Linear Algebra and Applications
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References:
-***Elementary Linear Algebra-Applications Version"***,
Howard Anton and Chris Rorres, 9th Edition, Wiley, 2010.

EVALUATING DETERMINANTS BY ROW REDUCTION

Let A be a square matrix. If A has a row of zeros or a column of zeros, then $\det(A) = 0$.

Let A be a square matrix. Then $\det(A) = \det(A^T)$.

Let A be an $n \times n$ *matrix.*

(a) *If B is the matrix that results when a single row or single column of A is multiplied by a scalar* k, *then* $\det(B) = k\det(A)$.

(b) *If B is the matrix that results when two rows or two columns of A are interchanged, then* $\det(B) = -\det(A)$.

(c) *If B is the matrix that results when a multiple of one row of A is added to another row or when a multiple of one column is added to another column, then* $\det(B) = \det(A)$.

Relationship	Operation
$\begin{vmatrix} ka_{11} & ka_{12} & ka_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = k \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$ $\det(B) = k\det(A)$	The first row of A is multiplied by k.
$\begin{vmatrix} a_{21} & a_{22} & a_{23} \\ a_{11} & a_{12} & a_{13} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = - \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$ $\det(B) = -\det(A)$	The first and second rows of A are interchanged.
$\begin{vmatrix} a_{11}+ka_{21} & a_{12}+ka_{22} & a_{13}+ka_{23} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$ $\det(B) = \det(A)$	A multiple of the second row of A is added to the first row.

Determinants of Elementary Matrices

Let E be an $n \times n$ elementary matrix.

(a) *If E results from multiplying a row of I_n by k, then* $\det(E) = k$.

(b) *If E results from interchanging two rows of I_n, then* $\det(E) = -1$.

(c) *If E results from adding a multiple of one row of I_n to another, then* $\det(E) = 1$.

$$\begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} = 3, \qquad \begin{vmatrix} 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{vmatrix} = -1, \qquad \begin{vmatrix} 1 & 0 & 0 & 7 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} = 1$$

The second row of I_4 was multiplied by 3.

The first and last rows of I_4 were interchanged.

7 times the last row of I_4 was added to the first row.

If A is a square matrix with two proportional rows or two proportional columns, then $\det(A) = 0$.

The following computation illustrates the introduction of a row of zeros when there are two proportional rows:

$$\begin{vmatrix} 1 & 3 & -2 & 4 \\ 2 & 6 & -4 & 8 \\ 3 & 9 & 1 & 5 \\ 1 & 1 & 4 & 8 \end{vmatrix} = \begin{vmatrix} 1 & 3 & -2 & 4 \\ 0 & 0 & 0 & 0 \\ 3 & 9 & 1 & 5 \\ 1 & 1 & 4 & 8 \end{vmatrix} = 0 \quad \leftarrow$$

The second row is 2 times the first, so we added -2 times the first row to the second to introduce a row of zeros.

Each of the following matrices has two proportional rows or columns; thus, each has a determinant of zero.

$$\begin{bmatrix} -1 & 4 \\ -2 & 8 \end{bmatrix}, \quad \begin{bmatrix} 1 & -2 & 7 \\ -4 & 8 & 5 \\ 2 & -4 & 3 \end{bmatrix}, \quad \begin{bmatrix} 3 & -1 & 4 & -5 \\ 6 & -2 & 5 & 2 \\ 5 & 8 & 1 & 4 \\ -9 & 3 & -12 & 15 \end{bmatrix}$$

Example: Evaluate det(A) by row reduction:

$$A=\begin{bmatrix}0 & 1 & 5\\ 3 & -6 & 9\\ 2 & 6 & 1\end{bmatrix}$$

We will reduce A to row-echelon form (which is upper triangular)

$$\det(A)=\begin{vmatrix}0 & 1 & 5\\ 3 & -6 & 9\\ 2 & 6 & 1\end{vmatrix}=-\begin{vmatrix}3 & -6 & 9\\ 0 & 1 & 5\\ 2 & 6 & 1\end{vmatrix}$$

$\leftarrow$ The first and second rows of A were interchanged.

$$=-3\begin{vmatrix}1 & -2 & 3\\ 0 & 1 & 5\\ 2 & 6 & 1\end{vmatrix}$$

$\leftarrow$ A common factor of 3 from the first row was taken through the determinant sign.

$$=-3\begin{vmatrix}1 & -2 & 3\\ 0 & 1 & 5\\ 0 & 10 & -5\end{vmatrix}$$

$\leftarrow$ -2 times the first row was added to the third row.

$$=-3\begin{vmatrix}1 & -2 & 3\\ 0 & 1 & 5\\ 0 & 0 & -55\end{vmatrix}$$

$\leftarrow$ -10 times the second row was added to the third row.

$$=(-3)(-55)\begin{vmatrix}1 & -2 & 3\\ 0 & 1 & 5\\ 0 & 0 & 1\end{vmatrix}$$

$\leftarrow$ A common factor of -55 from the last row was taken through the determinant sign.

$$=(-3)(-55)(1)=165$$

Using Column Operations to Evaluate a Determinant

Compute the determinant of

$$A = \begin{bmatrix} 1 & 0 & 0 & 3 \\ 2 & 7 & 0 & 6 \\ 0 & 6 & 3 & 0 \\ 7 & 3 & 1 & -5 \end{bmatrix}$$

$$\det(A) = \det \begin{bmatrix} 1 & 0 & 0 & 0 \\ 2 & 7 & 0 & 0 \\ 0 & 6 & 3 & 0 \\ 7 & 3 & 1 & -26 \end{bmatrix} = (1)(7)(3)(-26) = -546$$

Row Operations and Cofactor Expansion

$$A = \begin{bmatrix} 3 & 5 & -2 & 6 \\ 1 & 2 & -1 & 1 \\ 2 & 4 & 1 & 5 \\ 3 & 7 & 5 & 3 \end{bmatrix}$$

By adding suitable multiples of the second row to the remaining rows, we obtain

$$\det(A) = \begin{vmatrix} 0 & -1 & 1 & 3 \\ 1 & 2 & -1 & 1 \\ 0 & 0 & 3 & 3 \\ 0 & 1 & 8 & 0 \end{vmatrix}$$

$$= -\begin{vmatrix} -1 & 1 & 3 \\ 0 & 3 & 3 \\ 1 & 8 & 0 \end{vmatrix} \quad \leftarrow \text{Cofactor expansion along the first column}$$

$$= -\begin{vmatrix} -1 & 1 & 3 \\ 0 & 3 & 3 \\ 0 & 9 & 3 \end{vmatrix} \quad \leftarrow \text{We added the first row to the third row.}$$

$$= -(-1)\begin{vmatrix} 3 & 3 \\ 9 & 3 \end{vmatrix} \quad \leftarrow \text{Cofactor expansion along the first column}$$

$$= -18$$

Properties of Determinant Function

$\det(kA) = k^n \det(A)$

$$\begin{vmatrix} ka_{11} & ka_{12} & ka_{13} \\ ka_{21} & ka_{22} & ka_{23} \\ ka_{31} & ka_{32} & ka_{33} \end{vmatrix} = k^3 \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}$$

$\det(A+B) \neq \det(A) + \det(B)$

Consider

$$A = \begin{bmatrix} 1 & 2 \\ 2 & 5 \end{bmatrix}, \quad B = \begin{bmatrix} 3 & 1 \\ 1 & 3 \end{bmatrix}, \quad A+B = \begin{bmatrix} 4 & 3 \\ 3 & 8 \end{bmatrix}$$

We have $\det(A) = 1$, $\det(B) = 8$, and $\det(A+B) = 23$; thus

$$\det(A+B) \neq \det(A) + \det(B)$$

Let A, B, and C be $n \times n$ matrices that differ only in a single row, say the rth, and assume that the rth row of C can be obtained by adding corresponding entries in the rth rows of A and B. Then

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

The same result holds for columns.

$$\det\begin{bmatrix} 1 & 7 & 5 \\ 2 & 0 & 3 \\ 1+0 & 4+1 & 7+(-1) \end{bmatrix} = \det\begin{bmatrix} 1 & 7 & 5 \\ 2 & 0 & 3 \\ 1 & 4 & 7 \end{bmatrix} + \det\begin{bmatrix} 1 & 7 & 5 \\ 2 & 0 & 3 \\ 0 & 1 & -1 \end{bmatrix}$$

Determinant of a Matrix Product

$$\det(AB) = \det(A)\,\det(B)$$

$$A = \begin{bmatrix} 3 & 1 \\ 2 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} -1 & 3 \\ 5 & 8 \end{bmatrix}, \quad AB = \begin{bmatrix} 2 & 17 \\ 3 & 14 \end{bmatrix}$$

$$\det(A) = 1, \quad \det(B) = -23, \quad \text{and} \quad \det(AB) = -23$$

If B is an $n \times n$ *matrix and* E *is an* $n \times n$ *elementary matrix, then*

$$\det(EB) = \det(E)\,\det(B)$$

Determinant Test for Invertibility

A square matrix A is invertible if and only if $\det(A) \neq 0$.

Since the first and third rows of

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

are proportional, $\det(A) = 0$. Thus A is not invertible.

If A is invertible, then

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

Linear Systems of the form $Ax=\lambda x$

$$\lambda \mathbf{x} - A\mathbf{x} = \mathbf{0}$$

$$(\lambda I - A)\mathbf{x} = \mathbf{0}$$

$$x_1 + 3x_2 = \lambda x_1$$
$$4x_1 + 2x_2 = \lambda x_2$$

$$\begin{bmatrix} 1 & 3 \\ 4 & 2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \lambda \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$A = \begin{bmatrix} 1 & 3 \\ 4 & 2 \end{bmatrix} \quad \text{and} \quad \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

This system can be rewritten as

$$\lambda \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} - \begin{bmatrix} 1 & 3 \\ 4 & 2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

or

$$\lambda \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} - \begin{bmatrix} 1 & 3 \\ 4 & 2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

or

$$\begin{bmatrix} \lambda - 1 & -3 \\ -4 & \lambda - 2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\lambda I - A = \begin{bmatrix} \lambda - 1 & -3 \\ -4 & \lambda - 2 \end{bmatrix}$$

λ is called the characteristic value or the eigenvalue of A. Then the solutions are called eigenvector of A corresponding λ.

the system $(\lambda I - A)\mathbf{x} = \mathbf{0}$ has a nontrivial solution if and only if

$$\det(\lambda I - A) = 0$$

This is called the characteristic equation

Find the eigenvalues and corresponding eigenvectors of the matrix A

The characteristic equation of A is

$$\det(\lambda I - A) = \begin{vmatrix} \lambda - 1 & -3 \\ -4 & \lambda - 2 \end{vmatrix} = 0 \quad \text{or} \quad \lambda^2 - 3\lambda - 10 = 0$$

The factored form of this equation is $(\lambda + 2)(\lambda - 5) = 0$, so the eigenvalues of A are $\lambda = -2$ and $\lambda = 5$.

$$(\lambda I - A)\mathbf{x} = \mathbf{0};$$

$$\begin{bmatrix} \lambda - 1 & -3 \\ -4 & \lambda - 2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

If $\lambda - 2$, then 9 becomes

$$\begin{bmatrix} -3 & -3 \\ -4 & -4 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Solving this system yields (verify) $x_1 = -t, x_2 = t$, so the eigenvectors corresponding to $\lambda = -2$ are the nonzero solutions of the form

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} -t \\ t \end{bmatrix}$$

Equivalent Statements

If A is an $n \times n$ matrix, then the following statements are equivalent.

(a) *A is invertible.*

(b) $A\mathbf{x} = \mathbf{0}$ *has only the trivial solution.*

(c) *The reduced row-echelon form of A is* I_n.

(d) *A can be expressed as a product of elementary matrices.*

(e) $A\mathbf{x} = \mathbf{b}$ *is consistent for every* $n \times 1$ *matrix* b.

(f) $A\mathbf{x} = \mathbf{b}$ *has exactly one solution for every* $n \times 1$ *matrix* $\mathbf{b}$.

(g) $\det(A) \neq 0$.

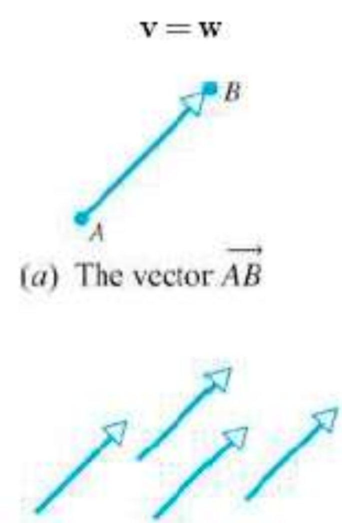
Vectors in 2-Space and 3-Space

- Many physical quantities, such as area, length, mass, and temperature, are completely described once the magnitude of the quantity is given. Such quantities are called scalars.
- Other physical quantities are not completely determined until both a magnitude and a direction are specified. These quantities are called vectors.
  - For example, wind movement is usually described by giving the speed and direction, say 20 mph northeast.
  - The wind speed and wind direction form a vector called the wind velocity.
  - Other examples of vectors are force and displacement.

Introduction to Vectors

- Directed line segments or arrows in 2-Space or 3-Space.
  - Direction of the arrow: Direction of the vector
  - Length of the arrow: Magnitude of the vector
  - The tail: Initial point
  - The tip: Terminal Point

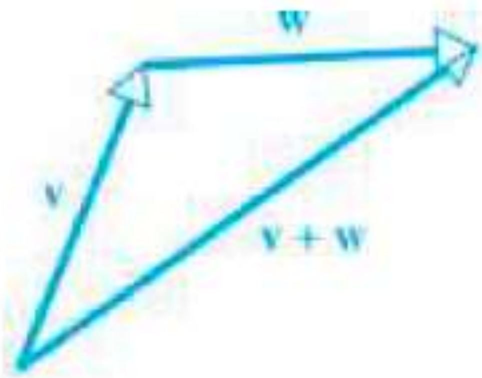
$$\mathbf{v} = \overrightarrow{AB}$$



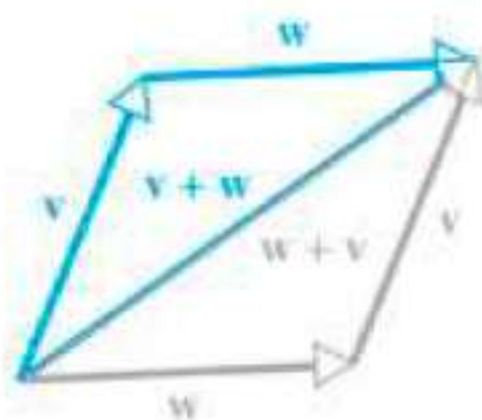
(b) Equivalent vectors

The Sum of Vectors

- v+w



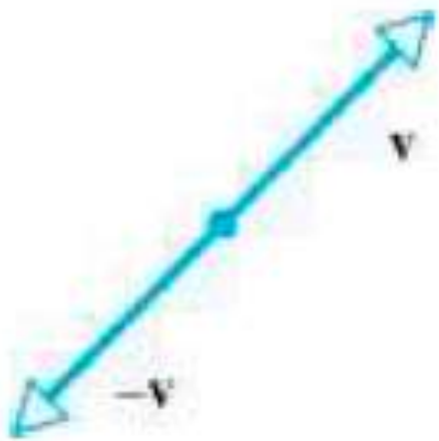
(*a*) The sum **v** + **w**



(*b*) **v** + **w** = **w** + **v**

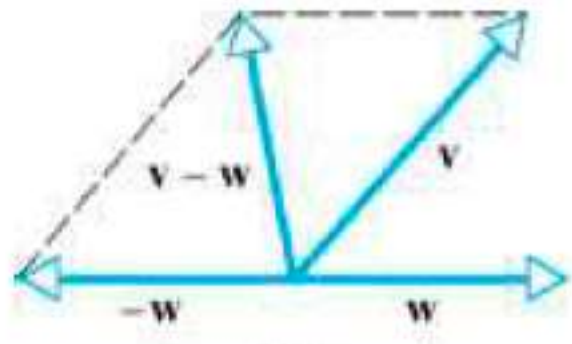
Zero Vector

- 0+v= v+0=v
- v+ (-v)=0

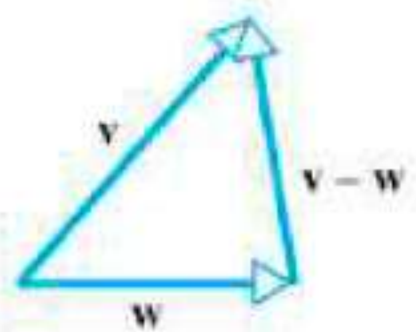


Difference

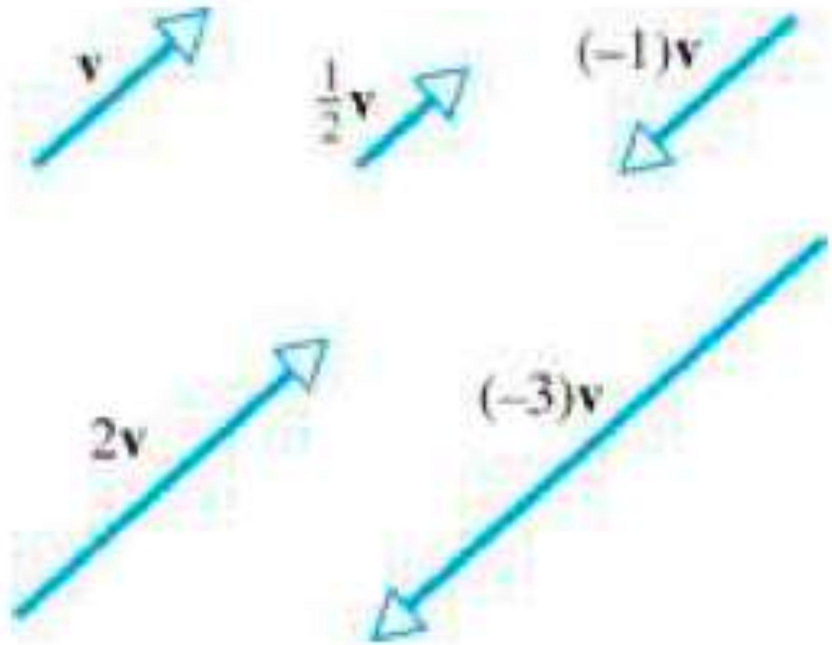
- v-w=v+(-w)



(a)



(b)

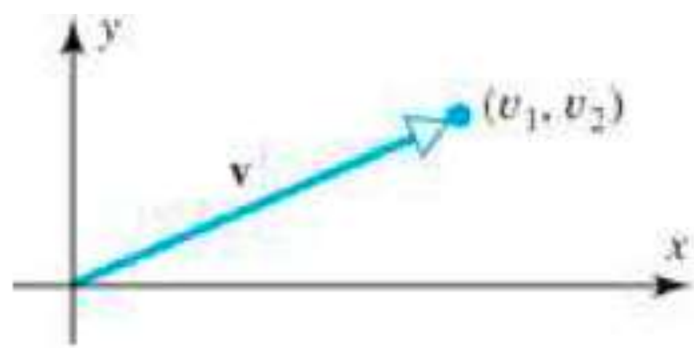


v
$\frac{1}{2}$v
(−1)v
2v
(−3)v

Vectors in Coordinate Systems

- The coordinates (v1,v2) of the terminal point of v are called the components of v

v= (v1,v2)

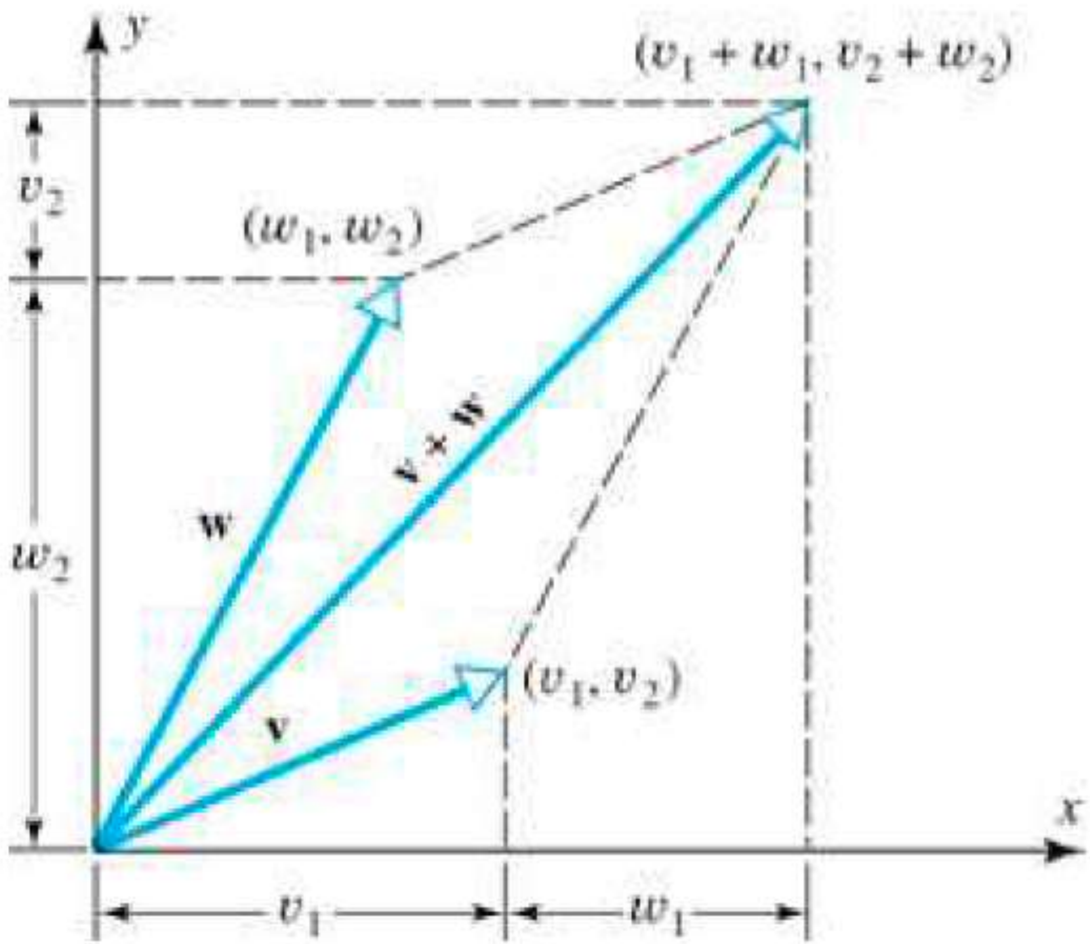


$$\mathbf{v} = (v_1, v_2) \qquad \text{and} \qquad \mathbf{w} = (w_1, w_2)$$

are equivalent if and only if

$$v_1 = w_1 \qquad \text{and} \qquad v_2 = w_2$$

$$\mathbf{v} + \mathbf{w} = (v_1 + w_1, v_2 + w_2)$$



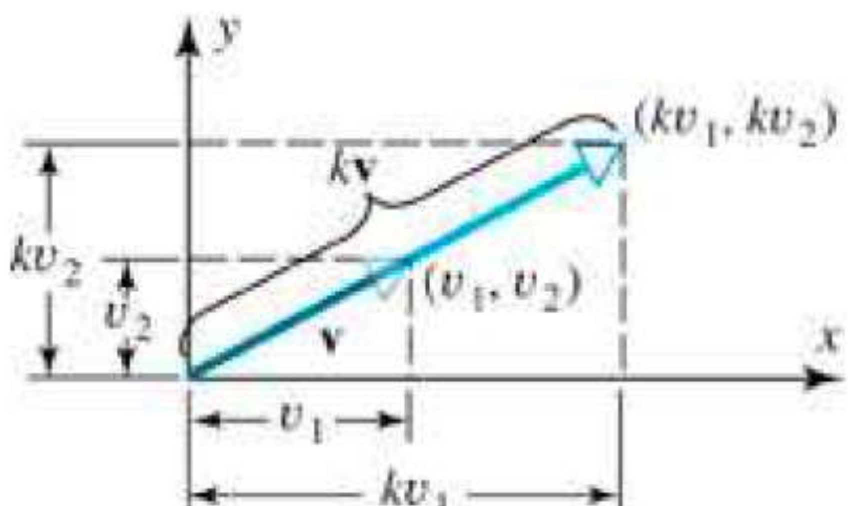
$$k\mathbf{v} = (kv_1, kv_2)$$

if $\mathbf{v} = (1, -2)$ and $\mathbf{w} = (7, 6)$, then

$$\mathbf{v} + \mathbf{w} = (1, -2) + (7, 6) = (1 + 7, -2 + 6) = (8, 4)$$

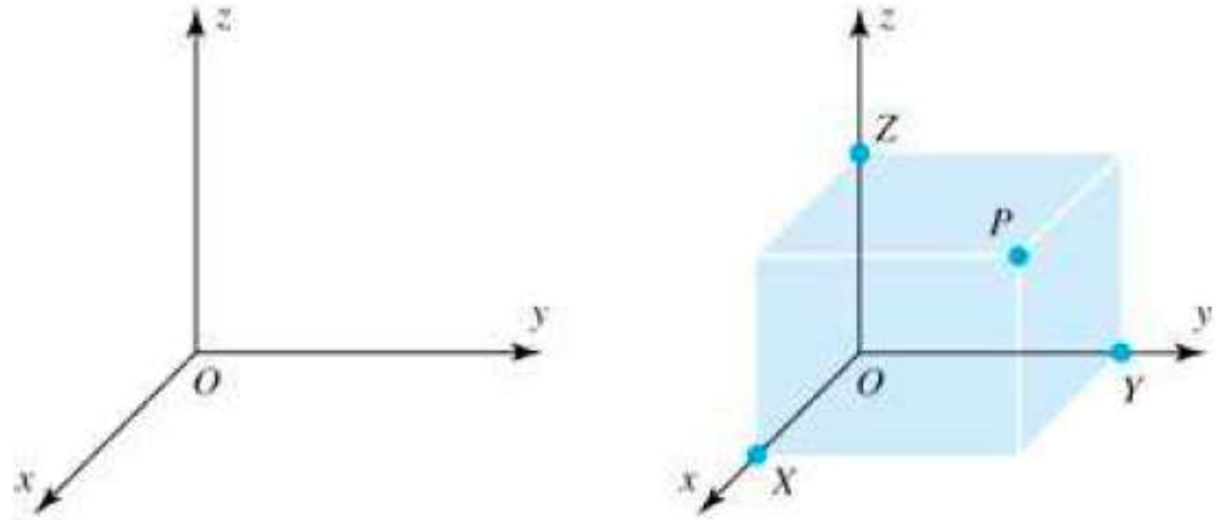
$$4\mathbf{v} = 4(1, -2) = (4(1), 4(-2)) = (4, -8)$$

$$\mathbf{v} - \mathbf{w} = (v_1 - w_1, v_2 - w_2)$$



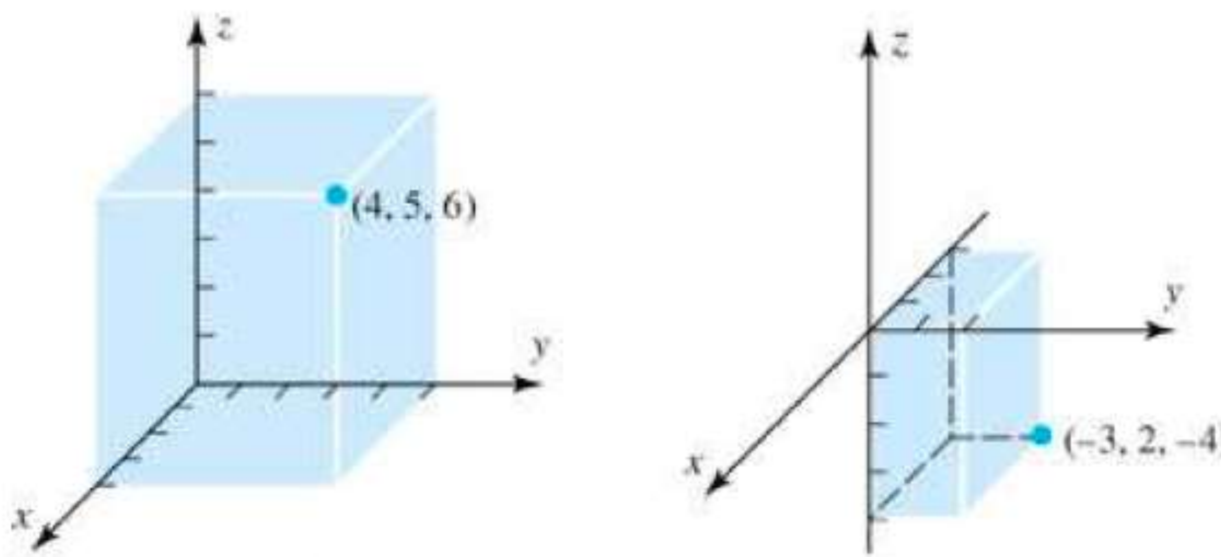
Vectors in 3-Space

- Can be represented by triples of real numbers by introducing a rectangular coordinate system.
- Axes and coordinate planes
- xy-plane
- xz-plane
- yz-plane



(a) (b)

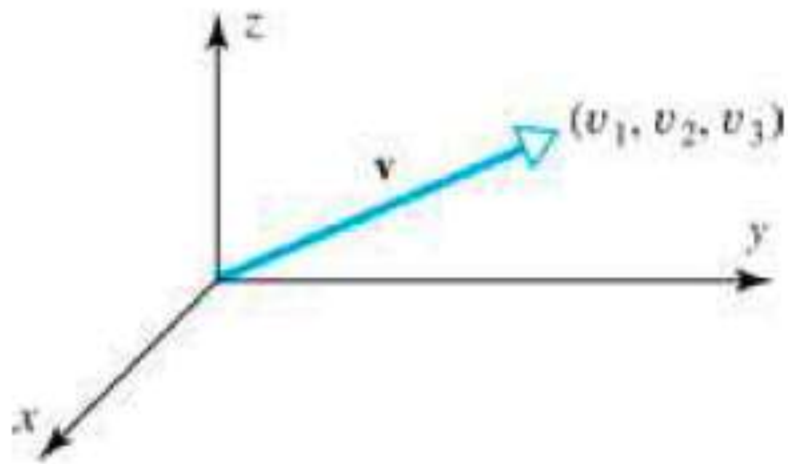
Figure 3.1.9



(a) (b)

components

$$\mathbf{v} = (v_1, v_2, v_3)$$



v and w are equivalent if and only if $v_1 = w_1$, $v_2 = w_2$, *and* $v_3 = w_3$

$\mathbf{v} + \mathbf{w} = (v_1 + w_1, v_2 + w_2, v_3 + w_3)$

$k\mathbf{v} = (kv_1, kv_2, kv_3)$, *where k is any scalar*

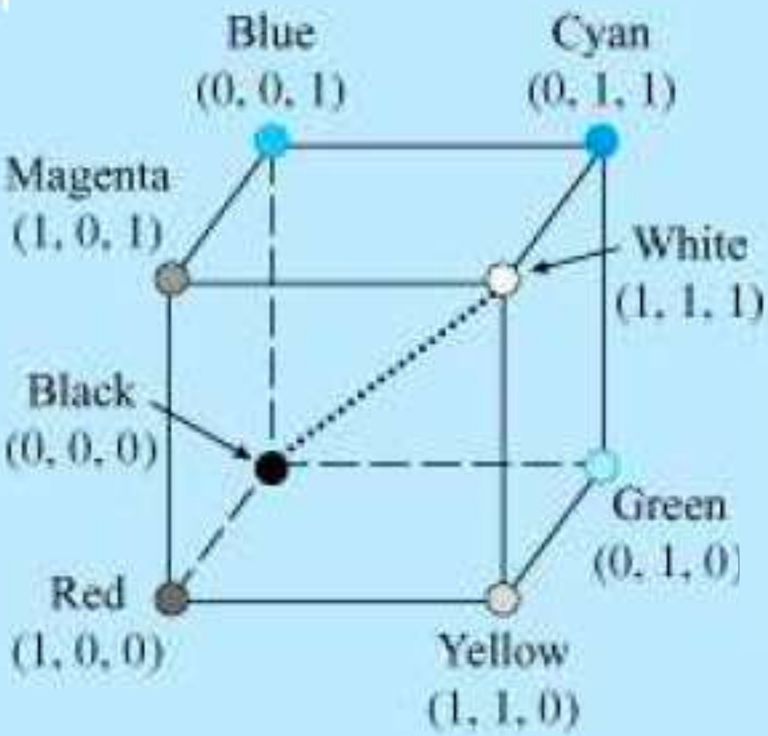
$\mathbf{v} = (1, -3, 2)$ and $\mathbf{w} = (4, 2, 1)$, then

$$\mathbf{v} + \mathbf{w} = (5, -1, 3), \qquad 2\mathbf{v} = (2, -6, 4), \qquad -\mathbf{w} = (-4, -2, -1),$$

$$\mathbf{v} - \mathbf{w} = \mathbf{v} + (-\mathbf{w}) = (-3, -5, 1)$$

Application to Computer Color Models (RGB)

- Red, Green and Blue



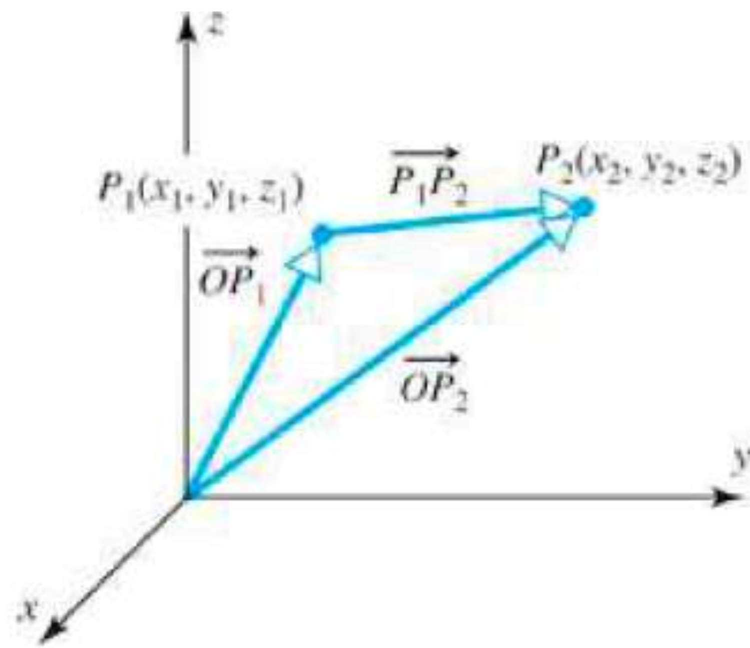
$$\mathbf{r} = (1, 0, 0) \quad \text{(pure red)},$$
$$\mathbf{g} = (0, 1, 0) \quad \text{(pure green)},$$
$$\mathbf{b} = (0, 0, 1) \quad \text{(pure blue)}$$

$$\begin{aligned} \mathbf{c} &= c_1\mathbf{r} + c_2\mathbf{g} + c_3\mathbf{b} \\ &= c_1(1, 0, 0) + c_2(0, 1, 0) + c_3(0, 0, 1) \\ &= (c_1, c_2, c_3) \end{aligned}$$

$$0 \le c_i \le 1$$

Sometimes a vector is positioned so that its initial point is not at the origin. If the vector $\overrightarrow{P_1P_2}$ has initial point $P_1(x_1, y_1, z_1)$ and terminal point $P_2(x_2, y_2, z_2)$, then

$$\overrightarrow{P_1P_2} = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$$



The vector $\overrightarrow{P_1P_2}$ is the difference of vectors $\overrightarrow{OP_2}$ and $\overrightarrow{OP_1}$, so

$$\overrightarrow{P_1P_2} = \overrightarrow{O}P_2 - \overrightarrow{O}P_1 = (x_2, y_2, z_2) - (x_1, y_1, z_1) = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$$

Finding the Components of a Vector

The components of the vector $\mathbf{v} = \overrightarrow{P_1P_2}$ with initial point $P_1(2, -1, 4)$ and terminal point $P_2(7, 5, -8)$ are

$$\mathbf{v} = (7-2, 5-(-1), (-8)-4) = (5, 6, -12)$$

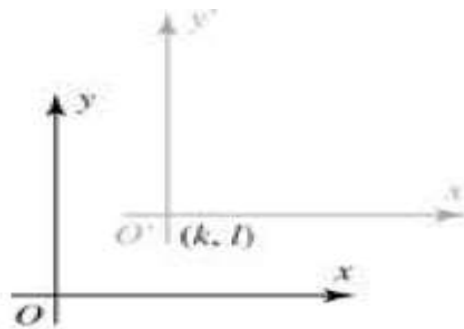
In 2-space the vector with initial point $P_1(x_1, y_1)$ and terminal point $P_2(x_2, y_2)$ is

$$\overrightarrow{P_1P_2} = (x_2 - x_1, y_2 - y_1)$$

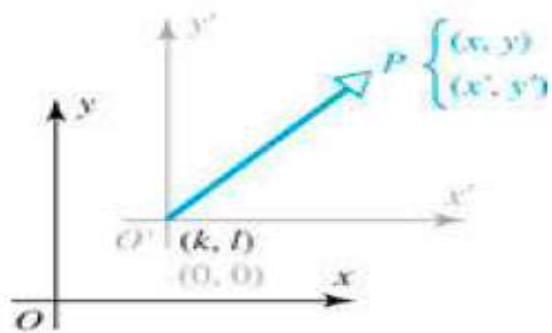
Translation of Axes

New axes parallel to the original ones.

$$x' = x - k, \qquad y' = y - 1$$



(a)



(b)

Using the Translation Equations

Suppose that an xy-coordinate system is translated to obtain an $x'y'$-coordinate system whose origin has xy-coordinates $(k, l) = (4, 1)$.

(a) Find the $x'y'$-coordinates of the point with the xy-coordinates $P(2, 0)$.

(b) Find the xy-coordinates of the point with $x'y'$-coordinates $Q(-1, 5)$.

Solution (a)

The translation equations are

$$x' = x - 4, \qquad y' = y - 1$$

so the $x'y'$-coordinates of $P(2, 0)$ are $x' = 2 - 4 = -2$ and $y' = 0 - 1 = -1$.

Solution (b)

The translation equations in (a) can be rewritten as

$$x = x' + 4, \qquad y = y' + 1$$

so the xy-coordinates of Q are $x = -1 + 4 = 3$ and $y = 5 + 1 = 6$.

In 3-space the translation equations are

$$x' = x - k, \qquad y' = y - l, \qquad z' = z - m$$

Vector Arithmetic

*If **u**, **v**, and **w** are vectors in 2- or 3-space and k and l are scalars, then the following relationships hold.*

(a) $\mathbf{u}+\mathbf{v}=\mathbf{v}+\mathbf{u}$

(b) $(\mathbf{u}+\mathbf{v})+\mathbf{w}=\mathbf{u}+(\mathbf{v}+\mathbf{w})$

(c) $\mathbf{u}+\mathbf{0}=\mathbf{0}+\mathbf{u}=\mathbf{u}$

(d) $\mathbf{u}+(-\mathbf{u})=\mathbf{0}$

(e) $k(l\mathbf{u})=(kl)\mathbf{u}$

(f) $k(\mathbf{u}+\mathbf{v})=k\mathbf{u}+k\mathbf{v}$

(g) $(k+l)\mathbf{u}=k\mathbf{u}+l\mathbf{u}$

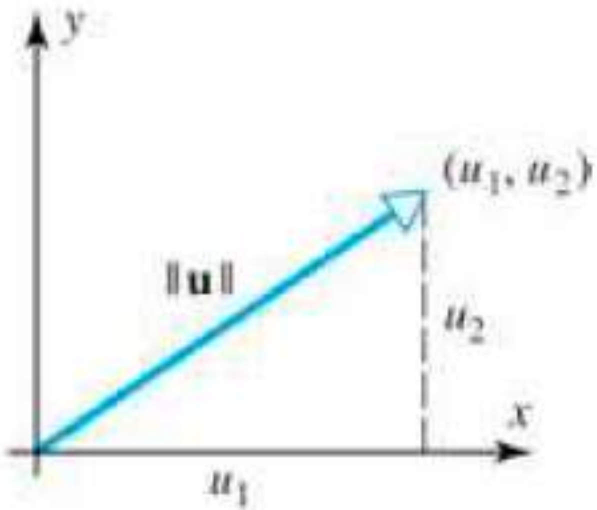
(h) $l\mathbf{u}=\mathbf{u}$

Proof of (b)

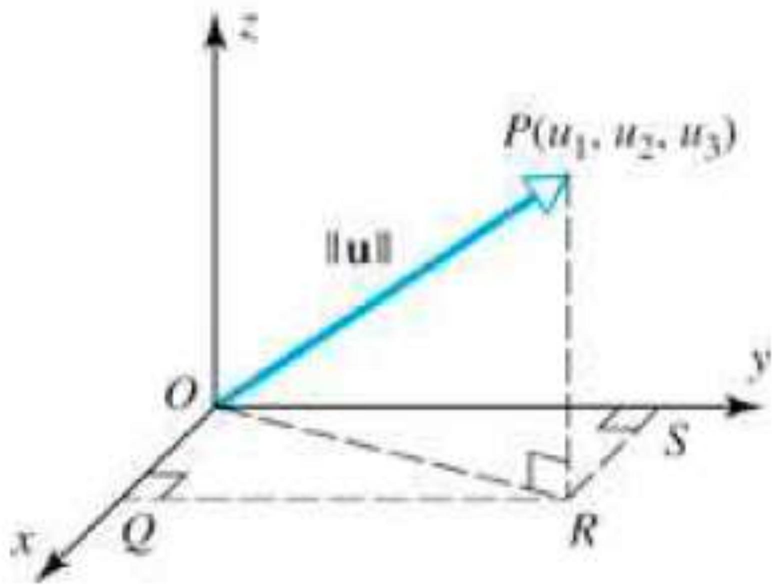
- U=(u1,u2,u3)
- V=(v1,v2,v3)
- W=(w1,w2,w3)

$$
\begin{aligned}
(\mathbf{u}+\mathbf{v})+\mathbf{w} &= [(u_1, u_2, u_3)+(v_1, v_2, v_3)]+(w_1, w_2, w_3) \\
&= (u_1+v_1, u_2+v_2, u_3, \ +v_3)+(w_1, w_2, w_3) \\
&= ([u_1+v_1]+w_1, [u_2+v_2]+w_2, [u_3+v_3]+w_3) \\
&= (u_1+[v_1+w_1], u_2+[v_2+w_2], u_3+[v_3+w_3]) \\
&= (u_1, u_2, u_3)+(v_1+w_1, v_2+w_2, v_3+w_3) \\
&= \mathbf{u}+(\mathbf{v}+\mathbf{w})
\end{aligned}
$$

Norm of a vector (length of a vector)



$$\|\mathbf{u}\| = \sqrt{u_1^2 + u_2^2}$$



$$\|\mathbf{u}\| = \sqrt{u_1^2 + u_2^2 + u_3^2}$$

$$d = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}$$

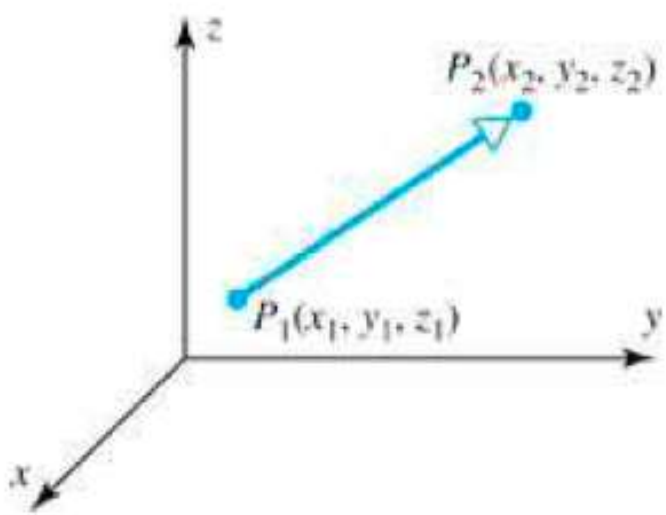
$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = 0.22(t - t_0)^2$$

If $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ are two points in 3-space, then the ***distance*** d between them is the norm of the vector $\overrightarrow{P_1P_2}$ (Figure 3.2.3). Since

$$\overrightarrow{P_1P_2} = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$$

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

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$



Finding norm and Distance

The norm of the vector $\mathbf{u} = (-3, 2, 1)$ is

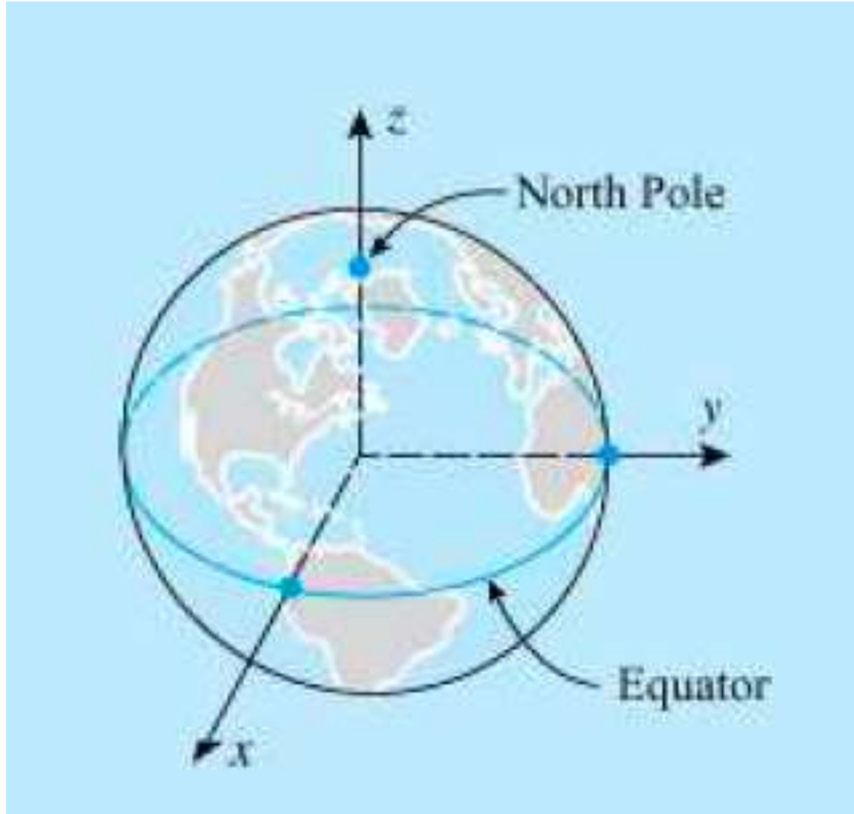
$$\|\mathbf{u}\| = \sqrt{(-3)^2 + (2)^2 + (1)^2} = \sqrt{14}$$

The distance d between the points $P_1(2, -1, -5)$ and $P_2(4, -3, 1)$ is

$$d = \sqrt{(4-2)^2 + (-3+1)^2 + (1+5)^2} = \sqrt{44} = 2\sqrt{11}$$

GPS..

- Global Positioning System (GPS) is used by military, ships, airplane pilot, automobiles.. To locate the current positions by communicating with the system of satellites.
- 24 Satellites which orbit the Earth every 12 hours at a height of 11k miles. These move in 6 orbital planes that have been chosen to make 5 and 8 satellites visible anywhere in earth.



Triangulation!!

Distance traveled by the signal $d = 0.469(t - t_0)$