CS418 Computer Graphics

Fall 2019, **Fall 2020**

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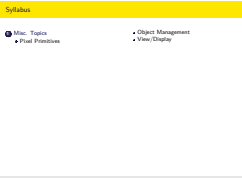
Syllabus

1. Misc. Topics
   - Pixel Primitives
- Object Management
- View/Display



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   - Pixel Primitives
   - Object Management
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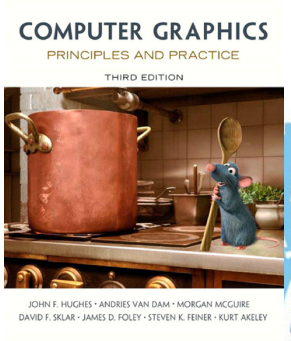
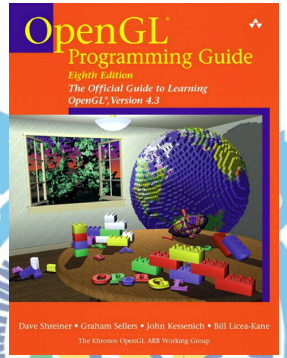
Books

D. Hearn et. al., Computer Graphics with OpenGL, 3rd edition

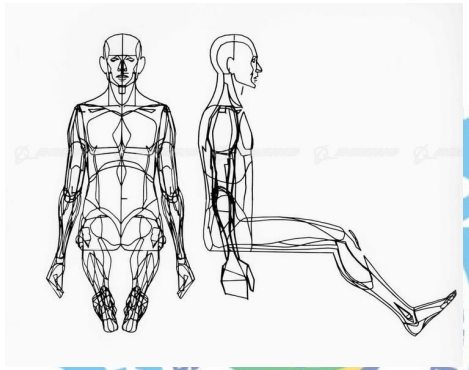


J. F. Hughes et. al., Computer Graphics: Principles and Practice, third edition.



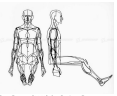
D. Shreiner et. al., OpenGL Programming Guide, Addison-Wesley, eighth edition.

Computer Graphics



Coined by William Fetter (1928-2002) at Boeing (1960) for Cockpit Designs

Computer Graphics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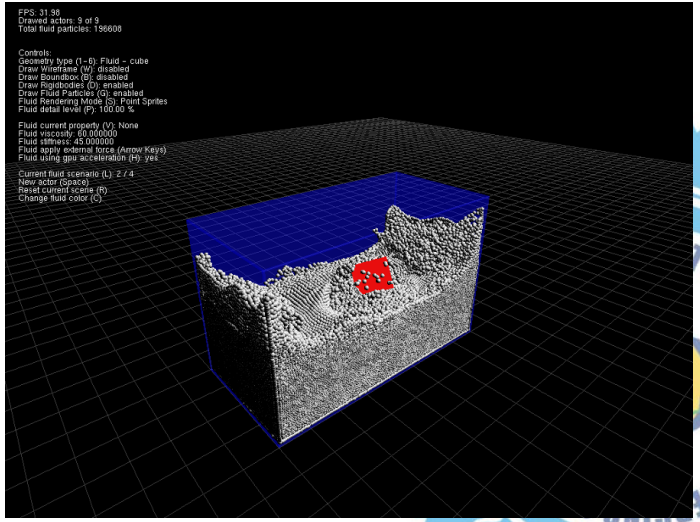
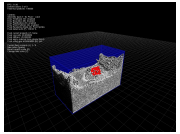
Applications



Scientific Visualizations (Simulations)

Applications



Scientific Visualizations (Simulations)

Applications (cont.)

Arts & Design (Zaheer Mukhtar)

Applications (cont.)

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Applications (cont.)

Computer Games

Applications (cont.)

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Applications (cont.)

Architecture (Buildings) & Layout Design

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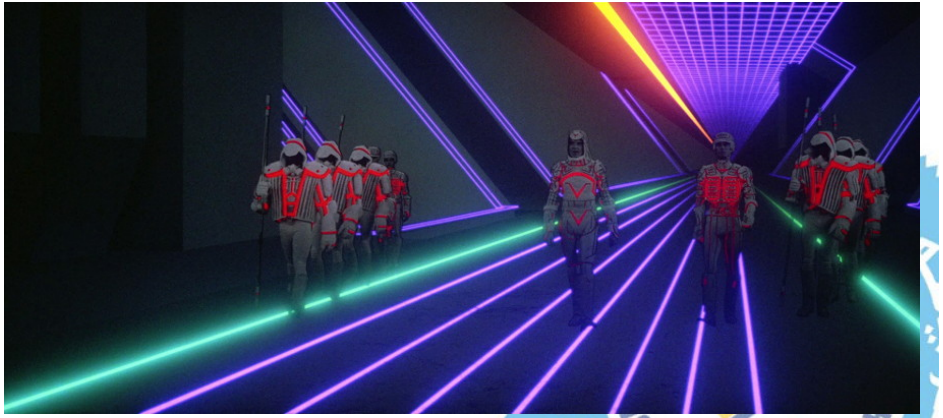
Applications (cont.)



Movie Industry (Tron, 1980)

Applications (cont.)

Movie Industry (Tron, 1980)

Computer Graphics Field

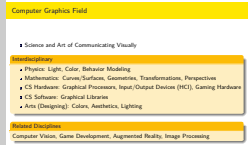
- Science and Art of Communicating Visually

Interdisciplinary

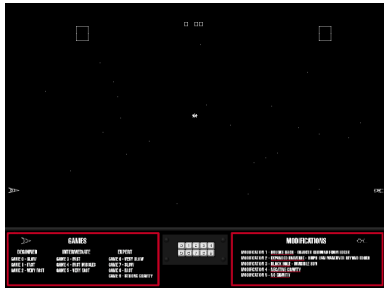
- Physics: Light, Color, Behavior Modeling
- Mathematics: Curves/Surfaces, Geometries, Transformations, Perspectives
- CS Hardware: Graphical Processors, Input/Output Devices (HCI), Gaming Hardware
- CS Software: Graphical Libraries
- Arts (Designing): Colors, Aesthetics, Lighting

Related Disciplines

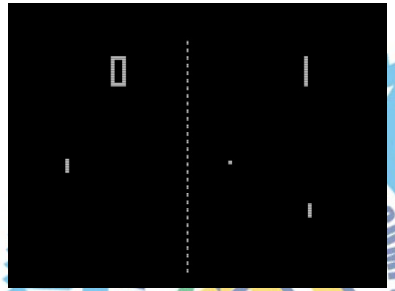
Computer Vision, Game Development, Augmented Reality, Image Processing



Historical Firsts



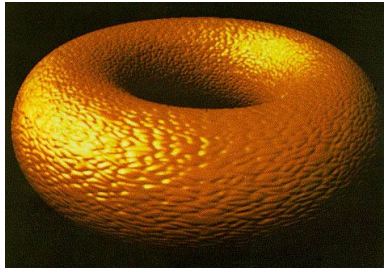
Spacewars at MIT (1962)



Pong for Atari (1973)

Historical Firsts
Spacewars at MIT (1962)
Pong for Atari (1973)

Historical Firsts (cont.)



First Wrinkled/Bumped Image
(Blinn 1978)

First Textured Image (Catmull 1974)

Historical Firsts (cont.)
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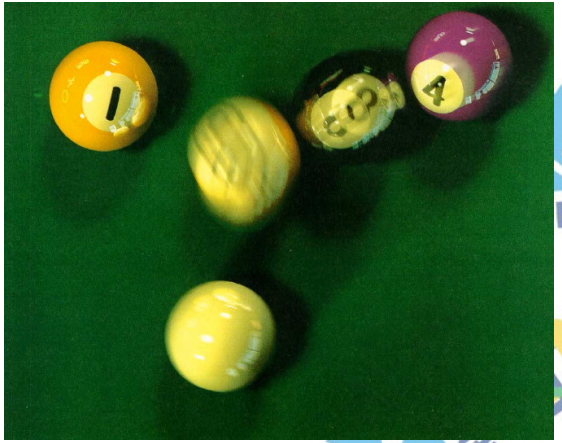

Historical Firsts (cont.)

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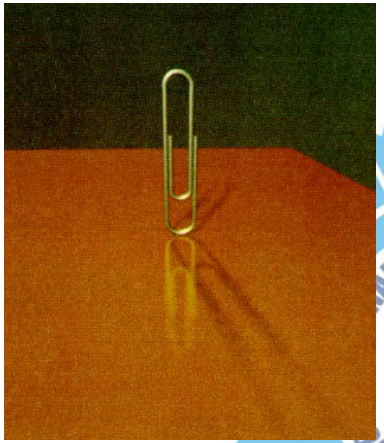

First raytraced images (Cook, 1984); motion blur, depth of field, translucency, reflections

Historical Firsts (cont.)
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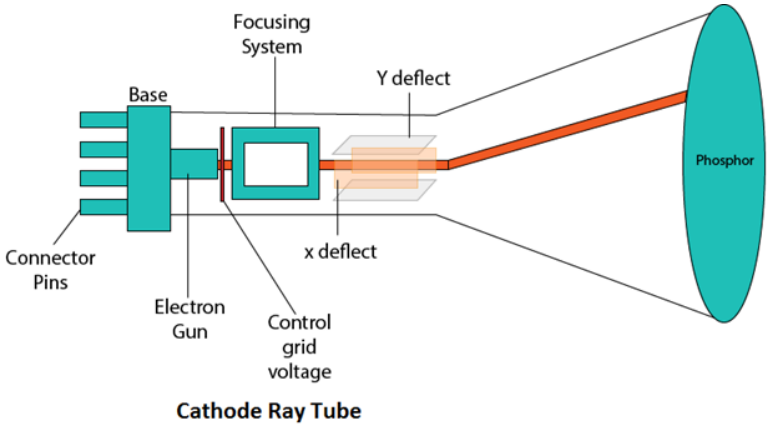
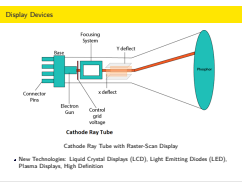
Display Devices



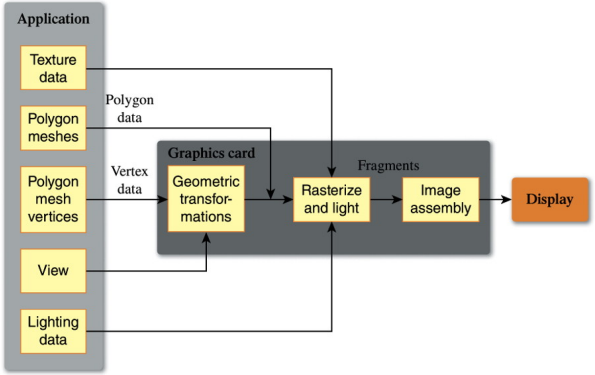
Cathode Ray Tube with Raster-Scan Display

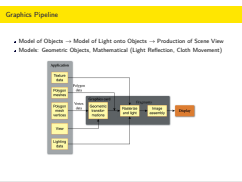
- New Technologies: Liquid Crystal Displays (LCD), Light Emitting Diodes (LED), Plasma Displays, High Definition



Graphics Pipeline

- Model of Objects → Model of Light onto Objects → Production of Scene View
- Models: Geometric Objects, Mathematical (Light Reflection, Cloth Movement)





Definitions

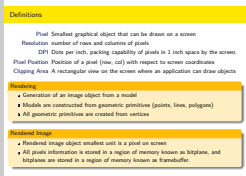
Pixel	Smallest graphical object that can be drawn on a screen
Resolution	number of rows and columns of pixels
DPI	Dots per inch, packing capability of pixels in 1 inch space by the screen.
Pixel Position	Position of a pixel (row, col) with respect to screen coordinates
Clipping Area	A rectangular view on the screen where an application can draw objects

Rendering

- Generation of an image object from a model
- Models are constructed from geometric primitives (points, lines, polygons)
- All geometric primitives are created from vertices

Rendered Image

- Rendered image object smallest unit is a pixel on screen
- All pixels information is stored in a region of memory known as bitplane, and bitplanes are stored in a region of memory known as framebuffer.



Screen Coordinate System

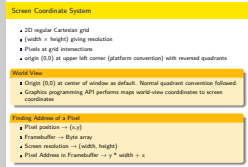
- 2D regular Cartesian grid
- (width $\times$ height) giving resolution
- Pixels at grid intersections
- origin (0,0) at upper left corner (platform convention) with reversed quadrants

World View

- Origin (0,0) at center of window as default. Normal quadrant convention followed.
- Graphics programming API performs maps world-view coorddinates to screen coordinates

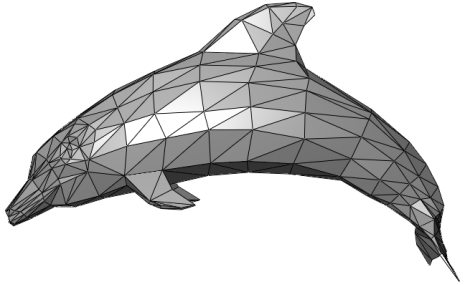
Finding Address of a Pixel

- Pixel position $\rightarrow$ (x,y)
- Framebuffer $\rightarrow$ Byte array
- Screen resolution $\rightarrow$ (width, height)
- Pixel Address in Framebuffer $\rightarrow$ y * width + x

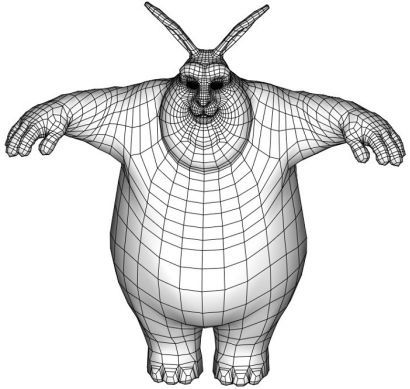


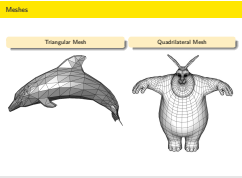
Meshes

Triangular Mesh



Quadrilateral Mesh





Issues

Issues: Quads vs Triangles

- Drawing on a Plane easy with Triangles
- Sub-Division may not result in new vertices
- Simplification by replacement of fine with coarse mesh
- Keep Geometry (Vertices) and Topology (Faces) separate

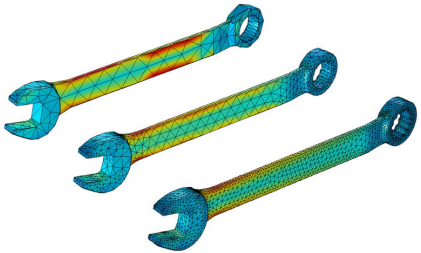


Figure 1: Coarse vs Fine Mesh

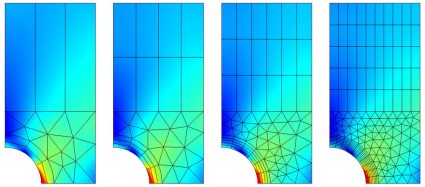
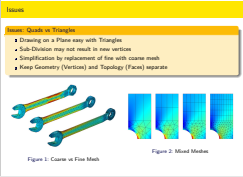


Figure 2: Mixed Meshes



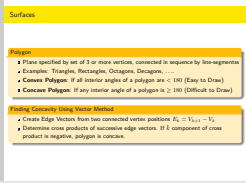
Surfaces

Polygon

- Plane specified by set of 3 or more vertices, connected in sequence by line-segmentss
- Examples: Triangles, Rectangles, Octagons, Decagons, ...
- **Convex Polygon**: If all interior angles of a polygon are < 180 (Easy to Draw)
- **Concave Polygon**: If any interior angle of a polygon is ≥ 180 (Difficult to Draw)

Finding Concavity Using Vector Method

- Create Edge Vectors from two connected vertex positions $E_k = V_{k+1} - V_k$
- Determine cross products of successive edge vectors. If $\hat{k}$ component of cross product is negative, polygon is concave.



Straight Line

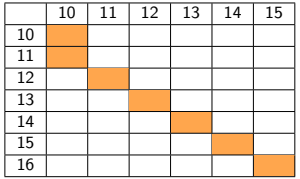
- $y = mx + b$
- $m = \dfrac{y_1 - y_0}{x_1 - x_0}$
- $b = y - mx$

Rasterization Effects

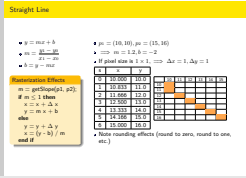
```
m = getSlope(p1, p2);
if m ≤ 1 then
    x = x + Δ x
    y = m x + b
else
    y = y + Δ y
    x = (y - b) / m
end if
```

- $p_1 = (10, 10), p_2 = (15, 16)$
- $\implies m = 1.2, b = -2$
- If pixel size is 1×1, $\implies \Delta x = 1, \Delta y = 1$

s	x	y
0	10.000	10.0
1	10.833	11.0
2	11.666	12.0
3	12.500	13.0
4	13.333	14.0
5	14.166	15.0
6	15.000	16.0



- Note rounding effects (round to zero, round to one, etc.)



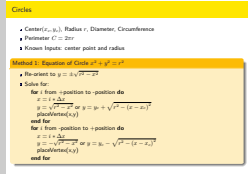
Circles

- Center(x_c, y_c), Radius r, Diameter, Circumference
- Perimeter $C = 2\pi r$
- Known Inputs: center point and radius

Method 1: Equation of Circle $x^2 + y^2 = r^2$

- Re-orient to $y = \pm\sqrt{r^2 - x^2}$
- Solve for:

for i from +position to -position **do**
  $x = i * \Delta x$
  $y = \sqrt{r^2 - x^2}$ or $y = y_c + \sqrt{r^2 - (x - x_c)^2}$
  placeVertex(x,y)
end for
for i from -position to +position **do**
  $x = i * \Delta x$
  $y = -\sqrt{r^2 - x^2}$ or $y = y_c - \sqrt{r^2 - (x - x_c)^2}$
  placeVertex(x,y)
end for



Circles (cont.)

Method 2: Polar Coordinates

- $x = x_c + r\cos\theta$
- $y = y_c + r\sin\theta$
- for loop $\theta = 0 \rightarrow 360$ for degrees
- for loop $i = 0 \rightarrow 2\pi$ for radians

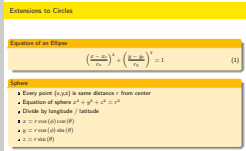
Extensions to Circles

Equation of an Ellipse

$$\left(\frac{x - x_c}{r_x}\right)^2 + \left(\frac{y - y_c}{r_y}\right)^2 = 1 \quad (1)$$

Sphere

- Every point (x,y,z) is same distance r from center
- Equation of sphere $x^2 + y^2 + z^2 = r^2$
- Divide by longitude / latitude
- $x = r\cos(\phi)\cos(\theta)$
- $y = r\cos(\phi)\sin(\theta)$
- $z = r\sin(\theta)$

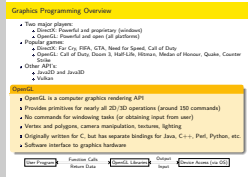


Graphics Programming Overview

- Two major players:
  - DirectX: Powerful and proprietary (windows)
  - OpenGL: Powerful and open (all platforms)
- Popular games:
  - DirectX: Far Cry, FIFA, GTA, Need for Speed, Call of Duty
  - OpenGL: Call of Duty, Doom 3, Half-Life, Hitman, Medan of Honour, Quake, Counter Strike
- Other API's:
  - Java2D and Java3D
  - Vulkan

OpenGL

- OpenGL is a computer graphics rendering API
- Provides primitives for nearly all 2D/3D operations (around 150 commands)
- No commands for windowing tasks (or obtaining input from user)
- Vertex and polygons, camera manipulation, textures, lighting
- Originally written for C, but has separate bindings for Java, C++, Perl, Python, etc.
- Software interface to graphics hardware



OpenGL History

- 1.0 (1992) :: Features in 5 sub-versions
- 2.0 (2004) :: Introduction of Shaders
- 3.0 (2008) :: Changes in the entire Pipeline
- 4.0 (2010) :: Performance (atomic), Architecture changes, OpenGL ES, WebGL ES

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Function Call Categories

- Primitives (Points, Lines, Polygons, Curves, etc.)
- Attributes (Colors, Patterns, etc.)
- Viewing (2D and 3D Camera Placement)
- Transformations (Matrices Translation, Rotation, etc.)
- Input and Output with keyboard, Mouse, or other devices
- Accessing Device and Platform related data

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OpenGL Components

- **GL** The underlying graphics library
- **GLU** OpenGL Utility Library (provides camera movement, image processing/transformation tools)
- **GLUT** OpenGL Utilities Toolkit: Provides window managers, Menus, Callback to display() function (Java uses AWT/Swing instead of GLUT)

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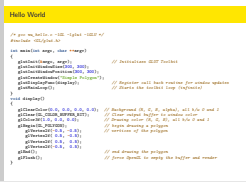
Hello World

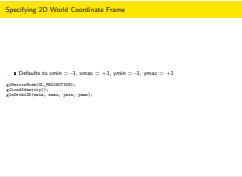
```c
/* gcc nu_hello.c -lGL -lglut -lGLU */
#include <GL/glut.h>

int main(int argc, char **argv)
{
   glutInit(&argc, argv);                 // Initializes GLUT Toolkit
   glutInitWindowSize(300, 300);
   glutInitWindowPosition(300, 300);
   glutCreateWindow("Simple Polygon");
   glutDisplayFunc(display);              // Register call back routine for window updates
   glutMainLoop();                        // Starts the toolkit loop (infinite)
}
void display()
{
   glClearColor(0.0, 0.0, 0.0, 0.0);  // Background (R, G, B, alpha), all b/w 0 and 1
   glClear(GL_COLOR_BUFFER_BIT);      // Clear output buffer to window color
   glColor3f(1.0, 0.0, 0.0);          // Drawing color (R, G, B), all b/w 0 and 1
   glBegin(GL_POLYGON);               // begin drawing a polygon
      glVertex2f(-0.5, -0.5);         // vertices of the polygon
      glVertex2f( 0.5, -0.5);
      glVertex2f( 0.5,  0.5);
      glVertex2f(-0.5,  0.5);
   glEnd();                           // end drawing the polygon
   glFlush();                         // force OpenGL to empty the buffer and render
}
```

Specifying 2D World Coordinate Frame

- Defaults to xmin = -1, xmax = +1, ymin = -1, ymax = +1

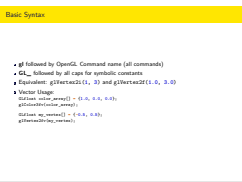
```
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
gluOrtho2D(xmin, xmax, ymin, ymax);
```

Basic Syntax

- **gl** followed by OpenGL Command name (all commands)
- **GL_** followed by all caps for symbolic constants
- Equivalent: `glVertex2i(1, 3)` and `glVertex2f(1.0, 3.0)`
- Vector Usage:

```
GLfloat color_array[] = {1.0, 0.0, 0.0};
glColor3fv(color_array);

GLfloat my_vertex[] = {-0.5, 0.5};
glVertex2fv(my_vertex);
```

Prefixes and Suffixes

Suffix	Data Type	C Type	OpenGL Type
b	8-bit int	signed char	GLbyte
s	16-bit int	signed short	GLshort
i	32-bit int	int	GLint
f	32-bit float	float	GLfloat
d	64-bit float	double	GLdouble
ub	8-bit uint	unsigned char	GLubyte
us	16-bit uint	unsigned short	GLushort
ui	32-bit uint	unsigned int	GLuint

Prefixes and Suffixes

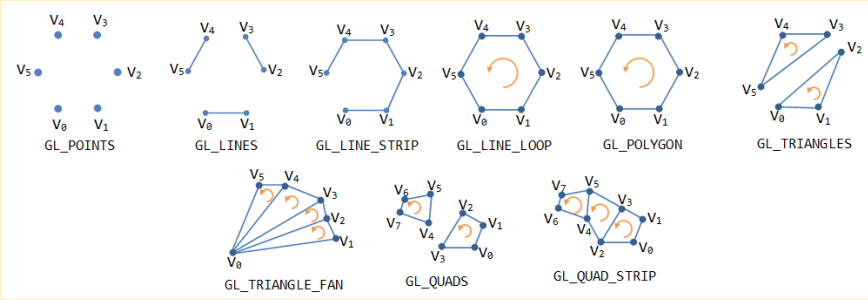
Suffix	Data Type	C Type	OpenGL Type
b	8-bit int	signed char	GLbyte
s	16-bit int	signed short	GLshort
i	32-bit int	int	GLint
f	32-bit float	float	GLfloat
d	64-bit float	double	GLdouble
ub	8-bit uint	unsigned char	GLubyte
us	16-bit uint	unsigned short	GLushort
ui	32-bit uint	unsigned int	GLuint

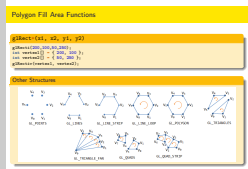
Polygon Fill Area Functions

glRect*(x1, x2, y1, y2)

```
glRecti(200,100,50,250);
int vertex1[] = { 200, 100 };
int vertex2[] = { 50, 250 };
glRectiv(vertex1, vertex2);
```

Other Structures





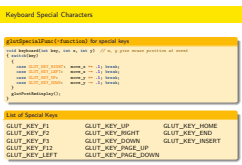
Keyboard Special Characters

glutSpecialFunc(*function) for special keys

```
void keyboard(int key, int x, int y)  // x, y give mouse position at event
{ switch(key)
  {
    case GLUT_KEY_RIGHT:  move_x += .1; break;
    case GLUT_KEY_LEFT:   move_x -= .1; break;
    case GLUT_KEY_UP:     move_y += .1; break;
    case GLUT_KEY_DOWN:   move_y -= .1; break;
  }
  glutPostRedisplay();
}
```

List of Special Keys

GLUT_KEY_F1	GLUT_KEY_UP	GLUT_KEY_HOME
GLUT_KEY_F2	GLUT_KEY_RIGHT	GLUT_KEY_END
GLUT_KEY_F3	GLUT_KEY_DOWN	GLUT_KEY_INSERT
GLUT_KEY_F12	GLUT_KEY_PAGE_UP	
GLUT_KEY_LEFT	GLUT_KEY_PAGE_DOWN	



Keyboard ASCII Characters

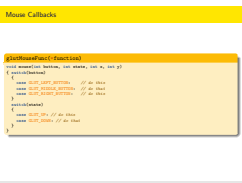
glutKeyboardFunc(*function) for ASCII keys

```
void keyboard(unsigned char key, int x, int y) // x, y give mouse position at event
{ switch(key)
  { // No special key for SHIFT
    case 'A':  case 'a':   move_x -= 1; break;
    case 'S':  case 's':   move_y -= 1; break;
    case 'D':  case 'd':   move_x += 1; break;
    case 'W':  case 'w':   move_y += 1; break;
  }
  glutPostRedisplay();
}
```


Mouse Callbacks

glutMouseFunc(*function)

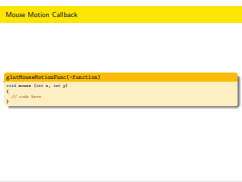
```
void mouse(int button, int state, int x, int y)
{ switch(button)
  {
    case GLUT_LEFT_BUTTON:    // do this
    case GLUT_MIDDLE_BUTTON:  // do that
    case GLUT_RIGHT_BUTTON:   // do this
  }
  switch(state)
  {
    case GLUT_UP: // do this
    case GLUT_DOWN: // do that
  }
}
```

Mouse Motion Callback

glutMouseMotionFunc(*function)

```
void mouse (int x, int y)
{
  // code here
}
```

Timer Function

glutTimerFunc(1000/25., timer, 0)

```
void timer(int x)
{
  rotate_x = x + 0.1;
  rotate_y = x - 0.1;
  glutPostRedisplay();
  glutTimerFunc(1000/25., timer, 0);
}
```


Storing Coordinate Points as Vector

- Save vertex coordinates as double-scripted array:

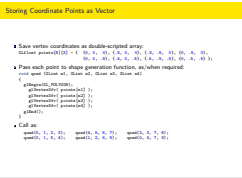
```
GLfloat points[8][3] = {  {0, 0,  0}, {.5, 0,  0}, {.5, .5,  0}, {0, .5,  0},
                          {0, 0, .5}, {.5, 0, .5}, {.5, .5, .5}, {0, .5, .5} };
```

- Pass each point to shape generation function, as/when required:

```
void quad (GLint n1, GLint n2, GLint n3, GLint n4)
{
  glBegin(GL_POLYGON);
    glVertex3fv( points[n1] );
    glVertex3fv( points[n2] );
    glVertex3fv( points[n3] );
    glVertex3fv( points[n4] );
  glEnd();
}
```

- Call as:

```
quad(0, 1, 2, 3);    quad(4, 5, 6, 7);    quad(2, 3, 7, 6);
quad(0, 1, 5, 4);    quad(1, 2, 6, 5);    quad(0, 4, 7, 3);
```

Reduce Number of GL Calls

- Store points as single scripted array

```
GLfloat points[] = {   0,  0,  0,     .5,  0,  0,     .5, .5,  0,     0, .5,  0,
                       0,  0, .5,     .5,  0, .5,     .5, .5, .5,     0, .5, .5 };
```

- Enable Client side Storage

```
glEnableClientState(GL_VERTEX_ARRAY);
glDisableClientState(GL_VERTEX_ARRAY)
```

- Link points to the Vertex Array

```
glVertexPointer(3, GL_FLOAT, 0, points);
```

- Which points make surfaces

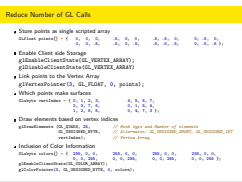
```
GLubyte vertIndex = { 0, 1, 2, 3,          4, 5, 6, 7,
                      2, 3, 7, 6,          0, 1, 5, 4,
                      1, 2, 6, 5,          0, 4, 7, 3 };
```

- Draw elements based on vertex indices

```
glDrawElements (GL_QUADS, 24,          // Mesh type and Number of elements
                GL_UNSIGNED_BYTE,      // Alternates: GL_UNSIGNED_SHORT, GL_UNSIGNED_INT
                vertIndex);            // Vertex Array
```

- Inclusion of Color Information

```
GLubyte colors[] = {  255, 0, 0,     255, 0, 0,     255, 0, 0,     255, 0, 0,
                      0, 0, 255,     0, 0, 255,     0, 0, 255,     0, 0, 255 };
glEnableClientState(GL_COLOR_ARRAY);
glColorPointer(3, GL_UNSIGNED_BYTE, 0, colors);
```

GLUT Functions for Polygons

- Wire structures vs Solid Structure
- Four sided Tetrahedron (Pyramid) `glutWireTetrahedron()` or `glutSolidTetrahedron()`
- Six sided Regular Hexahedron (Cube) `glutWireCube(edgeLength)` or `glutSolidCube(edgeLength)}`
- Eight sided Octahedron `glutWireOctahedron()` or `glutSolidOctahedron`
- Twelve sided Dodecahedron `glutWireDodecahedron()` or `glutSolidDodecahedron()`
- Twenty sided Icosahedron `glutWireIcosahedron()` or `glutSolidIcosahedron()`
- Center of all objects frawn at origin world coordinates.

GLUT Functions for Polygons

- Wire structures vs Solid Structure
- Four sided Tetrahedron (Pyramid) glutWireTetrahedron() or glutSolidTetrahedron()
- Six sided Regular Hexahedron (Cube) glutWireCube(edgeLength) or glutSolidCube(edgeLength)}
- Eight sided Octahedron glutWireOctahedron() or glutSolidOctahedron
- Twelve sided Dodecahedron glutWireDodecahedron() or glutSolidDodecahedron()
- Twenty sided Icosahedron glutWireIcosahedron() or glutSolidIcosahedron()
- Center of all objects frawn at origin world coordinates.

GLUT functions for Curved Surfaces

- `glutWireSphere(radius, longitude, latitude)`
- `glutWireCone(base, height, longitude, latitude)`
- `glutWireTorus(rCrossSection, rAxial, nConcentric, nRadialSlices)`
- `glutWireTeapot(size)`

GLUT functions for Curved Surfaces
- glutWireSphere(radius, longitude, latitude)
- glutWireCone(base, height, longitude, latitude)
- glutWireTorus(rCrossSection, rAxial, nConcentric, nRadialSlices)
- glutWireTeapot(size)

Texture Overview

- Mapping of 2D Image to 3D Object
- `Image[height][weight][4]`
- Texture Coordinates bounded in $[0, 1]$. OpenGL uses (s, t) to refer to them, others use (u, v).
- Pixels of textures called *texels*
- Mapping Operation: Takes 3D points to (u,v) coordinates (Easy for cubes, spheres, complicated for others)

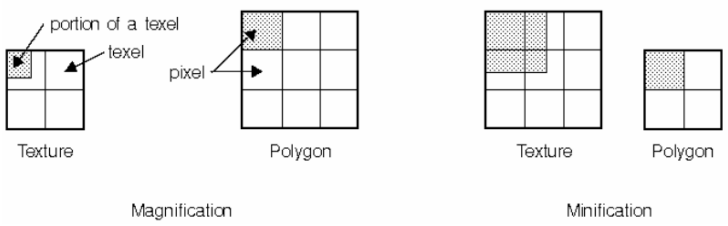
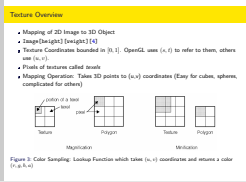


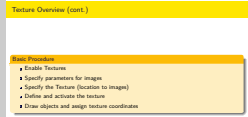
Figure 3: Color Sampling: Lookup Function which takes (u, v) coordinates and returns a color (r, g, b, a)



Texture Overview (cont.)

Basic Procedure

- Enable Textures
- Specify parameters for images
- Specify the Texture (location to images)
- Define and activate the texture
- Draw objects and assign texture coordinates

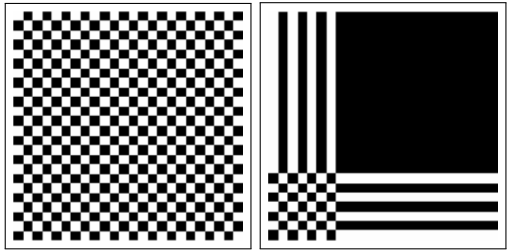


Texture Enabling

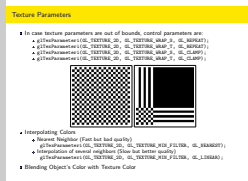
- Enabling of Textures
  - `glEnable(GL_TEXTURE_2D)`
  - `glDisable(GL_Texture_2D)`
- Create a Texture Object
  - `glGenTextures(1, &texture_id)`
  - Link: `glBindTexture(GL_TEXTURE_2D, texture_id)`
  - Unlink: `glBindTexture(0)`

Texture Parameters

- In case texture parameters are out of bounds, control parameters are:
  - `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);`
  - `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);`
  - `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP);`
  - `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP);`

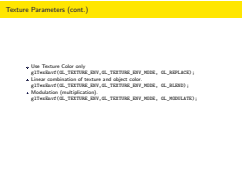


- Interpolating Colors
  - Nearest Neighbor (Fast but bad quality)
    `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);`
  - Interpolation of several neighbors (Slow but better quality)
    `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);`
- Blending Object's Color with Texture Color



Texture Parameters (cont.)

- Use Texture Color only
  `glTexEnvf(GL_TEXTURE_ENV,GL_TEXTURE_ENV_MODE, GL_REPLACE);`
- Linear combination of texture and object color.
  `glTexEnvf(GL_TEXTURE_ENV,GL_TEXTURE_ENV_MODE, GL_BLEND);`
- Modulation (multiplication).
  `glTexEnvf(GL_TEXTURE_ENV,GL_TEXTURE_ENV_MODE, GL_MODULATE);`



Texture Location an Activation

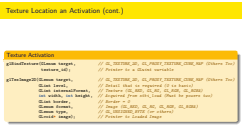
Texture Location

- Nothing in OpenGL to load an image !!!!!!!!
- 3rd Party APIS
  - Simple OpenGL Image Library (Link: lonesock.net/soil.html)
  - Single File Public Domain Libraries for C/C++ (Link: github.com/nothings/stb)
- `GLubyte *data = stbi_load("img.jpg", &width, &height, &channels, 0);`
  - Channel: Number of 8-bit components per pixel.
  - Param 5: Force different density on Channel.

Texture Location an Activation (cont.)

Texture Activation

```
glBindTexture(GLenum target,          // GL_TEXTURE_2D, GL_PROXY_TEXTURE_CUBE_MAP (Others Too)
              texture_id);            // Pointer to a GLuint variable

glTexImage2D(GLenum target,           // GL_TEXTURE_2D, GL_PROXY_TEXTURE_CUBE_MAP (Others Too)
             GLint level,             // Detail that is required (0 is basic)
             GLint internalFormat,    // Texture (GL_RED, GL_RG, GL_RGB, GL_RGBA)
             int width, int height,   // Acquired from stbi_load (Must be powers two)
             GLint border,            // Border = 0
             GLenum format,           // Image (GL_RED, GL_RG, GL_RGB, GL_RGBA)
             GLenum type,             // GL_UNSIGNED_BYTE (or others)
             GLvoid* image);          // Pointer to Loaded Image
```

Draw Objects and Assign Textures

```
glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, texture_id);

glBegin(GL_POLYGON);
  glTexCoord2f(0.0, 0.0);        glVertex3f( 0,   0,   0 );
  glTexCoord2f(1.0, 0.0);        glVertex3f( 0.5, 0,   0 );
  glTexCoord2f(1.0, 1.0);        glVertex3f( 0.5, 0.5, 0 );
  glTexCoord2f(0.0, 1.0);        glVertex3f( 0,   0.5, 0 );
glEnd();
glBindTexture(GL_TEXTURE_2D, 0);
glDisable(GL_TEXTURE_2D);
```


Draw Objects and Assign Textures

glEnable(GL_TEXTURE_2D);
glBindTexture(GL_TEXTURE_2D, texture_id);

glBegin(GL_POLYGON);
  glTexCoord2f(0.0, 0.0); glVertex3f(0, 0, 0);
  glTexCoord2f(1.0, 0.0); glVertex3f(0.5, 0, 0);
  glTexCoord2f(1.0, 1.0); glVertex3f(0.5, 0.5, 0);
  glTexCoord2f(0.0, 1.0); glVertex3f(0, 0.5, 0);
glEnd();
glBindTexture(GL_TEXTURE_2D, 0);
glDisable(GL_TEXTURE_2D);

Lighting and Illumination

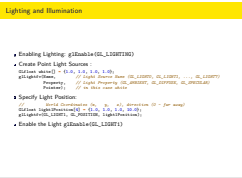
- Enabling Lighting: `glEnable(GL_LIGHTING)`
- Create Point Light Sources :

```
GLfloat white[] = {1.0, 1.0, 1.0, 1.0};
glLightfv(Name,         // Light Source Name (GL_LIGHT0, GL_LIGHT1, ..., GL_LIGHT7)
          Property,     // Light Property (GL_AMBIENT, GL_DIFFUSE, GL_SPECULAR)
          Pointer);     // in this case white
```

- Specify Light Position:

```
//          World Coordinates (x,   y,   z), direction (0 - far away)
GLfloat light1Position[4] = {1.0, 1.0, 1.0, 10.0};
glLightfv(GL_LIGHT1, GL_POSITION, light1Position);
```

- Enable the Light `glEnable(GL_LIGHT1)`



1. Misc. Topics
   - Pixel Primitives
   - Object Management
   - View/Display

2D Geometric Transforms

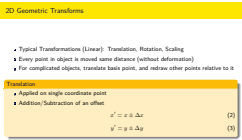
- Typical Transformations (Linear): Translation, Rotation, Scaling
- Every point in object is moved same distance (without deformation)
- For complicated objects, translate basis point, and redraw other points relative to it

Translation

- Applied on single coordinate point
- Addition/Subtraction of an offset

$$x' = x \pm \Delta x \tag{2}$$

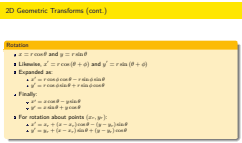
$$y' = y \pm \Delta y \tag{3}$$



2D Geometric Transforms (cont.)

Rotation

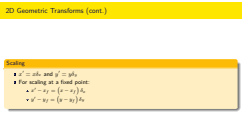
- $x = r\cos\theta$ and $y = r\sin\theta$
- Likewise, $x' = r\cos(\theta + \phi)$ and $y' = r\sin(\theta + \phi)$
- Expanded as:
  - $x' = r\cos\phi\cos\theta - r\sin\phi\sin\theta$
  - $y' = r\cos\phi\sin\theta + r\sin\phi\cos\theta$
- Finally:
  - $x' = x\cos\theta - y\sin\theta$
  - $y' = x\sin\theta + y\cos\theta$
- For rotation about points (x_r, y_r):
  - $x' = x_r + (x - x_r)\cos\theta - (y - y_r)\sin\theta$
  - $y' = y_r + (x - x_r)\sin\theta + (y - y_r)\cos\theta$



2D Geometric Transforms (cont.)

Scaling

- $x' = x\delta_x$ and $y' = y\delta_y$
- For scaling at a fixed point:
  - $x' - x_f = \left(x - x_f\right)\delta_x$
  - $y' - y_f = \left(y - y_f\right)\delta_y$



Transformations in OpenGL

- **Translation**: 4x4 matrix generated by `glTranslatef(x,y,z)` and applied to all vertices
- **Rotation**: 4x4 matrix generated by `glRotatef(theta,x,y,z)` and applied to all vertices
- **Scaling**: 4x4 matrix generated by `glScalef(x,y,z)` and applied to all vertices

Transformations in OpenGL

- **Translation**: 4x4 matrix generated by `glTranslatef(x,y,z)` and applied to all vertices
- **Rotation**: 4x4 matrix generated by `glRotatef(theta,x,y,z)` and applied to all vertices
- **Scaling**: 4x4 matrix generated by `glScalef(x,y,z)` and applied to all vertices

Homogeneous Coordinate System

$$\mathbf{P}' = M_1\mathbf{P} + M_2 \tag{4}$$

- $\mathbf{P}$ is cartesian coordinates (x, y)
- Homogeneous coordinate system aims to represent all transformations as matrix multiplications

$$\mathbf{P}'_h = M_c\mathbf{P}_h \tag{5}$$

- $\mathbf{P}_h$ is homogeneous coordinates (x_h, y_h, h)
- $x = x_h/h$, and $y = y_h/h$
- For convenience, $h = 1$

Translation

$$\begin{bmatrix} 1 & 0 & \Delta x \\ 0 & 1 & \Delta y \\ 0 & 0 & 1 \end{bmatrix}$$

Rotation

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

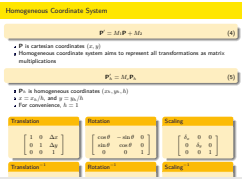
Scaling

$$\begin{bmatrix} \delta_x & 0 & 0 \\ 0 & \delta_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Translation^{-1}

Rotation^{-1}

Scaling^{-1}



Other Homogeneous Coordinate Transforms

Reflection in x

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

Reflection in y

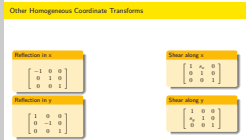
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Shear along x

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

Shear along y

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



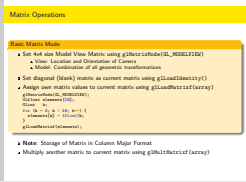
Matrix Operations

Basic Matrix Mode

- Set 4x4 size Model View Matrix using `glMatrixMode(GL_MODELVIEW)`
  - View: Location and Orientation of Camera
  - Model: Combination of all geometric transformations
- Set diagonal (blank) matrix as current matrix using `glLoadIdentity()`
- Assign own matrix values to current matrix using `glLoadMatrixf(array)`

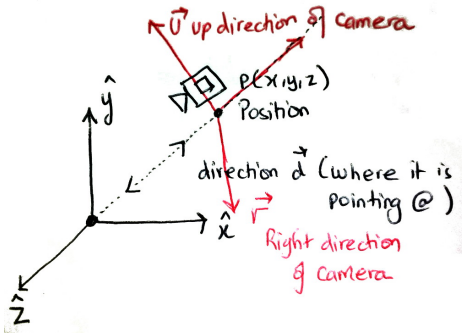
```
glMatrixMode(GL_MODELVIEW);
GLfloat elements[16];
GLint   k;
for (k = 0; k < 16; k++) {
  elements[k] = (float)k;
}
glLoadMatrixf(elements);
```

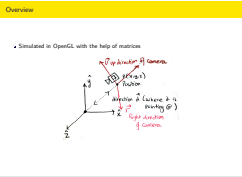
- **Note**: Storage of Matrix in Column Major Format
- Multiply another matrix to current matrix using `glMultMatrixf(array)`



Overview

- Simulated in OpenGL with the help of matrices





Overview (cont.)

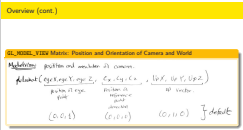
GL_MODEL_VIEW Matrix: Position and Orientation of Camera and World

Modelview position and orientation of camera.

gluLookat(eyeX, eyeY, eyeZ, Cx, Cy, Cz, UpX, UpY, UpZ)

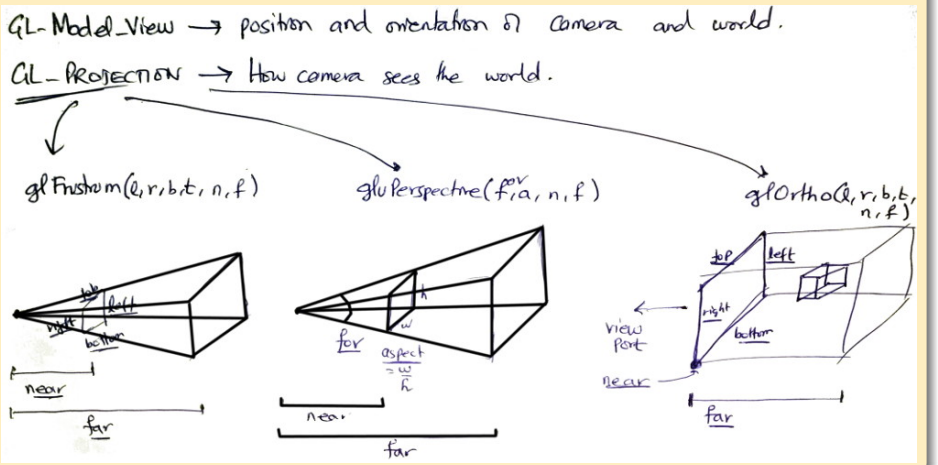
- eyeX, eyeY, eyeZ: position of eye point
- Cx, Cy, Cz: position of reference point / direction
- UpX, UpY, UpZ: up vector.

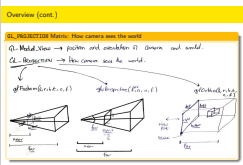
(0, 0, 1) (0, 0, 0) (0, 1, 0) } default



Overview (cont.)

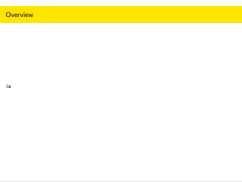
GL_PROJECTION Matrix: How camera sees the world





Overview

ia



Overview

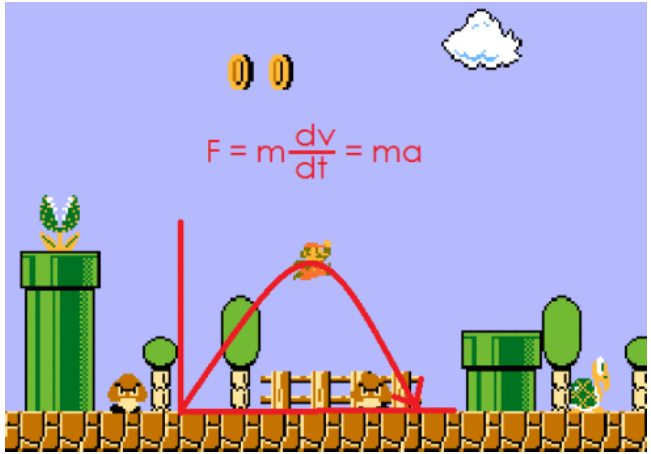


Figure 4: Physics in Super-Mario

Overview

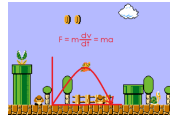
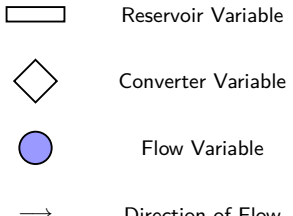


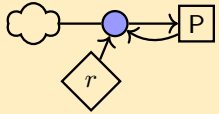
Figure 4: Physics in Super-Mario

Diagrammatic Representation



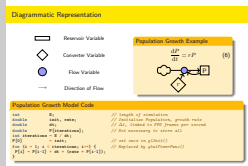
Population Growth Example

$$\frac{\mathrm{d}P}{\mathrm{d}t} = rP \qquad (6)$$



Population Growth Model Code

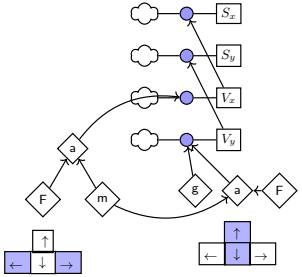
```
int             N;                      // length of simulation
double          init, rate;             // Initialize Population, growth rate
double          dt;                     // Δt, linked to FPS frames per second
double          P[iterations];          // Not necessary to store all
int iterations = N / dt;
P[0]            = init;                 // set once in glInit()
for (i = 1; i < iterations; i++) {      // Replaced by glutTimerFunc()
 P[i] = P[i-1] + dt * (rate * P[i-1]);
}
```

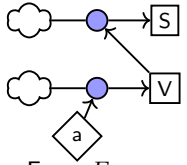



Base Model for Motion

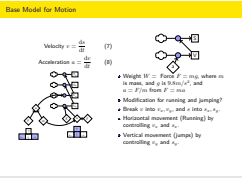
$$\text{Velocity } v = \frac{\mathrm{d}s}{\mathrm{d}t} \qquad (7)$$

$$\text{Acceleration } a = \frac{\mathrm{d}v}{\mathrm{d}t} \qquad (8)$$



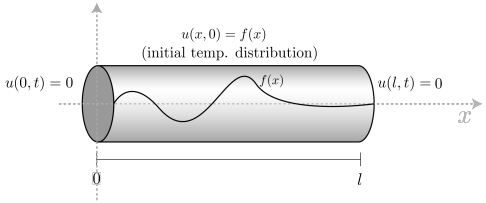


- Weight $W =$ Force $F = mg$, where m is mass, and g is $9.8m/s^2$, and $a = F/m$ from $F = ma$
- Modification for running and jumping?
- Break v into v_x, v_y, and s into s_x, s_y.
- Horizontal movement (Running) by controlling v_x and s_x.
- Vertical movement (jumps) by controlling v_y and s_y.



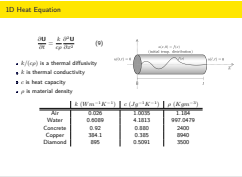
1D Heat Equation

$$\frac{\partial \mathbf{U}}{\partial t} = \frac{k}{c\rho}\frac{\partial^2 \mathbf{U}}{\partial x^2} \qquad (9)$$



- $k/(c\rho)$ is a thermal diffusivity
- k is thermal conductivity
- c is heat capacity
- ρ is material density

	$k\ (Wm^{-1}K^{-1})$	$c\ (Jg^{-1}K^{-1})$	$\rho\ (Kgm^{-3})$
Air	0.026	1.0035	1.184
Water	0.6089	4.1813	997.0479
Concrete	0.92	0.880	2400
Copper	384.1	0.385	8940
Diamond	895	0.5091	3500



Realization into OpenGL

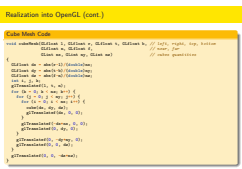
Display Code

```
glClearColor(0.0, 0.0, 0.0, 0.0);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
glEnable(GL_DEPTH_TEST);

glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
glOrtho(-5.,5.,-5,5.,-5.,5.);

glRotatef( rotate_y, 1.0, 0.0, 0.0 );
glRotatef( rotate_x, 0.0, 1.0, 0.0 );

cubeMesh(-2, +2., -2, 2, -2, 2, 10, 10, 10);

glFlush();
glutSwapBuffers();
```


Realization into OpenGL (cont.)

Cube Mesh Code

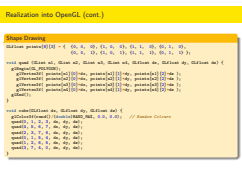
```
void cubeMesh(GLfloat l, GLfloat r, GLfloat t, GLfloat b, // left, right, top, bottom
              GLfloat n, GLfloat f,                       // near, far
              GLint nx, GLint ny, GLint nz)               // cubes quantities
{
  GLfloat dx = abs(r-l)/(double)nx;
  GLfloat dy = abs(t-b)/(double)ny;
  GLfloat dz = abs(f-n)/(double)nz;
  int i, j, k;
  glTranslatef(l, t, n);
  for (k = 0; k < nz; k++) {
    for (j = 0; j < ny; j++) {
      for (i = 0; i < nx; i++) {
        cube(dx, dy, dz);
        glTranslatef(dx, 0, 0);
      }
      glTranslatef(-dx*nx, 0, 0);
      glTranslatef(0, dy, 0);
    }
    glTranslatef(0, -dy*ny, 0);
    glTranslatef(0, 0, dz);
  }
  glTranslatef(0, 0, -dz*nz);
}
```

Realization into OpenGL (cont.)

Shape Drawing

```
GLfloat points[8][3] = {  {0, 0,  0}, {1, 0,  0}, {1, 1,  0}, {0, 1,  0},
                          {0, 0,  1}, {1, 0,  1}, {1, 1,  1}, {0, 1,  1} };

void quad (GLint n1, GLint n2, GLint n3, GLint n4, GLfloat dx, GLfloat dy, GLfloat dz) {
  glBegin(GL_POLYGON);
    glVertex3f( points[n1][0]*dx, points[n1][1]*dy, points[n1][2]*dz );
    glVertex3f( points[n2][0]*dx, points[n2][1]*dy, points[n2][2]*dz );
    glVertex3f( points[n3][0]*dx, points[n3][1]*dy, points[n3][2]*dz );
    glVertex3f( points[n4][0]*dx, points[n4][1]*dy, points[n4][2]*dz );
  glEnd();
}

void cube(GLfloat dx, GLfloat dy, GLfloat dz) {
  glColor3f(rand()/(double)RAND_MAX, 0.0, 0.0);   // Random Colours
  quad(0, 1, 2, 3, dx, dy, dz);
  quad(4, 5, 6, 7, dx, dy, dz);
  quad(2, 3, 7, 6, dx, dy, dz);
  quad(0, 1, 5, 4, dx, dy, dz);
  quad(1, 2, 6, 5, dx, dy, dz);
  quad(3, 7, 4, 0, dx, dy, dz);
}
```

Display

Sample Videos

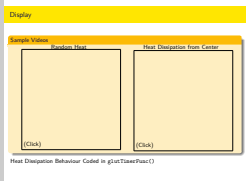
Random Heat

(Click)

Heat Dissipation from Center

(Click)

Heat Dissipation Behaviour Coded in `glutTimerFunc()`



Shaders (Non-Examinable)

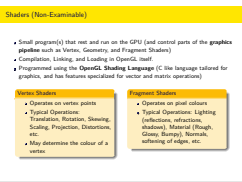
- Small program(s) that rest and run on the GPU (and control parts of the **graphics pipeline** such as Vertex, Geometry, and Fragment Shaders)
- Compilation, Linking, and Loading in OpenGL itself.
- Programmed using the **OpenGL Shading Language** (C like language tailored for graphics, and has features specialized for vector and matrix operations)

Vertex Shaders

- Operates on vertex points
- Typical Operations: Translation, Rotation, Skewing, Scaling, Projection, Distortions, etc.
- May determine the colour of a vertex

Fragment Shaders

- Operates on pixel colours
- Typical Operations: Lighting (reflections, refractions, shadows), Material (Rough, Glossy, Bumpy), Normals, softening of edges, etc.



General Syntax

```
#version version_number

flag type VariableName;

void main()
{
    variable_name =   // do something;
}
```

- **Version**: Typically 120 for version 1.20
- **flag**: Can be in, out, inout, attribute, varying, or uniform
  - **In**: Values passed into a function
  - **Out**: Values passed out of a function
  - **Attribute**: Link to vertex attributes (data associated with each vertex), so passed to vertex processor only
  - **Varying**: Passed from vertex processor to fragment processor
  - **Uniform**: Has global scope (does not change contents while changing from one shader program to another). In a way, serves as constants, accessible to both vertex and fragment shaders.

General Syntax

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  - Uniform: Has global scope (does not change contents while changing from one shader program to another). In a way, serves as constants, accessible to both vertex and fragment shaders.

General Syntax (cont.)

- **Type**: Can be conventional data types (int, float, etc.), or vector data types (intn, floatn, etc.), or matrix data types, (mat4), or aggregate data types (structs), or arrays

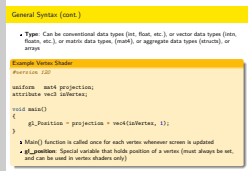
Example Vertex Shader

```
#version 120

uniform   mat4 projection;
attribute vec3 inVertex;

void main()
{
     gl_Position = projection * vec4(inVertex, 1);
}
```

- Main() function is called once for each vertex whenever screen is updated
- **gl_position**: Special variable that holds position of a vertex (must always be set, and can be used in vertex shaders only)



General Syntax (cont.)

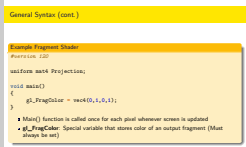
Example Fragment Shader

```
#version 120

uniform mat4 Projection;

void main()
{
     gl_FragColor = vec4(0,1,0,1);
}
```

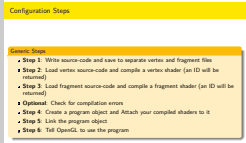
- Main() function is called once for each pixel whenever screen is updated
- **gl_FragColor**: Special variable that stores color of an output fragment (Must always be set)



Configuration Steps

Generic Steps

- **Step 1**: Write source-code and save to separate vertex and fragment files
- **Step 2**: Load vertex source-code and compile a vertex shader (an ID will be returned)
- **Step 3**: Load fragment source-code and compile a fragment shader (an ID will be returned)
- **Optional**: Check for compilation errors
- **Step 4**: Create a program object and Attach your compiled shaders to it
- **Step 5**: Link the program object
- **Step 6**: Tell OpenGL to use the program



Configuration Steps (cont.)

Step 1: Write your source code and save to files

- Our Vertex Shader

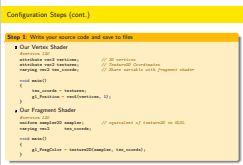
```
#version 120
attribute vec3 vertices;          // 3D vertices
attribute vec2 textures;          // Texture2D Coordinates
varying vec2 tex_coords;          // Share variable with fragment shader

void main()
{
     tex_coords = textures;
     gl_Position = vec4(vertices, 1);
}
```

- Our Fragment Shader

```
#version 120
uniform sampler2D sampler;        // equivalent of texture2D in GLSL
varying vec2      tex_coords;

void main()
{
     gl_FragColor = texture2D(sampler, tex_coords);
}
```

Configuration Steps (cont.)

Step 2: Load vertex source-code and compile vertex shader

```
int vs = glCreateShader(GL_VERTEX_SHADER);
glShaderSource(vs, readFile(vShader));
glCompileShader(vs);
```

Step 3: Load Fragment source-code and compile fragment shader

```
int fs = glCreateShader(GL_FRAGMENT_SHADER);
glShaderSource(fs, readFile(fShader));
glCompileShader(fs);
```


Configuration Steps (cont.)
Step 2: Load vertex source-code and compile vertex shader
int vs = glCreateShader(GL_VERTEX_SHADER);
glShaderSource(vs, readFile(vShader));
glCompileShader(vs);
Step 3: Load Fragment source-code and compile fragment shader
int fs = glCreateShader(GL_FRAGMENT_SHADER);
glShaderSource(fs, readFile(fShader));
glCompileShader(fs);

Configuration Steps (cont.)

Optional: Checking for Errors after Compilation

```
if(glGetShaderi(vs, GL_COMPILE_STATUS) != 1) {
                printf("%s\n", glGetShaderInfoLog(fs));
}

if(glGetShaderi(fs, GL_COMPILE_STATUS) != 1) {
                printf("%s\n", glGetShaderInfoLog(fs));
}
```

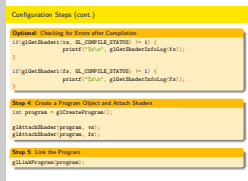
Step 4: Create a Program Object and Attach Shaders

```
int program = glCreateProgram();

glAttachShader(program, vs);
glAttachShader(program, fs);
```

Step 5: Link the Program

```
glLinkProgram(program);
```

Configuration Steps (cont.)

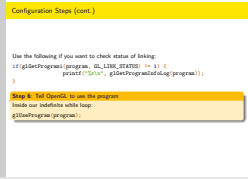
Use the following if you want to check status of linking:

```
if(glGetProgrami(program, GL_LINK_STATUS) != 1) {
                printf("%s\n", glGetProgramInfoLog(program));
}
```

Step 6: Tell OpenGL to use the program

Inside our indefinite while loop:

```
glUseProgram(program);
```

Pixel Level Primitives

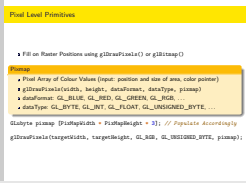
- Fill on Raster Positions using `glDrawPixels()` or `glBitmap()`

Pixmap

- Pixel Array of Colour Values (input: position and size of area, color pointer)
- `glDrawPixels(width, height, dataFormat, dataType, pixmap)`
- dataFormat: GL_BLUE, GL_RED, GL_GREEN, GL_RGB, ...
- dataType: GL_BYTE, GL_INT, GL_FLOAT, GL_UNSIGNED_BYTE, ...

```
GLubyte pixmap [PixMapWidth * PixMapHeight * 3]; // Populate Accordingly

glDrawPixels(targetWidth, targetHeight, GL_RGB, GL_UNSIGNED_BYTE, pixmap);
```

Pixel Level Primitives (cont.)

Bitmap Masks

- Assignment of Bit 0 or 1 to each element of a matrix (binary image)
- `glBitmap(width, height, offX, offY, screenX, screenY, bitShape)`
- offX, offY: Offset in Memory Location
- screenX, screenY: Offset on Screen (pixels)

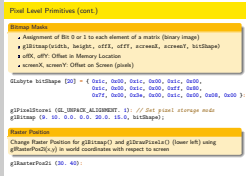
```
GLubyte bitShape [20] = { 0x1c, 0x00, 0x1c, 0x00, 0x1c, 0x00,
                          0x1c, 0x00, 0x1c, 0x00, 0xff, 0x80,
                          0x7f, 0x00, 0x3e, 0x00, 0x1c, 0x00, 0x08, 0x00 }:

glPixelStorei (GL_UNPACK_ALIGNMENT. 1): // Set pixel storage mods
glBitmap (9. 10. 0.0. 0.0. 20.0. 15.0, bitShape);
```

Raster Position

Change Raster Position for `glBitmap()` and `glDrawPixels()` (lower left) using glRasterPos2i(x,y) in world coordinates with respect to screen

```
glRasterPos2i (30. 40):
```

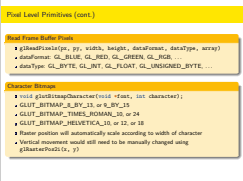
Pixel Level Primitives (cont.)

Read Frame Buffer Pixels

- `glReadPixels(px, py, width, height, dataFormat, dataType, array)`
- dataFormat: GL_BLUE, GL_RED, GL_GREEN, GL_RGB, ...
- dataType: GL_BYTE, GL_INT, GL_FLOAT, GL_UNSIGNED_BYTE, ...

Character Bitmaps

- `void glutBitmapCharacter(void *font, int character);`
- GLUT_BITMAP_8_BY_13, or 9_BY_15
- GLUT_BITMAP_TIMES_ROMAN_10, or 24
- GLUT_BITMAP_HELVETICA_10, or 12, or 18
- Raster position will automatically scale according to width of character
- Vertical movement would still need to be manually changed using `glRasterPos2i(x, y)`



Object Management using Display Lists

Display Lists

- Identify Objects as named entities (in OpenGL environment)
- Handler/Shortcut to Object
- Enclose object construction commands within:

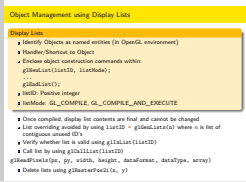
```
glNewList(listID, listMode);
...
glEndList();
```

- listID: Positive integer
- listMode: GL_COMPILE, GL_COMPILE_AND_EXECUTE

- Once compiled, display list contents are final and cannot be changed
- List overriding avoided by using `listID = glGenLists(n)` where n is list of contiguous unused ID's
- Verify whether list is valid using `glIsList(listID)`
- Call list by using `glCallList(listID)`

```
glReadPixels(px, py, width, height, dataFormat, dataType, array)
```

- Delete lists using `glRasterPos2i(x, y)`



View/Display Modification

Clipping Window

A 2D scene that is selected for display (where all objects out of this scene are clipped)

Viewport

- Objects identified in clipping window are mapped to viewports
- `glViewport(startx, starty, endx, endy)`
- Has it's own world coordinates