

Calculus III

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Contents

12 Vectors and the Geometry of Space	2
12.1 Three-Dimensional Coordinate Systems	2
3D Space	2
Distances and Spheres	3
12.2 Vectors	3
Geometric Description of Vectors	3
12.3 The Dot Product	5
12.4 The Cross Product	7
12.5 Equations of Lines and Planes	8
Lines	8
Planes	8

Chapter 12

Vectors and the Geometry of Space

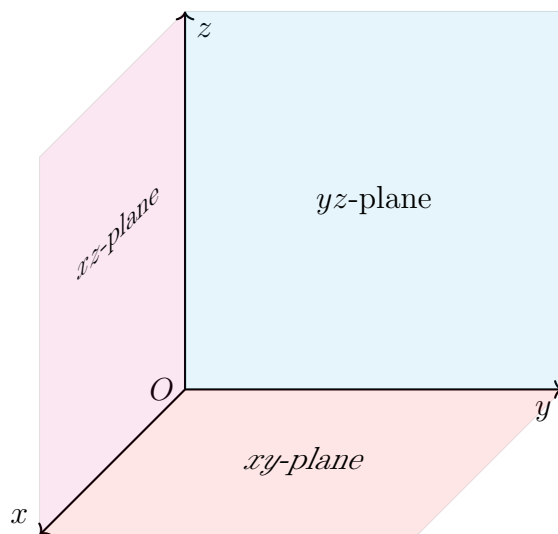
12.1 Three-Dimensional Coordinate Systems

Any point in a plane can be represented as an ordered pair of real numbers. Because this uses two numbers, a plane is called two-dimensional. To locate a point in space, a triplet of real-numbers is required.

3D Space

Before points can be represented in 3D space, a fixed point O (the origin) and three perpendicular lines that pass through it, called the **coordinate axes**. These axes are labeled the x -, y -, and z -axes. In general, the former two are horizontal while the third is vertical. The direction of the z -axis is determined by the **right-hand rule**. Curling the fingers of the right hand from the positive x -axis to the positive y -axis, the thumb will point in the direction of the positive z -axis.

The three coordinate axes determine the three **coordinate planes**.



Three planes divided space into eight **octants**. Illustrated above are the positive xz -, yz -, and xy -planes, constituting the **first octant**.

A point's **coordinates** are an ordered triple of real numbers. A point's **projection** onto a plane is the point with two of the same coordinates, the third becoming 0.

Plane	xy	yz	xz
(a, b, c)	$(a, b, 0)$	$(0, b, c)$	$(a, 0, c)$

The set of all ordered triples is the cartesian product of three sets of all real numbers, denoted appropriately by \mathbb{R}^3 and defined as

$$\mathbb{R}^3 = \mathbb{R} \times \mathbb{R} \times \mathbb{R} = \{(x, y, z) \mid x, y, z \in \mathbb{R}\}$$

A one-to-one correspondence between points in space and ordered triples in \mathbb{R}^3 is a **three-dimensional coordinate system**. It should be noted that the first octant can be described as the set of points for which all coordinates are positive.

Distances and Spheres

Distance Formula in Three Dimensions The distance $|P_1P_2|$ between points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ is

$$|P_1P_2| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Equation of a Sphere The equation of a sphere with center (h, k, l) and radius r is

$$(x - h)^2 + (y - k)^2 + (z - l)^2 = r^2$$

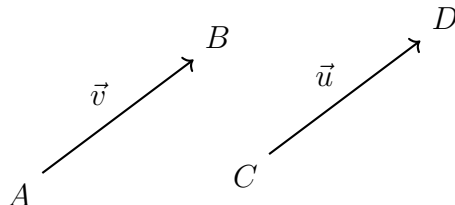
12.2 Vectors

The term **vector** is used to indicate a quantity with both magnitude and direction.

Geometric Description of Vectors

A vector is often represented by an arrow, the length of which represents its magnitude. A vector is denoted by a letter in boldface (\mathbf{v}) or with an arrow above a letter (\vec{v}).

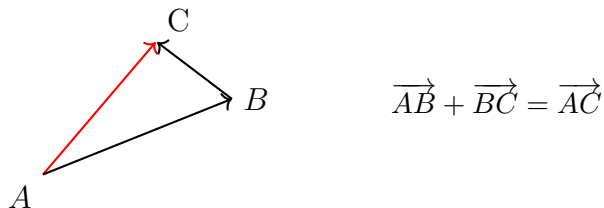
A **displacement vector** is a vector representing how something is displaced from its **initial point** (tail) to its **terminal point** (tip).



In the above figure, vector \vec{v} has initial point A and terminal point B . This can be indicated by writing $\vec{v} = \overrightarrow{AB}$. If $AB = CD$ and the angles relative to the same axis are equal, then the \vec{v} and \vec{u} are **equivalent** (or **equal**).

The only vector without a direction is the **zero vector**, denoted by $\vec{0}$, which has length 0.

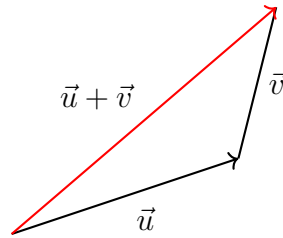
The sum of two vectors can be denoted with the initial point of the first and the terminal point of the second.



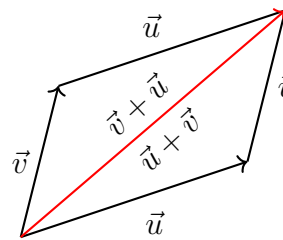
To add vectors, the one's tail can be moved to the other's tip and the resultant terminal point found.

Definition of Vector Addition The sum of two vectors position such that the initial point of one is the terminal point of the other is the vector from the initial point of the first to the terminal point of the second.

The definition of vector addition is sometimes referred to as the **Triangle Law**.



Doing the opposite addition results in the same resultant vector. This is made visible by the **Parallelogram Law**.

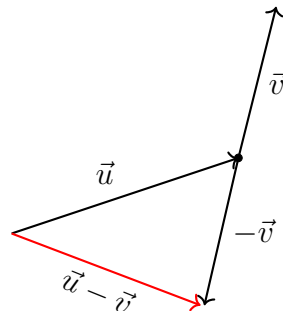


A **scalar** is a number that is not a vector.

Definition of Scalar Multiplication The **scalar multiple** $c\vec{v}$ of a scalar c and a vector \vec{v} is a vector of length $|c||\vec{v}|$ and whose direction is the same as \vec{v} is $c > 0$ and in the opposite direction if $c < 0$. If $c = 0$ or $\vec{v} = \vec{0}$, then $c\vec{v} = \vec{0}$.

The **negative** of a vector \vec{v} , denoted by $-\vec{v}$, is the scalar multiple of the \vec{v} and -1 .

The **difference** $\vec{u} - \vec{v}$ is the sum of \vec{u} and $-\vec{v}$.



A vector can be treated algebraically using **components**, which are the difference between the initial and terminal points in a dimension. The components of a vector \vec{u} in 2 dimension and a vector \vec{v} in 3 can be denoted as such:

$$\vec{u} = \langle u_1, u_2 \rangle$$

$$\vec{v} = \langle v_1, v_2, v_3 \rangle$$

Geometric vectors can be thought of as **representation** of algebraic vectors.

The representation of a vector with initial and terminal points is

$$\langle \Delta x, \Delta y, \Delta z \rangle$$

The **magnitude/length** of a vector, denoted $|\vec{v}|$ or $||\vec{v}||$ for a vector \vec{v} , is the length of any of its representations. This can be computed in n dimensions using the distance formula:

$$|\vec{v}| = \sqrt{\sum_{i=1}^n v_i^2}$$

Vectors can be added or subtracted algebraically by performing the desired operation their corresponding components.

$$\vec{u} \pm \vec{v} = \langle u_1 \pm v_1, u_2 \pm v_2, \dots, u_n \pm v_n \rangle$$

The scalar multiple of a vector can be found by multiplying each of its components by the scalar.

$$c\vec{v} = \langle cv_1, cv_2, \dots, cv_n \rangle$$

The set of all n -dimensional vectors is denoted by V_n . An n -dimensional vector is an n -tuple of real numbers, which are the vector's components.

Properties of Vectors If \vec{a} , \vec{b} , and \vec{c} are vectors in V_n and c and d are scalars, then

$$\begin{array}{ll} \vec{a} + \vec{b} = \vec{b} + \vec{a} & \vec{a} + (\vec{b} + \vec{c}) = (\vec{a} + \vec{b}) + \vec{c} \\ \vec{a} + \vec{0} = \vec{a} & \vec{a} + (-\vec{a}) = \vec{0} \\ c(\vec{a} + \vec{b}) = c\vec{a} + c\vec{b} & (c + d)\vec{a} = c\vec{a} + d\vec{a} \\ (cd)\vec{a} = c(d\vec{a}) & 1\vec{a} = \vec{a} \end{array}$$

A vector can be denoted in **unit-vector notation** as the sum of scalar multiples of **standard basis vectors** defined as such:

$$\hat{i} := \langle 0, 0, 1 \rangle \quad \hat{j} := \langle 0, 1, 0 \rangle \quad \hat{k} := \langle 0, 0, 1 \rangle$$

A vector can therefore be rewritten using its components as such:

$$\vec{v} = \langle v_x, v_y, v_z \rangle = v_x \hat{i} + v_y \hat{j} + v_z \hat{k}$$

A **unit vector** is a vector of length 1. The standard basis vectors are unit vectors in the directions of the axes. A unit vector \vec{u} in the same direction as a vector \vec{v} is

$$\vec{u} = \frac{\vec{a}}{|\vec{a}|}$$

The angle θ between a two-dimensional vector \vec{v} and the positive x -axis can be calculated using inverse tangent:

$$\theta = \arctan\left(\frac{v_y}{v_x}\right)$$

This can be used to find the components of a vector of a given magnitude r and direction θ .

12.3 The Dot Product

Definition of the Dot Product The dot product of two vectors in V_n is the sum of the products of their corresponding components.

$$\vec{u} \cdot \vec{v} = \sum_{i=1}^n u_i v_i$$

The dot product of two vectors is a real number. As such, the dot product is sometimes referred to as the **scalar/inner product**.

Properties of the Dot Product If \vec{a} , \vec{b} , and \vec{c} are vectors in V_n and c is a scalar, then

$$\begin{aligned}\vec{a} \cdot \vec{a} &= |\vec{a}|^2 & \vec{a} \cdot \vec{b} &= \vec{b} \cdot \vec{a} \\ \vec{a} \cdot (\vec{b} + \vec{c}) &= \vec{a} \cdot \vec{b} + \vec{a} \cdot \vec{c} & (c\vec{a}) \cdot \vec{b} &= c(\vec{a} \cdot \vec{b}) = \vec{a} \cdot (c\vec{b}) \\ \vec{0} \cdot \vec{a} &= 0\end{aligned}$$

If θ is the angle between vectors, \vec{u} and \vec{v} , then

$$\vec{u} \cdot \vec{v} = |\vec{u}||\vec{v}| \cos \theta$$

Rewritten for θ , it can be said that

$$\cos \theta = \frac{\vec{u} \cdot \vec{v}}{|\vec{u}||\vec{v}|}$$

Two vectors are **orthogonal** (perpendicular) if and only if their dot product is 0.

$$\vec{u} \perp \vec{v} \iff \vec{u} \cdot \vec{v} = 0$$

Two vectors are **parallel** if their dot product is equal to the product of their magnitudes, as θ is 0.

$$\vec{u} \parallel \vec{v} \iff \vec{u} \cdot \vec{v} = |\vec{u}||\vec{v}|$$

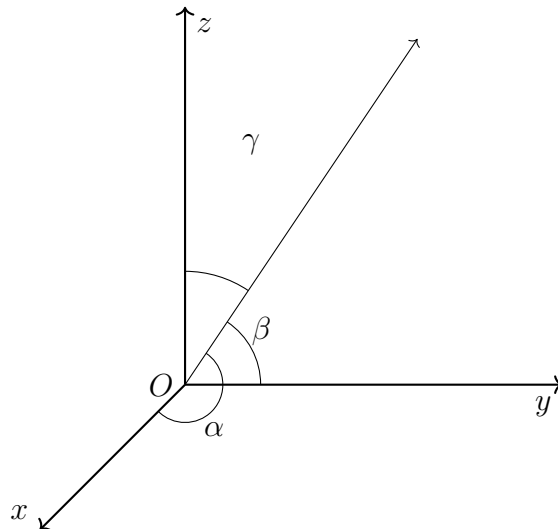
The **scalar projection** of a vector \vec{u} onto a vector \vec{v} is (the **component of \vec{u} along \vec{v}**) is the component of \vec{u} in the direction of \vec{v} . This is denoted and found as

$$\text{comp}_{\vec{v}} \vec{u} = |\vec{u}| \cos \theta = \frac{\vec{u} \cdot \vec{v}}{|\vec{v}|}$$

The **vector projection** of this is simply equal to this scalar multiplied by a unit vector in the direction of \vec{v} .

$$\text{proj}_{\vec{v}} \vec{u} = \frac{\vec{u} \cdot \vec{v}}{|\vec{v}|^2} \vec{v}$$

The **direction angles** of a nonzero vector are α , β , and γ . These are the angles made with the positive x -, y -, and z -axes respectively.



The cosines of these direction angles are called the **direction cosines**. These direction cosines can be derived using the dot products of the vector and the standard basis vectors.

$$\cos \alpha = \frac{\vec{v} \cdot \hat{i}}{|\vec{v}| |\hat{i}|} = \frac{v_x}{|\vec{v}|} \quad \cos \beta = \frac{\vec{v} \cdot \hat{j}}{|\vec{v}| |\hat{j}|} = \frac{v_y}{|\vec{v}|} \quad \cos \gamma = \frac{\vec{v} \cdot \hat{k}}{|\vec{v}| |\hat{k}|} = \frac{v_z}{|\vec{v}|}$$

Squaring both sides and adding,

$$\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = \frac{v_x^2 + v_y^2 + v_z^2}{v_x^2 + v_y^2 + v_z^2} = 1$$

Rewriting for the components, it can be seen that the direction cosines are the components of the unit vector in the direction of the vector.

$$\begin{aligned} \vec{v} &= \langle v_x, v_y, v_z \rangle = \langle |\vec{v}| \cos \alpha, |\vec{v}| \cos \beta, |\vec{v}| \cos \gamma \rangle = |\vec{v}| \langle \cos \alpha, \cos \beta, \cos \gamma \rangle \\ \frac{\vec{v}}{|\vec{v}|} &= \langle \cos \alpha, \cos \beta, \cos \gamma \rangle \end{aligned}$$

12.4 The Cross Product

A **determinant of order 2** is defined as the difference between the products of the diagonal terms and is denoted as such:

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

A **determinant of order 3** can be defined in terms of second-order determinants.

$$\begin{aligned} \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix} &= a_1 \begin{vmatrix} b_2 & b_3 \\ c_2 & c_3 \end{vmatrix} - a_2 \begin{vmatrix} b_1 & b_3 \\ c_1 & c_3 \end{vmatrix} + a_3 \begin{vmatrix} b_1 & b_2 \\ c_1 & c_2 \end{vmatrix} \\ &= a_1 b_2 c_3 - a_1 b_3 c_2 - a_2 b_1 c_3 + a_2 b_3 c_2 + a_3 b_1 c_2 - a_3 b_2 c_1 \end{aligned}$$

Definition of the Cross Product The **cross product** of two three-dimensional vectors \vec{a} and \vec{b} is

$$\vec{u} \times \vec{v} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \end{vmatrix} = \langle u_2 v_3 - u_3 v_2, u_3 v_1 - u_1 v_3, u_1 v_2 - u_2 v_1 \rangle$$

The cross product of two vectors is orthogonal to both.

The magnitude of the cross product of two vectors \vec{u} and \vec{v} with angle θ between them is $\vec{0}$.

$$|\vec{u} \times \vec{v}| = |\vec{u}| |\vec{v}| \sin \theta$$

Two vectors are parallel if and only if their cross product is equal to zero.

$$\vec{u} \parallel \vec{v} \iff \vec{u} \times \vec{v} = \vec{0}$$

The cross products of the standard basis vectors are as follows:

$$\begin{aligned} \hat{i} \times \hat{j} &= \hat{k} & \hat{j} \times \hat{k} &= \hat{i} & \hat{k} \times \hat{i} &= \hat{j} \\ \hat{j} \times \hat{i} &= -\hat{k} & \hat{k} \times \hat{j} &= -\hat{i} & \hat{i} \times \hat{k} &= -\hat{j} \end{aligned}$$

Properties of the Cross Product If \vec{a} , \vec{b} , and \vec{c} are vectors and c is a scalar, then

$$\begin{aligned}\vec{a} \times \vec{b} &= -\vec{b} \times \vec{a} & (c\vec{a}) \times \vec{b} &= c(\vec{a} \times \vec{b}) = \vec{a} \times (c\vec{b}) \\ \vec{a} \times (\vec{b} + \vec{c}) &= \vec{a} \times \vec{b} + \vec{a} \times \vec{c} & (\vec{a} + \vec{b}) \times \vec{c} &= \vec{a} \times \vec{c} + \vec{b} \times \vec{c} \\ \vec{a} \cdot (\vec{b} \times \vec{c}) &= (\vec{a} \times \vec{b}) \cdot \vec{c} & \vec{a} \times (\vec{b} \times \vec{c}) &= (\vec{a} \cdot \vec{c})\vec{b} - (\vec{a} \cdot \vec{b})\vec{c}\end{aligned}$$

12.5 Equations of Lines and Planes

Lines

A line in three dimensional space is defined by a known point and a direction. The direction can be described by a vector parallel to the line. A **vector equation** of a line has a parameter of some scalar which is multiplied by the parallel vector. The result is then added to the initial point.

$$\vec{r} = \vec{r}_0 + t\vec{v}$$

Rewritten in component form,

$$x = x_0 + v_x t \qquad y = y_0 + v_y t \qquad z = z_0 + v_z t$$

If a vector is used to describe a line's direction, its components are called the line's **direction numbers**. As any parallel vector can be used, any set of numbers proportional to a given set of direction numbers can also be used as a set of direction numbers for the line.

A line can also be described by eliminating the parameter, solving each component's equation for the parameter.

$$t = \frac{x - x_0}{v_x} = \frac{y - y_0}{v_y} = \frac{z - z_0}{v_z}$$

These equations are the **symmetric equations** of the line. It should be noted that the denominators are direction numbers. If one of the direction number is 0, the symmetric equations can still be found, simply equating the variable whose corresponding number is 0 to its known value. If v_x is 0,

$$x = x_0 \qquad \frac{y - y_0}{v_y} = \frac{z - z_0}{v_z}$$

The line segment from r_0 to r_1 is given by the vector equation

$$r(t) = (1 - t)r_0 + tr_1 \mid 0 \leq t \leq 1$$

Planes