Rendering - II

CS475 / 675, Fall 2016

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Today

Real-time graphics with OpenGL

Crysis (Crytek/EA, 2007)

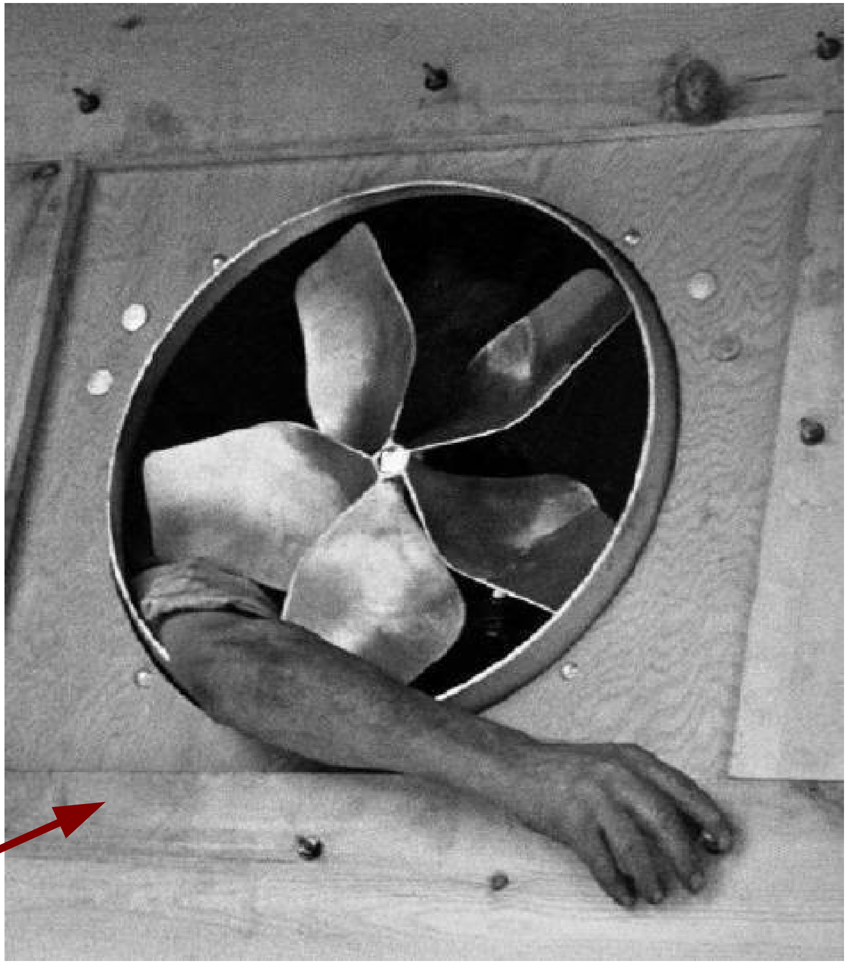
Hidden Surface Removal

Near objects hide (*occlude*) further objects

Elliott Erwitt, New York, 2000

Hidden Surface Removal

- Color at a rendered pixel depends primarily on the nearest object at that point
- Naïve solution: Sort and render objects back to front (*painter's algorithm*)
  - Inefficient
  - Not as easy as it sounds!
    - Is the man behind the wall or the wall behind the man?

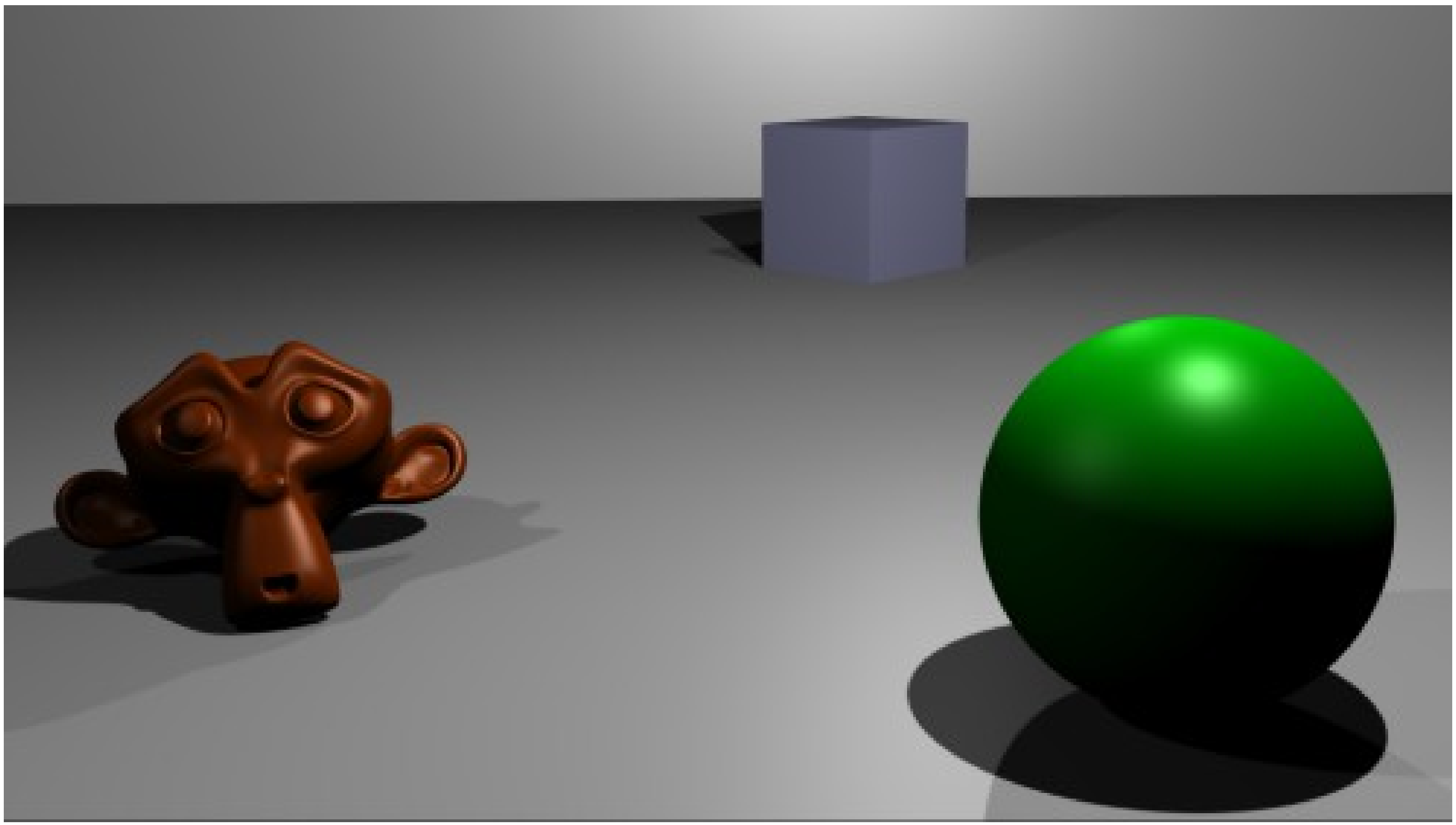


André Kertész, “Arm and Ventilator”, New York, 1937

Better Solutions

- *Raycasting/Raytracing:* Trace a ray through the pixel, see which object is hit first
- *Z-Buffer*
  - Draw objects one-by-one in any order
  - At each pixel, store closest depth value seen so far
    - Z axis is usually assumed to lie along the depth direction, hence this image of depth values is called the z-buffer
  - At pixel p, let an object have color c and depth d
    - If $d <$ old depth at p
      - new depth at $p = d$
      - new color at $p = c$

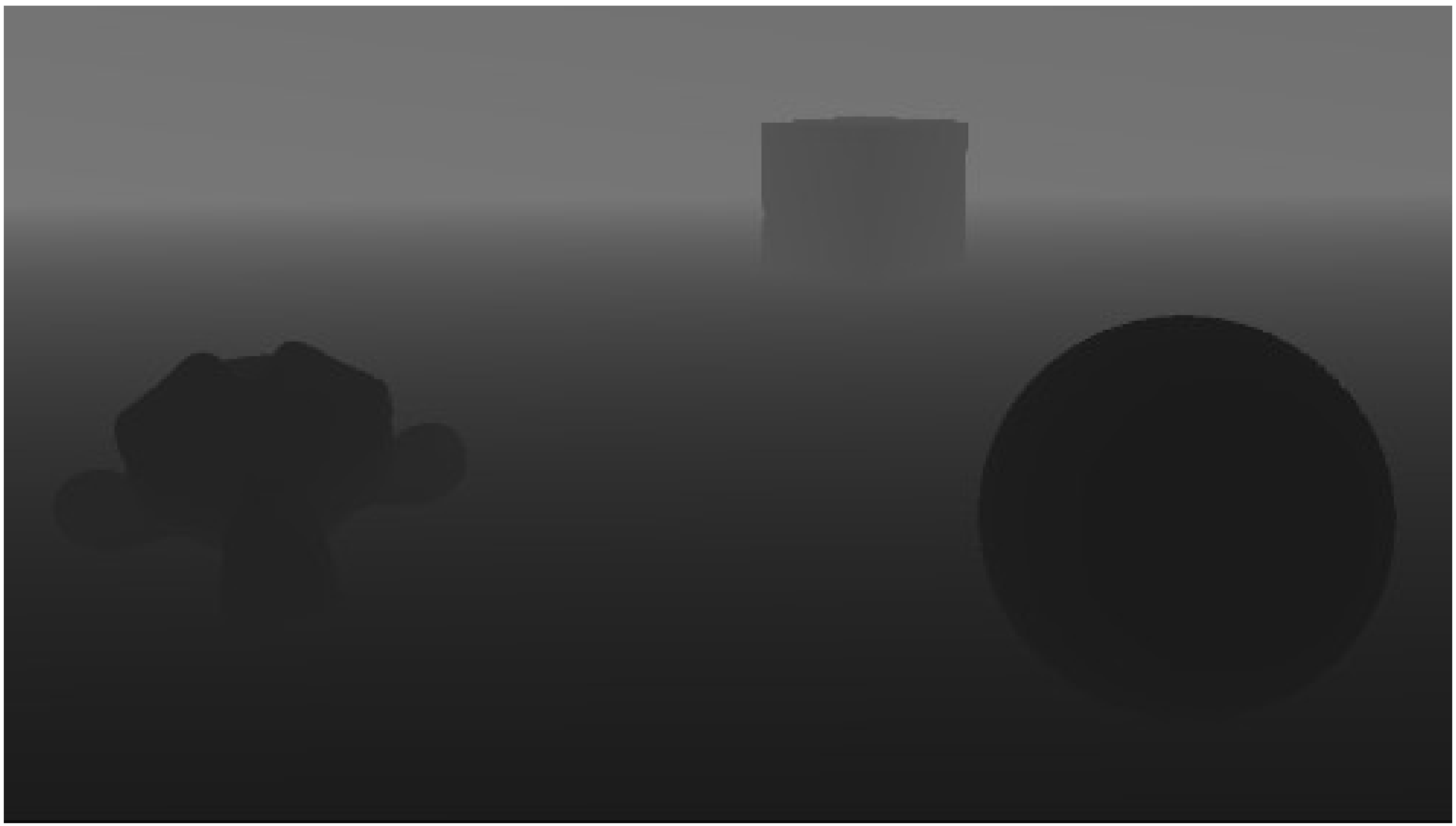
Z-Buffer: Example



Rendered 3D scene

(Wikipedia)

Z-Buffer: Example



Corresponding z-buffer (dark: near, light: far)

(Wikipedia)

Isn't raycasting simpler?

- Z-buffer algorithms have traditionally been easy to accelerate in hardware
  - No need for complicated data structures
  - Parallelizable in object space: Every object is drawn (nearly) independently of the others
    - Useful when scene can be divided into lots of small components, e.g. triangles
- But raytracing can be accelerated too!
  - Requires more sophisticated hardware
  - Different parallelization characteristics
    - Often better than z-buffers when there's lots of occlusion
  - Gaining popularity in recent times

Limitations of Z-Buffers

- Hard to do
  - reflections
  - refractions
  - shadows

- In fact, the only thing that's easy to do is diffuse shading (ADS/Phong) with direct lighting
  - This was good enough for most games for a long time
  - 99.99% of all 3D games use z-buffers, accelerated to ridiculous speeds by *graphics processing units* (GPUs)

Standard Z-Buffer Based APIs

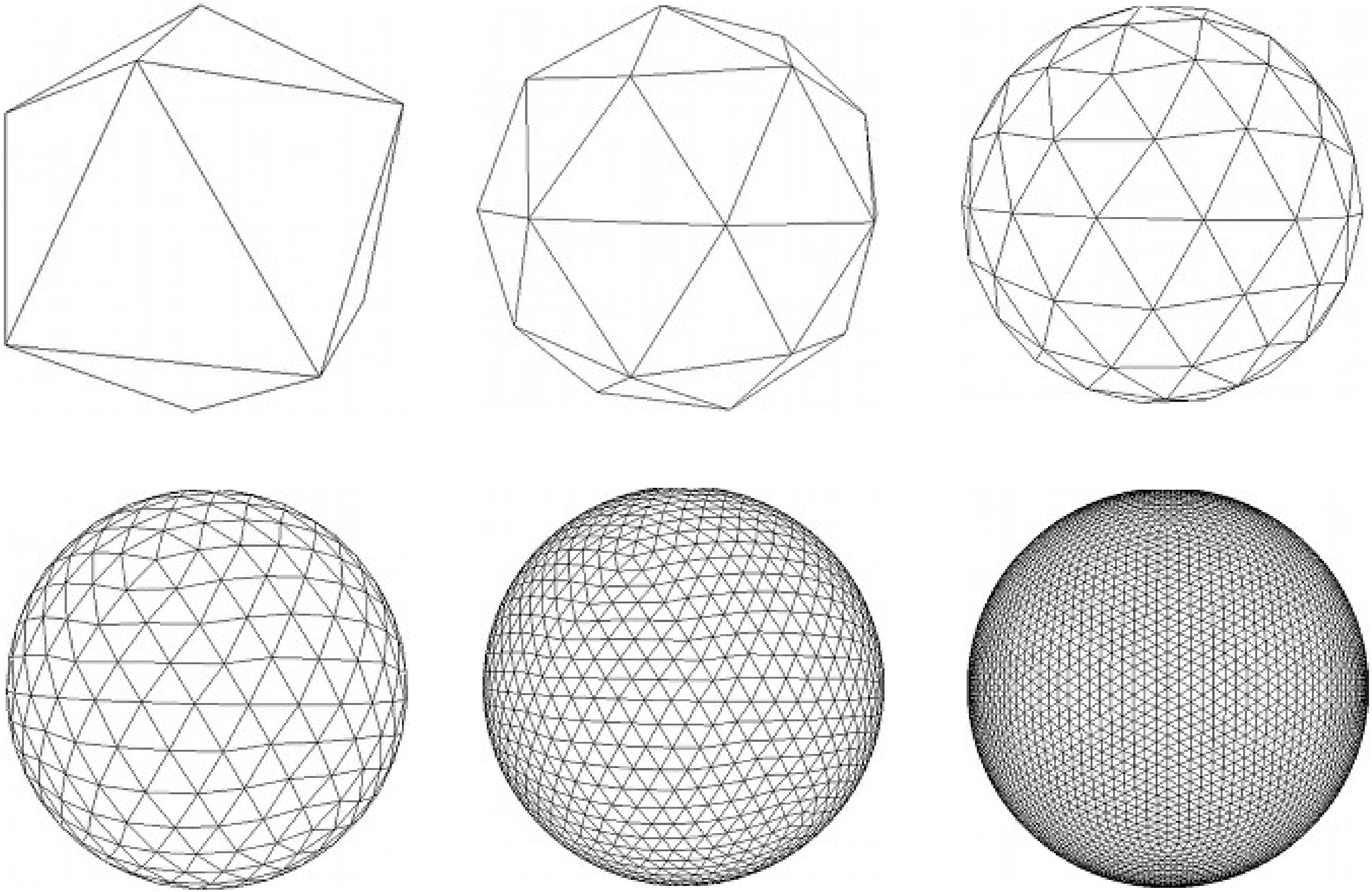
- Direct3D
  - Windows-only
  - http://www.microsoft.com/directx

- OpenGL
  - Windows, OS X, Linux, ...
    - ... which is why we'll look only at OpenGL in this course
  - http://www.opengl.org

Basic OpenGL

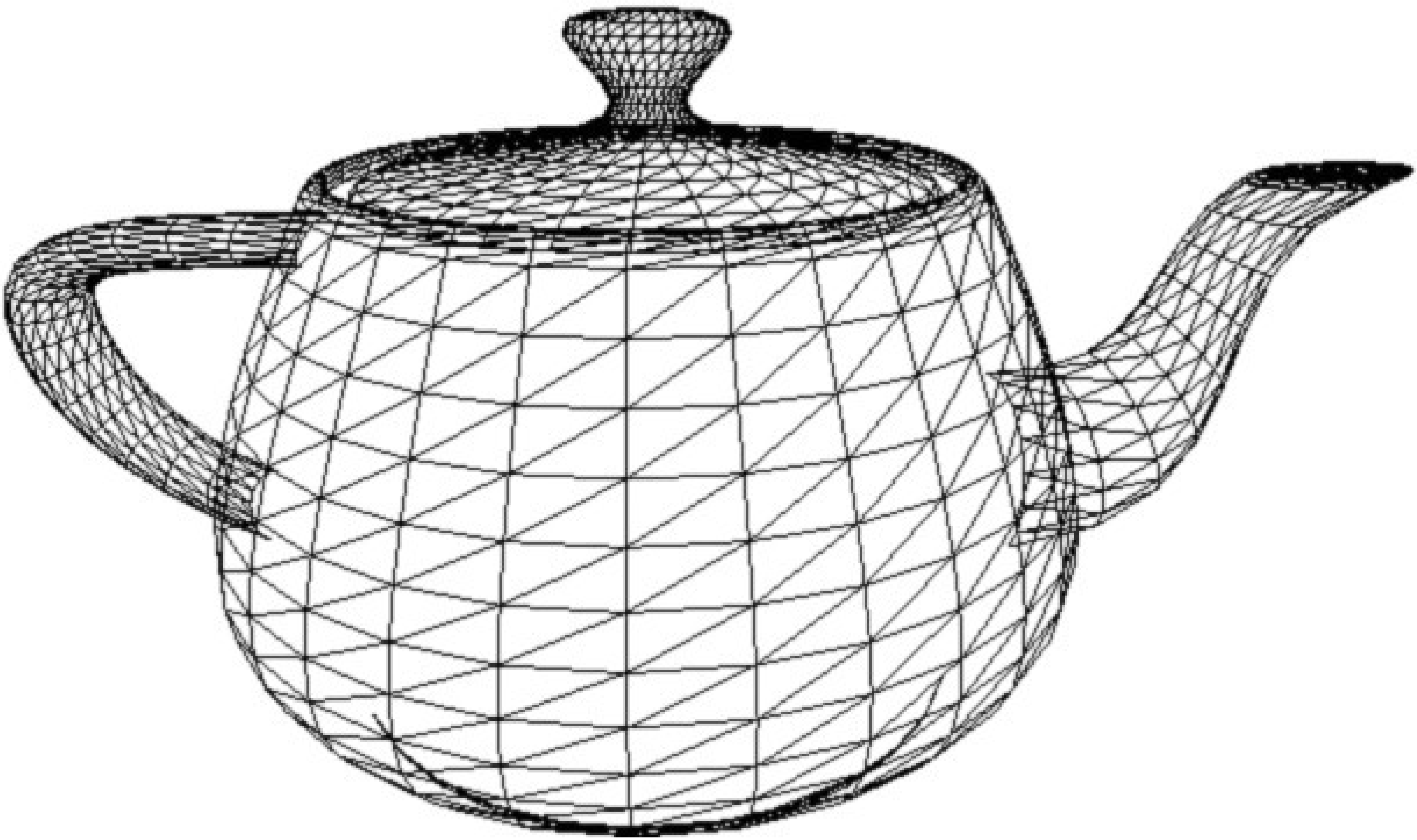
- Represent object surface as set of *primitive shapes*
    - Points
    - Lines
    - Triangles
    - Quad(rilateral)s
  - This process is called *tessellation*
- Draw primitives one by one
  - Batched and parallelized in hardware
- Let the z-buffer figure out which primitive determines the color at each pixel

Tessellating a Sphere with Triangles



(Ziyan Zhou)

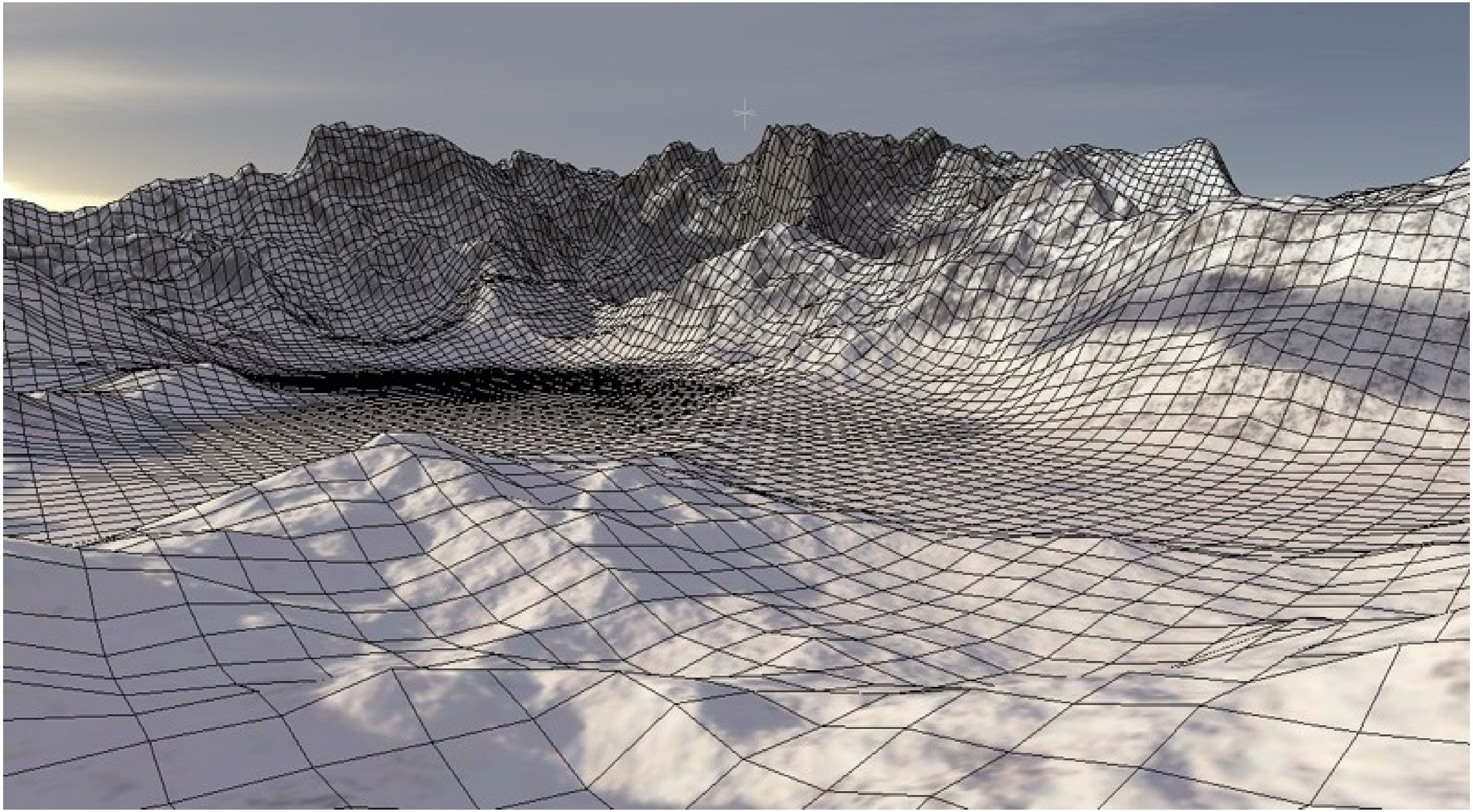
A Tessellated Teapot



Tessellated Animals

(Age of Empires, Microsoft)

Tessellated Terrain



(TFPSoft)

Tessellation

- Difficult to get right
  - Primitives must be evenly distributed
  - Primitives must not have awkward shapes (e.g. very “skinny” triangles)
  - This is important not just for display but even more so for physics simulation/finite element methods
- Many sophisticated algorithms exist
  - Often take equations of curved patches as input
  - We won't cover them in this course
  - In assignments we'll work with pre-tessellated models

Drawing Triangles in OpenGL

```
glBegin(GL_TRIANGLES);
    foreach triangle in object
    {
        // Tell OpenGL the normal and color of the triangle
        // Send the 3 vertex positions
    }
glEnd();
```

Note:

- Every collection of primitives must be placed between a glBegin/glEnd block
- Every three successive vertices in the block defines a triangle
- Instead of GL_TRIANGLES we could use GL_POINTS (every vertex is a point), GL_LINES (every 2 vertices defines a line), GL_QUADS (every 4 vertices defines a quad) etc.

Drawing Triangles in OpenGL

```
glBegin(GL_TRIANGLES);
    foreach triangle in object
    {
        glNormal3f(0.58f, 0.58f, 0.58f);    // (nx, ny, nz)
        glColor3f(1.0f, 0.0f, 0.0f);        // (R = 1, G = 0, B = 0)

        glVertex3f(1.0f, 0.0f, 0.0f);       // (x, y, z)
        glVertex3f(0.0f, 1.0f, 0.0f);
        glVertex3f(0.0f, 0.0f, 1.0f);
    }
glEnd();
```

Note:

- We set the normal and color per triangle (they can actually be set anywhere, anytime, and apply to all ***subsequent*** vertices)
- We set the positions per vertex

What's this ...3f business?

- glVertex has variants glVertex3f, glVertex3d
  - The first takes 3 float arguments (x, y, z)
  - The second takes 3 double arguments
  - OpenGL also has functions with a ...3i suffix – these obviously take 3 integers
- There's also glVertex2f
  - z is assumed to be 0
- ... and glVertex4f
  - Last argument is homogenous coordinate h, which is otherwise assumed to be 1
  - Similarly glColor4f is used to specify (R, G, B, α)

Transforming Objects

- Let's see a simple example first...

```
glLoadMatrixf(M);      // M is a 4x4 matrix stored in column-major form

// Draw the object using glBegin/glEnd
```

- **Note:**
  - The object is transformed by M before it is drawn
    - Each vertex $\mathbf{v}$ becomes $M * \mathbf{v}$
  - M is ***column-major***!
    - Array of 16 numbers: first column, then second column, ...
  - M is column-major!!
  - Did we mention M is **column-major**?!!

Composing Transformations

- Just specify the matrices to be composed one after the other

```
glLoadMatrixf(A);        // Initial matrix
glMultMatrixf(B);        // Note: MultMatrix, not LoadMatrix
glMultMatrixf(C);
...

// Draw the object using glBegin/glEnd
```

- The object is transformed by $A * B * C$
  - Each vertex $\mathbf{v}$ becomes $A * B * C * \mathbf{v}$
- **Note:** Transforms are applied ***last-to-first***!

OpenGL Convenience Functions

- glLoadIdentity() ≡ glLoadMatrixf(<*identity matrix*>)
- glTranslatef(tx, ty, tz) ≡ glMultMatrixf(T)
  - T is a matrix that translates by (t_X, t_Y, t_Z)
- glRotatef(angle, x, y, z) ≡ glMultMatrixf(R)
  - R is a matrix that rotates by $angle$ degrees around the axis (x, y, z)
- glScalef(sx, sy, sz) ≡ glMultMatrixf(S)
  - S is a matrix that scales by s_X along x, s_Y along y and s_Z along z
- (All the functions have …d versions, of course)

Transforming Objects

- A more complicated example:

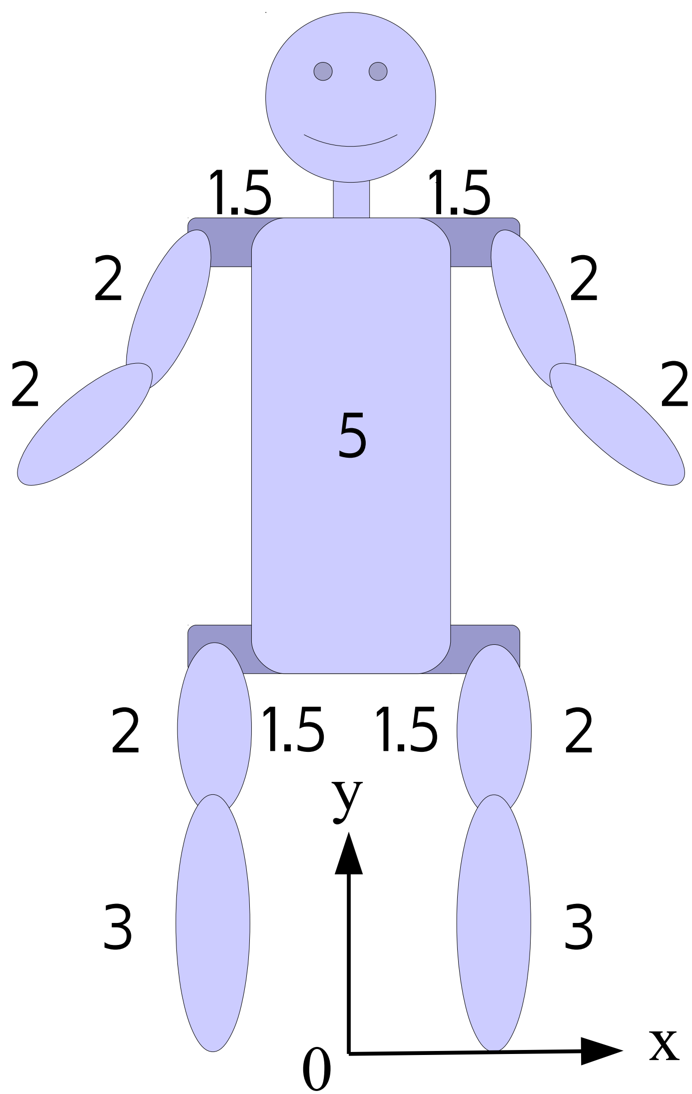
```
glMatrixMode(GL_MODELVIEW);
glPushMatrix();
    glMultMatrixf(M);

    // Draw the object using glBegin/glEnd

glPopMatrix();
```

- Questions:
  - Why all the pushing/popping?
  - What's with this MatrixMode business?

Hierarchical Modeling

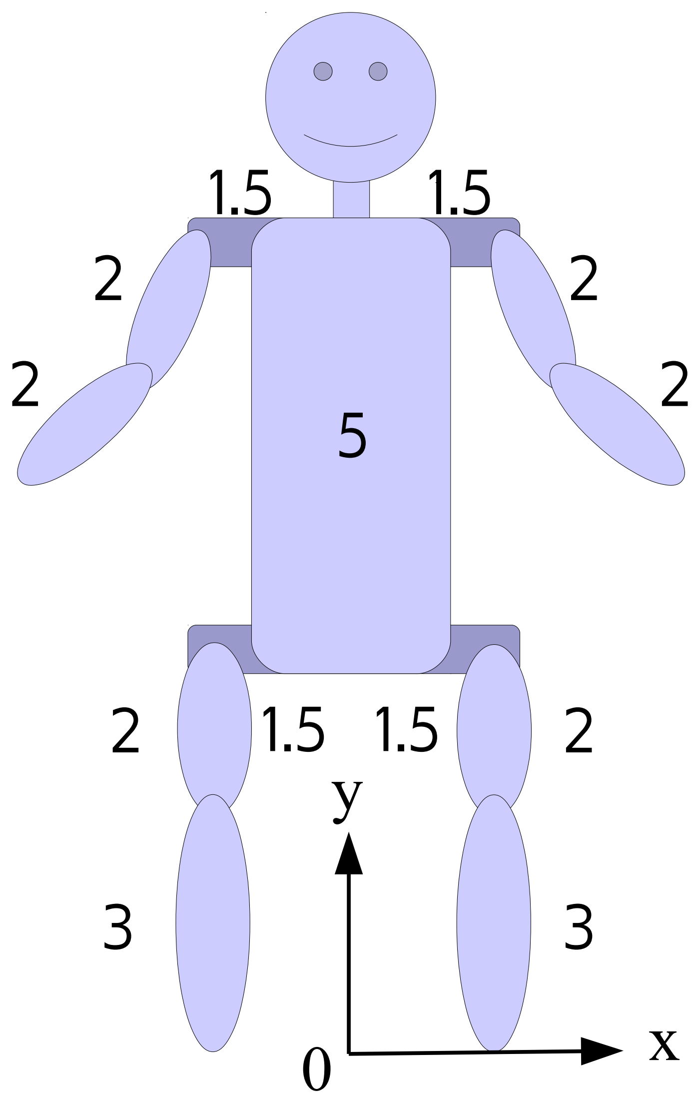
- Graphics systems maintain a *current transformation matrix* (CTM)
  - All geometry is transformed by the CTM
  - CTM defines object space in which geometry is specified
  - Transformation commands are concatenated onto the CTM (glMultMatrix). The last one added is applied first:
    - CTM = CTM * T
  - The CTM is reset with glLoadMatrix
- Graphics systems also maintain *transformation stack*
  - The CTM can be pushed onto the stack (glPushMatrix)
  - The CTM can be restored from the stack (glPopMatrix)

Example: Articulated Robot



- body
  - torso
    - head
    - shoulder
      - leftArm
        - upperArm
        - lowerArm
        - hand
      - rightArm
        - upperArm
        - lowerArm
        - hand
    - hips
      - leftLeg
        - upperLeg
        - lowerLeg
        - foot
      - rightLeg
        - upperLeg
        - lowerLeg
        - foot

Example: Articulated Robot (OpenGL)




```
glTranslatef(0, 1.5, 0);
drawTorso();
glPushMatrix();
glTranslatef(0, 5, 0);
    drawShoulder();
    glPushMatrix();
        glRotatef(neck_y, 0, 1, 0);
        glRotatef(neck_x, 1, 0, 0);
        drawHead();
    glPopMatrix();
    glPushMatrix();
        glTranslatef(1.5, 0, 0);
        glRotatef(l_shoulder_x);
        drawUpperArm();
        glPushMatrix();
            glTranslatef(0,-2,0);
            glRotatef(l_elbow_x, 1, 0, 0);
            drawLowerArm();
            ...
        glPopMatrix();
    glPopMatrix();
    ...
```

Recap

- **Z-buffer** to detect visible surfaces
- Surfaces **tessellated** into simple primitives
- **Draw primitives** with glBegin/glEnd blocks
  - glVertex, glNormal, glColor
- **Nested transform blocks**
  - glPushMatrix, glPopMatrix, glLoadMatrix, glMultMatrix

(We'll address the glMatrixMode business a little later)

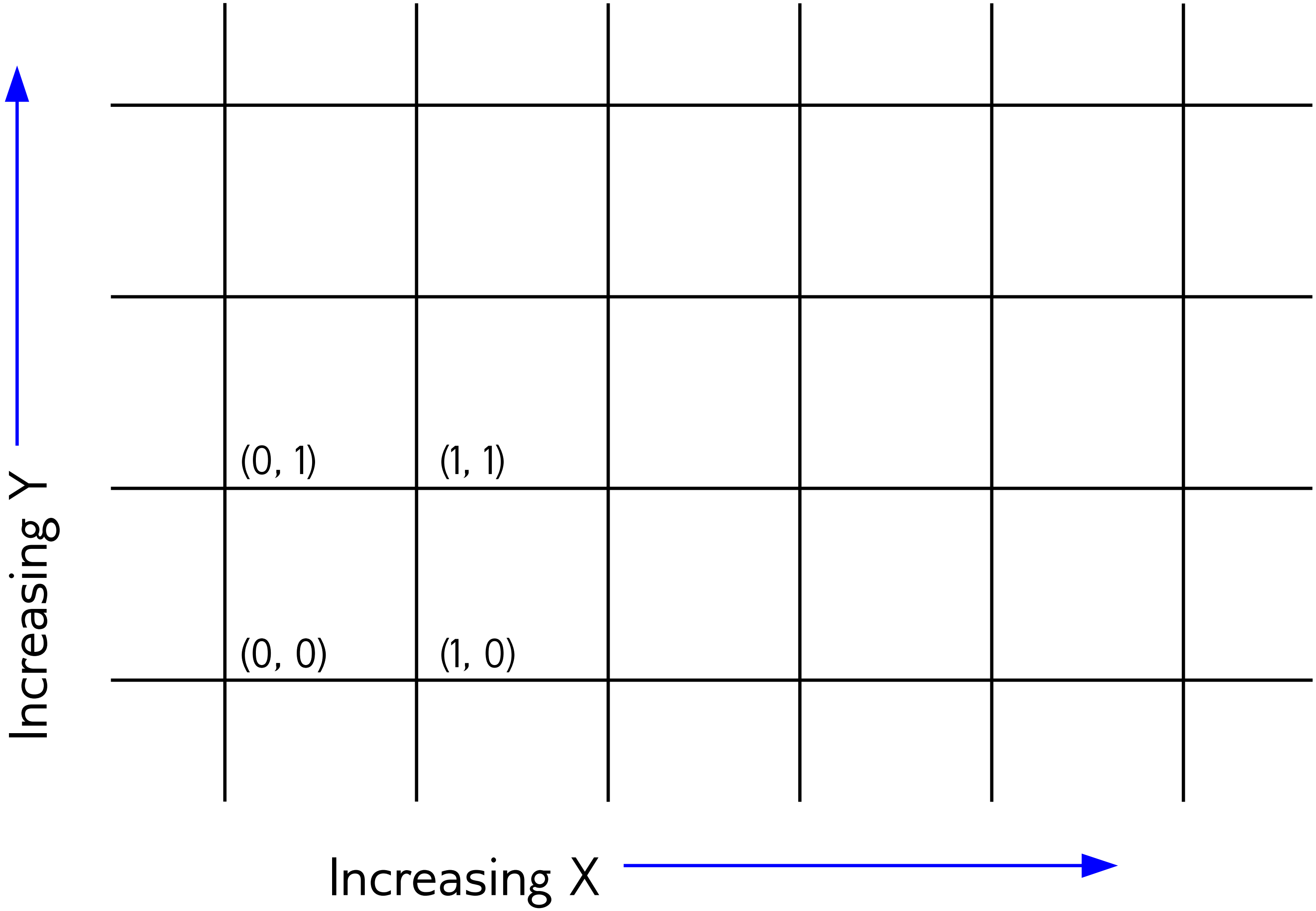
Drawing Triangles

- **Problem:** Given triangle Δ, color the pixels that it covers
- This is called *rasterization*

- **Two-step solution:**
  - Project the triangle to screen space
  - Compute the pixels covered by the projection

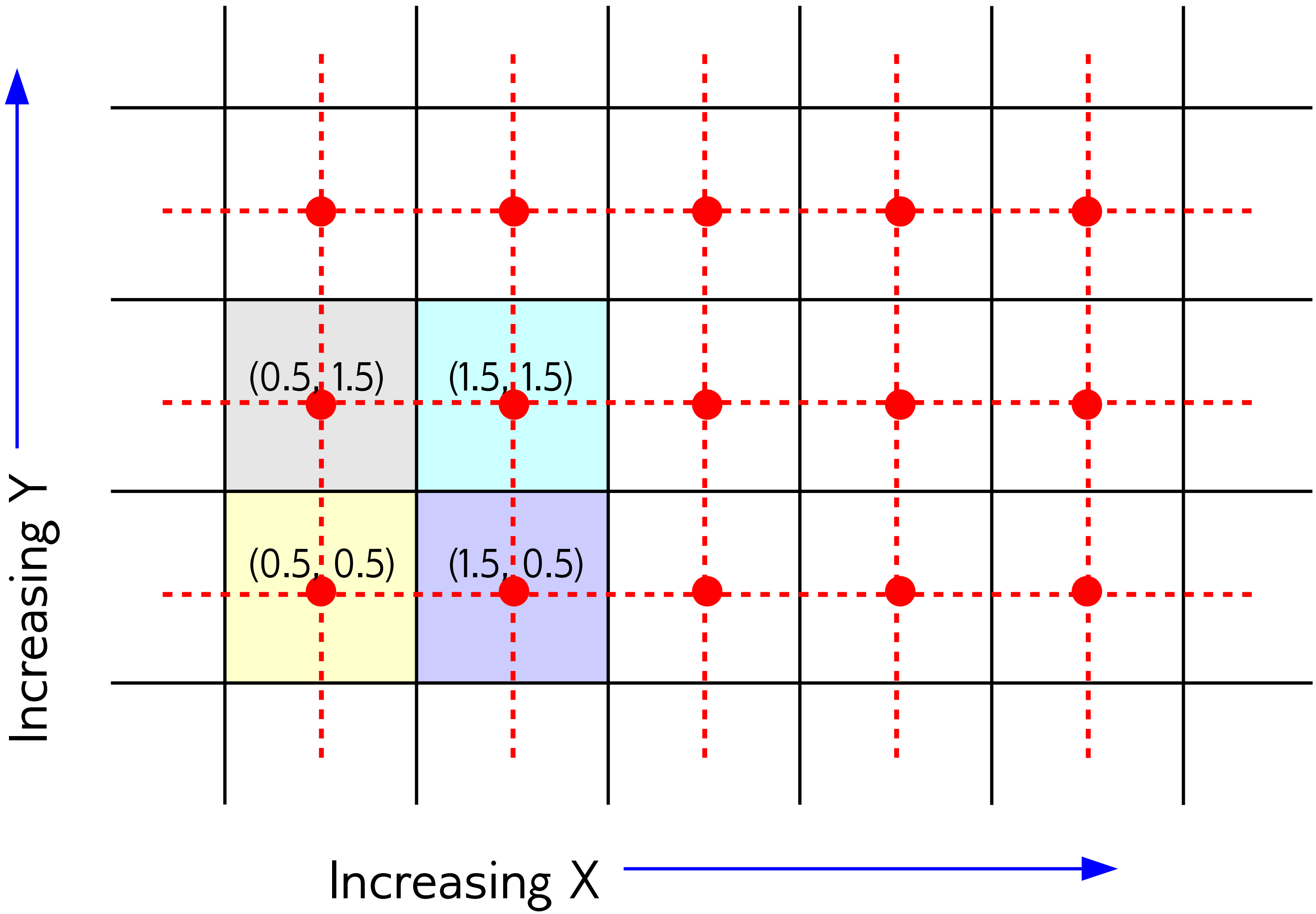
OpenGL Pixel Coordinates

The pixel grid is called the *framebuffer*



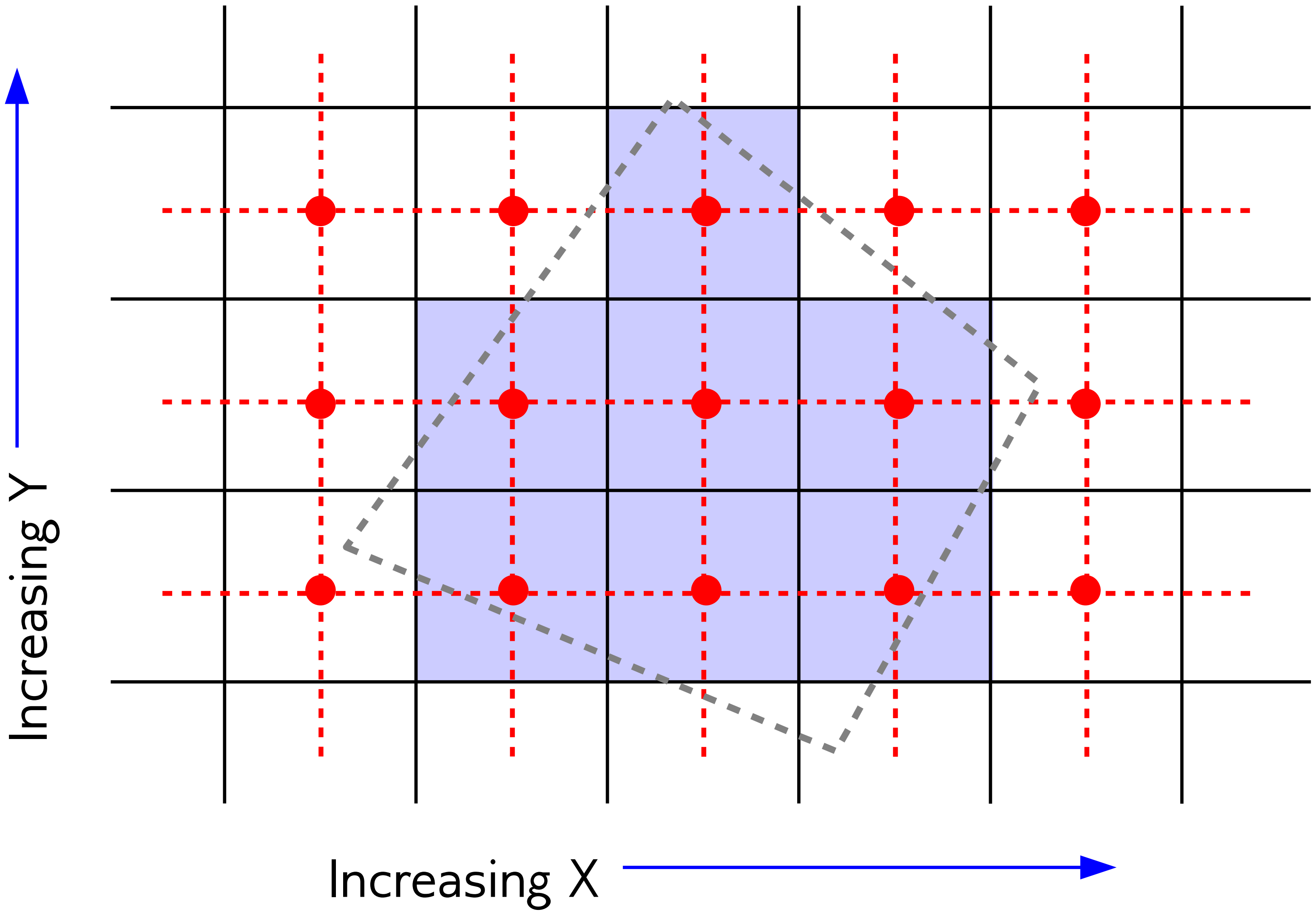
OpenGL Pixel Coordinates

Pixel centers are at ***half-integer*** coordinates



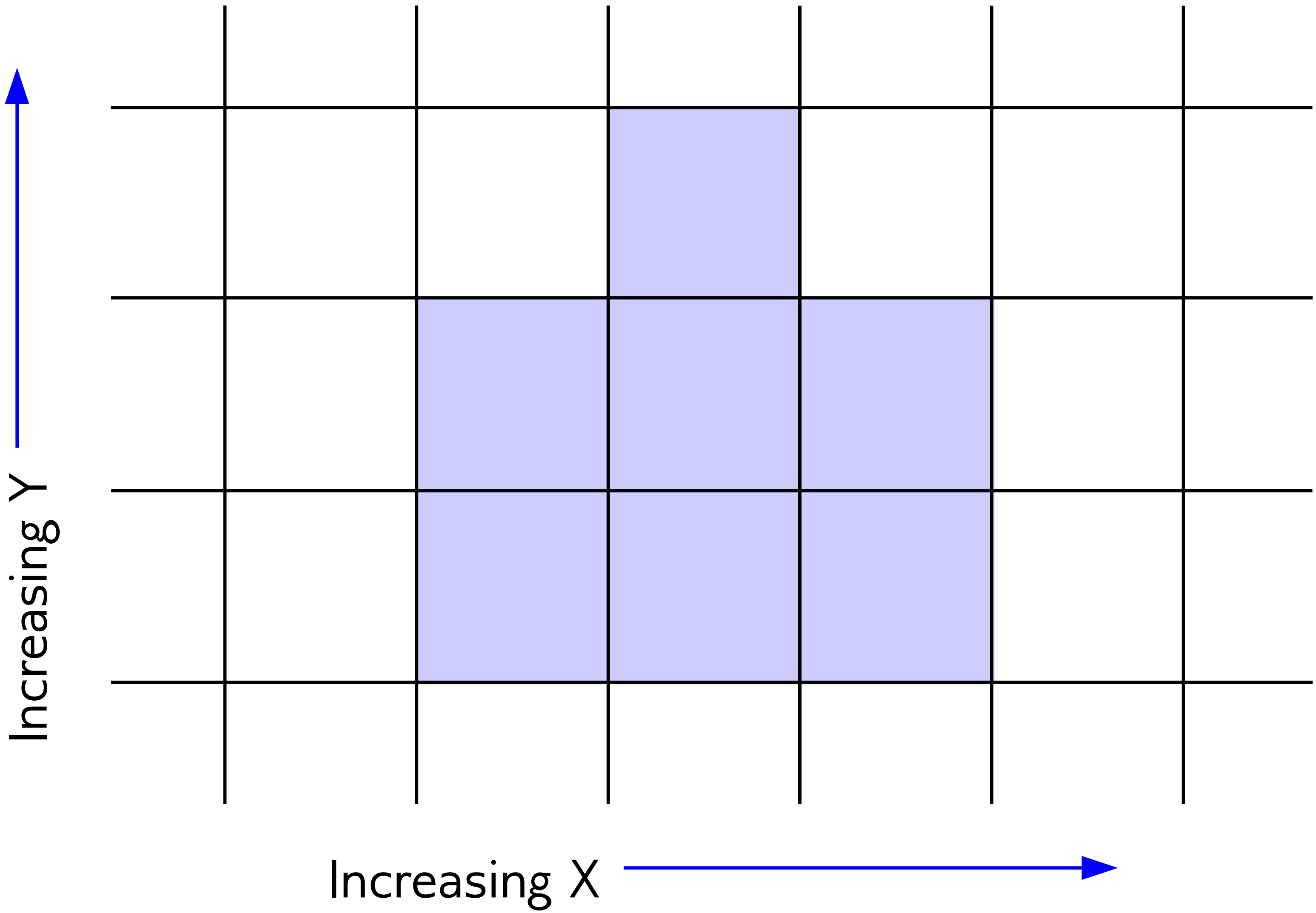
Rasterization Rules: Area Primitives

Output *fragment* if pixel center is inside area



Rasterization Rules: Area Primitives

Combine fragment color with existing pixel color

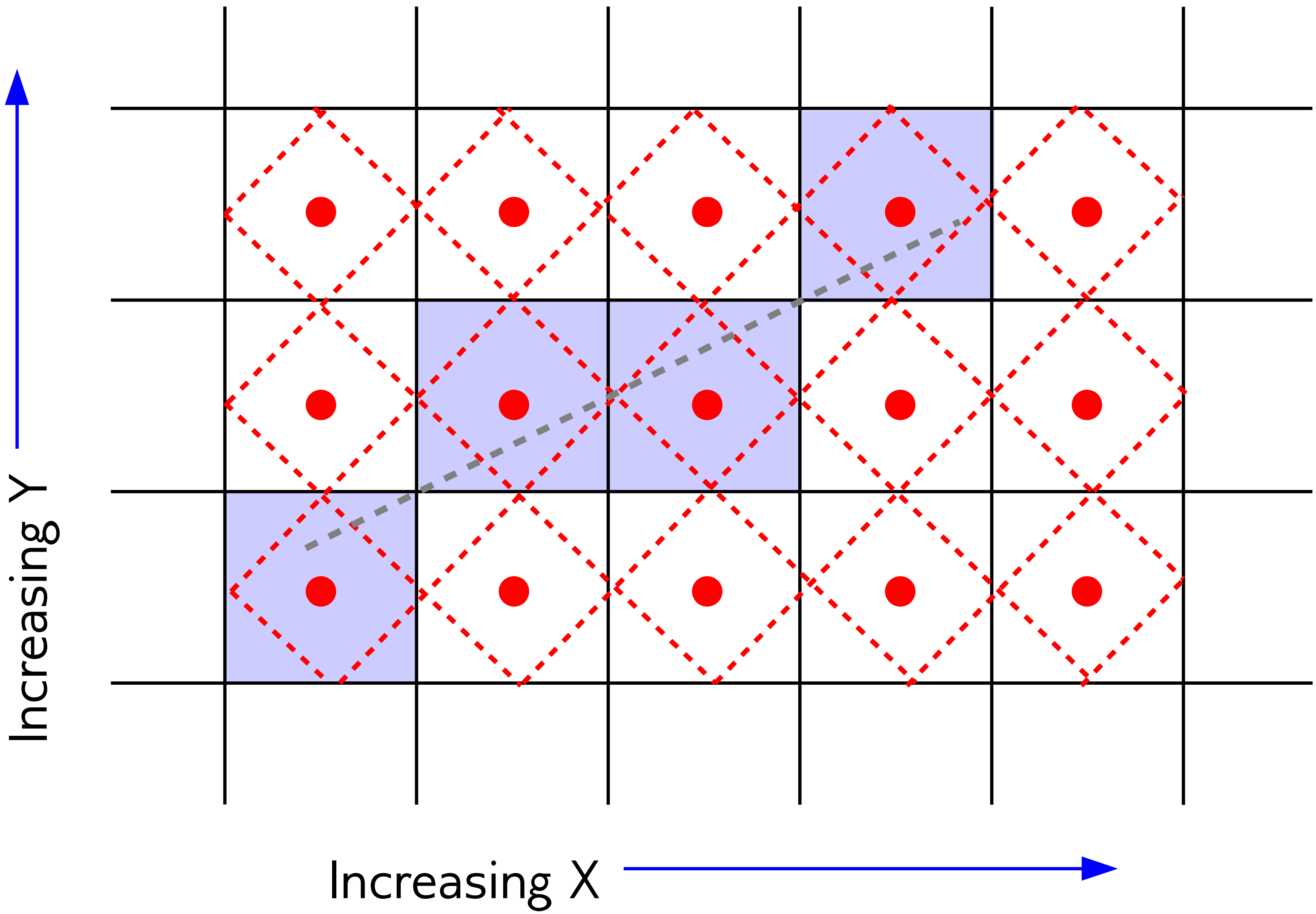


What do we mean by "combine"?

- Typically, we test the *fragment depth* against the z-buffer and replace the existing pixel if the fragment is closer
- For specific effects, we can:
  - Use other tests
  - *Blend* the fragment color with the existing color instead of replacing it
    - E.g. when combined with back-to-front rendering, can approximate transparency
  - We need to be very careful when doing this in parallel!

Rasterization Rules: Line Primitives

Output fragment if line intersects “diamond”



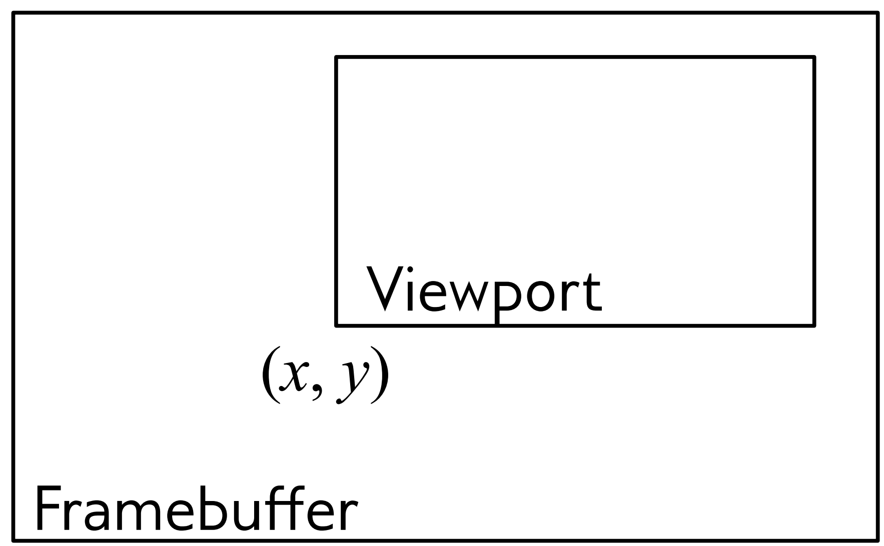
Specifying the Viewport

- *Viewport*: Active section of framebuffer
- glViewport(int x, int y, int width, int height)

Lower left corner (in pixels) — x, y

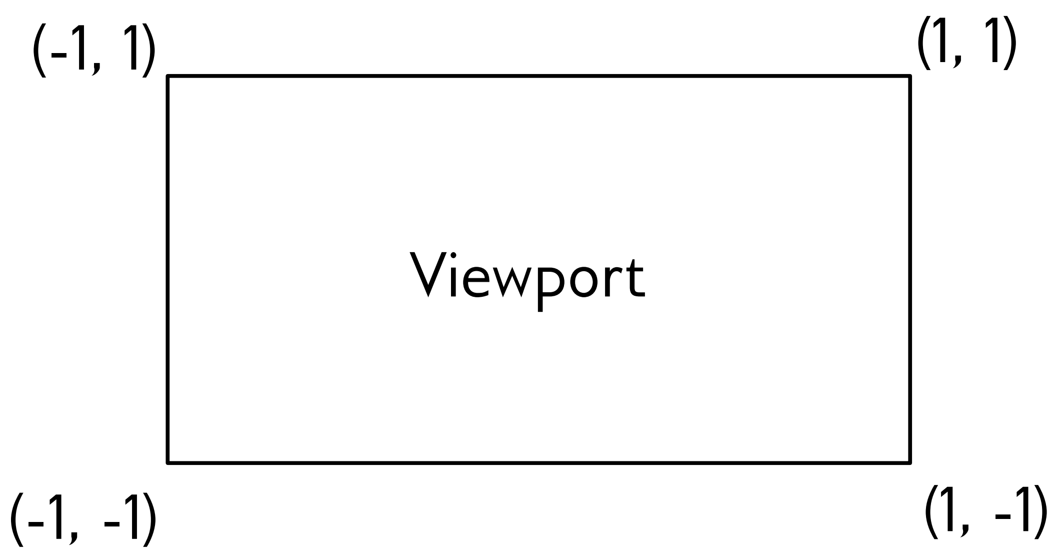
Viewport size (in pixels) — width, height

- Initially set to entire framebuffer



Normalized Device Coordinates

- Maps viewport to $[-1, 1]^2$
- Allows us to use a consistent set of coordinates for projection
- OpenGL handles the mapping from NDC to pixel coordinates

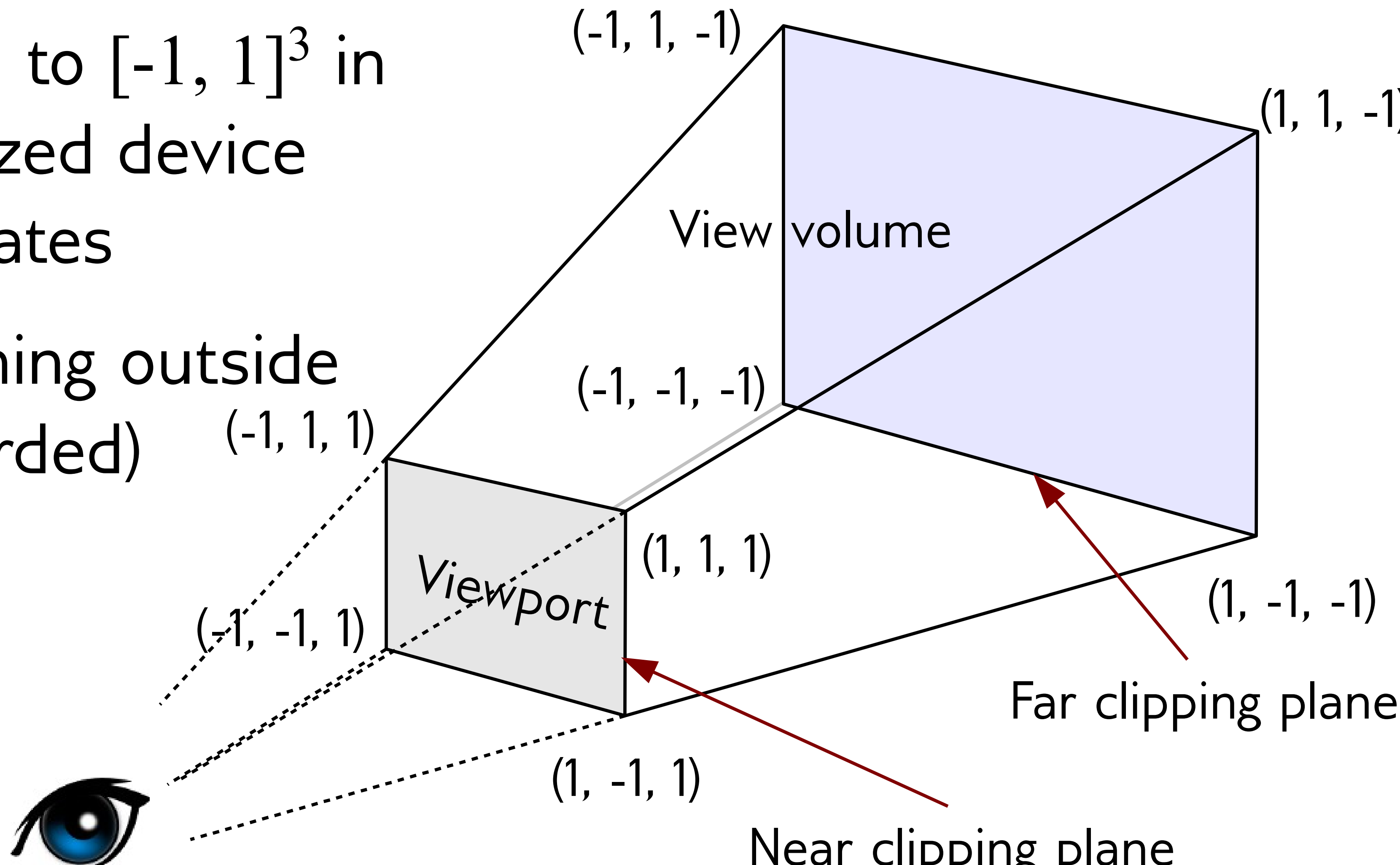


View Volume

Visible part of scene, typically frustum of a pyramid

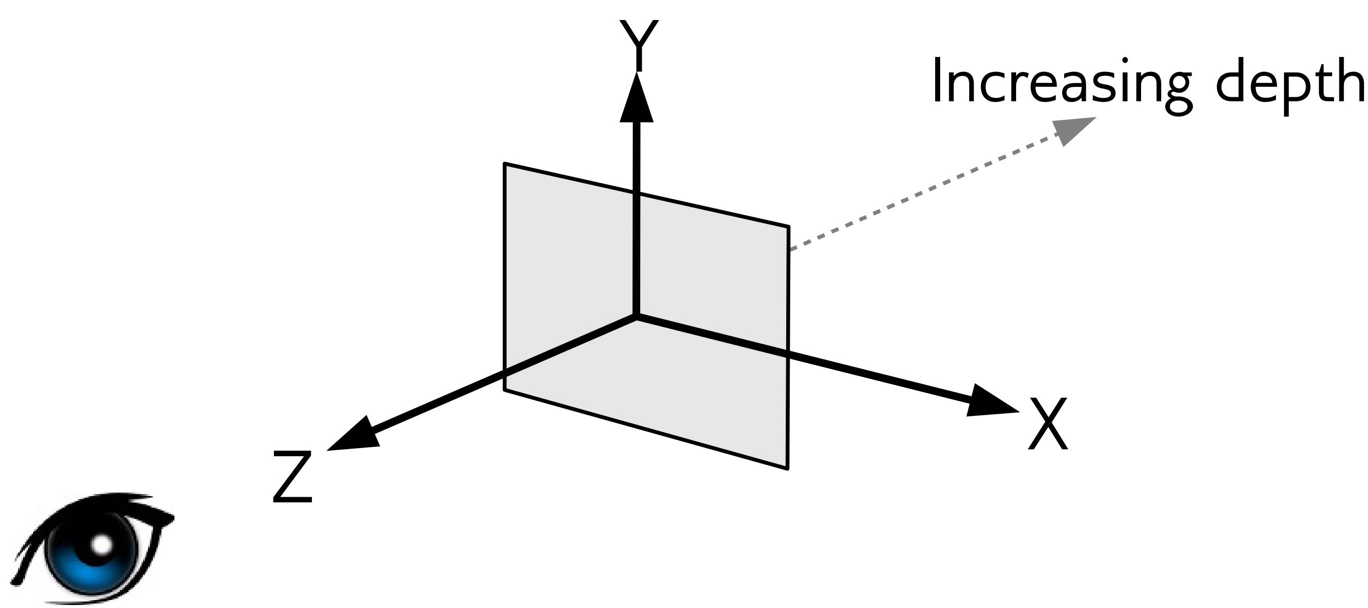
Mapped to $[-1, 1]^3$ in normalized device coordinates

(everything outside is discarded)



Projective Transformation

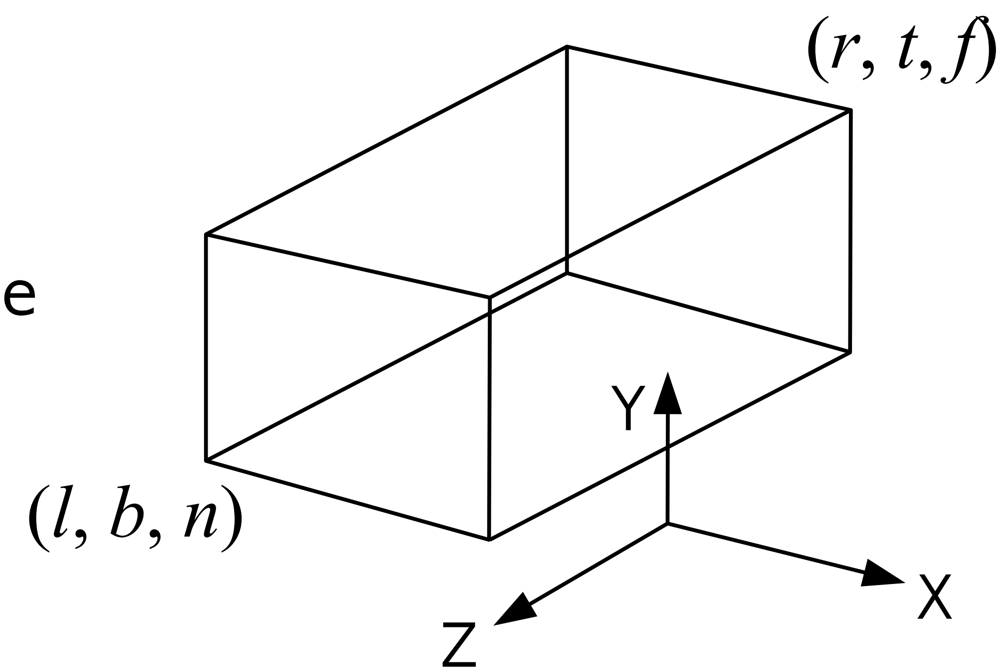
- Maps view volume to $[-1, 1]^3$ (NDC)
- Viewer is assumed to be looking along –Z
  - Consistent with XY coordinates for viewport



Orthographic (Parallel) Projection

- Viewer at infinity
- Object appears same size regardless of distance
- View volume assumed to have bounding planes

$$x = l \equiv \text{left plane}$$
$$x = r \equiv \text{right plane}$$
$$y = b \equiv \text{bottom plane}$$
$$y = t \equiv \text{top plane}$$
$$z = n \equiv \text{near plane}$$
$$z = f \equiv \text{far plane}$$



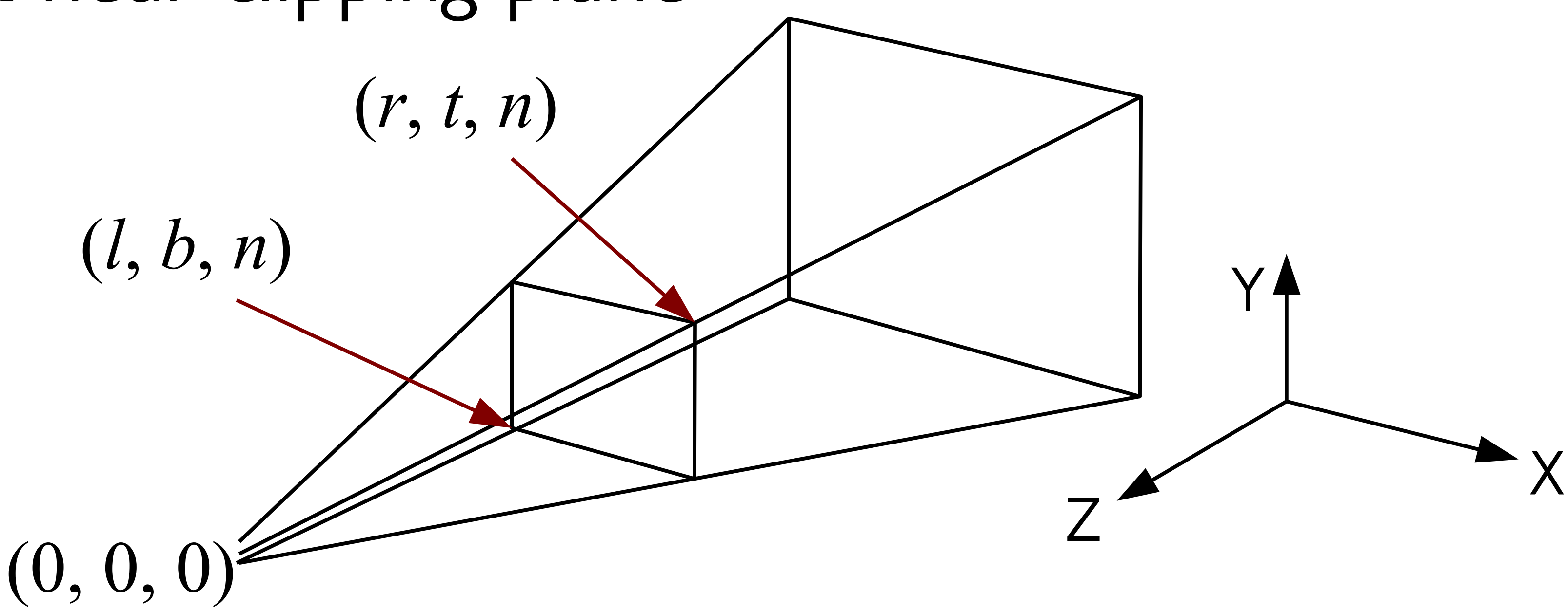
Orthographic Projection Matrix

$$\begin{bmatrix} \frac{2}{r-l} & 0 & 0 & -\frac{r+l}{r-l} \\ 0 & \frac{2}{t-b} & 0 & -\frac{t+b}{t-b} \\ 0 & 0 & \frac{2}{n-f} & -\frac{n+f}{n-f} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- Maps $[l, r] \times [b, t] \times [f, n]$ to $[-1, 1]^3$
- Since n and f are negative, $n > f$

Perspective Projection

- Objects further away appear smaller
- Rays converge at eye, assumed to be at origin
- (l, r, b, t) now specify boundaries of view volume at near clipping plane



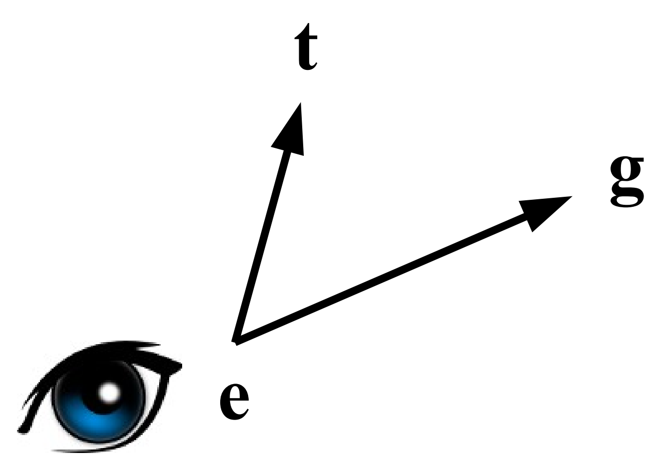
Perspective Projection Matrix

$$\begin{bmatrix} \frac{2n}{r-l} & 0 & \frac{l+r}{l-r} & 0 \\ 0 & \frac{2n}{t-b} & \frac{b+t}{b-t} & 0 \\ 0 & 0 & \frac{f+n}{n-f} & \frac{2fn}{f-n} \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

- We finally use that homogenous coordinate!
- Remember to divide by h to get the final point

Camera Transformation

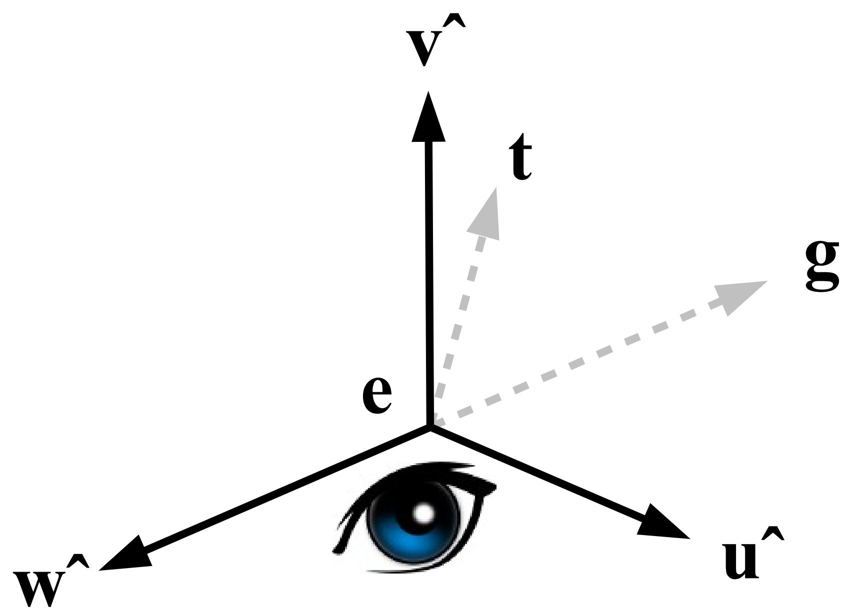
- The last missing piece is to align the camera with the direction of view
- Camera orientation is specified (in world coordinates) by:
  - the eye position $\mathbf{e}$
  - the gaze direction $\mathbf{g}$
  - the view-up vector $\mathbf{t}$
  - (neither $\mathbf{g}$ nor $\mathbf{t}$ need be unit, and $\mathbf{t}$ need not even be exactly perpendicular to $\mathbf{g}$)



Camera Transformation

- We construct an orthonormal basis $[\hat{\mathbf{u}}, \hat{\mathbf{v}}, \hat{\mathbf{w}}]$ from $\mathbf{g}$, $\mathbf{t}$

$$\hat{\mathbf{w}} = -\mathbf{g} / \|\mathbf{g}\|$$
$$\hat{\mathbf{u}} = (\mathbf{t} \times \hat{\mathbf{w}}) / \|\mathbf{t} \times \hat{\mathbf{w}}\|$$
$$\hat{\mathbf{v}} = \hat{\mathbf{w}} \times \hat{\mathbf{u}}$$



- $\hat{\mathbf{u}}$ is the target X axis, $\hat{\mathbf{v}}$ the target Y axis, and $\hat{\mathbf{w}}$ the target Z axis

Camera Transformation Matrix

$$\underbrace{\begin{bmatrix} u_x & u_y & u_z & 0 \\ v_x & v_y & v_z & 0 \\ w_x & w_y & w_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Change of basis to } uvw \text{ coordinates}} * \underbrace{\begin{bmatrix} 1 & 0 & 0 & -e_x \\ 0 & 1 & 0 & -e_y \\ 0 & 0 & 1 & -e_z \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{Translate eye to origin}}$$

Change of basis to *uvw* coordinates

Translate eye to origin

The Full Transformation Pipeline

Every object is transformed by

T = Projection * Camera * Model

Back to that glMatrixMode thing...

- OpenGL maintains multiple current transformation matrices, and corresponding stacks
- The important ones (for us) are:
  - the *Model-View Matrix* M, and
  - the *Projection Matrix* P
- The full transformation applied to an object is actually $P * M$ (in that order, right-to-left)
- By convention, the projective transform (perspective/orthographic) is put in P, and everything else (camera, model, ...) in M

OpenGL Matrix Modes

- To select the projection matrix (and stack):

  ```
  glMatrixMode(GL_PROJECTION);
  ```

- To select the model-view matrix (and stack):

  ```
  glMatrixMode(GL_MODELVIEW);
  ```

The Full Transform Once Again...

Every object is transformed by

$$T = \text{Projection} * \text{Camera} * \text{Model}$$

Projection → GL_PROJECTION

Camera * Model → GL_MODELVIEW

Recap

- **Z-buffer** to detect visible surfaces
- Surfaces **tessellated** into simple primitives
- **Draw primitives** with glBegin/glEnd blocks
  - glVertex, glNormal, glColor
  - Primitives are rasterized to framebuffer
- **Nested transform blocks**
  - glPushMatrix, glPopMatrix, glLoadMatrix, glMultMatrix
- **Projection * Camera * Model** transform applied to each object
  - Perspective/orthographic projection, camera (uvw) coordinates, GL_PROJECTION, GL_MODELVIEW