

SE102:Multivariable Calculus

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Definition

A (n -dimensional) **vector** is a n -tuple of real numbers

$$\mathbf{a} = (a_1, a_2, \dots, a_n)$$

with the following operations.

- ▶ (vector sum) For a vector $\mathbf{b} = (b_1, b_2, \dots, b_n)$,

$$\mathbf{a} + \mathbf{b} = (a_1 + b_1, a_2 + b_2, \dots, a_n + b_n).$$

- ▶ (scalar multiplication) For $k \in \mathbf{R}$, we define a vector $k\mathbf{a}$ as

$$k\mathbf{a} = (ka_1, ka_2, \dots, ka_n).$$

The set of all (n -dimensional) vectors is called the (n -dimensional) **vector space**, and denoted by \mathbf{R}^n .

Example

Let $O = (0, 0, 0)$ be the origin and $P = (a_1, a_2, a_3)$ a point in 3-dimensional space. Then the arrow \overrightarrow{OP} can be represented by the **position vector**

$$\overrightarrow{OP} = (a_1, a_2, a_3)$$

The scalar multiplication is a dilation, and the vector sum is a superposition. For points $Q = (b_1, b_2, b_3)$ and $R = (a_1 + b_1, a_2 + b_2, a_3 + b_3)$, the vector \overrightarrow{PR} is represented by the same vector as \overrightarrow{OQ} . Thus we have the following additive operation.

$$\overrightarrow{OP} + \overrightarrow{OQ} = \overrightarrow{OP} + \overrightarrow{PR} = \overrightarrow{OR}$$

Example

Let $c : (-\varepsilon, \varepsilon) \rightarrow \mathbf{R}^2$ be a parametrization of a curve on a plane. Suppose that each coordinate functions are given by differentiable function $x(t), y(t)$ defined on $(-\varepsilon, \varepsilon)$.

$$c(t) = (x(t), y(t))$$

Let us define $c'(t)$ as

$$c'(t) = (x'(t), y'(t))$$

We can consider $c'(t)$ as a vector, which represents the **velocity** at $c(t)$. The x, y -components of the vector $c'(t)$ represent the projective speed of $c(t)$ on x, y -axis respectively. We can decompose the velocity vector into the sum of horizontal and vertical velocity of $c(t)$.

$$c'(t) = (x'(t), 0) + (0, y'(t))$$

Example

Let us consider a function f sending every point in \mathbf{R}^2 to a point in \mathbf{R}^3 as follows.

$$f(u, v) = (x(u, v), y(u, v), z(u, v)) \quad (1)$$

The variables x, y, z are dependent to the variables u, v . The functions f (and also x, y, z as functions) contain(s) two or more independent or dependent variables. Such functions are called **multivariable functions**. If we write $\mathbf{a} = (u, v)$ and $\mathbf{b} = (x, y, z)$, the equation (1) can be written as $f(\mathbf{a}) = \mathbf{b}$. A multivariable function can be viewed as a *single variable* function which assigns a vector to another vector.

Definition

For a (n -dimensional) vector $\mathbf{a} = (a_1, a_2, \dots, a_n)$, the value

$$\|\mathbf{a}\| = \sqrt{a_1^2 + a_2^2 + \dots + a_n^2}$$

is called the **norm** of \mathbf{a} . A vector with norm 1 is called a **unit** vector. The norm $\|\mathbf{a}\|$ is 0 if and only if \mathbf{a} is a **zero vector**, that is,

$$\mathbf{0} + \mathbf{a} = \mathbf{a} + \mathbf{0} = \mathbf{a}$$

for any vector \mathbf{a} . For nonzero vector \mathbf{a} ,

$$\mathbf{u} = \mathbf{a}/\|\mathbf{a}\|$$

is called the **normalization** of \mathbf{a} .

Example

For each $i = 1, \dots, n$, the vector

$$\mathbf{e}_i = (0, \dots, 1, \dots, 0)$$

with 1 at i th place is called a (unit) **basis vector**. Especially, 3-dimensional basis vectors are denoted by

$$\mathbf{i} = (1, 0, 0), \quad \mathbf{j} = (0, 1, 0), \quad \mathbf{k} = (0, 0, 1)$$

A vector $\mathbf{a} = (a_1, a_2, \dots, a_n)$ can be decomposed as a linear sum of basis vectors.

$$\mathbf{a} = a_1 \mathbf{e}_1 + a_2 \mathbf{e}_2 + \dots + a_n \mathbf{e}_n$$

Thus the set

$$\{\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_n\}$$

is called the **basis**, and generates all n -dimensional vectors.

Definition

The **inner product** (also called **dot product**) of two vectors \mathbf{a} , \mathbf{b} is an operation defined by

$$\mathbf{a} \cdot \mathbf{b} = a_1b_1 + a_2b_2 + \cdots + a_nb_n$$

If $\mathbf{a} \cdot \mathbf{b} = 0$, then we say \mathbf{a} , \mathbf{b} are **orthogonal**.

Proposition

The inner product satisfies the following.

1. $\mathbf{a} \cdot (\mathbf{b} + \mathbf{c}) = \mathbf{a} \cdot \mathbf{b} + \mathbf{a} \cdot \mathbf{c}$
2. $\mathbf{a} \cdot (k\mathbf{b}) = k(\mathbf{a} \cdot \mathbf{b})$
3. $\mathbf{a} \cdot \mathbf{a} = \|\mathbf{a}\|^2$

Example

Let us parametrize a line l in \mathbf{R}^3 .

1. Suppose that l passes through $P = (x_0, y_0, z_0)$ and parallel to $\mathbf{a} = (a_1, a_2, a_3)$. Then the parametric equations of l is

$$l(t) = P + t\mathbf{a} \quad (2)$$

Equivalently, equation (2) can be written as a *symmetric form* as follows.

$$\frac{x - x_0}{a_1} = \frac{y - y_0}{a_2} = \frac{z - z_0}{a_3} \quad (3)$$

2. Suppose that l passes through two points P, Q . By substitute $\mathbf{a} = \overrightarrow{OP} - \overrightarrow{OQ}$ to (2) or (3), we get a parametric equation of l .

Theorem

Let \mathbf{a} , \mathbf{b} be nonzero 2-dimensional vectors. If θ is the angle between \mathbf{a} and \mathbf{b} , then

$$\mathbf{a} \cdot \mathbf{b} = \|\mathbf{a}\| \cdot \|\mathbf{b}\| \cdot \cos \theta$$

Definition

For nonzero vectors \mathbf{a} and \mathbf{b} with the same dimension, the vector defined by

$$\text{proj}_{\mathbf{b}} \mathbf{a} = \left(\frac{\mathbf{a} \cdot \mathbf{b}}{\|\mathbf{b}\|^2} \right) \mathbf{b}$$

is called the **projection of \mathbf{a} onto \mathbf{b}** .

Remark

As norm measures the *size* of a vector, the inner product measure the *direction*. For example, the direction of a 2-dimensional vector \mathbf{a} is determined by $0 \leq \theta_1, \theta_2 \leq \pi$ satisfying

$$\mathbf{a} \cdot \mathbf{e}_1 = \|\mathbf{a}\| \cos \theta_1$$

$$\mathbf{a} \cdot \mathbf{e}_2 = \|\mathbf{a}\| \cos \theta_2$$

In order to determine the direction of a 3-dimensional vector, say \mathbf{a} , we need three angles $0 \leq \alpha, \beta, \gamma \leq \pi$ satisfying

$$\cos \alpha = \frac{\mathbf{a} \cdot \mathbf{i}}{\|\mathbf{a}\|}, \quad \cos \beta = \frac{\mathbf{a} \cdot \mathbf{j}}{\|\mathbf{a}\|}, \quad \cos \gamma = \frac{\mathbf{a} \cdot \mathbf{k}}{\|\mathbf{a}\|} \quad (4)$$

Such quantities are called the **direction cosines**.

Definition

A $n \times m$ (n -by- m) **matrix** is a collection of nm numbers (or functions) arranged in the following way.

$$A = (a_{ij})_{n \times m} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{pmatrix}$$

The indices i, j of an entry a_{ij} represents the row and column indices respectively.

Example

1. A $n \times m$ matrix is called **square** matrix if $n = m$.
2. If A is a square matrix and $a_{ij} = 0$ for all $i \neq j$, then A is called **diagonal**.

$$A = \begin{pmatrix} a_{11} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & a_{nn} \end{pmatrix}$$

3. If the diagonal entries of a diagonal matrix are all 1, then it is called the **identity matrix**, and denoted by I_n .

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

4. If A is a square matrix and $a_{ij} = 0$ for all $i < j$ ($i > j$, respectively), then A is called **lower triangle** (**upper**

Definition

Let $A = (a_{ij})$ and $B = (b_{ij})$ be $n \times m$ matrix. Then we define

$$A + B = (a_{ij} + b_{ij})$$

$$k \cdot A = (ka_{ij})$$

Let C be a $m \times l$ matrices, then $A \cdot C$ is a $n \times l$ matrix whose entries are

$$\begin{aligned} A \cdot B &= (a_{i1}b_{1j} + a_{i2}b_{2j} + \cdots + a_{im}b_{mj})_{1 \leq i \leq n, 1 \leq j \leq l} \\ &= \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ \vdots & \vdots & & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{im} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{pmatrix} \begin{pmatrix} c_{11} \cdots c_{1j} \cdots c_{1l} \\ c_{21} \cdots c_{2j} \cdots c_{2l} \\ \vdots & \vdots & & \vdots \\ c_{m1} \cdots c_{mj} \cdots c_{ml} \end{pmatrix} \end{aligned}$$

Example

Suppose Bob, Larry, and Joanna worked in a fruits store for three days. Table 1 shows *how many* fruits each sold in total represented by the matrix A , and Table 2 shows *how much* was the fruits on each day represented by the matrix B .

	Apple	Orange	Banana
Bob	38	25	10
Larry	15	22	15
Joanna	8	70	27

Table: The volumn of sales of each person per items

	Day1	Day2	Day3
Apple	\$1.19	\$1.45	\$.99
Orange	\$1.70	\$0.99	\$2.1
Banana	\$2.19	\$3.5	\$1.29

Table: The prices of items per day

Example

The i, j -entries of the $A \cdot B$ represents the total revenue sold by the person i at the day j .

$$\begin{pmatrix} 38 & 25 & 10 \\ 15 & 22 & 15 \\ 8 & 70 & 27 \end{pmatrix} \begin{pmatrix} 1.19 & 1.45 & 0.99 \\ 1.70 & 0.99 & 2.1 \\ 2.19 & 3.5 & 1.29 \end{pmatrix}$$

A deeper, and more mathematical, thus important meaning of matrix multiplication will be discovered when we visit in the *chain rule* in later sections.

Proposition

Let A, B, C be matrices. Whenever the operations are valid, the following holds.

1. $(A \cdot B) \cdot C = A \cdot (B \cdot C)$
2. $A \cdot (B + C) = A \cdot B + A \cdot C$
3. $(B + C) \cdot A = B \cdot A + C \cdot A$
4. $k \cdot (A \cdot B) = (k \cdot A) \cdot B = A \cdot (k \cdot B)$

Proposition

The **transpose** of a matrix $A = (a_{ij})$ defined by

$$A^T = (a_{ji})$$

and it satisfies the following.

5. $(A^T)^T = A$
6. $k \cdot A^T = (k \cdot A)^T$
7. $(A + B)^T = A^T + B^T$
8. $(AB)^T = B^T A^T$

Definition

The **determinant** of 2×2 matrix A is defined as follows.

$$\det A = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}a_{21}$$

The **determinant** of 3×3 matrix B is defined as follows.

$$\begin{aligned} \det B = \begin{vmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{vmatrix} &= b_{11}b_{22}b_{33} + b_{12}b_{23}b_{31} + b_{13}b_{21}b_{32} \\ &\quad - b_{13}b_{22}b_{31} - b_{11}b_{23}b_{32} - b_{12}b_{21}b_{33} \end{aligned}$$

Definition

Let $\mathbf{a} = (a_1, a_2, a_3)$, $\mathbf{b} = (b_1, b_2, b_3)$ be two 3-dimensional vectors. The **cross-product** of \mathbf{a}, \mathbf{b} is a vector defined by

$$\mathbf{a} \times \mathbf{b} = (a_2b_3 - a_3b_2, a_3b_1 - a_1b_3, a_1b_2 - a_2b_1)$$

An easy way to remember the formula is the following.

$$\mathbf{a} \times \mathbf{b} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix}$$

Proposition

Let $\mathbf{a}, \mathbf{b}, \mathbf{c}$ be 3-dimensional vectors and k a constant. The following identity holds.

1. $\mathbf{a} \times \mathbf{0} = \mathbf{0} \times \mathbf{a} = \mathbf{0}$
2. $\mathbf{a} \times \mathbf{a} = \mathbf{0}$
3. $\mathbf{a} \times \mathbf{b} = -\mathbf{b} \times \mathbf{a}$
4. $\mathbf{a} \times (k\mathbf{b}) = (k\mathbf{a}) \times \mathbf{b} = k(\mathbf{a} \times \mathbf{b})$
5. $\mathbf{a} \times (\mathbf{b} + \mathbf{c}) = \mathbf{a} \times \mathbf{b} + \mathbf{a} \times \mathbf{c}$
6. $\mathbf{a} \cdot (\mathbf{a} \times \mathbf{b}) = \mathbf{b} \cdot (\mathbf{a} \times \mathbf{b}) = 0$ (This shows that the cross product $\mathbf{a} \times \mathbf{b}$ is normal to the plane spanned by \mathbf{a} and \mathbf{b} .)
7. $(\mathbf{a} \times \mathbf{b}) \times \mathbf{c} = (\mathbf{a} \cdot \mathbf{c})\mathbf{b} - (\mathbf{b} \cdot \mathbf{c})\mathbf{a}$

Theorem

Let \mathbf{a}, \mathbf{b} be two 3-dimensional vectors. Then

$$\|\mathbf{a} \times \mathbf{b}\| = \|\mathbf{a}\| \cdot \|\mathbf{b}\| \cdot |\sin \theta|$$

where θ is the angle between \mathbf{a} and \mathbf{b} .

Proposition

Let us denote $|A|$ by the determinant of a matrix A . Then the following holds

- 1. If A has a row (or a column) whose entries are all zero, then $|A| = 0$.*
- 2. Let B be the matrix obtained by interchanging two rows (or columns) of A . Then $|B| = -|A|$.*
- 3. Let B be a matrix obtained by multiply c on a row (or column) followed by adding it to another row (or column). Then $|B| = |A|$.*

Definition

Let A be a $n \times n$ matrix. A matrix B satisfying

$$A \cdot B = B \cdot A = I_n$$

is called the **inverse of** A , denoted by $B = A^{-1}$. If an inverse matrix A^{-1} exists, then A is said to be **non-singular**. Otherwise, it is called **singular**.

Theorem

A matrix A is singular if and only if $\det A = 0$.

Proposition

If A is a 2×2 matrix, then A^{-1} is

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

For a 3×3 -matrix B , the inverse is given by

$$B^{-1} = \frac{1}{\det B} \begin{pmatrix} c_{11} & -c_{21} & c_{31} \\ -c_{12} & c_{22} & -c_{32} \\ c_{13} & -c_{23} & c_{33} \end{pmatrix} \quad (5)$$

where each c_{ij} , called the **cofactor**, is the determinant of 2×2 -matrix obtained by deleting i th row and j th column. For example,

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

Notice that the row and column indices are switched in (5).

Definition

A **vector space** V is a set of element called **vectors** satisfying the following properties:

1. (Zero vector) V contains the **zero vector** $\mathbf{0}$, which is a unique vector satisfying $\mathbf{0} + \mathbf{v} = \mathbf{v} + \mathbf{0} = \mathbf{v}$ for all $\mathbf{v} \in V$.
2. (Vector sum) For any two vectors $\mathbf{v}, \mathbf{w} \in V$, the vector $\mathbf{v} + \mathbf{w}$ lies in V .
3. (Scalar multiplication) For any $k \in \mathbf{R}$ and $v \in V$, the vector $k\mathbf{v}$ lies in V .

A subset $V \subset \mathbf{R}^n$ is called a **vector subspace** if it is a vector space itself.

Example

Let $\mathcal{C}^1(\mathbf{R})$ be the set of all differentiable functions on \mathbf{R} whose derivatives are continuous on \mathbf{R} . Since f, g are such functions so is the function $h = f + g$. Also for any $k \in \mathbf{R}$, the function kf is differentiable and its derivative is continuous. Thus $\mathcal{C}^1(\mathbf{R})$ is a vector space. Likewise, we can define vector spaces $\mathcal{C}^n(\mathbf{R})$, $\mathcal{C}^\infty(\mathbf{R})$

Example

For each constant $k \in \mathbf{R}$, let V_k be the set of all points on the line $y = kx$ in \mathbf{R}^2 :

$$V_k = \{(x, y) \mid y = kx\}$$

Then V_k is a vector subspace of \mathbf{R}^2 . Let V_∞ be the vertical line $V_\infty = \{(0, y) \mid y \in \mathbf{R}\}$. Then V_∞ is also a vector subspace of \mathbf{R}^2

Example

Let P be the set of all point on the plane

$$P = \{(x, y, z) \mid ax + by + cz = 0\}$$

in \mathbf{R}^3 . By identifying points in P as position vectors, we can say P is a vector subspace of \mathbf{R}^3 , orthogonal to $\mathbf{n} = (a, b, c)$. In particular, let V, W be vector subspace of \mathbf{R}^n . Then so is $V \cap W$. For example, let V, W be vector subspace for two planes in \mathbf{R}^3 passing through the origin $\mathbf{0}$. Then $V \cap W$ is either a line (if V, W are transversal) or a plane (if $V = W$).

Definition

Let V a vector space and $\mathbf{v}_1, \dots, \mathbf{v}_m \in V$. We say the vector space subspace

$$W = \{a_1\mathbf{v}_1 + \dots + a_m\mathbf{v}_m \mid a_1, \dots, a_m \in \mathbf{R}\}$$

is **spanned** by $\mathbf{v}_1, \dots, \mathbf{v}_m$, and denote by $W = \text{span}\langle \mathbf{v}_1, \dots, \mathbf{v}_m \rangle$.

Definition

We say a vector space V is **spanned by** the set of vectors $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$, if every $v \in V$ can be expressed a linear combination of v_i 's:

$$v = a_1 \mathbf{v}_1 + \dots a_n \mathbf{v}_n$$

The set $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$ is said to be **linearly independent** if the coefficients satisfying

$$a_1 \mathbf{v}_1 + \dots a_n \mathbf{v}_n = \mathbf{0}$$

is the trivial ones, namely $a_1 = \dots = a_n = 0$.

Definition

Let $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$ be the set of linear independent vectors which spans the vector space V . Such set is called the **basis** of V , and its element is called the **basis vector**. The **dimension** of V is the number of basis vectors which spans V .

Problem

1. Show that the vectors $\|\mathbf{b}\|\mathbf{a} + \|\mathbf{a}\|\mathbf{b}$ and $\|\mathbf{b}\|\mathbf{a} - \|\mathbf{a}\|\mathbf{b}$ are orthogonal.
2. Show that $\|\mathbf{b}\|\mathbf{a} + \|\mathbf{a}\|\mathbf{b}$ bisects the angle between \mathbf{a} and \mathbf{b} .

Problem

1. Let $\mathbf{a} = (1, 2, 1)$, $\mathbf{b} = (2, 1, 2)$, and $\mathbf{u} = (0, 1, -1)$. Suppose that the vector \mathbf{u} can be decomposed by

$$\mathbf{u} = \mathbf{u}_1 + \mathbf{u}_2 + \mathbf{u}_3$$

where \mathbf{u}_1 is parallel to \mathbf{a} , \mathbf{u}_2 is parallel to \mathbf{b} , and \mathbf{u}_3 is orthogonal to both \mathbf{a} and \mathbf{b} . Find the vector \mathbf{u}_1 , \mathbf{u}_2 , \mathbf{u}_3 explicitly.

Problem

1. Find the distance between $P = (2, 1, 3)$ and the line $l(t) = (2, 3, -2) + t(-1, 1, -2)$.
2. Find the distance between two parallel planes

$$2x - 2y + z = 5, \quad 2x - 2y + z = 20$$

3. Find the distance between two skew lines

$$l_1(t) = (0, 5, -1) + t(2, 1, 3)$$

$$l_2(t) = (-1, 2, 0) + t(1, -1, 0)$$

Problem

Let $\mathbf{a} = (a_1, a_2, a_3)$, $\mathbf{b} = (b_1, b_2, b_3)$, $\mathbf{c} = (c_1, c_2, c_3)$. Verify that

$$(\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c} = \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix}$$

Problem

Imagine two concentric circles with radius a, b ($b < a$) which rolls on flat line with the same angular velocity. A curtate cycloid is a trajectory of a point on the circle of radius b . Find a set of parametric equation for the curtate cycloid with $a = 3$, $b = 2$.