

CEE6501 — Lecture 2.1

Matrix Representation and Operations

Learning Objectives

By the end of this lecture, you will:

- Understand matrices as **linear mappings** and as data structures
- Use consistent **notation** for scalars, vectors, and matrices
- Interpret matrix–vector and matrix–matrix products
- Reason about **dimensions, structure, and compatibility**
- Connect special matrix structure (symmetric/triangular/diagonal) to efficient solution strategies

Part 1 — Scalars, Vectors, and Matrices

What mathematical objects are we working with?

Scalars

A **scalar** is a single numerical value:

$$a \in \mathbb{R}$$

Scalars have magnitude but no direction or internal structure.

Vectors

A **vector** is an ordered collection of scalars:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^n$$

Vectors are treated as **column objects** by default.

Matrices

A **matrix** is a rectangular array of scalars:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \in \mathbb{R}^{m \times n}$$

Beyond being a table of numbers, a matrix represents a **linear mapping** between vector spaces:

$$\mathbf{A}\mathbf{x} = \mathbf{y}$$

That is, the matrix \mathbf{A} transforms an input vector $\{\mathbf{x}\}$ into an output vector $\{\mathbf{y}\}$.

A matrix can also be viewed as a rectangular array representing a **system of linear equations**, mapping an input vector $\{\mathbf{x}\}$ to an output vector $\{\mathbf{y}\}$:

For a 4×4 system:

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 = y_1$$

$$a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 = y_2$$

$$a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + a_{34}x_4 = y_3$$

$$a_{41}x_1 + a_{42}x_2 + a_{43}x_3 + a_{44}x_4 = y_4$$

Each row of \mathbf{A} defines one equation.

Each column of \mathbf{A} multiplies one unknown.

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}$$

Part 2 — Notation Conventions

How do we write linear algebra unambiguously in this class?

Why Notation Matters

Consistent notation:

- Makes dimensions immediately visible
- Prevents algebraic errors
- Allows equations to be read without ambiguity

Scalars

Scalars are written in **lowercase italic**:

$$a, b, c \in \mathbb{R}$$

Vectors

Vectors are written in **bold lowercase**:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \in \mathbb{R}^n$$

You may also see:

- $\{x\}$ (brace notation in some textbooks)

Matrices

Matrices are written in **bold uppercase**:

$$[A] = \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \in \mathbb{R}^{m \times n}$$

You may also see:

- $[A]$ (square-bracket notation in some textbooks)

Part 3 — Matrix Indexing

How do we refer to individual entries precisely?

Order (Size) of a Matrix

A matrix with m rows and n columns has size:

$$\mathbf{A} \in \mathbb{R}^{m \times n}$$

We say \mathbf{A} is of order:

$$m \times n$$

Matrix Elements

Each entry is called an **element**. The element in row i , column j is:

$$(\mathbf{A})_{ij} = a_{ij}$$

- First subscript $i \rightarrow$ row
- Second subscript $j \rightarrow$ column

Note: Python is 0-indexed, so row i , column j corresponds to `A[i-1, j-1]`.

```
In [10]: import numpy as np

A = np.array([[1, 2, 3],
              [4, 5, 6],
              [7, 8, 9]])

# a23 in math notation (row 2, column 3)
print(A[1, 2])    # Python indices: [2-1, 3-1]
```

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Meaning of Indices

For $\mathbf{A} \in \mathbb{R}^{m \times n}$:

- $i = 1, 2, \dots, m$
(rows)
- $j = 1, 2, \dots, n$
(columns)

So a_{ij} is the element in the i -th row and j -th column.

Example: A 4×3 Matrix

$$\mathbf{D} = \begin{bmatrix} 8 & 26 & 0 \\ 33 & 5 & 37 \\ 12 & 23 & 2 \\ 7 & 29 & 14 \end{bmatrix}$$

- Order: 4×3
- Rows:
 $i = 1,$
 $\dots, 4$
- Columns:
 $j = 1,$
 $\dots, 3$

Referring to Individual Elements

Elements of \mathbf{D} are d_{ij} .

Examples:

- $d_{13} = 0$
- $d_{31} = 12$
- $d_{42} = 29$

Part 4 — Types of Matrices

Matrix structure is not cosmetic — it reflects physics, modeling choices, and solver strategy.

Why Matrix Types Matter

In matrix structural analysis, matrix *structure* tells us:

- which DOFs are coupled
- which solvers we can use
- how expensive a computation will be

We will see the same matrix appear in multiple forms:

- stiffness matrices
- mass matrices
- constraint and penalty matrices

Column Matrix (Vector)

Definition

A matrix with a single column ($n = 1$), commonly called a **vector**:

$$\mathbf{x} \in \mathbb{R}^{m \times 1}$$

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix}$$

Column Matrix — Structural Interpretation

Column matrices (vectors) are the **primary carriers of information** in matrix structural analysis. Inputs and Outputs.

They represent:

- **Displacements \mathbf{u}** — the unknown DOFs we solve for
- **Loads \mathbf{f}** — the forces driving the system
- **Reactions** — forces at constrained DOFs

All structural analysis reduces to:

$$\mathbf{Ku} = \mathbf{f}$$

How to read this:

- each entry corresponds to **one degree of freedom**
- vectors define *what is unknown* and *what is applied*

Row Matrix

Definition

A matrix with a single row ($m = 1$):

$$\mathbf{c} \in \mathbb{R}^{1 \times n}$$

$$\mathbf{c} = [c_1 \quad c_2 \quad \cdots \quad c_n]$$

Row Matrix — Structural Interpretation

Row matrices act as **operators on DOF vectors**.

They take a **column vector input** and return a **scalar quantity**.

Let the displacement vector be:

$$\mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}$$

Let the selector vector be: $\mathbf{s}_1 = [0 \quad 1 \quad 0 \quad 0]$ $\mathbf{s}_2 = [1 \quad -1 \quad 0 \quad 0]$

DOF selection, s_1

$$\begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = u_2$$

DOF combination, s_2

$$\begin{bmatrix} 1 & -1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = u_1 - u_2$$

Interpretation:

- column vectors **store DOF values**
- row matrices **query or combine DOFs**
- output is a **single scalar condition**

Square Matrix

Definition

A matrix with the same number of rows and columns ($m = n$):

$$\mathbf{A} \in \mathbb{R}^{n \times n}$$

The **main diagonal** contains $a_{11}, a_{22}, \dots, a_{nn}$.

Square Matrix — Structural Meaning

Square matrices are the **heart of structural analysis**.

Direct stiffness method:

- **# equations = # unknown DOFs**
- **→ square global system**

$$\mathbf{K}\mathbf{u} = \mathbf{f}, \quad \mathbf{K} \in \mathbb{R}^{n \times n}$$

How to read \mathbf{K} :

- rows \rightarrow equilibrium at DOFs
- columns \rightarrow DOF influence

Why it matters:

- direct solvers (LU, Cholesky, LDL^T) require **square matrices**
- structural equilibrium problems naturally produce square systems
- Not square \rightarrow incomplete, over-constrained, or ill-posed.

Symmetric Matrix

Definition

A square matrix where the entries are mirrored about the main diagonal:

$$a_{ij} = a_{ji} \quad \Leftrightarrow \quad \mathbf{A}^T = \mathbf{A}$$

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{bmatrix}$$

Symmetric Matrix — Structural Meaning

(special case of square matrices)

Symmetry reflects **reciprocity and energy consistency**:

- **Reciprocity**: If moving DOF A causes a force at DOF B, then moving DOF B causes the same force at DOF A. The influence between two DOFs goes both ways

$$k_{ij} = k_{ji}$$

- **Energy consistency**: The structure behaves like a spring that stores energy. The work done does not depend on the order in which displacements are applied — only on the final configuration.

Why symmetry matters:

- store only half the matrix
- faster solvers (Cholesky, LDL^T)

In this course, stiffness matrices are symmetric for all situations:

- linear elastic analysis
- material nonlinearity (elastic, energy-based)
- geometric nonlinearity (conservative)

Triangular Matrices

Definition

A matrix where all entries on one side of the main diagonal are zero.

Lower triangular:

$$a_{ij} = 0 \ (j > i)$$

Upper triangular:

$$a_{ij} = 0 \ (j < i)$$

$$\mathbf{L} = \begin{bmatrix} \ell_{11} & 0 & 0 \\ \ell_{21} & \ell_{22} & 0 \\ \ell_{31} & \ell_{32} & \ell_{33} \end{bmatrix}, \quad \mathbf{U} = \begin{bmatrix} u_{11} & u_{12} & u_{13} \\ 0 & u_{22} & u_{23} \\ 0 & 0 & u_{33} \end{bmatrix}$$

Triangular Matrices — Structural Meaning

Triangular matrices appear in matrix structural analysis when a large system is **broken into simpler steps**.

Instead of solving

$$\mathbf{K}\mathbf{u} = \mathbf{f}$$

all at once, we factor the stiffness matrix:

$$\mathbf{K} = \mathbf{L}\mathbf{U} \quad \text{or} \quad \mathbf{K} = \mathbf{L}\mathbf{D}\mathbf{L}^T$$

This turns one difficult problem into **two easy ones**.

How to think about it:

- **Forward substitution** → uses the lower triangular matrix \mathbf{L}
- **Back substitution** → uses the upper triangular matrix \mathbf{U}

We will return to this in detail when we study **matrix solvers** in the next section.

Diagonal Matrix

Definition

A matrix where all off-diagonal entries are zero:

$$a_{ij} = 0 \quad \text{for } i \neq j$$

$$\mathbf{D} = \begin{bmatrix} d_1 & 0 & 0 \\ 0 & d_2 & 0 \\ 0 & 0 & d_3 \end{bmatrix}$$

Diagonal Matrix — Structural Interpretation

Diagonal matrices represent **uncoupled degrees of freedom**.

In matrix structural analysis, diagonal matrices commonly appear as:

- **Lumped mass matrices** in dynamics (each DOF has its own inertia)
- **Penalty stiffness matrices** for enforcing boundary conditions
- **Diagonal preconditioners** in iterative solvers (e.g., Jacobi, CG)

Interpretation:

- each diagonal term acts on **one DOF only**
- no force or displacement coupling between DOFs

Identity (Unit) Matrix

Definition

A matrix where all diagonal entries are 1 and all off-diagonal entries are 0:

$$I_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

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

$$\mathbf{I}\mathbf{x} = \mathbf{x}$$

Identity Matrix — Structural Interpretation

The identity matrix represents a **neutral operation** on a DOF vector.

In matrix structural analysis, it appears in:

- **Penalty methods:** $\mathbf{K} + \alpha\mathbf{I}$ for constraints
- **Regularization** of ill-conditioned stiffness matrices
- **Incremental–iterative solvers** (Newton updates)
- **Eigenvalue problems** and modal normalization

Interpretation:

- multiplying by \mathbf{I} leaves DOFs unchanged
- adding $\alpha\mathbf{I}$ stiffens DOFs *without introducing coupling*

Null (Zero) Matrix

Definition

A matrix where all entries equal to zero:

$$o_{ij} = 0$$
$$\mathbf{O} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Null Matrix — Structural Interpretation

Zero matrices encode **absence of coupling** between DOF sets.

In matrix structural analysis, they arise in:

- **Partitioned stiffness matrices:**

$$\begin{bmatrix} \mathbf{K}_{ff} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{cc} \end{bmatrix}$$

- Free vs constrained DOF separation
- Multi-component or multi-physics models before coupling

Interpretation:

- no force transfer between DOF groups
- modeling assumption of independent subsystems

Part 5 — Matrix Compatibility for Operations

When do operations make sense?

Addition

Addition requires identical dimensions:

$$\mathbf{A}, \mathbf{B} \in \mathbb{R}^{m \times n}$$

$$\mathbf{A} + \mathbf{B} = [a_{ij} + b_{ij}]$$

```
In [11]: import numpy as np

A = np.array([[1, 2],
              [3, 4]])
B = np.array([[10, 20],
              [30, 40]])

print('A =\n', A)
print('B =\n', B)
print('A + B =\n', A + B)
print('shape(A), shape(B) =', A.shape, B.shape)
```

```
A =
[[1 2]
 [3 4]]
B =
[[10 20]
 [30 40]]
A + B =
[[11 22]
 [33 44]]
shape(A), shape(B) = (2, 2) (2, 2)
```

Multiplication Compatibility

Matrix multiplication requires inner dimensions to match:

$$\mathbf{A} \in \mathbb{R}^{m \times n}, \quad \mathbf{B} \in \mathbb{R}^{n \times p}$$

$$\mathbf{C} = \mathbf{AB} \in \mathbb{R}^{m \times p}$$

```
In [12]: import numpy as np
A = np.random.randint(0, 10, (2, 3)) # 2x3
B = np.random.randint(0, 10, (3, 4)) # 3x4

C = A @ B # 2x4

print('shape(A), shape(B), shape(C) =', A.shape, B.shape, C.shape)
print('\nA=\n', A)
print('\nB=\n', B)
print('\nA @ B=\n', C)
```

```
shape(A), shape(B), shape(C) = (2, 3) (3, 4) (2, 4)
```

```
A=
```

```
[[8 2 2]
 [3 3 8]]
```

```
B=
```

```
[[6 8 9 3]
 [1 5 7 1]
 [9 6 1 2]]
```

```
A @ B=
```

```
[[68 86 88 30]
 [93 87 56 28]]
```

Part 6 — Matrix–Vector Multiplication

What does a matrix do to a vector?

Linear Mapping

A matrix defines a linear transformation:

$$\mathbf{y} = \mathbf{A}\mathbf{x}$$

Forward problem: given \mathbf{A} and \mathbf{x} , compute \mathbf{y} .

Component Form = Row Dot Product

Each output component is:

$$y_i = \sum_{j=1}^n a_{ij} x_j$$

This is the **dot product** between row i of \mathbf{A} and the vector \mathbf{x} :

$$y_i = (\text{row}_i(\mathbf{A})) \cdot \mathbf{x}$$

Annotated Figure: Computing One Component y_i

For a fixed row index i , the formula

$$y_i = \sum_{j=1}^n a_{ij} x_j$$

means: **take row i of \mathbf{A}** , multiply elementwise by \mathbf{x} , then sum.

$$\begin{bmatrix} y_1 \\ \boxed{y_2} \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ \boxed{a_{21}} & \boxed{a_{22}} & \boxed{a_{23}} & \boxed{a_{24}} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} \boxed{x_1} \\ \boxed{x_2} \\ \boxed{x_3} \\ \boxed{x_4} \end{bmatrix}$$

In [13]:

```

import numpy as np
# Example sizes
A = np.array([[2, 1, -1],
              [0, 3, 2],
              [4, -2, 1]], dtype=float)
x = np.array([1, 2, -1], dtype=float)

# Choose which component y_i to illustrate
i = 1 # second row (0-index)
y = A @ x

row_i = A[i, :]

print('Row i =', row_i)
print('Elementwise product row_i * x =', row_i * x)
print('y = A @ x =', y)
print(f'y_{{i+1}} (1-indexed) = sum_j a_{{{{i+1}}j}} x_j =', y[i])

```

```

Row i = [0. 3. 2.]
Elementwise product row_i * x = [ 0.  6. -2.]
y = A @ x = [ 5.  4. -1.]
y_2 (1-indexed) = sum_j a_{{2j}} x_j = 4.0

```

Same Product, Column Interpretation

Let $\mathbf{A} = [\mathbf{a}_1 \ \mathbf{a}_2 \ \cdots \ \mathbf{a}_n]$ (columns). Then:

$$\mathbf{Ax} = x_1\mathbf{a}_1 + x_2\mathbf{a}_2 + \cdots + x_n\mathbf{a}_n$$

So \mathbf{Ax} is a **linear combination of the columns of \mathbf{A}** .

Column Interpretation — Numerical Example

Step 1 — Choose \mathbf{A} and \mathbf{x}

$$\mathbf{A} = \begin{bmatrix} 2 & 1 \\ -1 & 3 \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} 4 \\ -2 \end{bmatrix}$$

Our goal is to compute:

$$\mathbf{y} = \mathbf{Ax}$$

Step 2 — Write \mathbf{A} by its columns

Let $\mathbf{A} = [\mathbf{a}_1 \ \mathbf{a}_2]$, where:

$$\mathbf{a}_1 = \begin{bmatrix} 2 \\ -1 \end{bmatrix}, \quad \mathbf{a}_2 = \begin{bmatrix} 1 \\ 3 \end{bmatrix}$$

The weights come from \mathbf{x} :

$$x_1 = 4, \quad x_2 = -2$$

Step 3 — Form the linear combination

$$\mathbf{Ax} = x_1 \mathbf{a}_1 + x_2 \mathbf{a}_2 = 4 \begin{bmatrix} 2 \\ -1 \end{bmatrix} + (-2) \begin{bmatrix} 1 \\ 3 \end{bmatrix}$$

Step 4 — Compute the weighted columns and sum

$$4 \begin{bmatrix} 2 \\ -1 \end{bmatrix} = \begin{bmatrix} 8 \\ -4 \end{bmatrix}, \quad (-2) \begin{bmatrix} 1 \\ 3 \end{bmatrix} = \begin{bmatrix} -2 \\ -6 \end{bmatrix}$$

Add them:

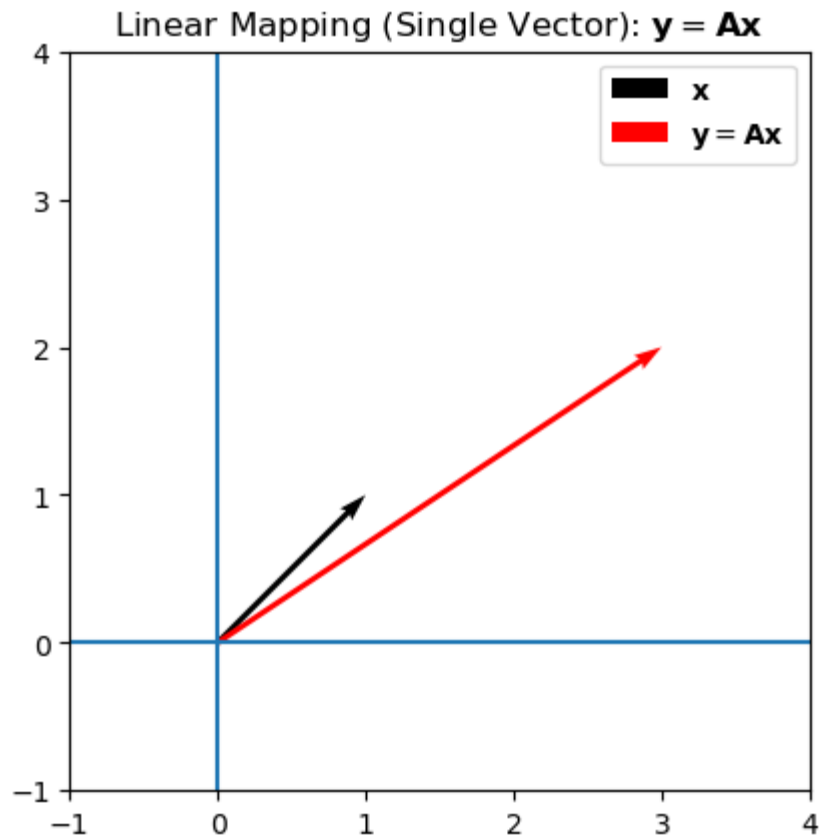
$$\mathbf{y} = \mathbf{Ax} = \begin{bmatrix} 8 \\ -4 \end{bmatrix} + \begin{bmatrix} -2 \\ -6 \end{bmatrix} = \begin{bmatrix} 6 \\ -10 \end{bmatrix}$$

Conclusion: \mathbf{Ax} is a weighted sum of the columns of \mathbf{A} .

Visual: Linear Mapping of a Single Vector in \mathbb{R}^2

We choose a matrix \mathbf{A} and a vector \mathbf{x} , then plot:

$$\mathbf{y} = \mathbf{A}\mathbf{x}$$



$$\mathbf{A} = \begin{bmatrix} 2. & 1. \\ -1. & 3. \end{bmatrix}$$

$$\mathbf{x} = \begin{bmatrix} 1. & 1. \end{bmatrix}$$

$$\mathbf{y} = \mathbf{A} @ \mathbf{x} = \begin{bmatrix} 3. & 2. \end{bmatrix}$$

Same Equation, Different Questions

$$\mathbf{y} = \mathbf{Ax} \iff \mathbf{Ax} = \mathbf{b}$$

The algebra is the same, but the **question changes**.

- **Forward problem**

Given \mathbf{A} and \mathbf{x} , compute the response \mathbf{y}

- **Inverse problem**

Given \mathbf{A} and \mathbf{b} , solve for the unknown \mathbf{x}

*Methods for the inverse problem are discussed in **Lecture 2.2***

Example: Solving for \mathbf{x} in $\mathbf{Ax} = \mathbf{b}$

Start with a system in unknowns x_1, x_2 :

$$\begin{aligned} 2x_1 + 1x_2 &= 5 \\ -1x_1 + 3x_2 &= 4 \end{aligned}$$

Group coefficients, unknowns, and constants:

$$\underbrace{\begin{bmatrix} 2 & 1 \\ -1 & 3 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} 5 \\ 4 \end{bmatrix}}_{\mathbf{b}}$$

```
In [15]: import numpy as np

A = np.array([[ 2, 1],
              [-1, 3]], dtype=float)
b = np.array([5, 4], dtype=float)

# Solve A x = b (preferred over explicit inversion)
x = np.linalg.solve(A, b)

# print('A=\n', A)
# print('b=\n', b)
print('x=\n', x)
print('\nCheck: A @ x =', A @ x)
print('Residual ||A x - b|| =', np.linalg.norm(A @ x - b))
```

```
x=
[1.57142857 1.85714286]
```

```
Check: A @ x = [5. 4.]
Residual ||A x - b|| = 0.0
```

Part 7 — Matrix–Matrix Multiplication

Multiplication composes linear transformations

Component Definition (Row–Column Dot Product)

Given two matrices

$$\mathbf{A} \in \mathbb{R}^{n \times m}, \quad \mathbf{B} \in \mathbb{R}^{m \times p},$$

their product

$$\mathbf{C} = \mathbf{AB}$$

$$(\mathbf{C})_{ij} = \sum_k a_{ik} b_{kj}$$

Interpretation:

- Fix i (a row of \mathbf{A})
- Fix j (a column of \mathbf{B})
- Take a dot product over k

Annotated Figure: Row i of \mathbf{A} with Column j of \mathbf{B}

Each entry of \mathbf{C} is computed as:

$$c_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \cdots + a_{im}b_{mj}$$

$$\begin{array}{ccc} \mathbf{A} & \mathbf{B} & = \mathbf{C} \\ (l \times m) & (m \times n) & (l \times n) \end{array}$$

equal

$$\begin{array}{c} \text{\textit{i}th row} \end{array} \left[\begin{array}{c|c|c|c|c} & & & & \\ \hline A_{i1} & A_{i2} & \cdots & \cdots & A_{im} \\ \hline & & & & \end{array} \right] \left[\begin{array}{c|c|c|c|c} & & & & \\ \hline & B_{1j} & & & \\ & B_{2j} & & & \\ & \vdots & & & \\ & \vdots & & & \\ & B_{mj} & & & \\ \hline \end{array} \right] = \left[\begin{array}{c|c|c|c|c} & & & & \\ \hline & & & & \\ & & & & \\ & & & & \\ & & & & \\ \hline & C_{ij} & & & \\ \hline \end{array} \right] \begin{array}{c} \text{\textit{i}th row} \end{array}$$

\uparrow j th column \uparrow j th column

Example: Non-Commutativity

In general:

$$\mathbf{AB} \neq \mathbf{BA}$$

Even when both products are defined, they can produce different results.

In [16]:

```
import numpy as np

A = np.array([[1, 2],
              [0, 1]], dtype=float)
B = np.array([[2, 0],
              [3, 1]], dtype=float)

AB = A @ B
BA = B @ A

print('\nA @ B=\n', AB)
print('\nB @ A=\n', BA)
print('\nAB equals BA?', np.allclose(AB, BA))
```

```
A @ B=
[[8. 2.]
 [3. 1.]]
```

```
B @ A=
[[2. 4.]
 [3. 7.]]
```

```
AB equals BA? False
```


Part 8 — Special Matrix Operations

Useful transformations and operations

Transpose

Interchanging rows and columns of a matrix

The **transpose** of a matrix is obtained by interchanging its rows and columns.

The transpose of \mathbf{A} is denoted by a superscript T :

$$\mathbf{A}^T$$

Definition (element-wise):

$$(\mathbf{A}^T)_{ij} = a_{ji}$$

Why the Transpose Matters

Transpose operations appear throughout:

- symmetry checks
- Cholesky and LDL^T factorizations
- strain–displacement and equilibrium operators
- assembling and manipulating stiffness matrices

Many structural matrices are symmetric by physics, not by accident

Transpose — Example (Rectangular Matrix)

Consider the 3×2 matrix

$$\mathbf{B} = \begin{bmatrix} 2 & -4 \\ -5 & 8 \\ 1 & 3 \end{bmatrix} \quad (3 \times 2)$$

Its transpose is

$$\mathbf{B}^T = \begin{bmatrix} 2 & -5 & 1 \\ -4 & 8 & 3 \end{bmatrix} \quad (2 \times 3)$$

Observation:

- rows of \mathbf{B} become columns of \mathbf{B}^T
- dimensions are swapped

Symmetric Matrices and the Transpose

Consider the matrix

$$\mathbf{C} = \begin{bmatrix} 2 & -1 & 6 \\ -1 & 7 & -9 \\ 6 & -9 & 5 \end{bmatrix}$$

This matrix satisfies

$$\mathbf{C}^T = \mathbf{C}$$

Definition:

- A matrix is **symmetric** if $a_{ij} = a_{ji}$

```
In [ ]: import numpy as np

A_sym = np.array([
    [ 2.0, -1.0,  6.0],
    [-1.0,  7.0, -9.0],
    [ 6.0, -9.0,  5.0]
])

print("A_sym =\n", A_sym)
print("\nA_sym^T =\n", A_sym.T)
print("\nIs A_sym symmetric?",
      np.allclose(A_sym, A_sym.T))
```

```
A_sym =
[[ 2. -1.  6.]
 [-1.  7. -9.]
 [ 6. -9.  5.]
```

```
A_sym^T =
[[ 2. -1.  6.]
 [-1.  7. -9.]
 [ 6. -9.  5.]
```

```
Is A_sym symmetric? True
```

```
In [ ]: import numpy as np

A_sym = np.array([
    [ 2.0, 1.0, 6.0],
    [-1.0, 7.0, -9.0],
    [ 6.0, -8.0, 5.0]
])

print("A_sym =\n", A_sym)
print("\nA_sym^T =\n", A_sym.T)
print("\nIs A_sym symmetric?",
      np.allclose(A_sym, A_sym.T))
```

```
A_sym =
[[ 2.  1.  6.]
 [-1.  7. -9.]
 [ 6. -8.  5.]]
```

```
A_sym^T =
[[ 2. -1.  6.]
 [ 1.  7. -8.]
 [ 6. -9.  5.]]
```

```
Is A_sym symmetric? False
```


Transpose of a Product

The transpose of a product of matrices reverses the order:

$$(\mathbf{AB})^T = \mathbf{B}^T \mathbf{A}^T$$

More generally,

$$(\mathbf{ABC})^T = \mathbf{C}^T \mathbf{B}^T \mathbf{A}^T$$

Key idea:

- transpose distributes over multiplication
- **order reverses**

Inverse of a Square Matrix

The matrix equivalent of division

The **inverse** of a square matrix \mathbf{A} is a matrix \mathbf{A}^{-1} such that

$$\mathbf{A}\mathbf{A}^{-1} = \mathbf{A}^{-1}\mathbf{A} = \mathbf{I}$$

Key points:

- Defined **only for square matrices**
- The inverse of a **symmetric matrix** is also symmetric
- If it exists, the inverse has the **same size** as \mathbf{A}
- Not all square matrices are invertible

Why Inverses Matter (Conceptually)

Consider the linear system

$$\mathbf{Ax} = \mathbf{b}$$

Since division by a matrix is not defined, we **cannot** write $\mathbf{x} = \mathbf{b}/\mathbf{A}$.

If \mathbf{A}^{-1} exists, we may premultiply:

$$\mathbf{A}^{-1}\mathbf{Ax} = \mathbf{A}^{-1}\mathbf{b}$$

which gives

$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{b}.$$

- In practice, we **rarely compute \mathbf{A}^{-1} explicitly**
- Solving systems is usually done via **factorization + substitution**

Orthogonal Matrices

A matrix \mathbf{A} is called **orthogonal** if its inverse is equal to its transpose:

$$\mathbf{A}^{-1} = \mathbf{A}^T$$

Equivalently,

$$\mathbf{A}^T \mathbf{A} = \mathbf{A} \mathbf{A}^T = \mathbf{I}$$

Common cases:

- **Local \leftrightarrow global coordinate transformations**
 - rotating element stiffness matrices
 - transforming displacement and force vectors
- **Rigid-body rotations**
 - no strain, no energy change

Matrix Partitioning

Breaking a large system into smaller, meaningful blocks

In many applications, especially **structural analysis**, it is useful to subdivide a matrix into **submatrices**.

This process is called **matrix partitioning**.

Partitioning allows us to:

- treat groups of rows/columns together
- express large systems compactly
- perform algebra using **block operations**

Submatrices can be manipulated like scalar entries, as long as their dimensions are compatible.

Motivation from Structural Analysis

In the direct stiffness method, degrees of freedom (DOFs) are naturally divided into:

- **free DOFs** (unknown displacements)
- **fixed DOFs** (prescribed displacements, often zero)

This leads to a natural block structure in the global system:

$$\mathbf{K}\mathbf{u} = \mathbf{f}$$

Partitioning lets us isolate the equations that actually need to be solved.

Example: Partitioning a Matrix

Consider a matrix $\mathbf{B} \in \mathbb{R}^{4 \times 3}$:

$$\mathbf{B} = \begin{bmatrix} 2 & -4 & -1 \\ -5 & 7 & 3 \\ 8 & -9 & 6 \\ 1 & 3 & 8 \end{bmatrix}$$

By drawing horizontal and vertical partition lines, we can write:

$$\mathbf{B} = \left[\begin{array}{cc|c} 2 & -4 & -1 \\ -5 & 7 & 3 \\ 8 & -9 & 6 \\ \hline 1 & 3 & 8 \end{array} \right]$$

Submatrices (Blocks)

$$\mathbf{B} = \begin{bmatrix} \mathbf{B}_{11} & \mathbf{B}_{12} \\ \mathbf{B}_{21} & \mathbf{B}_{22} \end{bmatrix}$$

The individual blocks are:

$$\mathbf{B}_{11} = \begin{bmatrix} 2 & -4 \\ -5 & 7 \\ 8 & -9 \end{bmatrix}, \quad \mathbf{B}_{12} = \begin{bmatrix} -1 \\ 3 \\ 6 \end{bmatrix}$$

$$\mathbf{B}_{21} = [1 \quad 3], \quad \mathbf{B}_{22} = [8]$$

Each block is itself a matrix of appropriate size.

Partitioned Matrix Multiplication

Given

$$\mathbf{B} = \begin{bmatrix} \mathbf{B}_{11}^{(3 \times 2)} & \mathbf{B}_{12}^{(3 \times 1)} \\ \mathbf{B}_{21}^{(1 \times 2)} & \mathbf{B}_{22}^{(1 \times 1)} \end{bmatrix} \in \mathbb{R}^{4 \times 3}$$

Suppose

$$\mathbf{C} = \begin{bmatrix} \mathbf{C}_{11}^{(2 \times 2)} \\ \mathbf{C}_{21}^{(1 \times 2)} \end{bmatrix} \in \mathbb{R}^{3 \times 2}$$

Then the product \mathbf{BC} can be written in block form as:

$$\mathbf{BC} = \begin{bmatrix} \mathbf{B}_{11}^{(3 \times 2)} \mathbf{C}_{11}^{(2 \times 2)} + \mathbf{B}_{12}^{(3 \times 1)} \mathbf{C}_{21}^{(1 \times 2)} \\ \mathbf{B}_{21}^{(1 \times 2)} \mathbf{C}_{11}^{(2 \times 2)} + \mathbf{B}_{22}^{(1 \times 1)} \mathbf{C}_{21}^{(1 \times 2)} \end{bmatrix} \in \mathbb{R}^{4 \times 2}$$

The result is a 2×1 **block matrix**, corresponding to an overall matrix of size 4×2 .

Key Requirement: Conformability

For block operations to be valid:

- block dimensions must be compatible
- partitioning of one matrix must match the partitioning of the other

In practice:

- rows of the second matrix are partitioned the same way as columns of the first

Looking Ahead

Next section:

We focus on **how inverses are constructed**, their limitations, and why numerical solvers usually avoid forming them explicitly.