## Chapter 2

Basics of Computer Graphics: Rendering Pipeline/OpenGL

## Your tasks for the weekend

- Piazza Discussion Group:
  - Register
  - Post review questions by Mon noon
    - Use private option, rev1 tag
- Start Assignment 1
  - Test programming environment on lab computers/Set laptop environment (optional)

## Assignment 1

- Experience OpenGL & GLUT
- Have FUN
- Description:
http://www.ugrad.cs.ubc.ca/~cs314/Vsep2013/a1/a1.pdf
- Deadline: Sep 20

## Your tasks for the weekend

- Sign and Submit Plagiarism Form
  - http://www.ugrad.cs.ubc.ca/~cs314/Vsep2013/plag.html
- Optional reading (Shirley: Introduction to CG)
  - Math refresher: Chapters 2, 4
    - **Lots of math coming in the next few weeks**
  - Background on graphics: Chapter 1

## Rendering

Goal:

- Transform (3D) computer models into images
- Photo-realistic (or not)

Interactive rendering:

- Fast, but (until recently) low quality
- Roughly follows a fixed pattern of operations
  - **Rendering Pipeline**

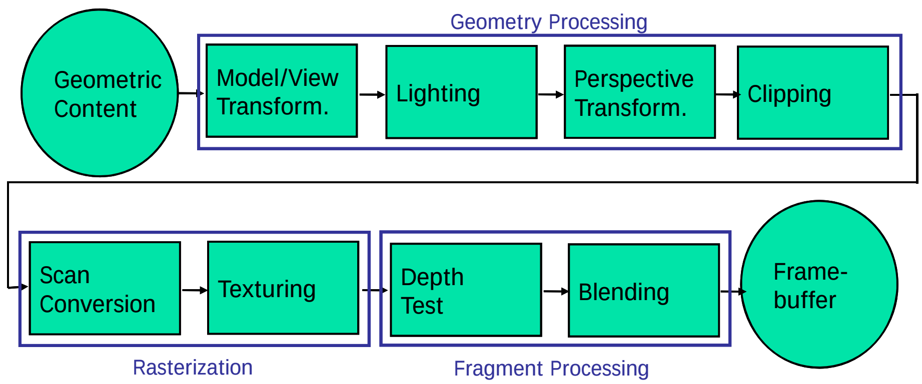
Offline rendering:

- Ray-tracing
- Global illumination

## Rendering Tasks (no particular order)

- Project 3D geometry onto image plane
  - Geometric transformations
- Determine which primitives/parts of primitives are visible
  - Hidden surface removal
- Determine which pixels geometric primitive covers
  - Scan conversion
- Compute color of every visible surface point
  - Lighting, shading, texture mapping

## The Rendering Pipeline




## Rendering Pipeline

- Abstract model of
  - sequence of operations to transform geometric model into digital image
  - graphics hardware workflow
- Underlying API (application programming interface) model for programming graphics hardware
  - OpenGL
  - Direct 3D
- **Actual implementations vary**

## Clicker Question

- Which of the tasks below is not part of the rendering pipeline?
  A. Scan Conversion
  B. Viewing Transformation
  C. Modeling
  D. Lighting

## (Tentative) Lecture Syllabus

- Introduction + Rendering Pipeline (week 1/2)
- Transformations (week 2/3)
- Scan Conversion (week 4/5)
- Clipping (week 5)
- Hidden Surface Removal (week 6/7)
- Review & Midterm (week 7)
  - Midterm: Oct 18
- Lighting Models (week 8)
- Texture mapping (week 9/10)
- Review & Midterm (week 10)
  - Midterm: Nov 8
- Ray Tracing (week 11)
- Shadows (week 11/12)
- Modeling (content creation) (week 12/13)
- Review (last lecture)

## Rendering Pipeline Implementation: OpenGL/GLut

## OpenGL

- API for graphics hardware
  - Started in 1989 by Kurt Akeley
- Designed to exploit graphics hardware
- Implemented on many different platforms

- **Pipeline processing**
  - **Event driven**
  - **Communication via state setting**

## GLUT: OpenGL Utility Toolkit

- **Event driven !!!**

```
int main(int argc, char **argv)
{
     // Initialize GLUT and open a window.
    glutInit(&argc, argv);
    glutInitDisplayMode(GLUT_RGB | GLUT_DOUBLE);
    glutInitWindowSize(800, 600);
    glutCreateWindow(argv[0]);

    // Register a bunch of callbacks for GLUT events.
    glutDisplayFunc(display);
    glutReshapeFunc(reshape);

    // Pass control to GLUT.
    glutMainLoop();

    return 0;
}
```

## Event-Driven Programming

- Main loop not under your control
  - vs. procedural
- Control flow through event callbacks
  - redraw the window now
  - key was pressed
  - mouse moved
- Callback functions called from main loop **when events occur**
  - mouse/keyboard, redrawing...

## Graphics State (global variables)

- Set state once, remains until overwritten
  - glColor3f(1.0, 1.0, 0.0) → set color to yellow
  - glSetClearColor(0.0, 0.0, 0.2) → dark blue bg
  - glEnable(LIGHT0) → turn on light
  - glEnable(GL_DEPTH_TEST) → hidden surf.

## OpenGL/GLUT Example

```
void display(void) {// Called when need to redraw screen.
     // Clear the buffer we will draw into.
    glClearColor(0, 0, 0, 1);
    glClear(GL_COLOR_BUFFER_BIT);

    // Initialize the modelview matrix.
    glMatrixMode(GL_MODELVIEW);
    glLoadIdentity();

    // Draw STUFF

    // Make the buffer we just drew into visible.
    glutSwapBuffers();
}
```

## GLUT Example

```
int main(int argc, char *argv[]) {
    .....
    // Schedule the first animation callback ASAP.
    glutTimerFunc(0, animate, 0);
    // Pass control to GLUT.
    glutMainLoop();
    return 0;
}
void animate(int last_frame = 0) {
    // Do stuff
    // Schedule the next frame.
    int current_time = glutGet(GLUT_ELAPSED_TIME);
    int next_frame = last_frame + 1000 / 30;
    glutTimerFunc(MAX(0, next_frame - current_time),
  animate, current_time);
}
```

## GLUT Input Events

```
  // you supply these kind of functions
void reshape(int w, int h);
void keyboard(unsigned char key, int x, int y);
void mouse(int but, int state, int x, int y);

  // register them with glut
glutReshapeFunc(reshape);
glutKeyboardFunc(keyboard);
glutMouseFunc(mouse);
```

## GLUT and GLU primitives

```
gluSphere(...)
gluCylinder(...)

glutSolidSphere(GLdouble radius, GLint slices, GLint stacks)
glutWireSphere(...)

glutSolidCube(GLdouble size)
glutWireCube(...)

glutSolidTorus(...)
glutWireTorus(...)

glutSolidTeapot(...)
glutWireTeapot(...)
```

- Note:
  - Have limited set of parameters
  - Control via global transformations (see a1 template)
  - **Need to save/restore setting**

## GLUT and GLU primitives

- Example (from a1):

```
void Turtle::draw() {
   glPushMatrix();   -> Save previous state
   glTranslatef(x_, y_, 0);
   // Turtle shell.
   glColor4fv(shell_);
   glBegin(GL_POLYGON);
   for (double i = 0; i < M_PI; i += M_PI / 12)
      glVertex3f(cos(i) * radius_, sin(i) * radius_, 0.0);
   glEnd();
   .....
   glPopMatrix();   -> Restore previous state
}
```

## GLUT and GLU primitives

- Basic Transformations:

```
// Different basic transformations
glTranslatef(…);
glRotatef(…);
glScalef(…);
```

## Lighting

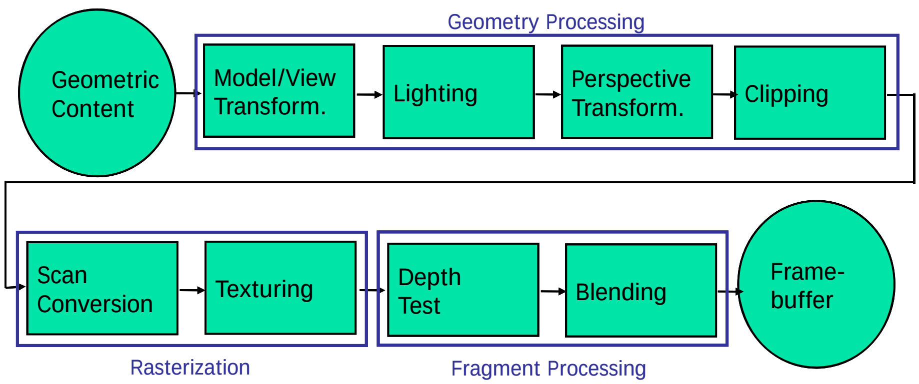
```
void setup_lighting(void) {

   // Turn on lighting, and two local lights.
   glEnable(GL_LIGHTING);
   glEnable(GL_LIGHT0);
   glEnable(GL_LIGHT1);
   glEnable(GL_COLOR_MATERIAL);

   // Set the intensity of the global ambient light.
   float ambient[] = {0.3, 0.3, 0.3, 1.0};
   glLightModelfv(GL_LIGHT_MODEL_AMBIENT, ambient);

   // Set up the diffuse intensities of the local light source.
   float diffuse[][4] = {
      0.8, 0.8, 0.8, 1,
      0.2, 0.2, 0.2, 1,
   };
   glLightfv(GL_LIGHT0, GL_DIFFUSE, diffuse[0]);
   glLightfv(GL_LIGHT1, GL_DIFFUSE, diffuse[1]);

   // Move the light near the top corner of the window.
   float light_positions[][4] = {
      0,  1, 2, 0, // From above-left
        0, -5, 0, 0, // From below
   };
   glLightfv(GL_LIGHT0, GL_POSITION, light_positions[0]);
   glLightfv(GL_LIGHT1, GL_POSITION, light_positions[1]);
}
```

## Rendering Pipeline in (More) Detail

## Clicker Question

- What does the function ‘glutMainLoop’ do?
  - A. Nothing
  - B. Calls rendering pipeline
  - C. Creates 3D content
  - D. Computes scene lighting

## The Rendering Pipeline

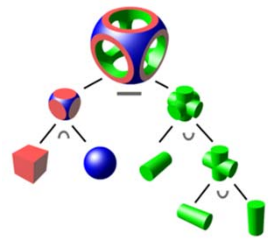



## 3D Content

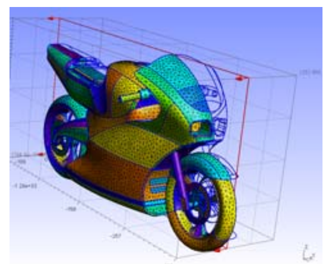
- Needs to represent models for
  - Shapes (objects)
  - Relations between different shapes
  - Object materials
  - Light sources
  - Camera

## Shapes: Representation options

- Volumetric - Boolean algebra with volumetric primitives
  - Spheres, cones, cylinders, tori, …



- Boundary representation – union of surface patches
  - Single basic primitive - Triangle Mesh
  - Higher order surface/curve primitives



## Shapes - Curves/Surfaces

- Mathematical representations:
  - Explicit functions
  - Parametric functions
  - Implicit functions

## Shapes: Explicit Functions

- Curves:
  - y is a function of x: $y := \sin(x)$
  - Only works in 2D
- Surfaces:
  - z is a function of x and y: $z := \sin(x) + \cos(y)$
  - Cannot define arbitrary shapes in 3D

## Shapes: Parametric Functions

- Curves:
  - 2D: x and y are functions of a parameter value t
  - 3D: x, y, and z are functions of a parameter value t

$$C(t) := \begin{pmatrix} \cos(t) \\ \sin(t) \\ t \end{pmatrix}$$

## Shapes: Parametric Functions

- Surfaces:
  - Surface S is defined as a function of parameter values s, t
  - Names of parameters can be different to match intuition:

$$S(\phi,\theta) := \begin{pmatrix} \cos(\phi)\cos(\theta) \\ \sin(\phi)\cos(\theta) \\ \sin(\theta) \end{pmatrix}$$

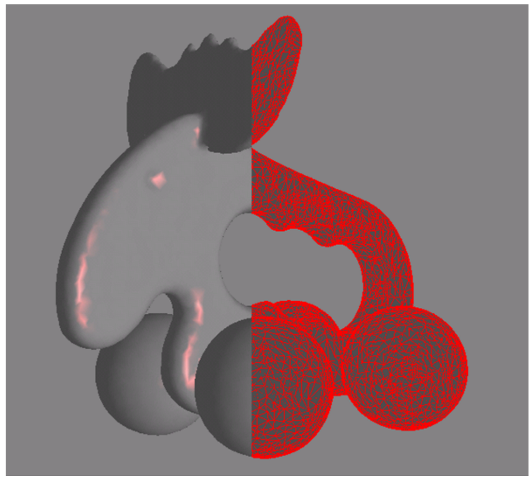
## Shapes: Implicit

- Surface (3D) or Curve (2D) defined by zero set (roots) of function
  - E.g:

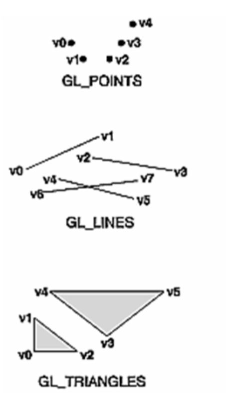
$$S(x,y,z) : x^2 + y^2 + z^2 - 1 = 0$$

## Shapes: Triangle Meshes

- Triangle = 3 vertices



## Open GL: (More) Shape Primitives




**glPointSize( float size);**
**glLineWidth( float width);**
**glColor3f( float r, float g, float b);**
**....**

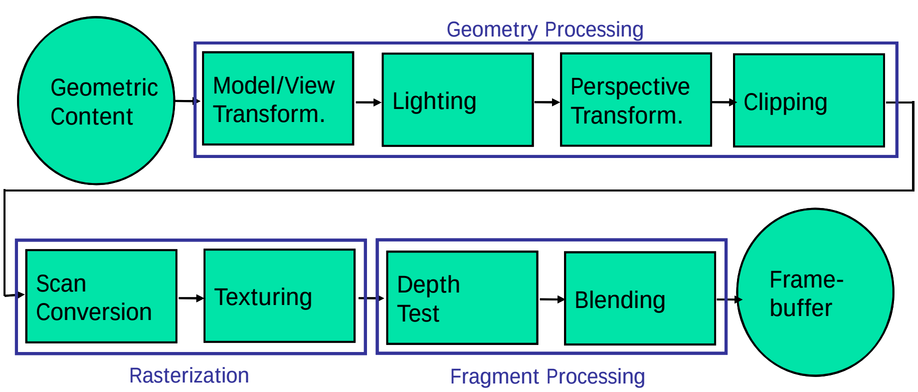
- TRIANGLE…

```
glColor3f(0,1,0);
glBegin( GL_TRIANGLES );
  glVertex3f( 0.0f, 0.5f, 0.0f );
  glVertex3f( -0.5f, -0.5f, 0.0f );
  glVertex3f( 0.5f, -0.5f, 0.0f );
glEnd();
```

## OpenGL – Shape Primitives

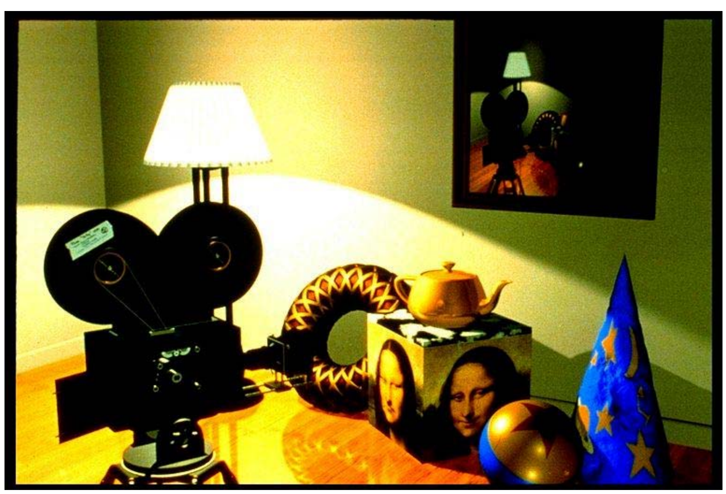
- How to interpret geometry
  - glBegin(<*mode of geometric primitives*>)
  - *mode* = GL_TRIANGLE, GL_POLYGON, etc.
- Feed vertices
  - glVertex3f(-1.0, 0.0, -1.0)
  - glVertex3f(1.0, 0.0, -1.0)
  - glVertex3f(0.0, 1.0, -1.0)
- Done
  - glEnd()

## The Rendering Pipeline

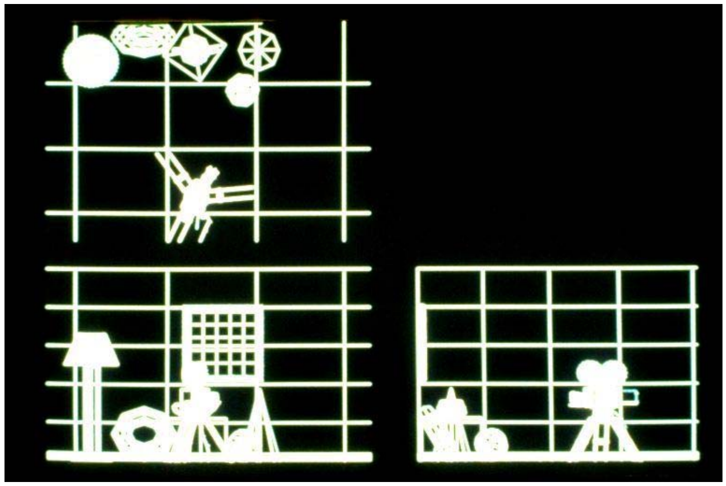


## Modeling and Viewing Transformations

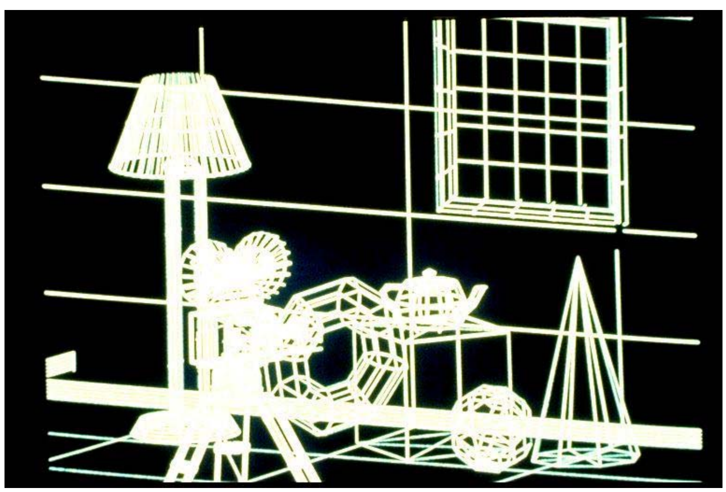
- Placing objects - Modeling transformations
  - Map points from object coordinate system to world coordinate system
- Placing camera - Viewing transformation
  - Map points from world coordinate system to camera (or eye) coordinate system



## Modeling Transformations: Object Placement

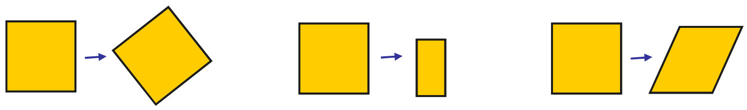


## Viewing Transformation: Camera Placement

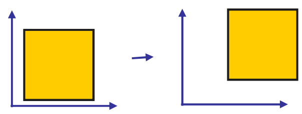


## Modeling & Viewing Transformations

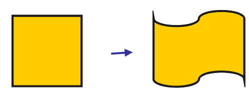
- Types of transformations:
  - Rotations, scaling, shearing



  - Translations



  - Other transformations (not handled by rendering pipeline):
    - Freeform deformation



## Modeling & Viewing Transformation

- Linear transformations
  - Rotations, scaling, shearing
  - Can be expressed as 3x3 matrix
  - E.g. scaling (non uniform):

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

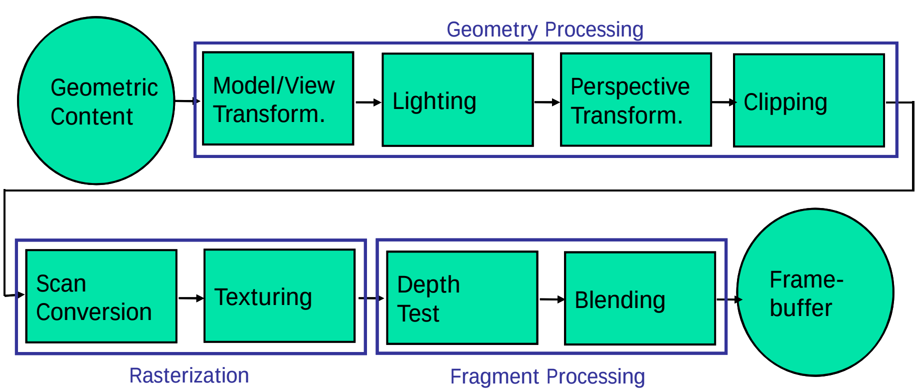
## Modeling & Viewing Transformation

- Affine transformations
  - Linear transformations + translations
  - Can be expressed as 3x3 matrix + 3 vector
  - E.g. scale+ translation:

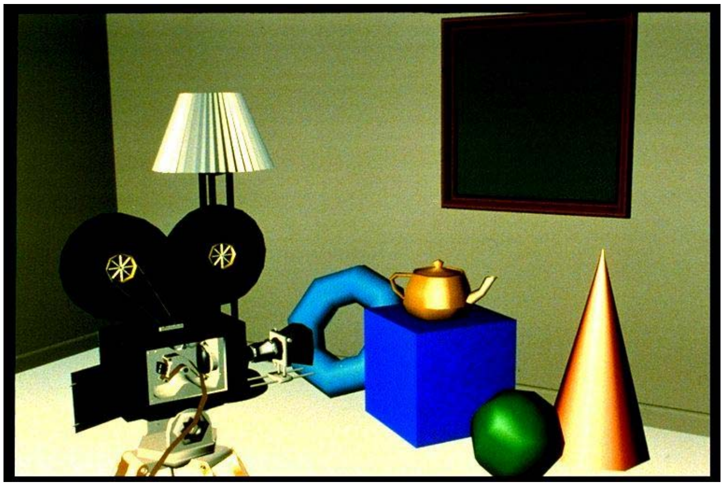
$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix}$$

  - Another representation: 4x4 homogeneous matrix

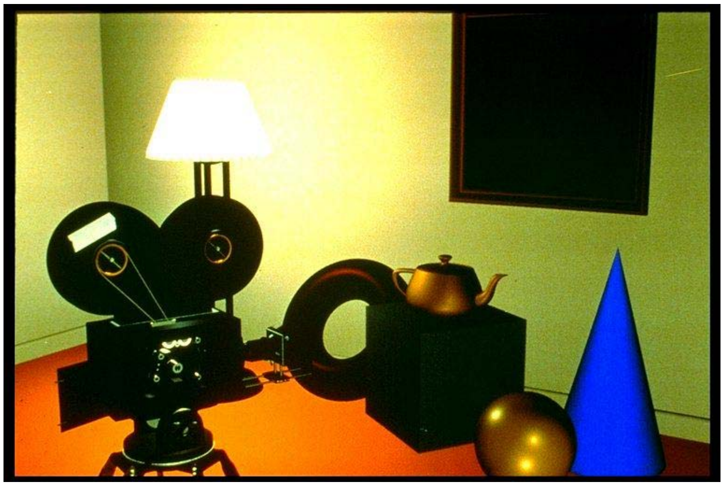
## The Rendering Pipeline



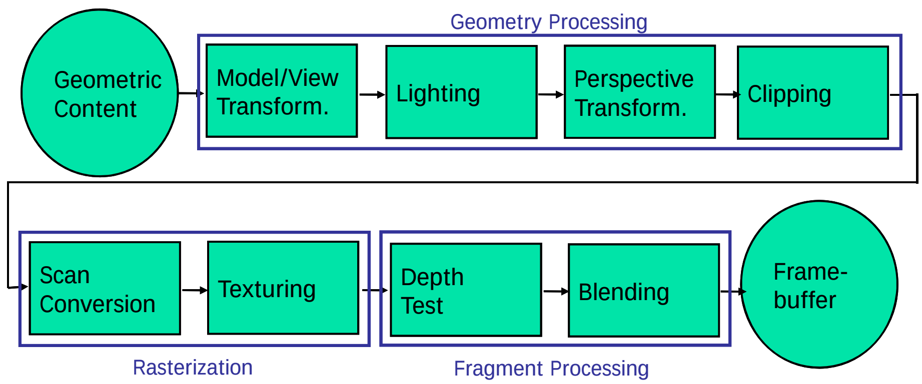
## Lighting



## Complex Lighting and Shading



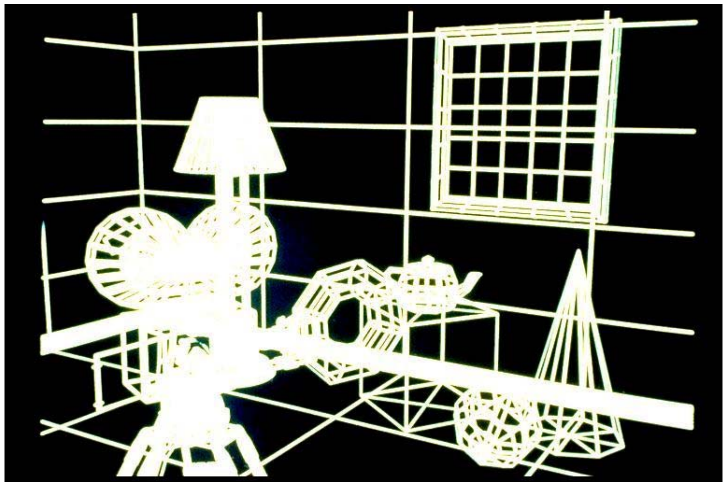
## The Rendering Pipeline




## Perspective Transformation

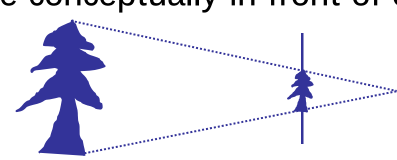
- Purpose:
  - Project 3D geometry to 2D image plane
  - Simulates a camera
- Camera model:
  - Pinhole camera (single view point)
  - More complex camera models exist, but are less common in CG

## Perspective Projection



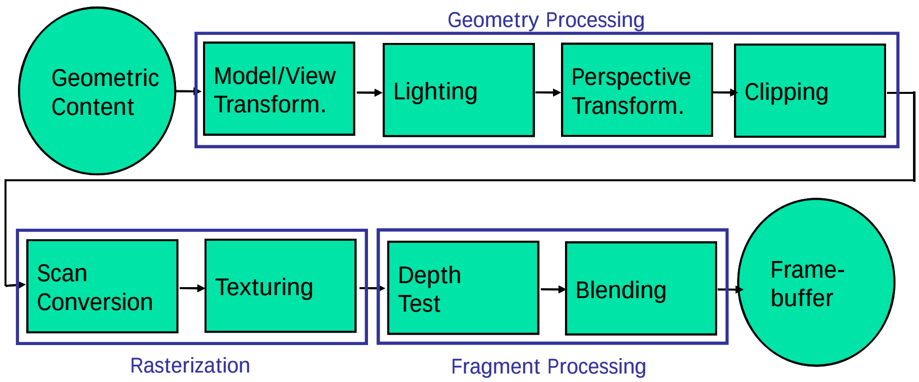
## Perspective Transformation

- In computer graphics:
  - Image plane conceptually in front of center of projection



  - Perspective transformations – subset of projective transformations
  - Linear & affine transformations also belong to this class
  - All projective transformations can be expressed as 4x4 matrix operations

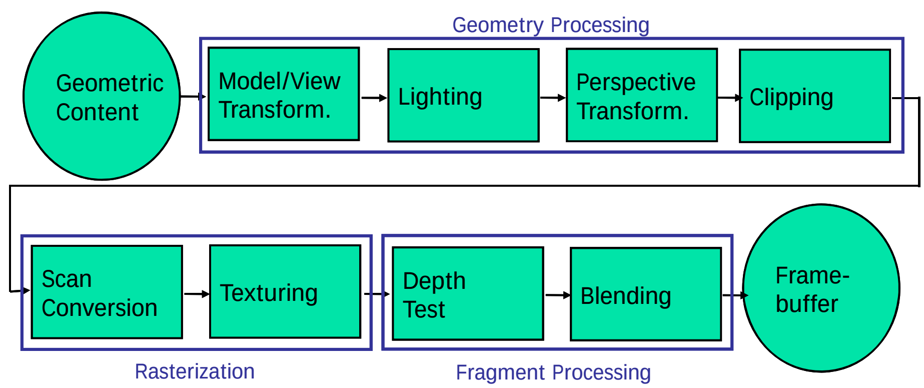
## The Rendering Pipeline




## Clipping

- Removing invisible geometry
  - Geometry outside viewing frustum
  - Plus too far or too near one

## The Rendering Pipeline

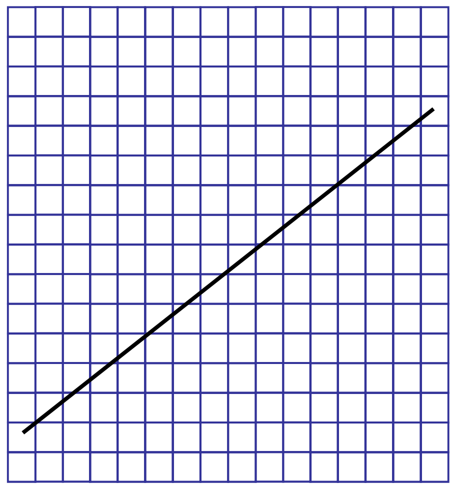



## Scan Conversion/Rasterization

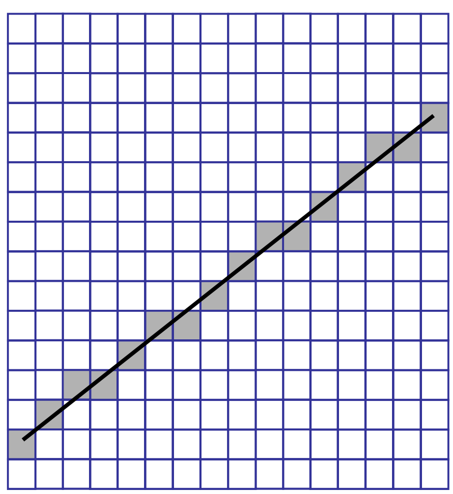
- Convert continuous 2D geometry to discrete
- Raster display – discrete grid of elements
- Terminology
  - **Pixel:** basic element on device


  - **Resolution:** number of rows & columns in device
    - Measured in
      - Absolute values (1K x 1K)
      - Density values (300 dots per inch)
  - **Screen Space:** Discrete 2D Cartesian coordinate system of the screen pixels

## Scan Conversion



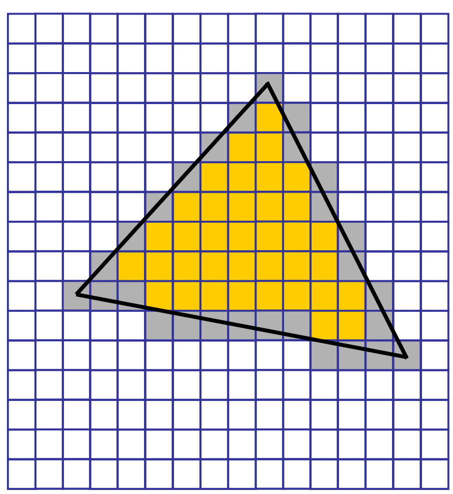
## Scan Conversion



## Scan Conversion

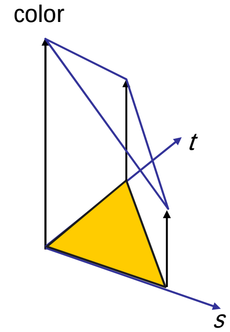
- Problem:
  - Line is infinitely thin, but image has finite resolution
  - Results in steps rather than a smooth line
    - Jaggies
    - Aliasing
  - One of the fundamental problems in computer graphics

## Scan Conversion



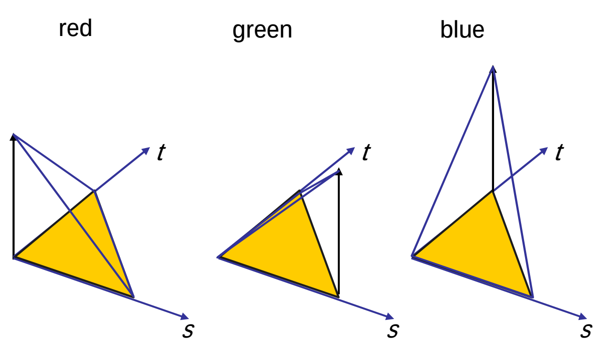
## Scan Conversion

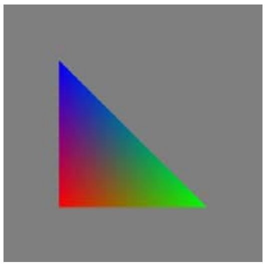
- Color interpolation
  - Linearly interpolate per-pixel color from vertex color values
  - Treat every channel of RGB color separately

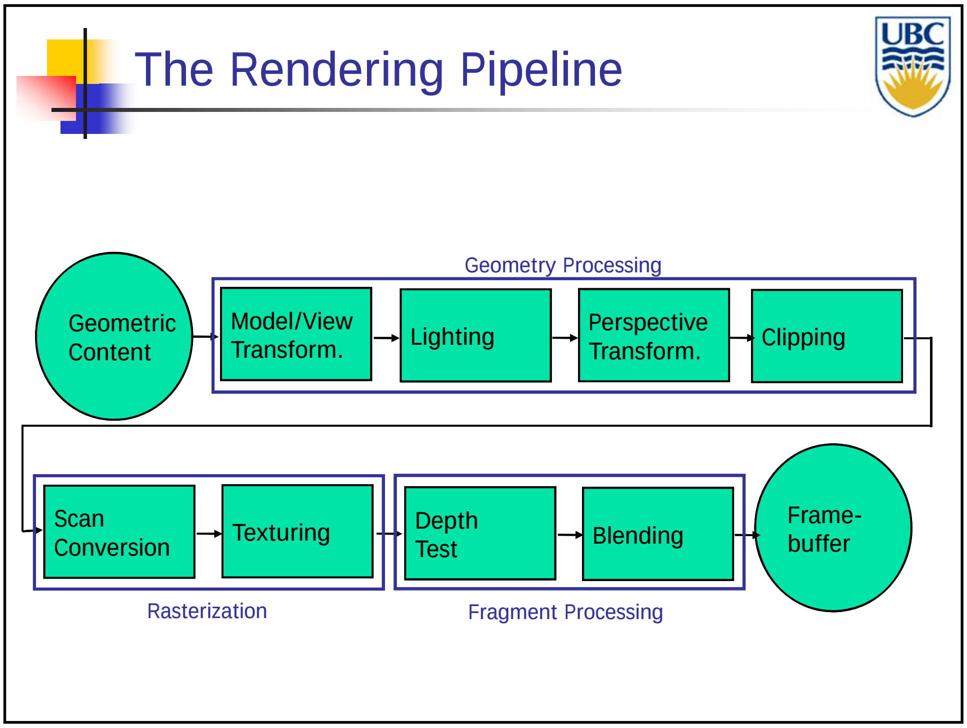


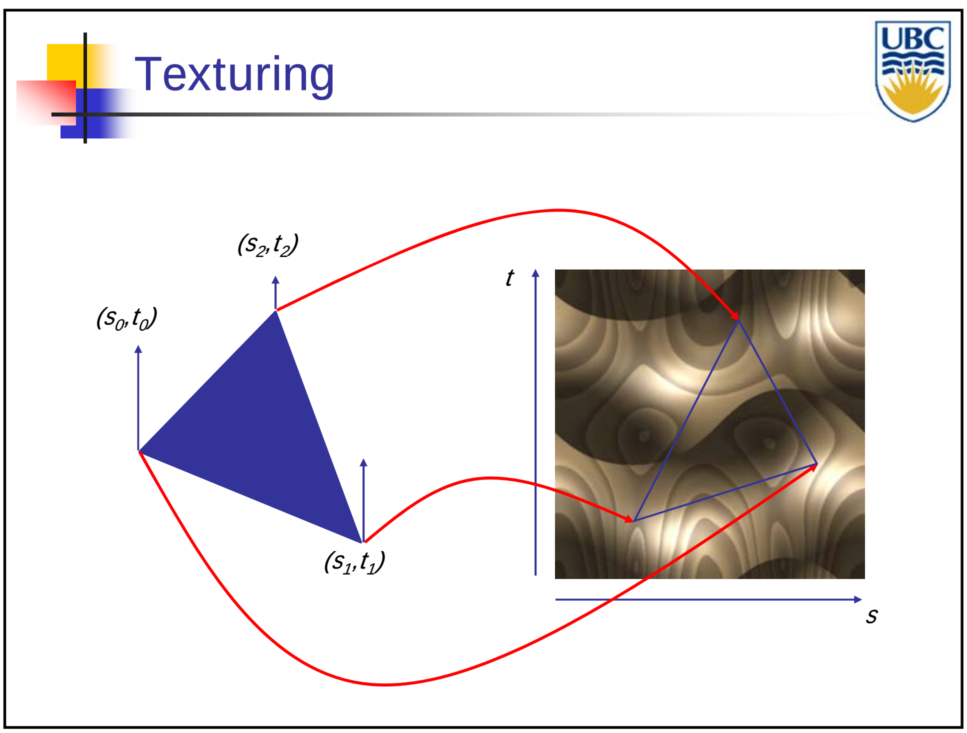

## Scan Conversion

- Color interpolation
  - Example:

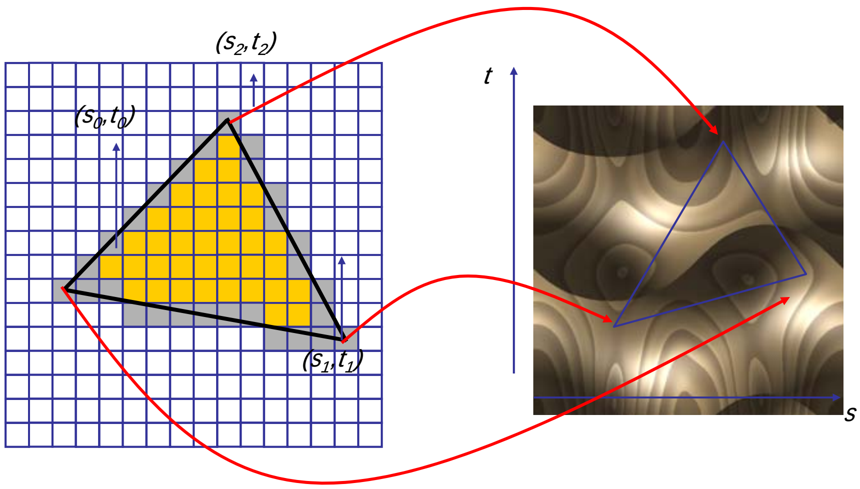



The Rendering Pipeline
Geometry Processing
Geometric Content
Model/View Transform.
Lighting
Perspective Transform.
Clipping
Scan Conversion
Texturing
Depth Test
Blending
Frame-buffer
Rasterization
Fragment Processing


Texturing
$(s_2,t_2)$
$(s_0,t_0)$
$(s_1,t_1)$
t
s

## Texturing



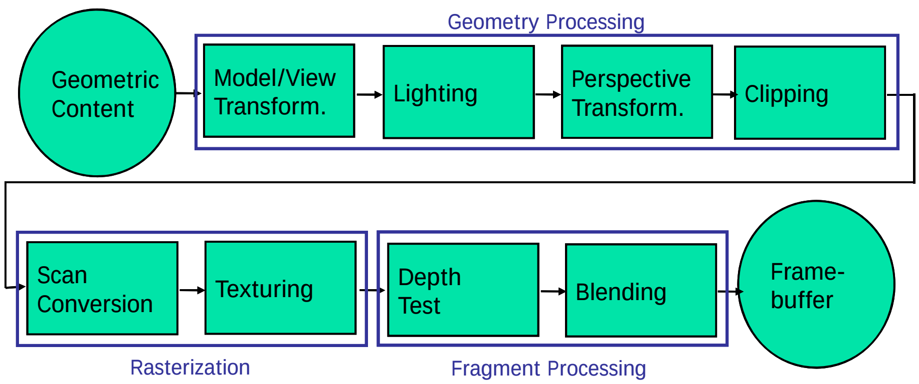

## Texture Mapping

## Displacement Mapping

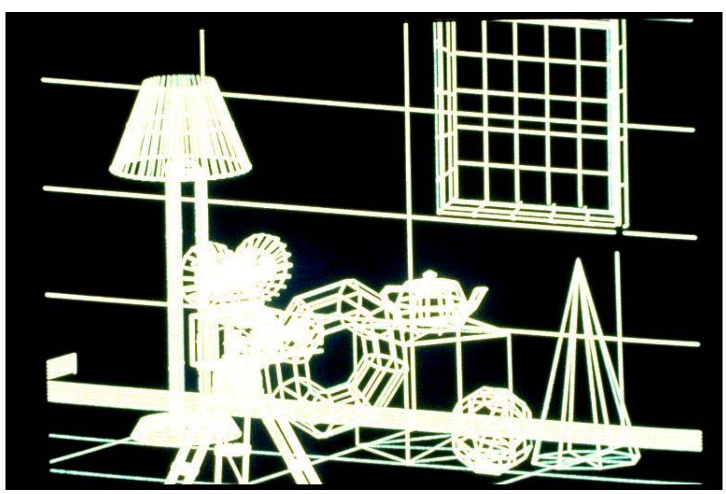
## Texturing

- Issues:
  - Computing 3D/2D map (low distortion)
  - How to map pixel from texture (texels) to screen pixels
    - Texture can appear widely distorted in rendering
    - Magnification / minification of textures
  - Filtering of textures
  - Preventing aliasing (anti-aliasing)

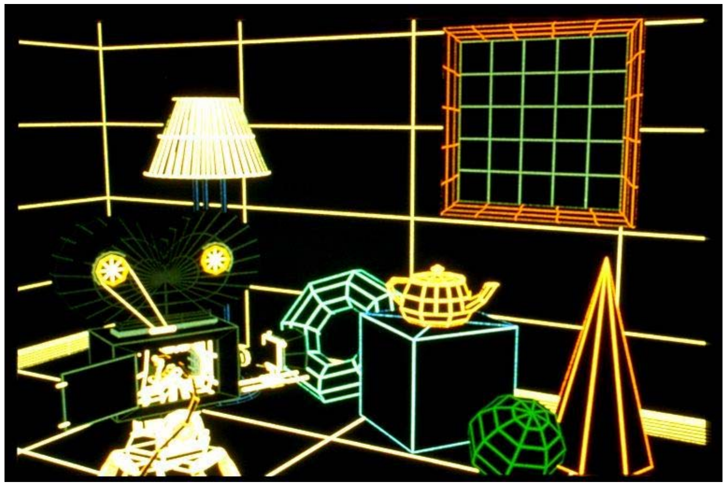
## The Rendering Pipeline



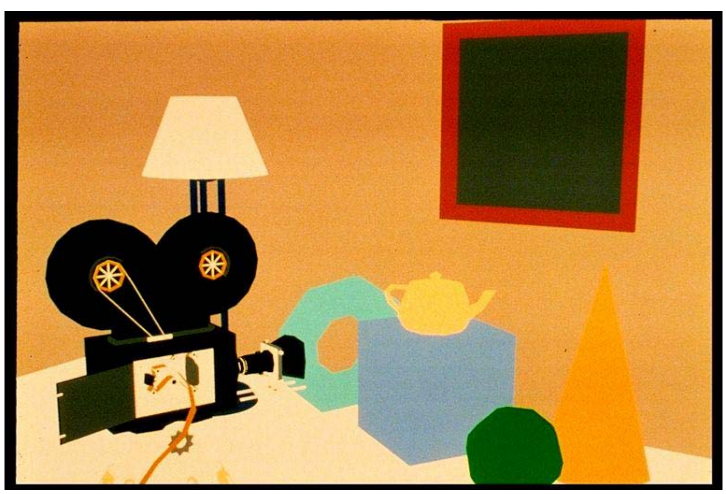

## Without Hidden Line Removal



## Hidden Line Removal



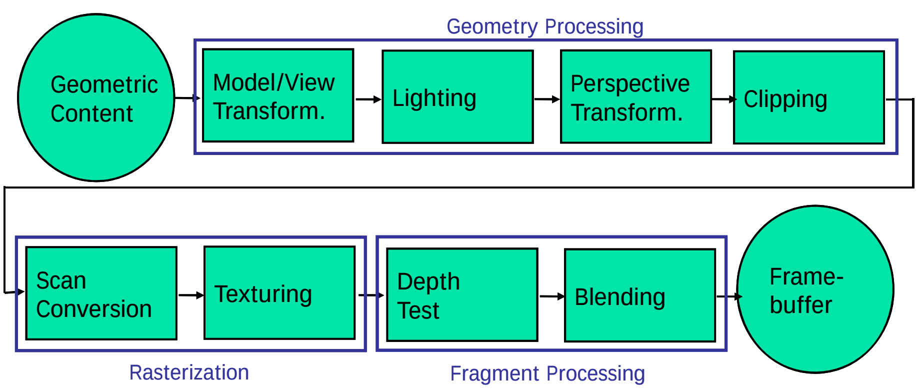
## Hidden Surface Removal



## Depth Test /Hidden Surface Removal

- Remove invisible geometry
  - Parts that are hidden behind other geometry
- Possible Implementations:
  - Pixel level decision
    - Depth buffer
  - Object space decision
    - E.g. intersection order for ray tracing

## The Rendering Pipeline



## Blending

- Blending:
  - Final image: specify pixel color
  - Draw from farthest to nearest
  - No blending – replace previous color
  - Blending: combine new & old values with some arithmetic operations
- Frame Buffer : video memory on graphics board that holds resulting image & used to display it

## Not Handled: Reflection/Shadows

## Clicker Quiz

- Which type of function is used in this curve description: $\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix}$?
  - A. Implicit
  - B. Explicit
  - C. Parametric
  - D. Quadratic