

Lecture 2: Linear Algebra

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Roadmap

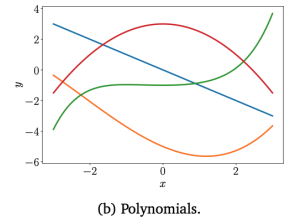
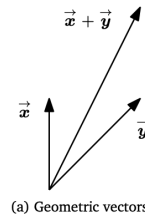
- (1) Systems of Linear Equations
- (2) Matrices
- (3) Solving Systems of Linear Equations
- (4) Vector Spaces
- (5) Linear Independence
- (6) Basis and Rank
- (7) Linear Mappings
- (8) Affine Spaces

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- Scalars: $a, b, c, \alpha, \beta, \gamma$
- Vectors: $\mathbf{x}, \mathbf{y}, \mathbf{z}$
- Matrices: $\mathbf{X}, \mathbf{Y}, \mathbf{Z}$
- Sets: $\mathcal{A}, \mathcal{B}, \mathcal{C}$
- (Ordered) tuple: $B = (\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3)$
- Matrix of column vectors: $\mathbf{B} = [\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3]$ or $\mathbf{B} = (\mathbf{b}_1 \ \mathbf{b}_2 \ \mathbf{b}_3)$
- Set of vectors: $\mathcal{B} = \{\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3\}$
- $\mathbb{R}, \mathbb{C}, \mathbb{Z}, \mathbb{N}, \mathbb{R}^n$, etc

- Algebra: a set of objects and a set of rules or operations to manipulate those objects
- Linear algebra
 - Object: vectors \mathbf{v}
 - Operations: their additions ($\mathbf{v} + \mathbf{w}$) and scalar multiplication ($k\mathbf{v}$)
- Examples
 - Geometric vectors
 - High school physics
 - Polynomials
 - Audio signals
 - Elements of \mathbb{R}^n



L2(1)

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System of Linear Equations

- For unknown variables $(x_1, \dots, x_n) \in \mathbb{R}^n$,

$$a_{11}x_1 + \dots + a_{1n}x_n = b_1$$

\vdots

$$a_{m1}x_1 + \dots + a_{mn}x_n = b_m$$

- Three cases of solutions

- No solution

$$\begin{array}{rcl} x_1 + x_2 + x_3 & = & 3 \\ x_1 - x_2 + 2x_3 & = & 2 \\ 2x_1 & + & 3x_3 = 1 \end{array}$$

- Unique solution

$$\begin{array}{rcl} x_1 + x_2 + x_3 & = & 3 \\ x_1 - x_2 + 2x_3 & = & 2 \\ & x_2 + 3x_3 & = 1 \end{array}$$

- Infinitely many solutions

$$\begin{array}{rcl} x_1 + x_2 + x_3 & = & 3 \\ x_1 - x_2 + 2x_3 & = & 2 \\ 2x_1 & + & 3x_3 = 5 \end{array}$$

- Question: Under what conditions, one of the above three cases occur.

L2(1)

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- A collection of linear equations

$$a_{11}x_1 + \cdots + a_{1n}x_n = b_1$$

$$\vdots$$

$$a_{m1}x_1 + \cdots + a_{mn}x_n = b_m$$

- Matrix representations:

$$\begin{pmatrix} a_{11} \\ \vdots \\ a_{m1} \end{pmatrix} x_1 + \cdots + \begin{pmatrix} a_{1n} \\ \vdots \\ a_{mn} \end{pmatrix} x_n = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix} \iff \underbrace{\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix}}_{\mathbf{A}} \underbrace{\begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}}_{\mathbf{x}} = \underbrace{\begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix}}_{\mathbf{b}}$$

- Understanding \mathbf{A} is the key to answering various questions about this linear system $\mathbf{Ax} = \mathbf{b}$.

L2(1)

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L2(2)

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- For two matrices $\mathbf{A} \in \mathbb{R}^{m \times n}$ and $\mathbf{B} \in \mathbb{R}^{m \times n}$,

$$\mathbf{A} + \mathbf{B} := \begin{pmatrix} a_{11} + b_{11} & \cdots & a_{1n} + b_{1n} \\ \vdots & & \vdots \\ a_{m1} + b_{m1} & \cdots & a_{mn} + b_{mn} \end{pmatrix} \in \mathbb{R}^{m \times n}$$

- For two matrices $\mathbf{A} \in \mathbb{R}^{m \times n}$ and $\mathbf{B} \in \mathbb{R}^{n \times k}$, the elements c_{ij} of the product $\mathbf{C} = \mathbf{AB} \in \mathbb{R}^{m \times k}$ is:

$$c_{ij} = \sum_{l=1}^n a_{il}b_{lj}, \quad i = 1, \dots, m, \quad j = 1, \dots, k.$$

- Example.** $\mathbf{A} = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 2 & 1 \end{pmatrix}$ and $\mathbf{B} = \begin{pmatrix} 0 & 2 \\ 1 & -1 \\ 0 & 1 \end{pmatrix}$, compute \mathbf{AB} and \mathbf{BA} .

L2(2)

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Identity Matrix and Matrix Properties

- A square matrix¹ \mathbf{I}_n with $I_{ii} = 1$ and $I_{ij} = 0$ for $i \neq j$, where n is the number of rows and columns. For example,

$$\mathbf{I}_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \mathbf{I}_4 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- Associativity:** For $\mathbf{A} \in \mathbb{R}^{m \times n}$, $\mathbf{B} \in \mathbb{R}^{n \times p}$, $\mathbf{C} \in \mathbb{R}^{p \times q}$, $(\mathbf{AB})\mathbf{C} = \mathbf{A}(\mathbf{BC})$
- Distributivity:** For $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{m \times n}$, and $\mathbf{C}, \mathbf{D} \in \mathbb{R}^{n \times p}$,
(i) $(\mathbf{A} + \mathbf{B})\mathbf{C} = \mathbf{AC} + \mathbf{BC}$ and (ii) $\mathbf{A}(\mathbf{C} + \mathbf{D}) = \mathbf{AC} + \mathbf{AD}$
- Multiplication with the identity matrix:** For $\mathbf{A} \in \mathbb{R}^{m \times n}$, $\mathbf{I}_m\mathbf{A} = \mathbf{AI}_n = \mathbf{A}$

¹# of rows = # of cols

L2(2)

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- For a square matrix $\mathbf{A} \in \mathbb{R}^{n \times n}$, \mathbf{B} is the **inverse** of \mathbf{A} , denoted by \mathbf{A}^{-1} , if

$$\mathbf{AB} = \mathbf{I}_n = \mathbf{BA}.$$

- Called **regular/invertible/nonsingular**, if it exists.
- If it exists, it is unique.
- (Q). How to compute?
- For 2×2 matrix,

$$\mathbf{A}^{-1} = \frac{1}{a_{11}a_{22} - a_{12}a_{21}} \begin{pmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{pmatrix}$$

- For a matrix $\mathbf{A} \in \mathbb{R}^{m \times n}$, the $\mathbf{B} \in \mathbb{R}^{n \times m}$ with $b_{ij} = a_{ji}$ is the **transpose** of \mathbf{A} , which we denote by \mathbf{A}^T .

- Example.** For $\mathbf{A} = \begin{pmatrix} 0 & 2 \\ 1 & -1 \\ 0 & 1 \end{pmatrix}$,

$$\mathbf{A}^T = \begin{pmatrix} 0 & 1 & 0 \\ 2 & -1 & 1 \end{pmatrix}$$

- If $\mathbf{A} = \mathbf{A}^T$, \mathbf{A} is called **symmetric**.

- $\mathbf{AA}^{-1} = \mathbf{I} = \mathbf{A}^{-1}\mathbf{A}$
- $(\mathbf{AB})^{-1} = \mathbf{B}^{-1}\mathbf{A}^{-1}$
- $(\mathbf{A} + \mathbf{B})^{-1} \neq \mathbf{A}^{-1} + \mathbf{B}^{-1}$
- $(\mathbf{A}^T)^T = \mathbf{A}$
- $(\mathbf{A} + \mathbf{B})^T = \mathbf{A}^T + \mathbf{B}^T$
- $(\mathbf{AB})^T = \mathbf{B}^T\mathbf{A}^T$
- If \mathbf{A} is invertible, so is \mathbf{A}^T .

- Multiplication by a scalar $\lambda \in \mathbb{R}$ to $\mathbf{A} \in \mathbb{R}^{m \times n}$
- **Example.** For $\mathbf{A} = \begin{pmatrix} 0 & 2 \\ 1 & -1 \\ 0 & 1 \end{pmatrix}$, $3 \times \mathbf{A} = \begin{pmatrix} 0 & 6 \\ 3 & -3 \\ 0 & 3 \end{pmatrix}$
- **Associativity**
 - $(\lambda\psi)\mathbf{C} = \lambda(\psi\mathbf{C})$
 - $\lambda(\mathbf{BC}) = (\lambda\mathbf{B})\mathbf{C} = \mathbf{B}(\lambda\mathbf{C}) = (\mathbf{BC})\lambda$
 - $(\lambda\mathbf{C})^T = \mathbf{C}^T\lambda^T = \mathbf{C}^T\lambda = \lambda\mathbf{C}^T$
- **Distributivity**
 - $(\lambda + \psi)\mathbf{C} = \lambda\mathbf{C} + \psi\mathbf{C}$
 - $\lambda(\mathbf{B} + \mathbf{C}) = \lambda\mathbf{B} + \lambda\mathbf{C}$

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L2(3)

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$$\begin{array}{rcl} -3x & + 2z & = -1 \\ x - 2y + 2z & = & -5/3 \\ -x - 4y + 6z & = & -13/3 \end{array}$$

- ρ_i : i -th equation
- Express the equation as its **augmented matrix**.

$$\begin{array}{c} \left(\begin{array}{ccc|c} -3 & 0 & 2 & -1 \\ 1 & -2 & 2 & -5/3 \\ -1 & -4 & 6 & -13/3 \end{array} \right) \xrightarrow[\begin{array}{c} (1/3)\rho_1 + \rho_2 \\ -(1/3)\rho_1 + \rho_3 \end{array}]{\begin{array}{c} (1/3)\rho_1 + \rho_2 \\ -(1/3)\rho_1 + \rho_3 \end{array}} \left(\begin{array}{ccc|c} -3 & 0 & 2 & -1 \\ 0 & -2 & 8/3 & -2 \\ 0 & -4 & 16/3 & -4 \end{array} \right) \\ \xrightarrow{-2\rho_2 + \rho_3} \left(\begin{array}{ccc|c} -3 & 0 & 2 & -1 \\ 0 & -2 & 8/3 & -2 \\ 0 & 0 & 0 & 0 \end{array} \right) \end{array}$$

The two nonzero rows give $-3x + 2z = -1$ and $-2y + (8/3)z = -2$.

L2(3)

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- Parametrizing $-3x + 2z = -1$ and $-2y + (8/3)z = -2$ gives:

$$\begin{array}{l} x = (1/3) + (2/3)z \\ y = 1 + (4/3)z \\ z = z \end{array} \quad \left| \quad \left\{ \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 1/3 \\ 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 2/3 \\ 4/3 \\ 1 \end{pmatrix} z \mid z \in \mathbb{R} \right\} \right.$$

This helps us understand the set of solutions, e.g., each value of z gives a different solution.

	z	0	1	2	$-1/2$
solution	$\begin{pmatrix} x \\ y \\ z \end{pmatrix}$	$\begin{pmatrix} 1/3 \\ 1 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 1 \\ 7/3 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 5/3 \\ 11/3 \\ 2 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 1/3 \\ -1/2 \end{pmatrix}$

L2(3)

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- The system $\begin{matrix} x + 2y - z = 2 \\ 2x - y - 2z + w = 5 \end{matrix}$ reduces in this way.

$$\left(\begin{array}{cccc|c} 1 & 2 & -1 & 0 & 2 \\ 2 & -1 & -2 & 1 & 5 \end{array} \right) \xrightarrow{-2\rho_1 + \rho_2} \left(\begin{array}{cccc|c} 1 & 2 & -1 & 0 & 2 \\ 0 & -5 & 0 & 1 & 1 \end{array} \right)$$

- It has solutions of this form.

$$\begin{pmatrix} x \\ y \\ z \\ w \end{pmatrix} = \begin{pmatrix} 12/5 \\ -1/5 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} z + \begin{pmatrix} -2/5 \\ 1/5 \\ 0 \\ 1 \end{pmatrix} w \quad \text{for } z, w \in \mathbb{R}$$

- Note that taking $z = w = 0$ shows that the first vector is a **particular solution** of the system.

L2(3)

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General = Particular + Homogeneous

- General approach
 - Find a particular solution to $\mathbf{Ax} = \mathbf{b}$
 - Find all solutions to the homogeneous equation $\mathbf{Ax} = \mathbf{0}$
 - 0 is a trivial solution
 - Combine the solutions from steps 1. and 2. to the general solution
- Questions: A formal algorithm that performs the above?
 - Gauss-Jordan method**: convert into a “beautiful” form (formally **reduced row-echelon** form)
 - Elementary transformations: (i) row swapping (ii) multiply by a constant (iii) row addition
- Such a form allows an algorithmic way of solving linear equations

L2(3)

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Example: Unique Solution

- Start as usual by getting echelon form.

$$\begin{array}{rcl} x + y - z = 2 & & x + y - z = 2 \\ 2x - y = -1 & \xrightarrow{-2\rho_1+\rho_2} & -3y + 2z = -5 \\ x - 2y + 2z = -1 & \xrightarrow{-1\rho_1+\rho_3} & -3y + 3z = -3 \end{array} \quad \xrightarrow{-1\rho_2+\rho_3} \quad \begin{array}{rcl} x + y - z = 2 & & x + y - z = 2 \\ -3y + 2z = -5 & & -3y + 2z = -5 \\ z = 2 & & z = 2 \end{array}$$

- Make all the leading entries one.

$$\xrightarrow{(-1/3)\rho_2} \begin{array}{rcl} x + y - z = 2 & & z = 2 \\ y - (2/3)z = 5/3 & & \\ z = 2 & & \end{array}$$

- Finish by using the leading entries to eliminate upwards, until we can read off the solution.

$$\begin{array}{rcl} x + y - z = 2 & & x + y = 4 \\ y - (2/3)z = 5/3 & \xrightarrow{\rho_3+\rho_1} & y = 3 \\ z = 2 & \xrightarrow{(2/3)\rho_3+\rho_2} & z = 2 \end{array} \quad \xrightarrow{-\rho_2+\rho_1} \quad \begin{array}{rcl} x & = & 1 \\ y & = & 3 \\ z & = & 2 \end{array}$$

L2(3)

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Example: Infinite Number of Solutions

- Start by getting echelon form and turn the leading entries to 1's.

$$\begin{array}{rcl} x - y - 2w = 2 & & \\ x + y + 3z + w = 1 & & \\ -y + z - w = 0 & & \end{array}$$

$$\xrightarrow{-1\rho_1+\rho_2} \left(\begin{array}{cccc|c} 1 & -1 & 0 & -2 & 2 \\ 0 & 2 & 3 & 3 & -1 \\ 0 & -1 & 1 & -1 & 0 \end{array} \right)$$

$$\xrightarrow{(1/2)\rho_2+\rho_3} \left(\begin{array}{cccc|c} 1 & -1 & 0 & -2 & 2 \\ 0 & 2 & 3 & 3 & -1 \\ 0 & 0 & 5/2 & 1/2 & -1/2 \end{array} \right)$$

$$\xrightarrow{\begin{smallmatrix} (1/2)\rho_2 \\ (2/5)\rho_3 \end{smallmatrix}} \left(\begin{array}{cccc|c} 1 & -1 & 0 & -2 & 2 \\ 0 & 1 & 3/2 & 3/2 & -1/2 \\ 0 & 0 & 1 & 1/5 & -1/5 \end{array} \right)$$

- Eliminate upwards.

$$\xrightarrow{-(3/2)\rho_3+\rho_2} \left(\begin{array}{cccc|c} 1 & -1 & 0 & -2 & 2 \\ 0 & 1 & 0 & 6/5 & -1/5 \\ 0 & 0 & 1 & 1/5 & -1/5 \end{array} \right)$$

$$\xrightarrow{\rho_2+\rho_1} \left(\begin{array}{cccc|c} 1 & 0 & 0 & -4/5 & 9/5 \\ 0 & 1 & 0 & 6/5 & -1/5 \\ 0 & 0 & 1 & 1/5 & -1/5 \end{array} \right)$$

- The parameterized solution set is:

$$\left\{ \begin{pmatrix} 9/5 \\ -1/5 \\ -1/5 \\ 0 \end{pmatrix} + \begin{pmatrix} 4/5 \\ -6/5 \\ -1/5 \\ 1 \end{pmatrix} w \mid w \in \mathbb{R} \right\}$$

L2(3)

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		<i>number of solutions of the homogeneous system</i>	
		<i>one</i>	<i>infinitely many</i>
<i>particular solution exists?</i>	<i>yes</i>	unique solution	infinitely many solutions
	<i>no</i>	no solutions	no solutions

Algorithms for Solving System of Linear Equations

1. Pseudo-inverse

$$\mathbf{Ax} = \mathbf{b} \iff \mathbf{A}^T \mathbf{Ax} = \mathbf{A}^T \mathbf{b} \iff \mathbf{x} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b}$$

- $(\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T$: *Moore-Penrose pseudo-inverse*
- many computations: matrix product, inverse, etc

2. Gaussian elimination

- intuitive and constructive way
- cubic complexity (in terms of # of simultaneous equations)

3. Iterative methods

- practical ways to solve indirectly
- (a) stationary iterative methods: Richardson method, Jacobi method, Gauss-Seidel method, successive over-relaxation method
- (b) Krylov subspace methods: conjugate gradients, generalized minimal residual, biconjugate gradients

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L2(4)

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- A set \mathcal{G} and an operation $\otimes : \mathcal{G} \times \mathcal{G} \mapsto \mathcal{G}$. $G := (\mathcal{G}, \otimes)$ is called a **group**, if:
 - 1. **Closure**. $\forall x, y \in \mathcal{G}, x \otimes y \in \mathcal{G}$
 - 2. **Associativity**. $\forall x, y, z \in \mathcal{G}, (x \otimes y) \otimes z = x \otimes (y \otimes z)$
 - 3. **Neutral element**. $\exists e \in \mathcal{G}, \forall x \in \mathcal{G}, x \otimes e = x$ and $e \otimes x = x$
 - 4. **Inverse element**. $\forall x \in \mathcal{G}, \exists y \in \mathcal{G}, x \otimes y = e$ and $y \otimes x = e$. We often use $x^{-1} = y$.
- $G = (\mathcal{G}, \otimes)$ is an **Abelian group**, if the following is additionally met:
 - **Communicativity**. $\forall x, y \in \mathcal{G}, x \otimes y = y \otimes x$

L2(4)

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- $(\mathbb{Z}, +)$ is an Abelian group
- $(\mathbb{N} \cup \{0\}, +)$ is not a group (because inverses are missing)
- (\mathbb{Z}, \cdot) is not a group
- (\mathbb{R}, \cdot) is not a group (because of no inverse for 0)
- $(\mathbb{R}^n, +)$, $(\mathbb{Z}^n, +)$ are Abelian, if $+$ is defined componentwise
- $(\mathbb{R}^{m \times n}, +)$ is Abelian (with componentwise $+$)
- $(\mathbb{R}^{n \times n}, \cdot)$
 - Closure and associativity follow directly
 - Neutral element: I_n
 - The inverse \mathbf{A}^{-1} may exist or not. So, generally, it is not a group. However, the set of invertible matrices in $\mathbb{R}^{n \times n}$ with matrix multiplication is a group, called **general linear group**.

L2(4)

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Definition. A real-valued vector space $V = (\mathcal{V}, +, \cdot)$ is a set \mathcal{V} with two operations

$+: \mathcal{V} \times \mathcal{V} \mapsto \mathcal{V}$ (vector addition)

$\cdot: \mathbb{R} \times \mathcal{V} \mapsto \mathcal{V}$ (scalar multiplication),

where

1. $(\mathcal{V}, +)$ is an Abelian group
2. **Distributivity.**
 - $\forall \lambda \in \mathbb{R}, \mathbf{x}, \mathbf{y} \in \mathcal{V}, \lambda \cdot (\mathbf{x} + \mathbf{y}) = \lambda \cdot \mathbf{x} + \lambda \mathbf{y}$
 - $\forall \lambda, \psi \in \mathbb{R}, \mathbf{x} \in \mathcal{V}, (\lambda + \psi) \cdot \mathbf{x} = \lambda \cdot \mathbf{x} + \psi \cdot \mathbf{x}$
3. **Associativity.** $\forall \lambda, \psi \in \mathbb{R}, \mathbf{x} \in \mathcal{V}, \lambda \cdot (\psi \cdot \mathbf{x}) = (\lambda\psi) \cdot \mathbf{x}$
4. **Neutral element.** $\forall \mathbf{x} \in \mathcal{V}, 1 \cdot \mathbf{x} = \mathbf{x}$

L2(4)

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- $\mathcal{V} = \mathbb{R}^n$ with
 - Vector addition: $\mathbf{x} + \mathbf{y} = (x_1 + y_1, \dots, x_n + y_n)$
 - Scalar multiplication: $\lambda \mathbf{x} = (\lambda x_1, \dots, \lambda x_n)$
- $\mathcal{V} = \mathbb{R}^{m \times n}$ with
 - Vector addition: $\mathbf{A} + \mathbf{B} = \begin{pmatrix} a_{11} + b_{11} & \cdots & a_{1n} + b_{1n} \\ \vdots & & \vdots \\ a_{m1} + b_{m1} & \cdots & a_{mn} + b_{mn} \end{pmatrix}$
 - Scalar multiplication: $\lambda \mathbf{A} = \begin{pmatrix} \lambda a_{11} & \cdots & \lambda a_{1n} \\ \vdots & & \vdots \\ \lambda a_{m1} & \cdots & \lambda a_{mn} \end{pmatrix}$

L2(4)

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Vector Subspaces

Definition. Consider a vector space $V = (\mathcal{V}, +, \cdot)$ and $\mathcal{U} \subset \mathcal{V}$. Then, $U = (\mathcal{U}, +, \cdot)$ is called **vector subspace** (simply linear subspace or subspace) of V if U is a vector space with two operations '+' and '·' restricted to $\mathcal{U} \times \mathcal{U}$ and $\mathbb{R} \times \mathcal{U}$.

Examples

- For every vector space V , V and $\{0\}$ are the trivial subspaces.
- The solution set of $\mathbf{Ax} = 0$ is the subspace of \mathbb{R}^n .
- The solution of $\mathbf{Ax} = \mathbf{b}$ ($\mathbf{b} \neq 0$) is not a subspace of \mathbb{R}^n .
- The intersection of arbitrarily many subspaces is a subspace itself.

L2(4)

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L2(5)

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- **Definition.** For a vector space V and vectors $\mathbf{x}_1, \dots, \mathbf{x}_n \in V$, every $\mathbf{v} \in V$ of the form $\mathbf{v} = \lambda_1 \mathbf{x}_1 + \dots + \lambda_k \mathbf{x}_k$ with $\lambda_1, \dots, \lambda_k \in \mathbb{R}$ is a **linear combination** of the vectors $\mathbf{x}_1, \dots, \mathbf{x}_n \in V$.
- **Definition.** If there is a non-trivial linear combination such that $0 = \sum_{i=1}^k \lambda_i \mathbf{x}_i$ with at least one $\lambda_i \neq 0$, the vectors $\mathbf{x}_1, \dots, \mathbf{x}_n$ are **linearly dependent**. If only the trivial solution exists, i.e., $\lambda_1 = \dots = \lambda_k = 0$, $\mathbf{x}_1, \dots, \mathbf{x}_n$ are **linearly independent**.
- **Meaning.** A set of linearly independent vectors consists of vectors that have no redundancy.
- **Useful fact.** The vectors $\{\mathbf{x}_1, \dots, \mathbf{x}_n\}$ are linearly dependent, iff (at least) one of them is a linear combination of the others.
 - $x - 2y = 2$ and $2x - 4y = 4$ are linearly dependent.

L2(5)

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- Gauss elimination to get the row echelon form
- All column vectors are linearly independent iff all columns are pivot columns (why?).
- Example.

$$\mathbf{x}_1 = \begin{pmatrix} 1 \\ 2 \\ -3 \\ 4 \end{pmatrix}, \quad \mathbf{x}_2 = \begin{pmatrix} 1 \\ 1 \\ 0 \\ 2 \end{pmatrix}, \quad \mathbf{x}_3 = \begin{pmatrix} -1 \\ -2 \\ 1 \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 1 & -1 \\ 2 & 1 & -2 \\ -3 & 0 & 1 \\ 4 & 2 & 1 \end{pmatrix} \rightsquigarrow \dots \rightsquigarrow \begin{pmatrix} 1 & 1 & -1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

- Every column is a pivot column. Thus, $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$ are linearly independent.

L2(5)

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Linear Combinations of Linearly Independent Vectors

- Vector space V with k linearly independent vectors $\mathbf{b}_1, \mathbf{b}_2, \dots, \mathbf{b}_k$
- m linear combinations $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_m$. (Q) Are they linearly independent?

$$\begin{array}{l} \mathbf{x}_1 = \lambda_{11}\mathbf{b}_1 + \lambda_{21}\mathbf{b}_2 + \dots + \lambda_{k1}\mathbf{b}_k \\ \vdots \\ \mathbf{x}_m = \lambda_{1m}\mathbf{b}_1 + \lambda_{2m}\mathbf{b}_2 + \dots + \lambda_{km}\mathbf{b}_k \end{array} \quad \left| \quad \mathbf{x}_j = \underbrace{(\mathbf{b}_1, \dots, \mathbf{b}_k)}_{\mathbf{B}} \underbrace{\begin{pmatrix} \lambda_{1j} \\ \vdots \\ \lambda_{kj} \end{pmatrix}}_{\lambda_j}, \quad \mathbf{x}_j = \mathbf{B}\lambda_j$$

- $\sum_{j=1}^m \psi_j \mathbf{x}_j = \sum_{j=1}^m \psi_j \mathbf{B}\lambda_j = \mathbf{B} \sum_{j=1}^m \psi_j \lambda_j$
- $\{\mathbf{x}\}$ linearly independent $\iff \{\lambda\}$ linearly independent

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$$\begin{aligned}
 \mathbf{x}_1 &= \mathbf{b}_1 - 2\mathbf{b}_2 + \mathbf{b}_3 - \mathbf{b}_4 \\
 \mathbf{x}_2 &= -4\mathbf{b}_1 - 2\mathbf{b}_2 + 4\mathbf{b}_4 \\
 \mathbf{x}_3 &= 2\mathbf{b}_1 + 3\mathbf{b}_2 - \mathbf{b}_3 - 3\mathbf{b}_4 \\
 \mathbf{x}_4 &= 17\mathbf{b}_1 - 10\mathbf{b}_2 + 11\mathbf{b}_3 + \mathbf{b}_4
 \end{aligned}$$

$$\mathbf{A} = (\lambda_1 \ \lambda_2 \ \lambda_3 \ \lambda_4) = \begin{pmatrix} 1 & -4 & 2 & 17 \\ -2 & -2 & 3 & -10 \\ 1 & 0 & -1 & 11 \\ -1 & -4 & -3 & 1 \end{pmatrix} \rightsquigarrow \dots \rightsquigarrow \begin{pmatrix} 1 & 0 & 0 & -7 \\ 0 & 1 & 0 & -15 \\ 0 & 0 & 1 & -18 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- The last column is not a pivot column. Thus, $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4$ are linearly dependent.

- (1) Systems of Linear Equations
- (2) Matrices
- (3) Solving Systems of Linear Equations
- (4) Vector Spaces
- (5) Linear Independence
- (6) **Basis and Rank**
- (7) Linear Mappings
- (8) Affine Spaces

- **Definition.** A vector space $V = (\mathcal{V}, +, \cdot)$ and a set of vectors $\mathcal{A} = \{\mathbf{x}_1, \dots, \mathbf{x}_k\} \subset \mathcal{V}$.
 - If every $\mathbf{v} \in \mathcal{V}$ can be expressed as a linear combination of $\mathbf{x}_1, \dots, \mathbf{x}_k$, \mathcal{A} is called a **generating set** of V .
 - The set of all linear combinations of \mathcal{A} is called the **span** of \mathcal{A} .
 - If \mathcal{A} spans the vector space V , we use $V = \text{span}[\mathcal{A}]$ or $V = \text{span}[\mathbf{x}_1, \dots, \mathbf{x}_k]$
- **Definition.** The minimal generating set \mathcal{B} of V is called **basis** of V . We call each element of \mathcal{B} **basis vector**. The number of basis vectors is called **dimension** of V .
- **Properties**
 - \mathcal{B} is a maximally² linearly independent set of vectors in V .
 - Every vector $\mathbf{x} \in V$ is a linear combination of \mathcal{B} , which is unique.

²Adding any other vector to this set will make it linearly dependent.
L2(6)

Examples

- Different bases \mathbb{R}^3

$$\mathcal{B}_1 = \left\{ \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \right\}, \mathcal{B}_2 = \left\{ \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \right\},$$

$$\mathcal{B}_3 = \left\{ \begin{pmatrix} 0.5 \\ 0.8 \\ 0.4 \end{pmatrix}, \begin{pmatrix} 1.8 \\ 0.3 \\ 0.3 \end{pmatrix}, \begin{pmatrix} -2.2 \\ -1.3 \\ 3.5 \end{pmatrix} \right\}$$
- Linearly independent, but not maximal. Thus, not a basis.

$$\mathcal{A} = \left\{ \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \end{pmatrix}, \begin{pmatrix} 2 \\ -1 \\ 0 \\ 2 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 0 \\ -4 \end{pmatrix} \right\}$$

- Want to find a basis of a subspace $U = \text{span}[\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_m]$
 1. Construct a matrix $\mathbf{A} = (\mathbf{x}_1 \ \mathbf{x}_2 \ \cdots \ \mathbf{x}_m)$
 2. Find the row-echelon form of \mathbf{A} .
 3. Collect the pivot columns.
- Logic: Collect \mathbf{x}_i so that we have only trivial solution. Pivot columns tell us which set of vectors is linearly independent.
- See example 2.17 (pp. 35)

L2(6)

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- **Definition.** The **rank** of $\mathbf{A} \in \mathbb{R}^{m \times n}$ denoted by $\text{rk}(\mathbf{A})$ is # of linearly independent columns
 - Same as the number of linearly independent rows

$$\mathbf{A} = \begin{pmatrix} 1 & 2 & 1 \\ -2 & -3 & 1 \\ 3 & 5 & 0 \end{pmatrix} \rightsquigarrow \cdots \rightsquigarrow \begin{pmatrix} 1 & 2 & 1 \\ 0 & 1 & 3 \\ 0 & 0 & 0 \end{pmatrix}$$

Thus, $\text{rk}(\mathbf{A}) = 2$.

- $\text{rk}(\mathbf{A}) = \text{rk}(\mathbf{A}^T)$

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- The **columns** (resp. **rows**) of \mathbf{A} span a subspace U (resp. W) with $\dim(U) = \text{rk}(\mathbf{A})$ (resp. $\dim(W) = \text{rk}(\mathbf{A})$), and a basis of U (resp. W) can be found by Gauss elimination of \mathbf{A} (resp. \mathbf{A}^T).
- For all $\mathbf{A} \in \mathbb{R}^{n \times n}$, $\text{rk}(\mathbf{A}) = n$, iff \mathbf{A} is regular (invertible).
- The linear system $\mathbf{A}\mathbf{x} = \mathbf{b}$ is solvable, iff $\text{rk}(\mathbf{A}) = \text{rk}(\mathbf{A}|\mathbf{b})$.
- For $\mathbf{A} \in \mathbb{R}^{m \times n}$, the subspace of solutions for $\mathbf{A}\mathbf{x} = 0$ possesses dimension $n - \text{rk}(\mathbf{A})$.
- $\mathbf{A} \in \mathbb{R}^{m \times n}$ has **full rank** if its rank equals the largest possible rank for a matrix of the same dimensions. The rank of the full-rank matrix \mathbf{A} is $\min(\# \text{ of cols}, \# \text{ of rows})$.

- (1) Systems of Linear Equations
- (2) Matrices
- (3) Solving Systems of Linear Equations
- (4) Vector Spaces
- (5) Linear Independence
- (6) Basis and Rank
- (7) **Linear Mappings**
- (8) Affine Spaces

- Interest: A mapping that preserves the structure of the vector space
- **Definition.** For vector spaces V, W , a mapping $\Phi : V \mapsto W$ is called a **linear mapping** (or homomorphism/linear transformation), if, for all $\mathbf{x}, \mathbf{y} \in V$ and all $\lambda \in \mathbb{R}$,
 - $\Phi(\mathbf{x} + \mathbf{y}) = \Phi(\mathbf{x}) + \Phi(\mathbf{y})$
 - $\Phi(\lambda \mathbf{x}) = \lambda \Phi(\mathbf{x})$
- **Definition.** A mapping $\Phi : \mathcal{V} \mapsto \mathcal{W}$ is called
 - **Injective** (단사), if $\forall \mathbf{x}, \mathbf{y} \in \mathcal{V}, \Phi(\mathbf{x}) = \Phi(\mathbf{y}) \implies \mathbf{x} = \mathbf{y}$
 - **Surjective** (전사), if $\Phi(\mathcal{V}) = \mathcal{W}$
 - **Bijective** (전단사), if it is injective and surjective.

L2(7)

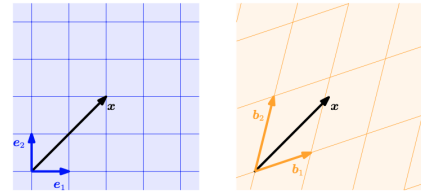
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- For bijective mapping, there exists an inverse mapping Φ^{-1} .
- **Isomorphism** if Ψ is linear and bijective.
- **Theorem.** Vector spaces V and W are isomorphic, iff $\dim(V) = \dim(W)$.
 - Vector spaces of the same dimension are kind of the same thing.
- Other properties
 - For two linear mappings Φ and Ψ , $\Phi \circ \Psi$ is also a linear mapping.
 - If Φ is an isomorphism, so is Φ^{-1} .
 - For two linear mappings Φ and Ψ , $\Phi + \Psi$ and $\lambda \Psi$ for $\lambda \in \mathbb{R}$ are linear.

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- A basis defines a coordinate system.



- Consider an ordered basis $B = (\mathbf{b}_1, \mathbf{b}_2, \dots, \mathbf{b}_n)$ of vector space V . Then, for any $\mathbf{x} \in V$, there exists a unique linear combination

$$\mathbf{x} = \alpha_1 \mathbf{b}_1 + \dots + \alpha_n \mathbf{b}_n.$$

- We call $\alpha = \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{pmatrix}$ the coordinate of \mathbf{x} with respect to $B = (\mathbf{b}_1, \mathbf{b}_2, \dots, \mathbf{b}_n)$.

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- Consider a vector space V and two coordinate systems defined by $B = (\mathbf{b}_1, \dots, \mathbf{b}_n)$ and $B' = (\mathbf{b}'_1, \dots, \mathbf{b}'_n)$.

- **Question.** For $(x_1, \dots, x_n)_B \rightarrow (y_1, \dots, y_n)_{B'}$, what is $(y_1, \dots, y_n)_{B'}$?

- **Theorem.**
$$\begin{pmatrix} y_1 \\ \vdots \\ y_n \end{pmatrix} = (\mathbf{b}'_1 \ \dots \ \mathbf{b}'_n)^{-1} (\mathbf{b}_1 \ \dots \ \mathbf{b}_n) \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}$$

- Regard $\mathbf{A}_\Phi = (\mathbf{b}'_1 \ \dots \ \mathbf{b}'_n)^{-1} (\mathbf{b}_1 \ \dots \ \mathbf{b}_n)$ as a linear map

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- $B = ((1, 0), (0, 1))$ and $B' = ((2, 1), (1, 2))$

- $(4, 2)_B \rightarrow (x, y)_{B'}$?

- Using $\begin{pmatrix} y_1 \\ \vdots \\ y_n \end{pmatrix} = (\mathbf{b}'_1 \ \dots \ \mathbf{b}'_n)^{-1} (\mathbf{b}_1 \ \dots \ \mathbf{b}_n) \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix},$

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}^{-1} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 4 \\ 2 \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} \end{pmatrix} \begin{pmatrix} 4 \\ 2 \end{pmatrix} = \begin{pmatrix} 2 \\ 0 \end{pmatrix}$$

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Transformation Matrix

- Two vector spaces
 - V with basis $B = (\mathbf{b}_1, \dots, \mathbf{b}_n)$ and W with basis $C = (\mathbf{c}_1, \dots, \mathbf{c}_m)$
- What is the coordinate in C -system for each basis \mathbf{b}_j ? For $j = 1, \dots, n$,

$$\mathbf{b}_j = \alpha_{1j}\mathbf{c}_1 + \dots + \alpha_{mj}\mathbf{c}_m \iff \mathbf{b}_j = (\mathbf{c}_1 \ \dots \ \mathbf{c}_m) \begin{pmatrix} \alpha_{1j} \\ \vdots \\ \alpha_{mj} \end{pmatrix}$$

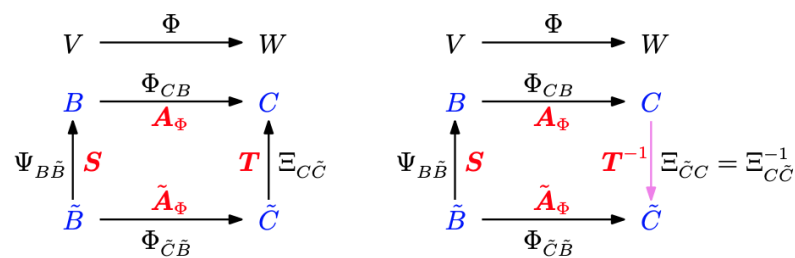
$$\implies (\mathbf{b}_1 \ \dots \ \mathbf{b}_n) = (\mathbf{c}_1 \ \dots \ \mathbf{c}_m) \overbrace{\begin{pmatrix} \alpha_{11} & \dots & \alpha_{1n} \\ \vdots & & \vdots \\ \alpha_{m1} & \dots & \alpha_{mn} \end{pmatrix}}^{\mathbf{A}_\Phi}$$

- $\hat{\mathbf{x}} = \mathbf{A}_\Phi \hat{\mathbf{y}}$, where $\hat{\mathbf{x}}$ is the vector w.r.t B and $\hat{\mathbf{y}}$ is the vector w.r.t. C

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- For linear mapping $\Phi : V \mapsto W$, consider bases B, B' of V and C, C' of W
 $B = (\mathbf{b}_1 \cdots \mathbf{b}_n), B' = (\mathbf{b}'_1 \cdots \mathbf{b}'_n) \quad C = (\mathbf{c}_1 \cdots \mathbf{c}_m), C' = (\mathbf{c}'_1 \cdots \mathbf{c}'_m).$
- (inter) transformation matrices \mathbf{A}_Φ from B to C and \mathbf{A}'_Φ from B' to C'
- (intra) transformation matrices S from B' to B and T from C' to C
- Theorem.** $\mathbf{A}'_\Phi = T^{-1} \mathbf{A}_\Phi S$

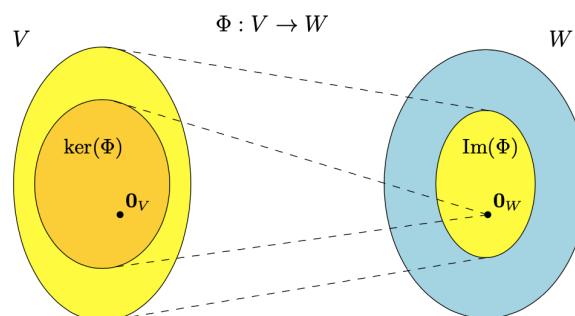


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Image and Kernel

- Consider a linear mapping $\Phi : V \mapsto W$. The **kernel** (or **null space**) is the set of vectors in V that maps to $0 \in W$ (i.e., neutral element).
- Definition.** $\ker(\Phi) := \Phi^{-1}(0_W) = \{\mathbf{v} \in V : \Phi(\mathbf{v}) = 0_W\}$
- Image/range:** set of vectors $w \in W$ that can be reached by Φ from any vector in V
- V : **domain**, W : **codomain**



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- $0_V \in \ker(\Phi)$ (because $\Phi(0_V) = 0_W$)
- Both $\text{Im}(\Phi)$ and $\ker(\Phi)$ are subspaces of W and V , respectively.
- Φ is one-to-one (injective) $\iff \ker(\Phi) = \{0\}$ (i.e., only 0 is mapped to 0)
- Since Φ is a linear mapping, there exists $\mathbf{A} \in \mathbb{R}^{m \times n}$ such that $\Phi : \mathbf{x} \mapsto \mathbf{A}\mathbf{x}$. Then, $\text{Im}(\Phi) = \text{column space of } \mathbf{A}$ which is the span of column vectors of \mathbf{A} .
- $\text{rk}(\mathbf{A}) = \dim(\text{Im}(\Phi))$
- $\ker(\Phi)$ is the solution set of the homogeneous system of linear equations $\mathbf{A}\mathbf{x} = 0$

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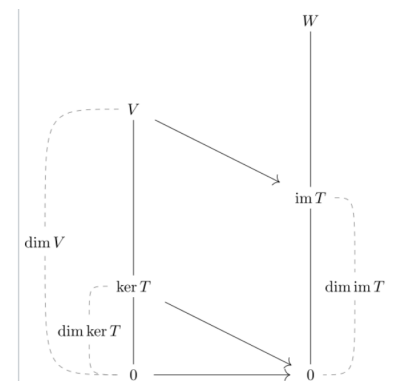
Rank-Nullity Theorem

Theorem.

$$\dim(\ker(\Phi)) + \dim(\text{Im}(\Phi)) = \dim(V)$$

- If $\dim(\text{Im}(\Phi)) < \dim(V)$, the kernel contains more than just 0.
- If $\dim(\text{Im}(\Phi)) < \dim(V)$, $\mathbf{A}_\Phi \mathbf{x} = 0$ has infinitely many solutions.
- If $\dim(V) = \dim(W)$ (e.g., $V = W = \mathbb{R}^n$), the followings are equivalent: Φ is
 - (1) injective, (2) surjective, (3) bijective,
 - In this case, Φ defines $\mathbf{y} = \mathbf{A}\mathbf{x}$, where \mathbf{A} is regular.
- **Simplified version.** For $\mathbf{A} \in \mathbb{R}^{m \times n}$,

$$\text{rk}(\mathbf{A}) + \text{nullity}(\mathbf{A}) = n$$



²Nullity: the dimension of null space (kernel)

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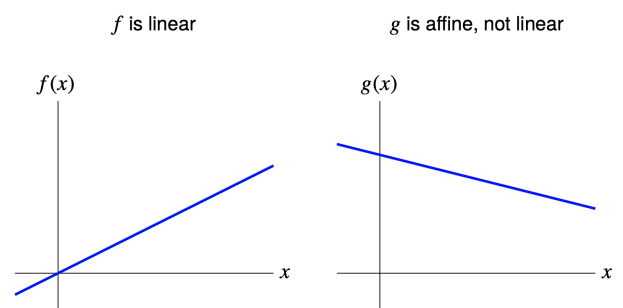
- (1) Systems of Linear Equations
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Linear vs. Affine Function

- **linear function**: $f(x) = ax$
- **affine function**: $f(x) = ax + b$
- sometimes (ignorant) people refer to affine functions as linear



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- Spaces that are offset from the origin. Not a vector space.
- **Definition.** Consider a vector space V , $\mathbf{x}_0 \in V$ and a subspace $U \subset V$. Then, the subset $L = \mathbf{x}_0 + U := \{\mathbf{x}_0 + \mathbf{u} : \mathbf{u} \in U\}$ is called **affine subspace** or **linear manifold** of V .
- U is called **direction** or **direction space**, and \mathbf{x}_0 is **support** point.
- An affine subspace is not a vector subspace of V for $\mathbf{x}_0 \notin U$.
- **Parametric equation.** A k -dimensional affine space $L = \mathbf{x}_0 + U$. If $(\mathbf{b}_1, \dots, \mathbf{b}_k)$ is an ordered basis of U , any element $\mathbf{x} \in L$ can be uniquely described as

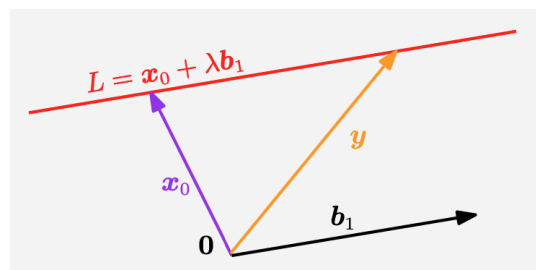
$$\mathbf{x} = \mathbf{x}_0 + \lambda_1 \mathbf{b}_1 + \dots + \lambda_k \mathbf{b}_k, \quad \lambda_1, \dots, \lambda_k \in \mathbb{R}$$

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Example

- In \mathbb{R}^2 , one-dimensional affine subspace: **line**. $\mathbf{y} = \mathbf{x}_0 + \lambda \mathbf{b}_1$. $U = \text{span}[\mathbf{b}_1]$
- In \mathbb{R}^3 , two-dimensional affine subspace: **plane**. $\mathbf{y} = \mathbf{x}_0 + \lambda_1 \mathbf{b}_1 + \lambda_2 \mathbf{b}_2$. $U = \text{span}[\mathbf{b}_1, \mathbf{b}_2]$
- In \mathbb{R}^n , $(n-1)$ -dimensional affine subspace: **hyperplane**. $\mathbf{y} = \mathbf{x}_0 + \sum_{k=1}^{n-1} \lambda_k \mathbf{b}_k$.
 $U = \text{span}[\mathbf{b}_1, \dots, \mathbf{b}_n]$



- For a linear mapping $\Phi : V \mapsto W$ and a vector $\mathbf{a} \in W$, the mapping $\phi : V \mapsto W$ with $\phi(\mathbf{x}) = \mathbf{a} + \Phi(\mathbf{x})$ is an **affine mapping** from V to W . The vector \mathbf{a} is called the **translation vector**.

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Questions?

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Review Questions

1)

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