

Multivariable Calculus

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1

Vectors in \mathbb{R}^n Space

1.1 Definition and Properties

Vector is a geometrical object that has both magnitude and direction. Examples include force and velocity.

Properties in n th dimension vector space for Euclidean vector where e_i is the basis vector for the i th axis (for convenience we will use $\mathbf{i}, \mathbf{j}, \mathbf{k}$ denote the basis vector in a 3-d space):

1.2 Addition/Subtraction

$$\mathbf{a} \pm \mathbf{b} = \sum_{i=1}^n (a_i \pm b_i) e_i \quad (1.1)$$

1.3 Scalar Multiplication

$$k\mathbf{a} = \sum_{i=1}^n k a_i \cdot e_i \quad (1.2)$$

1.4 Dot Product

$$\begin{aligned} \mathbf{a} \cdot \mathbf{b} &= \sum_{i=1}^n a_i * b_i \\ &= \|\mathbf{a}\| \|\mathbf{b}\| \cos \theta \end{aligned} \quad (1.3)$$

(Result is a scalar) Dot product has the following properties:

- (a) $\mathbf{a} \cdot \mathbf{b} = \mathbf{b} \cdot \mathbf{a}$ (*Commutative*)
- (b) $\mathbf{a} \cdot (\mathbf{b} + \mathbf{c}) = \mathbf{a} \cdot \mathbf{b} + \mathbf{a} \cdot \mathbf{c}$ (*Distributive*)
- (c) $k(\mathbf{a} \cdot \mathbf{b}) = (k\mathbf{a}) \cdot \mathbf{b} = \mathbf{a} \cdot (k\mathbf{b})$ (*Associative*)
- (d) $\mathbf{a} \cdot \mathbf{a} = \|\mathbf{a}\|^2$
- (e) $\mathbf{0} \cdot \mathbf{a} = 0$

1.5 Direction Angles\Cosines

The directional angles α , β and γ between the vector \mathbf{v} and basis vectors \mathbf{i} , \mathbf{j} , \mathbf{k} in a 3-d space satisfy the following equations:

$$\cos \alpha = \frac{\mathbf{v} \cdot \mathbf{i}}{\|\mathbf{v}\| \|\mathbf{i}\|} = \frac{v_1}{\|\mathbf{v}\|} \quad (1.4)$$

$$\cos \beta = \frac{\mathbf{v} \cdot \mathbf{j}}{\|\mathbf{v}\| \|\mathbf{j}\|} = \frac{v_2}{\|\mathbf{v}\|} \quad (1.5)$$

$$\cos \gamma = \frac{\mathbf{v} \cdot \mathbf{k}}{\|\mathbf{v}\| \|\mathbf{k}\|} = \frac{v_3}{\|\mathbf{v}\|} \quad (1.6)$$

According to their definitions we can also see that:

$$\begin{aligned} \cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma &= \frac{v_1^2 + v_2^2 + v_3^2}{\sqrt{v_1^2 + v_2^2 + v_3^2}^2} \\ &= 1 \end{aligned} \quad (1.7)$$

1.6 Orthogonal Projections

The orthogonal projection of \mathbf{v} on an arbitrary non-zero vector \mathbf{b} can be written as:

$$proj_{\mathbf{b}} \mathbf{v} = \frac{\mathbf{v} \cdot \mathbf{b}}{\|\mathbf{b}\|^2} \mathbf{b} \quad (1.8)$$

Moreover, we can see that $\mathbf{v} - proj_{\mathbf{b}} \mathbf{v}$ is the vector component of \mathbf{v} orthogonal to \mathbf{b} .

1.7 Cross Product

$$\begin{aligned} \mathbf{a} \times \mathbf{b} &= \det \begin{bmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{bmatrix} \\ &= (a_2 b_3 - a_3 b_2) \mathbf{i} - (a_1 b_3 - a_3 b_1) \mathbf{j} + (a_1 b_2 - a_2 b_1) \mathbf{k} \\ &= \|\mathbf{a}\| \|\mathbf{b}\| \sin \theta \mathbf{n} \end{aligned} \quad (1.9)$$

(\mathbf{n} is the vector that perpendicular to both \mathbf{a} and \mathbf{b} and its direction is decided by the right hand rule in a right-handed coordinate system.)

(Result is a vector that is orthogonal to both \mathbf{a} and \mathbf{b})

At the same time, we can see that

$$\mathbf{i} \times \mathbf{j} = \mathbf{k} \quad \mathbf{j} \times \mathbf{i} = -\mathbf{k} \quad (1.10)$$

$$\mathbf{j} \times \mathbf{k} = \mathbf{i} \quad \mathbf{k} \times \mathbf{j} = -\mathbf{i} \quad (1.11)$$

$$\mathbf{k} \times \mathbf{i} = \mathbf{j} \quad \mathbf{i} \times \mathbf{k} = -\mathbf{j} \quad (1.12)$$

What's more, the area A of the parallelogram that has \mathbf{a} and \mathbf{b} as adjacent sides is:

$$A = \|\mathbf{a} \times \mathbf{b}\| \quad (1.13)$$

Thus, $\mathbf{a} \times \mathbf{b} = \mathbf{0}$ if \mathbf{a} and \mathbf{b} are parallel vectors. More useful properties of cross product:

- (a) $\mathbf{a} \times \mathbf{b} = -\mathbf{b} \times \mathbf{a}$ (*Anti - Commutative*)
- (b) $\mathbf{a} \times (\mathbf{b} + \mathbf{c}) = \mathbf{a} \times \mathbf{b} + \mathbf{a} \times \mathbf{c}$ (*Distributive*)
- (c) $(\mathbf{b} + \mathbf{c}) \times \mathbf{a} = \mathbf{b} \times \mathbf{a} + \mathbf{c} \times \mathbf{a}$
- (d) $k(\mathbf{a} \times \mathbf{b}) = (k\mathbf{a}) \times \mathbf{b} = \mathbf{a} \times (k\mathbf{b})$ (*Associative*)
- (e) $\mathbf{a} \times \mathbf{0} = \mathbf{0} \times \mathbf{a} = \mathbf{0}$
- (f) $\mathbf{a} \cdot \mathbf{a} = 0$

1.8 Scalar triple product

$$(\mathbf{a} \cdot \mathbf{b} \times \mathbf{c}) = \det \begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix} \quad (1.14)$$

If we switch two rows of this matrix, the product will be multiplied by -1 .

The absolute value of scalar triple product will give us the volume of the parallelepiped that has \mathbf{a} , \mathbf{b} , \mathbf{c} as adjacent edges. Therefore, $\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) = 0$ iff they lie on the same plane.

2

Lines and Planes

2.1 Equations of Lines

The line in 3-d space that passes through the point $P_0(x_0, y_0, z_0)$ and is parallel to the non-zero vector $\mathbf{v} = \langle a, b, c \rangle = a\mathbf{i} + b\mathbf{j} + c\mathbf{k}$ has equations:

$$x = x_0 + at, \quad y = y_0 + bt, \quad z = z_0 + ct \quad (\textit{Parametric}) \quad (2.1)$$

$$l = \langle x_0, y_0, z_0 \rangle + t \langle a, b, c \rangle \quad (\textit{Vector}) \quad (2.2)$$

If two lines doesn't intercept or parallel to each other in a 3-d space, they are skew.

2.2 Equations of Planes

Definition: A vector perpendicular to a plane is called a **normal** to that plane.

A plane which passing through $P_0(x_0, y_0, z_0)$ and having $\mathbf{n} = \langle a, b, c \rangle$ as its normal has equations:

$$a(x - x_0) + b(y - y_0) + c(z - z_0) = 0 \quad (\textit{Point - Normal form}) \quad (2.3)$$

$$ax + by + cz + d = 0 \quad (d = -ax_0 - by_0 - cz_0) (\textit{General form}) \quad (2.4)$$

2.3 Angle between Planes

For two planes that have \mathbf{n}_1 and \mathbf{n}_2 as its normal, the acute angle between them θ can be obtained from the following equation:

$$\cos \theta = \frac{|\mathbf{n}_1 \cdot \mathbf{n}_2|}{\|\mathbf{n}_1\| \|\mathbf{n}_2\|} \quad (2.5)$$

2.4 Distance

The distance D between a point $P_0(x_0, y_0, z_0)$ and the plane $ax + by + cz + d = 0$ is:

$$D = \frac{|ax_0 + by_0 + cz_0 + d|}{\sqrt{a^2 + b^2 + c^2}} \quad (2.6)$$

Example: Distance between two skew lines:

Solution Find two parallel planes passing through the two skew lines by taking the cross product of their direction vectors, and find the distance between these two planes.

Example: Find the equation of the plane that passes through the line of intersection of the planes $P_1 : x - z = 1$ and $P_2 : y + 2z = 3$ and is perpendicular to the plane $P_3 : x + y - 2z = 1$.

Solutions: Find the direction vector for the line of intersection of P_1 and P_2 by taking the cross product of their normal vectors. Then take the cross product of the direction vector of the line and the normal vector of P_3 to find the normal vector of the desired plane. Then find a point on the line of intersection and solve for the plane.

2.5 Cylindrical and Spherical Coordinates

Definition. The three coordinates (r, θ, z) of a point P are defined as:

r is the Euclidean distance from the z -axis to the point P .

θ is the angle between x -axis and the line from the origin to the projection of P on xy -plane.

The height z is the signed distance from the xy -plane to the point P .

Conversion between Rectangular and Cylindrical Coordinates:

Suppose the rectangular and cylindrical coordinate of the same point is

respectively (x, y, z) and (r, θ, z) .

Rectangular to Cylindrical

$$r = \sqrt{x^2 + y^2}$$

$$\tan \theta = \frac{y}{x}$$

$$z = z$$

Cylindrical to Rectangular

$$x = r \cos \theta$$

$$y = r \sin \theta$$

$$z = z$$

Note that θ is not always $\tan^{-1} \frac{y}{x}$. To find the correct θ , we must know which quadrant of xy -plane the point lies over.

Definition. The spherical coordinates of a point P are then defined as follows:

The radius ρ is the Euclidean distance from the origin O to P .

The azimuth θ is the signed angle measured from the azimuth reference direction to the orthogonal projection of the line segment OP on the xy -plane.

The inclination ϕ is the angle between the z -axis and the line segment OP .

Conversion Between Spherical and Other Two kinds of Coordinates:

Suppose the rectangular, cylindrical, and spherical coordinate of the same point is respectively (x, y, z) , (r, θ, z) , and (ρ, θ, ϕ) . θ in cylindrical coordinate is the same as θ in spherical coordinate.

Spherical to Rectangular or Cylindrical

$$r = \rho \sin \phi$$

$$x = r \cos \theta = \rho \sin \phi \cos \theta$$

$$y = r \sin \theta = \rho \sin \phi \sin \theta$$

$$z = \rho \cos \phi$$

Rectangular to Spherical

$$\rho = \sqrt{r^2 + z^2} = \sqrt{x^2 + y^2 + z^2}$$

$$\tan \theta = \frac{y}{x}$$

$$\cos \phi = \frac{z}{\rho} = \frac{z}{\sqrt{x^2 + y^2 + z^2}}$$

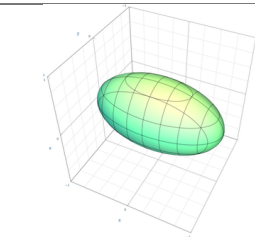
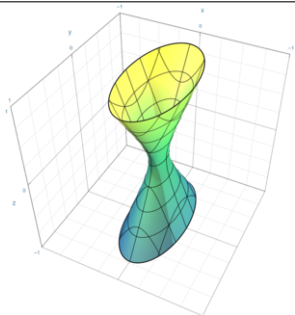
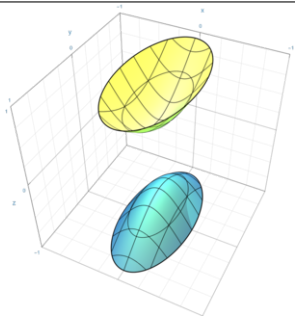
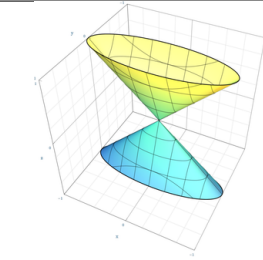
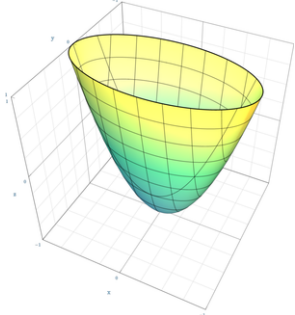
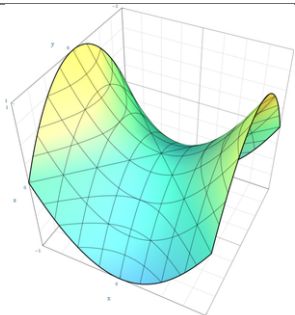
3

Quadric Surfaces

3.1 Traces

To help graphing a complex surface in a 3-d space, we obtain traces, or the curves(mesh lines) formed by cutting this surface with well-chosen planes. Usually, surfaces are built up from traces in planes that are parallel to the coordinate planes.

3.2 Type of Quadric Surfaces

Name	Equation	Figure
Ellipsoid	$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$	
Hyperboloid of one sheet	$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{z^2}{c^2} = 1$	
Hyperboloid of two sheets	$\frac{z^2}{c^2} - \frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$	
Elliptic cone	$z^2 = \frac{x^2}{a^2} + \frac{y^2}{b^2}$	
Elliptic paraboloid	$z = \frac{y^2}{a^2} + \frac{x^2}{b^2}$	
Hyperbolic paraboloid	$z = \frac{y^2}{b^2} - \frac{x^2}{a^2}$	

4

Calculus of Vector-Valued Functions

4.1 Orientation/Direction of its graph

The direction a graph of a vector-valued function goes when its parameter, t , increases is called the *orientation* or *direction of increasing parameter*.

4.2 Domain and Natural Domain

The domain of a vector-valued function is the set of all allowable values of t . The natural domain of a vector-valued function is the intersection of its component functions' domain.

4.3 Radius Vector/Position Vector

If a function can be expressed as $\mathbf{F}(t) = \langle f(t), g(t), h(t) \rangle$, then the position vector of it at $t = k$ is $\langle f(k), g(k), h(k) \rangle$.

4.4 Vector Form of A Line Segment

For two vectors \mathbf{r}_0 and \mathbf{r}_1 that has its initial point at origin, the line passes through the terminal points of them can be written as:

$$\mathbf{r} = \mathbf{r}_0 + t(\mathbf{r}_1 - \mathbf{r}_0) \quad (4.1)$$

And this is called the *two-point vector form o a line*.

4.5 Calculus of Vector-Valued Functions

The Calculus of vector-valued functions in 2-d and 3-d space is similar to "normal" functions: **just apply each operator to its component functions and "sum" them up.** The definition of integrable, differentiable and continuous is also similar: **each property requires its component functions have the corresponding property.**

The tangent line of the graph at point $\mathbf{r}(t_0)$:

$$\mathbf{r} = \mathbf{t}_0 + t\mathbf{r}'(t_0) \quad (4.2)$$

For the dot product and cross product, which are unique to vector-valued functions, the derivative is defined as following:

$$\frac{d}{dt}[\mathbf{r}_1(t) \cdot \mathbf{r}_2(t)] = \mathbf{r}_1(t) \cdot \frac{d\mathbf{r}_2}{dt} + \frac{d\mathbf{r}_1}{dt} \cdot \mathbf{r}_2(t) \quad (4.3)$$

$$\frac{d}{dt}[\mathbf{r}_1(t) \times \mathbf{r}_2(t)] = \mathbf{r}_1(t) \times \frac{d\mathbf{r}_2}{dt} + \frac{d\mathbf{r}_1}{dt} \times \mathbf{r}_2(t) \quad (4.4)$$

In 2-d space, the tangent line to a circle is perpendicular to the radius at the point of tangency. Similarly, in for a vector-valued function, if $\|\mathbf{r}(t)\|$ is constant for all t , then:

$$\mathbf{r}(t) \cdot \mathbf{r}'(t) = 0 \quad (4.5)$$

that is, $\mathbf{r}(t)$ and $\mathbf{r}'(t)$ are orthogonal for all t .

4.6 Arc Length

In a 2-d space, the arc length L of a parametric curve $\mathbf{x} = \mathbf{x}(t), \mathbf{y} = \mathbf{y}(t), (a \leq t \leq b)$ can be given as:

$$L = \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt \quad (4.6)$$

Lemma. In a 2-d space, the arc length L of a function $\mathbf{y} = \mathbf{f}(\mathbf{x})$ that itself and its derivative is continuous on $[\mathbf{a}, \mathbf{b}]$ is:

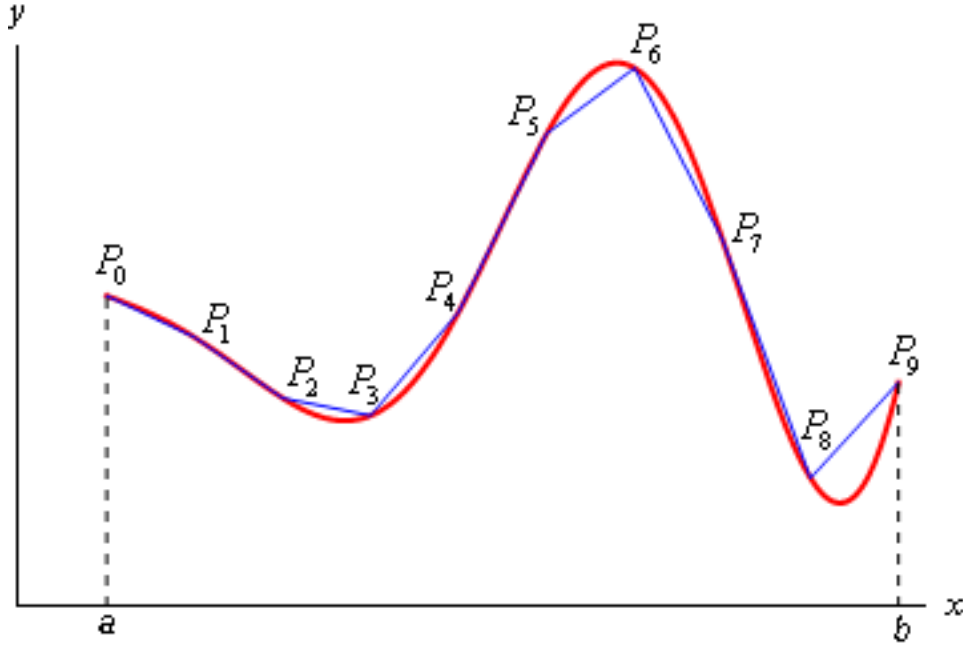
$$L = \int ds \quad (4.7)$$

where

$$ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx \quad \text{if } y = f(x), a \leq x \leq b$$

$$ds = \sqrt{1 + \left(\frac{dx}{dy}\right)^2} dy \quad \text{if } x = g(y), c \leq y \leq d$$

Proof. As we can see in the figure below, the arc length is the sum of distance between n consecutive points when $n \rightarrow \infty$



Arc Length L can be written as:

$$L = \lim_{n \rightarrow \infty} \sum_{i=1}^n \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$$

Additionally, we can see that

$$\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} = \sqrt{\Delta x^2 + \Delta y_i^2}$$

According to Mean Value Theorem, there exists an \bar{x} such that

$$\Delta y_i = f'(\bar{x}_i) \Delta x$$

Thus

$$\begin{aligned} \sqrt{\Delta x^2 + \Delta y_i^2} &= \sqrt{\Delta x^2 + \Delta y_i^2} \\ &= \sqrt{\Delta x^2 + (f'(\bar{x}_i) \Delta x)^2} \\ &= \sqrt{1 + [f'(\bar{x}_i)]^2} \Delta x \end{aligned}$$

The exact length of the given curve is

$$\begin{aligned}
 L &= \lim_{n \rightarrow \infty} \sum_{i=1}^n \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \\
 &= \lim_{n \rightarrow \infty} \sum_{i=1}^n \sqrt{1 + [f'(\bar{x}_i)]^2} \Delta x \\
 &= \int_a^b \sqrt{1 + [f'(x)]^2} dx \\
 &= \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx
 \end{aligned}$$

□

Now we can prove Theorem (4.6):

Proof. Recall that $x = x(t)$, $y = y(t)$, therefore

$$\begin{aligned}
 L &= \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx \\
 &= \int_a^b \sqrt{1 + \frac{\left(\frac{dy}{dt}\right)^2}{\left(\frac{dx}{dt}\right)^2}} \frac{dx}{dt} dt \\
 &= \int_a^b \sqrt{1 + \frac{\left(\frac{dy}{dt}\right)^2}{\left(\frac{dx}{dt}\right)^2}} \frac{dx}{dt} dt \\
 &= \int_a^b \frac{1}{\left|\frac{dx}{dt}\right|} \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} \frac{dx}{dt} dt
 \end{aligned}$$

If we assume that $\frac{dx}{dt} \geq 0$, then

$$L = \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$$

□

Analogously, the arc length L of a smoothly parametrized function (**have a continuously turning tangent vector**) in 3-d space is

$$\begin{aligned}
 L &= \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2} dt \\
 &= \int_a^b \left\| \frac{d\mathbf{r}}{dt} \right\| dt
 \end{aligned} \tag{4.8}$$

4.7 Arc Length as A Parameter

Sometime it would be more convenient to replace \mathbf{t} with \mathbf{s} , which is the length of arc measured along the curve from some fixed reference point. There are three steps:

Step 1. Select an reference point.

Step 2. Choose one direction from the reference point as the positive direction.

Step 3. Change the length \mathbf{s} to a "signed" length, which means \mathbf{s} is positive if \mathbf{s} "moves along the curve" to its positive direction.

Note that there are infinitely many different arc length parameterizations.

Theorem 4.7.1. Chain Rule *Let $\mathbf{r}(\mathbf{t})$ be a vector-valued function in 2-d/3-d space that is differentiable with respect to \mathbf{t} . If $\mathbf{t} = \mathbf{g}(\tau)$ is a change of parameter in which \mathbf{g} is differentiable with respect to τ , then $\mathbf{r}(\mathbf{g}(\tau))$ is differentiable with respect to τ and*

$$\frac{d\mathbf{r}}{d\tau} = \frac{d\mathbf{r}}{d\mathbf{t}} \frac{d\mathbf{t}}{d\tau} \quad (4.9)$$

A change in parameter is smooth if $\mathbf{r}(\mathbf{g}(\tau))$ is smooth and $\mathbf{r}(\mathbf{t})$ is smooth. For all τ , $\frac{d\mathbf{t}}{d\tau} > 0$ is called a positive change of parameter while $\frac{d\mathbf{t}}{d\tau} < 0$ is called a negative change of parameter.

Theorem 4.7.2. *Let \mathbf{C} be the graph of a smooth vector-valued function $\mathbf{r}(\mathbf{t})$ in 2-d or 3-d space, and let $\mathbf{r}(\mathbf{t}_0)$ be any point on \mathbf{C} . Then the following formula defines a positive change of parameter from \mathbf{t} to \mathbf{s} , where \mathbf{s} is an arc length parameter having $\mathbf{r}(\mathbf{t}_0)$ as its reference point:*

$$\mathbf{s} = \int_{\mathbf{t}_0}^{\mathbf{t}} \left\| \frac{d\mathbf{r}}{d\mathbf{u}} \right\| d\mathbf{u} \quad (4.10)$$

Theorem 4.7.3. *If \mathbf{C} is the graph of a smooth vector-valued function $\mathbf{r}(\mathbf{t})$ in 2-d or 3-d space, where \mathbf{t} is a general parameter, and if \mathbf{s} is the arc length parameter for \mathbf{C} defined by **Theorem 2**, then for every value of \mathbf{t} the tangent vector has length*

$$\left\| \frac{d\mathbf{r}}{d\mathbf{t}} \right\| = \frac{d\mathbf{s}}{d\mathbf{t}} \quad (4.11)$$

Proof. This can be derived from applying the Fundamental Theorem of Calculus to Theorem 2. \square

Theorem 4.7.4. *If C is the graph of a smooth vector-valued function $\mathbf{r}(t)$ in 2-d or 3-d space, where s is the arc length parameter, then for every value of s the tangent vector to C has length*

$$\left\| \frac{d\mathbf{r}}{ds} \right\| = 1 \quad (4.12)$$

Proof. Let $t = s$ in **Theorem 3**. □

Theorem 4.7.5. *If C is the graph of a smooth vector-valued function $\mathbf{r}(t)$ in 2-d or 3-d space, and if*

$$\left\| \frac{d\mathbf{r}}{dt} \right\| = 1 \quad (4.13)$$

for every value of t , then t is an arc length parameter that has its reference point at the point on C where $t = 0$.

Proof. The formula

$$s = \int_0^t \left\| \frac{d\mathbf{r}}{du} \right\| du$$

defines an arc length parameter for C with reference point $\mathbf{r}(0)$. Note that

$$\left\| \frac{d\mathbf{r}}{dt} \right\| = 1$$

by hypothesis. Thus the formula can be rewrite as

$$s = \int_0^t du = t - 0 = t$$

□

4.8 Unit Tangent, Normal, and Binormal Vectors

Definition. The unit tangent of a smooth vector-valued function $\mathbf{r}(t)$ in 2-d space or 3-d space that points in the direction of increasing parameter can be expressed as:

$$\mathbf{T}(t) = \frac{\mathbf{r}'(t)}{\|\mathbf{r}'(t)\|}$$

and it's called the *unit tangent vector* to C at t .

Note that for all smooth parameterization which induce the same direction have the same unit tangent vector.

Recall that if a vector-valued function $\mathbf{r}(t)$ has constant norm, then $\mathbf{r}(t)$ and $\mathbf{r}'(t)$ are orthogonal. Because $\mathbf{T}(t)$ has constant norm 1, so $\mathbf{T}(t)$ and

$\mathbf{T}'(t)$ are orthogonal. This implies that $\mathbf{T}'(t)$ is perpendicular to the tangent line to C at t , so we say that $\mathbf{T}'(t)$ is *normal* to C at t . If $\mathbf{T}'(t) \neq \mathbf{0}$, then

$$\mathbf{N}(t) = \frac{\mathbf{T}'(t)}{\|\mathbf{T}'(t)\|}$$

is the *principle unit normal vector*, or simply *unit normal vector* to C at t and points in the same direction as $\mathbf{T}'(t)$.

The unit normal vector always points toward the concave side of C in 2-d space.

According to **Theorem 4.7.4**, $\|\mathbf{r}'(t)\| = 1$. Thus

$$\mathbf{T}(s) = \mathbf{r}'(s)$$

and consequently

$$\mathbf{N}(s) = \frac{\mathbf{r}''(s)}{\|\mathbf{r}''(s)\|}$$

Definition. The binormal vector to C at t can be defined as

$$\begin{aligned} \mathbf{B}(t) &= \mathbf{T}(t) \times \mathbf{N}(t) \\ &= \frac{\mathbf{r}'(t) \times \mathbf{r}''(t)}{\|\mathbf{r}'(t) \times \mathbf{r}''(t)\|} \end{aligned}$$

that is, the cross product of its unit tangent vector and unit normal vector and the direction of binormal vector is determined by the right-hand rule. $\|\mathbf{B}(t)\| = 1$ since $\|\mathbf{T}(t) \times \mathbf{N}(t)\| = \|\mathbf{T}(t)\| \|\mathbf{N}(t)\| \sin(\pi/2) = 1$.

In terms of arc length parameteriation, it can be expressed as

$$\mathbf{B}(s) = \frac{\mathbf{r}'(s) \times \mathbf{r}''(s)}{\|\mathbf{r}''(s)\|}$$

Together with unit tangent vector and unit normal vector, the binormal vector define three mutually perpendicular planes that point through that point – the **TB**-plane (called the *rectifying plane*), the **TN**-plane (called the *osculating plane*), and the **NB**-plane (called the *normal plane*). The coordinate system(right-hand) system determined by these three vectors is called the **TNB**-frame.

4.9 Curvature

Definition. If C is a smooth curve in 2-d space or 3-d space that is parametrized by arc length, then the *curvature* of C , denoted by $\kappa = \kappa(s)$, is defined by

$$\kappa(s) = \left\| \frac{d\mathbf{T}}{ds} \right\| = \|\mathbf{r}''(s)\|$$

Theorem 4.9.1. *If $\mathbf{r}(t)$ is a smooth vector-valued function in 2-d space or 3-d space, then for each value of t at which $\mathbf{T}(t)$ and $\mathbf{r}''(t)$ exist, the curvature κ can be expressed as*

$$\begin{aligned}\kappa(t) &= \frac{\|\mathbf{T}'(t)\|}{\|\mathbf{r}'(t)\|} \\ &= \frac{\|\mathbf{r}'(t) \times \mathbf{r}''(t)\|}{\|\mathbf{r}'(t)\|^3}\end{aligned}$$

Definition. If at P $\kappa \neq 0$, then there exists a unique circle Ω passing through P on the concave side of C such that the curvature of Ω is κ and it shares a common tangent vector with C . Then Ω is called a *osculating circle* or *circle of curvature* at P , $1/\kappa$ is called the radius of curvature at P , and the center of Ω is called the center of curvature at P .

Definition. Let $\phi(s)$ be the angle measured counterclockwise from the direction of the positive x -axis to the unit tangent vector \mathbf{T} in terms of arc length. Then

$$\kappa(s) = \left| \frac{d\phi}{ds} \right|$$

4.10 Motion Along A Curve

Definition. If a particle moves along a smooth vector-valued function $\mathbf{r}(t)$, then the velocity of this particle is

$$\mathbf{v}(t) = \mathbf{r}'(t) = \frac{ds}{dt} \mathbf{T}(t)$$

where $\mathbf{v}(t)$ is the tangent vector at t . The direction of $\mathbf{v}(t)$ gives the instantaneous direction of motion at t . The magnitude of $\mathbf{v}(t)$ is the instantaneous rate of change of arc length as a function of time, or just simply speed.

Definition. The acceleration of this particle with velocity of $\mathbf{v}(t)$ is $\mathbf{a}(t) = \mathbf{v}'(t) = \mathbf{r}''(t)$. What's more

$$\mathbf{a}(t) = \frac{d^2s}{dt^2} \mathbf{T}(t) + \kappa(t) \left(\frac{ds}{dt} \right)^2 \mathbf{N}(t)$$

If the particle is travelling on a circle with radius r , the speed v_0 is constant, and $\|\mathbf{a}(t)\| = \frac{v_0^2}{r}$.

Statement. *Over a time interval $[t_1, t_2]$, the distance traveled by a particle is*

$$s = \int_{t_1}^{t_2} \|\mathbf{v}(t)\| dt$$

Definition. If $a_T = \frac{d^2s}{dt^2}$ and $a_N = \kappa(t)(\frac{ds}{dt})^2$, then

$$\mathbf{a} = a_T \mathbf{T} + a_N \mathbf{N}$$

and a_T is called the *tangential component of acceleration* and a_N is called *normal component of acceleration*. $a_T \mathbf{T}$ is the *tangential vector component of acceleration* and $a_N \mathbf{N}$ is called the *normal vector component of acceleration*.

Statement.

$$\begin{aligned} a_T &= \frac{\mathbf{v} \cdot \mathbf{a}}{\|\mathbf{v}\|} \\ a_N &= \frac{\|\mathbf{v} \times \mathbf{a}\|}{\|\mathbf{v}\|} \\ \kappa &= \frac{\|\mathbf{v} \times \mathbf{a}\|}{\|\mathbf{v}\|^3} \end{aligned}$$

In 2-d space, the cross product can be computed by viewing $\mathbf{r}(t) = \langle x(t), y(t) \rangle$ as $\mathbf{r}(t) = \langle x(t), y(t), 0 \rangle$ in 3-d space.

Statement.

$$\|\mathbf{a}\|^2 = a_T^2 + a_N^2$$

for all smooth position functions.

4.11 Projectile Motion

Theorem 4.11.1. For a projectile motion

$$\begin{aligned} \mathbf{r}(t) &= -\frac{gt^2}{2} \mathbf{j} + t\mathbf{v}_0 + s_0 \mathbf{j} \\ &= \left(-\frac{gt^2}{2} + s_0\right) \mathbf{j} + t\mathbf{v}_0 \end{aligned}$$

where \mathbf{g} is the gravitational acceleration, \mathbf{v}_0 is the initial velocity, and s_0 is the initial height.

5

Multivariable Calculus

5.1 Definition of Multivariable functions and their graph

Definition. A *real-valued function f of n real variables* is a mapping that assign an ordered pair of n real numbers to a real number in $D \subset \mathbb{R}^n$.

Definition. If f is a function of two variables and k is a real number, then the *level curve of f of height k* is $\{(x, y) | f(x, y) = k\}$. A collection of many level curves for a function f all drawn in the same xy -plane is called a *contour plot/map of f* .

5.2 Properties of Sets in 2-d and 3-d space

Definition. For $r > 0$ and a point P , the *open ball of radius r centered at P* means the set of all points whose distance to P is less than r and denotes $B_r(P)$.

Suppose $D \subset \mathbb{R}^2$ or $D \subset \mathbb{R}^3$.

Definition. A point P is said to be an *interior point* of D if $\exists r > 0 (B_r(P) \subset D)$.

Definition. A point P is said to be an *boundary point* of D if $\forall r > 0 ((B_r(P) \cap D \neq \emptyset) \wedge (B_r(P) \setminus D \neq \emptyset))$

Definition. For a set D in 2-d and 3-d space, the set of all its interior points is called the *interior* of D . The set of all its boundary points is called the *boundary* of D .

Definition. A set is to be said *open* if it contains none of its boundary points, and when it contains all of its boundary points, it's called a *closed* set.

However, some sets are **neither** open or close.

Statement. A set D in n -space is both open and closed iff $D = \mathbb{R}^n$ or $D = \emptyset$.

Definition. A subset D of \mathbb{R}^n is said to be *bounded* if $\exists r > 0 \exists P (D \subset B_r(P))$. That is, the set is contained in some set with finite radius. It's *unbounded* if it's not bounded.

Definition. A point P is said to be the *accumulation point* of some $D \subset \mathbb{R}^n$ if $B_r(P) \subset D \wedge \forall r > 0 (B_r(P) \setminus D \setminus \{P\} \neq \emptyset)$.