3D Graphics and API with OpenGL

Human-Centered CAD Lab.

Contents

- 3D Graphics API & OpenGL
- Interactive Computer Graphics
- Example of OpenGL Programming
  - Preparatory
  - Simple code
  - GLUT Functions
- Transformation Matrix
- Matrix Manipulation
- Other Settings

3D Graphics API & OpenGL (1)

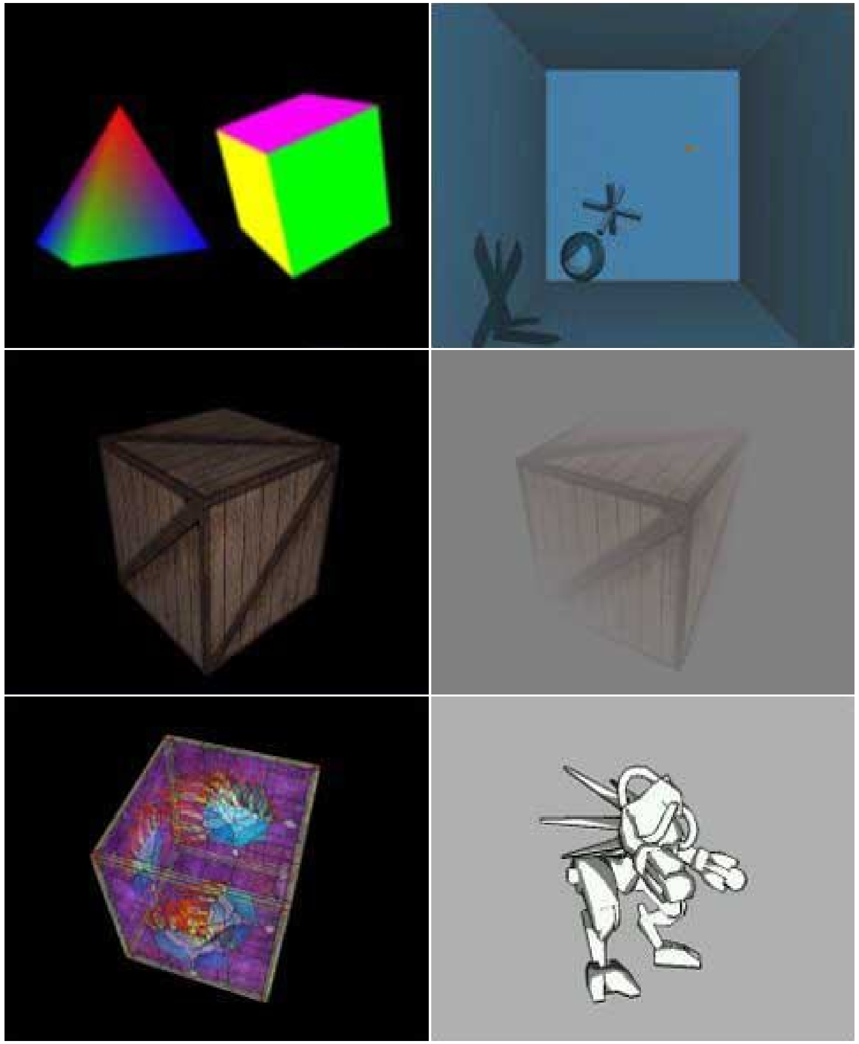
- 3D Graphics = modeling + rendering + animation
  - A model is a computer representation of an object
  - Rendering is the process of creating an image from a model
  - Animation is the process of generating repeated renderings of a scene
- Graphics API(Application Programming Interface)
  - We need interfaces to the graphics acceleration hardware.
  - The most popular 3D modeling technique is polygon or triangular mesh
  - The set of vertices/polygons enters the rendering pipeline
  - Two best-known interfaces are OpenGL and DirectX.

3D Graphics API & OpenGL (2)

- What is OpenGL ?
  - OpenGL is an acronym for Open Graphics Library
    - OpenGL Architecture Review Board (ARB)
    - Version 2.1 released on August 2, 2006
  - Most Widely Adopted Graphics Standard
    - Easy-to-use / Well-documented
    - High Visual Quality and Performance
    - Portable/Reliable/Stable/Scalable
    - Low-level graphics commands
  - Platform-independent graphics API.
    - UNIX, Linux, Windows9X/NT/2000/XP, OS/2, MacOS, BeOS, etc.

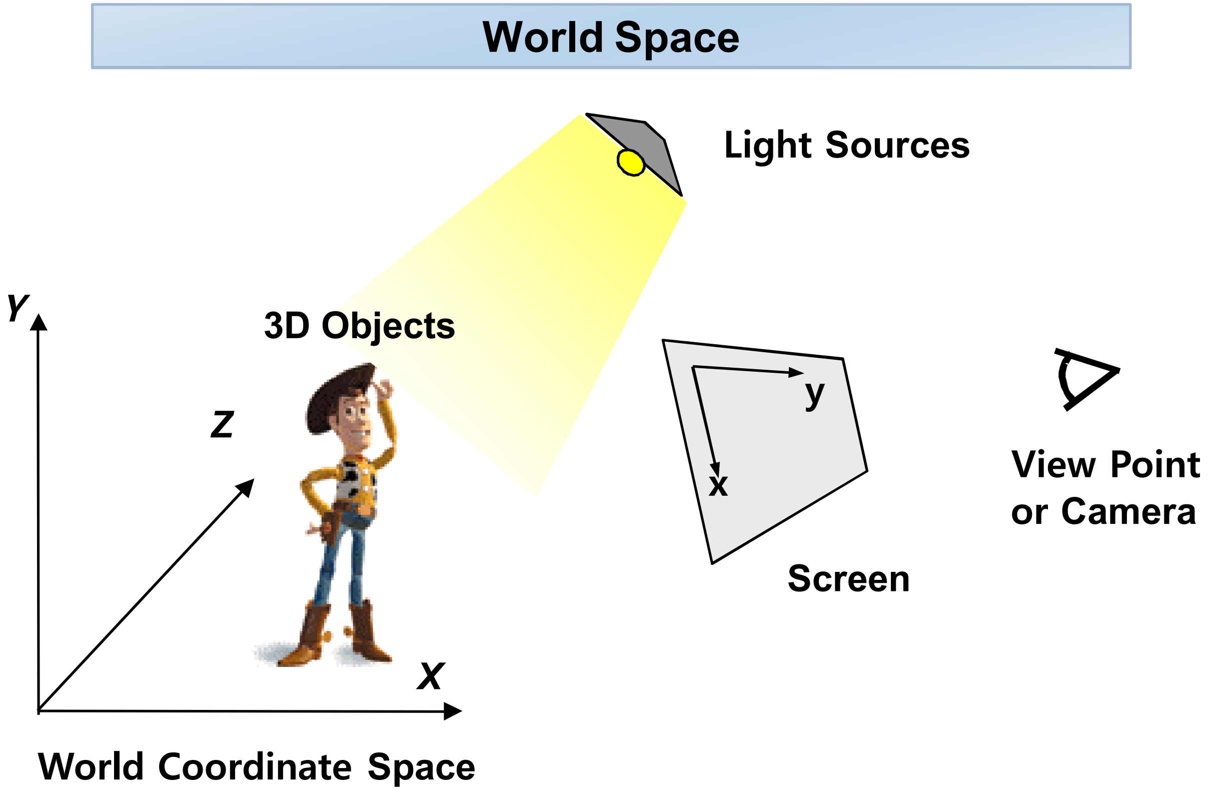
3D Graphics API & OpenGL (3).

- What can we do with OpenGL?
  - Modeling Primitives
  - Drawing Curve/Surfaces
  - Colors and Shading
  - Lights and Shadows
  - Texture mapping
  - Fog / Anti-aliasing
  - Blending / Transparency
  - And… So many things.



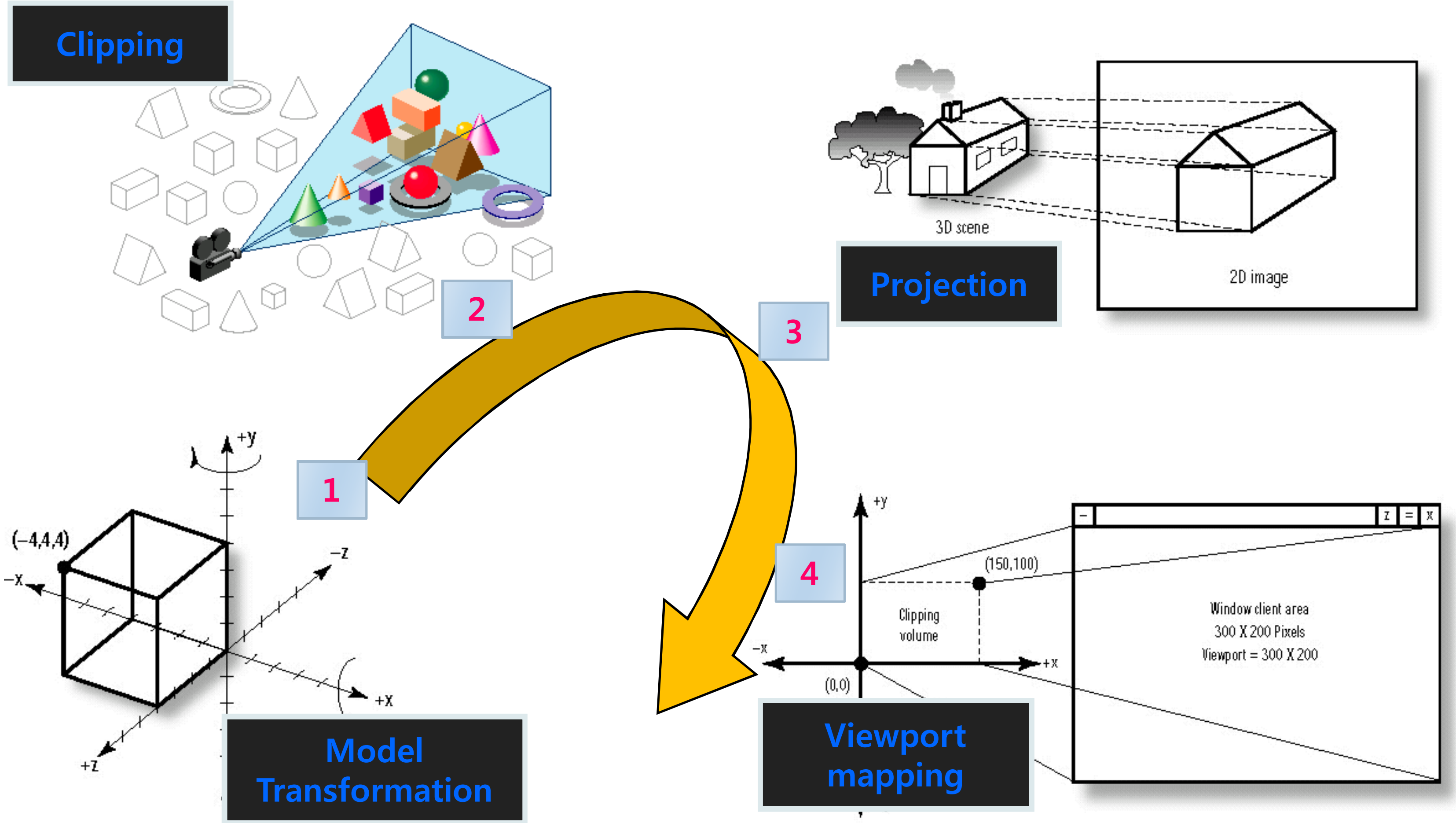
Interactive Computer Graphics (1)

- Problem Specification
  - 3D Objects → 2D Shaded image



Interactive Computer Graphics (2)

- 3D Objects to 2D image



Clipping

2

3

Projection

1

4

Model Transformation

Viewport mapping

Interactive Computer Graphics (3)

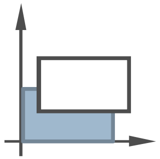
- Transformation Matrix
  - 3D coordinate transformation
  - 3D coordinate → 4D homogeneous coordinate
  - rotate/translate/scale/project is represented by 4x4 matrix
  - All transformation is implemented by multiplying matrices

Some Studies in 2D

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} a \\ b \end{bmatrix} \Rightarrow \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & a \\ 0 & 1 & b \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

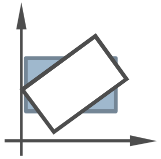
$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \Rightarrow \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1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

Interactive Computer Graphics (4)



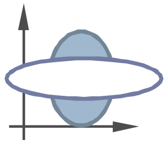
$$\begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Translation



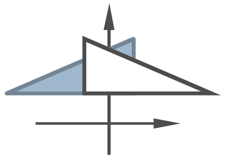
$$\begin{bmatrix} cos\theta & -sin\theta & 0 & 0 \\ sin\theta & cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation (about z-axis)



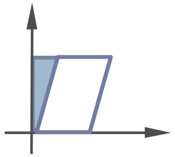
$$\begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Scaling



$$\begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Mirroring (about yz-plane)

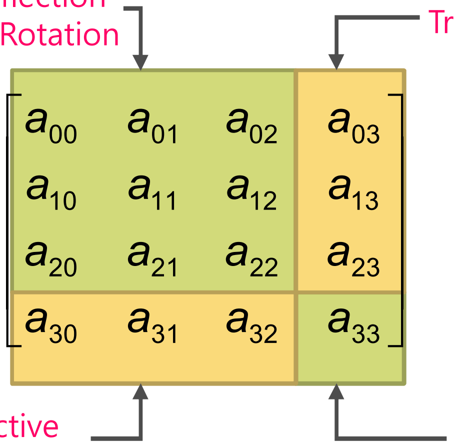


$$\begin{bmatrix} 1 & sh_x & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Shearing

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} \Rightarrow \begin{bmatrix} xh \\ yh \\ zh \\ h \end{bmatrix}$$

Homogeneous Coordinates



Scaling / Reflection / Shearing / Rotation

Translation

$$\begin{bmatrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ a_{30} & a_{31} & a_{32} & a_{33} \end{bmatrix}$$

Perspective transformation

Global Scaling

4x4 Transformation Matrix

Interactive Computer Graphics (5)

- Vertex transformation for each step in OpenGL

$$\begin{bmatrix} x_O \\ y_O \\ z_O \\ w_O \end{bmatrix} \rightarrow \begin{bmatrix} \text{ModelView} \\ \text{Matrix} \end{bmatrix} \rightarrow \begin{bmatrix} x_e \\ y_e \\ z_e \\ w_e \end{bmatrix} \rightarrow \begin{bmatrix} \text{Projection} \\ \text{Matrix} \end{bmatrix} \rightarrow \begin{bmatrix} x_c \\ y_c \\ z_c \\ w_c \end{bmatrix} \rightarrow \begin{bmatrix} \text{Perspective} \\ \text{Division} \end{bmatrix} \rightarrow \begin{bmatrix} x_c / w_c \\ y_c / w_c \\ z_c / w_c \end{bmatrix} \rightarrow \cdots$$

Original Vertex

Transformed Eye coordinates

Clip coordinates

Normalized Device coordinates

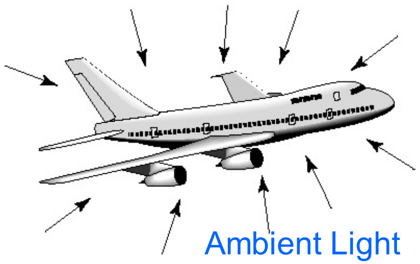
$$\cdots \rightarrow \begin{bmatrix} \text{Viewport} \\ \text{Transformation} \end{bmatrix} \rightarrow$$

Window coordinates

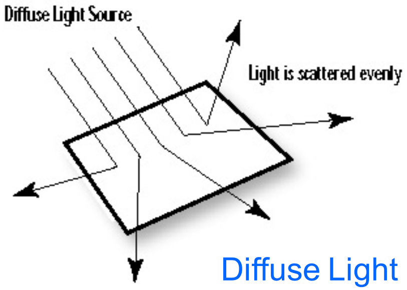
Most geometric transformation → “4x4 Matrix Multiplication”

Interactive Computer Graphics (6)

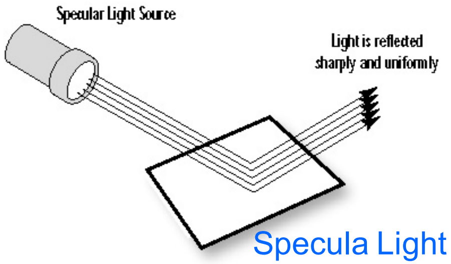
- Lighting
  - Color of point calculated with material property, normal vector, position of light



Ambient Light

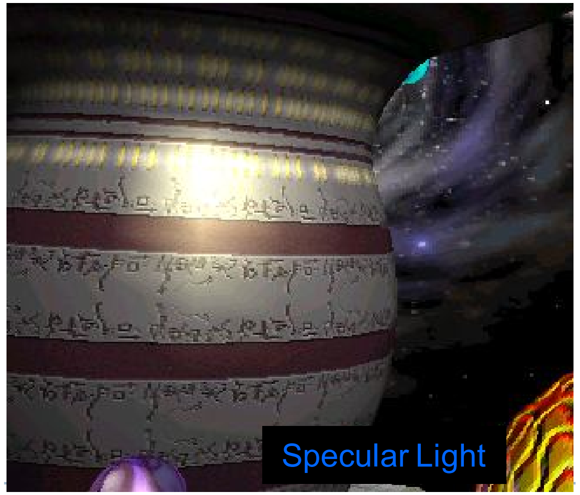


Diffuse Light



Specula Light

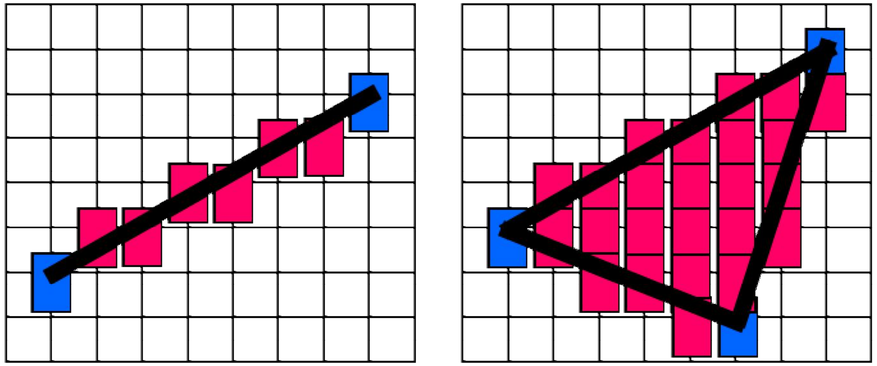
Diffuse Light



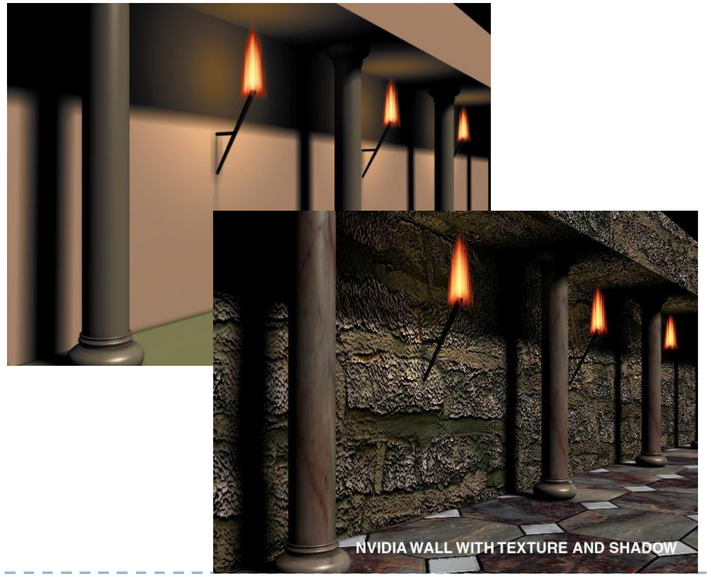
Interactive Computer Graphics (7)

- Rasterization
  - Lighting
  - Scan Converting
  - Hidden Surface Removal
  - Texture Mapping

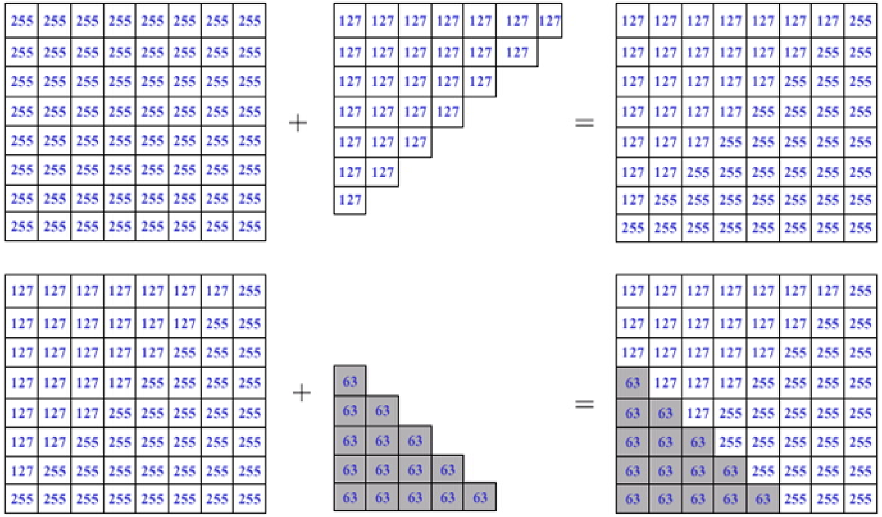
Scan Conversion of a line and a triangle



Benefits of the texture-mapping



Hidden Surface Removal with Z-buffer method



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63				
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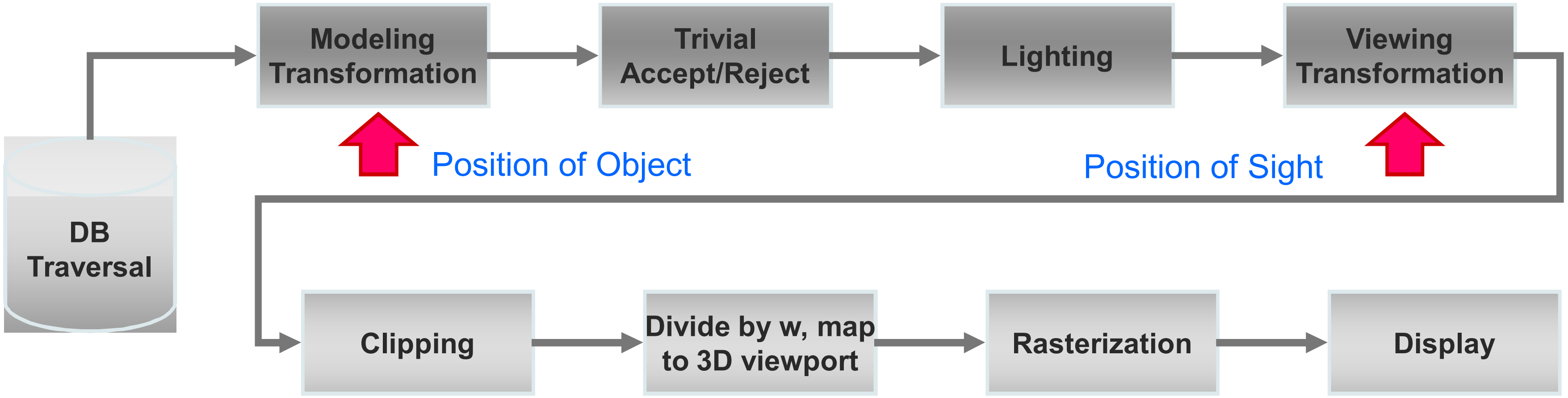
Interactive Computer Graphics (8).

- Standard 3D Graphics Pipeline
  - Model Coord. → World Coord. → View Coord.→ Lighting → Projection → Frustum Culling → Normalized Device Coord. → ViewPort → Rasterization
- OpenGL is..
  - Parallel process of geometric primitives and image data
  - State Machine / Z-buffer & Gouraud Shading

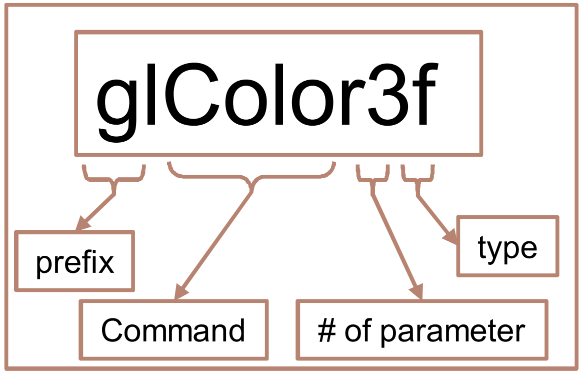


Preparatory (1)

- Needs for OpenGL programming
  - Device driver for Hardware acceleration of OpenGL
    - nVidia / ATI graphic card drivers
  - Development Toolkit (IDE)
    - Microsoft Visual Studio6, .NET 2003, .NET2005
  - OpenGL Programming Environment
    - header(.h) / library(.lib)
      - □ Header files : gl.h, glu.h, glaux.h, glut.h
      - □ Library files : opengl32.lib, glu32.lib, glut32.lib (by Microsoft)
        opengl.lib, glu.lib, glut.lib (by SGI)
  - Microsoft natively supports OpenGL
    - From Windows 98/NT4.0, but NOT include GLUT

Preparatory (2)

- OpenGL Command Syntax
  - About 130 functions.
  - All of functions has a prefix gl
    - Ex) glTranslate3f()
  - All of variables has a prefix GL_
    - Ex) GL_LIGHTING



<Example>
glColor3b
glColor3i
glColor3f
glColor3d
…
glColor4f
glColor4fv
…

Suffix	C++ type	OpenGL Type Definition
b	signed char	GLbyte
s	short	GLshort
i	long	GLint, GLsizei
f	float	GLfloat, GLclampf
d	double	GLdouble, GLclampd
ub	unsigned char	GLubyte, GLboolean
us	unsigned short	GLushort
ui	unsigned long	GLuint, GLenum, GLbitfield

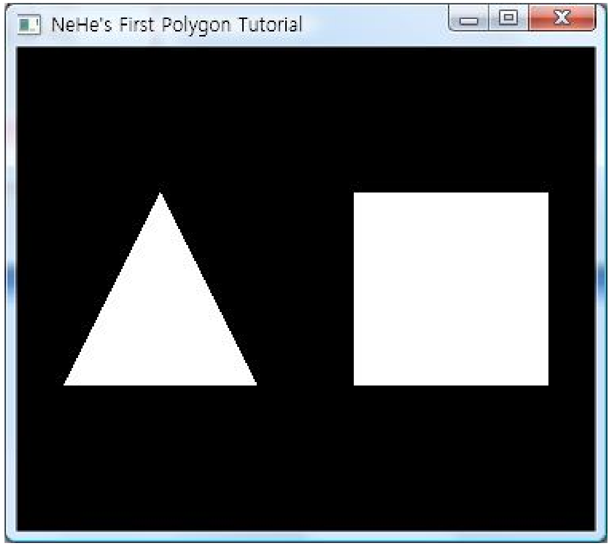
Preparatory (3).

- OpenGL related Libraries
  - OpenGL Utility library (GLU)
    - Prefix glu `gluLookAt();`
  - OpenGL Programming Guide Auxiliary library (AUX)
    - Prefix aux `auxSolidBox()`
  - OpenGL Utility Toolkits (GLUT)
    - Prefix glut `glutSolidCube()`
    - by Mark J. Kilgard, Silicon Graphics, Inc.
  - High-level Graphics Library
    - Open Inventor
    - OpenGL Performer, OpenGL Optimizer .etc

Simple code (1)

- Chunk of OpenGL code

```
#include <whateverYouNeed.h>
main()
{
            InitializeAWindowPlease();
            glClearColor (1.0, 1.0, 1.0, 1.0);
            glClear (GL_COLOR_BUFFER_BIT);
            glColor3f (0.0, 0.0, 0.0);
            glOrtho(0.0, 1.0, 0.0, 1.0, -1.0, 1.0);

            glBegin(GL_POLYGON);
                        glVertex3f (0.25, 0.25, 0.0);
                        glVertex3f (0.75, 0.25, 0.0);
                        glVertex3f (0.75, 0.75, 0.0);
                        glVertex3f (0.25, 0.75, 0.0);
            glEnd();
            glFlush();
            UpdateTheWindowAndCheckForEvents();
}
```



Simple code (2)

- Sample code using GLAUX library

```
#include "windows.h"
#include <GL/gl.h>
#include <GL/glu.h>
#include <GL/glaux.h>

void myinit (void)
{
     glClearColor (1.0, 1.0, 1.0, 1.0);
}

void CALLBACK display(void)
{
     glClear (GL_COLOR_BUFFER_BIT);

     glColor3f (0.0, 0.0, 0.0);
     glBegin(GL_POLYGON);
        glVertex3f (0.25, 0.25, 0.0);
        glVertex3f (0.75, 0.25, 0.0);
        glVertex3f (0.75, 0.75, 0.0);
        glVertex3f (0.25, 0.75, 0.0);
     glEnd ();

     glFlush ();
}
```

```
void CALLBACK myReshape(GLsizei w, GLsizei h)
{
        glMatrixMode(GL_PROJECTION);
        glLoadIdentity();
        glOrtho(0.0, 1.0, 0.0, 1.0, -1.0, 1.0);
        glMatrixMode(GL_MODELVIEW);
}

int main(int argc, char** argv)
{
        auxInitDisplayMode (AUX_SINGLE | AUX_RGB);
        auxInitPosition (0, 0, 500, 500);
        auxInitWindow ("Smooth Shading");
        myinit();
        auxReshapeFunc (myReshape);
        auxMainLoop(display);
        return 0;
}
```

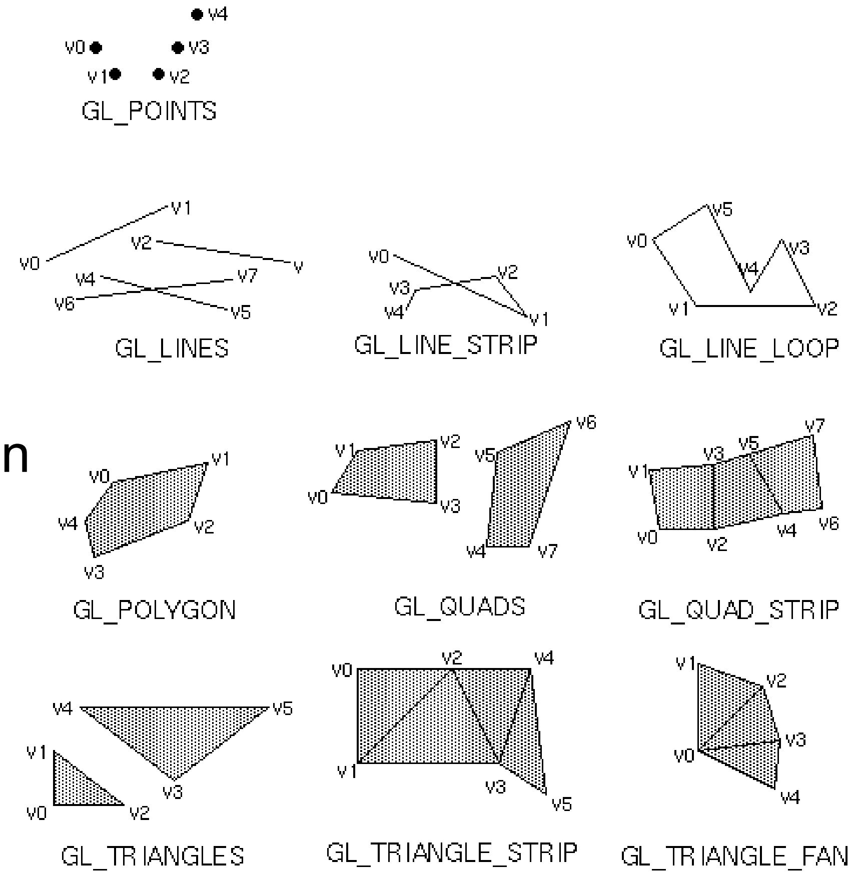
Simple code (3).

- Drawing Objects
  - Create vertices

```
glVertex2s(2, 3);
glVertex3d(0.0, 0.0, 3.14159265);
glVertex4f(2.3f, 1.0f, -2.2f, 2.0f);
```

  - Create primitives
    - Point, Line, Triangle, Polygon

```
glBegin(GL_POLYGON);
            glVertex2f(0.0, 0.0);
            glVertex2f(0.0, 3.0);
            glVertex2f(4.0, 3.0);
            glVertex2f(6.0, 1.5);
            glVertex2f(4.0, 0.0);
glEnd();
```



GLUT Functions (1)

Initializing and Exiting a Window

-void glutInit(int *argcp, char **argv);
-void glutInitDisplayMode(unsigned int mode);
-void glutInitWindowSize(int width, int height);
-void glutInitWindowPosition(int x, int y);
-void glutDestroyWindow(int win);

Loading the Color Map

-void glutSetColor(int cell, GLfloat red, GLfloat green, GLfloat blue);
-GLfloat glutGetColor(int cell, int component);
-void glutSwapBuffers(void);
-void glutStrokeCharacter(void *font, int character);

Managing Background Process

-void glutIdleFunc(void (*func)(void));

Running the Program

-void glutMainLoop(void);

GLUT Functions (2).

Initializing and Drawing Three-Dimensional Objects

-void glutSolidSphere(GLdouble radius, GLint slices, GLint stacks);
-void glutWireSphere(GLdouble radius, GLint slices, GLint stacks);
-void glutSolidCone(GLdouble base, GLdouble height, GLint slices, GLint stacks);
-void glutWireCone(GLdouble base, GLdouble height, GLint slices, GLint stacks);
-void glutSolidTorus(GLdouble innerRadius, GLdouble outerRadius, GLint nsides, GLint rings);
-void glutWireTorus(GLdouble innerRadius, GLdouble outerRadius, GLint nsides, GLint rings);
-void glutSolidCube(GLdouble size);
-void glutSolidDodecahedron(void);
-void glutSolidOctahedron(void);
-void glutSolidTetrahedron(void);
-void glutSolidIcosahedron(void);
-void glutSolidTeapot(GLdouble size);
-void glutWireCube(GLdouble size);
-void glutWireDodecahedron(void);
-void glutWireOctahedron(void);
-void glutWireTetrahedron(void);
-void glutWireIcosahedron(void);
-void glutWireTeapot(GLdouble size);

Handling Window and Input Events

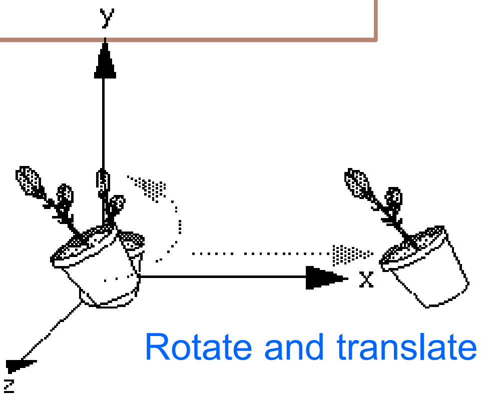
-void glutReshapeFunc(void (*func)(int width, int height));
-void glutKeyboardFunc(void (*func)(unsigned char key, int x, int y));
-void glutMouseFunc(void (*func)(int button, int state, int x, int y));

Transformation Matrix (1)

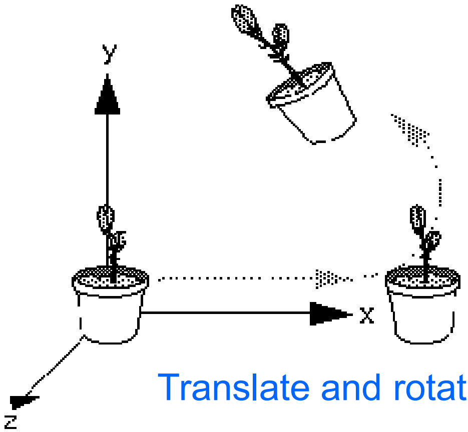
- General Transform Command
  - glMultiMatrix*() function - 4x4 matrix multiplication
  - The order of transformation is important

```
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
glMultMatrixf(N);
glMultMatrixf(M);
glMultMatrixf(L);
glBegin(GL_POINTS);
glVertex3f(v);
glEnd();
```

Transformation result = N (M (L · v)
= N ·M ·L ·v



Rotate and translate



Translate and rotate

Transformation Matrix (2)

- Matrix Mode
  - ModelView matrix mode [GL_MODELVIEW]
    - Transform object position (change local coordinate)

```
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
```

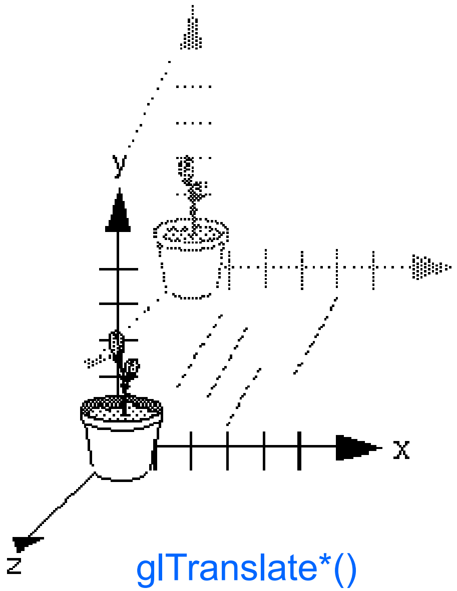
  - Projection matrix mode [GL_PROJECTION]
    - Matrix for 2D projection
    - Define the viewing volume

```
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
```

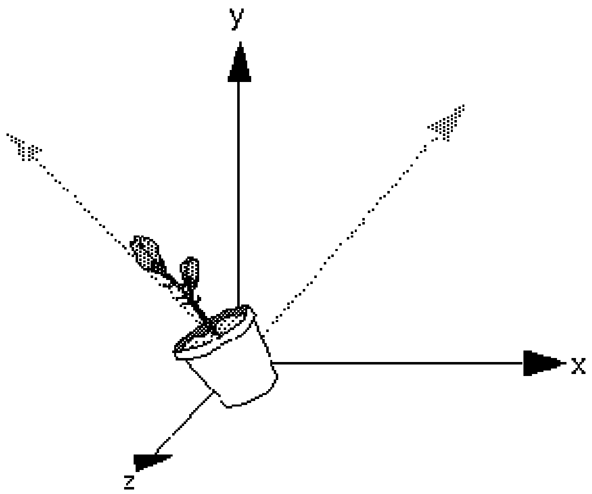
Transformation Matrix (3)

- Modeling Transform [GL_MODELVIEW]
  - 3 routine for modeling transform in OpenGL

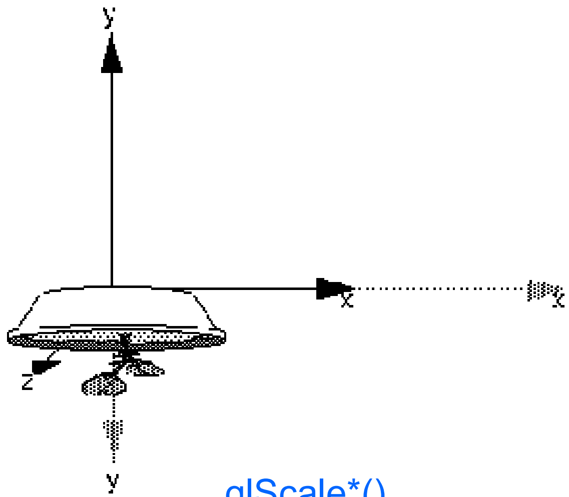
glTranslate*(), glRotate*(), glScale*()



glTranslate*()



glRotate*()

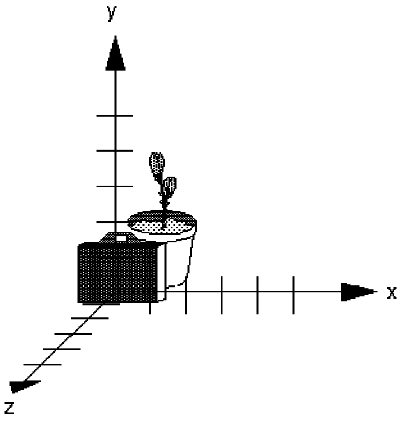


glScale*()

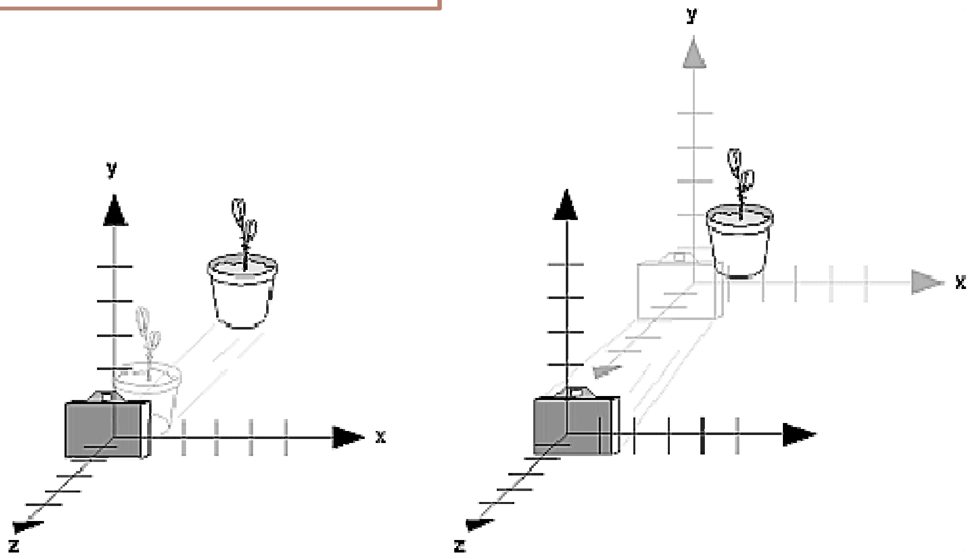
Transformation Matrix (4)

- Viewing Transform [GL_MODELVIEW]
  - 2 routine for viewing transform in OpenGL

glTranslate*(), glRotate*()



Initial state of
viewing vs. modeling coord.

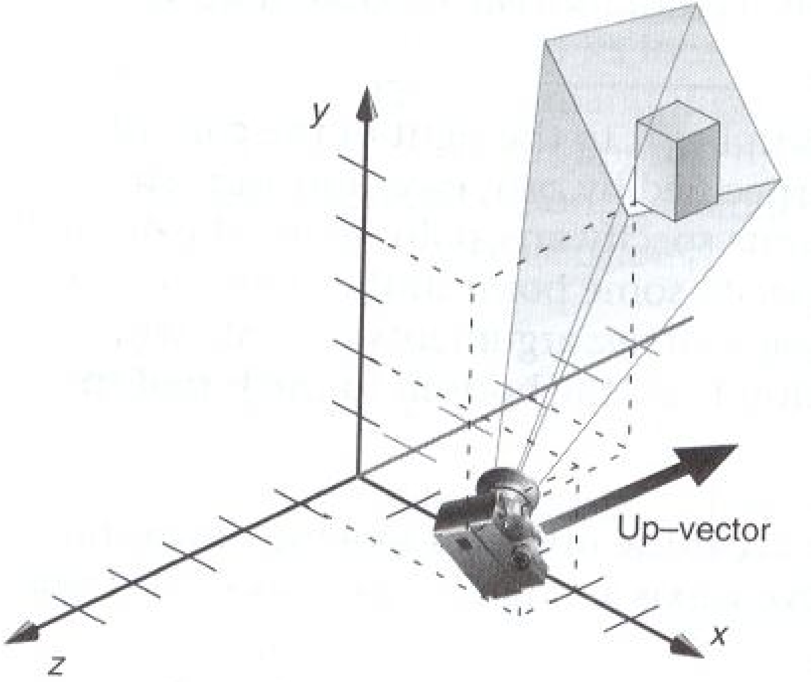


glTranslatef(0.0, 0.0, -5.0);

Transformation Matrix (5)

- Viewing Transform [GL_MODELVIEW]
  - gluFunction to define the viewing transform easily

```
void gluLookAt( GLdouble eyex, GLdouble eyey, GLdouble eyez, GLdouble centerx,
GLdouble centery, GLdouble centerz, GLdouble upx, GLdouble upy, GLdouble upz )
```

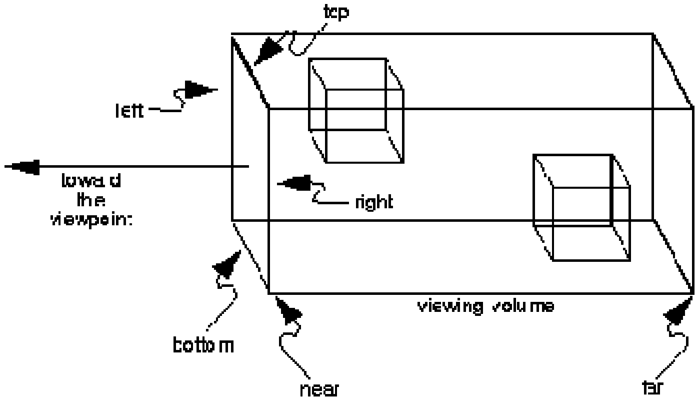


Transformation Matrix (6)

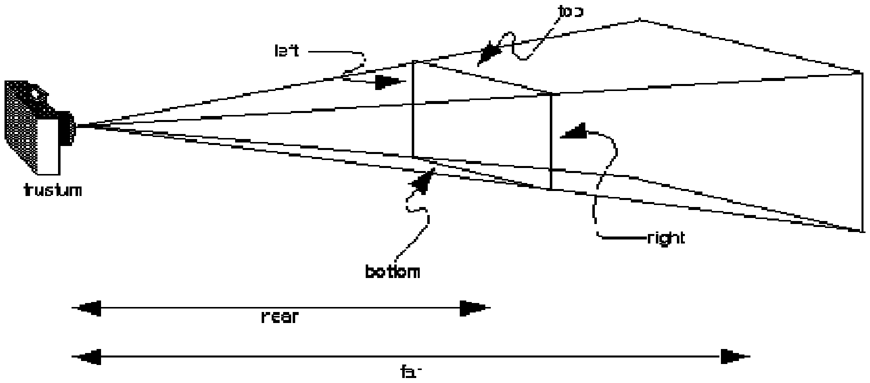
- Projection Transform [GL_PROJECTION]
  - Viewing volume is determined by view coordinate
    - So must be called in Projection Matrix mode

```
void glOrtho( GLdouble left, GLdouble right, GLdouble bottom, GLdouble top, GLdouble zNear, GLdouble zFar )
```

```
void glFrustum( GLdouble left, GLdouble right, GLdouble bottom, GLdouble top, GLdouble zNear, GLdouble zFar)
```



orthogonal projection using glOrtho()

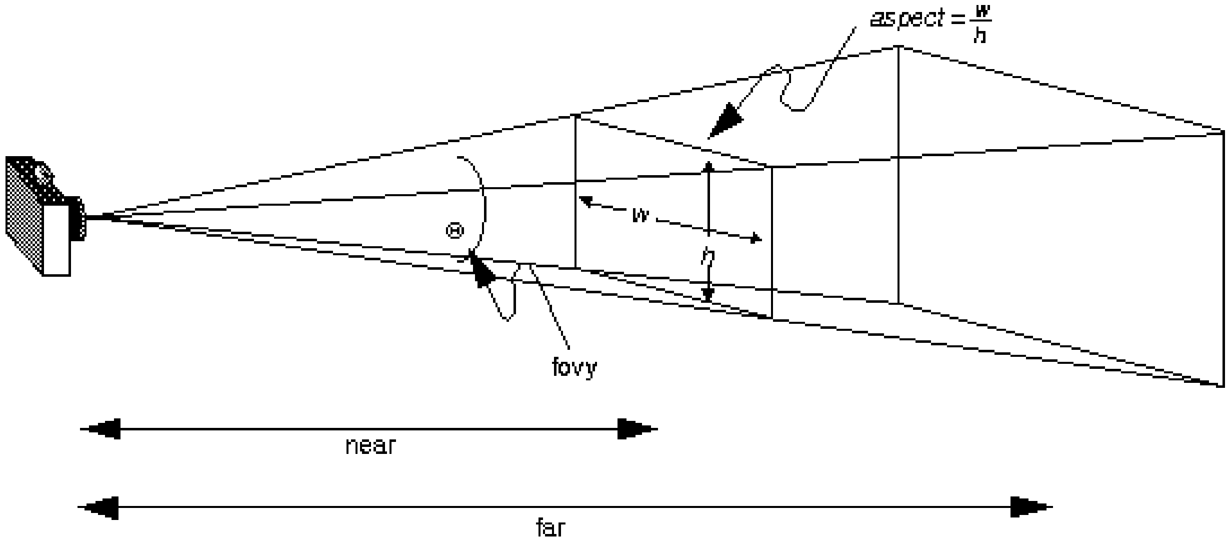


perspective projection using glFrustum()

Transformation Matrix (7)

- Projection Transform [GL_PROJECTION]
  - gluFunction to define viewing volume easily

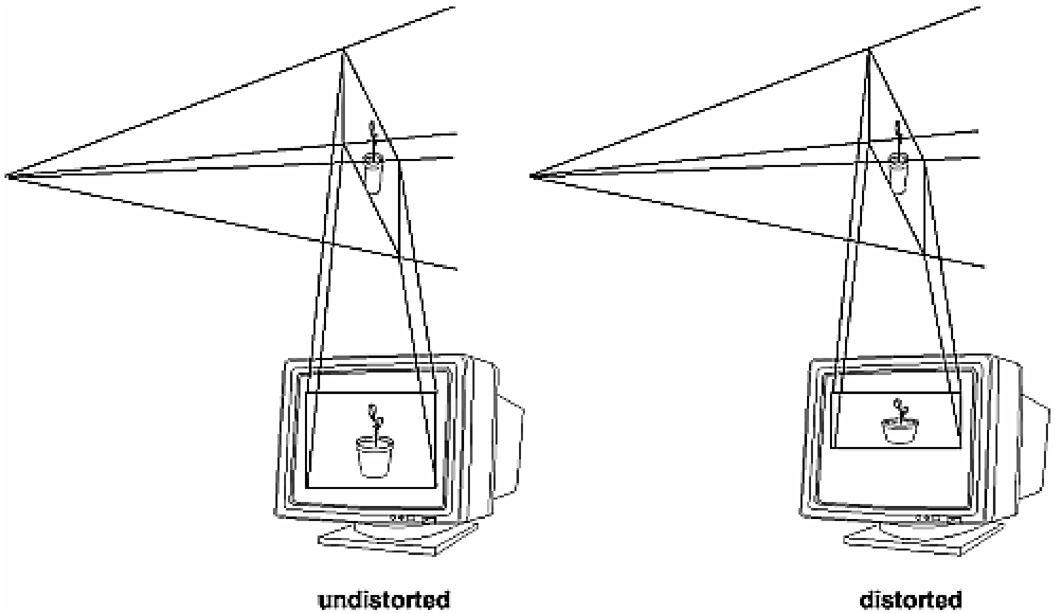
```
void gluPerspective( GLdouble fovy, GLdouble aspect, GLdouble znear, GLdouble zfar)
```



Perspective viewing volume using gluPerspective()

Transformation Matrix (8).

- Viewport Transform
  - Mapping the projected image to the 2D window
  - May expect distortion from different aspect ratio
  - Can use multiple viewport



Distortion from difference between the aspect ratios of viewing volume and window

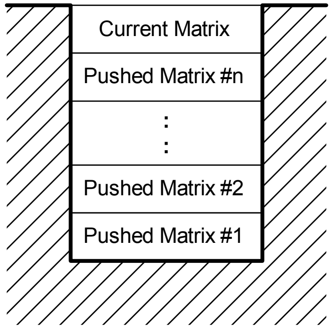
** MUST change the aspect ratio of viewing volume to fit with that of window

Matrix Manipulation (1)

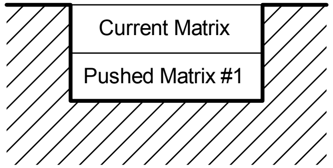
- Push/Pop Matrix
  - To draw several objects with hierarchy, we must save transformation matrix of previous step
    - assembly #n: A···N · M
    - sub-assembly #ni: A···N · M · L
    - assembly #n+1: A···N · M

```
glPushMatrix();
glMultiMatrix(L);
DrawSubAssy(ni);
glPopMatrix();
```

- Matrix Stack of ModelView / Projection Matrix



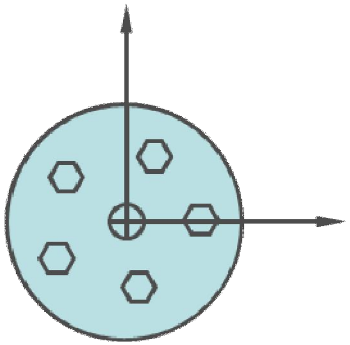
Modelview
Matrix Stack
(32, 4*4 Matrix)

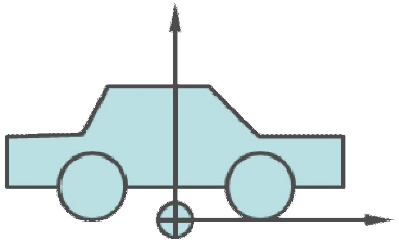


Projection
Matrix Stack
(2, 4*4 Matrix)

Matrix Manipulation (2).

- Example code of Push/Pop Matrix





```
void draw_wheel_and_bolts( )
{
        long I;
        draw_wheel( );
        for( i = 0; i < 5; i++ ) {
                glPushMatrix( );
                    glRotatef( 72.0*i 0.0, 0.0, 1.0 );
                    glTranslatef( 3.0, 0.0, 0.0 );
                    draw_bolt( );
                glPopMatrix( );
        }
}
void draw_body_and_wheel_and_bolts ( )
{
        draw_car_body( );
        glPushMatrix( );
                glTranslatef( 40, 0, 30 );          // move to first wheel's
                draw_wheel_and_bolts( );
        glPopMatrix( );
        glPushMatrix( );
                glTranslatef( 40, 0, -30 );         // move to second wheel's
                draw_wheel_and_bolts( );
        glPopMatrix( );
        .........................                   // move to last wheels'
}
```

Other Settings (1)

- Color
  - RGBA mode
    - Set red, green, blue, alpha values as float (0.0 ~ 1.0)
      - □ Ex) 1.0, 0.0, 0.0 → red , 0.5, 0.5, 0.5 → gray
    - Using glColor*() function
      - □ Ex) glColor4f(1.0f, 0.0f, 0.0f, 1.0f);
  - Color Indexed mode
    - Set index of color as color-lookup-table
    - Using glIndex*() function
    - Can specify your own color-table
      - □ Ex) auxSetOneColor(), glutSetOnColor()
  - RGBA mode is widely used.

Other Settings (2)

- Lighting
  - Determine the color of the object at final 2D raster graphic
  - Using glLight*() function
  - GL_AMBIENT / GL_DIFFUSE / GL_SPECULAR

w=0
Directional light
w=1
Positional light

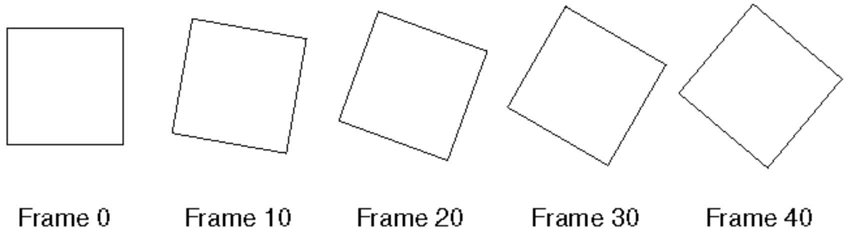
```
GLfloat light_ambient[]     = { 0.0, 0.0, 0.0, 1.0 };
GLfloat light_diffuse[]     = { 1.0, 1.0, 1.0, 1.0 };
GLfloat light_specular[]    = { 1.0, 1.0, 1.0, 1.0 };
GLfloat light_position[]    = { 1.0, 1.0, 1.0, 0.0 };

glLightfv(GL_LIGHT0, GL_AMBIENT, light_ambient);
glLightfv(GL_LIGHT0, GL_DIFFUSE, light_diffuse);
glLightfv(GL_LIGHT0, GL_SPECULAR, light_specular);
glLightfv(GL_LIGHT0, GL_POSITION, light_position);

glEnable(GL_LIGHTING);
glEnable(GL_LIGHT0);
```

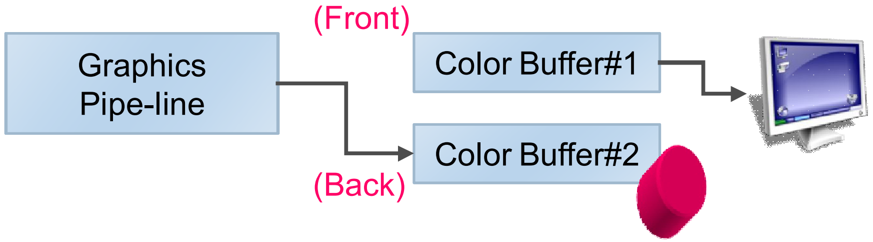
```
GLfloat light1_ambient[] = { 0.2, 0.2, 0.2, 1.0 };
GLfloat light1_diffuse[] = { 1.0, 1.0, 1.0, 1.0 };
GLfloat light1_specular[] = { 1.0, 1.0, 1.0, 1.0 };
GLfloat light1_position[] = { -2.0, 2.0, 1.0, 1.0 };
GLfloat spot_direction[] = { -1.0, -1.0, 0.0 };

glLightfv(GL_LIGHT1, GL_AMBIENT, light1_ambient);
glLightfv(GL_LIGHT1, GL_DIFFUSE, light1_diffuse);
glLightfv(GL_LIGHT1, GL_SPECULAR, light1_specular);
glLightfv(GL_LIGHT1, GL_POSITION, light1_position);

glLightf(GL_LIGHT1, GL_CONSTANT_ATTENUATION, 1.5);
glLightf(GL_LIGHT1, GL_LINEAR_ATTENUATION, 0.5);
glLightf(GL_LIGHT1, GL_QUADRATIC_ATTENUATION, 0.2);
glLightf(GL_LIGHT1, GL_SPOT_CUTOFF, 45.0);
glLightfv(GL_LIGHT1, GL_SPOT_DIRECTION, spot_direction);
glLightf(GL_LIGHT1, GL_SPOT_EXPONENT, 2.0);

glEnable(GL_LIGHT1);
```

Other Settings (3)

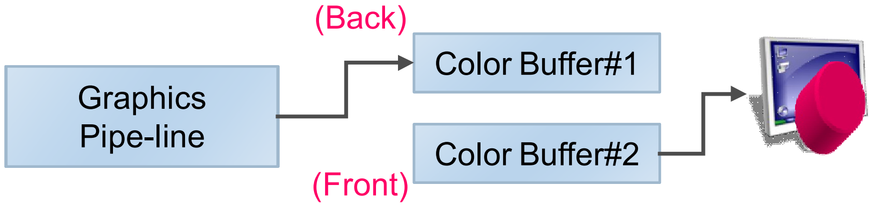
- Double buffering to avoid flickering

```
void glClearColor( GLclampf red, GLclampf green,
                                   GLclampf blue, GLclampf alpha )
        // define default color buffer in RGBA mode
void glClearIndex( GLfloat index )
        // define default color buffer in color-index mode
void glClearDepth( GLclampd depth )
        // depth 0.0 ~ 1.0
void glClearStencil( GLint s )
void glClearAccum(GLfloat red, GLfloat green,
                                    GLfloat blue, GLfloat alpha )
void glClear( GLbitfield mask )
        // initialize frame buffer as default
        // mask      GL_COLOR_BUFFER_BIT,
                     GL_DEPTH_BUFFER_BIT,
                     GL_STENCIL_BUFFER_BIT,
                     GL_ACCUM_BUFFER_BIT
void glDrawBuffer( GLenum mode )
        // define color buffer to draw
        // default   single buffer mode : GL_FRONT
                     double buffer mode : GL_BACK
void glutSwapBuffers();
        //MUST SwapBuffer after draw an object
                              in double-buffering mode
```





glutSwapBuffers();



Other Settings (4).

- Sample code using double-buffering

```
#include "windows.h"
#include <GL/gl.h>
#include <GL/glu.h>
#include <GL/glaux.h>

void myinit (void)
{
     glClearColor (1.0, 1.0, 1.0, 1.0);
}

void CALLBACK display(void)
{
     glClear (GL_COLOR_BUFFER_BIT);

     glColor3f (0.0, 0.0, 0.0);
     glBegin(GL_POLYGON);
         glVertex3f (0.25, 0.25, 0.0);
         glVertex3f (0.75, 0.25, 0.0);
         glVertex3f (0.75, 0.75, 0.0);
         glVertex3f (0.25, 0.75, 0.0);
     glEnd ();
     glFlush ();
     auxSwapBuffers();
}
```

```
void CALLBACK myReshape(GLsizei w, GLsizei h)
{
       glMatrixMode(GL_PROJECTION);
       glLoadIdentity();
       glOrtho(0.0, 1.0, 0.0, 1.0, -1.0, 1.0);
       glMatrixMode(GL_MODELVIEW);
}

int main(int argc, char** argv)
{
       auxInitDisplayMode (AUX_DOUBLE | AUX_RGB);
       auxInitPosition (0, 0, 500, 500);
       auxInitWindow ("Smooth Shading");
       myinit();
       auxReshapeFunc (myReshape);
       auxMainLoop(display);
       return 0;
}
```

** Compare with 18 Page

Useful Site for OpenGL

- OpenGL Manual Page
  - http://www.opengl.org/documentation/specs/man_pages/hardcopy/GL/html/
- OpenGL Utility Toolkit (GLUT) API
  - http://www.opengl.org/documentation/specs/glut/spec3/spec3.html
- OpenGL FAQ and Troubleshooting Guide
  - http://www.opengl.org/resources/faq/technical/
- Forum (Tutorial & Sourcecode)
  - http://nehe.gamedev.net/
  - http://www.codeguru.com/