CS535
Interactive Computer Graphics

Fall 2016

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Who am I?

- CGVLAB: [www.cs.purdue.edu/cgvlab](http://www.cs.purdue.edu/cgvlab)
- Home page: [www.cs.purdue.edu/homes/aliaga](http://www.cs.purdue.edu/homes/aliaga)

Research Computer Graphics/Computer Vision:
- Urban Modeling: 3D acquisition, forward and inverse procedural modeling, urban design and planning
- Projector-Camera Systems: spatially-augmented reality, appearance editing, radiometric compensation
- 3D digital fabrication: genuinity detection, tamper detection, multiple appearance generation
Who are you?
Syllabus

• Math Review
• Cameras, Calibration, and Projections
  – Camera models, perspective projection, non-traditional cameras
• Graphics Pipeline
  – Transformation, rasterization, shading
• Texture Mapping and GPU programming
• Surfaces and Triangulation
Syllabus

• Spatial Hierarchies and Visibility
• Procedural Modeling
• Ray Tracing and Illumination
• Colors
• Images and Computer Vision
• Visualization
Syllabus

• Course summary
Graphics, OpenGL, GLUT, GLUI, Qt, CUDA, OpenCL, OpenCV, and more!

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History

- 1950: MIT Whirlwind (CRT)
- 1955: Sage, Radar with CRT and light pen
- 1958: Willy Higinbotham “Tennis”
- 1960: MIT “Spacewar” on DEC-PDP-1
- 1963: Ivan Sutherland’s “Sketchpad” (CAD)
- 1968: Tektronix storage tube
- 1968: Evans & Sutherland’s flight simulators
- 1968: Douglas Engelbart: computer mouse
- 1969: ACM SIGGRAPH
- 1970: Xerox GUI
- 1971: Gouraud shading
- 1974: Z-buffer
- 1975: Phong Model
- 1979: Eurographics
- 1981: Apollo Workstation, PC
- 1982: Whitted: Ray tracing
- 1982: SGI
- 1984: X Window System
- 1984: 1st SGI Workstation
- ->1995: SGI dominance
- ->2003: PC dominance
- Today: programmable graphics hardware (again)
Applications

• Training
• Education
• Computer-aided design (CAD)
• Scientific Visualization
• E-commerce
• Computer art
• Entertainment
Ivan Sutherland (1963) - SKETCHPAD

- pop-up menus
- constraint-based drawing
- hierarchical modeling
Display hardware

- vector displays
  - 1963 – modified oscilloscope
  - 1974 – Evans and Sutherland Picture System
- raster displays
  - 1975 – Evans and Sutherland frame buffer
  - 1980s – cheap frame buffers
  - 1990s – liquid-crystal displays
  - 2000s – micro-mirror projectors
  - 2010s – high dynamic range displays
- other
  - stereo, head-mounted displays
  - autostereoscopic displays
Input hardware

• 2D
  – light pen, tablet, mouse, joystick, track ball, touch panel, etc.
  – 1970s & 80s - CCD analog image sensor + frame grabber
Input hardware

- 2D

• light pen, tablet, mouse, joystick, track ball, touch panel, etc.

- 1970s & 80s: CCD analog image sensor + frame grabber
Input hardware

• 2D
  – light pen, tablet, mouse, joystick, track ball, touch panel, etc.
  – 1970s & 80s - CCD analog image sensor + frame grabber
  – 1990s & 2000’s - CMOS digital sensor + in-camera processing
High Dynamic Range Imaging

- negative film = 130:1 (7 stops)
- paper prints = 46:1
- combine multiple exposures = 250,000:1 (18 stops)

[Debevec97]

[Nayar00]
Input hardware

- **2D**
  - light pen, tablet, mouse, joystick, track ball, touch panel, etc.
  - 1970s & 80s - CCD analog image sensor + frame grabber
  - 1990s & 2000’s - CMOS digital sensor + in-camera processing → high-dynamic range (HDR)

- **3D**
  - 1980s - 3D trackers
  - 1990s - active rangefinders

- **4D and higher**
  - multiple cameras
  - multi-arm gantries
Rendering

• 1960s - the visibility problem
  – Roberts (1963), Appel (1967) - hidden-line algorithms
  – Sutherland (1974) - visibility = sorting
• **1960s - the visibility problem**
  - Roberts (1963), Appel (1967) - hidden line algorithms
  - Sutherland (1974) - visibility = sorting

• **1970s - raster graphics**
  - Gouraud (1971) - diffuse lighting
  - Phong (1974) - specular lighting
  - Blinn (1974) - curved surfaces, texture
  - Crow (1977) - anti-aliasing
1960s - the visibility problem
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1970s - raster graphics
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- Blinn (1974) - curved surfaces, texture
- Crow (1977) - anti-aliasing
• early 1980s - global illumination
  – Whitted (1980) - ray tracing
  – Goral, Torrance et al. (1984), Cohen (1985) - radiosity
  – Kajiya (1986) - the rendering equation
• early 1980s - global illumination
  – Whitted (1980) - ray tracing
  – Goral, Torrance et al. (1984), Cohen (1985) - radiosity
  – Kajiya (1986) - the rendering equation

• late 1980s - photorealism
  – Cook (1984) - shade trees
  – Perlin (1985) - shading languages
  – Hanrahan and Lawson (1990) - RenderMan
• early 1990s - non-photorealistic rendering
  – Drebin et al. (1988), Levoy (1988) - volume rendering
  – Haeberli (1990) - impressionistic paint programs
  – Salesin et al. (1994-) - automatic pen-and-ink illustration
• early 1990s - non-photorealistic rendering
  – Drebin et al. (1988), Levoy (1988) - volume rendering
  – Haeberli (1990) - impressionistic paint programs
  – Salesin et al. (1994-) - automatic pen and ink illustration
ACM SIGGRAPH

• Exciting conference
  – Papers at http://kesen.realtimerendering.com/

• Other conferences
  – Eurographics, I3D, etc.
Computer Graphics Pipeline

• How do we create a rendering such as this?
Computer Graphics Pipeline

- Design the scene (technical drawing in “wireframe”)
Computer Graphics Pipeline

- Apply perspective transformations to the scene geometry for a virtual camera
Computer Graphics Pipeline

- Hidden lines removed and colors added
Computer Graphics Pipeline

- Geometric primitives filled with constant color
Computer Graphics Pipeline

• View-independent lighting model added
Computer Graphics Pipeline

- View-dependent lighting model added
Computer Graphics Pipeline

- Texture mapping: pictures are wrapped around objects
Computer Graphics Pipeline

• Reflections, shadows, and bumpy surfaces
Computer Graphics Pipeline

Modeling Transformation
- Transform into 3D world coordinate system

Lighting
- Simulate illumination and reflectance

Viewing Transformation
- Transform into 3D camera coordinate system

Clipping
- Clip primitives outside camera’s view

Projection Transformation
- Transform into 2D camera coordinate system

Scan Conversion
- Draw pixels (incl. texturing, hidden surface…)

Image
Linear Algebra

• Why do we need it?
  – Modeling transformation
    • Move “objects” into place relative to a world origin
  – Viewing transformation
    • Move “objects” into place relative to camera
  – Perspective transformation
    • Project “objects” onto image plane
Transformations

- Most popular transformations in graphics
  - Translation
  - Rotation
  - Scale
  - Projection

- In order to use a single matrix for all, we use homogeneous coordinates...
Transformations

\[
\begin{bmatrix}
x' \\
y' \\
z' \\
w'
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y \\
z \\
w
\end{bmatrix}
\]

Identity

\[
\begin{bmatrix}
x' \\
y' \\
z' \\
w'
\end{bmatrix} = \begin{bmatrix}
sx & 0 & 0 & 0 \\
0 & sy & 0 & 0 \\
0 & 0 & sz & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y \\
z \\
w
\end{bmatrix}
\]

Scale

\[
\begin{bmatrix}
x' \\
y' \\
z' \\
w'
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & tx \\
0 & 1 & 0 & ty \\
0 & 0 & 1 & tz \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y \\
z \\
w
\end{bmatrix}
\]

Translation

\[
\begin{bmatrix}
x' \\
y' \\
z' \\
w'
\end{bmatrix} = \begin{bmatrix}
-1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y \\
z \\
w
\end{bmatrix}
\]

Mirror over X axis
Transformations

Rotate around Z axis:
\[
\begin{bmatrix}
x' \\
y' \\
z' \\
w'
\end{bmatrix} =
\begin{bmatrix}
\cos\Theta & -\sin\Theta & 0 & 0 \\
\sin\Theta & \cos\Theta & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
w
\end{bmatrix}
\]

Rotate around Y axis:
\[
\begin{bmatrix}
x' \\
y' \\
z' \\
w'
\end{bmatrix} =
\begin{bmatrix}
\cos\Theta & 0 & -\sin\Theta & 0 \\
0 & 1 & 0 & 0 \\
\sin\Theta & 0 & \cos\Theta & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
w
\end{bmatrix}
\]

Rotate around X axis:
\[
\begin{bmatrix}
x' \\
y' \\
z' \\
w'
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos\Theta & -\sin\Theta & 0 \\
0 & \sin\Theta & \cos\Theta & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
w
\end{bmatrix}
\]

Perspective projection

\[
\begin{bmatrix}
\frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\
0 & \frac{2n}{t-b} & \frac{r+l}{t-b} & 0 \\
0 & 0 & \frac{-(f+n)}{f-n} & -2fn \\
0 & 0 & \frac{f-n}{f-n} & f-n
\end{bmatrix}
\]
Representations

• How are the objects described in a computer?
  – Points (or vertices)
  – Lines
  – Triangles
  – Polygons
  – Curved surfaces, etc.
  – Functions
Representations

• What information is needed per geometric primitive?
  – Color
  – Normal
  – Material properties (e.g. textures...)
Texture Mapping

- Map a “texture” onto the surface of an object
  - Wood, marble, or any “pattern”
Texture Mapping

- A texture is a two-dimensional array of “texels”, indexed by a (u,v) texture coordinate.
- At each screen pixel, a texel can be used to substitute a geometric primitives surface color.
Texture Mapping
Texture Mapping
Lighting and Shading

• Light sources
  – Point light
    • Models an omnidirectional light source (e.g., a bulb)
  – Directional light
    • Models an omnidirectional light source at infinity
  – Spot light
    • Models a point light with direction

• Light model
  – Ambient light
  – Diffuse reflection
  – Specular reflection
Lighting and Shading

- Diffuse reflection
  - Lambertian model

\[ I_D = K_D (N \cdot L) I_L \]
Lighting and Shading

• Specular reflection
  – Phong model

\[ I_S = K_S (V \cdot R)^n I_L \]
Lighting and Shading
Lighting and Shading

...shadows?
Advanced Topics: Ray tracing
Advanced Topics: Global Illumination
OpenGL

• Software interface to graphics hardware
• ~150 distinct commands
• Hardware-independent and widely supported
  – To achieve this, no windowing tasks are included
• GLU (Graphics Library Utilities)
  – Provides some higher-level modeling features such as curved surfaces, objects, etc.
• Open Inventor (old)
  – A higher-level object-oriented software package
OpenGL Online

- Programming Guide v1.1 (“Red book”)  


- Current version is >4.0
OpenGL

• Rendering parameters
  – Lighting, shading, lots of little details...

• Texture information
  – Texture data, mapping strategies

• Matrix transformations
  – Projection
  – Model view
  – (Texture)
  – (Color)
Matrix Transformations
Matrix Transformations

• Each of modelview and projection matrix is a 4x4 matrix
• OpenGL functions
  – glMatrixMode(…)
  – glLoadIdentity(…)
  – glLoadMatrixf(…)
  – glMultMatrix(…)
  – glTranslate(…)
  – glScale(…)
  – glRotate(…)
  – glPushMatrix()
  – glPopMatrix()
Matrix Transformations

{  
  ...
  ...
  ...
  
glMatrixMode(GL_MODELVIEW);
  glLoadIdentity();
  glMultMatrixf(N); /* apply transformation */
  glMultMatrixf(M); /* apply transformation M */
  glMultMatrixf(L); /* apply transformation L */
  glBegin(GL_POINTS);
    glVertex3f(v); /* draw transformed vertex v */
  glEnd();
  ...
  ...
  ...
}

= draw transformed point “N(M(Lv))”
Modelview Transformations

\begin{align*}
gl\text{Translate3f}(tx,ty,tz) \\
gl\text{Rotatef}(45,0,0,1) \\
gl\text{Scalef}(2,-0.5,1.0)
\end{align*}
Modelview Transformations

```c
// Rotate then Translate
glRotatef(d, rx, ry, rz);
glTranslate3f(tx, ty, tz);

// Translate then Rotate
glTranslate3f(tx, ty, tz);
glRotatef(d, rx, ry, rz);
```
Modelview Transformations

void pilotView(GLdouble planex, GLdouble planey, GLdouble planez, GLdouble roll, GLdouble pitch, GLdouble heading)
{
  glRotated(roll, 0.0, 0.0, 1.0);
  glRotated(pitch, 0.0, 1.0, 0.0);
  glRotated(heading, 1.0, 0.0, 0.0);
  glTranslated(-planex, -planey, -planez);
}

void polarView(GLdouble distance, GLdouble twist, GLdouble elevation, GLdouble azimuth)
{
  glTranslated(0.0, 0.0, -distance);
  glRotated(-twist, 0.0, 0.0, 1.0);
  glRotated(-elevation, 1.0, 0.0, 0.0);
  glRotated(azimuth, 0.0, 0.0, 1.0);
}
Projection Transformations

```c
void glFrustum(GLdouble left, GLdouble right, GLdouble bottom, GLdouble top, GLdouble near, GLdouble far);
```
Projection Transformations

```c
void gluPerspective(GLdouble fovy, GLdouble aspect, GLdouble near, GLdouble far);
```
void glOrtho(GLdouble left, GLdouble right, GLdouble bottom,
             GLdouble top, GLdouble near, GLdouble far);

void gluOrtho2D(GLdouble left, GLdouble right,
                GLdouble bottom, GLdouble top);
Matrix Transformations

draw_wheel_and_bolts()
{
    long i;
    draw_wheel();
    for(i=0;i<5;i++)
    {
        glPushMatrix();
        glRotatef(72.0*i,0.0,0.0,1.0);
        glTranslatef(3.0,0.0,0.0);
        draw_bolt();
        glPopMatrix();
    }
}
Simple OpenGL Program

{  
  <Initialize OpenGL state>

  <Load and define textures>

  <Specify lights and shading parameters>

  <Load projection matrix>

  For each frame

    <Load model view matrix>
    <Draw primitives>

  End frame

}
#include <GL/gl.h>
main()
{
    InitializeAWindowPlease();
    glMatrixMode(GL_PROJECTION);
    glOrtho(0.0, 1.0, 0.0, 1.0, -1.0, 1.0);
    glClearColor (0.0, 0.0, 0.0, 0.0);
    glClear (GL_COLOR_BUFFER_BIT);
    glColor3f (1.0, 1.0, 1.0);
    glMatrixMode(GL_MODELVIEW);
    glLoadIdentity();
    glTranslate3f(1.0, 1.0, 1.0):
    glBegin(GL_POLYGON);
        glVertex3f (0.25, 0.25, 0.0);
        glVertex3f (0.75, 0.25, 0.0);
        glVertex3f (0.75, 0.75, 0.0);
        glVertex3f (0.25, 0.75, 0.0);
    glEnd();
    glFlush();
    UpdateTheWindowAndCheckForEvents();
}
(Free)GLUT

• = Graphics Library Utility Toolkit
  – Adds functionality such as windowing operations to OpenGL

• Event-based callback interface
  – Display callback
  – Resize callback
  – Idle callback
  – Keyboard callback
  – Mouse movement callback
  – Mouse button callback
Simple OpenGL + GLUT Program

#include <…>

DisplayCallback()
{
    // Clear window
    // Load Projection matrix
    // Load Modelview matrix
    // Draw primitives
    // Swap buffers
}

IdleCallback()
{
    // Do some computations
    // Maybe force a window refresh
}

KeyCallback()
{
    // Handle key presses
}

MouseMovementCallback
{
    // Handle mouse movement
}

MouseButtonsCallback
{
    // Handle mouse buttons
}

Main()
{
    // Initialize GLUT and callbacks
    // Create a window
    // Initialize OpenGL state
    // Enter main event loop
}
Simple OpenGL + GLUT Program

```c
#include <GL/gl.h>
#include <GL/glu.h>
#include <GL/glut.h>

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

void display(void)
{
    glClear (GL_COLOR_BUFFER_BIT);
    glColor3f (1.0, 1.0, 1.0);
    glLoadIdentity ();
    gluLookAt (0, 0, 5, 0, 0, 0, 0, 1, 0);
    glScalef (1.0, 2.0, 1.0);
    glutWireCube (1.0);
    glFlush ();
}

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

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);
    glutMainLoop();
    return 0;
}
```
Example Program with Lighting

```c
#include <GL/gl.h>
#include <GL/glu.h>
#include <GL/glut.h>

void init(void)
{
    GLfloat mat_specular[] = { 1.0, 1.0, 1.0, 1.0 };  
    GLfloat mat_shininess[] = { 50.0 };  
    GLfloat light_position[] = { 1.0, 1.0, 1.0, 0.0 };  
    glClearColor (0.0, 0.0, 0.0, 0.0);  
    glShadeModel (GL_SMOOTH);  
    glMaterialfv(GL_FRONT, GL_SPECULAR, mat_specular);  
    glMaterialfv(GL_FRONT, GL_SHININESS, mat_shininess);  
    glLightfv(GL_LIGHT0, GL_POSITION, light_position);  
    glEnable(GL_LIGHTING);  
    glEnable(GL_LIGHT0);  
    glMatrixMode(GL_PROJECTION);  
    glLoadIdentity();  
    if (w <= h)
        glOrtho (-1.5, 1.5, -1.5*(GLfloat)h/(GLfloat)w,  
                1.5*(GLfloat)h/(GLfloat)w, -10.0, 10.0);  
    else
        glOrtho (-1.5*(GLfloat)w/(GLfloat)h,  
                1.5*(GLfloat)w/(GLfloat)h, -1.5, 1.5, -10.0, 10.0);  
    glMatrixMode(GL_MODELVIEW);  
    glLoadIdentity();
}

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

```c
void display(void)
{
    glClear (GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);  
    glutSolidSphere (1.0, 20, 16);  
    glFlush ();
}

void reshape (int w, int h)
{
    glViewport (0, 0, (GLsizei) w, (GLsizei) h);  
    glMatrixMode (GL_PROJECTION);  
    glLoadIdentity();  
    if (w <= h)
        glOrtho (-1.5, 1.5, -1.5*(GLfloat)h/(GLfloat)w,  
                  1.5*(GLfloat)h/(GLfloat)w, -10.0, 10.0);  
    else
        glOrtho (-1.5*(GLfloat)w/(GLfloat)h,  
                  1.5*(GLfloat)w/(GLfloat)h, -1.5, 1.5, -10.0, 10.0);  
    glMatrixMode(GL_MODELVIEW);  
    glLoadIdentity();
}
```
Simple OpenGL + GLUT Program
GLUI

- Graphics Library User Interface
GLUI

- = Graphics Library User Interface
GLUI

- = Graphics Library User Interface
Qt

- Qt is a cross-platform application and UI framework with APIs for C++ programming and Qt Quick for rapid UI creation
Alternatives graphics pipeline?

• Traditional pipeline...ok
• Parallel pipeline
  – Cluster of PCs?
  – Cluster of PS3?
  – What must be coordinated? What changes? What are the bottlenecks?

– Sort-first vs. Sort-last pipeline
  • PixelFlow
  • Several hybrid designs
What can you do with a graphics pipeline?

- Uhm...graphics
What can you do with a graphics pipeline?

- Uhm...graphics
- Paperweight?
What can you do with a graphics pipeline?

• Uhm...graphics
• Paperweight?

• How about large number crunching tasks?
• How about general (parallelizable) tasks?
CUDA and OpenCL

• NVIDIA defined “CUDA” (new)
  – Compute Unified Device Architecture
  – http://www.nvidia.com/object/cuda_home.html#

• Khrono’s group defined “OpenCL” (newer)
  – Open Standard for Parallel Programming of Heterogeneous Systems
  – http://www.khronos.org/opencl/
CUDA Example

• Rotate a 2D image by an angle

  – On the CPU (PC)
    • simple-tex.pdf

  – On the GPU (graphics card)
    • simple-tex-kernel.pdf
OpenCL Example

• Compute a Fast Fourier Transform
  – On the CPU (PC)
    • cl-cpu.pdf
  – On the GPU (graphics card)
    • cl-gpu.pdf
GLSL

• OpenGL Shading Language
  – Specification
  – Quick reference
  – Example:
    • phong.pix
    • phong.vrt
OpenCV

• A library for computer-vision related software
• Derived from research work and high-performance code from Intel
• http://opencv.willowgarage.com/wiki/
  – e.g., find fundamental matrix