CSCI 420 Computer Graphics
Lecture 6

Viewing and Projection

Shear Transformation
Camera Positioning
Simple Parallel Projections
Simple Perspective Projections
[Angel, Ch. 4]

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Reminder: Affine Transformations

- Given a point [x y z], form homogeneous coordinates [x y z 1].

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- The transformed point is [x' y' z'].

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Transformation Matrices in OpenGL

- Transformation matrices in OpenGL are vectors of 16 values (column-major matrices)

m = {m_1, m_2, ..., m_{16}} represents

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

- Some books transpose all matrices!

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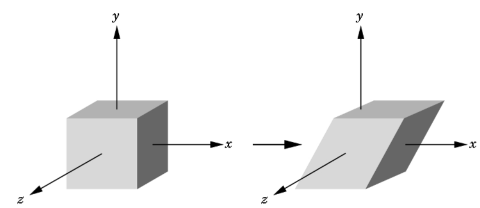
Shear Transformations

- x-shear scales x proportional to y
- Leaves y and z values fixed



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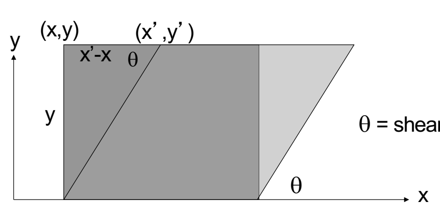
Specification via Shear Angle

- $\cot(\theta) = (x' - x) / y$
- $x' = x + y \cot(\theta)$
- $y' = y$
- $z' = z$

$$H_x(\theta) = \begin{bmatrix} 1 & \cot(\theta) & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



θ = shear angle

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Specification via Ratios

- For example, shear in both x and z direction
- Leave y fixed
- Slope α for x-shear, γ for z-shear
- Solve

$$H_{x,z}(\alpha,\gamma) \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x + \alpha y \\ y \\ z + \gamma y \\ 1 \end{bmatrix}$$

- Yields

$$H_{x,z}(\alpha,\gamma) = \begin{bmatrix} 1 & \alpha & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & \gamma & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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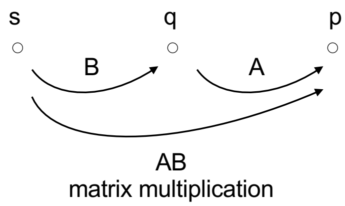
Composing Transformations

- Let p = A q, and q = B s.
- Then p = (A B) s .



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Composing Transformations

- Fact: Every affine transformation is a composition of rotations, scalings, and translations
- So, how do we compose these to form an x-shear?
- Exercise!

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Outline

- Shear Transformation
- Camera Positioning
- Simple Parallel Projections
- Simple Perspective Projections

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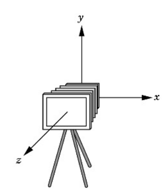
Transform Camera = Transform Scene

- Camera position is identified with a frame
- Either move and rotate the objects
- Or move and rotate the camera
- Initially, camera at origin, pointing in negative z-direction



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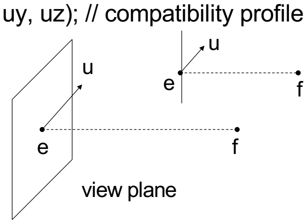
The Look-At Function

- Convenient way to position camera
- OpenGLMatrix::LookAt(ex, ey, ez, fx, fy, fz, ux, uy, uz); // core profile
- gluLookAt(ex, ey, ez, fx, fy, fz, ux, uy, uz); // compatibility profile
- e = eye point
- f = focus point
- u = up vector



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OpenGL code (camera positioning)

```
void display()
{
  glClear (GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT);
  openGLMatrix.SetMatrixMode(OpenGLMatrix::ModelView);
  openGLMatrix.LoadIdentity();
  openGLMatrix.LookAt(ex, ey, ez,  fx, fy, fz,  ux, uy, uz);
  openGLMatrix.Translate(x, y, z); // (if needed) apply transforms
  ...
  float m[16]; // column-major
  openGLMatrix.GetMatrix(m); // fill "m" with the matrix entries
  pipelineProgram->SetUniformVariableMatrix4fv(
     "modelViewMatrix", GL_FALSE, m);
  renderBunny();
  glutSwapBuffers();
}
```

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Implementing the Look-At Function

Plan:

1. Transform world frame to camera frame
   - Compose a rotation R with translation T
   - W = T R
2. Invert W to obtain viewing transformation V
   - $V = W^{-1} = (T R)^{-1} = R^{-1} T^{-1}$
   - Derive R, then T, then $R^{-1} T^{-1}$

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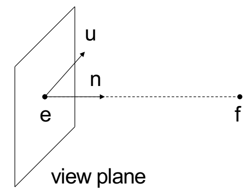
World Frame to Camera Frame I

- Camera points in negative z direction
- n = (f – e) / |f – e| is unit normal to view plane
- Therefore, R maps $[0\ \ 0\ \ -1]^T$ to $[n_x\ \ n_y\ \ n_z]^T$



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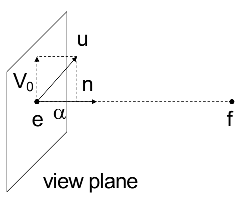
World Frame to Camera Frame II

- R maps $[0,1,0]^T$ to projection of u onto view plane
- This projection v equals:
  - $\alpha = (u \cdot n) / |n| = u \cdot n$
  - $v_0 = u - \alpha\, n$
  - $v = v_0 / |v_0|$



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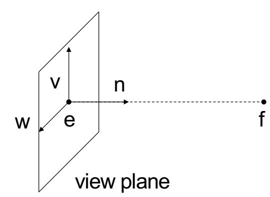
World Frame to Camera Frame III

- Set w to be orthogonal to n and v
- w = n x v
- (w, v, -n) is right-handed



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Summary of Rotation

- gluLookAt(e_x, e_y, e_z, f_x, f_y, f_z, u_x, u_y, u_z);
- n = (f – e) / |f – e|
- v = (u – (u · n) n) / |u – (u · n) n|
- w = n x v
- Rotation must map:
  - (1,0,0) to w
  - (0,1,0) to v
  - (0,0,-1) to n

$$\begin{bmatrix} w_x & v_x & -n_x & 0 \\ w_y & v_y & -n_y & 0 \\ w_z & v_z & -n_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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World Frame to Camera Frame IV

- Translation of origin to $e = [e_x\ \ e_y\ \ e_z\ \ 1]^T$

$$T = \begin{bmatrix} 1 & 0 & 0 & e_x \\ 0 & 1 & 0 & e_y \\ 0 & 0 & 1 & e_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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World Frame to Camera Frame

- $V = W^{-1} = (T R)^{-1} = R^{-1} T^{-1}$
- R is rotation, so $R^{-1} = R^T$

$$R^{-1} = \begin{bmatrix} w_x & w_y & w_z & 0 \\ v_x & v_y & v_z & 0 \\ -n_x & -n_y & -n_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- T is translation, so T^{-1} negates displacement

$$T^{-1} = \begin{bmatrix} 1 & 0 & 0 & -e_x \\ 0 & 1 & 0 & -e_y \\ 0 & 0 & 1 & -e_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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Putting it Together

- Calculate $V = R^{-1} T^{-1}$

$$V = \begin{bmatrix} w_x & w_y & w_z & -w_x e_x - w_y e_y - w_z e_z \\ v_x & v_y & v_z & -v_x e_x - v_y e_y - v_z e_z \\ -n_x & -n_y & -n_z & n_x e_x + n_y e_y + n_z e_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- This is different from book [Angel, Ch. 5.3.2]
- There, u, v, n are right-handed (here: u, v, -n)

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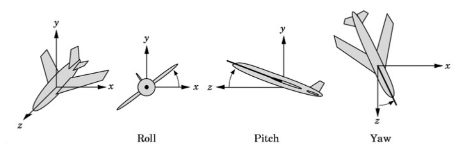
Other Viewing Functions

- Roll (about z), pitch (about x), yaw (about y)



- Assignment 2 poses a related problem

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Outline

- Shear Transformation
- Camera Positioning
- Simple Parallel Projections
- Simple Perspective Projections

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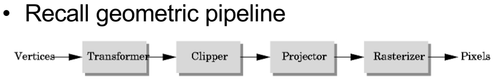
Projection Matrices

- Recall geometric pipeline



- Projection takes 3D to 2D
- Projections are not invertible
- Projections are described by a 4x4 matrix
- Homogenous coordinates crucial
- Parallel and perspective projections

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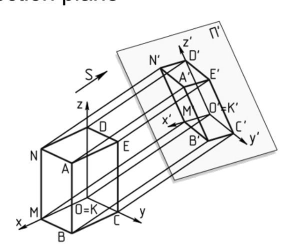
Parallel Projection

- Project 3D object to 2D via parallel lines
- The lines are not necessarily orthogonal to projection plane



source: Wikipedia

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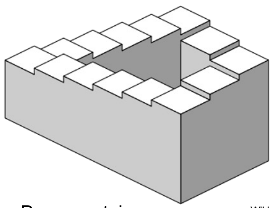
Parallel Projection

- Problem: objects far away do not appear smaller
- Can lead to “impossible objects” :



Penrose stairs   source: Wikipedia

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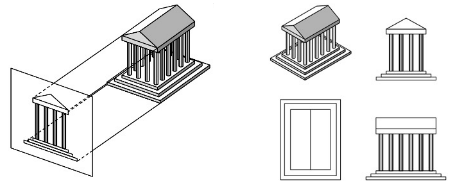
Orthographic Projection

- A special kind of parallel projection: projectors perpendicular to projection plane
- Simple, but not realistic
- Used in blueprints (multiview projections)



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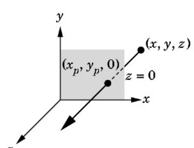
Orthographic Projection Matrix

- Project onto z = 0
- $x_p = x$, $y_p = y$, $z_p = 0$
- In homogenous coordinates



$$\begin{bmatrix} x_p \\ y_p \\ z_p \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

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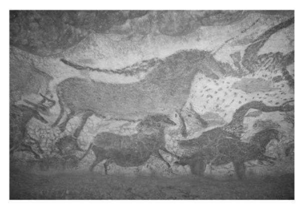
Perspective

- Perspective characterized by foreshortening
- More distant objects appear smaller
- Parallel lines appear to converge
- Rudimentary perspective in cave drawings:



Lascaux, France
source: Wikipedia

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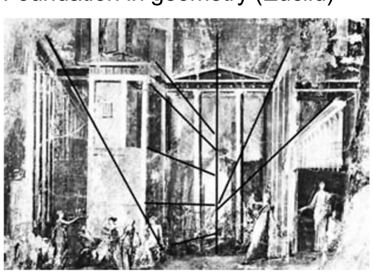
Discovery of Perspective

- Foundation in geometry (Euclid)



Mural from Pompeii, Italy

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Middle Ages

- Art in the service of religion
- Perspective abandoned or forgotten

Ottonian manuscript, ca. 1000

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Renaissance

- Rediscovery, systematic study of perspective

Filippo Brunelleschi
Florence, 1415

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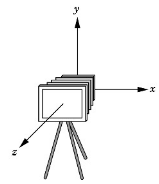
Projection (Viewing) in OpenGL

- Remember: camera is pointing in the negative z direction



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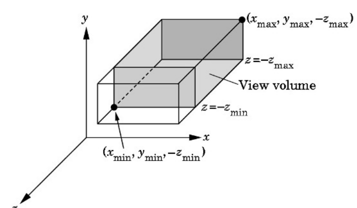
Orthographic Viewing in OpenGL (core profile)

- OpenGLMatrix::Ortho(xmin, xmax, ymin, ymax, near, far)



z_{min} = near, z_{max} = far

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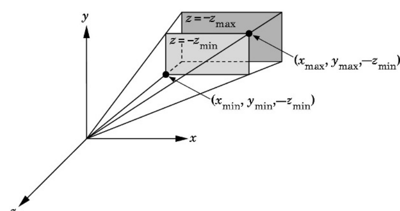
Perspective Viewing in OpenGL

- Two interfaces: glFrustum and gluPerspective
- {OpenGLMatrix::, gl}Frustum(
  xmin, xmax, ymin, ymax, near, far);



z_{min} = near, z_{max} = far

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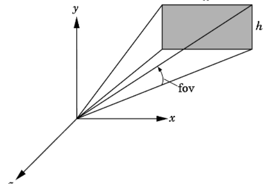
Field of View Interface

- {OpenGLMatrix::, glu}Perspective(
  fovy, aspectRatio, near, far);
- near and far as before
- aspectRatio = w / h
- Fovy specifies field of view as height (y) angle



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OpenGL code (reshape)

```
void reshape(int x, int y)
{
  glViewport(0, 0, x, y);

  openGLMatrix.SetMatrixMode(OpenGLMatrix::Projection);
  openGLMatrix.LoadIdentity();
  openGLMatrix.Perspective(60.0, 1.0 * x / y, 0.01, 10.0);
  openGLMatrix.SetMatrixMode(OpenGLMatrix::ModelView);
}
```

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OpenGL code

```
void displayFunc()
{
  …

  openGLMatrix.SetMatrixMode(OpenGLMatrix::Projection);
  float p[16]; // column-major
  openGLMatrix.GetMatrix(p);
  const GLboolean isRowMajor = GL_FALSE;
  pipelineProgram->SetUniformVariableMatrix4fv(
     "projectionMatrix", isRowMajor, p);
  …

  renderBunny();
  glutSwapBuffers();
}
```

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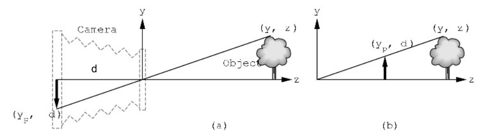
Perspective Viewing Mathematically



- d = focal length
- $y/z = y_p/d$ so $y_p = y/(z/d) = y\, d / z$
- Note that y_p is non-linear in the depth z!

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Exploiting the 4th Dimension

- Perspective projection is not affine:

$$M \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{x}{z/d} \\ \frac{y}{z/d} \\ d \\ 1 \end{bmatrix} \quad \text{has no solution for M}$$

- Idea: exploit homogeneous coordinates

$$p = w \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad \text{for arbitrary } w \neq 0$$

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Perspective Projection Matrix

- Use multiple of point

$$(z/d) \begin{bmatrix} \frac{x}{z/d} \\ \frac{y}{z/d} \\ d \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ \frac{z}{d} \end{bmatrix}$$

- Solve

$$M \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ \frac{z}{d} \end{bmatrix} \quad \text{with} \quad M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{1}{d} & 0 \end{bmatrix}$$

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Projection Algorithm

Input: 3D point (x,y,z) to project

1. Form $[x\ y\ z\ 1]^T$
2. Multiply M with $[x\ y\ z\ 1]^T$; obtaining $[X\ Y\ Z\ W]^T$
3. Perform perspective division:
   X / W, Y / W, Z / W

Output: (X / W, Y / W, Z / W)
(last coordinate will be d)

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Perspective Division

- Normalize $[x\ y\ z\ w]^T$ to $[(x/w)\ (y/w)\ (z/w)\ 1]^T$
- Perform perspective division after projection

- Projection in OpenGL is more complex (includes clipping)

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