Unit-4: 3D Transformation

Overview

3D computer graphics or three dimensional computer graphics are graphics that use a three-dimensional representation of geometric data that is stored in the computer for the purpose of performing calculations and rendering 2D images.

2D is "flat" using the horizontal and vertical (X & Y) dimensions, the image has only two dimensions. 3D adds the depth (Z) dimension. This third dimension allows for rotation and visualization from multiple perspectives.

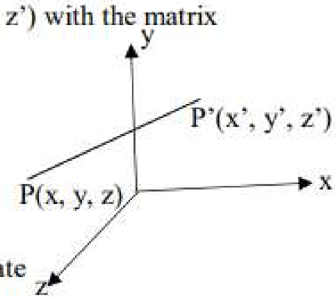
We can perform different transformation by specifying the three dimensional transformation vector, however the 3D transformation is more complex than 2D transformation.

➢ 3D Geometric Transformation

▪ 3D Translation

A point is translated from position P(x, y, z) to position P'(x', y', z') with the matrix operation as:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$



Parameter t_x, t_y, t_z specify transition distances for the coordinate directions x, y, z. This matrix representation is equivalent to three equations:

$x' = x + t_x$

$y' = y + t_y$

$z' = z + t_z$

▪ 3D Rotation

Rotation about Z-axis

$x' = x\cos\theta - y\sin\theta$

$y' = x\sin\theta + y\cos\theta$

$z' = z$

$$R_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

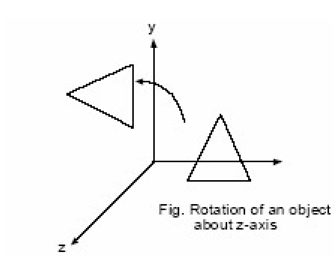


Fig. Rotation of an object about z-axis

Rotation about x-axis

$x' = x$

$y' = ycos\theta - zsin\theta$

$z' = ysin\theta + zcos\theta$

$$\therefore R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

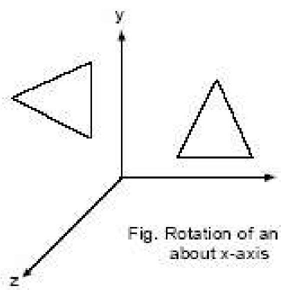


Fig. Rotation of an object about x-axis

Rotation about y-axis

$y' = y$

$z' = zcos\theta - xsin\theta$

$x' = zsin\theta + xcos\theta$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} cos\theta & 0 & sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -sin\theta & 0 & cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

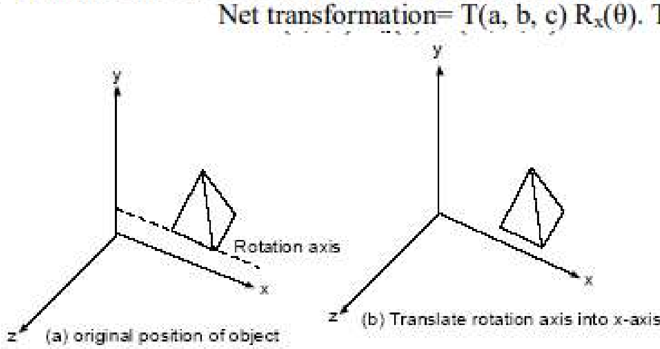
#General 3D rotation (Rotation about any coordinate axis)

➢ ***Parallel to any of the co-axis:***

When an object is to be rotated about an axis that is parallel to one of the co-ordinate axis, we need to perform some series of transformation.

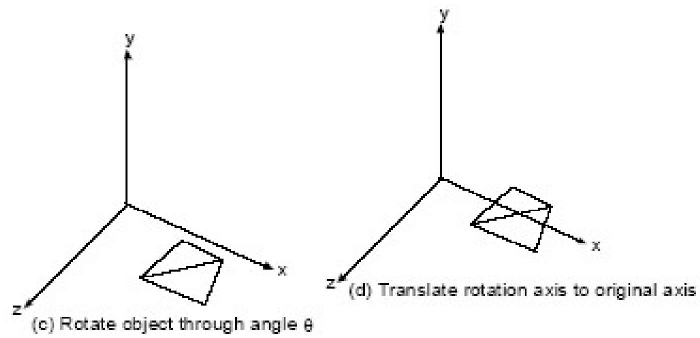
1. Translate the object so that the rotation axis coincides with the parallel co-ordinate axis. T(-a,-b,-c) where, (a, b, c) is any point on the rotation axis.
2. Performed the specified rotation about the axis. $R_x(\theta)$
3. Translate the object so that the rotation axis is moved to its original position. T(a, b, c).

Net transformation= T(a, b, c) $R_x(\theta)$. T(-a,-b,-c)



(a) original position of object

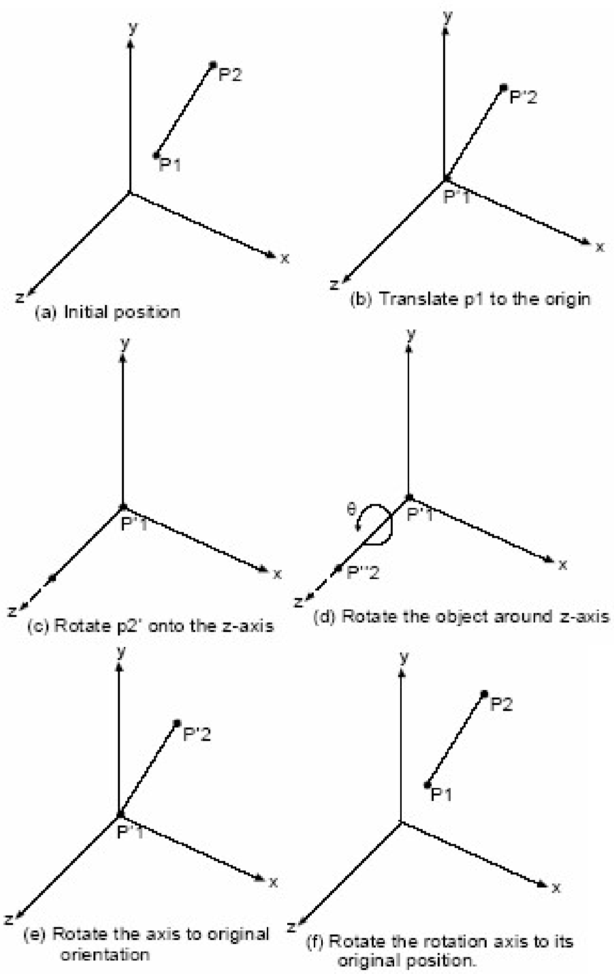
(b) Translate rotation axis into x-axis



- ***Not parallel to any of the co-axis:***

When an object is to be rotated about an axis that is not parallel to one of the co-ordinate axes, we need to perform some series of transformation.

1. Translate the object such that rotation axis passes through co-ordinate origin.
2. Rotate the object such that axis of rotation coincides with one of the co-ordinate axis.
3. Perform the specific rotation about selected coordinate axis.
4. Apply inverse rotation to bring the rotation axis back to its original orientation.
5. Apply inverse translation to bring the rotation axis back to its original position.



1) Translate P1 to origin

$$T(-x_1,-y_1,-z_1) = \begin{bmatrix} 1 & 0 & 0 & -x_1 \\ 0 & 1 & 0 & -y_1 \\ 0 & 0 & 1 & -z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

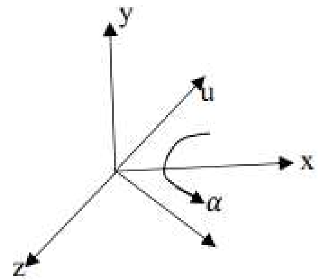
2) Find transformation that will bring rotation axis P1P2 on z-axis. This will be accomplished in two steps:

a) Rotation by angle α about x axis that bring vector $\vec{u}$ into x-z plane, where,

$$\vec{v} = \vec{p_2} - \vec{p_1} = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$$

Unit vector along $\vec{v}$, $\vec{u} = \frac{\vec{v}}{|\vec{v}|} = (a, b, c)$ where,

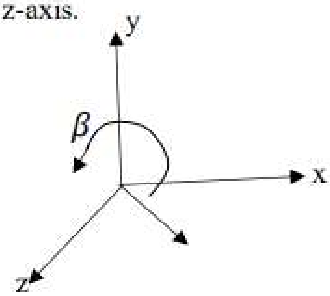
$a = \frac{x_2 - x_1}{|\vec{v}|}, b = \frac{y_2 - y_1}{|\vec{v}|}, c = \frac{z_2 - z_1}{|\vec{v}|}$



$$\therefore R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c/d & -b/d & 0 \\ 0 & b/d & c/d & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where, $d = \sqrt{b^2 + c^2}$

b) Rotate by angle β about y axis that brings $\vec{u}$ on z-axis.



$$R_y(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} d & 0 & -a & 0 \\ 0 & 1 & 0 & 0 \\ a & 0 & d & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

3) Rotation about z-axis.

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4) Find the $R_y^{-1}(\beta)$, $R_x^{-1}(\alpha)$, T^{-1}i.e. $T(x_1, y_1, z_1)$.

5) Find composite transformation for general rotation by 'θ' (anticlockwise).

$$M = T(x_1, y_1, z_1).R_x^{-1}(\alpha).R_y^{-1}(\beta).R_z(\theta).R_y(\beta).R_x(\alpha).T(-x_1, -y_1, -z_1)$$

Q. Find the new co-ordinates of a unit cube 90 degree rotated about an axis defined by its end points A(2, 1, 0) and B(3, 3, 1).

Solution:

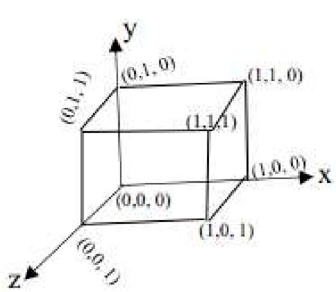


Fig: unit cube

Now,
Translating the point (A) to the origin,

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

Now, rotate the $A'B'$ about x-axis by angle α until vector $\vec{u}$ lies on xz-plane. Where,
$\vec{v} = \vec{B} - \vec{A}$ =(3, 3, 1)-(2, 1, 0)=(1, 2, 1)

Unit vector along $\vec{v}$, $\vec{u} = \frac{\vec{v}}{|\vec{v}|} = \frac{(1,\ 2,\ 1)}{\sqrt{6}} = (\frac{1}{\sqrt{6}}, \frac{2}{\sqrt{6}}, \frac{1}{\sqrt{6}})$ = (a, b, c) (say)

And, $d = \sqrt{b^2 + c^2} = \sqrt{\frac{5}{6}}$

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha & 0 \\ 0 & sin\alpha & cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c/d & -b/d & 0 \\ 0 & b/d & c/d & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/\sqrt{5} & -2/\sqrt{5} & 0 \\ 0 & 2/\sqrt{5} & 1/\sqrt{5} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Again, rotating $A'B'$ about y-axis by angle β until it coincides with z-axis.

$$R_y(\beta) = \begin{bmatrix} cos\beta & 0 & sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta & 0 & cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} d & 0 & -a & 0 \\ 0 & 1 & 0 & 0 \\ a & 0 & d & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \sqrt{5/6} & 0 & -1/\sqrt{6} & 0 \\ 0 & 1 & 0 & 0 \\ 1/\sqrt{6} & 0 & \sqrt{5/6} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotating the unit cube 90 degree about z-axis.

$$R_z(90^0) = \begin{bmatrix} cos90^0 & -sin90^0 & 0 & 0 \\ sin90^0 & cos90^0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The combined transformation rotation matrix about the arbitrary axis becomes,
$R(\theta) = T^{-1}R_x^{-1}(\alpha).R_y^{-1}(\beta).R_z(90^0).R_y(\beta).R_x(\alpha).T$

$$R(\theta) = \begin{bmatrix} 1 & 0 & 0 & 2 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/\sqrt{5} & 2/\sqrt{5} & 0 \\ 0 & -2/\sqrt{5} & 1/\sqrt{5} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{5/6} & 0 & 1/\sqrt{6} & 0 \\ 0 & 1 & 0 & 0 \\ -1/\sqrt{6} & 0 & \sqrt{5/6} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \sqrt{5/6} & 0 & -1/\sqrt{6} & 0 \\ 0 & 1 & 0 & 0 \\ 1/\sqrt{6} & 0 & \sqrt{5/6} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/\sqrt{5} & -2/\sqrt{5} & 0 \\ 0 & 2/\sqrt{5} & 1/\sqrt{5} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -2 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\therefore R(\theta) = \begin{bmatrix} 0.116 & -0.075 & 0.983 & 1.742 \\ 0.742 & 0.667 & 0.075 & -1.151 \\ -0.650 & 0.741 & 0.167 & 0.560 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Now, multiplying $R(\theta)$ by the matrix of original unit cube;
$P' = R(\theta).P$

$$P' = \begin{bmatrix} 0.116 & -0.075 & 0.983 & 1.742 \\ 0.742 & 0.667 & 0.075 & -1.151 \\ -0.650 & 0.741 & 0.167 & 0.560 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

$$P' = \begin{bmatrix} 2.650 & 1.667 & 1.834 & 2.816 & 2.7525 & 1.742 & 1.909 & 2.891 \\ -0.558 & -0.484 & 0.258 & 0.184 & -1.225 & -1.152 & -0.409 & -0.483 \\ 1.467 & 1.301 & 0.650 & 0.817 & 0.726 & 0.566 & -0.091 & 0.076 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

- **3D Scaling**

Matrix representation for scaling transformation of a position $P = (x, y, z)$ relative to the coordinate origin can be written as;

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

→For scaling of point P(x, y, z) w.r.t to fixed point (x_f, y_f, z_f) can be represented with the following transformation.

1. Translate the fixed point to the origin. $T(-x_f, -y_f, -z_f)$
2. Apply scaling w.r.to origin. $S(s_x, s_y, s_z)$
3. Translate the fixed point back to its original position. $T(x_f, y_f, z_f)$

$$= \begin{bmatrix} 1 & 0 & 0 & x_f \\ 0 & 1 & 0 & y_f \\ 0 & 0 & 1 & z_f \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -x_f \\ 0 & 1 & 0 & -y_f \\ 0 & 0 & 1 & -z_f \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} s_x & 0 & 0 & (1-s_x)x_f \\ 0 & s_y & 0 & (1-s_y)y_f \\ 0 & 0 & s_z & (1-s_z)z_f \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- **3D Reflection**

In 3D-reflection the reflection takes place about a plane.

(a) About xy-plane (z-axis)

This transformation changes the sign of the z coordinates, leaving the x and y coordinate values unchanged.

$$R_{fxy} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(b) About xz-plane (y-axis)

This transformation changes the sign of the y coordinates, leaving the x and z coordinate values unchanged.

$$R_{fxz} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(c) About yz-plane (x-axis)

This transformation changes the sign of the x coordinates, leaving the y and z coordinate values unchanged.

$$R_{fyz} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- **3D Shearing**

Shearing transformations are used to modify objects shape.

(a) Z-axis shearing

This transformation alters x and y coordinates values by amount that is proportional to the z values while leaving z coordinate unchanged.

$x' = x + s_{hx}z$
$y' = y + s_{hy}z$
$z' = z$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & s_{hx} & 0 \\ 0 & 1 & s_{hy} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

(b) X-axis shearing

This transformation alters y and z coordinates values by amount that is proportional to the x values while leaving x- coordinate unchanged.

$x' = x$
$y' = y + s_{hy}x$
$z' = z + s_{hz}x$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ s_{hy} & 1 & 0 & 0 \\ s_{hz} & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

(c) Y- axis shearing

This transformation alters x and z coordinates values by amount that is proportional to the y values while leaving y- coordinate unchanged.

$x' = x + s_{hx}y$
$y' = y$
$z' = z + s_{hz}y$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & s_{hx} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & s_{hz} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Q. A homogenous coordinate point P(3, 2, 1) is translated in x, y, z direction by -2, -2 & -2 unit respectively followed by successive rotation of 60^0 about x- axis. Find the final position of homogenous coordinate.

Solution:

Here,
$t_x = -2$
$t_y = -2$
$t_z = -2$

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

$$R_x(60^0) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos60 & -sin60 & 0 \\ 0 & sin60 & cos60 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

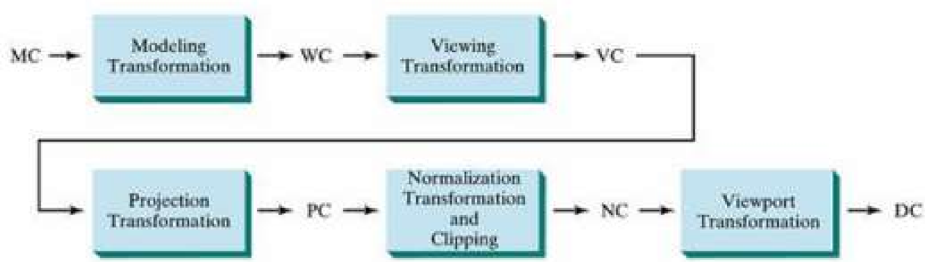
Composite transformation

$$R_x(60^0).T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -2 \\ 0 & 1 & 0 & -2 \\ 0 & 0 & 1 & -2 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & -2 \\ 0 & \frac{1}{2} & -\frac{\sqrt{3}}{2} & -1+\sqrt{3} \\ 0 & \frac{\sqrt{3}}{2} & \frac{1}{2} & -\sqrt{3}-1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Now,

$$P' = M.P = \begin{bmatrix} 1 & 0 & 0 & -2 \\ 0 & \frac{1}{2} & -\frac{\sqrt{3}}{2} & -1+\sqrt{3} \\ 0 & \frac{\sqrt{3}}{2} & \frac{1}{2} & -\sqrt{3}-1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 3 \\ 2 \\ 1 \\ 1 \end{bmatrix} =$$

3D Viewing Pipeline



General three-dimensional transformation pipeline, from modeling coordinates to world coordinates to viewing coordinates to projection coordinates to normalized coordinates and, ultimately, to device coordinates.

Modeling transformation and viewing transformation can be done by 3D transformations. The viewing-coordinate system is used in graphics package as a reference for specifying the observer viewing position and the position of the projection plane. Projection operations convert the viewing-coordinate description (3D) to coordinate position on the projection plane (2D). (Usually combined with clipping, visual-surface identification, and surface rendering). Normalization transformation & clipping and view port transformation maps the coordinate positions on the projection plane to the output device.

❖ Projection

- Projection is any method of mapping three dimensional (3D) objects into two dimensional (2D) view plane (screen). In general, projection transforms a N-dimension points to N-1 dimensions.
- Two types of projection:
  a) Parallel projection:

  In parallel projection, coordinate positions are transformed to view plane along parallel line.

- A parallel projection preserves relative proportion of objects so that accurate views of various sides of an object are obtained but doesn't give realistic representation of the 3D objects.
- Can be used for exact measurement so parallel lines remain parallel.

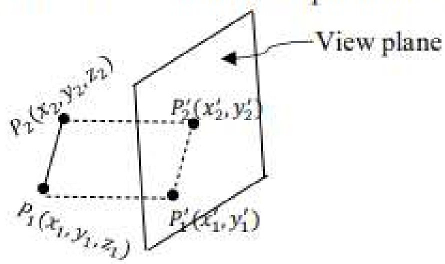


Fig: Parallel projection of an object to the view plane

b) Perspective projection:

In perspective projection, objects positions are transformed to the view plane along lines that converge to point behind view plane.

- A perspective projection produces realistic views but does not preserve relative proportions. Projections of distance objects from view plane are smaller than the projections of objects of the same size that are closer to the projection place.

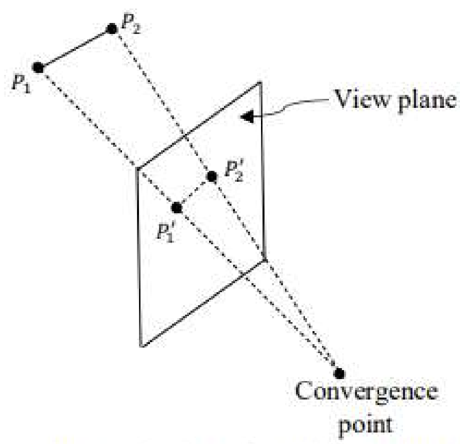


Fig: Perspective projection of an object to the view plane

The World to Screen Transformation

The world-to-screen transformation in 3D computer graphics involves converting 3D coordinates in a virtual world to 2D coordinates on a screen. Here's a breakdown of the steps involved in this transformation:

1. **Modeling and Object Coordinates:**
    - Objects in the 3D world are represented by 3D models, consisting of vertices, edges, and faces.
    - Each vertex of the 3D model has coordinates in its own object coordinate system.
2. **World Coordinates:**
    - Objects in the scene are placed in a global or world coordinate system.

- Transformations such as translation, rotation, and scaling may be applied to move and orient objects within the world.

3. **Viewing Transformation:**
    - The viewing transformation involves setting up a virtual camera or eye within the 3D world.
    - The camera is positioned and oriented to define the viewer's perspective.
    - This transformation moves the entire world to a coordinate system relative to the camera.
4. **Projection Transformation:**
    - Perspective or orthographic projection is applied to convert 3D coordinates to 2D coordinates.
    - Perspective projection simulates how objects appear smaller as they move away from the viewer.
    - Orthographic projection results in a simpler, non-perspective view.
5. **Homogeneous Coordinates:**
    - The resulting 3D coordinates from the projection are often in homogeneous coordinates.
    - Homogeneous coordinates facilitate subsequent transformations and perspective division.
6. **Viewport Transformation:**
    - The 3D coordinates are mapped to the 2D screen space, considering the dimensions of the display (viewport).
    - This involves scaling and translating the coordinates to fit within the screen.
7. **Clipping:**
    - Clipping may be performed to discard any objects or parts of objects that are outside the view frustum (the portion of 3D space visible to the camera).
8. **Rasterization:**
    - The remaining 2D coordinates are then converted into pixels on the screen through a process known as rasterization.
    - This involves determining which pixels are covered by the 2D primitives (points, lines, and triangles) and assigning colors to those pixels.

The combined effect of these transformations is to simulate the perspective and appearance of a 3D scene on a 2D screen. These transformations are often implemented using matrices and are part of the graphics pipeline in computer graphics systems. The resulting 2D image is what the user sees on the display, representing a view of the 3D virtual world.