Computer Graphics

5 - Rendering Pipeline,Viewing & Projection 1

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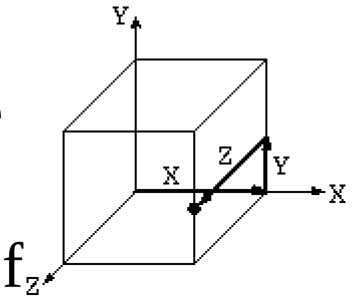
Spring 2021

Topics Covered

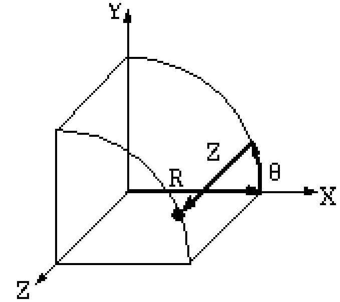
- Coordinate System & Reference Frame
- Rendering Pipeline & Vertex Processing
- Modeling transformation
- Viewing transformation
- Projection Transformation
  - Orthographic (Orthogonal) Projection

Coordinate System & Reference Frame

- Coordinate system
  - A system which uses one or more numbers, or coordinates, to uniquely determine the position of points.

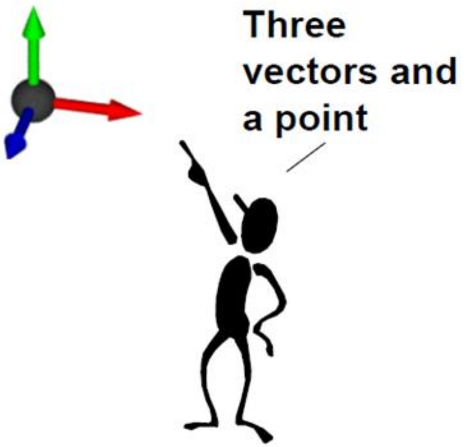


Cartesian (X,Y,Z components) coordinate system 0 (C.S. 0)



Cylindrical (R,q,Z components) coordinate system 1 (C.S. 1)

- Reference frame
  - Abstract coordinate system + physical reference points (to uniquely fix the coordinate system).



Coordinate System & Reference Frame

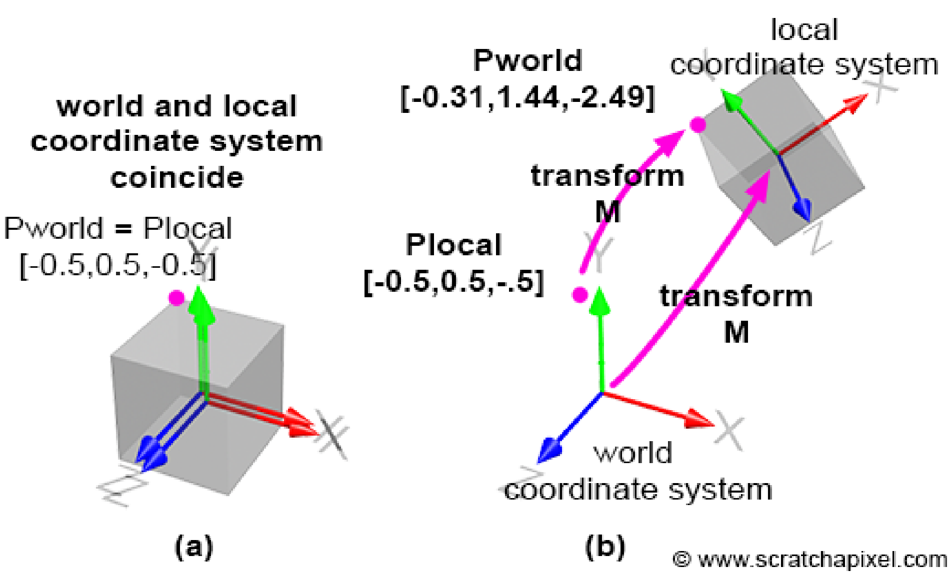
- Two terms are slightly different:
  - **Coordinate system** is a mathematical concept, about a choice of "language" used to describe observations.
  - **Reference frame** is a physical concept related to state of motion.
  - You can think the coordinate system determines the way one describes/observes the motion in each reference frame.

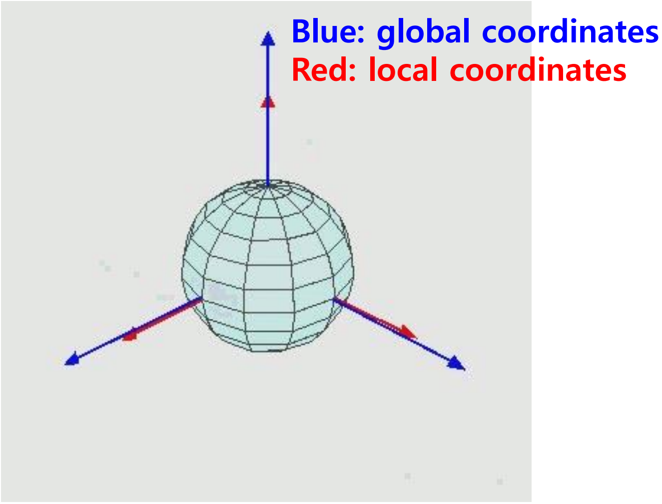
- But these two terms are often mixed.

Global & Local Coordinate System(or Frame)

- **Global coordinate system** (or **Global frame**)
  - A coordinate system(or frame) attached to the **world.**
  - A.k.a. **world** coordinate system, **fixed** coordinate system

- **Local coordinate system** (or **Local frame**)
  - A coordinate system(or frame) attached to a **moving object.**





https://commons.wikimedia.org/wiki/File:Euler2a.gif

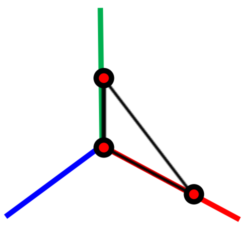
Rendering Pipeline

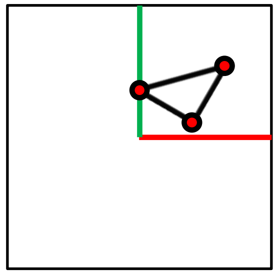
Rendering Pipeline

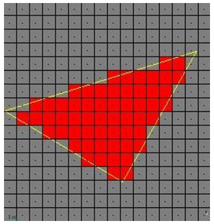
- A conceptual model that describes what steps a graphics system needs to perform to render a 3D scene to a 2D image.

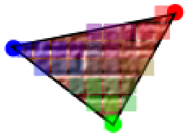
- Also known as **graphics pipeline**.

Rendering Pipeline









vertex processing → **rasterization** → **fragment processing** → output merging

vertex processing

: performs a sequence of vertex transformations

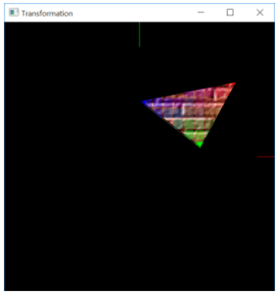
rasterization

: assembles polygons & converts each polygon into a set of fragments (pixels)

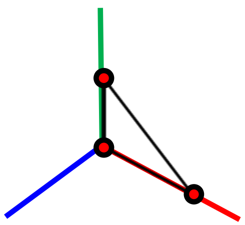
fragment processing

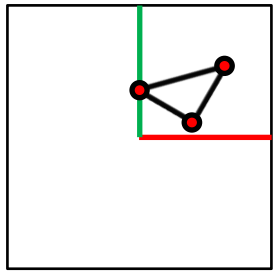
: determines color of each fragment with light & texture

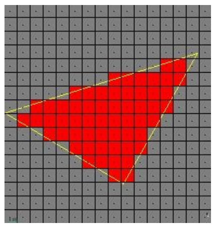
output merging

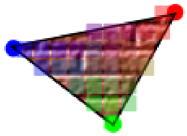


Rendering Pipeline

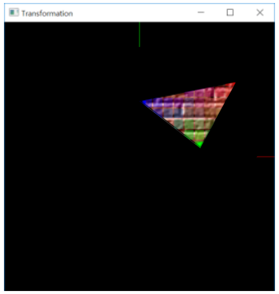








vertex processing → **rasterization** → **fragment processing** → output merging



: performs a sequence of **vertex transformations**

What we've been done so far

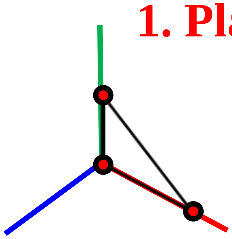
→ We'll see today & next lecture

Vertex Processing

Set vertex positions

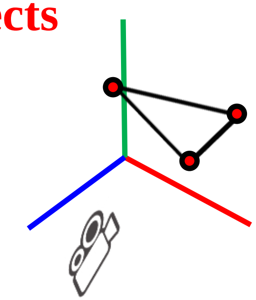
Transformed vertices

Vertex positions in 2D viewport



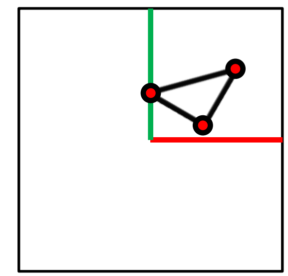
1. Placing objects

M



?

Let's think a "camera" is watching the "scene".



glVertex3fv($\mathbf{p}_1$)
glVertex3fv($\mathbf{p}_2$)
glVertex3fv($\mathbf{p}_3$)

glMultMatrixf($\mathbf{M}^T$)
glVertex3fv($\mathbf{p}_1$)
glVertex3fv($\mathbf{p}_2$)
glVertex3fv($\mathbf{p}_3$)

…or
glVertex3fv($\mathbf{Mp}_1$)
glVertex3fv($\mathbf{Mp}_2$)
glVertex3fv($\mathbf{Mp}_3$)

Then what we have to do are…

2. Placing the "camera"
3. Selecting a "lens"
4. Displaying on a "cinema screen"

In Terms of CG Transformation,

- 1. Placing objects

→ **Modeling transformation**

- 2. Placing the “camera”

→ **Viewing transformation**

- 3. Selecting a “lens”

→ **Projection transformation**

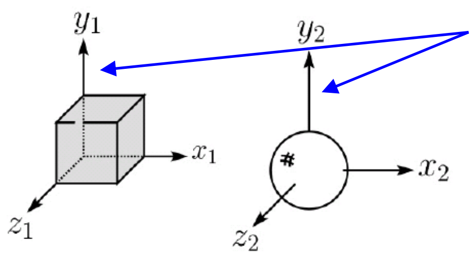
- 4. Displaying on a “cinema screen”

→ **Viewport transformation**

- All these transformations just work by **matrix multiplications**!

Vertex Processing (Transformation Pipeline)

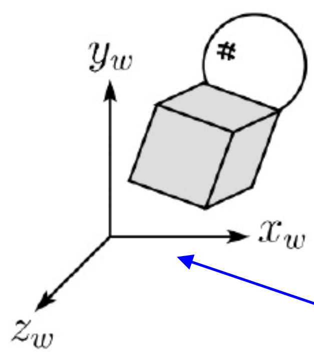
Object space



local coordinate system

Translate, scale, rotate, ... any affine transformations

(What we've already covered in prev. lectures)

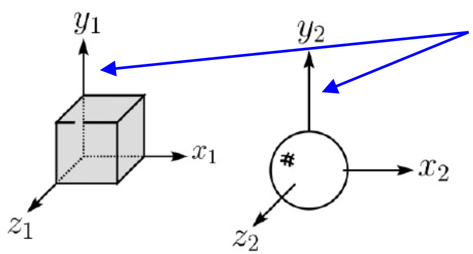


global coordinate system

World space

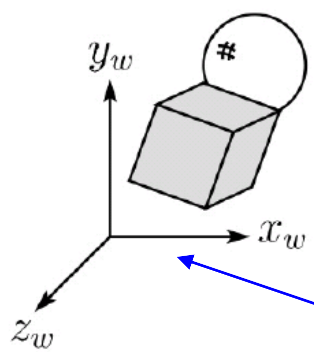
Vertex Processing (Transformation Pipeline)

Object space



local coordinate system

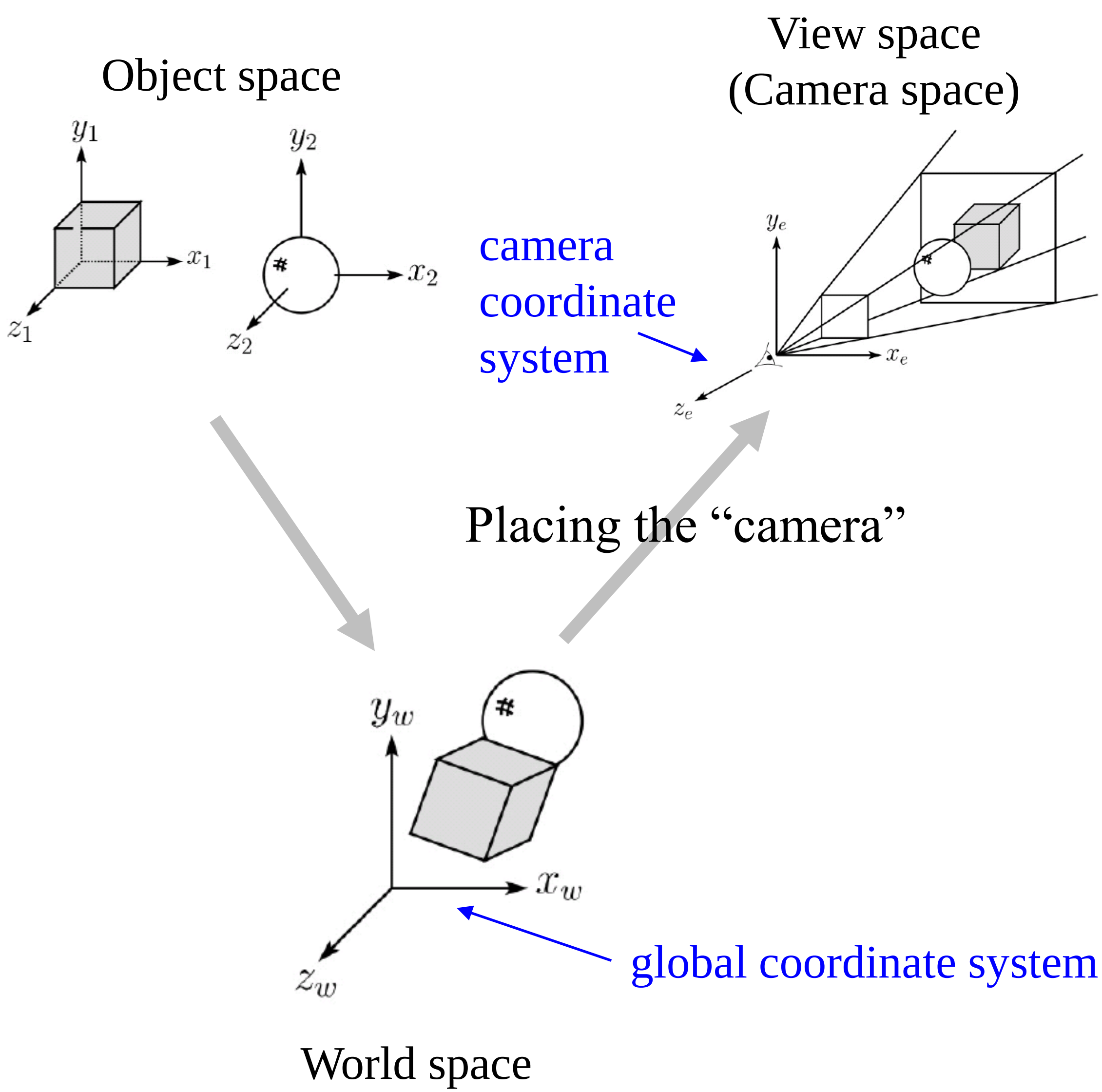
Modeling transformation



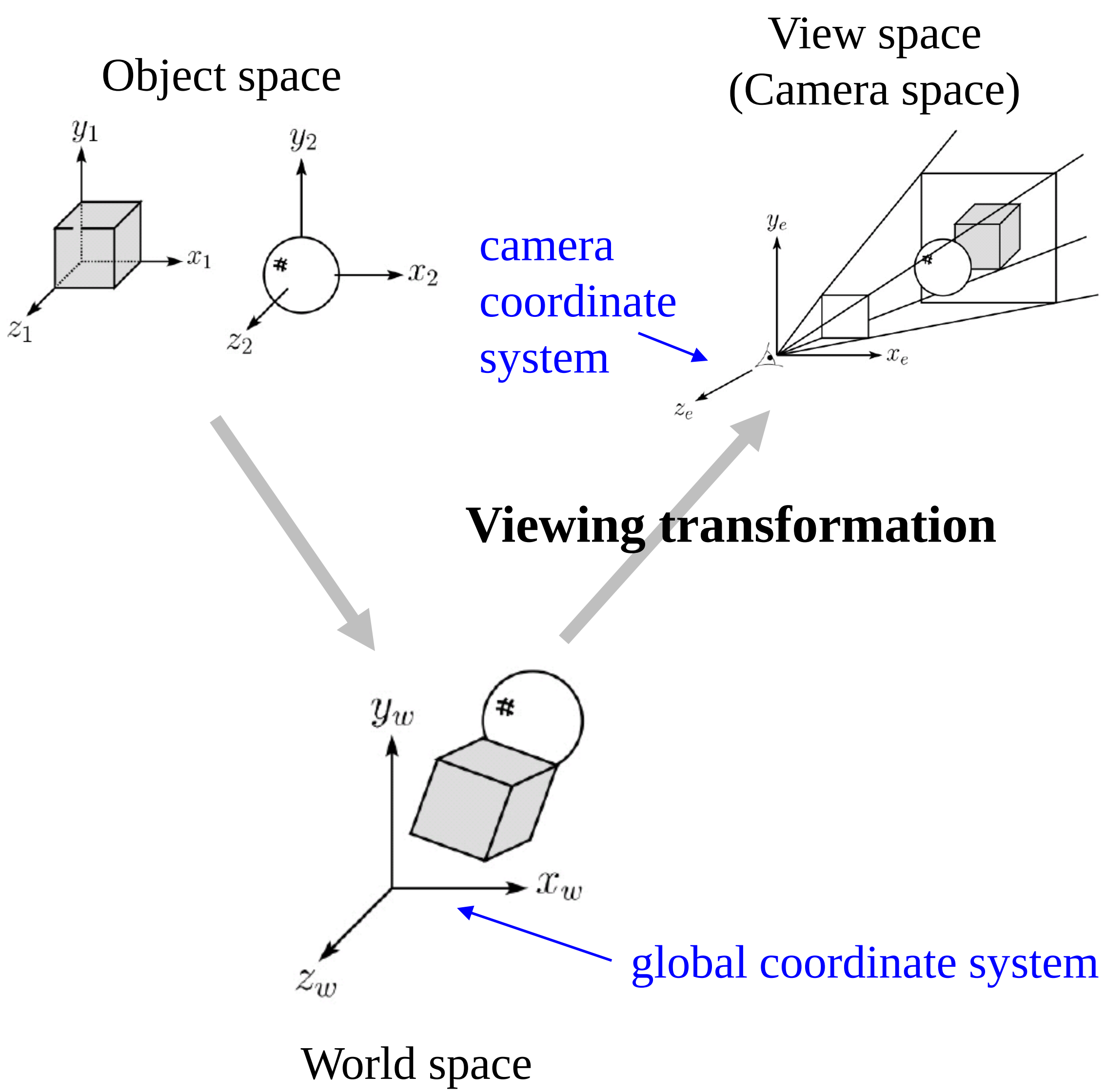
global coordinate system

World space

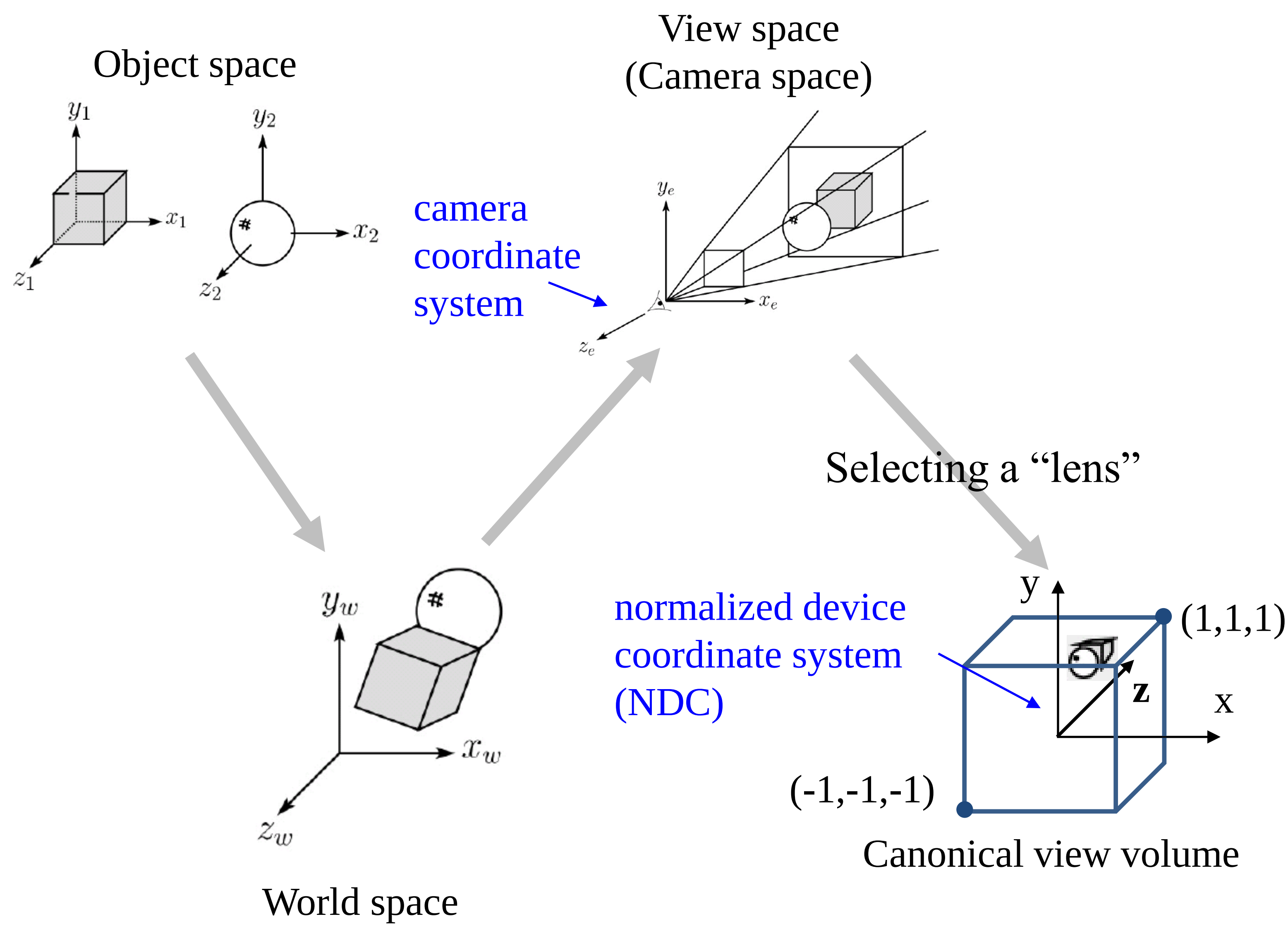
Vertex Processing (Transformation Pipeline)



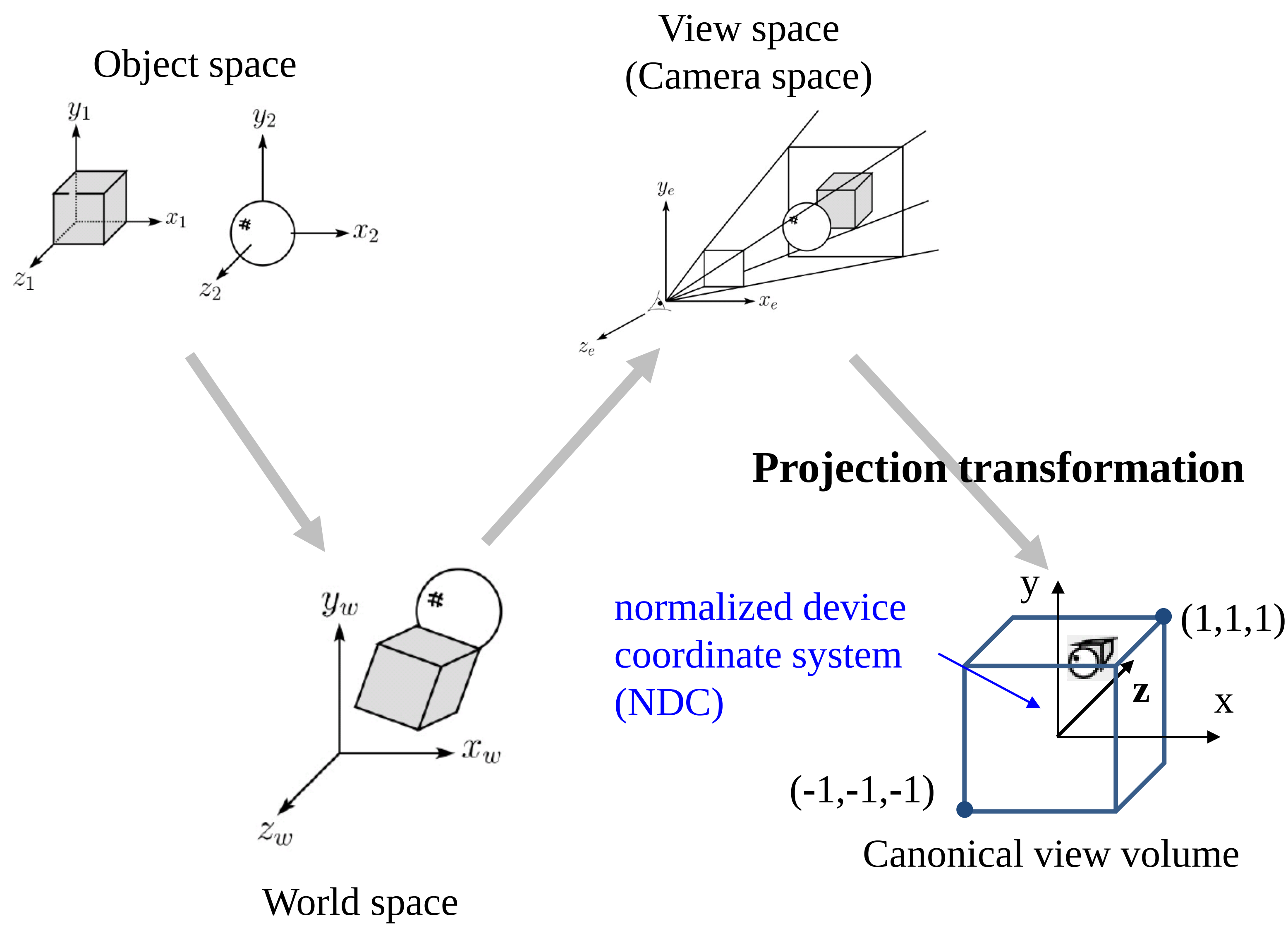
Vertex Processing (Transformation Pipeline)



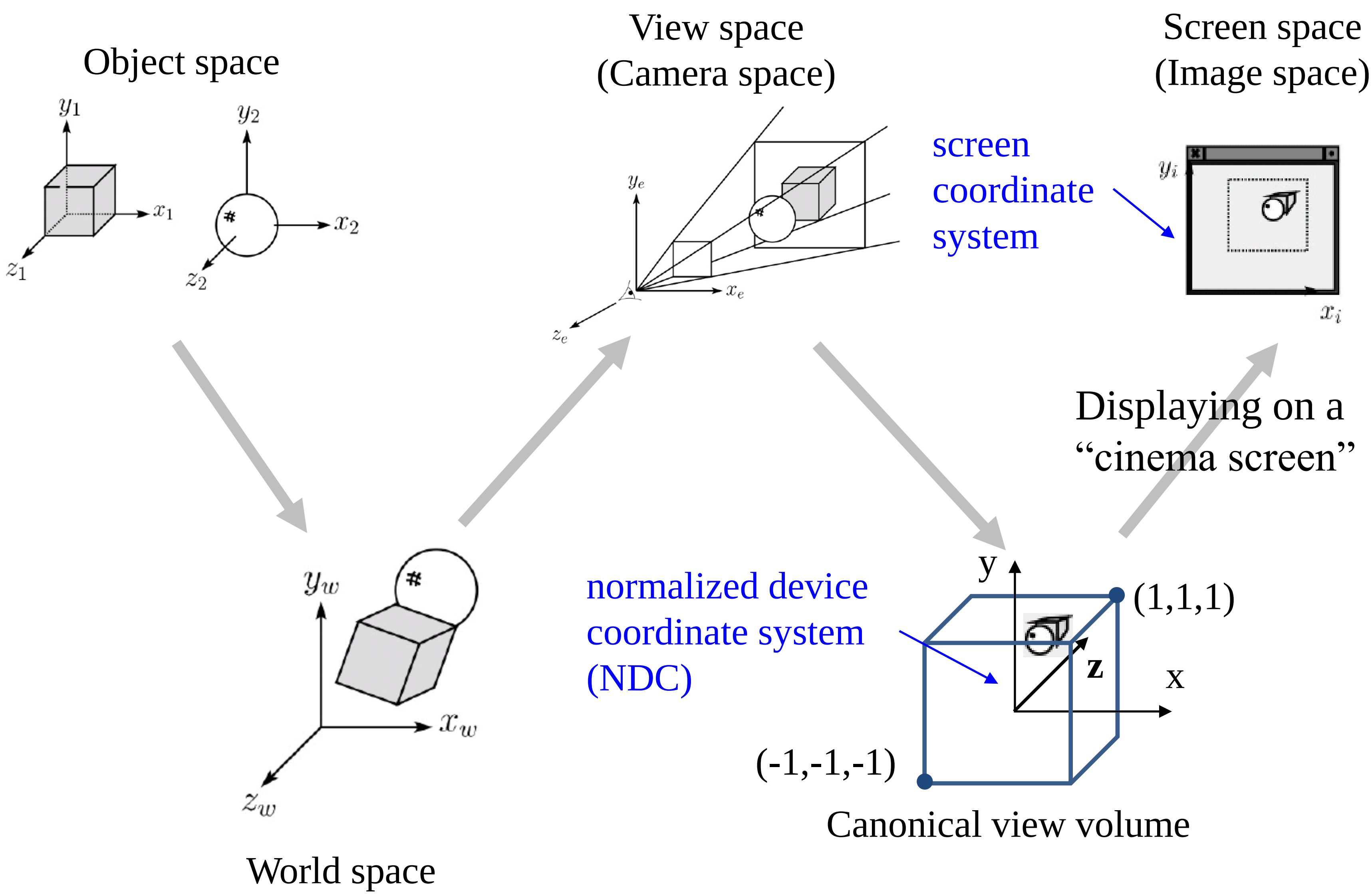
Vertex Processing (Transformation Pipeline)



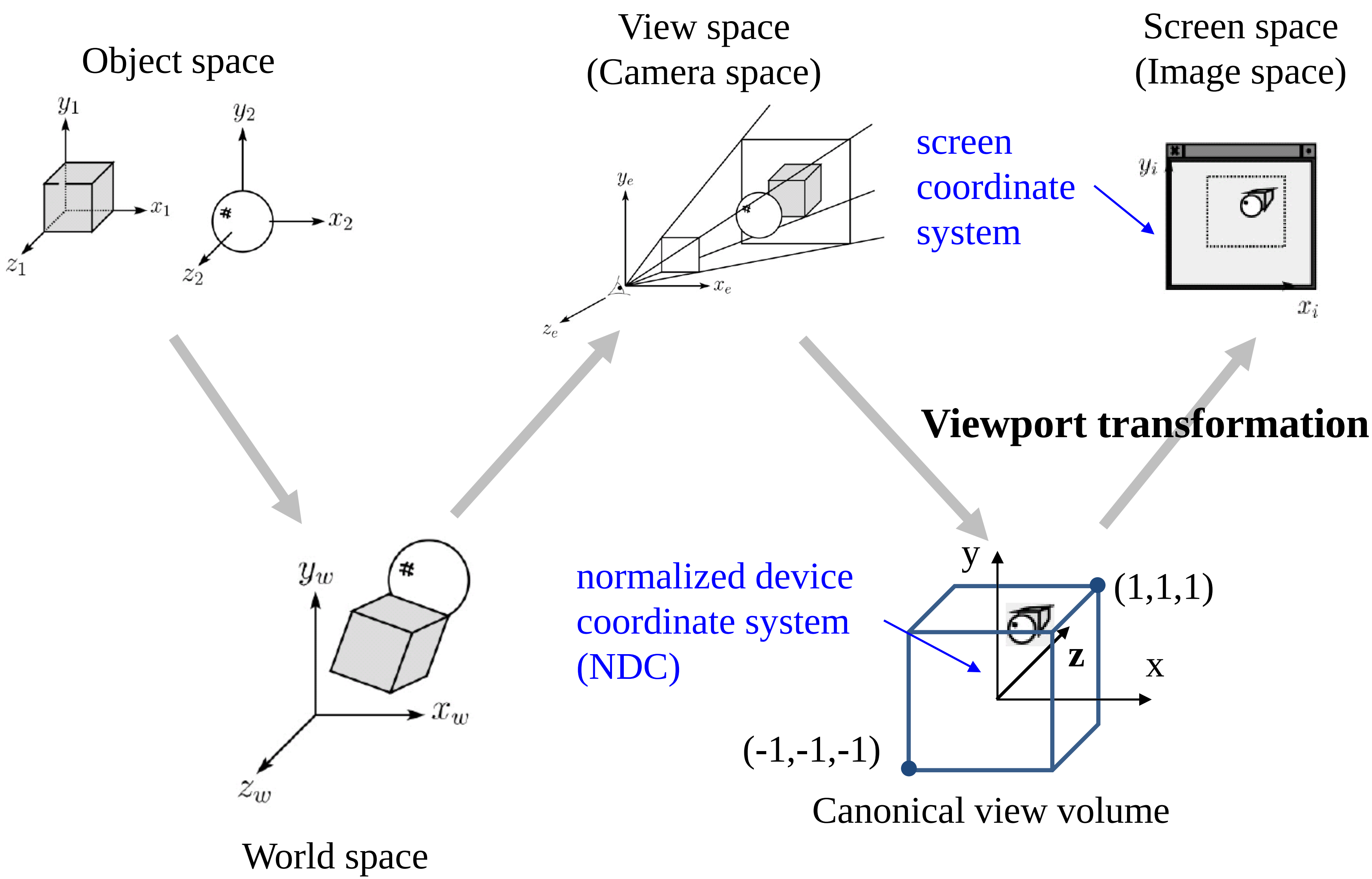
Vertex Processing (Transformation Pipeline)



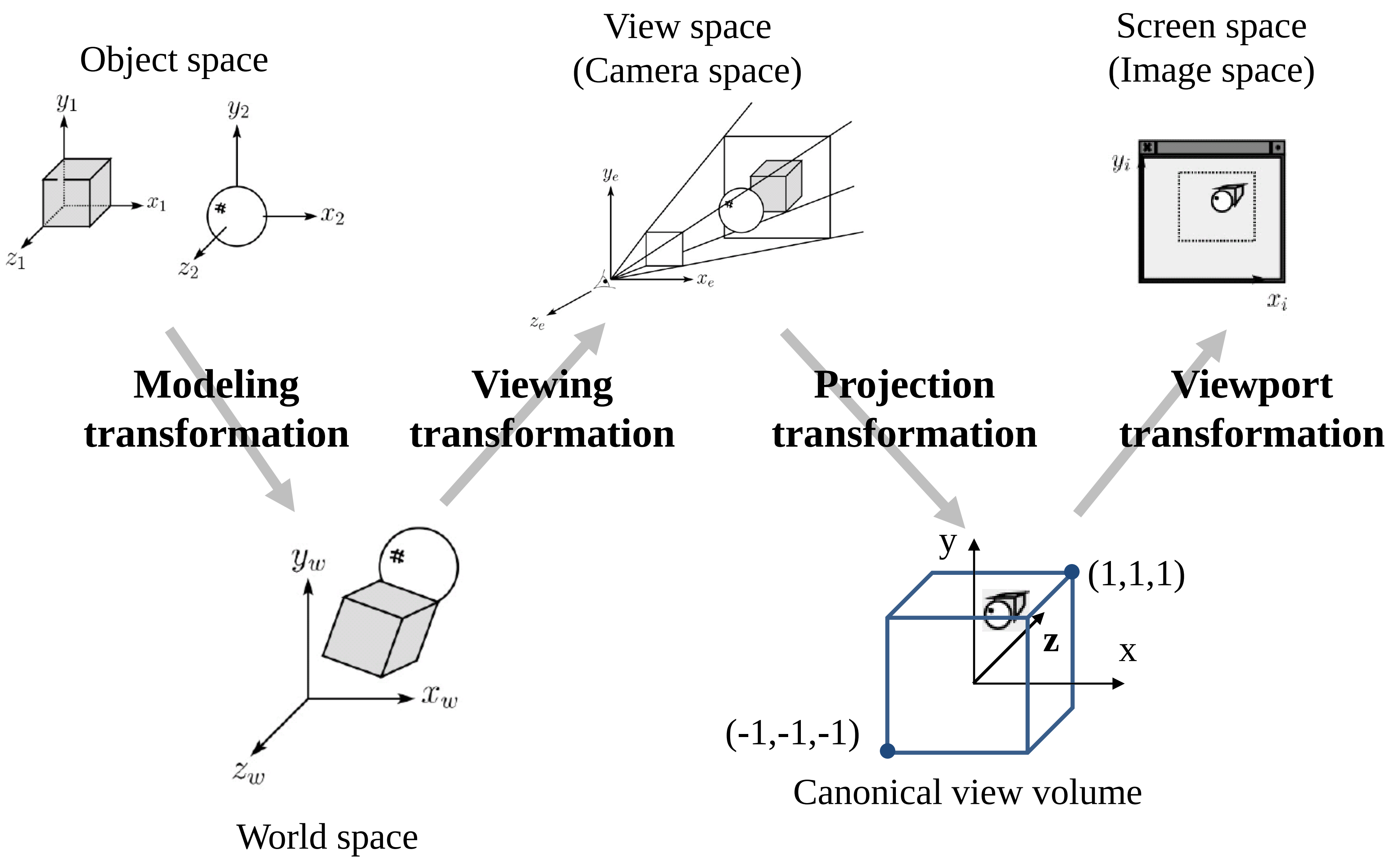
Vertex Processing (Transformation Pipeline)



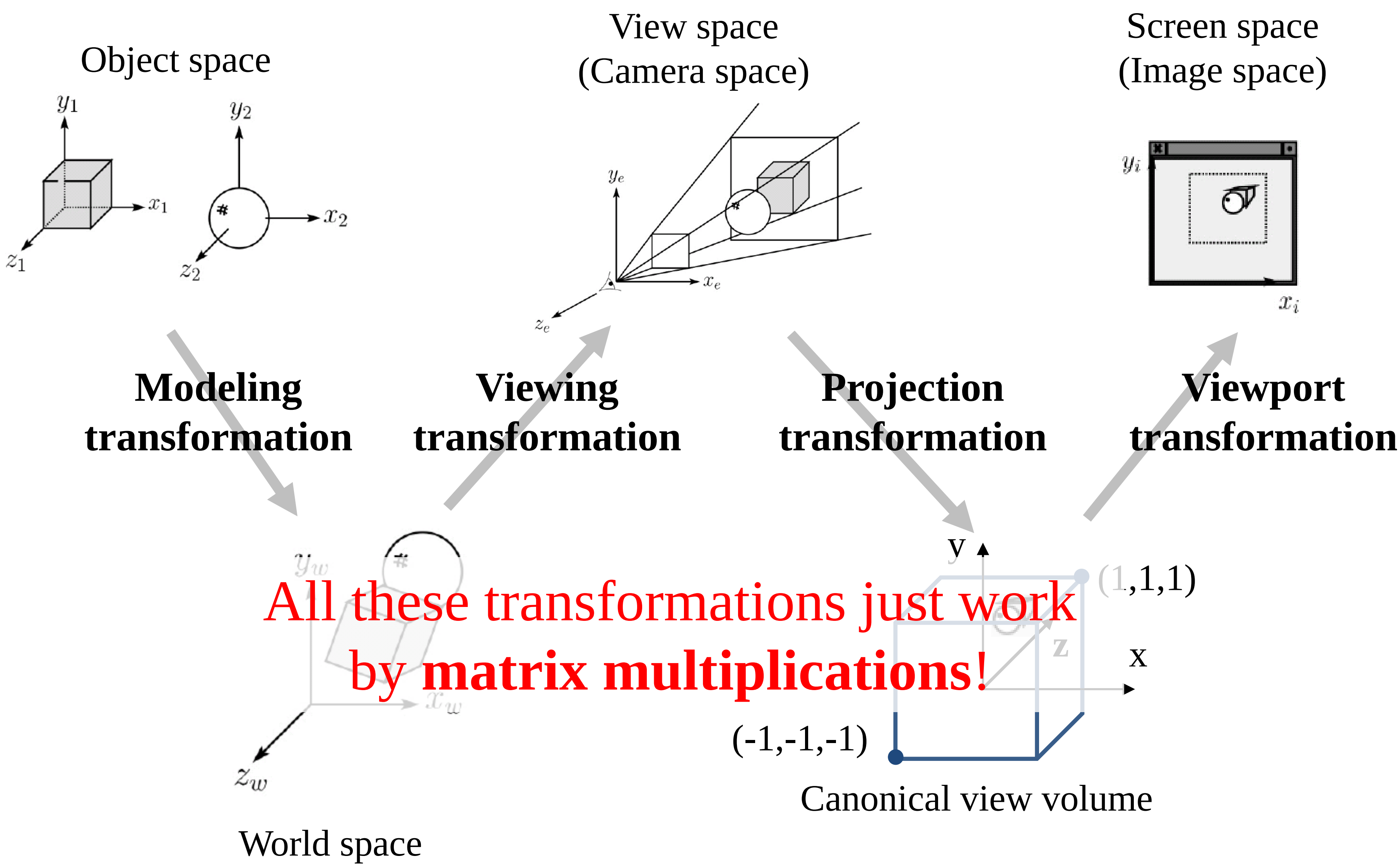
Vertex Processing (Transformation Pipeline)



Vertex Processing (Transformation Pipeline)

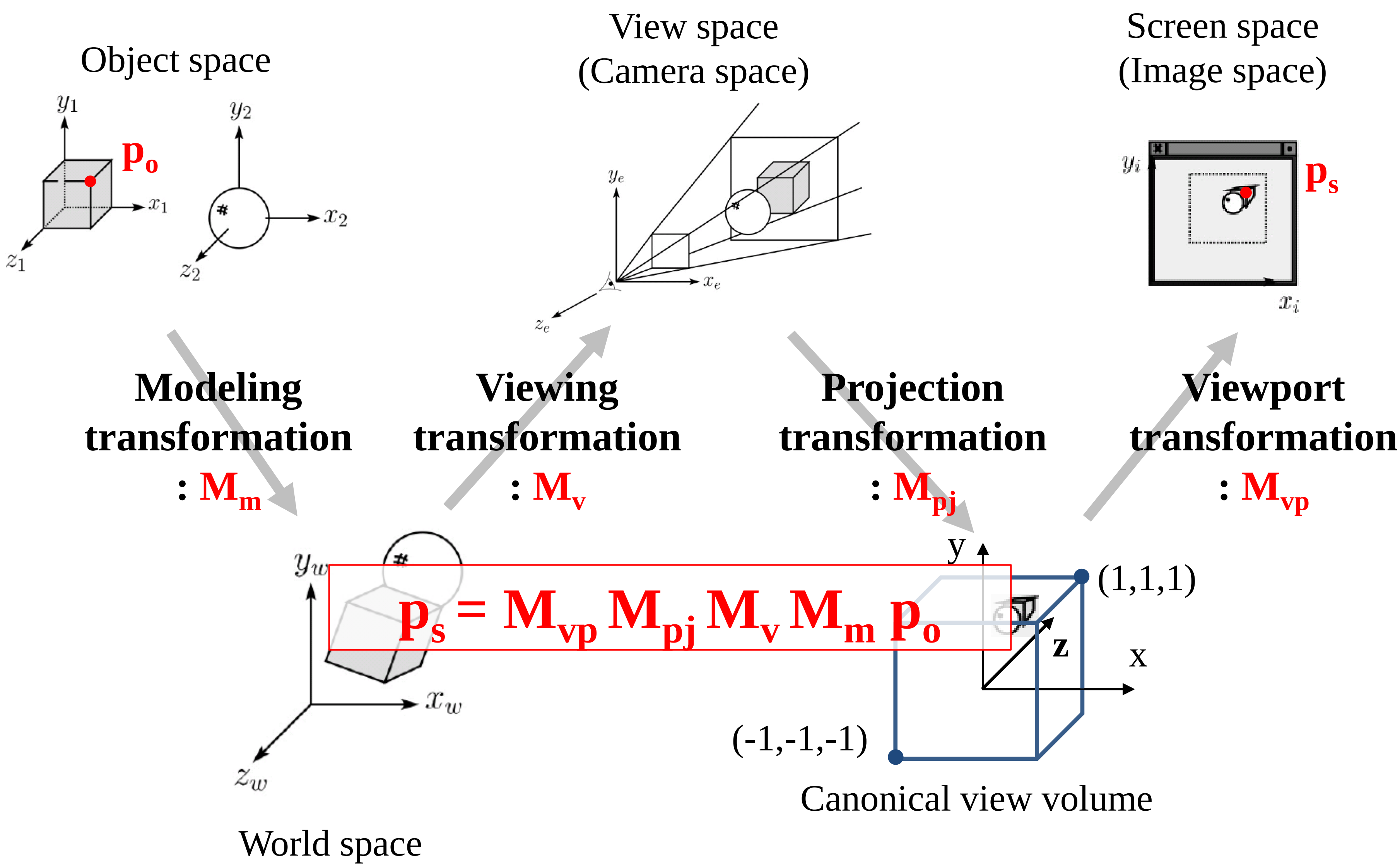


Vertex Processing (Transformation Pipeline)

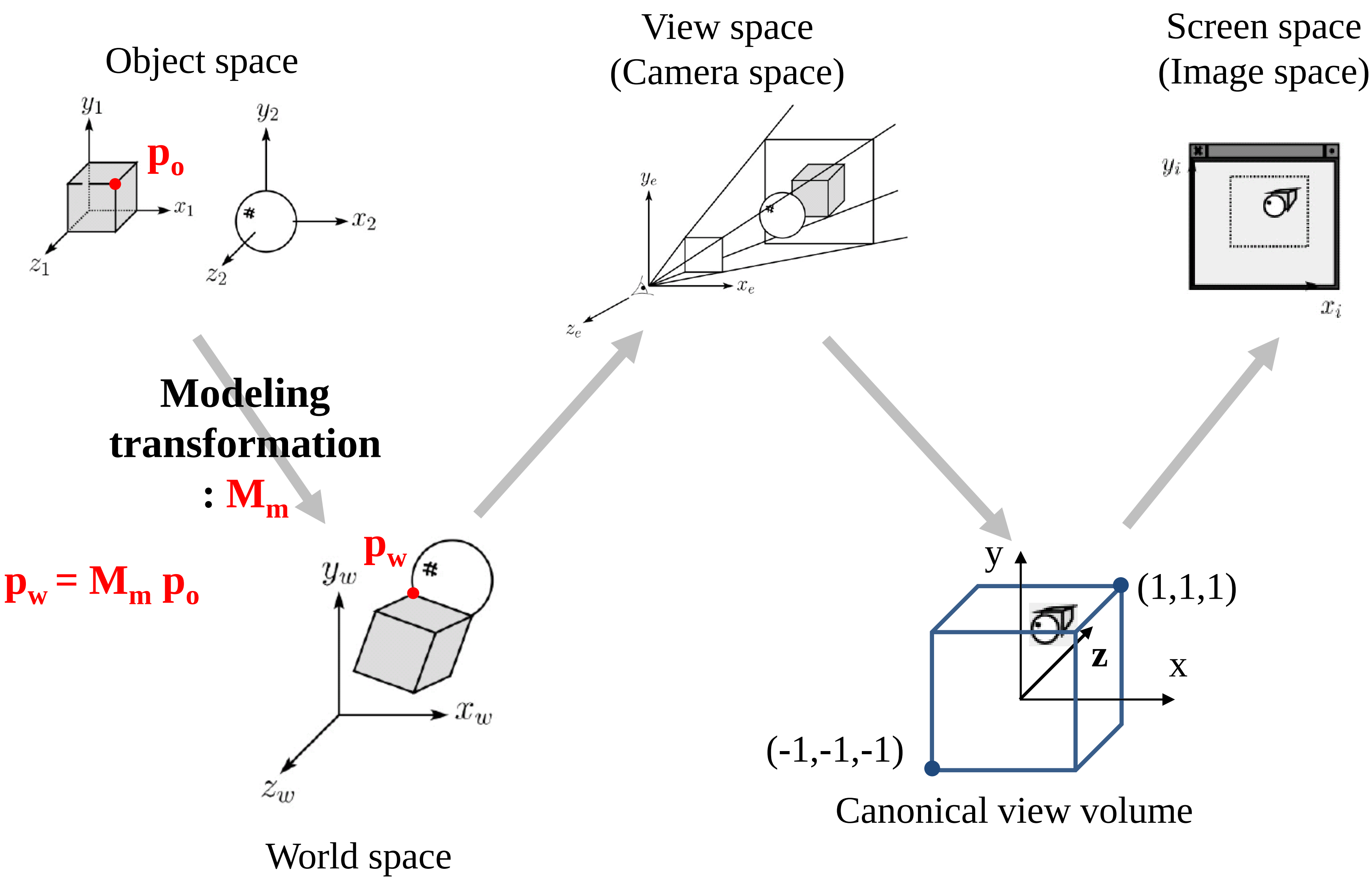


All these transformations just work by **matrix multiplications!**

Vertex Processing (Transformation Pipeline)

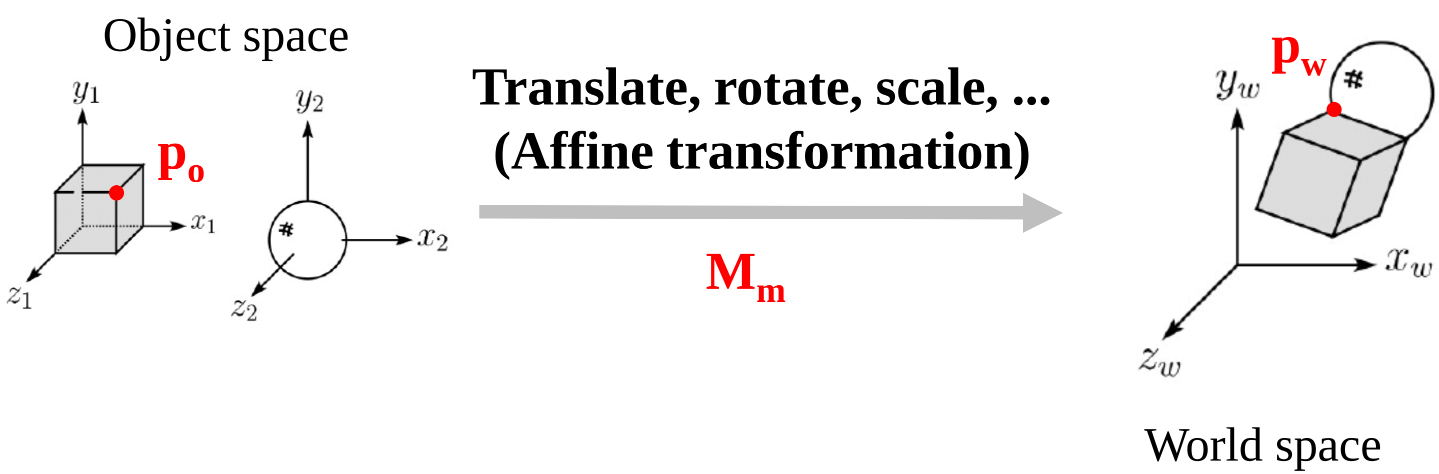


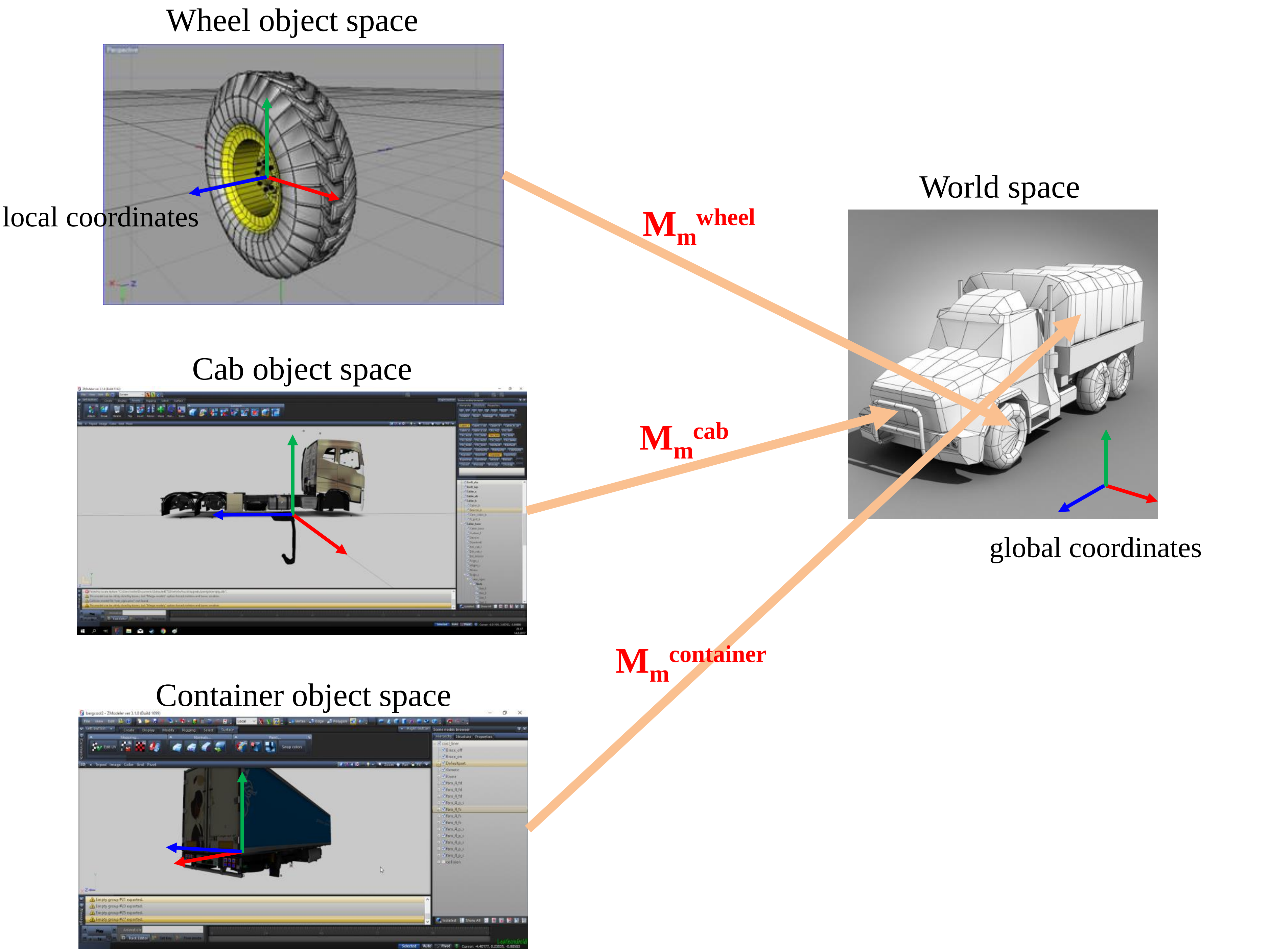
Modeling Transformation



Modeling Transformation

- Geometry would originally have been in the **object's local coordinates**;
- Transform into world coordinates is called the *modeling matrix*, M_m
- Composite affine transformations
- (What we've covered so far!)




Wheel object space
local coordinates
World space
M_m^{wheel}
Cab object space
M_m^{cab}
global coordinates
Container object space
$M_m^{container}$

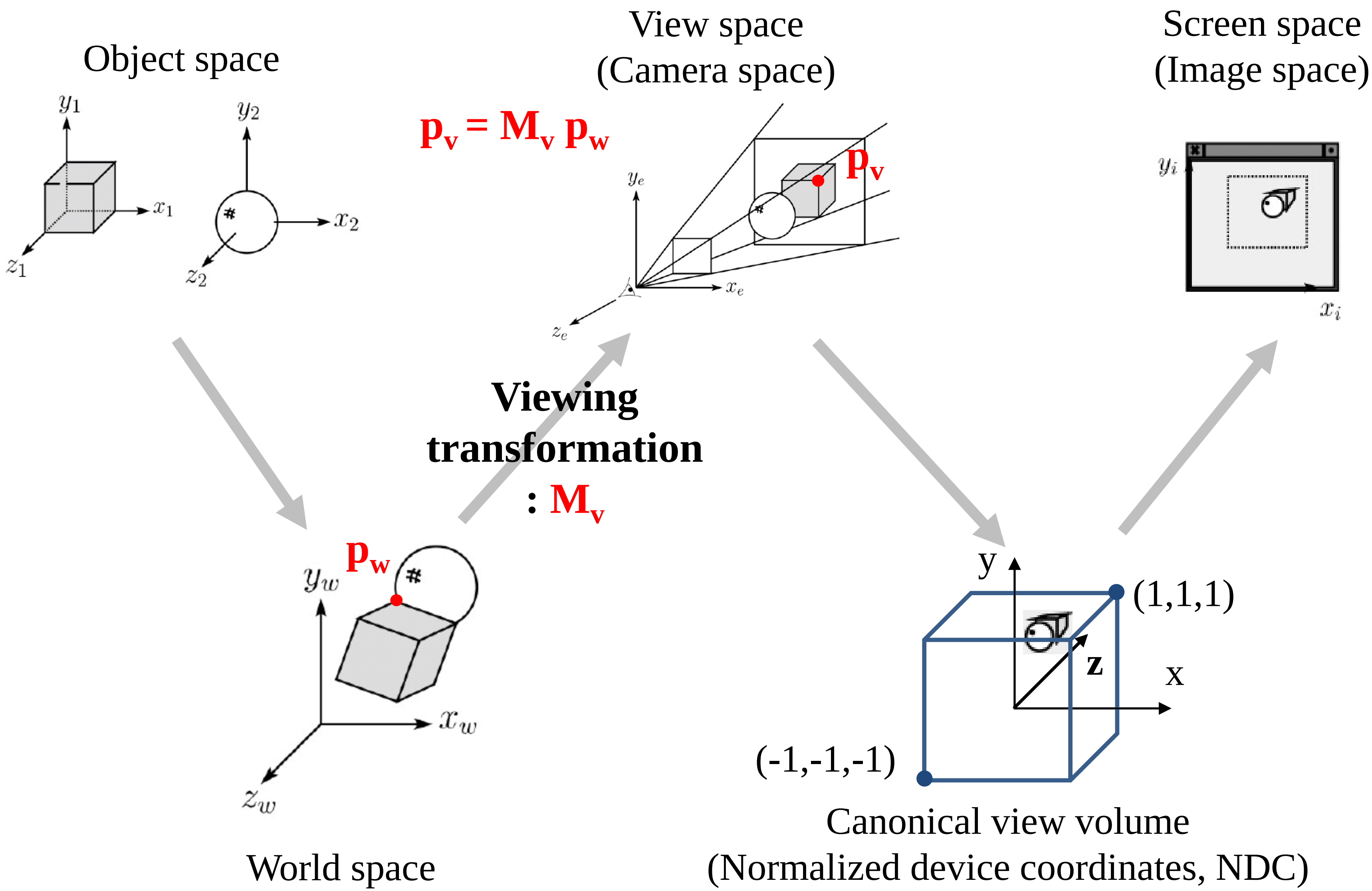
Quiz #1

- Go to https://www.slido.com/
- Join #**cg-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers in the above format to be checked for "attendance".

Viewing Transformation



Recall that...

- 1. Placing objects

→ **Modeling transformation**

- 2. Placing the “camera”

→ **Viewing transformation**

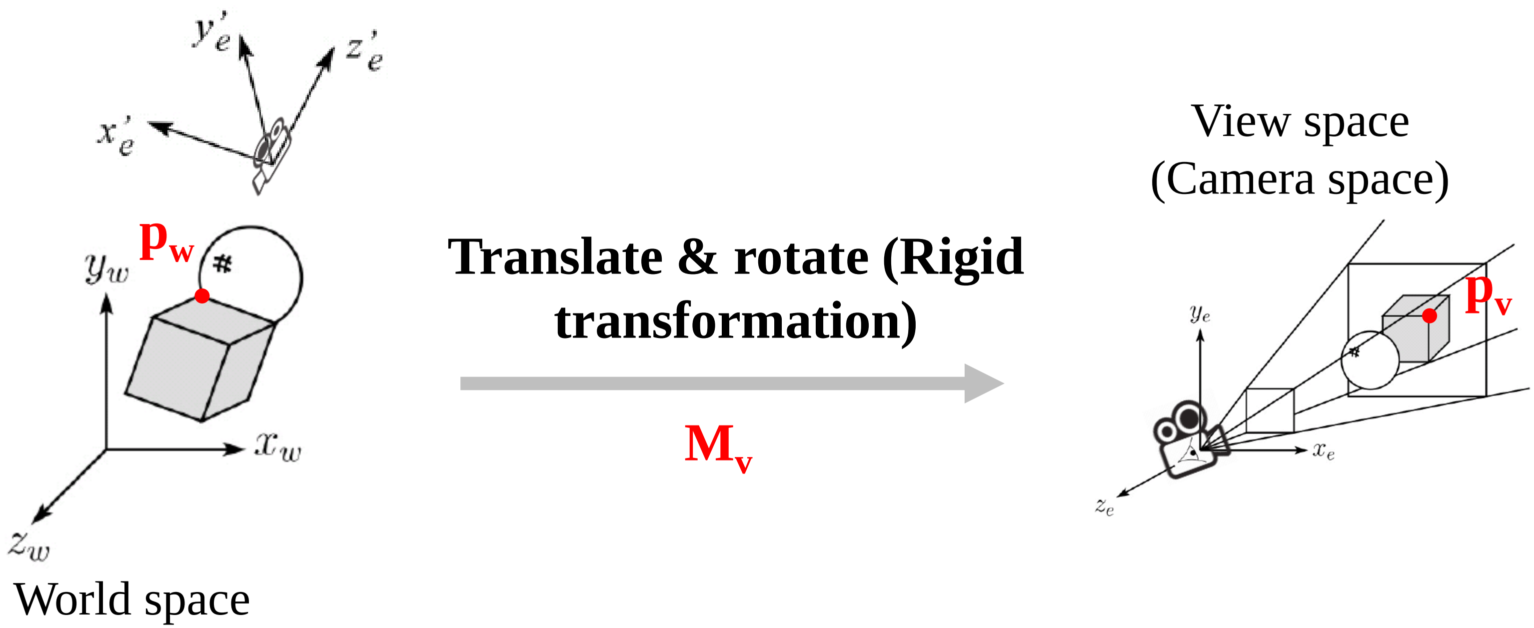
- 3. Selecting a “lens”

→ **Projection transformation**

- 4. Displaying on a “cinema screen”

→ **Viewport transformation**

Viewing Transformation



- **Placing the camera** and **expressing all object vertices from the camera's point of view**

- Transformation from world to view space is traditionally called the *viewing matrix*, M_v

Viewing Transformation

- Placing the camera
- **→ How to set the camera’s position & orientation?**

- Expressing all object vertices from the camera's point of view
- **→ How to define the camera’s coordinate system (frame)?**

1. Setting Camera's Position & Orientation

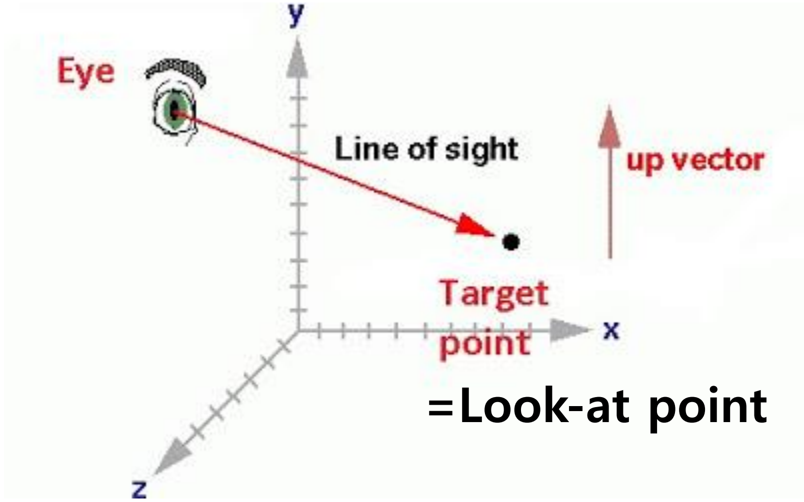
- Many ways to do this

- One intuitive way is using:

- **Eye point**
  - Position of the camera

- **Look-at point**
  - The target of the camera

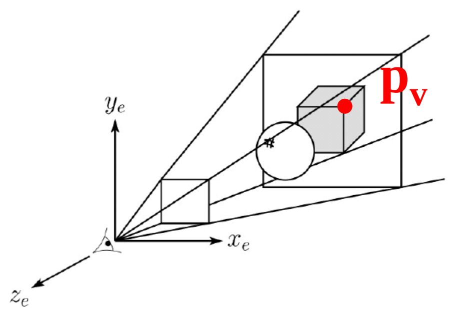
- **Up vector**
  - Roughly defines which direction is *up*



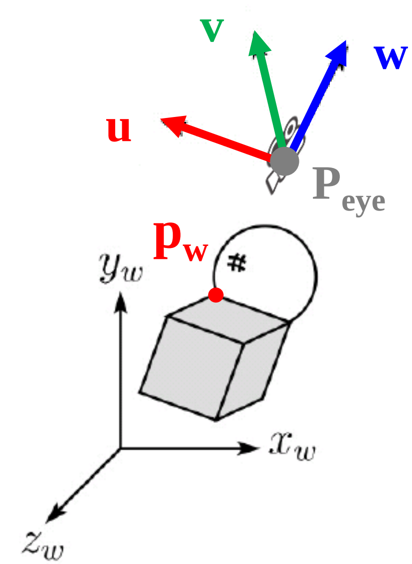
2. Defining Camera's Coordinate System

- Given **eye point**, **look-at point**, **up vector**, we can get camera frame ($\mathbf{P}_{\mathbf{eye}}$, **u, v, w**).
  - For details, see *5 - reference-viewing.pdf*

View space
(Camera space)

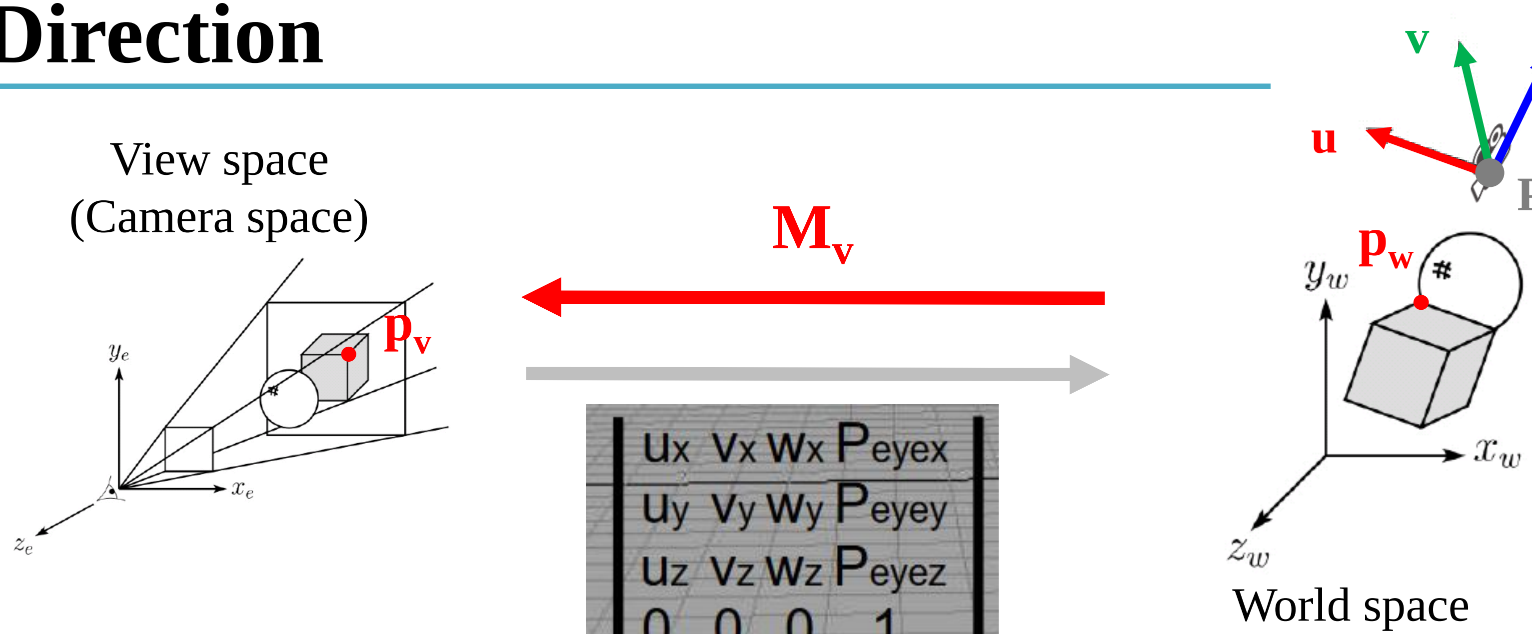


$$\begin{bmatrix} u_x & v_x & w_x & P_{eyex} \\ u_y & v_y & w_y & P_{eyey} \\ u_z & v_z & w_z & P_{eyez} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



World space

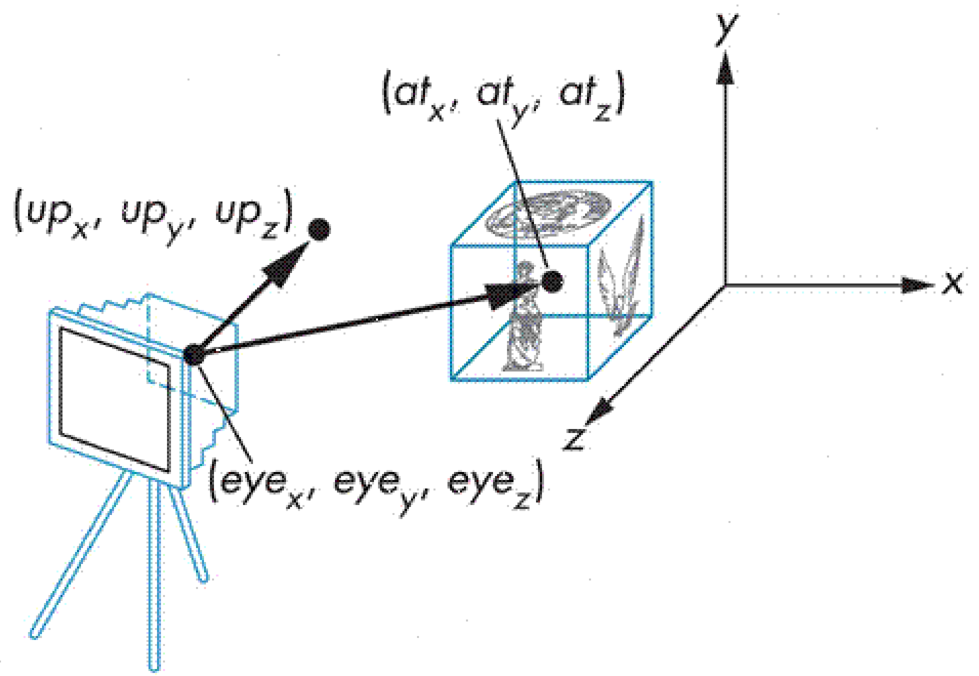
Viewing Transformation is the Opposite Direction



$$\begin{vmatrix} u_x & v_x & w_x & P_{eyex} \\ u_y & v_y & w_y & P_{eyey} \\ u_z & v_z & w_z & P_{eyez} \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$\mathbf{M_v} = \begin{vmatrix} u_x & v_x & w_x & P_{eyex} \\ u_y & v_y & w_y & P_{eyey} \\ u_z & v_z & w_z & P_{eyez} \\ 0 & 0 & 0 & 1 \end{vmatrix}^{-1} = \begin{bmatrix} u_x & u_y & u_z & -\mathbf{u}\cdot\mathbf{p}_{eye} \\ v_x & v_y & v_z & -\mathbf{v}\cdot\mathbf{p}_{eye} \\ w_x & w_y & w_z & -\mathbf{w}\cdot\mathbf{p}_{eye} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

gluLookAt()



gluLookAt (eye_x,eye_y,eye_z,at_x,at_y,at_z,up_x, up_y,up_z)
: creates a viewing matrix and right-multiplies the current transformation matrix by it

$C \leftarrow CM_v$

[Practice] gluLookAt()

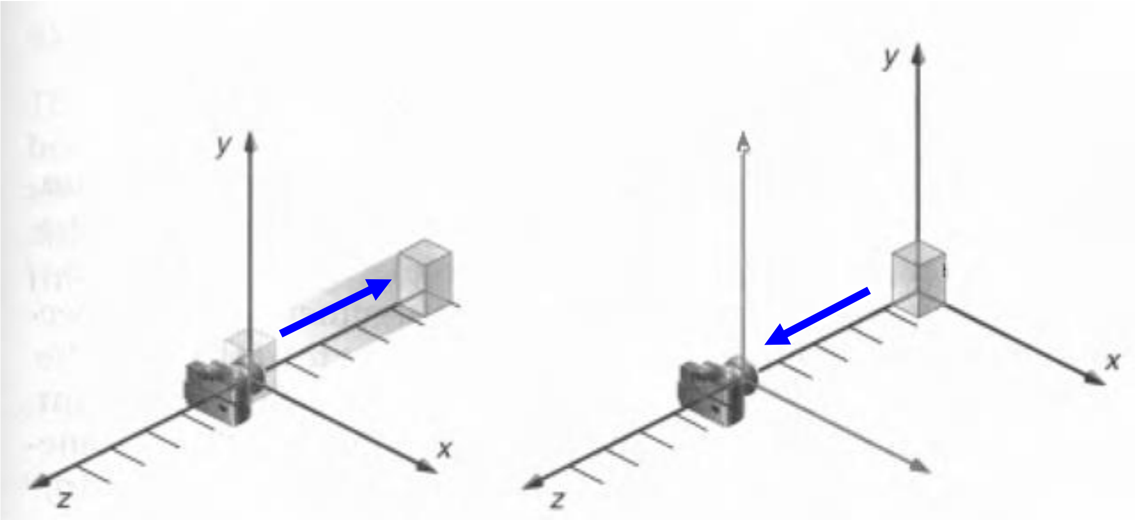
```
import glfw
from OpenGL.GL import *
from OpenGL.GLU import *
import numpy as np

gCamAng = 0.
gCamHeight = .1

def render():
    # enable depth test (we'll see details later)
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT)
    glEnable(GL_DEPTH_TEST)

    glLoadIdentity()

    # use orthogonal projection (we'll see details later)
    glOrtho(-1,1, -1,1, -1,1)

    # rotate "camera" position (right-multiply the current matrix by viewing
matrix)
    # try to change parameters
    gluLookAt(.1*np.sin(gCamAng),gCamHeight,.1*np.cos(gCamAng), 0,0,0, 0,1,0)

    drawFrame()

    glColor3ub(255, 255, 255)
    drawTriangle()
```

```
def drawFrame():
    glBegin(GL_LINES)
    glColor3ub(255, 0, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([1.,0.,0.]))
    glColor3ub(0, 255, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([0.,1.,0.]))
    glColor3ub(0, 0, 255)
    glVertex3fv(np.array([0.,0.,0]))
    glVertex3fv(np.array([0.,0.,1.]))
    glEnd()

def drawTriangle():
    glBegin(GL_TRIANGLES)
    glVertex3fv(np.array([.0,.5,0.]))
    glVertex3fv(np.array([.0,.0,0.]))
    glVertex3fv(np.array([.5,.0,0.]))
    glEnd()

def key_callback(window, key, scancode, action, 
mods):
    global gCamAng, gCamHeight
    if action==glfw.PRESS or action==glfw.REPEAT:
        if key==glfw.KEY_1:
            gCamAng += np.radians(-10)
        elif key==glfw.KEY_3:
            gCamAng += np.radians(10)
        elif key==glfw.KEY_2:
            gCamHeight += .1
        elif key==glfw.KEY_W:
            gCamHeight += -.1
```

```
def main():
    if not glfw.init():
        return
    window = 
glfw.create_window(640,640,'gluLookAt()', 
None,None)
    if not window:
        glfw.terminate()
        return
    glfw.make_context_current(window)
    glfw.set_key_callback(window, 
key_callback)

    while not 
glfw.window_should_close(window):
        glfw.poll_events()
        render()
        glfw.swap_buffers(window)

    glfw.terminate()

if __name__ == "__main__":
    main()
```

Moving Camera vs. Moving World

- Actually, these are two **equivalent operations**
- Translate camera by (1, 0, 2) == Translate world by (-1, 0, -2)
- Rotate camera by 60° about y ==Rotate world by -60° about y

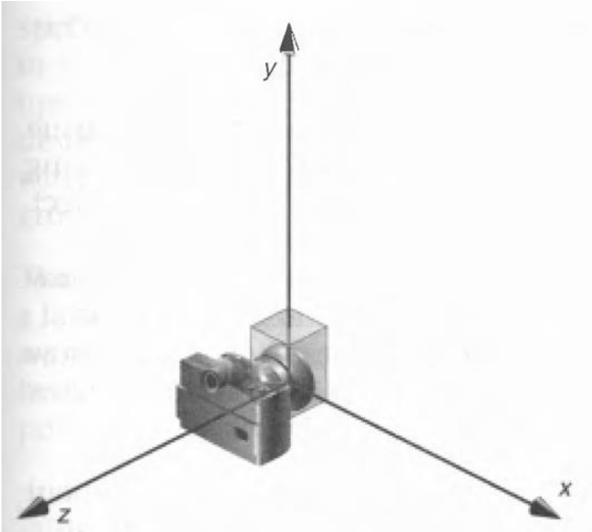


Moving Camera vs. Moving World

- Thus **you also can use glRotate*() or glTranslate*() to manipulate the camera!**

- Using gluLookAt() is just one option of many other choices to manipulate the camera.

- By default, OpenGL places a camera at the origin pointing in **negative z direction**.



Modelview Matrix

- As we've just seen, moving camera & moving world are equivalent operations.

- That's why OpenGL combines a *viewing matrix* M_v and a *modeling matrix* M_m into a ***modelview*** *matrix* $M=M_vM_m$

Quiz #2

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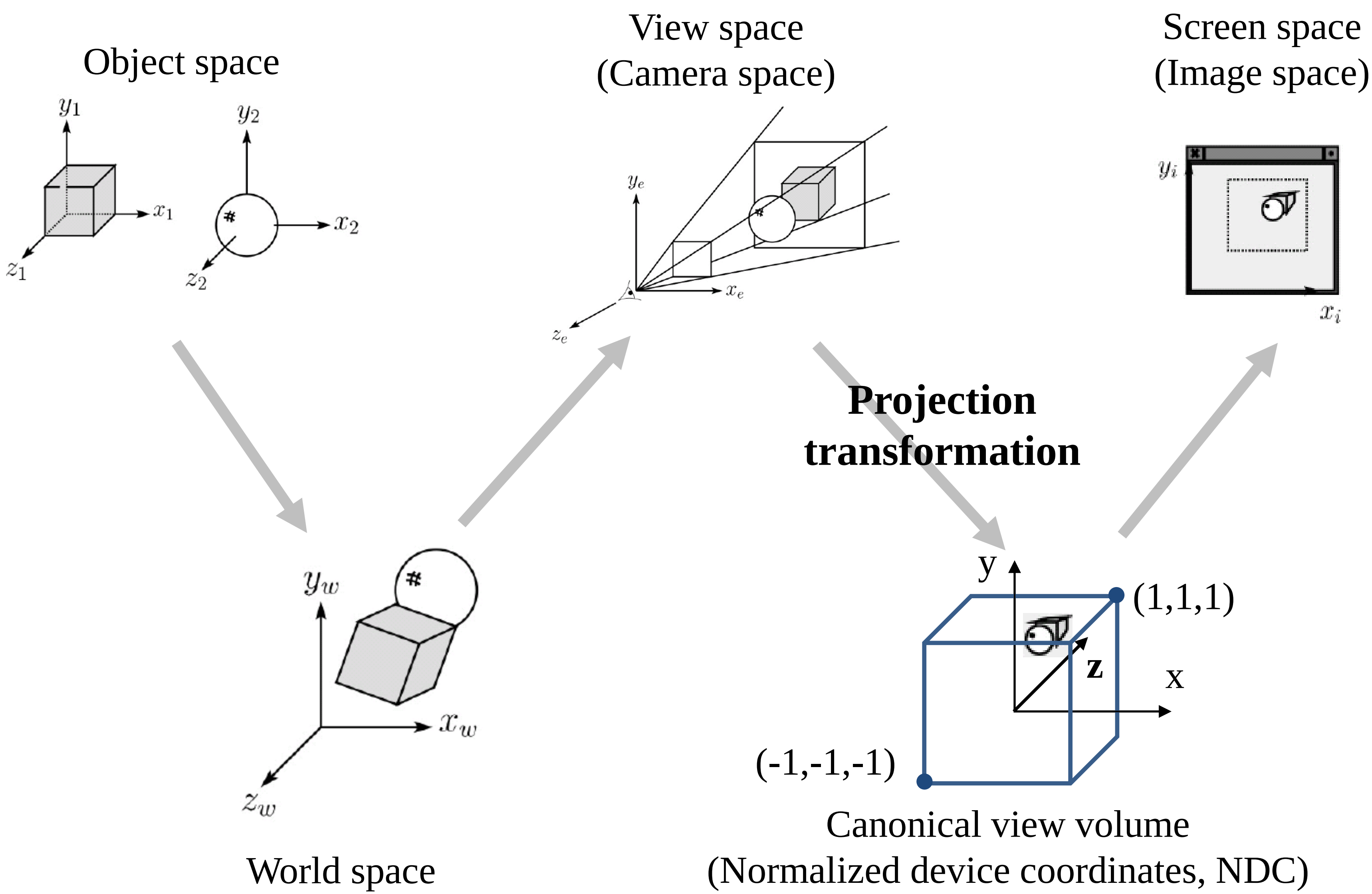
Projection Transformation



Recall that...

- 1. Placing objects

→ **Modeling transformation**

- 2. Placing the "camera"

→ **Viewing transformation (covered in the last class)**

- 3. Selecting a "lens"

→ **Projection transformation**

- 4. Displaying on a "cinema screen"

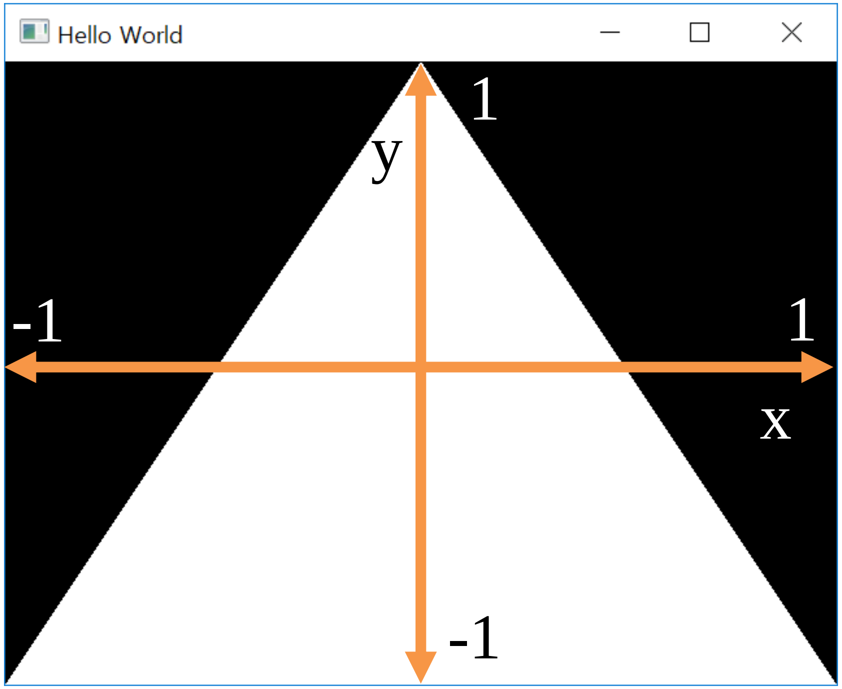
→ **Viewport transformation**

Review:Normalized Device Coordinates

- Remember that you could draw the triangle anywhere in a 2D square ranging from [-1, -1] to [1, 1].

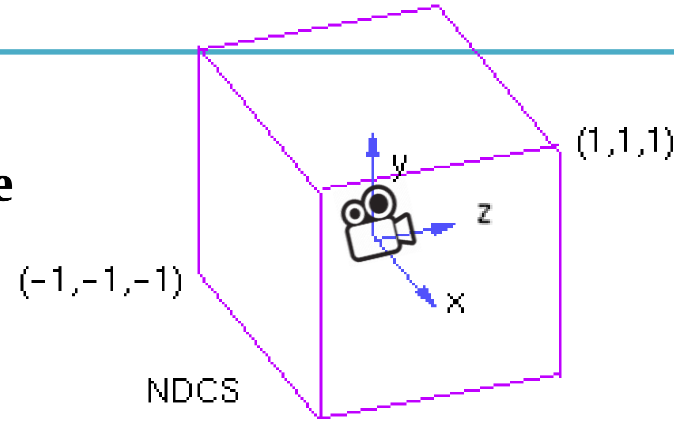
- Called **normalized device coordinates (NDC)**

- Also known as **canonical view volume**

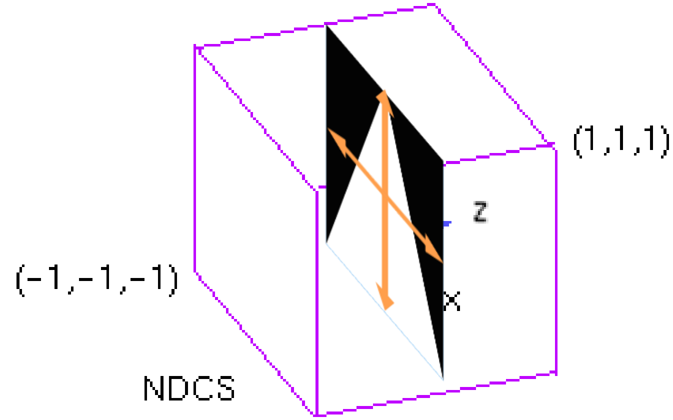


Canonical View "Volume"

- Actually, a canonical view volume is a **3D cube** ranging from [-1,-1,-1] to [1,1,1] in OpenGL
  - Its coordinate system is NDC

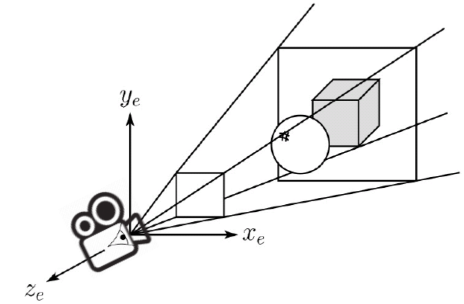


- Its **xy** plane is a 2D "viewport"



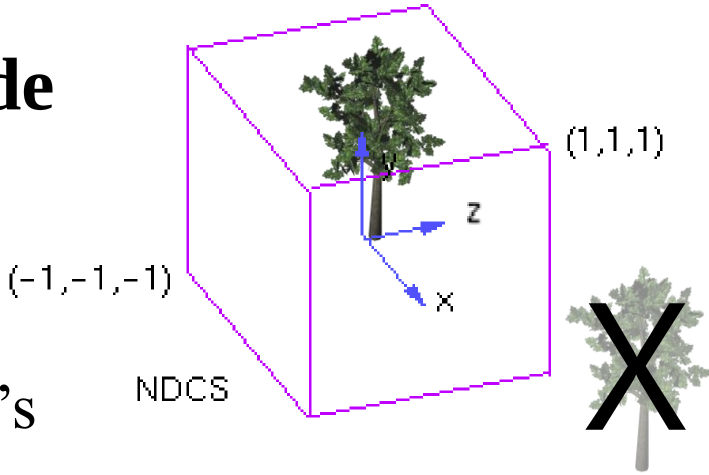
- Note that NDC in OpenGL is a left-handed coordinate system
  - Viewing direction in NDC : +z direction

- But OpenGL's projection functions change the hand-ness – Thus view, world, model spaces use right-handed coordinate system
  - Viewing direction in view space : -z direction



Canonical View Volume

- OpenGL only draws objects **inside** the canonical view volume
  - To draw objects only in the camera's view
  - Not to draw objects too near or too far from the camera



Do we always have to use the cube of size 2 as a view volume?

- No. You can set any size visible volume and draw objects inside it.
  - Even you can use “frustums” as well as cuboids

- Then everything in the visible volume is mapped (projected) into the canonical view volume.

- Then 3D points in the canonical view volume are projected onto its xy plane as 2D points.

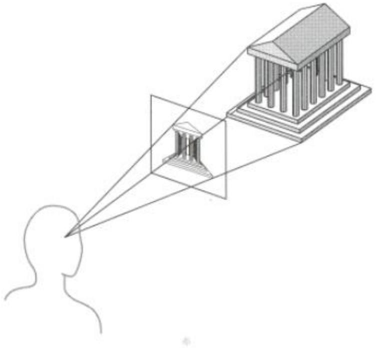
- → **Projection transformation**

Projection in General

- General definition:

- Transforming points in n-space to m-space ($m<n$)

Projection in Computer Graphics



- Mapping 3D coordinates to 2D screen coordinates.

- Two stages:
  - Map an arbitrary view volume to a canonical view volume
  - ~~Map 3D points in the canonical view volume onto its xy plane : But we still need z values of points for depth test, so do not consider this second stage~~

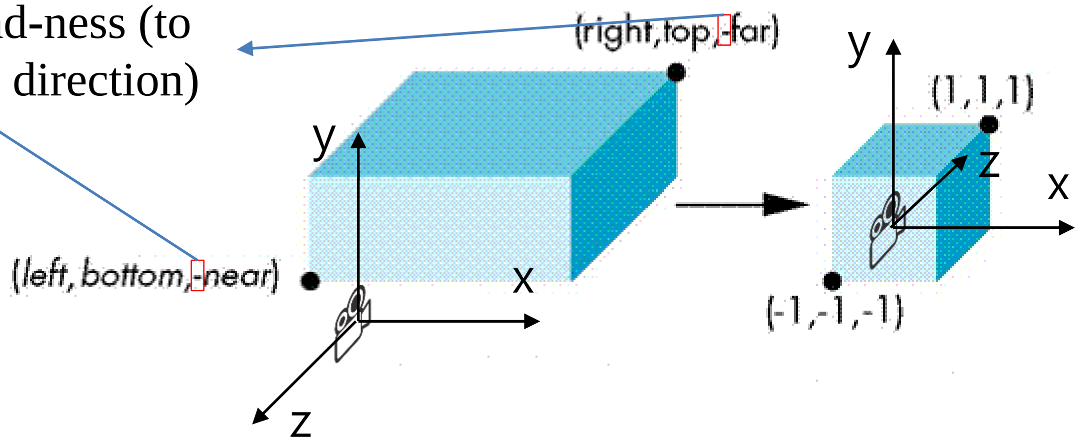
- Two common projection methods
  - Orthographic projection
  - Perspective projection

Orthographic (Orthogonal) Projection

- View volume : Cuboid (직육면체)
- Orthographic projection : Mapping from a cuboid view volume to a canonical view volume
  - Combination of scaling & translation

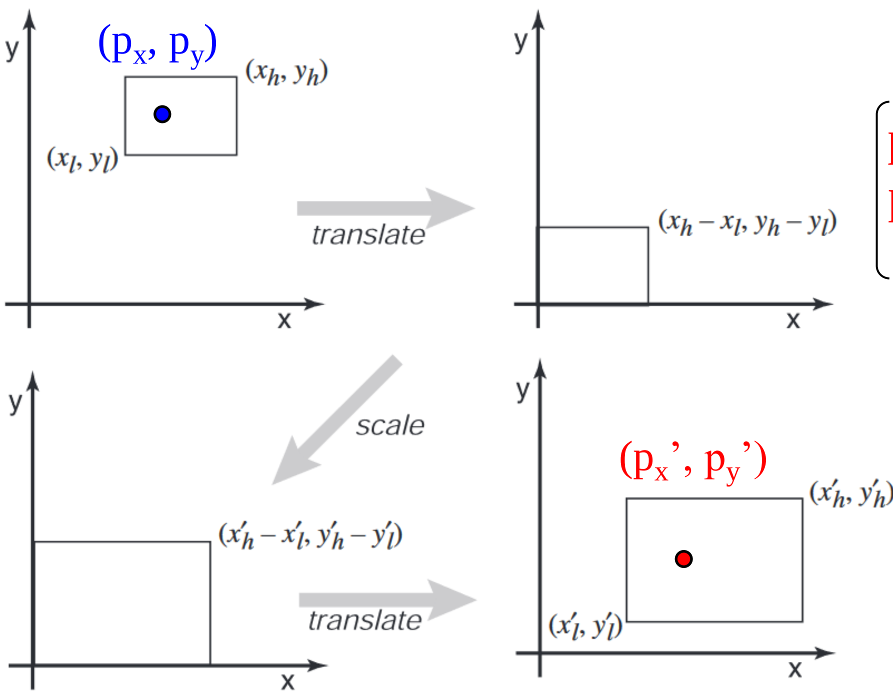
    → "Windowing" transformation

to change hand-ness (to flip positive z direction)



Windowing Transformation

- Transformation that maps a point (p_x, p_y) in a rectangular space from (x_l, y_l) to (x_h, y_h) to a point (p_x', p_y') in a rectangular space from (x_l', y_l') to (x_h', y_h')



$$\begin{pmatrix}p_x'\\ p_y'\\ 1\end{pmatrix} = \begin{bmatrix}1&0&x_l'\\ 0&1&y_l'\\ 0&0&1\end{bmatrix}\begin{bmatrix}\frac{x_h'-x_l'}{x_h-x_l}&0&0\\ 0&\frac{y_h'-y_l'}{y_h-y_l}&0\\ 0&0&1\end{bmatrix}\begin{bmatrix}1&0&-x_l\\ 0&1&-y_l\\ 0&0&1\end{bmatrix}\begin{pmatrix}p_x\\ p_y\\ 1\end{pmatrix}$$

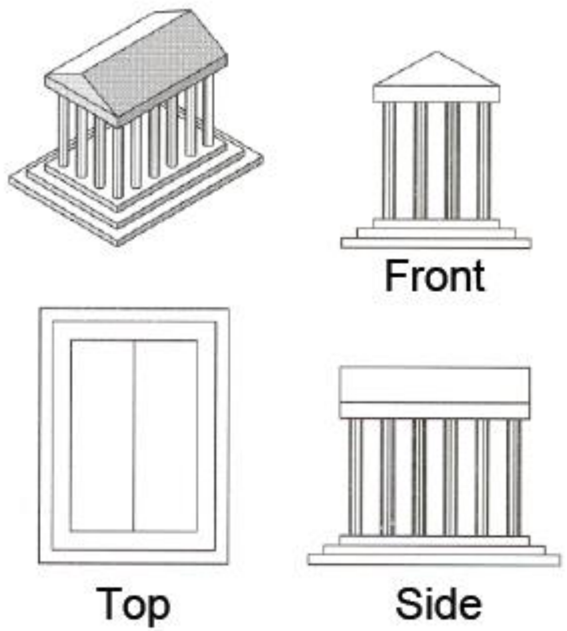
$$\begin{pmatrix}p_x'\\ p_y'\\ 1\end{pmatrix} = \begin{bmatrix}\frac{x_h'-x_l'}{x_h-x_l}&0&\frac{x_l'x_h-x_h'x_l}{x_h-x_l}\\ 0&\frac{y_h'-y_l'}{y_h-y_l}&\frac{y_l'y_h-y_h'y_l}{y_h-y_l}\\ 0&0&1\end{bmatrix}\begin{pmatrix}p_x\\ p_y\\ 1\end{pmatrix}$$

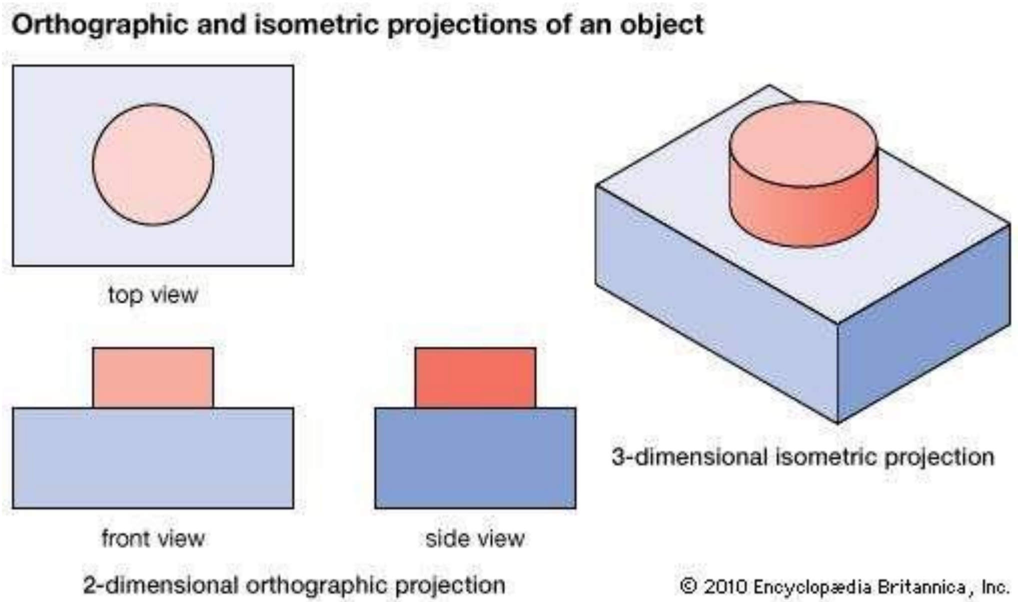
Orthographic Projection Matrix

- By extending the matrix to 3D and substituting
  - x_h=right, x_l=left, x_h'=1, x_l'=-1
  - y_h=top, y_l=bottom, y_h'=1, y_l'=-1
  - z_h=-far, z_l=-near, z_h'=1, z_l'=-1

$$M_{orth} = \begin{bmatrix} \frac{2}{right-left} & 0 & 0 & -\frac{right+left}{right-left} \\ 0 & \frac{2}{top-bottom} & 0 & -\frac{top+bottom}{top-bottom} \\ 0 & 0 & \frac{-2}{far-near} & -\frac{far+near}{far-near} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

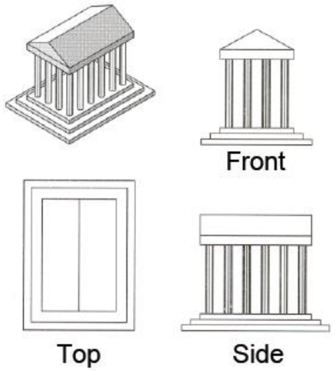
Examples of Orthographic Projection





An object always stay the same size, no matter its distance from the viewer.

Properties of Orthographic Projection

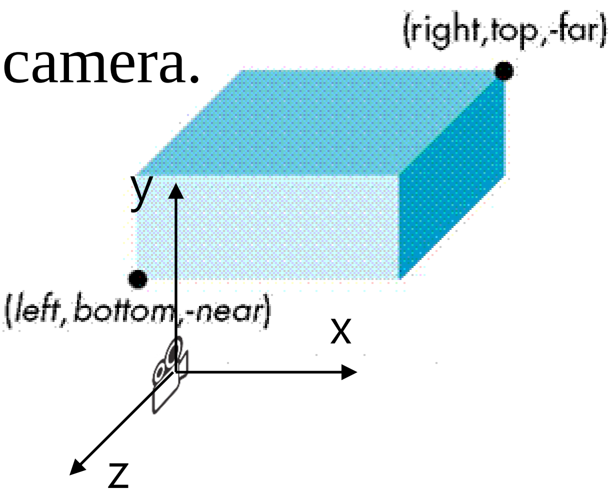


- Not realistic looking
- Good for exact measurement
- Most often used in CAD, architectural drawings, etc. where taking exact measurement is important
- Affine transformation

  - parallel lines remain parallel
  - ratios are preserved
  - angles are often not preserved

glOrtho()

- glOrtho(left, right, bottom, top, zNear, zFar)
- : Creates a orthographic projection matrix and right-multiplies the current transformation matrix by it
- Sign of zNear, zFar:
  - positive value: the plane is in front of the camera
  - negative value: the plane is behind the camera.
- $C \leftarrow CM_{orth}$



[Practice] glOrtho

```python
import glfw
from OpenGL.GL import *
from OpenGL.GLU import *
import numpy as np

gCamAng = 0.
gCamHeight = 1.

# draw a cube of side 1, centered at the origin.
def drawUnitCube():
    glBegin(GL_QUADS)
    glVertex3f( 0.5, 0.5,-0.5)
    glVertex3f(-0.5, 0.5,-0.5)
    glVertex3f(-0.5, 0.5, 0.5)
    glVertex3f( 0.5, 0.5, 0.5)

    glVertex3f( 0.5,-0.5, 0.5)
    glVertex3f(-0.5,-0.5, 0.5)
    glVertex3f(-0.5,-0.5,-0.5)
    glVertex3f( 0.5,-0.5,-0.5)

    glVertex3f( 0.5, 0.5, 0.5)
    glVertex3f(-0.5, 0.5, 0.5)
    glVertex3f(-0.5,-0.5, 0.5)
    glVertex3f( 0.5,-0.5, 0.5)

    glVertex3f( 0.5,-0.5,-0.5)
    glVertex3f(-0.5,-0.5,-0.5)
    glVertex3f(-0.5, 0.5,-0.5)
    glVertex3f( 0.5, 0.5,-0.5)
```

```python
    glVertex3f(-0.5, 0.5, 0.5)
    glVertex3f(-0.5, 0.5,-0.5)
    glVertex3f(-0.5,-0.5,-0.5)
    glVertex3f(-0.5,-0.5, 0.5)

    glVertex3f( 0.5, 0.5,-0.5)
    glVertex3f( 0.5, 0.5, 0.5)
    glVertex3f( 0.5,-0.5, 0.5)
    glVertex3f( 0.5,-0.5,-0.5)
    glEnd()

def drawCubeArray():
    for i in range(5):
        for j in range(5):
            for k in range(5):
                glPushMatrix()
                glTranslatef(i,j,-k-1)
                glScalef(.5,.5,.5)
                drawUnitCube()
                glPopMatrix()

def drawFrame():
    glBegin(GL_LINES)
    glColor3ub(255, 0, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([1.,0.,0.]))
    glColor3ub(0, 255, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([0.,1.,0.]))
    glColor3ub(0, 0, 255)
    glVertex3fv(np.array([0.,0.,0]))
    glVertex3fv(np.array([0.,0.,1.]))
    glEnd()
```

```
def render():
    global gCamAng, gCamHeight
glClear(GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT)
    glEnable(GL_DEPTH_TEST)

    # draw polygons only with boundary edges
    glPolygonMode( GL_FRONT_AND_BACK, GL_LINE )

    glLoadIdentity()

    # test other parameter values
    # near plane: 10 units behind the camera
    # far plane: 10 units in front of
 the camera
    glOrtho(-5,5, -5,5, -10,10)

gluLookAt(1*np.sin(gCamAng),gCamHeight,1*np.cos(
gCamAng), 0,0,0, 0,1,0)

    drawFrame()
    glColor3ub(255, 255, 255)

    drawUnitCube()

    # test
    # drawCubeArray()
```

```
def key_callback(window, key, scancode, action,
mods):
    global gCamAng, gCamHeight
    if action==glfw.PRESS or
action==glfw.REPEAT:
        if key==glfw.KEY_1:
            gCamAng += np.radians(-10)
        elif key==glfw.KEY_3:
            gCamAng += np.radians(10)
        elif key==glfw.KEY_2:
            gCamHeight += .1
        elif key==glfw.KEY_W:
            gCamHeight += -.1

def main():
    if not glfw.init():
        return
    window =
glfw.create_window(640,640,'glOrtho()',
None,None)
    if not window:
        glfw.terminate()
        return
    glfw.make_context_current(window)
    glfw.set_key_callback(window, key_callback)

    while not glfw.window_should_close(window):
        glfw.poll_events()
        render()
        glfw.swap_buffers(window)

    glfw.terminate()

if __name__ == "__main__":
    main()
```

Quiz #3

- Go to https://www.slido.com/
- Join #**cg-ys**
- Click “Polls”

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers in the above format to be checked for “attendance”.

Next Time

- Lab in this week:
  - Lab assignment 5

- Next lecture:
  - 6 - Viewing & Projection 2, Mesh

- **Class Assignment #1**
  - **Due: 23:59, April 11, 2021**

- Acknowledgement: Some materials come from the lecture slides of
  - Prof. Jinxiang Chai, Texas A&M Univ., http://faculty.cs.tamu.edu/jchai/csce441_2016spring/lectures.html