2. Vectors and Matrices

- review on vectors
- matrix notation
- special matrices
- matrix operations
- inverse of matrices
- elementary matrices
- determinants
- linear equations in matrix form

Vector notation

n-vector x:

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

- also written as $x = (x_1, x_2, \ldots, x_n)$
- set of n-vectors is denoted $\mathbf{R}^n$ (Euclidean space)
- x_i: ith **element** or **component** or **entry** of x
- x is also called a column vector
- $y = \begin{bmatrix} y_1 & y_2 & \cdots & y_n \end{bmatrix}$ is called a row vector

unless stated otherwise, a vector typically means a column vector

Special vectors

zero vectors: $x = (0, 0, \ldots, 0)$

all-ones vectors: $x = (1, 1, \cdots, 1)$ (we will denote it by $\mathbf{1}$)

standard unit vectors: e_k has only 1 at the kth entry and zero otherwise

$$e_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad e_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad e_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

(standard unit vectors in $\mathbf{R}^3$)

unit vectors: any vector u whose norm (magnitude) is 1, $i.e.$,

$$\|u\| \triangleq \sqrt{u_1^2 + u_2^2 + \cdots + u_n^2} = 1$$

example: $u = (1/\sqrt{2}, 2/\sqrt{6}, -1/\sqrt{2})$

Vector operations

scalar multiplication of a vector x with a scalar α

$$\alpha x = \begin{bmatrix} \alpha x_1 \\ \alpha x_2 \\ \vdots \\ \alpha x_n \end{bmatrix}$$

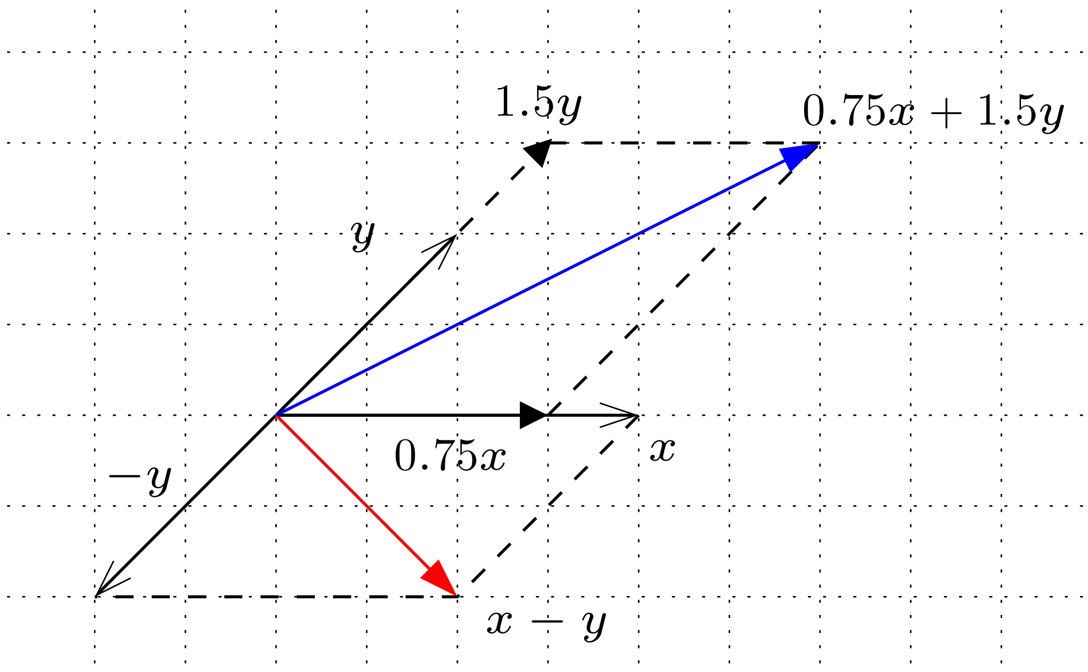
addition and subtraction of two n-vector x, y

$$x + y = \begin{bmatrix} x_1 + y_1 \\ x_2 + y_2 \\ \vdots \\ x_n + y_n \end{bmatrix}, \qquad x - y = \begin{bmatrix} x_1 - y_1 \\ x_2 - y_2 \\ \vdots \\ x_n - y_n \end{bmatrix}$$

Geometrical interpretation

for $n \leq 3$: x is a point with coordinates x_i

example: $x = (4,0)$, $y = (2,2)$



$$0.75x = \begin{bmatrix} 3 \\ 0 \end{bmatrix}, \quad 1.5y = \begin{bmatrix} 3 \\ 3 \end{bmatrix}, \quad 0.75x + 1.5y = \begin{bmatrix} 6 \\ 3 \end{bmatrix}, \quad x - y = \begin{bmatrix} 2 \\ -2 \end{bmatrix}$$

Inner products

definition: the inner product of two n-vectors x, y is

$$x_1 y_1 + x_2 y_2 + \cdots + x_n y_n$$

also known as the **dot product** of vectors x, y

notation: $x^T y$

properties ✎

- $(\alpha x)^T y = \alpha(x^T y)$ for scalar α
- $(x + y)^T z = x^T z + y^T z$
- $x^T y = y^T x$

Euclidean norm

$$\|x\| = \sqrt{x_1^2 + x_2^2 + \cdots + x_n^2} = \sqrt{x^T x}$$

properties

- also written $\|x\|_2$ to distinguish from other norms
- $\|\alpha x\| = |\alpha| \|x\|$ for scalar α
- $\|x + y\| \leq \|x\| + \|y\|$ (triangle inequality)
- $\|x\| \geq 0$ and $\|x\| = 0$ only if $x = 0$

interpretation

- $\|x\|$ measures the *magnitude* or length of x
- $\|x - y\|$ measures the *distance* between x and y

Matrix notation

an $m \times n$ matrix A is defined as

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}, \quad \text{or} \quad A = [a_{ij}]_{m \times n}$$

- a_{ij} are the **elements**, or **coefficients**, or **entries** of A
- set of $m \times n$-matrices is denoted $\mathbf{R}^{m \times n}$
- A has m rows and n columns (m, n are the **dimensions**)
- the (i, j) entry of A is also commonly denoted by A_{ij}
- A is called a **square** matrix if $m = n$

Special matrices

zero matrix: $A = 0$

$$A = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & 0 \end{bmatrix}$$

$a_{ij} = 0$, for $i = 1, \ldots, m, j = 1, \ldots, n$

identity matrix: $A = I$

$$A = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & 1 \end{bmatrix}$$

a square matrix with $a_{ii} = 1, a_{ij} = 0$ for $i \neq j$

diagonal matrix:

$$A = \begin{bmatrix} a_1 & 0 & \cdots & 0 \\ 0 & a_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & a_n \end{bmatrix}$$

a square matrix with $a_{ij} = 0$ for $i \neq j$

triangular matrix:

a square matrix with zero entries in a triangular part

upper triangular

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ 0 & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \\ 0 & 0 & \cdots & a_{nn} \end{bmatrix}$$

$a_{ij} = 0$ for $i \geq j$

lower triangular

$$A = \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ a_{21} & a_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

$a_{ij} = 0$ for $i \leq j$

Addition and scalar multiplication

addition of two $m \times n$-matrices A and B

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

scalar multiplication of an $m \times n$-matrix A with a scalar β

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

Multiplication

product of $m \times r$-matrix A with $r \times n$-matrix B:

$$(AB)_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \cdots + a_{ir}b_{rj} = \sum_{k=1}^{r} a_{ik}\, b_{kj}$$

dimensions must be compatible: $\#$ of columns in $A = \#$ of rows in B

- $(AB)_{ij}$ is the dot product of the i^{th} row of A and the j^{th} column of B
- $AB \neq BA$ in general ! (even if the dimensions make sense)
- there are exceptions, $e.g.$, $AI = IA$ for all square A
- $A(B + C) = AB + AC$

Matrix transpose

the transpose of an $m \times n$-matrix A is

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

properties ✎

- A^T is $n \times m$
- $(A^T)^T = A$
- $(\alpha A + B)^T = \alpha A^T + B^T$, $\quad \alpha \in \mathbf{R}$
- $(AB)^T = B^T A^T$
- a square matrix A is called **symmetric** if $A = A^T$, *i.e.*, $a_{ij} = a_{ji}$

Block matrix notation

example: 2×2-block matrix A

$$A = \begin{bmatrix} B & C \\ D & E \end{bmatrix}$$

for example, if B, C, D, E are defined as

$$B = \begin{bmatrix} 2 & 1 \\ 3 & 8 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 1 & 7 \\ 1 & 9 & 1 \end{bmatrix}, \quad D = \begin{bmatrix} 0 & 1 \end{bmatrix}, \quad E = \begin{bmatrix} -4 & 1 & -1 \end{bmatrix}$$

then A is the matrix

$$A = \begin{bmatrix} 2 & 1 & 0 & 1 & 7 \\ 3 & 8 & 1 & 9 & 1 \\ 0 & 1 & -4 & 1 & -1 \end{bmatrix}$$

note: dimensions of the blocks must be compatible

Column and Row partitions

write an $m \times n$-matrix A in terms of its columns or its rows

$$A = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix} = \begin{bmatrix} b_1^T \\ b_2^T \\ \vdots \\ b_m^T \end{bmatrix}$$

- a_j for $j = 1, 2, \ldots, n$ are the columns of A
- b_i^T for $i = 1, 2, \ldots, m$ are the rows of A

example:

$$A = \begin{bmatrix} 1 & 2 & 1 \\ 4 & 9 & 0 \end{bmatrix}$$

the column and row vectors are

$$a_1 = \begin{bmatrix} 1 \\ 4 \end{bmatrix}, \quad a_2 = \begin{bmatrix} 2 \\ 9 \end{bmatrix}, \quad a_3 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad b_1^T = \begin{bmatrix} 1 & 2 & 1 \end{bmatrix}, \quad b_2^T = \begin{bmatrix} 4 & 9 & 0 \end{bmatrix}$$

Matrix-vector product

product of $m \times n$-matrix A with n-vector x

$$Ax = \begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \\ a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n \end{bmatrix}$$

- dimensions must be compatible: $\#$ columns in $A = \#$ elements in x

if A is partitioned as $A = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix}$, then

$$Ax = a_1x_1 + a_2x_2 + \cdots + a_nx_n$$

- Ax is a linear combination of the column vectors of A
- the coefficients are the entries of x

Product with standard unit vectors

post-multiply with a column vector

$$Ae_k = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} a_{1k} \\ a_{2k} \\ \vdots \\ a_{mk} \end{bmatrix} = \text{the } k\text{th column of } A$$

pre-multiply with a row vector

$$\begin{aligned} e_k^T A &= \begin{bmatrix} 0 & 0 & \cdots & 1 & \cdots & 0 \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \\ &= \begin{bmatrix} a_{k1} & a_{k2} & \cdots & a_{kn} \end{bmatrix} = \text{the } k\text{th row of } A \end{aligned}$$

Trace

Definition:

trace of a square matrix A is the sum of the diagonal entries in A

$$\mathbf{tr}(A) = a_{11} + a_{22} + \cdots + a_{nn}$$

example:

$$A = \begin{bmatrix} 2 & 1 & 4 \\ 0 & -1 & 5 \\ 3 & 4 & 6 \end{bmatrix}$$

trace of A is $2 - 1 + 6 = 7$

properties ✎

- $\mathbf{tr}(A^T) = \mathbf{tr}(A)$
- $\mathbf{tr}(\alpha A + B) = \alpha\,\mathbf{tr}(A) + \mathbf{tr}(B)$
- $\mathbf{tr}(AB) = \mathbf{tr}(BA)$

Inverse of matrices

Definition:

a *square* matrix A is called **invertible** or **nonsingular** if there exists B s.t.

$$AB = BA = I$$

- B is called an **inverse** of A
- it is also true that B is invertible and A is an inverse of B
- if no such B can be found A is said to be **singular**

assume A is invertible

- an inverse of A is unique
- the inverse of A is denoted by A^{-1}

assume A, B are invertible

Facts ✎

- $(\alpha A)^{-1} = \alpha^{-1} A^{-1}$ for nonzero α
- A^T is also invertible and $(A^T)^{-1} = (A^{-1})^T$
- AB is invertible and $(AB)^{-1} = B^{-1} A^{-1}$
- $(A + B)^{-1} \neq A^{-1} + B^{-1}$

Inverse of 2×2 matrices

the matrix

$$A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

is invertible if and only if

$$ad - bc \neq 0$$

and its inverse is given by

$$A^{-1} = \frac{1}{ad - bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$$

example:

$$A = \begin{bmatrix} 2 & 1 \\ -1 & 3 \end{bmatrix}, \quad A^{-1} = \frac{1}{7} \begin{bmatrix} 3 & -1 \\ 1 & 2 \end{bmatrix}$$

Elementary matrices

Definition: a matrix obtained by performing a *single* row operation on the identity matrix I_n is called an **elementary** matrix

examples:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ k & 0 & 1 \end{bmatrix}$$ add k times the first row to the third row of I_3

$$\begin{bmatrix} 1 & 0 \\ 0 & k \end{bmatrix}$$ multiply a nonzero k with the second row of I_2

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$ interchange the second and the third rows of I_3

an elementary matrix is often denoted by E

Inverse operations

row operations on E that produces I and vice versa

$I \to E$	$E \to I$
add k times row i to row j	add $-k$ times row i to row j
multiply row i by $k \neq 0$	multiply row i by $1/k$
interchange row i and j	interchange row i and j

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ k & 0 & 1 \end{bmatrix} \implies \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -k & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ k & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$E = \begin{bmatrix} 1 & 0 \\ 0 & k \end{bmatrix} \implies \begin{bmatrix} 1 & 0 \\ 0 & 1/k \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & k \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \implies \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Facts ✌

- every elementary matrix is invertible
- the inverse is also an elementary matrix

from the examples in page 2-23

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ k & 0 & 1 \end{bmatrix} \implies E^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -k & 0 & 1 \end{bmatrix}$$

$$E = \begin{bmatrix} 1 & 0 \\ 0 & k \end{bmatrix} \implies E^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & 1/k \end{bmatrix}$$

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \implies E^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Row operations by matrix multiplication

assume A is $m \times n$ and E is obtained by performing a row operation on I_m

$$EA = \text{the matrix obtained by performing this same row operation on } A$$

example:

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 0 & 1 & -1 \\ 1 & 1 & 0 \end{bmatrix}$$

- add -2 times the third row to the second row of A

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -2 \\ 0 & 0 & 1 \end{bmatrix} \qquad EA = \begin{bmatrix} 1 & 2 & 3 \\ -2 & -1 & -1 \\ 1 & 1 & 0 \end{bmatrix}$$

- multiply 2 with the first row of A

$$E = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad EA = \begin{bmatrix} 2 & 4 & 6 \\ 0 & 1 & -1 \\ 1 & 1 & 0 \end{bmatrix}$$

- interchange the first and the third rows of A

$$E = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \quad EA = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & -1 \\ 1 & 2 & 3 \end{bmatrix}$$

Inverse via row operations

assume A is invertible

- A is reduced to I by a finite sequence of row operations

$$E_1, E_2, \ldots, E_k$$

  such that

$$E_k \cdots E_2 E_1 A = I$$

- the reduced echelon form of A is I
- the inverse of A is therefore given by the product of elementary matrices

$$A^{-1} = E_k \cdots E_2 E_1$$

example: write the augmented matrix $\left[A \mid I\right]$

$$\left[\begin{array}{ccc|ccc} 2 & 4 & 3 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 & 1 & 0 \\ 1 & 0 & 4 & 0 & 0 & 1 \end{array}\right]$$

and apply row operations until the left side is reduced to I

$$\begin{array}{c} -2R_2 + R_1 \rightarrow R_1 \\ -R_2 + R_3 \rightarrow R_3 \end{array} \qquad \left[\begin{array}{ccc|ccc} 0 & 0 & 1 & 1 & -2 & 0 \\ 1 & 2 & 1 & 0 & 1 & 0 \\ 0 & -2 & 3 & 0 & -1 & 1 \end{array}\right]$$

$$R_1 \leftrightarrow R_2 \qquad \left[\begin{array}{ccc|ccc} 1 & 2 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & -2 & 0 \\ 0 & -2 & 3 & 0 & -1 & 1 \end{array}\right]$$

$$-3R_2 + R_3 \rightarrow R_3 \qquad \left[\begin{array}{ccc|ccc} 1 & 2 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & -2 & 0 \\ 0 & -2 & 0 & -3 & 5 & 1 \end{array}\right]$$

$$R_3/(-2) \rightarrow R_3 \qquad \left.\begin{array}{ccc|ccc} 1 & 2 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & -2 & 0 \\ 0 & 1 & 0 & \frac{3}{2} & -\frac{5}{2} & -\frac{1}{2} \end{array}\right.$$

$$R_2 \leftrightarrow R_3 \qquad \left.\begin{array}{ccc|ccc} 1 & 2 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & \frac{3}{2} & -\frac{5}{2} & -\frac{1}{2} \\ 0 & 0 & 1 & 1 & -2 & 0 \end{array}\right.$$

$$-2R_2 + R_1 \rightarrow R_1 \qquad \left.\begin{array}{ccc|ccc} 1 & 0 & 1 & -3 & 6 & 1 \\ 0 & 1 & 0 & \frac{3}{2} & -\frac{5}{2} & -\frac{1}{2} \\ 0 & 0 & 1 & 1 & -2 & 0 \end{array}\right.$$

$$-R_3 + R_1 \rightarrow R_1 \qquad \left.\begin{array}{ccc|ccc} 1 & 0 & 0 & -4 & 8 & 1 \\ 0 & 1 & 0 & \frac{3}{2} & -\frac{5}{2} & -\frac{1}{2} \\ 0 & 0 & 1 & 1 & -2 & 0 \end{array}\right.$$

the inverse of A is

$$\begin{bmatrix} -4 & 8 & 1 \\ \frac{3}{2} & -\frac{5}{2} & -\frac{1}{2} \\ 1 & -2 & 0 \end{bmatrix}$$

Invertible matrices

✌ **Theorem:** for a square matrix A, the following statements are equivalent

1. A is invertible
2. $Ax = 0$ has only the trivial solution $(x = 0)$
3. the reduced echelon form of A is I
4. A is expressible as a product of elementary matrices

Inverse of special matrices

diagonal matrix

$$A = \begin{bmatrix} a_1 & 0 & \cdots & 0 \\ 0 & a_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & a_n \end{bmatrix}$$

a diagonal matrix is invertible iff the diagonal entries are all nonzero

$$a_{ii} \neq 0, \quad i = 1, 2, \ldots, n$$

the inverse of A is given by

$$A^{-1} = \begin{bmatrix} 1/a_1 & 0 & \cdots & 0 \\ 0 & 1/a_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & 1/a_n \end{bmatrix}$$

the diagonal entries in A^{-1} are the inverse of the diagonal entries in A

triangular matrix:

upper triangular | **lower triangular**

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ 0 & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \\ 0 & 0 & \cdots & a_{nn} \end{bmatrix} \qquad A = \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ a_{21} & a_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

$$a_{ij} = 0 \text{ for } i \geq j \qquad a_{ij} = 0 \text{ for } i \leq j$$

a triangular matrix is invertible iff the diagonal entries are all nonzero

$$a_{ii} \neq 0, \quad \forall i = 1, 2, \ldots, n$$

more is true ...

- product of lower (upper) triangular matrices is lower (upper) triangular
- the inverse of a lower (upper) triangular matrix is lower (upper) triangular

symmetric matrix: $A = A^T$

✎

- for any square matrix A, AA^T and A^TA are always symmetric
- if A is symmetric and invertible, then A^{-1} is symmetric
- if A is invertible, then AA^T and A^TA are also invertible

Determinants

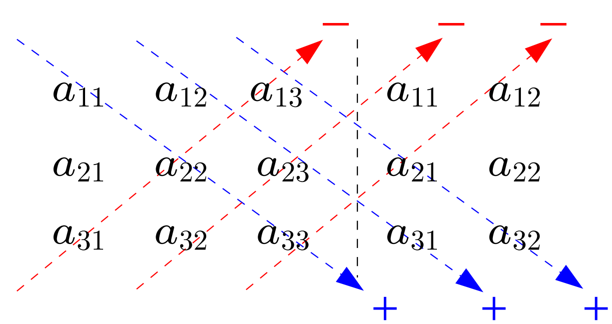
the determinant is a *scalar value* associated with a square matrix A

commonly denoted by $\det(A)$ or $|A|$

determinants of 2×2 matrices:

$$\det \begin{bmatrix} a & b \\ c & d \end{bmatrix} = ad - bc$$

determinants of 3×3 matrices: let $A = \{a_{ij}\}$



$$\det A = a_{11}a_{22}a_{33} + a_{12}a_{23}a_{31} + a_{13}a_{21}a_{32}$$
$$-(a_{31}a_{22}a_{13} + a_{32}a_{23}a_{11} + a_{33}a_{21}a_{12})$$

for a square matrix of any order, it can be computed by

- cofactor expansion
- performing elementray row operations

Minor and Cofactor

Minor of entry a_{ij}: denoted by M_{ij}

- the determinant of the resulting submatrix after deleting the ith row and jth column of A

Cofactor of entry a_{ij}: denoted by C_{ij}

- $C_{ij} = (-1)^{(i+j)} M_{ij}$

example:

$$A = \begin{bmatrix} 3 & 1 & -2 \\ 5 & 0 & 2 \\ 1 & -1 & 2 \end{bmatrix}, \quad M_{23} = \begin{vmatrix} 3 & 1 \\ 1 & -1 \end{vmatrix} = -4, \quad C_{23} = (-1)^{(2+3)} M_{23} = 4$$

Determinants by Cofactor Expansion

Theorem: the determinant of an $n \times n$-matrix A is given by

$$\det(A) = a_{1j}C_{1j} + a_{2j}C_{2j} + \cdots + a_{nj}C_{nj}$$

and

$$\det(A) = a_{i1}C_{i1} + a_{i2}C_{i2} + \cdots + a_{in}C_{in}$$

regardless of which row or column of A is chosen

example: pick the first row to compute $\det(A)$

$$A = \begin{bmatrix} 3 & 1 & -2 \\ 5 & 0 & 2 \\ 1 & -1 & 2 \end{bmatrix}, \quad \det(A) = a_{11}C_{11} + a_{12}C_{12} + a_{13}C_{13}$$

$$\begin{aligned} \det(A) &= 3(-1)^2 \begin{vmatrix} 0 & 2 \\ -1 & 2 \end{vmatrix} + 1(-1)^3 \begin{vmatrix} 5 & 2 \\ 1 & 2 \end{vmatrix} - 2(-1)^4 \begin{vmatrix} 5 & 0 \\ 1 & -1 \end{vmatrix} \\ &= 3(1)(2) + (-1)(8) - 2(1)(-5) = 8 \end{aligned}$$

Basic properties of determinants

✌ let A, B be any square matrices

- $\det(A) = \det(A^T)$
- if A has a row of zeros or a column of zeros, then $\det(A) = 0$
- $\det(A + B) \neq \det(A) + \det(B)$!

determinants of special matrices:

- the determinant of a diagonal or triangular matrix is given by the product of the diagonal entries
- $\det(I) = 1$

(these properties can be proved from the def. of cofactor expansion)

✌ another basic properties; suppose the following is true

- A and B are equal except for the entries in their kth row (column)
- C is defined as that matrix identical to A and B except that its kth row (column) is the sum of the kth rows (columns) of A and B

then we have

$$\det(C) = \det(A) + \det(B)$$

example:

$$A = \begin{bmatrix} 1 & 0 & 1 \\ 2 & 1 & 1 \\ 1 & 2 & -1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 & 1 \\ 2 & 1 & 1 \\ 3 & 0 & 2 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 1 \\ 2 & 1 & 1 \\ 4 & 2 & 1 \end{bmatrix}$$

$$\det(A) = 0, \quad \det(B) = -1, \quad \det(C) = -1$$

Determinants under row operations

- multiply k to a row or a column

$$\begin{vmatrix} ka_{11} & ka_{12} & ka_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = k \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

- interchange between two rows or two columns

$$\begin{vmatrix} a_{21} & a_{22} & a_{23} \\ a_{11} & a_{12} & a_{13} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = - \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

- add k times the ith row (column) to the jth row (column)

$$\begin{vmatrix} a_{11} + ka_{21} & a_{12} + ka_{22} & a_{13} + ka_{23} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

(the proof of determinants under row operations is left as an exercise)

example: B is obtained by performing the following operations on A

$$R_2 + 3R_1 \to R_2, \quad R_3 \leftrightarrow R_1, \quad -4R_1 \to R_1$$

$$A = \begin{bmatrix} 2 & 3 & -2 \\ 3 & 1 & 0 \\ -3 & -3 & 3 \end{bmatrix} \quad \Longrightarrow \quad \det(B) = (-4) \cdot (-1) \cdot 1 \cdot \det(A)$$

the changes of det. under elementary operations lead to obvious facts ✎

- $\det(\alpha A) = \alpha^n \det(A), \quad \alpha \neq 0$
- If A has two rows (columns) that are equal, then $\det(A) = 0$

Determinants of elementary matrices

let B be obtained by performing a row operation on A then

$$B = EA \quad \text{and} \quad \det(B) = \det(EA)$$

$$E = \begin{bmatrix} k & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \det(B) = k\det(A) \quad (\det(E) = k)$$

$$E = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \det(B) = -\det(A) \quad (\det(E) = -1)$$

$$E = \begin{bmatrix} 1 & k & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \det(B) = \det(A) \quad (\det(E) = 1)$$

conclusion: $\det(EA) = \det(E)\det(A)$

Determinants of product and inverse

✌ let A, B be $n \times n$ matrices

- A is invertible if and only if $\det(A) \neq 0$
- if A is invertible, then $\det(A^{-1}) = 1/\det(A)$
- $\det(AB) = \det(A)\det(B)$

Adjugate formula

the adjugate of A is the transpose of the matrix of cofactors from A

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

if A is invertible then

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

Proof.

- the cofactor expansion using the cofactors from different row is zero

$$a_{i1}C_{k1} + a_{i2}C_{k2} + \ldots + a_{in}C_{kn} = 0, \quad \text{for } i \neq k$$

- $A \operatorname{adj}(A) = \det(A) \cdot I$

Linear equation in matrix form

the linear system of m equations in n variables

$$\begin{aligned}
a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1 \\
a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2 \\
\vdots &= \vdots \\
a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n &= b_m
\end{aligned}$$

in matrix form: $Ax = b$ where

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}, \quad x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad b = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

Applications

a set of linear equations $Ax = b$ (with $A \in \mathbf{R}^{m \times n}$) is

- **square** if $m = n$ (*A is square*)

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

- **underdetermined** if $m < n$ (*A is fat*)

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

- **overdetermined** if $m > n$ (*A is skinny*)

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

Cramer's rule

consider a linear system $Ax = b$ when A is **square**

if A is invertible then the solution is unique and given by

$$x = A^{-1}b$$

each component of x can be calculated by using the Cramer's rule

Cramer's rule

$$x_1 = \frac{|A_1|}{|A|}, \quad x_2 = \frac{|A_2|}{|A|}, \quad \ldots \quad , \quad x_n = \frac{|A_n|}{|A|}$$

where A_j is the matrix obtained by replacing b in the jth column of A

(its proof is left as an exercise)

example:

$$A = \begin{bmatrix} 3 & 1 & -2 \\ 5 & 0 & 2 \\ 1 & -1 & 2 \end{bmatrix}, \quad b = \begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix}$$

since $\det(A) = 8$, A is invertible and the solution is

$$x = A^{-1}b = \frac{1}{8}\begin{bmatrix} 2 & 0 & 2 \\ -8 & 8 & -16 \\ -5 & 4 & -5 \end{bmatrix}\begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 1 \\ -5 \\ -2 \end{bmatrix}$$

using Cramer's rule gives

$$x_1 = \frac{1}{8}\begin{vmatrix} 2 & 1 & -2 \\ 1 & 0 & 2 \\ 2 & -1 & 2 \end{vmatrix}, \quad x_2 = \frac{1}{8}\begin{vmatrix} 3 & 2 & -2 \\ 5 & 1 & 2 \\ 1 & 2 & 2 \end{vmatrix}, \quad x_3 = \frac{1}{8}\begin{vmatrix} 3 & 1 & 2 \\ 5 & 0 & 1 \\ 1 & -1 & 2 \end{vmatrix}$$

which yields

$$x_1 = 1, \quad x_2 = -5, \quad x_3 = -2$$

MATLAB commands

some commonly used commands for working with matrices

- `eye(n)` produces an identity matrix of size n
- `zeros(m,n)` creates a zero matrix of size $m \times n$
- `inv(A)` finds the inverse of A
- `det(A)` finds the determinant of A
- `trace(A)` finds the trace of A

to solve $Ax = b$ when A is square use

- `A\b` (compute $A^{-1}b$)

References

Chapter 1-2 in

H. Anton, *Elementary Linear Algebra*, 10th edition, Wiley, 2010

Lecture note on

Matrices and Vectors, EE103, L. Vandenberghe, UCLA