CS559: Computer Graphics

Lecture 12: OpenGL: ModelView

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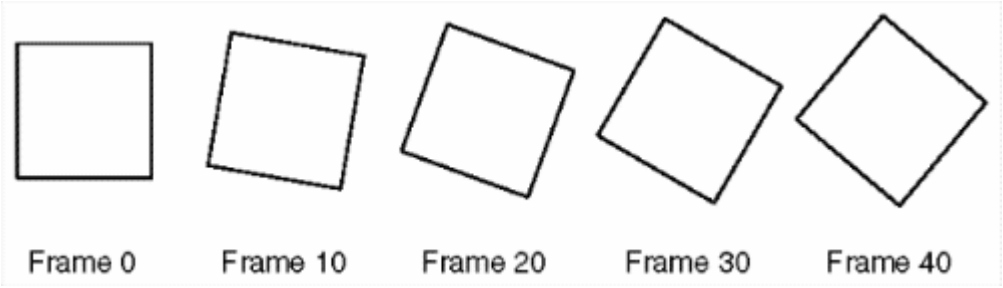
Spring 2010

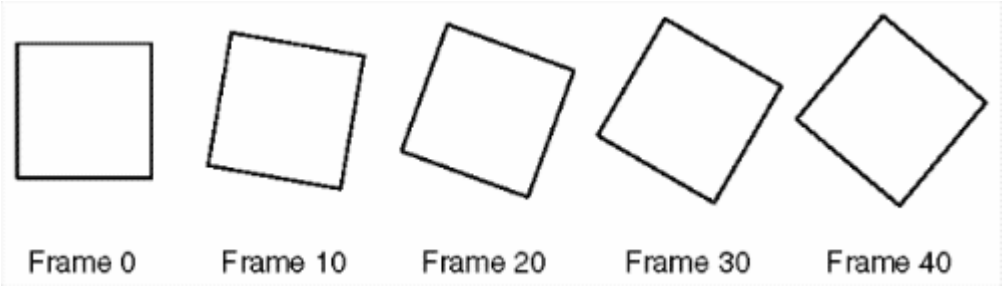
Animation Example




```
int main(int argc, char** argv){
     glutInit(&argc, argv);
     glutInitDisplayMode (GLUT_DOUBLE | GLUT_RGB);
     glutInitWindowSize (250, 250);
     glutInitWindowPosition (100, 100);
     glutCreateWindow (argv[0]);
     init ();
     glutDisplayFunc(display);



}
```

```
void init(void) {
     glClearColor (0.0, 0.0, 0.0, 0.0);
     glShadeModel (GL_FLAT);
}
```

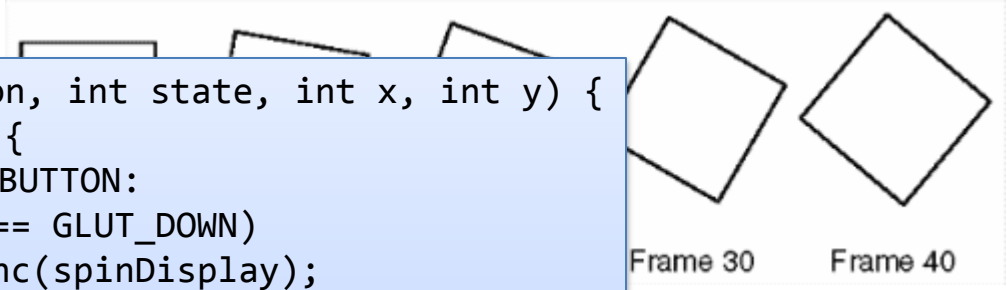
Animation Example




```
static GLfloat spin = 0.0;

void display(void){
     glClear(GL_COLOR_BUFFER_BIT);
     glPushMatrix();
     glRotatef(spin, 0.0, 0.0, 1.0);
     glColor3f(1.0, 1.0, 1.0);
     glRectf(-25.0, -25.0, 25.0, 25.0);
     glPopMatrix();
     glutSwapBuffers();
}
```

```
int main(int argc, char** argv){
     glutInit(&argc, argv);
     glutInitDisplayMode (GLUT_DOUBLE | GLUT_RGB);
     glutInitWindowSize (250, 250);
     glutInitWindowPosition (100, 100);
     glutCreateWindow (argv[0]);
     init ();
     glutDisplayFunc(display);
     glutMouseFunc(mouse);
```

Animation Example

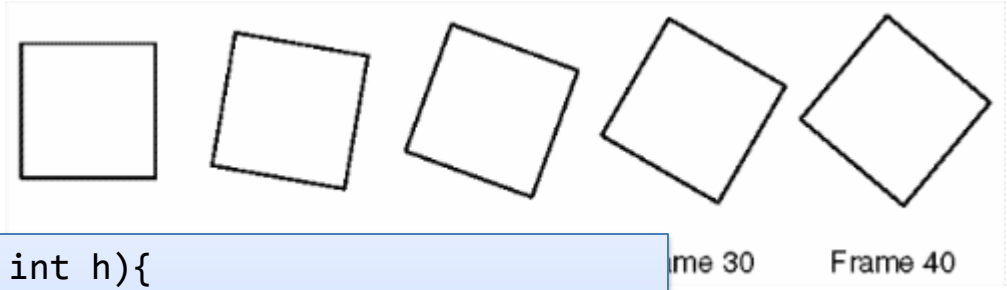



```
void mouse(int button, int state, int x, int y) {
    switch (button) {
     case GLUT_LEFT_BUTTON:
          if (state == GLUT_DOWN)
          glutIdleFunc(spinDisplay);
          break;
     case GLUT_MIDDLE_BUTTON:
          if (state == GLUT_DOWN)
          glutIdleFunc(NULL);
          break;
     default:
          break;
     }
}
```

```
rgc, char** argv){
&argc, argv);
isplayMode (GLUT_DOUBLE | GLUT_RGB);
indowSize (250, 250);
indowPosition (100, 100);
eWindow (argv[0]);

ayFunc(display);
glutMouseFunc(mouse);
glutReshapeFunc(reshape);
```

```
spinDisplay(void){
     spin = spin + 2.0;
     if (spin > 360.0) spin -= 360.0;
     glutPostRedisplay();
}
```

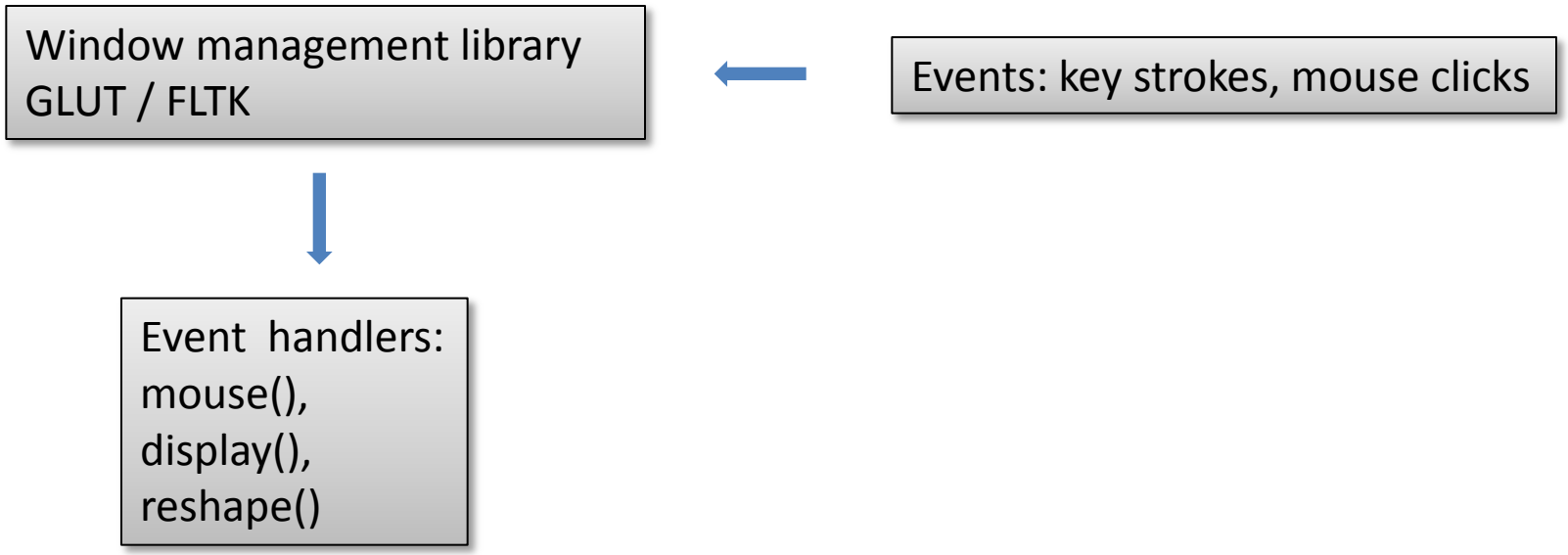
Animation Example




```
void reshape(int w, int h){
     glViewport (0, 0, (GLsizei) w, (GLsizei) h);
     glMatrixMode(GL_PROJECTION);
     glLoadIdentity();
     glOrtho(-50.0, 50.0, -50.0, 50.0, -1.0, 1.0);
     glMatrixMode(GL_MODELVIEW);
     glLoadIdentity();
}
```

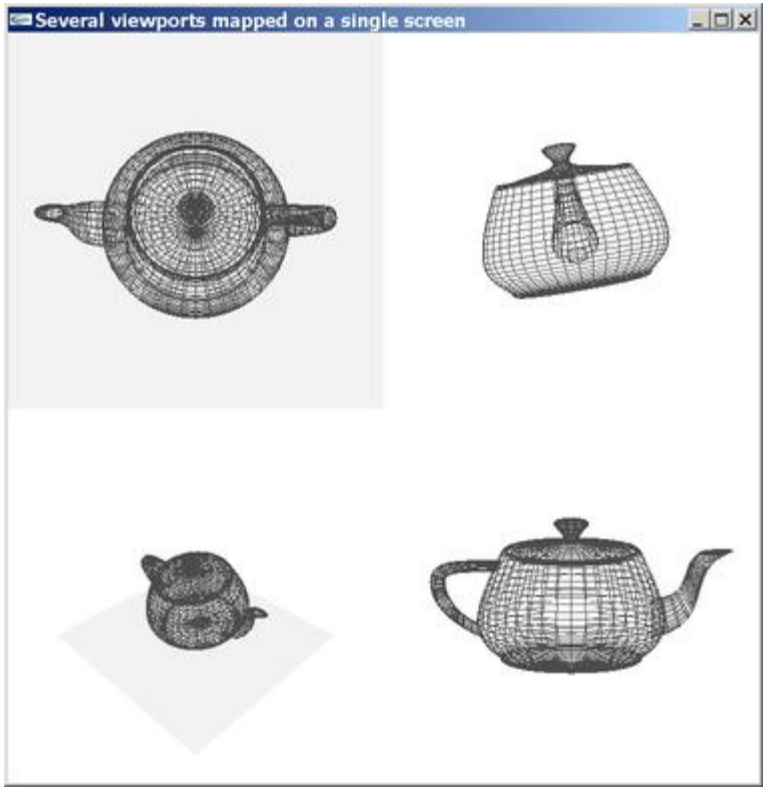
```
c, char** argv){
rgc, argv);
playMode (GLUT_DOUBLE | GLUT_RGB);
dowSize (250, 250);
dowPosition (100, 100);
indow (argv[0]);
     init ();
     glutDisplayFunc(display);
     glutMouseFunc(mouse);
     glutReshapeFunc(reshape);
     glutMainLoop();   return 0;
}
```

Event-Driven Programming



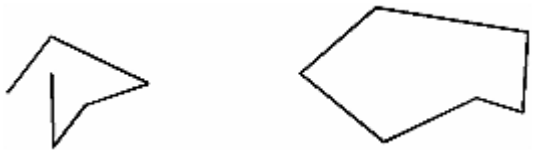
Viewport

```
void reshape (int w, int h) {
    glViewport (0, 0, w, h);
    glMatrixMode (GL_PROJECTION);
    glLoadIdentity ();
    gluOrtho2D (0.0, w, 0.0, h);
}
```

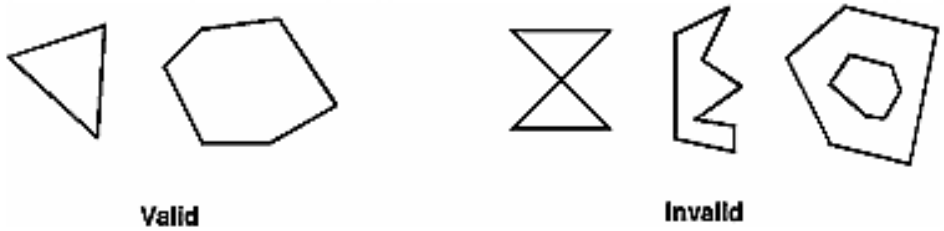


Points, lines, and polygons

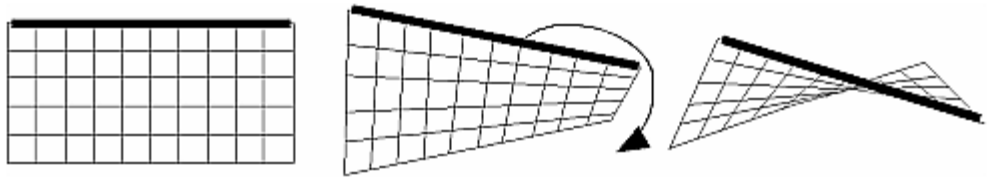
- Points
- Lines



- Polygons



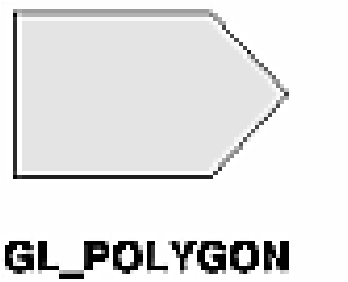
Simple Polygonss: Convex & planar



Nonplanar Polygon Transformed to Nonsimple Polygon

Drawing Primitives

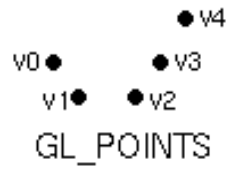
```
glBegin(GL_POLYGON);
glVertex2f(0.0, 0.0);
glVertex2f(0.0, 3.0);
glVertex2f(4.0, 3.0);
glVertex2f(6.0, 1.5);
glVertex2f(4.0, 0.0);
glEnd();
```



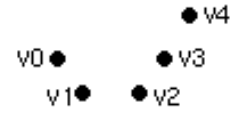
Drawing Primitives

```
glBegin(GL_POINTS);
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();
```

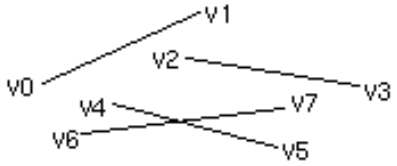
Drawing Primitives



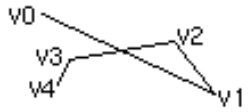
Drawing Primitives



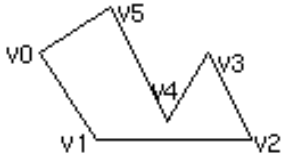
GL_POINTS



GL_LINES

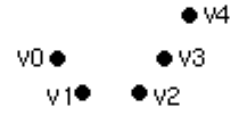


GL_LINE_STRIP

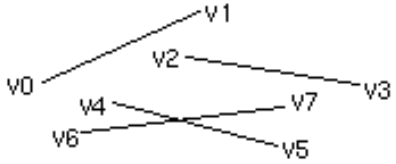


GL_LINE_LOOP

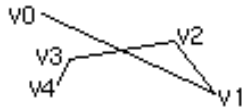
Drawing Primitives



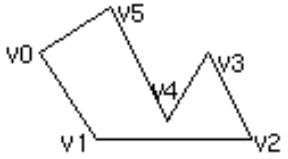
GL_POINTS



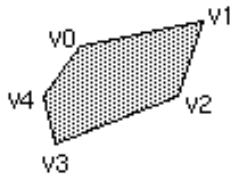
GL_LINES



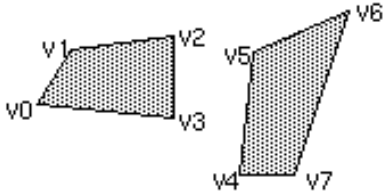
GL_LINE_STRIP



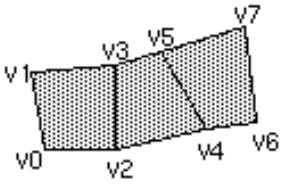
GL_LINE_LOOP



GL_POLYGON

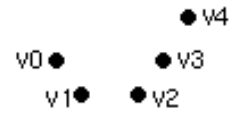


GL_QUADS

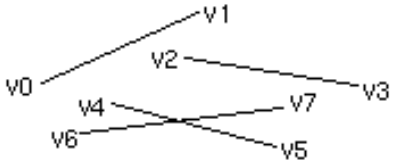


GL_QUAD_STRIP

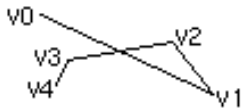
Drawing Primitives



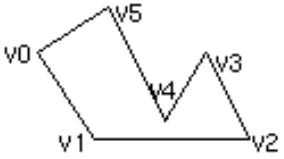
GL_POINTS



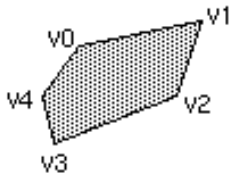
GL_LINES



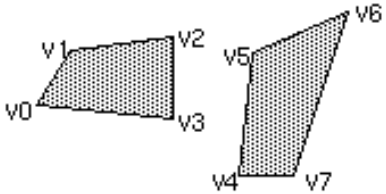
GL_LINE_STRIP



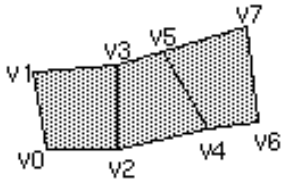
GL_LINE_LOOP



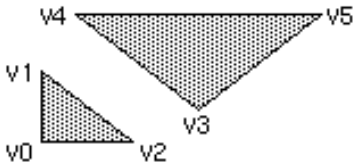
GL_POLYGON



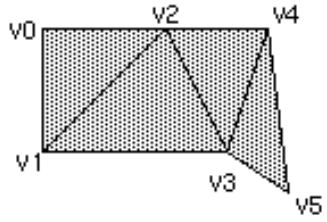
GL_QUADS



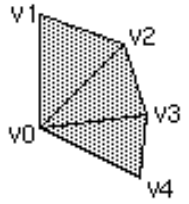
GL_QUAD_STRIP



GL_TRIANGLES



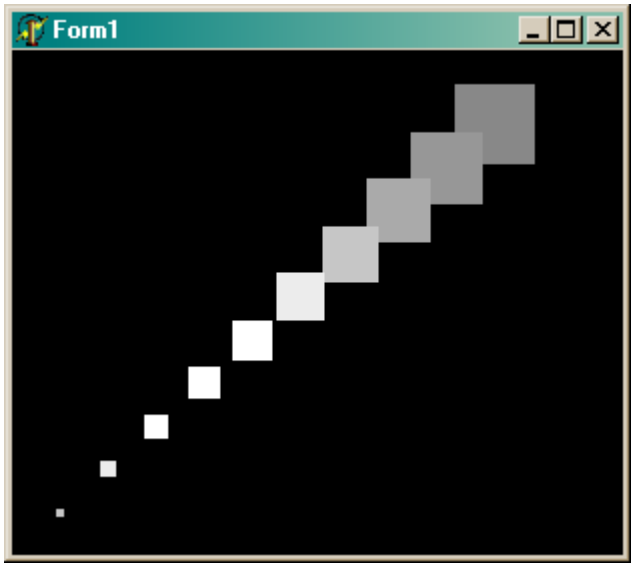
GL_TRIANGLE_STRIP

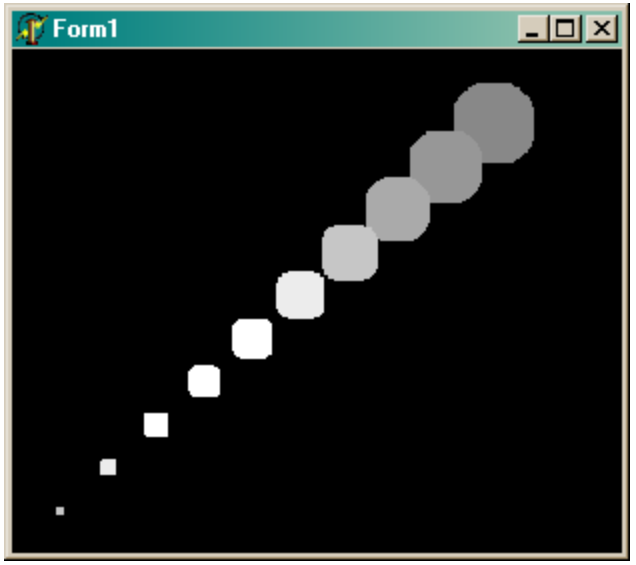


GL_TRIANGLE_FAN

Primitive Details

- glPointSize(GLfloat size)
  - Approximate the point by squares for anti-aliasing

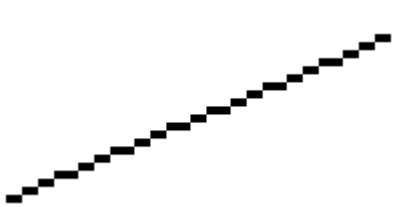





```
glEnable(GL_POINT_SMOOTH);
```

Primitive Details

- glLineWidth(GLfloat width)
  - Approximate the line by a rectangle for anti-aliasing

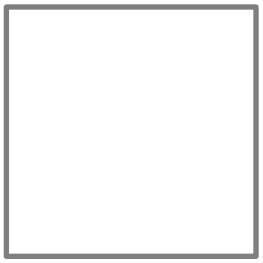


```
glEnable (GL_LINE_SMOOTH);
glLineWidth (1.5);
```

Primitive Details

- glPolygonMode(*GLenum face, GLenum mode);*
  - face: GL_FRONT, GL_BACK
  - mode: GL_POINT, GL_LINE, GL_FILL

```
glPolygonMode(GL_FRONT, GL_FILL);
glRectf(0, 0, 100, 100);
```

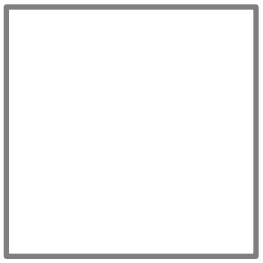


```
glPolygonMode(GL_FRONT, GL_LINE);
glRectf(0, 0, 100, 100);
```

Primitive Details

- glPolygonMode(*GLenum face, GLenum mode);*
  - face: GL_FRONT, GL_BACK
  - mode: GL_POINT, GL_LINE, GL_FILL

```
glPolygonMode(GL_FRONT, GL_FILL);
glRectf(0, 0, 100, 100);
```



```
glPolygonMode(GL_BACK, GL_LINE);
glRectf(0, 0, 100, 100);
```

Primitive Details

- Determine Polygon Orientation

$$area(P_1P_2P_3P_4)$$

$$= area(P_1P_2Q_2Q_1) + area(P_2P_3Q_3Q_2)$$

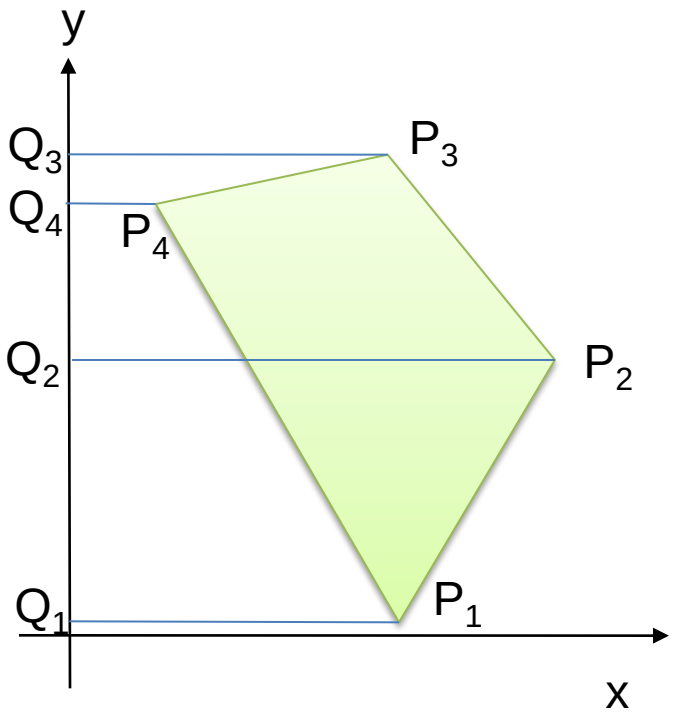
$$- area(P_3P_4Q_4Q_3) - area(P_4P_1Q_4Q_1)$$

$$area = \sum_{n=1}^{N} \frac{1}{2}(x_i + x_{i+1})(y_{i+1} - y_i)$$

$$= \frac{1}{2}\left(\sum_{n=1}^{N} x_i y_{i+1} - \sum_{n=1}^{N} x_i y_i + \sum_{n=1}^{N} x_{i+1} y_{i+1} - \sum_{n=1}^{N} x_{i+1} y_i \right)$$

$$= \frac{1}{2} \sum_{n=1}^{N} \left(x_i y_{i+1} - x_{i+1} y_i \right)$$

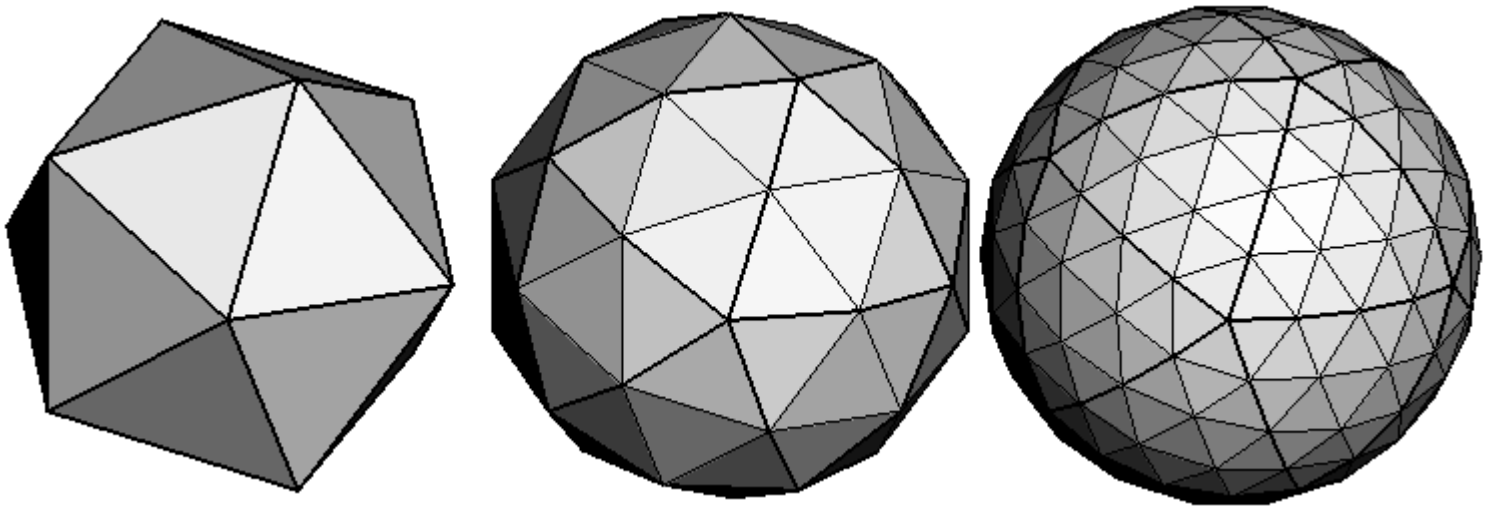
Orientation == sign of the area



Stokes' Theorem

$$\iint_R dxdy = \oint_{\partial R} xdy$$

Icosahedron



Icosahedron

```
//initial icosahedron
Static float t[20][3][3] = {…};

void display(void)
{









}
```

Icosahedron

```
//initial icosahedron
Static float t[20][3][3] = {…};

void display(void)
{
  //clear buffer
  //set up viewport and frustum

  if (animation) angle+=0.3;
  if (angle>360) angle-=360.0;

  glLoadIdentity();
  glRotatef(angle,1,0,1);









}
```

Icosahedron

```
//initial icosahedron
Static float t[20][3][3] = {…};

void display(void)
{
  //clear buffer
  //set up viewport and frustum

  if (animation) angle+=0.3;
  if (angle>360) angle-=360.0;

  glLoadIdentity();
  glRotatef(angle,1,0,1);

  // subdivide each face of the triangle
  for (int i = 0; i < 20; i++)
  {
    Subdivide(t[i][0], t[i][1], t[i][2], subdiv);
  }




}
```

Icosahedron

```
//initial icosahedron
Static float t[20][3][3] = {…};

void display(void)
{
  //clear buffer
  //set up viewport and frustum

  if (animation) angle+=0.3;
  if (angle>360) angle-=360.0;

  glLoadIdentity ();
  glRotatef(angle,1,0,1);

  // subdivide each face of the triangle
  for (int i = 0; i < 20; i++)
  {
    Subdivide(t[i][0], t[i][1], t[i][2], subdiv);
  }



  glFlush();
  glutSwapBuffers();
}
```

Icosahedron

```
void Subdivide(GLfloat v1[3], GLfloat v2[3], GLfloat v3[3], int depth)
{









}
```

Icosahedron

```
void Subdivide(GLfloat v1[3], GLfloat v2[3], GLfloat v3[3], int depth)
{
  if (depth == 0) {
     glColor3f(0.5,0.5,0.5);
     glBegin(GL_TRIANGLES);
     glVertex3fv(v1);  glVertex3fv(v2);  glVertex3fv(v3);
     glEnd();
  }









}
```

Icosahedron

```
void Subdivide(GLfloat v1[3], GLfloat v2[3], GLfloat v3[3], int depth)
{
  if (depth == 0) {
     glColor3f(0.5,0.5,0.5);
     glBegin(GL_TRIANGLES);
     glVertex3fv(v1);  glVertex3fv(v2);  glVertex3fv(v3);
     glEnd();
  }
  else
  {
    GLfloat v12[3], v23[3], v31[3];
    for (int i = 0; i < 3; i++) {
       v12[i] = (v1[i]+v2[i])/2.0;
       v23[i] = (v2[i]+v3[i])/2.0;
       v31[i] = (v3[i]+v1[i])/2.0;
     }
     Normalize(v12); Normalize(v23); Normalize(v31);



  }
}
```

Icosahedron

```
void Subdivide(GLfloat v1[3], GLfloat v2[3], GLfloat v3[3], int depth)
{
  if (depth == 0) {
     glColor3f(0.5,0.5,0.5);
     glBegin(GL_TRIANGLES);
     glVertex3fv(v1);  glVertex3fv(v2);  glVertex3fv(v3);
     glEnd();
  }
  else
  {
    GLfloat v12[3], v23[3], v31[3];
    for (int i = 0; i < 3; i++) {
       v12[i] = (v1[i]+v2[i])/2.0;
       v23[i] = (v2[i]+v3[i])/2.0;
       v31[i] = (v3[i]+v1[i])/2.0;
     }
     Normalize(v12); Normalize(v23); Normalize(v31);
     Subdivide(v1, v12, v31, depth-1);
     Subdivide(v2, v23, v12, depth-1);
     Subdivide(v3, v31, v23, depth-1);
     Subdivide(v12, v23, v31, depth-1);
  }
}
```

So far

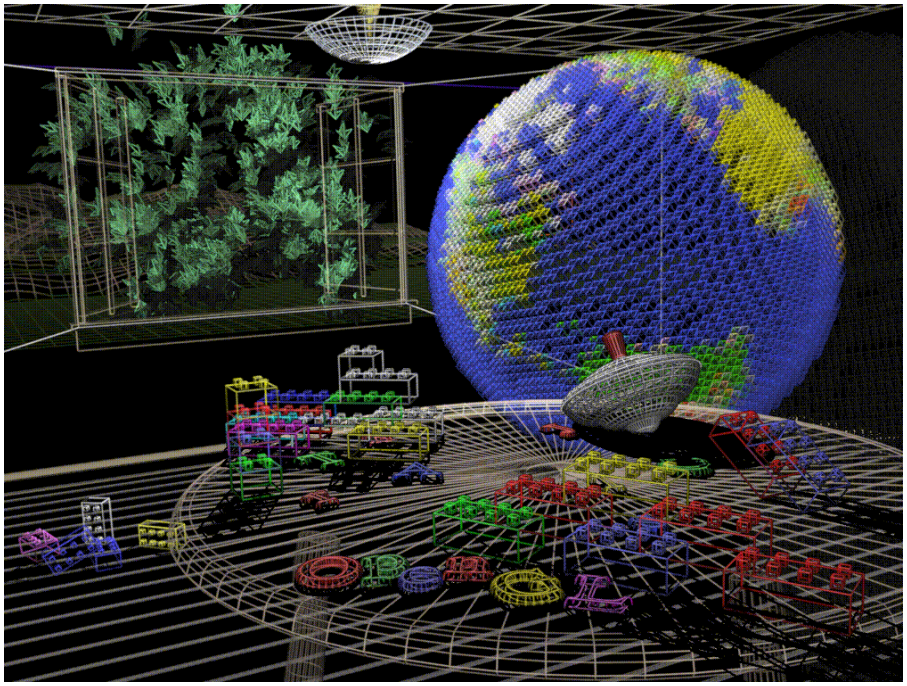
- Fixed Camera location

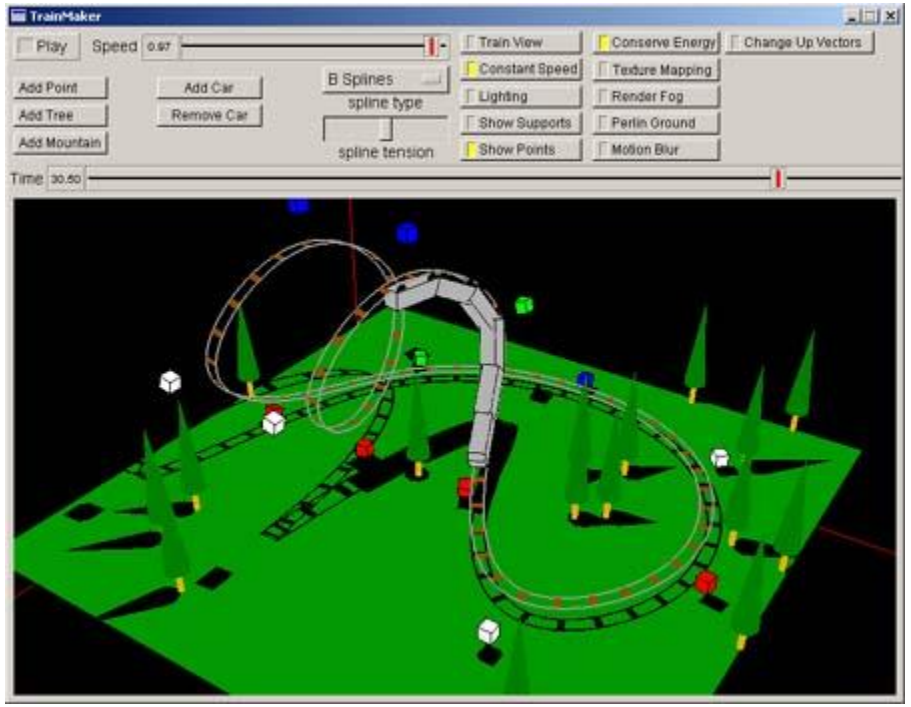
  => Change Camera location

- Single object

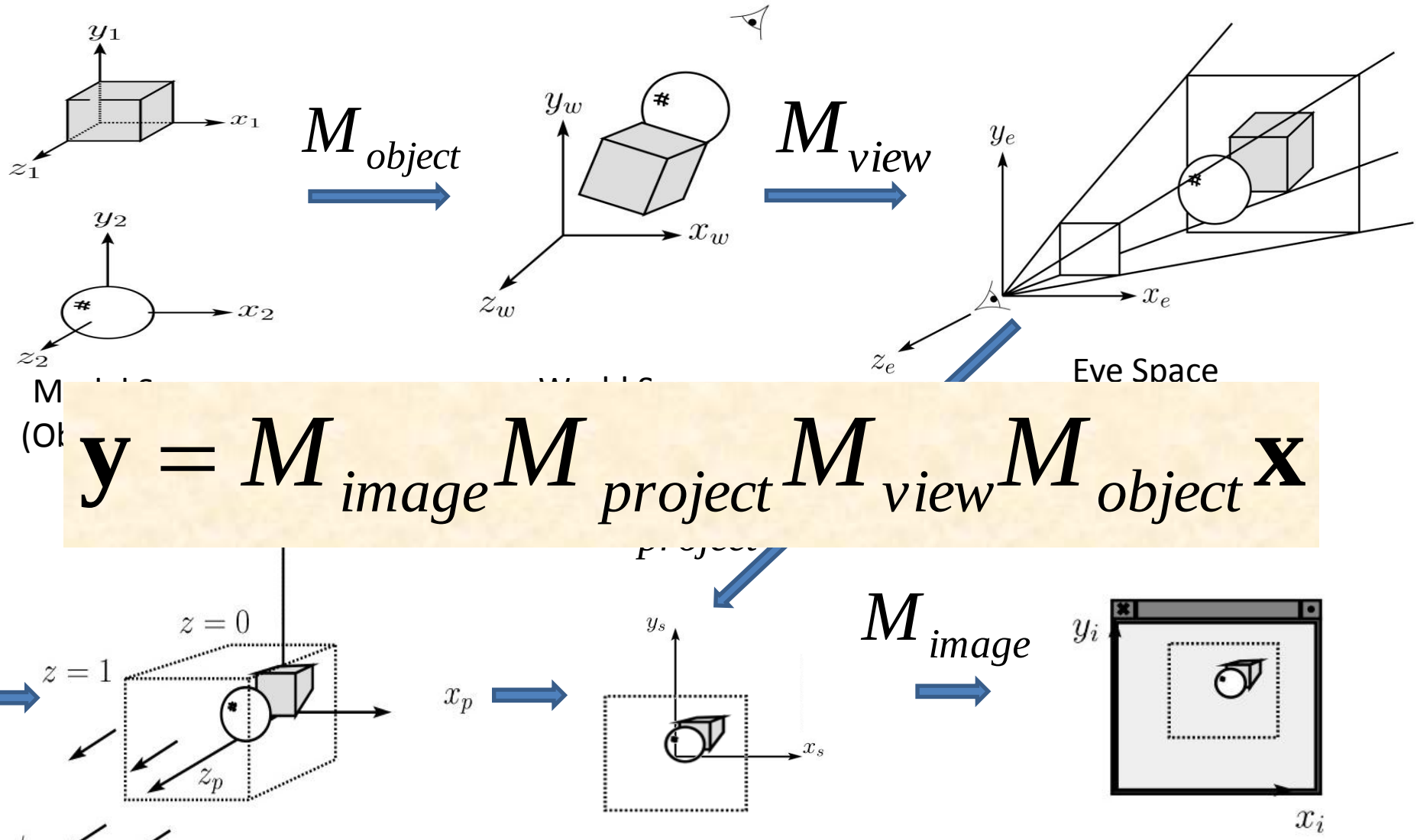
  => Multiple objects

Examples of multiple objects





3D Geometry Pipeline



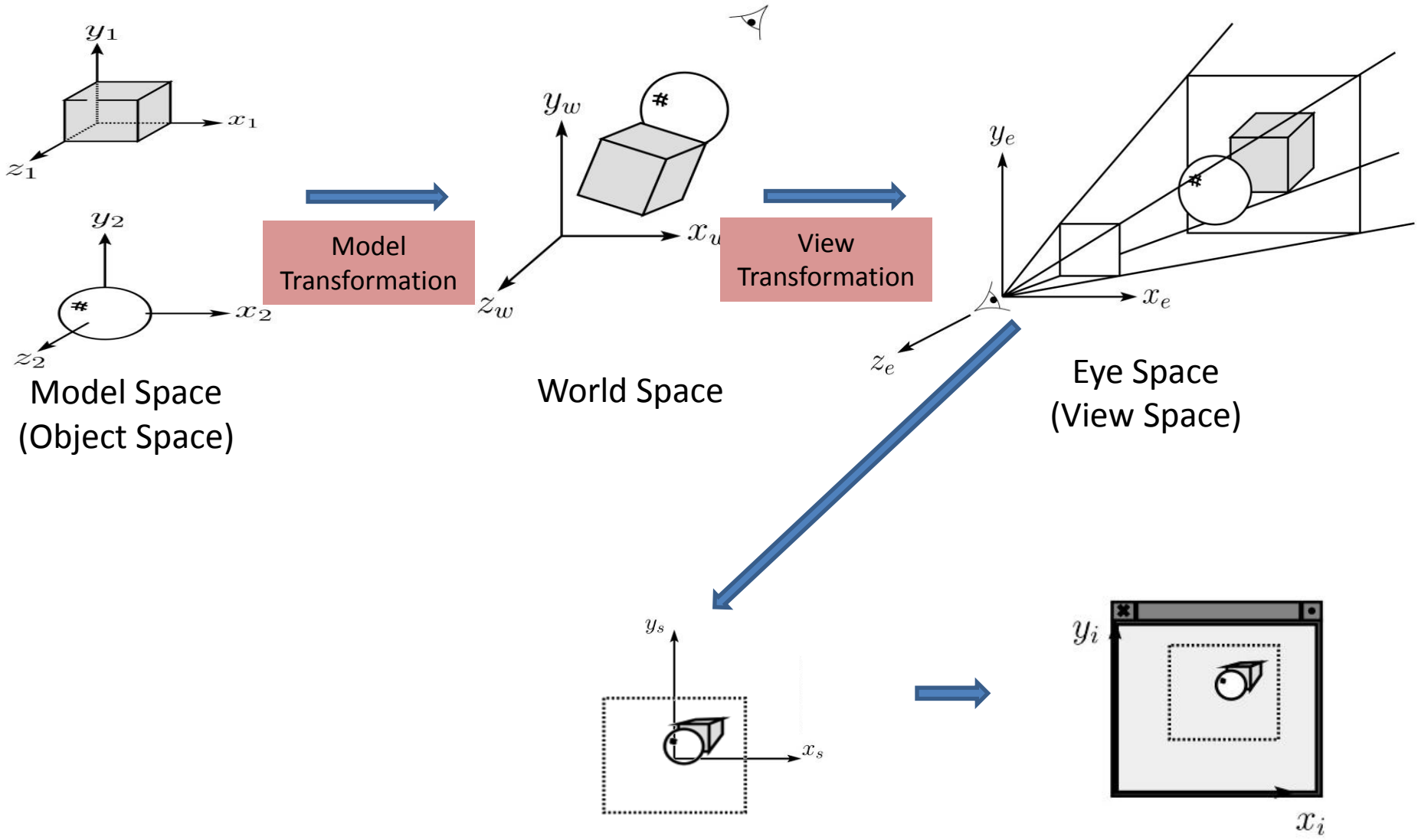
Eye Space

Canonical View Space

Screen Space (2D)

Image Space (pixels)
Raster Space

3D Geometry Pipeline



Model Space
(Object Space)

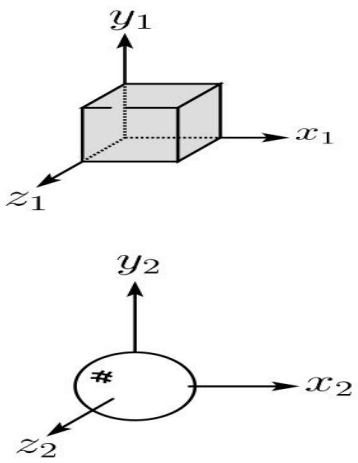
World Space

Eye Space
(View Space)

Screen Space (2D)

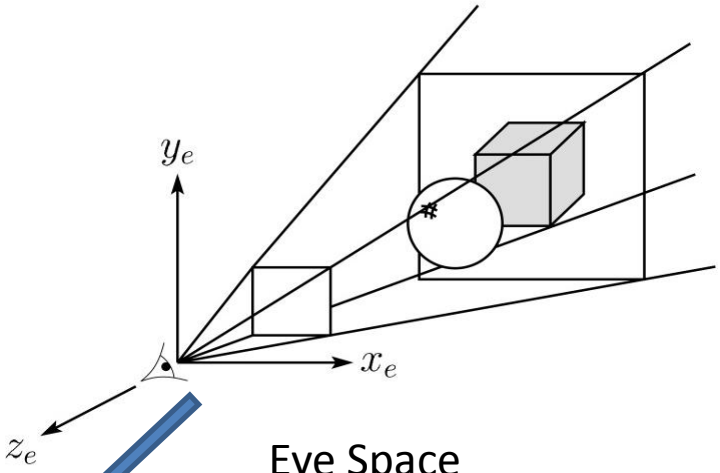
Image Space (pixels)
Raster Space

3D Geometry Pipeline



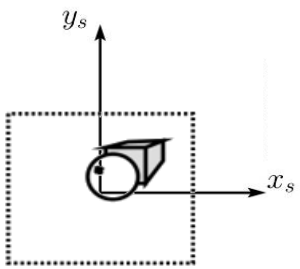
Model Space
(Object Space)

Model View
Transformation



Eye Space
(View Space)

Projection



Screen Space (2D)

View port
Transformation

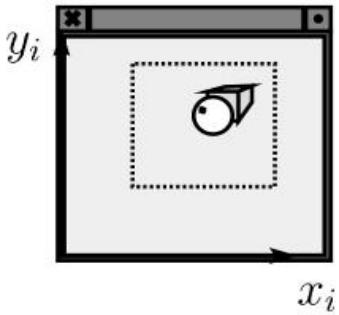
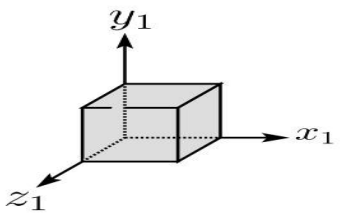
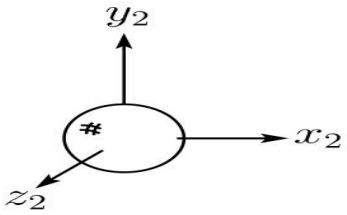


Image Space (pixels)
Raster Space

3D Geometry Pipeline

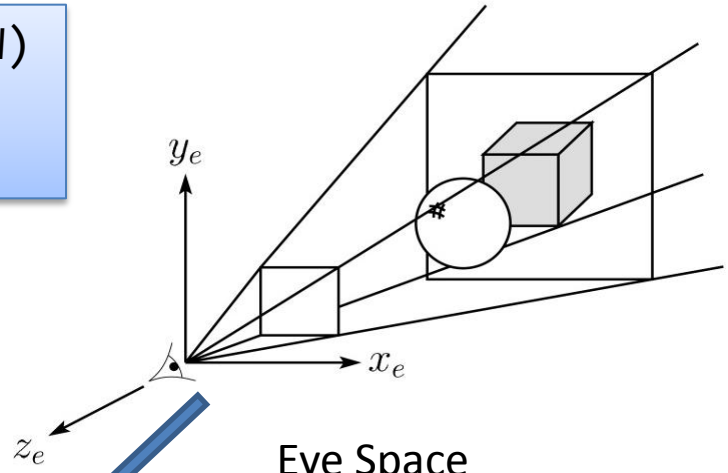




Model Space
(Object Space)

```
glMatrixMode(GL_MODELVIEW)
glLoadIdentity();
glRotate(…);
```

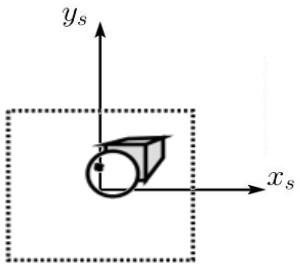
Model View Transformation



Eye Space
(View Space)

```
glMatrixMode(GL_Projection)
glLoadIdentity();
glFrustum(…);
```

Projection



Screen Space (2D)

```
glViewport(…);
```

View port Transformation

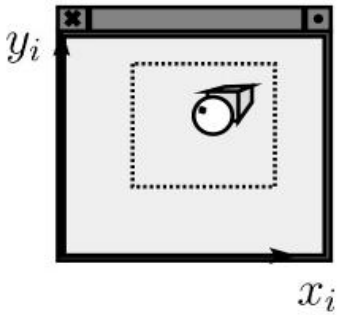
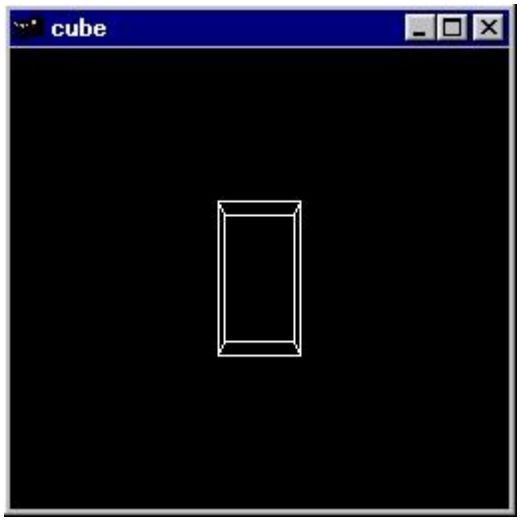


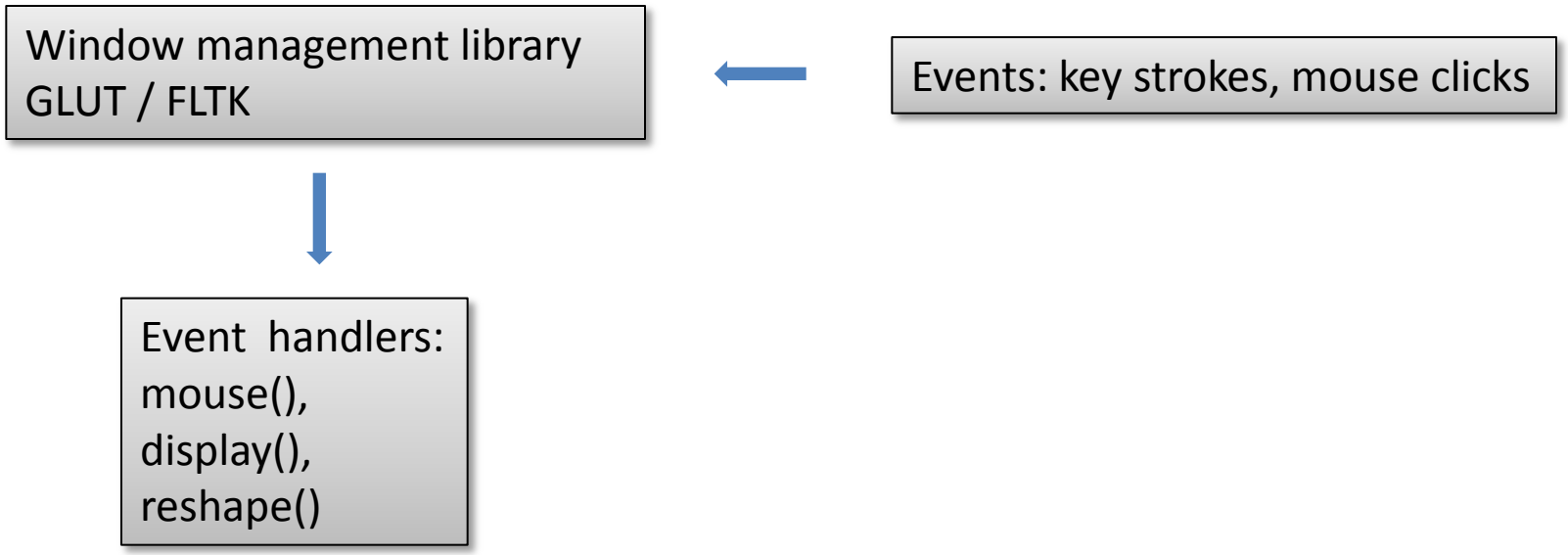
Image Space (pixels)
Raster Space

Cube.cpp



Cube.cpp

- Event-Driven Programming



Cube.cpp

```
int main(int argc, char** argv)
{
   glutInit(&argc, argv);
   glutInitDisplayMode (GLUT_SINGLE | GLUT_RGB);
   glutInitWindowSize (500, 500);
   glutInitWindowPosition (100, 100);
   glutCreateWindow (argv[0]);
   init ();
   glutDisplayFunc(display);
   glutReshapeFunc(reshape);
   glutKeyboardFunc(keyboard);
   glutMainLoop();
   return 0;
}
```

```
void keyboard(unsigned char key, int x, int y) {
   switch (key) {
      case 27:  //correspond to ESC
         exit(0);
         break;
   }
}
```

Cube.cpp

```
int main(int argc, char** argv)
{
   glutInit(&argc, argv);
   glutInitDisplayMode (GLUT_SINGLE | GLUT_RGB);
   glutInitWindowSize (500, 500);
   glutInitWindowPosition (100, 100);
   glutCreateWindow (argv[0]);
   init ();
   glutDisplayFunc(display);
   glutReshapeFunc(reshape);
   glutKeyboardFunc(keyboard);
   glutMainLoop();
   return 0;
}
```

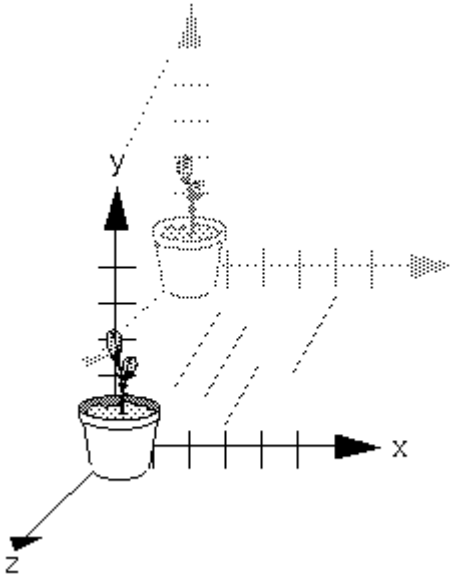
```
void reshape (int w, int h) {
   glViewport(0, 0, w, h);
   glMatrixMode(GL_PROJECTION);
   glLoadIdentity();
   glFrustum(-1.0, 1.0, -1.0, 1.0, 1.5, 20.0);
}
```

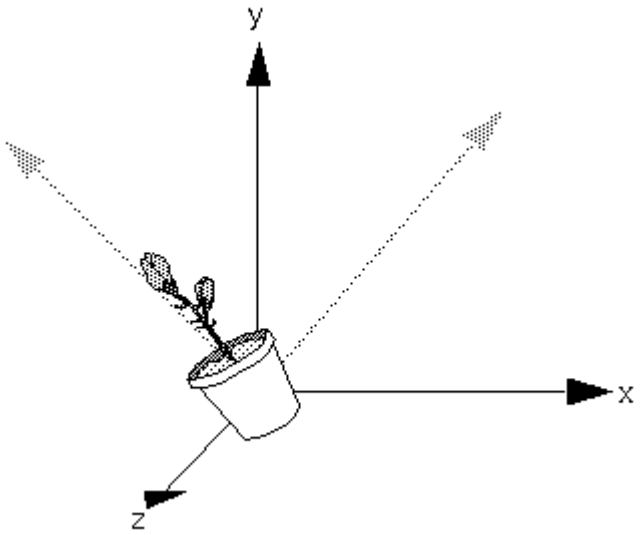
Cube.cpp

```
int main(int argc, char** argv)
{
   glutInit(&argc, argv);
   glutInitDisplayMode (GLUT_SINGLE | GLUT_RGB);
   glutInitWindowSize (500, 500);
   glutInitWindowPosition (100, 100);
   glutCreateWindow (argv[0]);
   init ();
   glutDisplayFunc(display);
   glutReshapeFunc(reshape);
   glutKeyboardFunc(keyboard);
   glutMainLoop();
```

```
void display(void) {
   glClear(GL_COLOR_BUFFER_BIT);
   glColor3f(1.0, 1.0, 1.0);
   glMatrixMode(GL_MODELVIEW);
   glLoadIdentity();             /* clear the matrix */
           /* viewing transformation  */
   gluLookAt(0.0, 0.0, 5.0, 0.0, 0.0, 0.0, 0.0, 1.0, 0.0);
   glScalef(1.0, 2.0, 1.0);      /* modeling transformation */
   glutWireCube(1.0);
   glFlush();
}
```

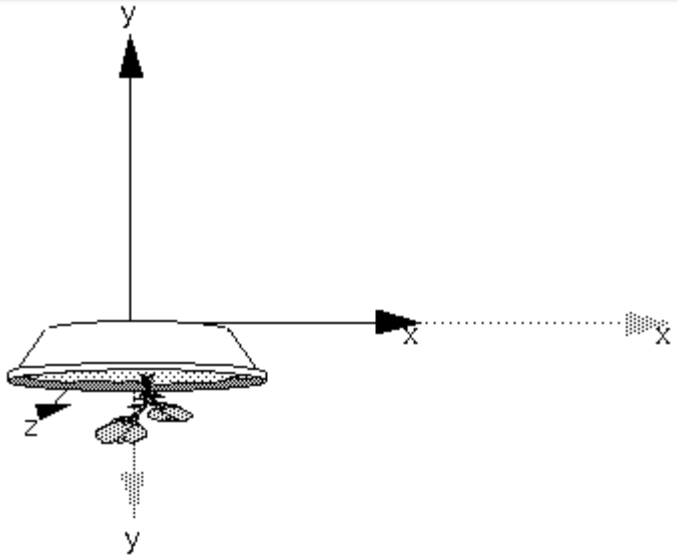
Modeling Transformation





`glTranslatef(float x, float y, float z)`

`glRotatef(float angle, float x, float y, float z)`



`glScalef(float x, float y, float z)`

`glScalef(2.0, -0.5, 1.0)`

General Modeling Transform

```
glLoadIdentity()
```

```
glLoadMatrixf(float *M)
```

```
glMultiMatrixf(float *M)
```

$$\mathbf{M} = \begin{bmatrix} m_1 & m_5 & m_9 & m_{13} \\ m_2 & m_6 & m_{10} & m_{14} \\ m_3 & m_7 & m_{11} & m_{15} \\ m_4 & m_8 & m_{12} & m_{16} \end{bmatrix}$$

double M[4][4];
M[2][1] corresponds to???

M[10]

Matrix Chain

```
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
glMultMatrixf(N);                       /* apply transformation N */
glMultMatrixf(M);                       /* apply transformation M */
glMultMatrixf(L);                       /* apply transformation L */
glBegin(GL_POINTS);
glVertex3f(v);                          /* draw transformed vertex v */
glEnd();                                /* which is (N*(M*(L*v))) */
```

Matrix Chain

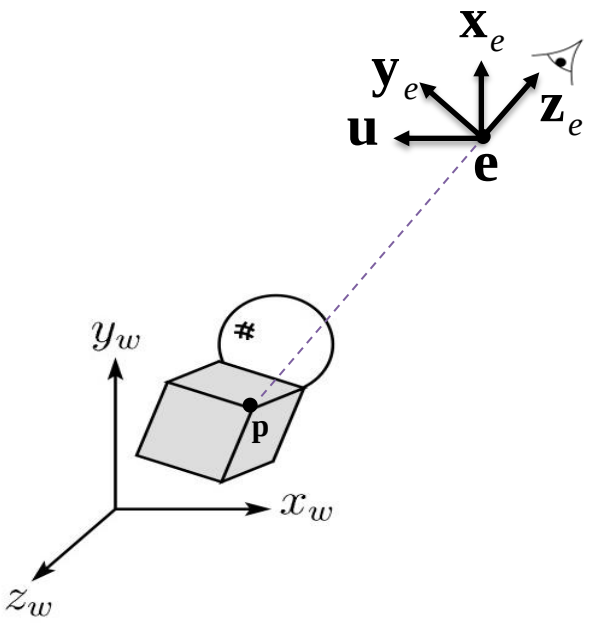
```
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();

glMultMatrixf(V);

glMultMatrixf(R);

glMultMatrixf(T);

glBegin(GL_POINTS);
glVertex3f(v);
glEnd();
```

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

gluLookat(…);

glRotatef(…);

glTranslatef(…);

glBegin(GL_POINTS);
glVertex3f(v);
glEnd();
```

gluLookAt

```
gluLookAt(
    float eyex, float eyey, float eyez,
    float px, float py, float pz,
    float upx, float upy, float upz )
```

1. Give eye location e
2. Give target position p
3. Give upward direction u



$$\mathbf{z}_e = -\frac{\mathbf{p}-\mathbf{e}}{|\mathbf{p}-\mathbf{e}|}$$

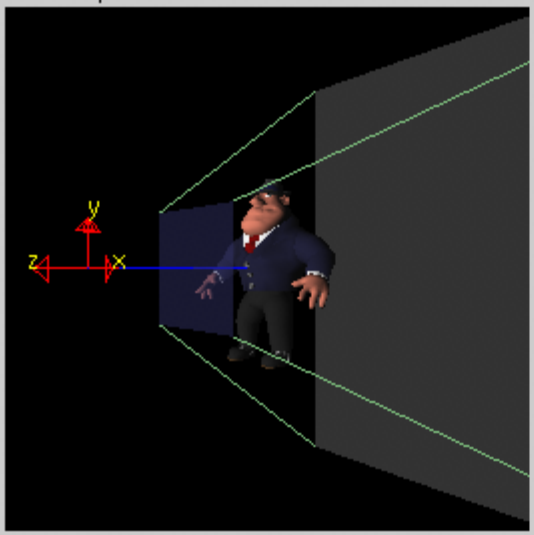
$$\mathbf{x}_e = \frac{\mathbf{u}\times\mathbf{z}_e}{|\mathbf{u}\times\mathbf{z}_e|}$$

$$\mathbf{y}_e = \frac{\mathbf{z}_e\times\mathbf{x}_e}{|\mathbf{z}_e\times\mathbf{x}_e|}$$

$$\mathbf{M}_v = \begin{bmatrix} - & \mathbf{x}_e^{\mathrm{T}} & - & 0 \\ - & \mathbf{y}_e^{\mathrm{T}} & - & 0 \\ - & \mathbf{z}_e^{\mathrm{T}} & - & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & | \\ 0 & 1 & 0 & -\mathbf{e} \\ 0 & 0 & 1 & | \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

gluLookAt

World-space view



Screen-space view

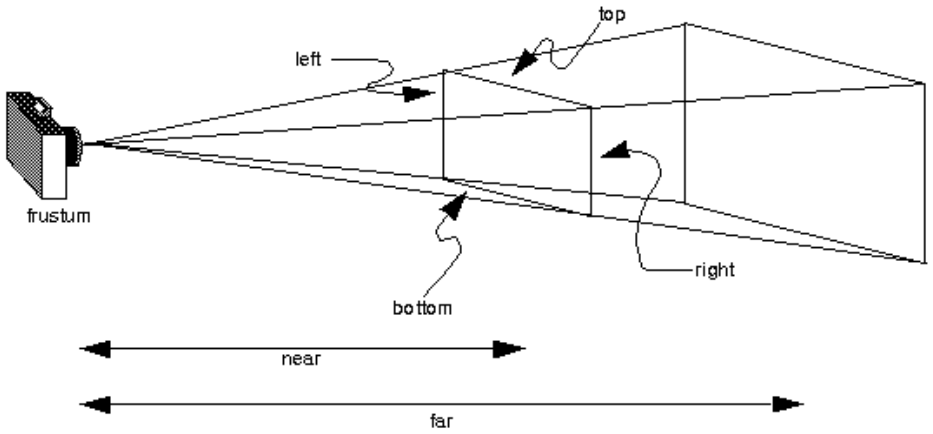
Command manipulation window

```
                    fovy  aspect  zNear  zFar
gluPerspective(  60.0  , 1.00  , 1.0   , 10.0  );
    gluLookAt(  0.00  , 0.00  , 2.00  ,    <- eye
                0.00  , 0.00  , 0.00  ,    <- center
                0.00  , 1.00  , 0.00  );   <- up
```

Click on the arguments and move the mouse to modify values.

glFrustum

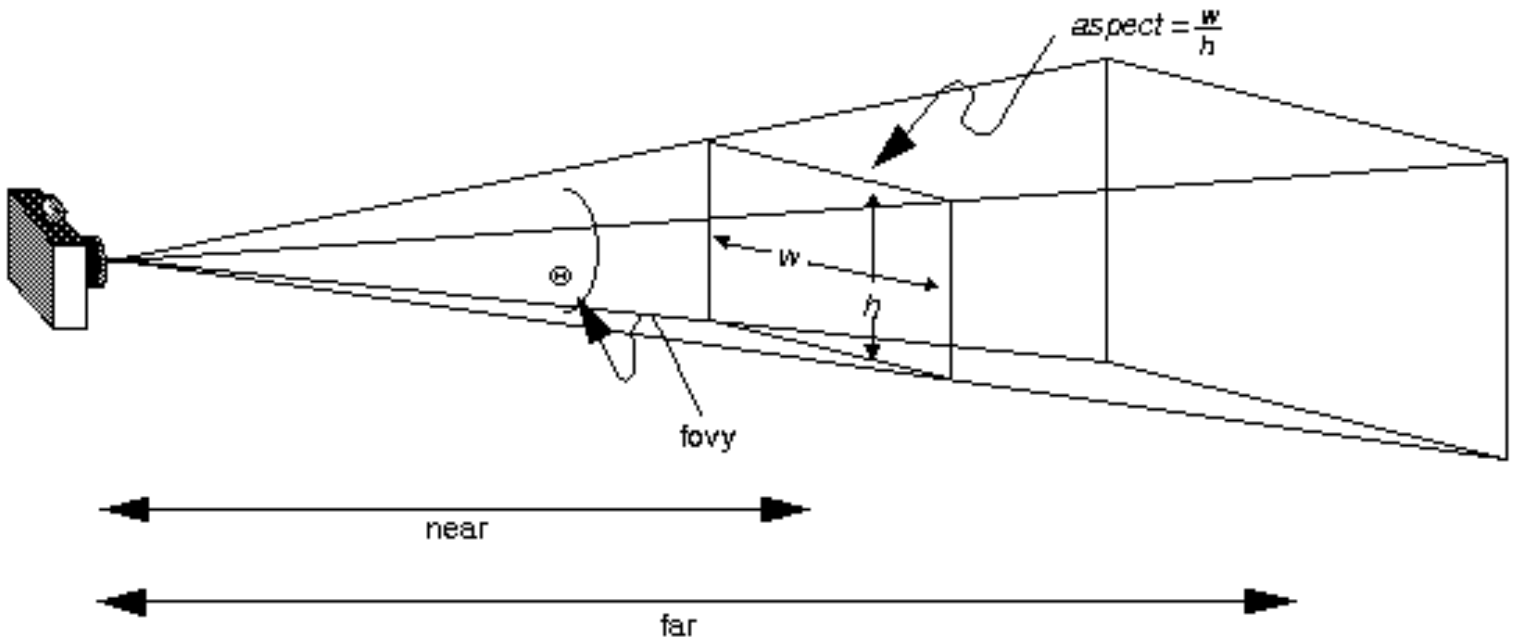
```
glFrustum(double left, double right, double bottom, double top, double near, double far)
```



$$\mathbf{M}_{view->canonical} = \mathbf{M}_O \mathbf{M}_P = \begin{bmatrix} \frac{2}{(r-l)} & 0 & 0 & \frac{-(r+l)}{(r-l)} \\ 0 & \frac{2}{(t-b)} & 0 & \frac{-(t+b)}{(t-b)} \\ 0 & 0 & \frac{2}{(n-f)} & \frac{-(n+f)}{(n-f)} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} n & 0 & 0 & 0 \\ 0 & n & 0 & 0 \\ 0 & 0 & (n+f) & -nf \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

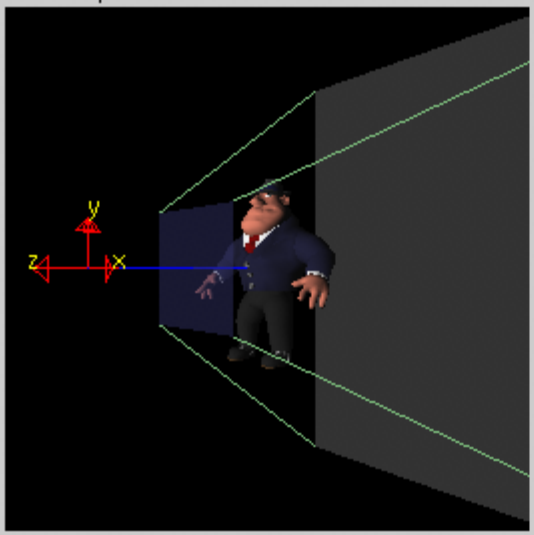
gluPerspective

```
gluPerspective(double fovy, double aspect, double zNear, double zFar)
```



gluPerspective

World-space view



Screen-space view

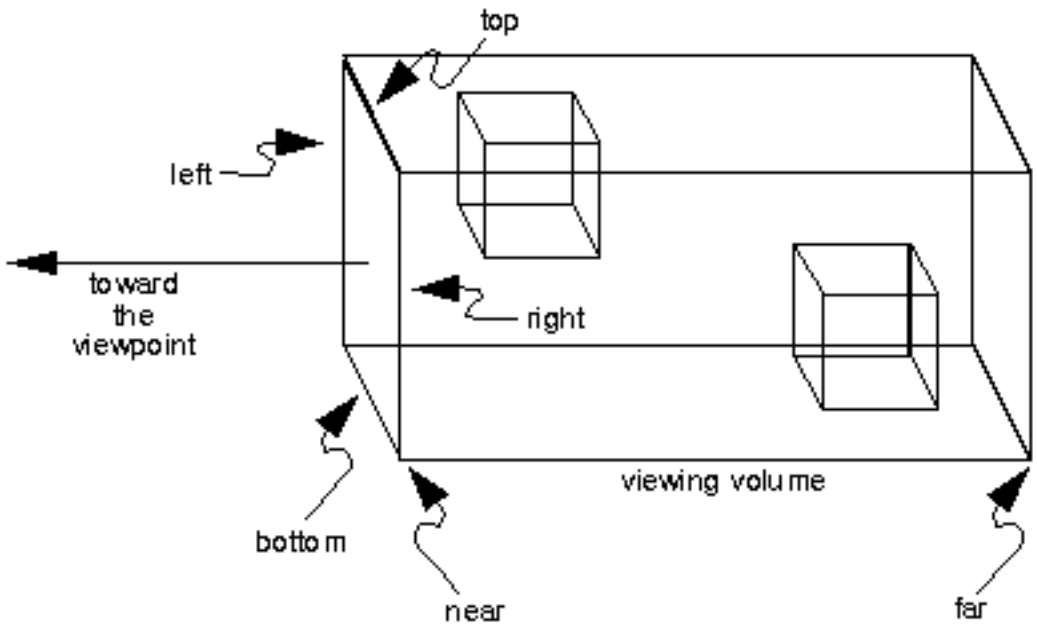
Command manipulation window

```
                    fovy  aspect  zNear  zFar
gluPerspective(  60.0  , 1.00  , 1.0   , 10.0  );
    gluLookAt(  0.00  , 0.00  , 2.00  ,    <- eye
                0.00  , 0.00  , 0.00  ,    <- center
                0.00  , 1.00  , 0.00  );   <- up
```

Click on the arguments and move the mouse to modify values.

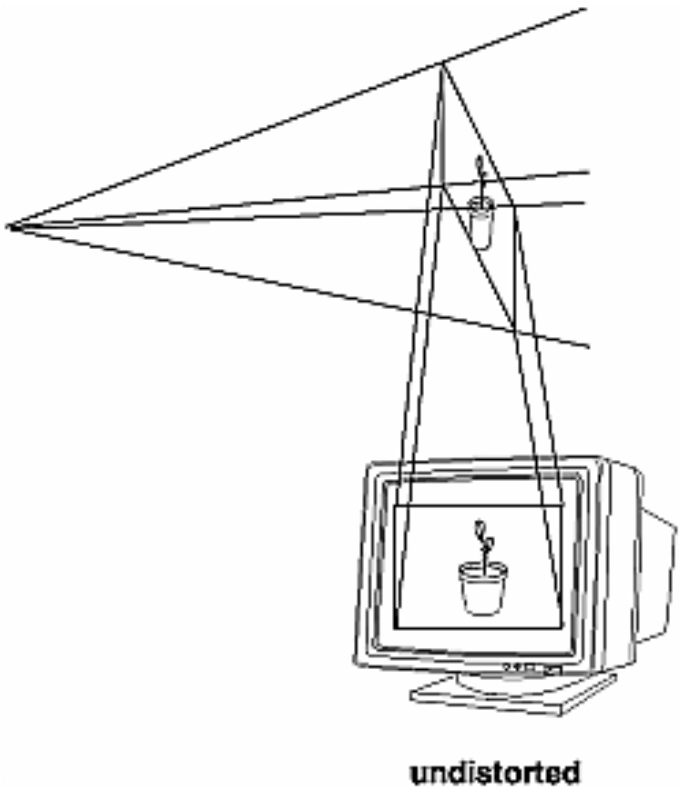
Orthographic Projection

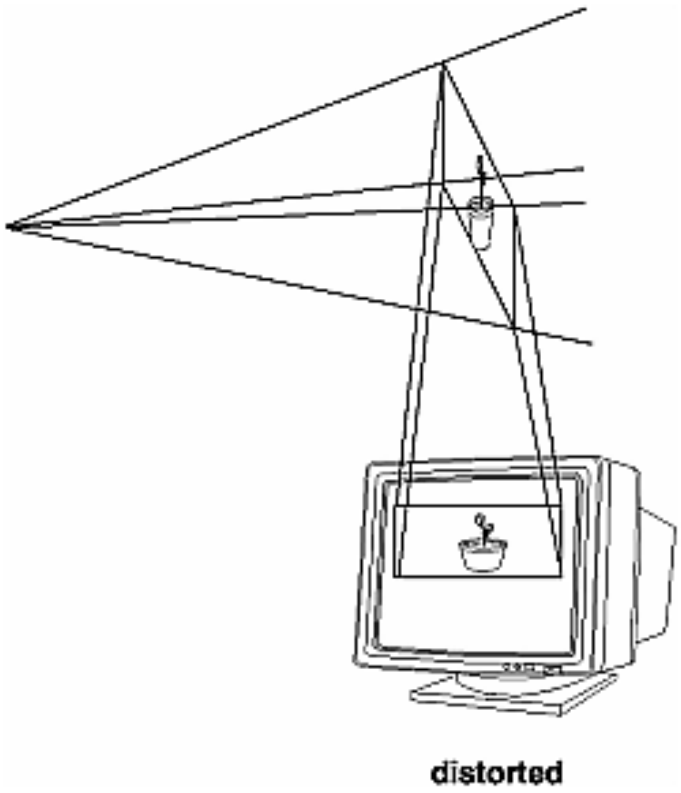
```
glOrtho(double left, double right, double bottom,
double top, double near, double far);
```



Viewport Transformation

```
glViewport(int x, int y, int width, int height);
```






```
glFrustum(double left, double right, double bottom, double top, double near, double far)
gluPerspective(double fovy, double aspect, double zNear, double zFar)
```

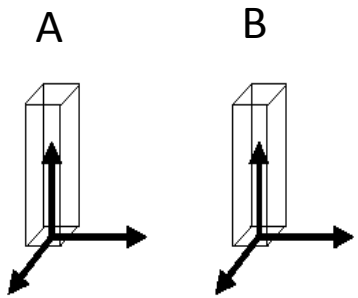
Revisit cube.cpp

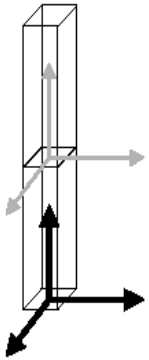
```
int main(int argc, char** argv)
{
   glutInit(&argc, argv);
   glutInitDisplayMode (GLUT_SINGLE | GLUT_RGB);
   glutInitWindowSize (500, 500);
   glutInitWindowPosition (100, 100);
   glutCreateWindow (argv[0]);
   init ();
   glutDisplayFunc(display);
   glutReshapeFunc(reshape);
   glutKeyboardFunc(keyboard);
   glutMainLoop();
   return 0;
}
```

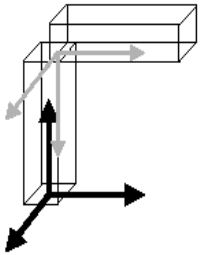
```
void reshape (int w, int h) {
   glViewport(0, 0, w, h);
   glMatrixMode(GL_PROJECTION);
   glLoadIdentity();
   glFrustum(-1.0, 1.0, -1.0, 1.0, 1.5, 20.0);
}
```

```
void display(void) {
   glClear(GL_COLOR_BUFFER_BIT);
   glColor3f(1.0, 1.0, 1.0);
   glMatrixMode(GL_MODELVIEW);
   glLoadIdentity();              /* clear the matrix */
           /* viewing transformation  */
   gluLookAt(0.0, 0.0, 5.0, 0.0, 0.0, 0.0, 0.0, 1.0, 0.0);
   glScalef(1.0, 2.0, 1.0);       /* modeling transformation */
   glutWireCube(1.0);
   glFlush();
}
```

Connecting primitives





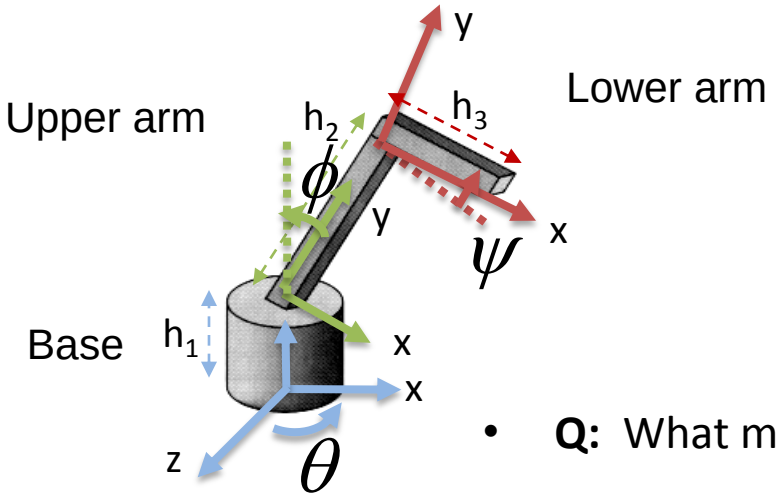


```
glLoadIdentity();
draw_block_A();
glTranslate(0, h, 0);
Draw_block_B();
```

```
glLoadIdentity();
draw_block_A();
glTranslate(0, h, 0);
glRotate(-90, 0, 0, 1);
Draw_block_B();
```

3D Example: A robot arm

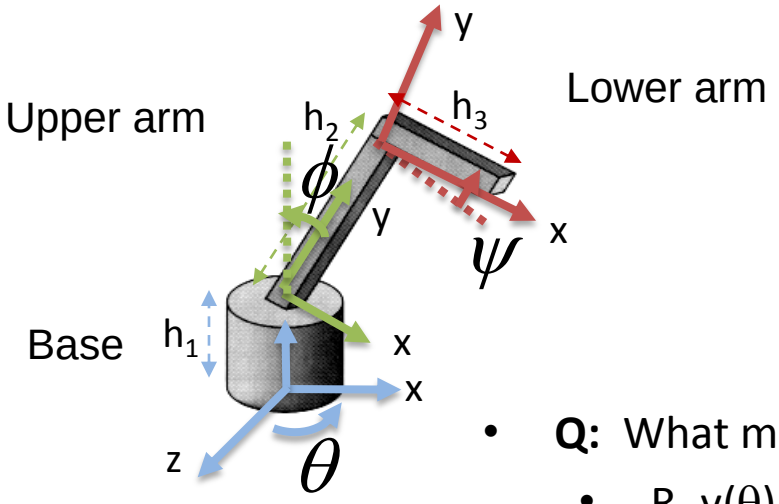
- Consider this robot arm with 3 degrees of freedom:
  - Base rotates about its vertical axis by θ
  - Upper arm rotates in its *xy*-plane by ϕ
  - Lower arm rotates in its *xy*-plane by ψ



- **Q:** What matrix do we use to transform the base to the world?
- **Q:** What matrix for the upper arm to the base?
- **Q:** What matrix for the lower arm to the upper arm?

3D Example: A robot arm

- Consider this robot arm with 3 degrees of freedom:
  - Base rotates about its vertical axis by θ
  - Upper arm rotates in its *xy*-plane by ϕ
  - Lower arm rotates in its *xy*-plane by ψ



- **Q:** What matrix do we use to transform the base to the world?
  - R_y(θ)
- **Q:** What matrix for the upper arm to the base?
  - T(0,h1,0)R_z(ϕ)
- **Q:** What matrix for the lower arm to the upper arm?
  - T(0,h2,0)R_z(ψ)

Robot arm implementation

- The robot arm can be displayed by keeping a global matrix and computing it at each step:

```
Matrix M_model;
display(){
     . . .
     robot_arm();
     . . .
}
robot_arm()
{
     M_model = R_y(theta);
     base();
     M_model = R_y(theta)*T(0,h1,0)*R_z(phi);
     upper_arm();
     M_model = R_y(theta)*T(0,h1,0)*R_z(phi)*T(0,h2,0)*R_z(psi);
     lower_arm();
}
```

- **Q:** What matrix do we use to transform the base to the world?
  - R_y(θ)
- **Q:** What matrix for the upper arm to the base?
  - T(0,h1,0)R_z(ϕ)
- **Q:** What matrix for the lower arm to the upper arm?
  - T(0,h2,0)R_z(ψ)

How to translate the whole robot?

Do the matrix computations seem wasteful?

Robot arm implementation, better

- Instead of recalculating the global matrix each time, we can just update it *in place* by concatenating matrices on the right:

```
Matrix M_model;
display(){
    . . .
    M_model = identity;
    robot_arm();
    . . .
}
robot_arm()
{
    M_model *= R_y(theta);
    base();
    M_model *= T(0,h1,0)*R_z(phi);
    upper_arm();
    M_model *= T(0,h2,0)*R_z(psi);
    lower_arm();
}
```

Robot arm implementation, OpenGL

- OpenGL maintains the **model-view matrix**, as a global state variable which is updated by concatenating matrices on the ***right***.

```
display()
{
    . . .
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity();
    robot_arm();
    . . .
}
robot_arm()
{
    glRotatef( theta, 0.0, 1.0, 0.0 );
    base();
    glTranslatef( 0.0, h1, 0.0 );
    glRotatef( phi, 0.0, 0.0, 1.0 );
    lower_arm();
    glTranslatef( 0.0, h2, 0.0 );
    glRotatef( psi, 0.0, 0.0, 1.0 );
    upper_arm();
}
```