle x, a^{(1)} \rangle - d_1 \\ \vdots \\ \langle x, a^{(m)} \rangle - d_m \end{bmatrix}$$

7. Solving this system gives the values for  $\beta_1, \dots, \beta_m$ . Once the  $\beta_i$  values are known, the projection  $x^*$  is given by:

$$x^* = x - \sum_{i=1}^m \beta_i a^{(i)}$$

- **Intuition:** This is subtracting the orthogonal components of  $x$  (i.e. removing the error vector) to get  $x$  in the subspace.

**Example:**

1. Consider the case where  $m = 1$ . The affine set  $\mathcal{A}$  is defined as:

$$\mathcal{A} = \{x \mid a^T x = d\}$$

where  $a$  is a vector and  $d$  is a scalar.

2. To project  $x$  onto the affine subspace, we start by using the orthogonality condition:

$$\langle x, a \rangle - d = \beta \langle a, a \rangle$$

This ensures that the difference between  $x$  and its projection  $x^*$  lies in the direction of  $a$ .

3. Solving for  $\beta$ , we get:

$$\beta = \frac{\langle x, a \rangle - d}{\langle a, a \rangle} = \frac{a^T x - d}{\|a\|_2^2}$$

This provides the scalar  $\beta$ , which tells us how much of the vector  $a$  needs to be subtracted from  $x$ .

4. The projection  $x^*$  onto the affine subspace is then:

$$x^* = x - \beta a = x - \left( \frac{a^T x - d}{\|a\|_2^2} \right) a$$

This gives the final expression for the projection of  $x$  onto the affine set  $\mathcal{A}$ .

### 3.4.4 Show that the two affine sets are equal

**Derivation:** We define set  $A$  as follows:

$$A = \left\{ x \in \mathbb{R}^n \mid x = \sum_{i=1}^d \alpha_i v^{(i)} + c \right\}$$

where  $v^{(i)}$  are the basis vectors,  $\alpha_i$  are scalar coefficients, and  $c$  is a fixed vector (the translation vector of the affine set).

Now, we define set  $B$  as:

$$B = \left\{ x \in \mathbb{R}^n \mid a^{(i)T} x = d_i, i = 1, 2, \dots, m \right\}$$

where  $a^{(i)}$  are orthogonal vectors, and  $d_i$  are scalars defining the affine constraints.

**Step 1: Show  $A \subseteq B$ .**

Assume  $x \in A$ , then we can write:

$$x = \sum_{i=1}^d \alpha_i v^{(i)} + c$$

Substitute this into the condition for set  $B$ :

$$a^{(i)T} x = a^{(i)T} \left( \sum_{j=1}^d \alpha_j v^{(j)} + c \right)$$

Expanding the expression:

$$a^{(i)T}x = \sum_{j=1}^d \alpha_j a^{(i)T}v^{(j)} + a^{(i)T}c$$

Since the vectors  $a^{(i)}$  are orthogonal to the vectors  $v^{(j)}$ , we have:

$$a^{(i)T}v^{(j)} = 0 \quad \text{for all } i, j$$

Therefore, the equation simplifies to:

$$a^{(i)T}x = a^{(i)T}c$$

We define  $d_i = a^{(i)T}c$ . Hence,

$$a^{(i)T}x = d_i \quad \text{for all } i$$

Thus,  $x \in B$ .

**Step 2: Show  $B \subseteq A$ .**

Assume  $x \in B$ , then we know:

$$a^{(i)T}x = d_i \quad \text{for all } i = 1, 2, \dots, m$$

This implies that the vector  $x$  satisfies all the affine constraints defined by the vectors  $a^{(i)}$  and scalars  $d_i$ . Now, consider the vector  $c$  such that:

$$a^{(i)T}c = d_i$$

Subtracting this from the affine constraint for  $x$ , we get:

$$a^{(i)T}(x - c) = 0 \quad \text{for all } i$$

This shows that  $x - c$  lies in the null space of the vectors  $a^{(i)}$ . Therefore,  $x - c$  must lie in the span of the vectors  $v^{(i)}$ , meaning:

$$x - c = \sum_{i=1}^d \alpha_i v^{(i)}$$

for some scalars  $\alpha_1, \alpha_2, \dots, \alpha_d$ . Thus,

$$x = \sum_{i=1}^d \alpha_i v^{(i)} + c$$

Therefore,  $x \in A$ .

**Conclusion:**

Since we have shown that  $A \subseteq B$  and  $B \subseteq A$ , we conclude that:

$$A = B$$

This proves that the definition of the affine set in terms of orthogonal vectors and the definition in terms of basis vectors are equivalent.

### 3.5 Summary

**Definition:****Subspace:**

$$S = \left\{ \mathbf{x} \mid \mathbf{x} = \sum_{i=1}^d \alpha_i \mathbf{v}^{(i)} \right\}$$

$$S = \left\{ \mathbf{x} \mid (\mathbf{a}^{(i)})^\top \mathbf{x} = 0, i = 1, \dots, m \right\}$$

**Affine Space:**

$$A = \left\{ \mathbf{x} \mid \mathbf{x} = \sum_{i=1}^d \alpha_i \mathbf{v}^{(i)} + \mathbf{c} \right\}$$

$$A = \left\{ \mathbf{x} \mid (\mathbf{a}^{(i)})^\top \mathbf{x} = d_i, i = 1, \dots, m \right\}$$

**Process:** You have three types of Gram Matrix that you can have, which can all be used to solve the projection problems.

- If you have a set of vectors that are linearly independent, then Gram matrix (i.e. the matrix in every projection problem) is invertible.
- If Gram matrix is orthogonal, then Gram Matrix is diagonal matrix (i.e. identity scaled by some factor)
- If Gram matrix is orthonormal, you have an identity matrix.

### 3.6 Hyperplanes and half-spaces

**Definition:**

- **Hyperplane:** an affine space for the special case  $m = 1$ .

$$\mathcal{H} = \{ \mathbf{x} \mid \mathbf{a}^\top \mathbf{x} = b \} \quad (8)$$

- **Half-space:**

$$\mathcal{H}_+ = \{ \mathbf{x} \mid \mathbf{a}^\top \mathbf{x} \geq b \} \quad (9)$$

$$\mathcal{H}_- = \{ \mathbf{x} \mid \mathbf{a}^\top \mathbf{x} \leq b \} \quad (10)$$

- $\mathbf{x} \in \mathcal{H}_+ \implies$  angle between  $\mathbf{a}$  and  $\mathbf{x}$  is acute.
- $\mathbf{x} \in \mathcal{H}_- \implies$  angle between  $\mathbf{a}$  and  $\mathbf{x}$  is obtuse.

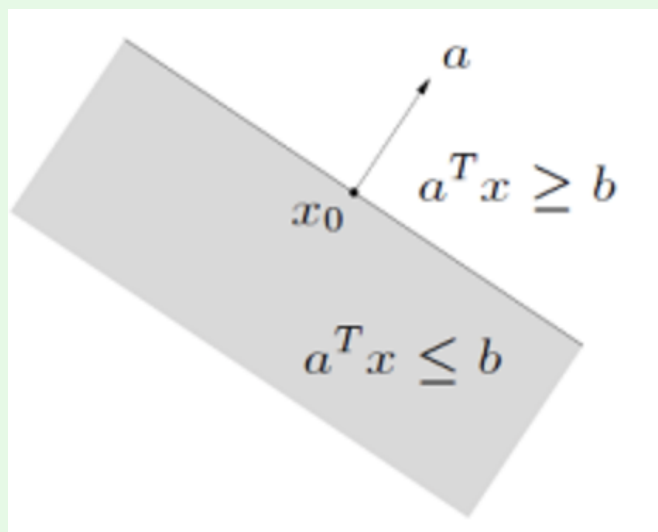


Figure 15: 2D Hyperplane which is the line then the half space, which is separating the line into the above and below b.

**Intuition:**

- In 2D: A hyperplane is a straight line dividing the plane into two regions.
- In 2D: A half-space is the region on one side of a line, which describes all points on one side of the line.
- In 3D: A hyperplane is a flat plane dividing the space into two regions.
- In 3D: A half-space is the region on one side of a plane, which includes all points on one side of the plane.

## 4 Problem set 1

## 5 Non-Euclidean Projection, Functions, Gradients and Hessians (Ch. 2.3-2.4)

### 5.1 Non-Euclidean projection

Intuition:

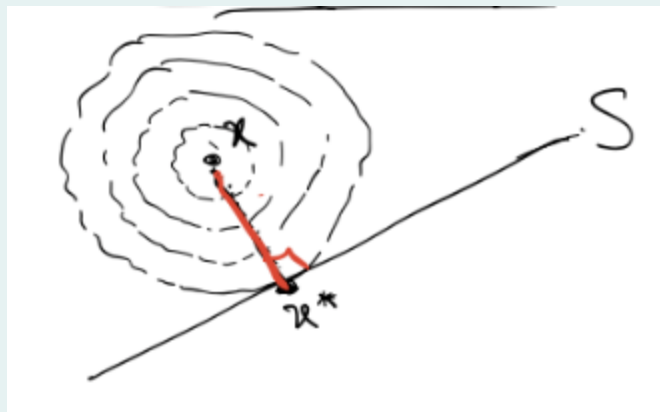


Figure 16:  $l_2$  norm

- **Key:**  $\mathbf{x}^* = \arg \min_{\mathbf{y} \in S} \|\mathbf{x} - \mathbf{y}\|_2$  has the orthogonality principle holds (i.e.  $\mathbf{x} - \mathbf{x}^* \perp S$ )

The projection problem is well-defined in the case of  $l_1$ -norm or  $l_\infty$ -norm, but these norms have **no associated notion of angle and orthogonality**. The following plots show that the vector  $\mathbf{x}$  is not orthogonal to  $\mathbf{x}^*$ .

- **Note:** To get these projections, this must be done through linear programming.

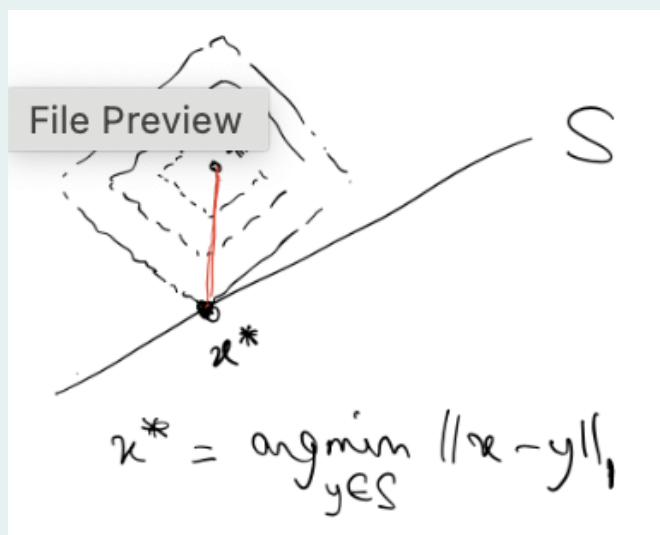


Figure 17:  $l_1$  norm



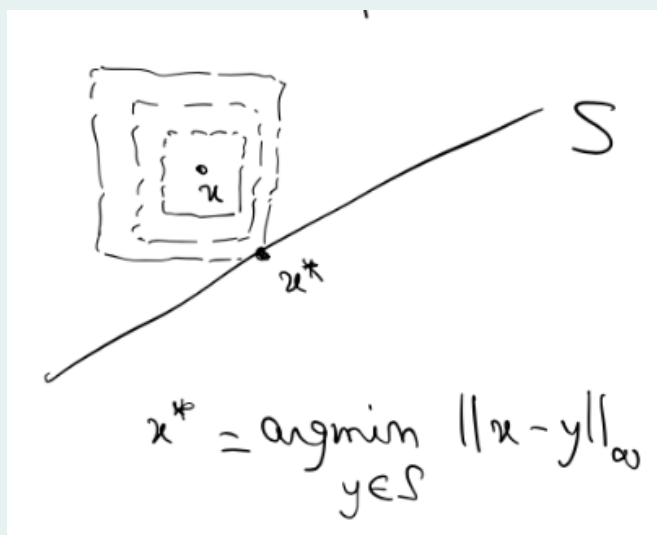


Figure 18: l-infinity norm

## 5.2 Functions

**Definition:** A function is a mapping from a set (domain) to another set (range).

**Example:** Projection function

$$x^* = \arg\min_{y \in \mathcal{H}} \|x - y\| = \text{Proj}_{\mathcal{H}}(x)$$

If  $\mathcal{H}$  is linear (or convex), then  $x^*$  is unique.

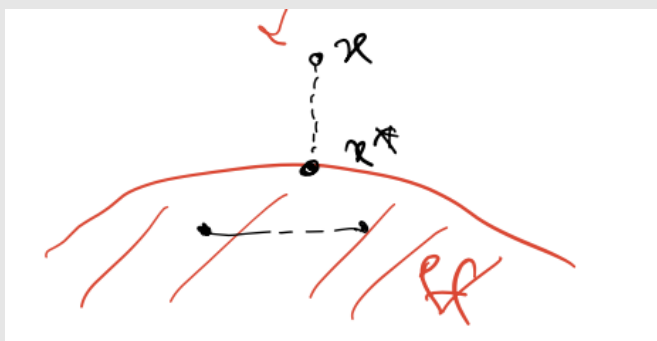


Figure 19: Function: Convex projection because we are projecting one input and getting one output

If  $\mathcal{H}$  is non-convex, the projection might not be unique and the function is not well-defined (i.e. not a function).



Figure 20: Not a function: Non Convex projection because we are projecting one input and getting two outputs

### 5.2.1 Terminology of functions

#### Definition:

- **Map:**  $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ , e.g.  $f(x) = Ax$
- **Operator:**  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ , e.g.  $f(x) = e^x$
- **Functional:**  $f : \mathbb{R}^n \rightarrow \mathbb{R}$ , e.g.  $f(x) = \|x\|_p$

### 5.2.2 Common Sets

#### Definition: Given a functional $f : \mathbb{R}^n \rightarrow \mathbb{R}$ :

- **Graph:**  $\{(x, f(x)) \in \mathbb{R}^{n+1} | x \in \mathbb{R}^n\} \subseteq \mathbb{R}^{n+1}$
- **Epigraph (on or above):**  $\{(x, t) \in \mathbb{R}^{n+1} | x \in \mathbb{R}^n, f(x) \leq t\} \subseteq \mathbb{R}^{n+1}$
- **Level set:**  $L_t = \{x \in \mathbb{R}^n | f(x) = t\} \subseteq \mathbb{R}^n$   
– Parametrized by  $t$  (i.e. scalar).
- **Sublevel set:**  $\{x \in \mathbb{R}^n | f(x) \leq t\} \subseteq \mathbb{R}^n$

#### Example:

- Examples:
- $f(x) = \|x\|_2$  (in  $\mathbb{R}^2$ )

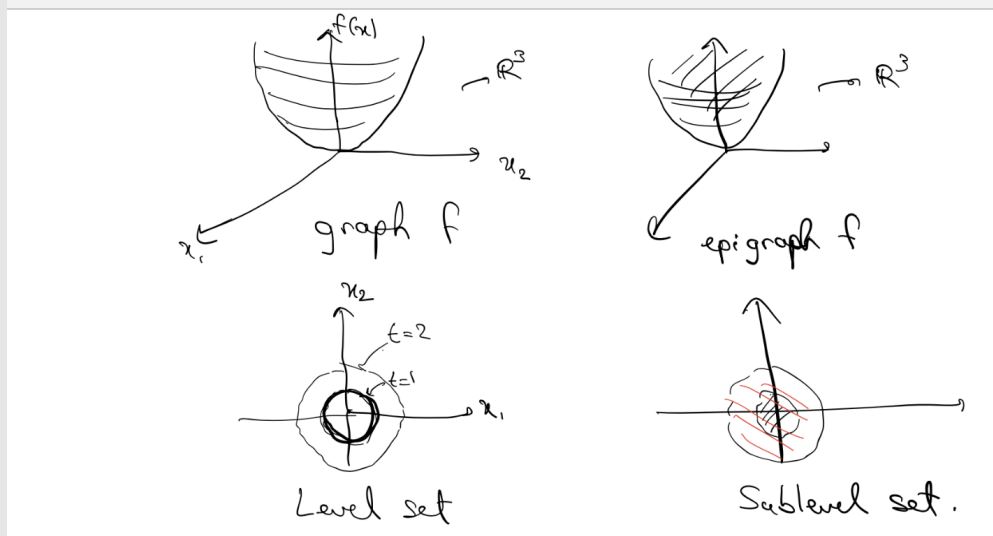


Figure 21: Example of the different common sets.

- The graph is the cup.
- The epigraph is the cup and every inside the cup (i.e. volume)
- The level set is the cross section which is projected onto the  $x_1$  and  $x_2$  axis. (i.e. where  $f(x) = t$ )
- The sublevel set is the level set and everything inside of it.

**Example:**

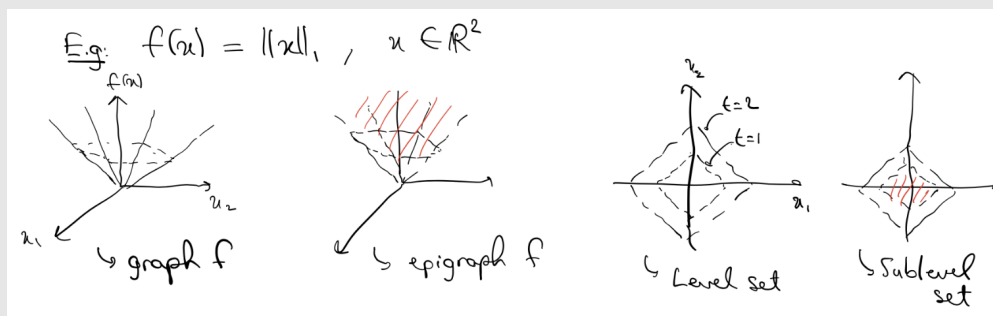


Figure 22: Example of the different common sets for the  $l_1$  norm.

**Example:**

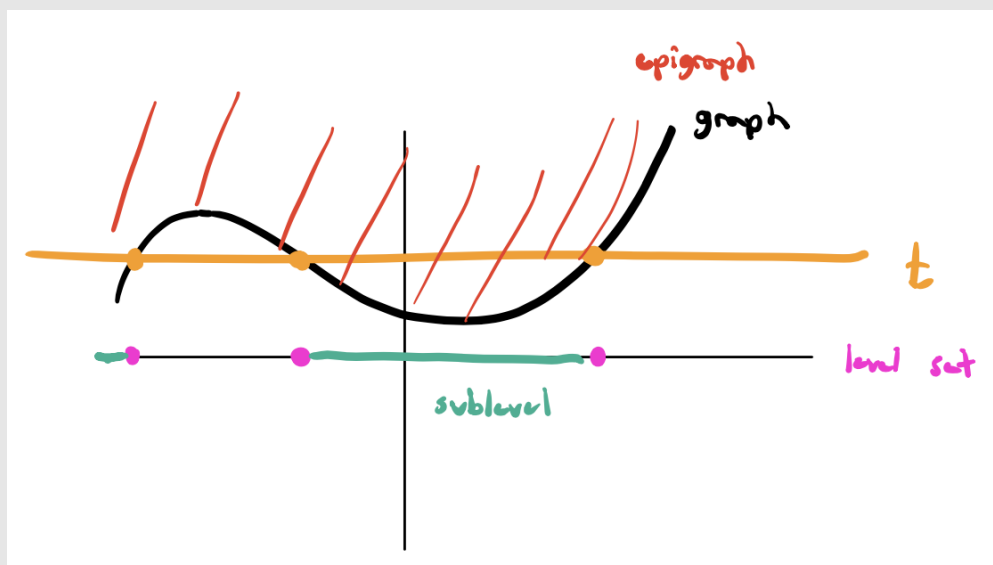


Figure 23: Example of a 2D function.

### 5.2.3 Linear functions

**Definition:** A function  $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is linear if:

- **Homogeneity:**  $f(\alpha x) = \alpha f(x) \quad \forall x \in \mathbb{R}^n, \alpha \in \mathbb{R}$ .
- **Additivity:**  $f(x^{(1)} + x^{(2)}) = f(x^{(1)}) + f(x^{(2)}) \quad \forall x^{(1)}, x^{(2)} \in \mathbb{R}^n$ .

Together, these two properties imply that

$$f\left(\sum_{i=1}^d \alpha_i x^{(i)}\right) = \sum_{i=1}^d \alpha_i f(x^{(i)})$$

- **Subspace:** A function  $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is linear if and only if there exists a matrix  $A \in \mathbb{R}^{m \times n}$  such that  $f(x) = Ax$ .
- **Affine translation:** A function  $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is **affine** if and only if there exist a matrix  $A \in \mathbb{R}^{m \times n}$  and a vector  $b \in \mathbb{R}^m$  such that:  $f(x) = Ax + b$
- **Special Case** For  $m = 1$ ,

$$f(x) = a^\top x + b \rightarrow \text{affine function}$$

$$f(x) = a^\top x \rightarrow \text{linear function}$$

**Example:**

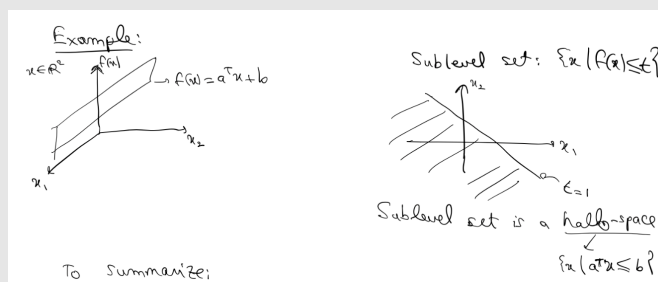


Figure 24: Example 2 of using the linear function, where the sublevel sets are the half-spaces.

**Definition:**

- If  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is **linear**, then the graph of  $f$  is a subspace.
- If  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is **affine**, then the graph of  $f$  is a hyperplane.
- If  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is linear or affine, then the sublevel sets are half-spaces.

### 5.3 Function approximations

**Motivation:** 1st and 2nd order functions are useful to prove convex and non-convex functions.

#### 5.3.1 Gradients

**Definition:** The gradient  $\nabla f$  of a function  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is defined as

$$\nabla f = \begin{bmatrix} \frac{\partial f}{\partial x_1} \\ \vdots \\ \frac{\partial f}{\partial x_n} \end{bmatrix} \in \mathbb{R}^n \quad (11)$$

#### 5.3.2 First-Order Approximation

**Definition:** For  $f : \mathbb{R}^n \rightarrow \mathbb{R}$ , the first-order approximation around  $\bar{x}$  is:

$$f(x) \approx f(\bar{x}) + \nabla f(\bar{x})^\top (x - \bar{x}) \quad (12)$$

- **Recall:** The first-order approximation of  $f : \mathbb{R} \rightarrow \mathbb{R}$  using the Taylor series at the point  $\bar{x}$  is

$$f(x) \approx f(\bar{x}) + \left. \frac{\partial f}{\partial x} \right|_{x=\bar{x}} \cdot (x - \bar{x})$$

- **Notation:**  $\nabla f(\bar{x}) = \nabla f(x) \Big|_{x=\bar{x}}$

**Example:**

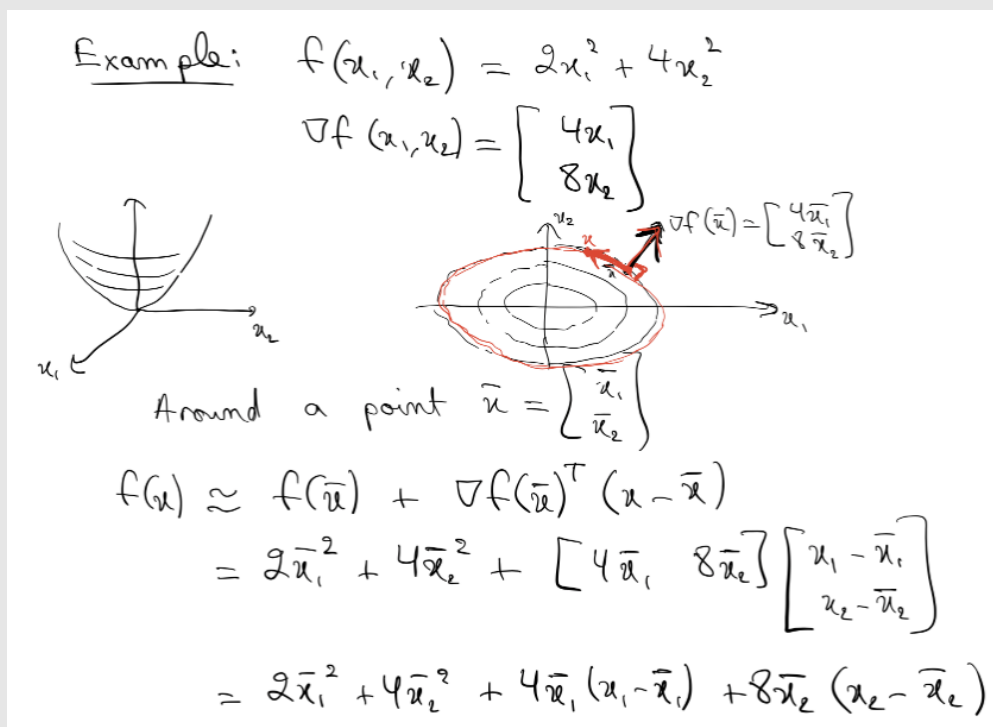


Figure 25: Example of using function approximation for first order. The arrow denotes  $x - x^*$  along the level curve.

### 5.3.3 Gradient properties

#### Intuition:

- The gradient points in the direction where the function is increasing.
  - **Why is the gradient orthogonal to the level sets?**
    - **Explanation:** Level sets are defined as:  $\{x \mid f(x) = t\}$
- But by first order approximation:

$$f(x) \approx f(\bar{x}) + \nabla f(\bar{x})^T (x - \bar{x})$$

So we want to find which direction of the gradient makes  $f(x)$  constant (i.e. be on the level set), so we want to go in the direction such that  $f(x) = f(\bar{x})$ , therefore,

$$\nabla f(\bar{x})^T (x - \bar{x}) = 0$$

Since we want the first order approximation to be  $f(x) = f(\bar{x})$ . This means that the gradient is orthogonal to  $x - x^*$ , which is on the level set. This means that the gradient is orthogonal to the level sets.

- **What about the norm of  $\nabla f(x)$ ?** The norm of  $\nabla f(x)$  gives an indication of the steepness of the graph.
  - **Explanation?**

$$\begin{aligned} f(x) - f(\bar{x}) &\approx (\nabla f(\bar{x}))^T (x - \bar{x}) \\ &= \|\nabla f(\bar{x})\|_2 \|x - \bar{x}\|_2 \left\langle \frac{\nabla f(\bar{x})}{\|\nabla f(\bar{x})\|_2}, \frac{x - \bar{x}}{\|x - \bar{x}\|_2} \right\rangle \\ &= \|\nabla f(\bar{x})\|_2 \|x - \bar{x}\|_2 \cos \theta \end{aligned}$$

- \*  $\theta$  is the angle between  $\nabla f(x)$  and  $(x - \bar{x})$ .
- \* **Key:** The larger  $\|\nabla f(\bar{x})\|_2$ , the larger the change in  $f(x)$  (i.e.  $f(x) - f(\bar{x})$ )
- \* **Minimizing/Maximizing:**
  - $\cos(\theta) = -1$ , which means that this is minimizing  $f(x) - f(\bar{x})$  (i.e. going in the opposite direction of the gradient) because the change (i.e.  $f(x) - f(\bar{x})$ ) is negative.

- $\cos(\theta) = 1$ , which means that this is maximizing  $f(x) - f(\bar{x})$  (i.e. going in the direction of the gradient) because the change (i.e.  $f(x) - f(\bar{x})$ ) is positive.
- $\cos(\theta) = 0$ , which means orthogonal (perpendicular) to the gradient, meaning there is no change in the function value in this direction. The function remains constant in this direction (i.e. level set).

### 5.3.4 Tangent plane

**Definition:** In general, the tangent plane is defined by:

$$\left\{ \begin{bmatrix} x \\ t \end{bmatrix} \in \mathbb{R}^{n+1} \mid t = f(\bar{x}) + \nabla f(\bar{x})^\top (x - \bar{x}) \right\} \quad (13)$$

- The tangent plane at  $\bar{x}$  is defined by the first-order approximation.

This can also be written as:

$$\left\{ \begin{bmatrix} x \\ t \end{bmatrix} \in \mathbb{R}^{n+1} \mid \begin{bmatrix} \nabla f(\bar{x})^\top & -1 \end{bmatrix} \begin{bmatrix} x \\ t \end{bmatrix} = -f(\bar{x}) + \nabla f(\bar{x})^\top \bar{x} \right\} \quad (14)$$

In compact form:

$$a^\top \begin{bmatrix} x \\ t \end{bmatrix} = b \quad (15)$$

- $a^\top = [\nabla f(\bar{x})^\top \quad -1]$
- $b = -f(\bar{x}) + \nabla f(\bar{x})^\top \bar{x}$

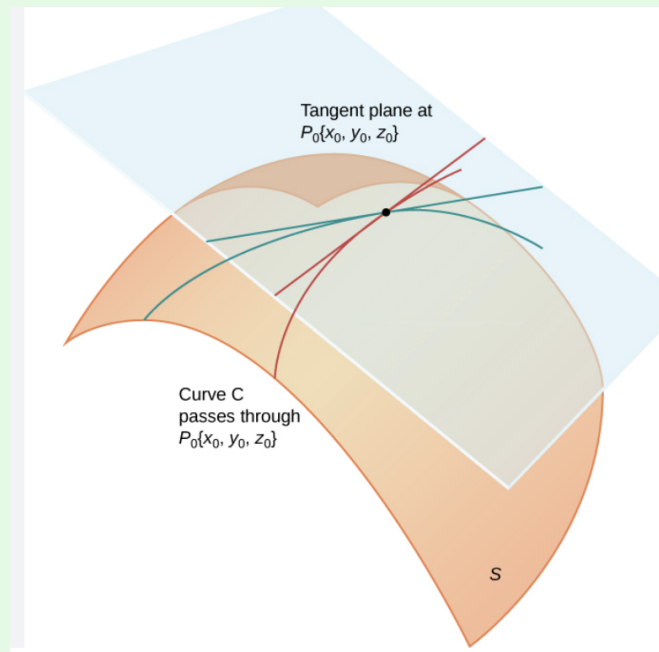


Figure 26: Tangent plane.

**Example:** Given  $f(x_1, x_2) = 2x_1^2 + x_2^2$ , the gradient of  $f(x)$  is:

$$\nabla f(x) = \begin{pmatrix} 4x_1 \\ 2x_2 \end{pmatrix}$$

For the point  $\bar{x} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ , we have:

$$\nabla f(\bar{x}) = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Thus, the first-order approximation is:

$$f(x) \approx f(\bar{x}) + \nabla f(\bar{x})^\top (x - \bar{x}) = 0$$



Figure 27: The tangent plane is defined as the xy-plane since the first order approximation is zero.

Now, for the point  $\bar{x} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ , we have:

$$\nabla f(\bar{x}) = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \quad f(\bar{x}) = 2$$

The first-order approximation is:

$$\begin{aligned} f(x) &\approx f(\bar{x}) + \nabla f(\bar{x})^\top (x - \bar{x}) = 2 + \begin{pmatrix} 4 \\ 0 \end{pmatrix}^\top \begin{pmatrix} x_1 - 1 \\ x_2 \end{pmatrix} \\ &= 2 + 4(x_1 - 1) = 2 + 4x_1 - 4 \\ &= 4x_1 - 2 \end{aligned}$$

Thus, the tangent plane is defined by:

$$\{(x_1, x_2, t) \mid t = 4x_1 - 2\}$$

Using the general form, it can be expressed as In the previous example, the tangent plane was defined by:

$$\left\{ \begin{bmatrix} x_1 \\ x_2 \\ t \end{bmatrix} \mid \begin{bmatrix} 4 & 0 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ t \end{bmatrix} = 2 \right\}$$



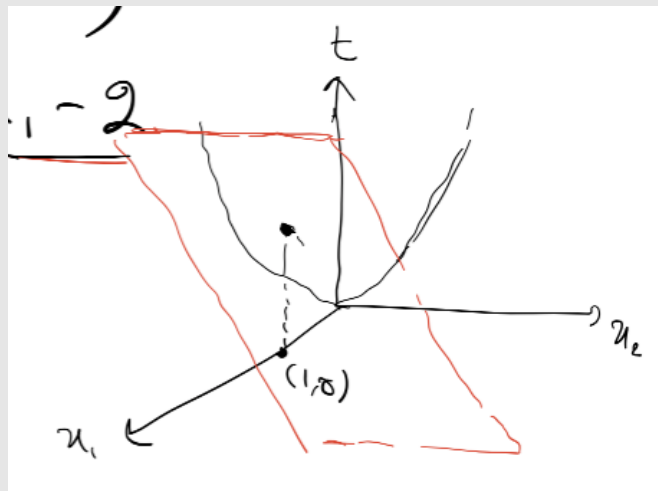


Figure 28: The tangent plane is defined as this plane.

### 5.3.5 Second order approximations

**Definition:** Given a function  $f : \mathbb{R}^n \rightarrow \mathbb{R}$ , the second-order approximation of  $f(x)$  around  $\bar{x}$  is:

$$f(x) \approx f(\bar{x}) + \nabla f(\bar{x})^\top (x - \bar{x}) + \frac{1}{2} (x - \bar{x})^\top \nabla^2 f(\bar{x}) (x - \bar{x}) \quad (16)$$

- **Recall:** The Taylor series expansion of  $f : \mathbb{R} \rightarrow \mathbb{R}$  is:

$$f(x) \approx f(\bar{x}) + \left. \frac{\partial f}{\partial x} \right|_{x=\bar{x}} (x - \bar{x}) + \frac{1}{2} \left. \frac{\partial^2 f}{\partial x^2} \right|_{x=\bar{x}} (x - \bar{x})^2$$

### 5.3.6 Hessians

**Definition:** Hessian matrix  $\nabla^2 f(x)$  is given by:

$$\nabla^2 f(x) = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \frac{\partial^2 f}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{bmatrix} \quad (17)$$

- This is an  $n \times n$  matrix.
- **Note:** The Hessian matrix is symmetric when  $f$  has continuous partial derivatives, because in that case:

$$\frac{\partial^2 f}{\partial x_i \partial x_j} = \frac{\partial^2 f}{\partial x_j \partial x_i}$$

### 5.3.7 Approximating

**Intuition:** If the function you are approximating is 1st order, then 1st and 2nd order approximations will do fit it perfectly. If the function is 2nd order, then only 2nd order will approximate it perfectly. You can prove this by definition of Taylor series to show its equal to the function.

## 6 Matrices, Range, Null Space, Eigenvalues, Eigenvectors, Matrix Diagonalization (Ch. 3.1-3.5)

### 6.1 Matrices

**Definition:** Matrices are two-dimensional arrays of numbers. A general matrix  $A$  is denoted as:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix} = [a^{(1)} \quad \cdots \quad a^{(n)}] \in \mathbb{R}^{m \times n} \quad (\text{or } \mathbb{C}^{m \times n} \text{ for complex numbers}) \quad (18)$$

#### 6.1.1 Matrix Transpose

**Definition:** Given a matrix  $A$  with columns  $a^{(i)}$ , its transpose  $A^\top$  is:

$$A^\top = \begin{bmatrix} (a^{(1)})^\top \\ \vdots \\ (a^{(n)})^\top \end{bmatrix} \in \mathbb{R}^{n \times m} \quad (19)$$

- **Note:**  $(A^\top A)^\top = A^\top A$

#### 6.1.2 Matrix Multiplication

**Definition:** The multiplication of  $A^\top$  and a matrix  $B$  is given by:

$$A^\top B = \begin{bmatrix} (a^{(1)})^\top \\ \vdots \\ (a^{(n)})^\top \end{bmatrix} [b^{(1)} \quad \cdots \quad b^{(n)}] = \begin{bmatrix} (a^{(1)})^\top b^{(1)} & \cdots & (a^{(1)})^\top b^{(n)} \\ \vdots & \ddots & \vdots \\ (a^{(n)})^\top b^{(1)} & \cdots & (a^{(n)})^\top b^{(n)} \end{bmatrix} \in \mathbb{R}^{n \times n} \quad (20)$$

For regular matrix multiplication  $AB$ , we have:

$$AB = [a^{(1)} \quad \cdots \quad a^{(n)}] \begin{bmatrix} (b^{(1)})^\top \\ \vdots \\ (b^{(n)})^\top \end{bmatrix} = \sum_{i=1}^n a^{(i)} (b^{(i)})^\top \in \mathbb{R}^{m \times m} \quad (21)$$

(Note: Try to think why this is the same as before.)

#### 6.1.3 Matrix vector multiplication

**Definition:**

$$Ax = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \sum_{i=1}^n x_i a^{(i)} \in \mathbb{R}^{m \times 1}$$

#### 6.1.4 Block Matrix Product

**Definition:** For a block matrix product:

$$\begin{bmatrix} A & B \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} = AX + BY \quad (22)$$

(Analogous to vectors:  $\begin{bmatrix} a & b \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = ax + by$ )

### 6.1.5 Types of Matrices

**Definition:**

- **Square matrix:**  $m = n$
- **Diagonal matrix:**  $a_{ij} = 0 \quad \forall i \neq j$
- **Identity matrix:**  $a_{ij} = 0 \quad \forall i \neq j, a_{ii} = 1 \quad \forall i$
- **Triangular matrix:**  $A = QR$  ( $R$  is upper triangular)
- **Orthogonal matrix:**  $A^\top A = AA^\top = cI$
- **Orthonormal matrix:**  $A^\top A = AA^\top = I$  (i.e. inverse of  $A$  is  $A^\top$ )
- **Symmetric matrix:**  $A = A^\top$

### 6.1.6 Matrices as Linear Maps

**Definition:** Matrices are used as linear maps, where:

$$y = Ax$$

$$\begin{bmatrix} y \end{bmatrix} \in \mathbb{R}^m = \begin{bmatrix} A \end{bmatrix} \in \mathbb{R}^{m \times n} \quad \begin{bmatrix} x \end{bmatrix} \in \mathbb{R}^n$$

This represents a **linear function**.

For an **affine function**, the equation becomes:

$$y = Ax + b$$

**Intuition:** Linear functions imply a linear mapping. Let  $\mathbf{v} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ .

1.  $A = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

$$A\mathbf{v} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

- Geometric Interpretation:  $A$  leaves the vector  $\mathbf{v}$  unchanged (identity transformation).

2.  $A = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

$$A\mathbf{v} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

- Geometric Interpretation:  $A$  swaps the  $x$  and  $y$  components of the vector, flip it over the line  $y = x$ .

3.  $A = \begin{bmatrix} \frac{1}{\sqrt{2}} & 0 \\ 0 & 1 \end{bmatrix}$

$$A\mathbf{v} = \begin{bmatrix} \frac{1}{\sqrt{2}} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ 1 \end{bmatrix}$$

- Geometric Interpretation:  $A$  scales the  $x$  component of  $\mathbf{v}$  by a factor of  $\frac{1}{\sqrt{2}}$  while leaving the  $y$  component unchanged.

4.  $A = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

$$A\mathbf{v} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

- Geometric Interpretation:  $A$  rotates the vector  $\mathbf{v}$  by  $90^\circ$  counterclockwise.

5.  $A = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$

$$A\mathbf{v} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} \cos \theta - \sin \theta \\ \sin \theta + \cos \theta \end{bmatrix}$$

- Geometric Interpretation:  $A$  rotates the vector  $\mathbf{v}$  by an angle  $\theta$  counterclockwise.

6.  $A = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$

$$A\mathbf{v} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$$

- Geometric Interpretation:  $A$  shears the vector  $\mathbf{v}$ , combining both components into the  $x$ -coordinate while leaving the  $y$ -coordinate unchanged.

## 6.2 Range Space

### Definition:

$$\mathcal{R}(A) = \{Ax \mid x \in \mathbb{R}^n\} \subseteq \mathbb{R}^m \quad (23)$$

$$= \left\{ \sum_{i=1}^n x_i a^{(i)} \mid x \in \mathbb{R}^n \right\} \quad (24)$$

$$= \text{span}\{a^{(1)}, a^{(2)}, \dots, a^{(n)}\} \quad (25)$$

- $\mathcal{R}(A)$  is a subspace (closed under addition and scalar multiplication).
- **Note:**  $A$  can consist of different column vectors that still span the space. E.g. In 2D,  $(1, 0)$  and  $(0, 1)$  can be used, but  $(1, 1)$  and  $(1, 0)$  can be used as well, which would have different  $A$ .
- **Note:**  $\mathcal{R}(A) = \mathcal{R}(A^T)$  iff  $A = A^T$  (i.e. symmetric).

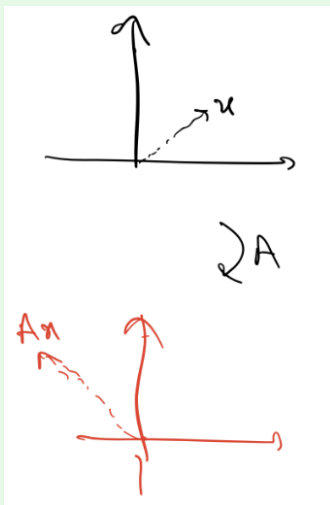


Figure 29: Range space.

### 6.3 Null Space

**Definition:** Set of all vectors that map to zero.

$$\mathcal{N}(A) = \{x \in \mathbb{R}^n \mid Ax = 0\} \subseteq \mathbb{R}^n \quad (26)$$

- $\mathcal{N}(A)$  is also a subspace (closed under addition and scalar multiplication).

### 6.4 Fundamental theorem of algebra

**Definition:** For any matrix  $A \in \mathbb{R}^{m \times n}$ , the subspaces are orthogonal to each other (i.e. orthogonal complement)

$$\mathcal{R}(A) \perp \mathcal{N}(A^T) \quad (27)$$

$$\mathcal{R}(A^T) \perp \mathcal{N}(A) \quad (28)$$

Therefore, since  $S \oplus S^\perp = V$ , then the direct sum of the two subspaces (i.e. if you take one vector from one subspace, and another vector from the other subspace, the sum of these vectors would be in  $\mathbb{R}^n$  or  $\mathbb{R}^m$ )

$$\mathcal{R}(A) \oplus \mathcal{N}(A^T) = \mathbb{R}^m \quad (29)$$

- $\dim(\mathcal{R}(A)) + \dim(\mathcal{N}(A^T)) = m$

$$\mathcal{R}(A^T) \oplus \mathcal{N}(A) = \mathbb{R}^n \quad (30)$$

- $\dim(\mathcal{R}(A^T)) + \dim(\mathcal{N}(A)) = n$

**Derivation: Why Does This Hold?** Recall the definition of orthogonal complement:

- $\forall x \in S, y \in S^\perp$ , we have that  $\langle x, y \rangle = 0$
- $x \in V$  can be decomposed as  $x = x^* + v$ , where  $x^* \in S$  and  $v \in S^\perp$

Therefore,

$$\dim V = \dim S + \dim S^\perp$$

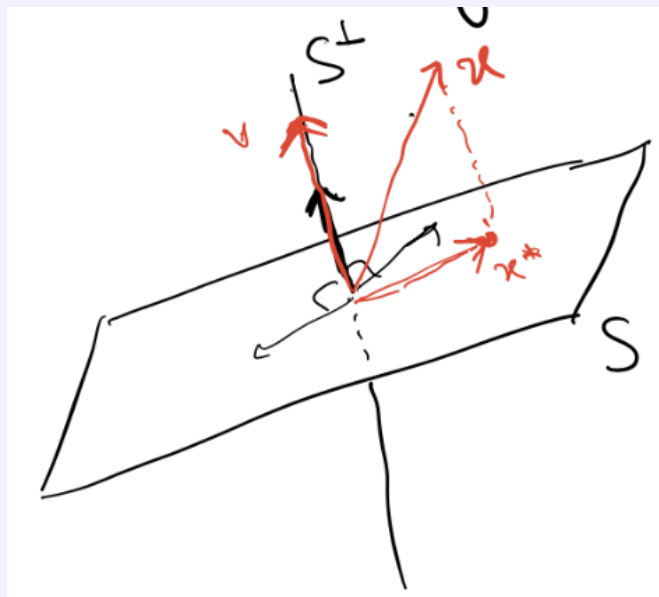


Figure 30: Orthogonal complement.

Now using this definition of orthogonal complement, let's apply it to the range space and null space of  $A$ : Consider

$$\mathcal{R}(A) = \left\{ y \mid y = \sum_{i=1}^n \alpha_i a^{(i)} \right\}$$

$$\mathcal{N}(A^\top) = \left\{ x \mid (a^{(i)})^\top x = 0, i = 1, \dots, n \right\}$$

$$A^\top = \begin{bmatrix} (a^{(1)})^\top \\ \vdots \\ (a^{(n)})^\top \end{bmatrix}$$

Consider  $y \in \mathcal{R}(A)$  so  $y = \sum_{i=1}^n \alpha_i a^{(i)}$ , and  $x \in \mathcal{N}(A^\top)$ ,

$$\langle y, x \rangle = \left\langle \sum_{i=1}^n \alpha_i a^{(i)}, x \right\rangle = \sum_{i=1}^n \alpha_i \langle a^{(i)}, x \rangle$$

Since  $x \in \mathcal{N}(A^\top)$ , this implies that  $\langle a^{(i)}, x \rangle = 0$ , so:

$$\langle y, x \rangle = 0$$

Thus, any  $y \in \mathcal{R}(A)$  is orthogonal to any  $x \in \mathcal{N}(A^\top)$ .

Therefore,  $\mathcal{R}(A) \oplus \mathcal{N}(A^\top) = \mathbb{R}^m$ , and  $\dim(\mathcal{R}(A)) + \dim(\mathcal{N}(A^\top)) = m$ .

**Example:**

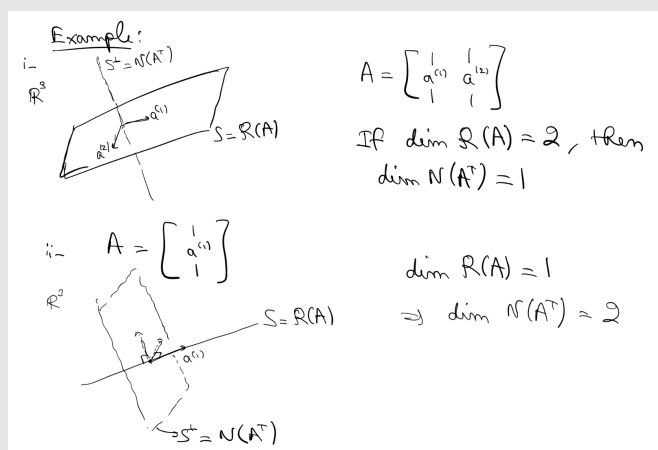


Figure 31: Example of fundamental theorem of linear algebra.

- Given the range of  $A$ , we can find the null space of  $A$  by finding what is orthogonal to it.

#### 6.4.1 Rank of $A$

**Definition:**

$$\text{Rank}(A) = \dim(\mathcal{R}(A^\top)) = \dim(\mathcal{R}(A))$$

- i.e. number of independent rows or independent columns.

## 6.5 Determinant

### Definition:

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \quad (31)$$

$$\det(A) = a_{11}a_{22} - a_{12}a_{21} \quad (32)$$

The volume of the region transformed by matrix  $A$  is given by:

$$\det(A) \quad (33)$$

**Intuition:** Graphically, the determinant represents the volume of the parallelogram spanned by the column vectors of  $A$ .

- Starting from a unit square, the matrix  $A$  transforms this square into a parallelogram.
- The area of the transformed parallelogram, denoted as  $P$ , equals the determinant:

$$\text{vol}(P) = \det(A)$$

**Why? It is easy to see this for a diagonal matrix, where:**

$$A = \begin{bmatrix} a_{11} & 0 \\ 0 & a_{22} \end{bmatrix}$$

The matrix  $A$  scales the unit square by  $a_{11}$  along one axis and by  $a_{22}$  along the other axis. This results in a rectangle with area:

$$\text{vol}(P) = a_{11}a_{22} = \det(A)$$

For instance, applying  $A$  to the basis vectors:

$$A \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} \\ 0 \end{bmatrix}, \quad A \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ a_{22} \end{bmatrix}$$

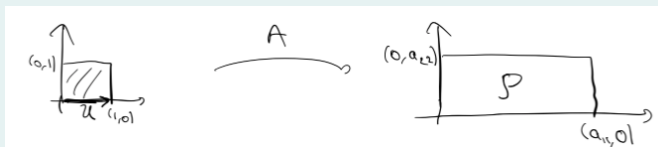


Figure 32: Diagonal

**What if the matrix is not diagonal? Consider an upper triangular matrix:**

$$A = \begin{bmatrix} a_{11} & a_{12} \\ 0 & a_{22} \end{bmatrix}$$

The matrix  $A$  still transforms the unit square, but now the parallelogram  $P$  is slanted due to the non-zero  $a_{12}$ . The area of the parallelogram is still given by the determinant:

$$\text{vol}(P) = a_{11}a_{22} = \det(A)$$

Again, applying  $A$  to the basis vectors:

$$A \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} \\ 0 \end{bmatrix}, \quad A \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} a_{12} \\ a_{22} \end{bmatrix}$$

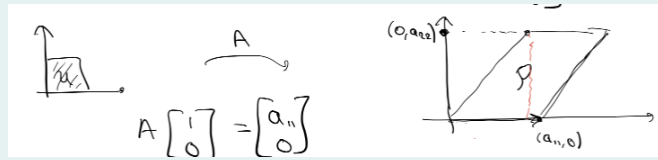


Figure 33: Upper triangular

For a general matrix  $A$ , we can use the  $QR$  factorization, where:

$$A = QR$$

$R$  is an upper triangular matrix and  $Q$  is an orthogonal matrix (i.e.,  $Q^T Q = I$ ).

- The orthogonal matrix  $Q$  represents a rotation, which preserves volume (the area remains unchanged).
- Therefore, the volume is determined by the determinant of  $R$ .

$$\text{vol}(P) = \det(R) = r_{11}r_{22} = \det(A)$$

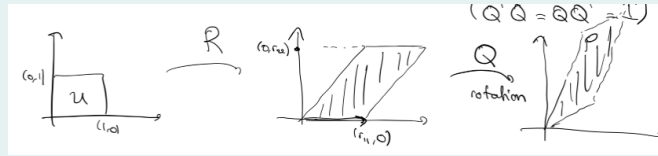


Figure 34: General matrix

## 6.6 Matrix inner product and norm

**Definition:** Set of matrices  $A \in \mathbb{R}^{m \times n}$  is a vector space. We can define an inner product over this space:

$$\langle A, B \rangle = \text{tr}(B^T A) = \text{tr}(A^T B) \quad (34)$$

- $\text{tr}$  : Trace is the sum of diagonal elements of a square matrix.

### 6.6.1 Frobenius Norm

**Definition:** For  $A, B \in \mathbb{R}^{m \times n}$ , then

$$\|A\|_F = \sqrt{\langle A, A \rangle} = \sqrt{\text{tr}(A^T A)} = \sqrt{\sum_{i,j} a_{ij}^2} \quad (35)$$

**Intuition:** Let

$$A = [a^{(1)} \quad \dots \quad a^{(n)}]$$

then

$$A^T A = \begin{bmatrix} (a^{(1)})^T \\ \vdots \\ (a^{(n)})^T \end{bmatrix} [a^{(1)} \quad \dots \quad a^{(n)}] = \begin{bmatrix} (a^{(1)})^T a^{(1)} & \dots & (a^{(1)})^T a^{(n)} \\ \vdots & \ddots & \vdots \\ (a^{(n)})^T a^{(1)} & \dots & (a^{(n)})^T a^{(n)} \end{bmatrix}$$

- **Note:** The matrix multiplication shows us why the trace can be written as  $\sum_{i,j} a_{ij}^2$ .

$$\text{— e.g. } (a^{(1)})^T a^{(1)} = a_{11}^2 + a_{21}^2 + \dots + a_{n1}^2$$



If we think of the matrix as a long column vector of the column vectors of  $A$ , then

$$\begin{bmatrix} a^{(1)} \\ \vdots \\ a^{(n)} \end{bmatrix}$$

so we can think of the Frobenius norm as the  $l_2$  norm exactly since it's  $\sqrt{\sum_{i,j} a_{ij}^2}$ , which is identical to the expression for  $l_2$ -norm.

### 6.6.2 Operator norm (Motivation for eigenvalues and eigenvectors):

**Intuition:** Let  $A \in \mathbb{R}^{m \times n}$  be a linear map from  $\mathbb{R}^n$  to  $\mathbb{R}^m$ .

- Think of the matrix as a mapping from  $\mathbb{R}^n$  to  $\mathbb{R}^m$ .

$$v \longrightarrow Av \quad (\text{ellipse})$$

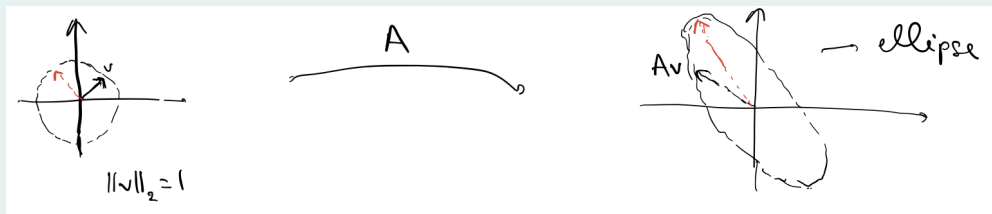


Figure 35: Matrix norm that maximizes  $Av$  given  $v$  with unit norm.

**Question:** Which direction of  $v$  on the unit circle results in  $Av$  with the largest magnitude? **Operator norm**, which can be defined for all  $p$  values.

$$\|A\|_2 = \max_{\|v\|_2=1} \|Av\|_2$$

$$\|A\|_1 = \max_{\|v\|_1=1} \|Av\|_1$$

$$\|A\|_\infty = \max_{\|v\|_\infty=1} \|Av\|_\infty$$

**"Interesting" directions (i.e. directions of interest):**

1. **Max/Min amplification direction:**

$$\max_{\|v\|_2=1} \|Av\|_2 = \|A\|_2, \quad \min_{\|v\|_2=1} \|Av\|_2$$

- Later, we will see that this is related to the **singular values** of the matrix.

2. **Invariant direction:** (square matrix  $A \in \mathbb{R}^{n \times n}$ )

$$Av = \lambda v$$

- $v$  is the eigenvector and  $\lambda$  is the eigenvalue.
- Note:** In 2D, there are 2 eigenvectors (i.e. parallel with same and opposite direction)

## 6.7 Eigenvalues and Eigenvectors

**Definition:** For  $A \in \mathbb{R}^{n \times n}$ , a non-zero vector  $v$  is an eigenvector of  $A$  with associated eigenvalue  $\lambda$  if

$$Av = \lambda v$$

- **Consequence:**  $(A - \lambda I)v = 0$ , therefore,  $v \in \mathcal{N}(A - \lambda I)$ , where  $\mathcal{N}(A - \lambda I)$  is the null space of  $(A - \lambda I)$ .

### 6.7.1 Characteristic polynomial

**Definition:** The above leads to a polynomial equation in  $\lambda$  of degree  $n$ . The roots are the eigenvalues of  $A$ .

$$\det(A - \lambda I) = 0$$

- **Roots can be real or complex.** If complex, they occur in conjugate pairs.
- **Note:** The determinant is equal to 0 because  $Av = \lambda v$  (i.e. linearly dependent), and LD vectors have determinant of 0 by definition, so we want to find  $\lambda$  s.t. the determinant is 0.

**Warning:**  $n$  roots doesn't mean there are  $n$  distinct eigen values.

- e.g. For  $(\lambda - 1)^2$ , there are 2 roots, but there is only one eigenvalue.

### 6.7.2 Geometric and algebraic multiplicity

**Definition:**

**Algebraic multiplicity:**  $AM(\lambda)$  is the number of times a given eigenvalue appears as a root of the characteristic equation  $\det(A - \lambda I) = 0$ .

- For example,  $(\lambda - 1)^2$  has root 1 with multiplicity 2.
- i.e. If  $p(x) = (x - \lambda)^m q(x)$ , where  $\lambda$  is not a root of  $q(x)$ , then  $AM(\lambda) = m$

**Geometric multiplicity:**  $GM(\lambda) = \dim \mathcal{N}(A - \lambda I)$

- **Key:** If we know the rank of  $A - \lambda I$ , then we can use FToLA to find the  $GM(\lambda) = \dim \mathcal{N}(A - \lambda I)$ .

**Theorem:** In general, for any matrix  $A \in \mathbb{R}^{n \times n}$  (square matrix),

$$GM(\lambda) \leq AM(\lambda).$$

### 6.7.3 Defective and non-defective

**Definition:**

**Defective Matrix:** If  $GM(\lambda) < AM(\lambda)$  for some  $\lambda$

- **Note:** Defective doesn't mean that it's not invertible.
- **Key:** Cannot construct  $n$  linearly independent vectors because  $\exists$  a  $\lambda$  s.t.  $\sum AM = n$  but  $\sum GM < n$ .

**Non-defective Matrix:** If  $GM(\lambda) = AM(\lambda)$ , then the matrix is **diagonalizable** (i.e. non-defective).

- **"Most" matrices are non-defective.** In other words, the set of non-defective matrices is dense (a random matrix is almost surely non-defective).

### 6.7.4 Eigenvectors corresponding to different eigenvalues are l.i.

**Theorem: Lemma:** If  $u^{(1)}, \dots, u^{(k)}$  are eigenvectors then,

$$u^{(i)} \notin \phi_j = \mathcal{N}(A - \lambda_j I) \text{ for } i \neq j \quad (36)$$

- i.e. An eigen vector of  $i$  of one null space cannot be in another eigenvector's null space.

**Derivation:** *Why?* Prove by contradiction, assume  $u^{(i)}$  is in the null space of  $\phi_j$ .

- If  $Au^{(i)} = \lambda_i u^{(i)}$  and  $u^{(i)} \in \mathcal{N}_j$ , then  $Au^{(i)} = \lambda_j u^{(i)}$ .
- Therefore,  $(\lambda_i - \lambda_j)u^{(i)} = 0$ , which is impossible since  $\lambda_i \neq \lambda_j$  and  $u^{(i)}$  is a non-zero vector by definition of eigenvectors.

**Theorem:** Eigenvectors corresponding to different eigenvalues are linearly independent.

**Warning:** Holds for any defective or non-defective matrix.

- **Same eigenvalue (key subtle detail):** Eigenvectors corresponding to an eigenvalue can be linearly dependent or independent (**but not guaranteed to be l.i.**).
  - e.g. If  $\dim((N)(A - \lambda I)) = 2$ , you can find 2 basis vectors (i.e. eigenvectors), but **not** any two vectors.
  - Since we can choose two vectors to be linearly independent or dependent, you have to choose the linearly independent vectors.
    - \* i.e. Any vector in  $(N)(A - \lambda I)$  is an eigenvector, but not every 2 eigenvectors in  $(N)(A - \lambda I)$  is linearly independent.
    - \* e.g. If  $v$  is an eigenvector, then  $2v$  is also an eigenvector.
  - **Construction:** So choose two linearly independent vectors to be the eigenvectors of that space.
- **Different eigenvalue:** For eigenvectors corresponding to different eigenvalues though, we are guaranteed for them to be linearly independent since they live in different null spaces.

**Derivation:** Let  $\lambda_1, \dots, \lambda_k$  be distinct eigenvalues,  $u^{(1)}, \dots, u^{(k)}$  be the corresponding eigenvectors, and  $\phi_i = \mathcal{N}(A - \lambda_i I)$ , the null space corresponding to eigenvalue  $\lambda_i$ .

Proof by contradiction, assume that  $u^{(1)}, \dots, u^{(k)}$  are linearly dependent, i.e.,

$$u^{(1)} = \sum_{i=2}^k \alpha_i u^{(i)}.$$

- i.e. The first eigenvector can be written as a linear combination of the other eigenvectors.

**Part 1:**

$$Au^{(1)} = \sum_{i=2}^k \alpha_i Au^{(i)} = \sum_{i=2}^k \alpha_i \lambda_i u^{(i)}.$$

- 2nd part: By definition of  $u^{(1)}$
- 3rd part: Since  $u^{(i)}$  is an eigenvector with corresponding  $\lambda_i$

**Part 2:**

$$\lambda_1 u^{(1)} = \sum_{i=2}^k \alpha_i \lambda_1 u^{(i)}.$$

- **Key:**  $\lambda_1$  is inside the summation, while for part 1, it was  $\lambda_i$

**Combining both part 1 and part 2:** But  $Au^{(1)} = \lambda_1 u^{(1)}$ , so

$$Au^{(1)} - \lambda_1 u^{(1)} = \sum_{i=2}^k \alpha_i (\lambda_i - \lambda_1) u^{(i)} = 0,$$

which implies that  $\{u^{(2)}, \dots, u^{(k)}\}$  is linearly dependent because  $\lambda_1 - \lambda_i \neq 0$  since they are distinct, so there exists constants not all 0 to make the linear combination equal to 0

- i.e. not linearly independent as the only constants that would satisfy this is all constants being 0.

Continue with the same argument to show that  $\{u^{(3)}, \dots, u^{(k)}\}$  is linearly dependent, and so on.

Eventually,  $\{u^{(k-1)}, u^{(k)}\}$  are linearly dependent, so:

$$u^{(k)} = \alpha u^{(k-1)}.$$

But this is impossible by the previous lemma since an eigenvector of one null space cannot be in another eigenvector's null space (i.e. cannot write on as a l.c. of the other). Therefore,  $\{u^{(1)}, \dots, u^{(k)}\}$  is linearly independent.

## 6.8 Matrix Diagonalization

**Intuition:** The previous theorem leads us to the diagonalization of a non-defective square matrix  $A \in \mathbb{R}^{n \times n}$ .

The idea is to look at the null space  $\mathcal{N}(A - \lambda_i I)$ .

- When  $\lambda_1, \dots, \lambda_n$  are distinct, then  $u^{(1)}, \dots, u^{(n)}$  are linearly independent, so the set  $\{u^{(1)}, \dots, u^{(n)}\}$  forms a basis for  $\mathbb{R}^n$ .
- If some  $\lambda_i$  is a repeated eigenvalue. For example, if  $AM(\lambda_i) = 2$ , then  $GM(\lambda_i) = 2$  because it's non-defective matrix (i.e. non-defective by definition means that  $AM(\lambda) = GM(\lambda)$ ) so  $\dim \mathcal{N}(A - \lambda_i I) = 2$ .
  - This means we can find  $\{u^{(i,1)}, u^{(i,2)}\}$  that span this null space.
  - So, if we assemble all these  $u^{(i,j)}$ 's, then we get a basis for  $\mathbb{R}^n$ .

**Theorem:** Let  $\lambda_i$  for  $i = 1, \dots, k$ , be distinct eigenvalues of a non-defective matrix  $A \in \mathbb{R}^{n \times n}$ . Let  $\mu_i$  be the multiplicity of  $\lambda_i$  (i.e.,  $AM(\lambda_i) = GM(\lambda_i) = \mu_i$ ).

Let

$$U^{(i)} = [u^{(i,1)} \quad \dots \quad u^{(i,\mu_i)}]$$

be a matrix of eigenvectors that form a basis for  $\mathcal{N}(A - \lambda_i I)$ .

Then

$$U = [U^{(1)} \quad \dots \quad U^{(k)}]$$

is a complete set of basis vectors for  $\mathbb{R}^n$ .

Then the **Eigendecomposition** is

$$A = U \Lambda U^{-1}$$

where

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 & \dots & 0 \\ 0 & \lambda_1 & 0 & 0 & \dots & 0 \\ 0 & 0 & \lambda_2 & 0 & \dots & 0 \\ 0 & 0 & 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \dots & \lambda_n \end{bmatrix}$$

is a diagonal matrix with the eigenvalues of  $A$  on the diagonal.

- Where  $\lambda_1$  appears  $\mu_1$  times on the diagonal (indicating multiplicity), followed by  $\lambda_2$  appears  $\mu_2$  and so on.

### Warning:

- This is an extension of the previous theorem, since we are only considering non-defective matrices, which means  $AM = GM$ , so then you can find  $n$  linearly independent vectors.
  - **Defective:** We cannot find  $n$  linearly independent vectors because  $GM < AM$ .
- But, the same key subtlety pops up as for the same eigenvalue, we have to choose eigenvectors in that space that are linearly independent by **construction**.

**Warning:** You cannot orthonormalize these  $n$  linearly independent vectors using Gram because they are not in the same space (i.e. if you Gram-Schmidt it, you will get non-eigenvectors).

- Therefore orthonormalizing vectors in the same space (i.e. same eigenvalue) retains the eigenvector property, but across spaces, will lose the eigenvector properties.

**Derivation:**  $Au^{(i,j)} = \lambda_i u^{(i,j)}$ , where  $u^{(i,j)}$  is an eigenvector with eigenvalue  $\lambda_i$ , then this implies that

$$A \begin{bmatrix} u^{(1,1)} & \dots & u^{(1,\mu_1)} & u^{(2,1)} & \dots & u^{(2,\mu_2)} & \dots & u^{(n,\mu_n)} \end{bmatrix} = U \begin{bmatrix} \lambda_1 & 0 & 0 & 0 & \dots & 0 \\ 0 & \lambda_1 & 0 & 0 & \dots & 0 \\ 0 & 0 & \lambda_2 & 0 & \dots & 0 \\ 0 & 0 & 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \dots & \lambda_n \end{bmatrix}$$

- i.e. Generalizing to all the eigenvectors with their corresponding eigenvalues.

Thus, we have:

$$AU = U\Lambda$$

which implies:

$$A = U\Lambda U^{-1}$$

where  $U$  is invertible because its columns (the eigenvectors) are linearly independent, and  $U$  is a square matrix.

### 6.8.1 What does this diagonalization mean?

**Intuition:** This applies to any non-defective (or diagonalizable) matrix  $A \in \mathbb{R}^{n \times n}$ . We start with the eigendecomposition of a matrix  $A$ :

$$A = U\Lambda U^{-1}$$

- $U = \begin{bmatrix} u^{(1)} & \dots & u^{(n)} \end{bmatrix}$ .

Let  $x \in \mathbb{R}^n$  be any vector. Then:

$$Ax = U\Lambda U^{-1}x.$$

Let  $\tilde{x} = U^{-1}x$ , so that:

$$Ax = U\Lambda\tilde{x} \quad \text{and} \quad x = U\tilde{x} = \begin{bmatrix} u^{(1)} & \dots & u^{(n)} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \vdots \\ \tilde{x}_n \end{bmatrix} = \sum_{i=1}^n \tilde{x}_i u^{(i)}.$$

- $\tilde{x} = U^{-1}x$ : Coordinates of  $x$  in the new basis  $\{u^{(1)}, \dots, u^{(n)}\}$ .
  - Since  $x$  is a linear combination of eigenvectors, therefore, we are **transforming** to the basis of eigenvectors, where  $x$  can be written as  $\sum_{i=1}^n \tilde{x}_i u^{(i)}$ .
- $\Lambda\tilde{x}$  means that we are scaling  $\tilde{x}_i$  by the corresponding eigenvalue  $\lambda_i$ .
- $y = Ax = U\Lambda\tilde{x}$  means that we are changing the coordinates back to the original basis.
  - Since the inverse of  $U^{-1}$  is  $U$ , therefore, after scaling by  $\Lambda$ , we are essentially transforming from the basis of eigenvectors to the original basis by applying the inverse transformation.

#### Warning:

- **Change of basis to eigenvector basis:**  $U^{-1}x$  transforms  $x$  from the original basis to the eigenvector basis. The  $i$ th component of  $x$  is represented by  $\tilde{x}_i$  (i.e. coordinate) in the new basis.
- **Scaling:**  $\tilde{x}$  get scaled by their corresponding eigenvalues in  $\Lambda$
- **Change of basis to original basis:**  $\tilde{x}$  then gets transformed back to original basis by applying the inverse transformation of  $U^{-1}$ , which is  $U$ .

## 6.9 Application: Google's PageRank Algorithm

### 6.9.1 How to measure importance of a webpage

**Intuition:** The following two methods are insufficient as there are loop holes.

- **Web Search:** Mapping keywords to URLs.
- **Hyperlinks:** Hyperlinks that link to a webpage give an indication of how "important" the webpage is.

Therefore, the importance of a webpage should depend on the importance of the webpages linking to it.

### 6.9.2 Example: Random Walk across Webpages

**Example:** Bot performs a random walk across the webpages. Let  $x_i^{(t)}$  be the probability that the bot is on page  $i$  at time  $t$ .

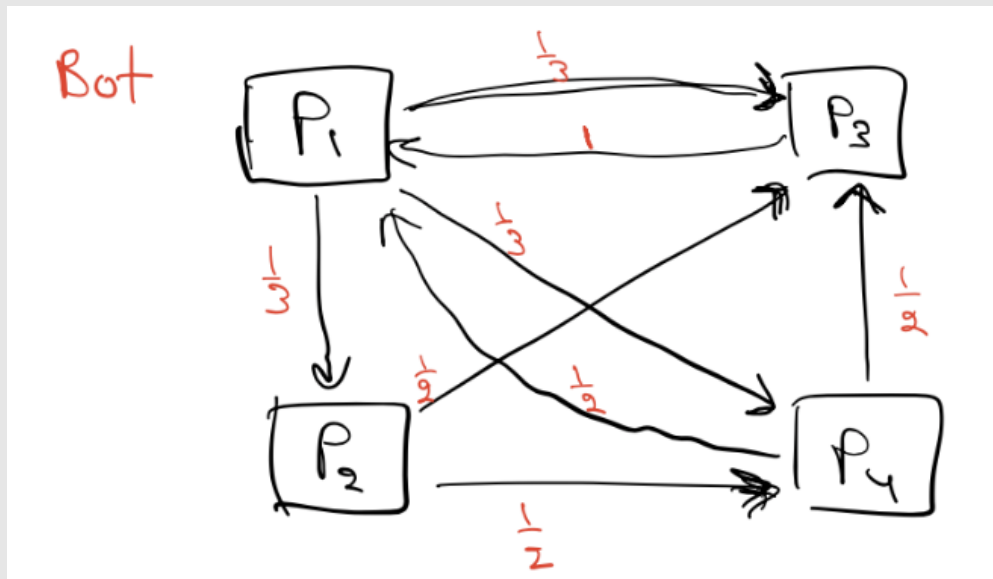


Figure 36: P are the pages, and the numbers in red are the probabilities of going to that page with the bot

$$x_1^{(t+1)} = 1 \cdot x_3^{(t)} + \frac{1}{2}x_4^{(t)}$$

$$x_2^{(t+1)} = \frac{1}{3}x_1^{(t)}$$

$$x_3^{(t+1)} = \frac{1}{3}x_1^{(t)} + \frac{1}{2}x_2^{(t)} + \frac{1}{2}x_4^{(t)}$$

$$x_4^{(t+1)} = \frac{1}{3}x_1^{(t)} + \frac{1}{2}x_2^{(t)}$$

This system can be written as:

$$\begin{bmatrix} x_1^{(t+1)} \\ x_2^{(t+1)} \\ x_3^{(t+1)} \\ x_4^{(t+1)} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & \frac{1}{2} \\ \frac{1}{3} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{3} & \frac{1}{2} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1^{(t)} \\ x_2^{(t)} \\ x_3^{(t)} \\ x_4^{(t)} \end{bmatrix}$$

- $P$  is the transition probability matrix.

### 6.9.3 Convergence to a Steady State Distribution

**Definition:** The evolution of the system is given by  $x^{(t+1)} = Px^{(t)}$ . As  $t \rightarrow \infty$ ,  $x^{(t)} \rightarrow x^{(\infty)}$  (under certain conditions) s.t.  $Px^{(\infty)} = x^{(\infty)}$ .

- i.e. The steady state  $x^{(\infty)}$  is the eigenvector of  $P$  with eigenvalue 1. That is,  $Px^{(\infty)} = x^{(\infty)}$ .

### 6.9.4 Conditions for Convergence

**Definition:** When the Markov chain is both irreducible and aperiodic, then  $x^{(t)} \rightarrow x^{(\infty)}$  as  $t \rightarrow \infty$ .

- An **aperiodic Markov chain** means the Markov chain does not exhibit periodic behavior, meaning it doesn't alternate between certain states but can visit them in an irregular pattern.
- An **irreducible Markov chain** means that there is a path from every state (webpage) to every other state, ensuring eventual convergence to a steady state.

**Example:** Examples of divergence

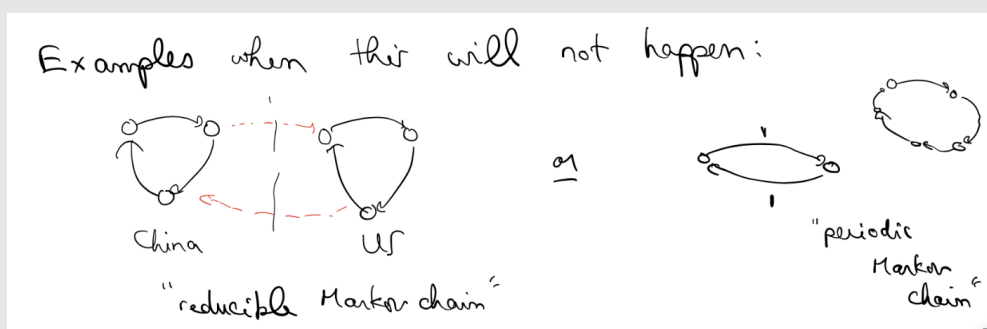


Figure 37: Non-convergent Markov chains

- Reducible Markov chains have disconnected chains, meaning that it will never converge since they are separated.
- Periodic Markov chains will always oscillate between webpages.
- **Key:** The convergence of the PageRank vector depends on the initial condition and the structure of the Markov chain.

### 6.9.5 Practical Modification

**Intuition:** In practice, the following adjustment ensures irreducibility and aperiodicity in web surfing:

- With probability 85%, the robot follows one of the hyperlinks from the current webpage.
- With probability 15%, the robot jumps to a totally random webpage on the Internet.

This ensures that the Markov chain is irreducible and aperiodic, i.e.,  $x^{(t)} \rightarrow x^{(\infty)}$ .

### 6.9.6 Why is 1 an eigenvalue of P?

**Derivation:**

1. Fact:  $\det(A) = \det(A^T)$ .
2. Recall that the set of eigenvalues of a matrix is given by:

$$\{\lambda : \det(P - \lambda I) = 0\}$$

3. Using the fact that the determinant of a matrix equals the determinant of its transpose, we have:

$$\{\lambda : \det((P - \lambda I)^T) = 0\}$$

4. This implies:

$$\{\lambda : \det(P^T - \lambda I) = 0\}$$

5. Thus, the set of eigenvalues of  $P$  is the same as the set of eigenvalues of  $P^T$ .
6. Consider the following equation:

$$P^T \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} = 1 \cdot \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$$

- Since the sum of the columns equal to 1 for  $P$ , therefore, the sums of the rows equal to 1 for  $P^T$ .
- Therefore, if multiply  $P^T$  by the ones vector, then this will yield the sums of each row (i.e. 1)
- So, 1 is an eigenvalue of  $P$ .

### 6.9.7 What about other eigenvalues?

**Definition:** All other eigenvalues  $\lambda_i$  satisfy:

$$|\lambda_i| \leq 1$$

**Derivation:**

1. We know that  $Px = \lambda x$ . By applying  $P$   $t$  times, we get:

$$P(P(\dots(Px))) = P^t x = \lambda^t x$$

2. Thus,  $P^t x = \lambda^t x$ , and since every entry of  $P^t x \leq 1$  because it's a probability distribution. Therefore, we should have that every entry of  $P^t x$  is bounded.
3. If  $|\lambda_i| > 1$ , then  $\lambda_i^t$  diverges to infinity as  $t \rightarrow \infty$ . But, for stability:
  - Since  $P^T x = \lambda^T x$  and  $P^T x \leq 1 \implies |\lambda_i| \leq 1 \quad \forall i$

### 6.9.8 Convergence via Power Iteration

**Definition:** We can express the eigenvalue decomposition of the matrix  $P$  as follows:

1. The eigenvalue decomposition of  $P$  is given by:

$$P = U\Lambda U^{-1}$$

where  $U$  is the matrix of eigenvectors, and  $\Lambda$  is the diagonal matrix of eigenvalues.

2. After  $t$  iterations of applying  $P$ , we have:

$$P^t x = (U\Lambda U^{-1})(U\Lambda U^{-1}) \dots (U\Lambda U^{-1})x = U\Lambda^t U^{-1}x$$

3. Breaking this down, we get:

$$P^t x = U \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & \lambda_2^t & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_n^t \end{bmatrix} U^{-1}x$$

4. As  $t \rightarrow \infty$ , if  $|\lambda_i| < 1$  for  $i = 2, 3, \dots, n$ , then:

$$\lambda_i^t \rightarrow 0$$

Hence, the system converges to:

$$a_1 u^{(1)}$$

- $u^{(1)}$  is the eigenvector corresponding to the largest eigenvalue  $\lambda_1 = 1$ .
  - $U^{-1}x = a$
5. By normalizing the vector  $x^{(t)}$  at each iteration, we obtain  $u^{(1)}$ , which corresponds to the eigenvalue  $\lambda_1 = 1$ . This process is known as the **power iteration method**.



## 7 Problem set 2

### 7.1 Calculating inverse of a matrix

**Process:** Given an  $n \times n$  matrix  $A$ , the inverse matrix  $A^{-1}$  can be found through the following steps:

1. **Check if the matrix is invertible:**

- To be invertible, the matrix must have a non-zero determinant:  $\det(A) \neq 0$ .
- If  $\det(A) = 0$ , the matrix is singular and does not have an inverse.

2. **Find the determinant of the matrix:**

- The determinant of an  $n \times n$  matrix  $A$  is a scalar value that can be computed using cofactor expansion (also known as Laplace's expansion) along any row or column of the matrix.
- **e.g.** For the first row, the determinant of a matrix  $A = [a_{ij}]$  is given by:

$$\det(A) = \sum_{j=1}^n (-1)^{1+j} a_{1j} \det(A_{1j})$$

- Here,  $A_{1j}$  is the  $(n-1) \times (n-1)$  matrix obtained by removing the first row and  $j$ -th column of  $A$ .

3. **Find the cofactors of the matrix:**

- The cofactor of an element  $a_{ij}$  in the matrix  $A$  is denoted by  $C_{ij}$ .
- The cofactor is given by:

$$C_{ij} = (-1)^{i+j} \det(A_{ij})$$

- Here,  $A_{ij}$  is the  $(n-1) \times (n-1)$  matrix obtained by deleting the  $i$ -th row and the  $j$ -th column from  $A$ .
- You will compute the cofactor for each element in the matrix  $A$ , creating a cofactor matrix.

4. **Form the cofactor matrix (matrix of cofactors):**

- Construct the cofactor matrix by placing each cofactor  $C_{ij}$  at the corresponding position in a new matrix:

$$\text{Cofactor Matrix} = \begin{pmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{pmatrix}$$

5. **Form the adjugate (or adjoint) matrix:**

- The adjugate matrix, denoted as  $\text{adj}(A)$ , is the transpose of the cofactor matrix.
- In other words, swap the rows and columns of the cofactor matrix:

$$\text{adj}(A) = \begin{pmatrix} C_{11} & C_{21} & \cdots & C_{n1} \\ C_{12} & C_{22} & \cdots & C_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ C_{1n} & C_{2n} & \cdots & C_{nn} \end{pmatrix}$$

6. **Calculate the inverse matrix:**

- The inverse of the matrix  $A$  is given by the formula:

$$A^{-1} = \frac{1}{\det(A)} \text{adj}(A)$$

- Here,  $\det(A)$  is the determinant of the matrix  $A$ , and  $\text{adj}(A)$  is the adjugate matrix.
- Multiply each element of the adjugate matrix by  $\frac{1}{\det(A)}$ .

7. **Verify the inverse (optional):**

- Multiply the matrix  $A$  by its inverse  $A^{-1}$ . You should get the identity matrix  $I_n$ , where:

$$A \times A^{-1} = A^{-1} \times A = I_n$$

- The identity matrix  $I_n$  has 1's along the diagonal and 0's elsewhere:

$$I_n = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix}$$

## 7.2 Finding rank and dimension/basis for range and null space of $A$ and $A$ transpose

### Process:

1. Find the REF of the matrix (i.e. each leading entry in a row is to the right of the leading entry in the previous row, with all entries below leading entries being zeros).
2.  $\text{rank}(A)$  is the number of pivots.
3.  $\dim(N(A^T)) = \text{Total num. of rows} - \text{rank}(A)$
4.  $\dim(N(A)) = \text{Total num. of cols} - \text{rank}(A)$ 
  - **Note:** This makes sense from the FTLA, since the total is basically the universal space.
5.  $R(A)$ : Span of column vectors where there is a pivot (can use REF or original matrix's vectors).
6.  $R(A^T)$ : Span of row vectors where there is a pivot (can use REF or original matrix's vectors).
7.  $N(A)$ : Solve  $Ax = 0$  and find  $x$ , where there is probably a free variable. Check by subbing  $x$  into  $Ax = 0$ 
  - You can use the REF of  $A$  for this.
8.  $N(A^T)$ : Solve  $A^T x = 0$  and find  $x$ , where there is probably a free variable. Check by subbing  $x$  into  $A^T x = 0$ 
  - **Key:** Have to find the REF of  $A^T$ , which is not equivalent to the REF of  $A$ .

## 8 Symmetric Matrices, Orthogonal Matrices, Spectral Decomposition, Positive Semidefinite Matrices, Ellipsoids (Ch. 4.1-4.4)

### 8.1 Symmetric matrices

**Definition:** Set of real symmetric matrices is

$$S^n = \{A \in \mathbb{R}^{n \times n} \mid A = A^T\}$$

- i.e. a matrix  $A$  is symmetric if  $a_{ij} = a_{ji} \forall i, j$

Set of complex symmetric matrices is

$$S^n = \{A \in \mathbb{C}^{n \times n} \mid A = A^H\}$$

- $A^H$  represents the Hermitian transpose (conjugate transpose) of  $A$ .

#### 8.1.1 Example of symmetric matrix: Hessian Matrix

**Example:** Recall: The Hessian matrix  $\nabla^2 f$  of a function  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  with continuous partial derivatives (i.e. must be continuous for symmetric matrix) is a symmetric matrix:

$$[\nabla^2 f]_{ij} = \frac{\partial^2 f}{\partial x_i \partial x_j} = \frac{\partial^2 f}{\partial x_j \partial x_i} = [\nabla^2 f]_{ji}.$$

**Example:** Consider a quadratic function  $q : \mathbb{R}^n \rightarrow \mathbb{R}$ :

$$\begin{aligned} q(x) &= \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n a_{ij} x_i x_j + \sum_{i=1}^n c_i x_i + d \\ &= \frac{1}{2} \begin{bmatrix} x_1 & \dots & x_n \end{bmatrix} \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} c_1 & \dots & c_n \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} + d \\ &= \frac{1}{2} x^\top A x + c^\top x + d. \end{aligned}$$

#### Gradient of the Quadratic Function

Let

$$q(x) = \frac{1}{2} x^\top A x + c^\top x + d.$$

Then,

$$\nabla(c^\top x) = \begin{bmatrix} \frac{\partial}{\partial x_1}(c^\top x) \\ \vdots \\ \frac{\partial}{\partial x_n}(c^\top x) \end{bmatrix} = \begin{bmatrix} c_1 \\ \vdots \\ c_n \end{bmatrix} = c.$$

Now let's solve  $\nabla \left( \frac{1}{2} x^\top A x \right)$ , for the  $k$ th component:

$$\begin{aligned} \frac{\partial}{\partial x_k} \left( \frac{1}{2} x^\top A x \right) &= \frac{\partial}{\partial x_k} \left( \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n a_{ij} x_i x_j \right) \\ &= \frac{\partial}{\partial x_k} \left( \frac{1}{2} a_{kk} x_k^2 + \sum_{i \neq k} a_{ik} x_i x_k \right) \\ &= a_{kk} x_k + \sum_{i \neq k} a_{ik} x_i \\ &= [a_{k1} \quad \dots \quad a_{kn}] \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}. \end{aligned}$$

Thus,

- $\nabla \left( \frac{1}{2} x^\top A x \right) = A x$
- $\nabla q(x) = A x + c$
- $\nabla^2 q(x) = A$

**Warning:** If  $A$  is not symmetric, we can replace  $A$  by  $\frac{A + A^\top}{2}$  without changing the evaluation of the function.

- e.g.  $4x_1x_2 + 5x_2x_1 = 9x_1x_2$ . This is non-symmetric since  $a_{12} \neq a_{21}$ , but we can symmetrize this by taking the average of the two points  
 $- 4.5x_1x_2 + 4.5x_2x_1 = 9x_1x_2$ . This symmetry was found as  $\frac{a_{12} + a_{21}}{2}$

Therefore, we can always assume that  $A$  is symmetric

- Since we can always change a non-symmetric matrix  $A$  into a symmetric matrix  $\frac{A + A^\top}{2}$  since  $\left( \frac{A + A^\top}{2} \right)^\top = \frac{A + A^\top}{2}$

### 8.1.2 Theorem

**Theorem:** Let  $A \in S^n$  be a real symmetric matrix. Let  $\lambda_1, \dots, \lambda_n$  be its eigenvalues (not necessarily distinct). Then:

1.  $\lambda_1, \dots, \lambda_n$  are real, and  $\text{AM}(\lambda_i) = \text{GM}(\lambda_i)$  for all  $i$ .
2. Eigenvectors corresponding to different eigenvalues are orthogonal.

**Warning:** The implication from the theorem

1. This means all symmetric matrices are diagonalizable.
2.  $U^T U = I$  (i.e.  $U^{-1} = U^T$ )

**Derivation:** 1) Let  $\lambda$  be an eigenvalue with eigenvector  $u$ .

$$A u = \lambda u \tag{1}$$

Let's consider the conjugate transpose:

$$\begin{aligned} (A u)^H &= (\lambda u)^H \\ \implies u^H A^H &= \bar{\lambda} u^H \end{aligned} \tag{2}$$

Now set up two equivalent equations starting with  $u^H Au$ :

- 

$$u^H Au = \lambda u^H u \quad \text{Multiply equation (1) by } u^H$$

- 

$$\begin{aligned} u^H Au &= u^H A^H u \quad \text{since } A \text{ is symmetric } A^H = A \\ &= \bar{\lambda} u^H u \quad \text{Multiply equation (2) by } u \end{aligned}$$

- $A$  is real and symmetric and  $A = A^H$  since the Hermitian takes the transpose and the conjugate.
  - \*  $A^H = A^T$  since the conjugate of a real matrix is the real matrix
  - \*  $A = A^T$  because it's symmetric.
  - \* Therefore,  $A^H = A$

Thus, we have:

$$(\lambda - \bar{\lambda})u^H u = 0$$

So,  $\lambda = \bar{\lambda}$ , meaning that  $\lambda$  is real.

For the proof of  $\text{AM}(\lambda) = \text{GM}(\lambda)$ , check Theorem 4.1 in the OptM book.

**Derivation: 2)** Let  $\lambda_i$  and  $\lambda_j$  be two different eigenvalues, and let  $v^{(i)}$  and  $v^{(j)}$  be the corresponding eigenvectors.

$$Av^{(i)} = \lambda_i v^{(i)} \tag{1}$$

$$Av^{(j)} = \lambda_j v^{(j)} \tag{2}$$

Now set up two equivalent equations starting with  $(v^{(j)})^T Av^{(i)}$ :

- 

$$(v^{(j)})^T Av^{(i)} = \lambda_i (v^{(j)})^T v^{(i)} \quad \text{Multiply (1) by } (v^{(j)})^T$$

- 

$$\begin{aligned} (v^{(j)})^T Av^{(i)} &= (v^{(j)})^T A^T v^{(i)} \quad \text{Since } A = A^T \\ &= (Av^{(j)})^T v^{(i)} \quad (AB)^T = B^T A^T \\ &= \lambda_j (v^{(j)})^T v^{(i)} \end{aligned}$$

Thus, we have:

$$(\lambda_i - \lambda_j)(v^{(j)})^T v^{(i)} = 0$$

Since  $\lambda_i \neq \lambda_j$ , we must have:

$$(v^{(j)})^T v^{(i)} = 0$$

Therefore,  $v^{(i)}$  and  $v^{(j)}$  are orthogonal.

**Warning:** For these two derivations:  $u^H Au$  and  $(v^{(j)})^T Av^{(i)}$  were used to use the properties of symmetric matrices.

- $(u^H Au)^H = u^H Au$

## 8.2 Spectral decomposition

### 8.2.1 Spectral theorem

**Theorem:** Let  $A \in S^n$  be a real symmetric matrix. Let  $\lambda_1, \dots, \lambda_n \in \mathbb{R}$  be its eigenvalues.

Then, there exists a set of real eigenvectors  $u^{(1)}, \dots, u^{(n)}$ , which are orthonormal (i.e.,  $u^{(i)} \perp u^{(j)}$  for  $i \neq j$ , and  $\|u^{(i)}\| = 1$  for all  $i$ ).

Equivalently, the eigendecomposition of  $A$  becomes:

$$A = U\Lambda U^T$$

- $\Lambda = \begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_n \end{bmatrix}$
- $U = [u^{(1)} \quad \dots \quad u^{(n)}]$
- **Note:** This is called the "spectral decomposition" of  $A$ .
  - Previously, we had  $A = U\Lambda U^{-1}$ , but for a symmetric matrix  $U^{-1} = U^T$ .

**Derivation:** We already proved that  $\lambda_1, \dots, \lambda_n$  are real.

Without loss of generality (WLOG), we can take the eigenvectors to be real. Why?

1.  $A\mathbf{v} = \lambda\mathbf{v}$  implies

$$\text{Re}\{A\mathbf{v}\} = \text{Re}\{\lambda\mathbf{v}\}$$

2. Since  $\lambda$  is real, this becomes

$$A \text{Re}\{\mathbf{v}\} = \lambda \text{Re}\{\mathbf{v}\}$$

3. Therefore,  $\text{Re}\{\mathbf{v}\}$  is an eigenvector with eigenvalue  $\lambda$ .

Now, let's prove that the set of real eigenvectors are orthonormal:

1. Now, since  $\text{AM}(\lambda_i) = \text{GM}(\lambda_i) = m_i$  (since diagonalizable), we can take  $m_i$  eigenvectors  $u^{(i,1)}, \dots, u^{(i,m_i)}$  which form an orthonormal basis of  $\mathcal{N}(A - \lambda_i I)$ 
  - i.e. by construction, we can form an orthonormal basis for this space by using Gram-Schmidt for example
  - $\lambda_1$ :  $u^{(1)}, \dots, u^{(1,m_1)}$  (these vectors can be chosen to be orthogonal within this space.)
  - $\lambda_2$ :  $u^{(2)}, \dots, u^{(2,m_2)}$  (these vectors can be chosen to be orthogonal within this space.)
2. Previously, we showed that across different  $\mathcal{N}(A - \lambda_i I)$ 's, the  $u^{(i)}$  are orthogonal.
3. Therefore,  $\{u^{(1,1)}, \dots, u^{(1,m_1)}, u^{(2,1)}, \dots, u^{(2,m_2)}, \dots\}$  forms an orthonormal basis of  $n$  eigenvectors

Now we can assemble everything together:

1. So,

$$A u^{(i,j)} = \lambda_i u^{(i,j)}$$

2. Therefore, if we let  $U = [u^{(1,1)} \quad \dots \quad u^{(n,m_n)}]$ . Then,

$$AU = U\Lambda$$

$$\bullet \Lambda = \begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_n \end{bmatrix}.$$

3. Since the columns of  $U$  form an orthonormal basis, we have

$$U^T U = \begin{bmatrix} (u^{(1)})^T \\ \vdots \\ (u^{(n)})^T \end{bmatrix} [u^{(1)} \quad \dots \quad u^{(n)}] = I$$

4. Therefore,  $U^{-1} = U^T$ , meaning  $U$  is an orthogonal matrix.
5. Multiply both sides of  $AU = U\Lambda$  by  $U^T$ :

$$A = U\Lambda U^T$$

## 8.2.2 Difference between Eigendecomposition and Spectral Decomposition

**Definition:** Eigendecomposition of a diagonalizable matrix

$$A = U\Lambda U^{-1}$$

- $U = [u^{(1)} \quad \dots \quad u^{(n)}]$  eigenvectors form a basis for  $\mathbb{R}^n$
- $\Lambda = \begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_n \end{bmatrix}$

Eigendecomposition of a symmetric matrix  $A$

$$A = U\Lambda U^T$$

- $U = [u^{(1)} \quad \dots \quad u^{(n)}]$  eigenvectors form an orthonormal basis

## 8.3 Orthogonal matrices

**Definition:**  $U$  is an orthogonal matrix if

$$U = [u^{(1)} \quad \dots \quad u^{(n)}],$$

- $(u^{(i)})^\top u^{(j)} = \begin{cases} 0 & \text{if } i \neq j \\ 1 & \text{if } i = j \end{cases}$
- i.e.  $U^{-1} = U^T$
- i.e. Columns of an orthogonal matrix are orthonormal.

### 8.3.1 What happens when we multiply a vector by an orthogonal matrix?

**Derivation:**

$$y = Ux$$

**Answer:**  $Ux$  is a rotation of  $x$ , plus a possible flip.

**Why?** Let's start with proving two facts:

- **Why? Fact 1:** If  $U$  is orthogonal, then

$$\|Ux\|_2 = \|x\|_2.$$

– **Proof:**

$$\begin{aligned} \|Ux\|_2^2 &= (Ux)^\top (Ux) \\ &= x^\top U^\top Ux \\ &= x^\top Ix \\ &= \|x\|_2^2. \end{aligned}$$

- **Fact 2:** Suppose  $x$  and  $y$  have an angle  $\Theta$  between them. Then  $Ux$  and  $Uy$  have the same angle  $\Theta$  between them.

– **Proof (1-2):** By previous lecture, we showed that

$$\cos \Theta = \frac{\langle x, y \rangle}{\|x\|_2 \|y\|_2} = \frac{x^\top y}{\|x\|_2 \|y\|_2}.$$



– Now, prove 2-1,

$$\begin{aligned}
 \frac{\langle Ux, Uy \rangle}{\|Ux\|_2 \|Uy\|_2} &= \frac{(Uy)^\top (Ux)}{\|Ux\|_2 \|Uy\|_2} \\
 &= \frac{y^\top U^\top U x}{\|x\|_2 \|y\|_2} \quad \text{by fact 1} \\
 &= \frac{y^\top x}{\|x\|_2 \|y\|_2} = \cos \Theta \quad \text{by } U^\top U = I
 \end{aligned}$$

Thus, the angle remains unchanged after applying  $U$ .

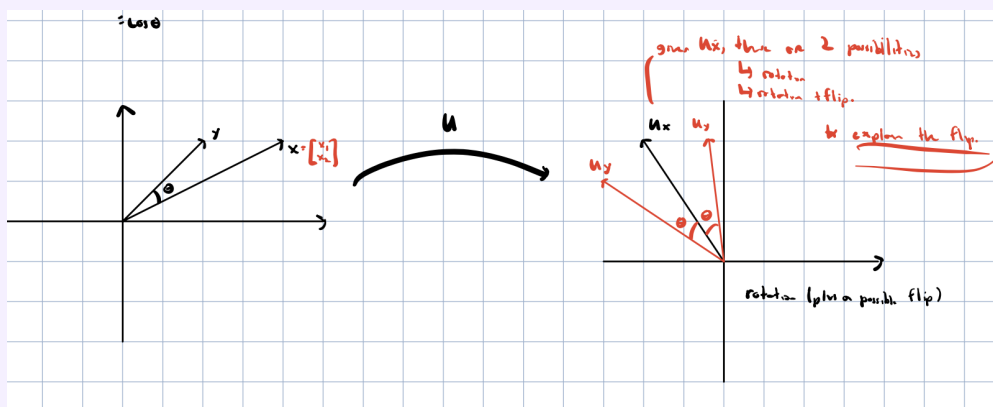


Figure 38: Orthogonal matrix performed on two vectors causes a rotation and possibly a flip.

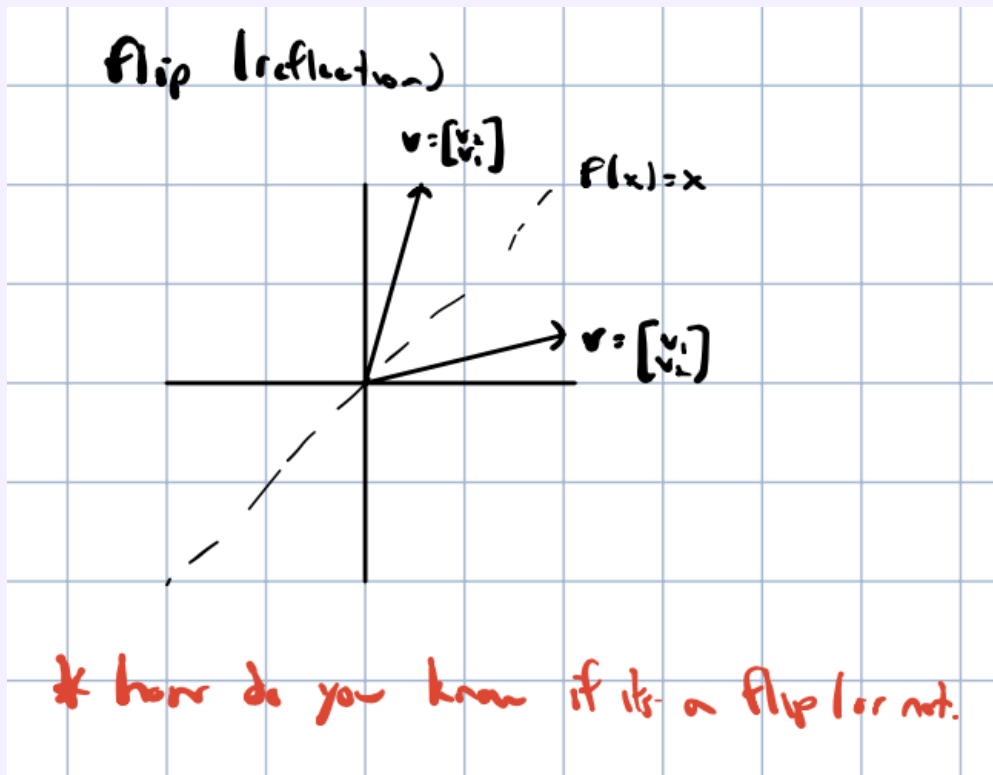


Figure 39: Flip.

**Example:** Examples of flipping in orthogonal matrices.

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_2 \\ x_1 \\ x_3 \end{bmatrix}$$

This is flipping across the  $x_1, x_2$  hyperplane.

$$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_3 \\ x_2 \\ x_1 \end{bmatrix}$$

This is flipping across the  $x_3, x_1$  hyperplane.

### 8.3.2 What kind of transformation corresponds to multiplying by a symmetric matrix?

**Derivation:**

$$\begin{aligned} y &= Ax = U\Lambda U^\top x \\ U^\top y &= \Lambda U^\top x \\ \tilde{y} &= \Lambda \tilde{x} \end{aligned}$$

- $\tilde{y}$ :  $U^\top y$
- $\tilde{x}$ :  $U^\top x$

So, an interpretation of  $y = Ax$  is:

1. Rotation (or flip) of  $x$  to get  $\tilde{x}$ , where  $\tilde{x} = U^\top x$ .
2. The  $i$ -th component of  $\tilde{x}$  is scaled by  $\lambda_i$ , where  $\tilde{y} = \Lambda \tilde{x}$ .
3. Rotation (or flip)  $\tilde{y}$  back to  $y$ , where  $y = U\tilde{y}$ .

Now, let's look at  $\tilde{x} = U^\top x$ :

$$\tilde{x} = U^\top x = \begin{bmatrix} (u^{(1)})^\top \\ \vdots \\ (u^{(n)})^\top \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} \langle u^{(1)}, x \rangle \\ \vdots \\ \langle u^{(n)}, x \rangle \end{bmatrix}$$

Recall: The projection of  $x$  onto a subspace spanned by  $u^{(i)}$  is just  $\langle u^{(i)}, x \rangle u^{(i)}$

- So, we can think of  $U^\top x$  as the coordinates of  $x$  in the orthonormal basis  $\{u^{(1)}, \dots, u^{(n)}\}$ .

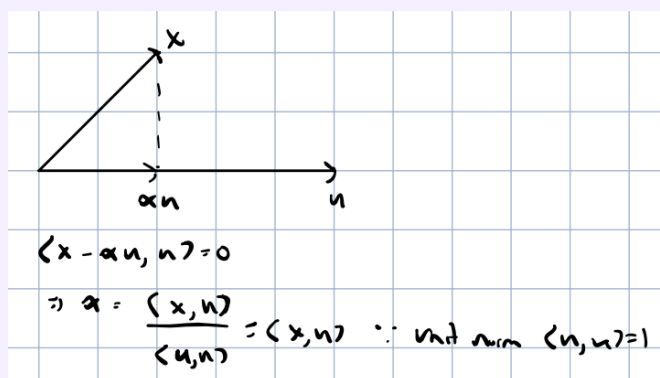


Figure 40: Projection

**Warning:** The interpretation is the same as the eigendecomposition for non-defective (but not necessarily symmetric matrices), but the change of basis is represented by rotations and flips since we have orthonormal matrices.

## 8.4 Positive semidefinite matrices

## 8.5 Ellipsoids

## **9 Singular Value Decomposition, Principal Component Analysis (Ch. 5.1, 5.3.2)**

### **9.1 Singular value decomposition**

### **9.2 Principle component analysis**

## 10 Interpretations of SVD, Low-Rank Approximation (Ch. 5.2-5.3.1)

### 10.1 Interpretation of SVD

### 10.2 Low-rank approximation

## **11 Least Squares, Overdetermined and Underdetermined Linear Equations (Ch. 6.1-6.4)**

**11.1 Least squares**

**11.2 Overdetermined linear equation**

**11.3 Underdetermined linear equation**

## **12 Regularized Least-Squares, Convex Sets and Convex Functions (Ch. 6.7.3, 8.1-8.4)**

### **12.1 Regularized least-squares**

### **12.2 Convex sets and convex functions**

## **13 Lagrangian Method for Constrained Optimization, Linear Programming and Quadratic Programming (Ch. 8.5, 9.1-9.6)**

**13.1 Lagrangian method for constrained optimization**

**13.2 Linear programming and quadratic programming**



- 14 Numerical Algorithms for Unconstrained and Constrained Optimization (Ch. 12.1-12.3)**
- 14.1 Numerical algorithms for unconstrained optimization**
- 14.2 Numerical algorithms for constrained optimization**