CPSC 314
17 – LIGHTING AND SHADING

Textbook: 14

UGRAD.CS.UBC.CA/~CS314

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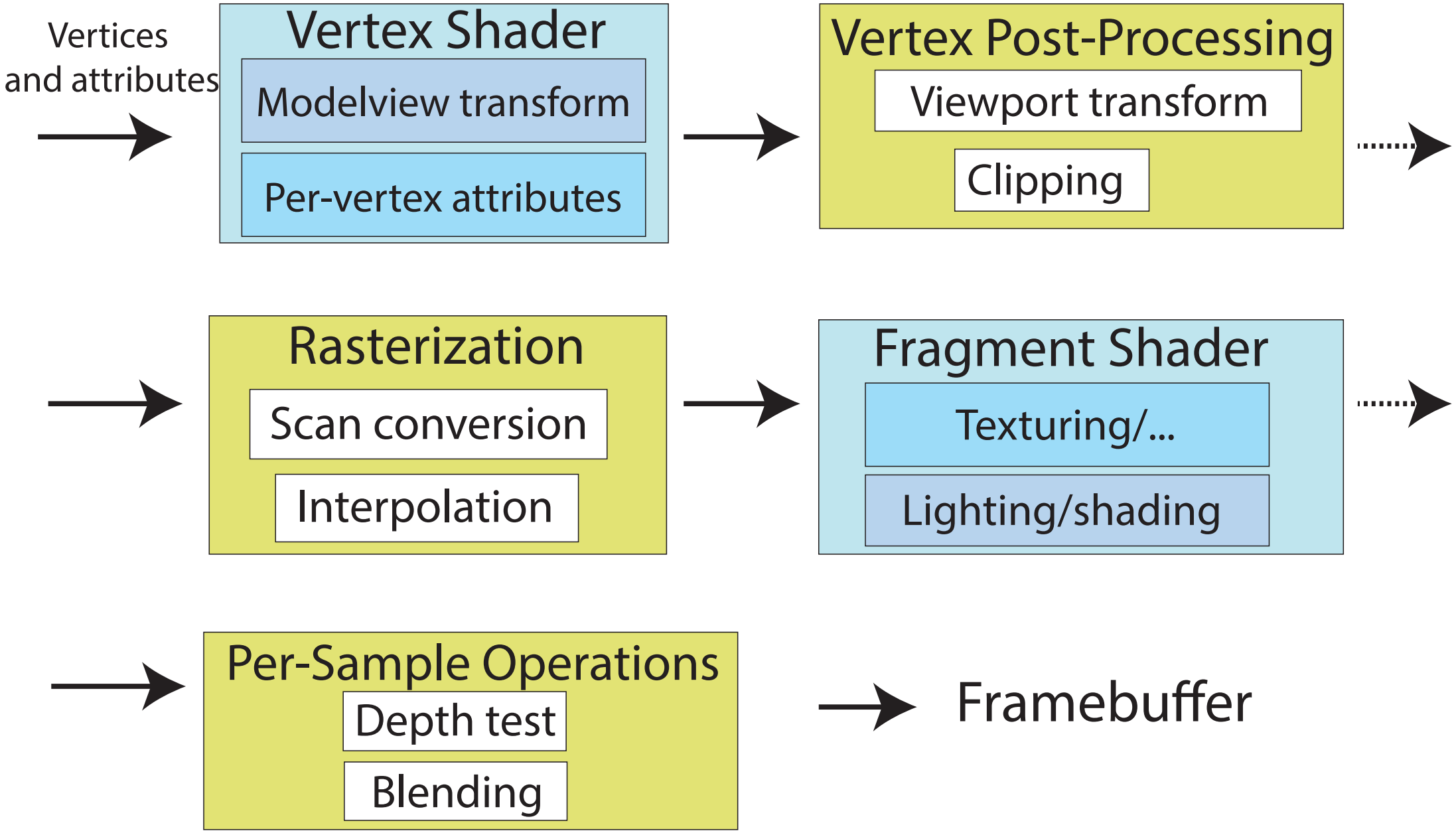
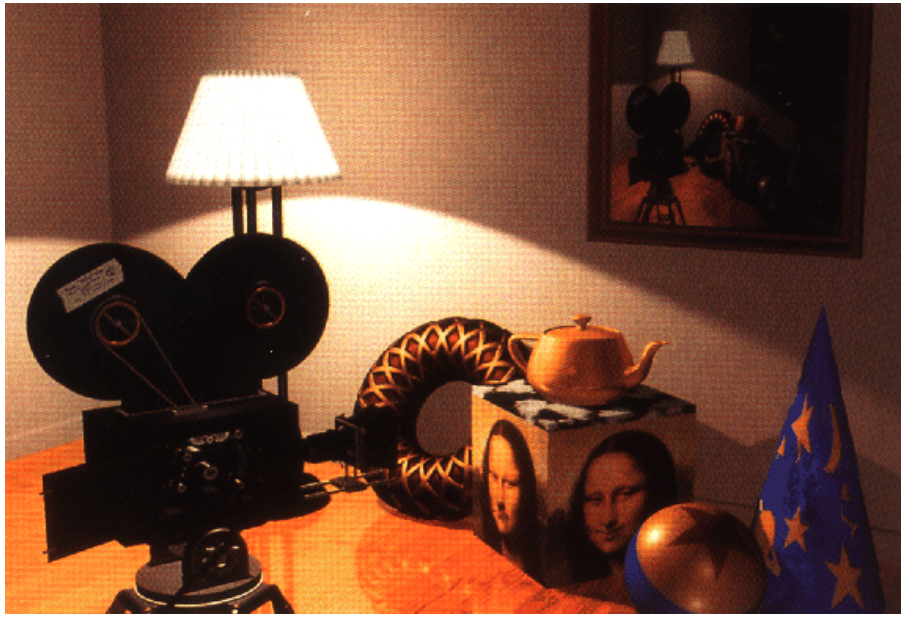
THE RENDERING PIPELINE



LIGHTING/SHADING

- Goal
  - Model the interaction of light with surfaces to render realistic images
  - Generate per (pixel/vertex) color



FACTORS

- Light sources
  - Location, type & color
- Surface materials
  - How surfaces reflect light
- Transport of light
  - How light moves in a scene
- Viewer position

FACTORS

- Light sources
  - Location, type & color
- Surface materials
  - How surfaces reflect light
- Transport of light
  - How light moves in a scene
- Viewer position

- How can we do this in the pipeline?

ILLUMINATION MODELS/ALGORITHMS

Local illumination - Fast

Ignore real physics, approximate the look

Interaction of each object with light

- Compute on surface (light to viewer)

Global illumination – Slow

Physically based

Interactions between objects

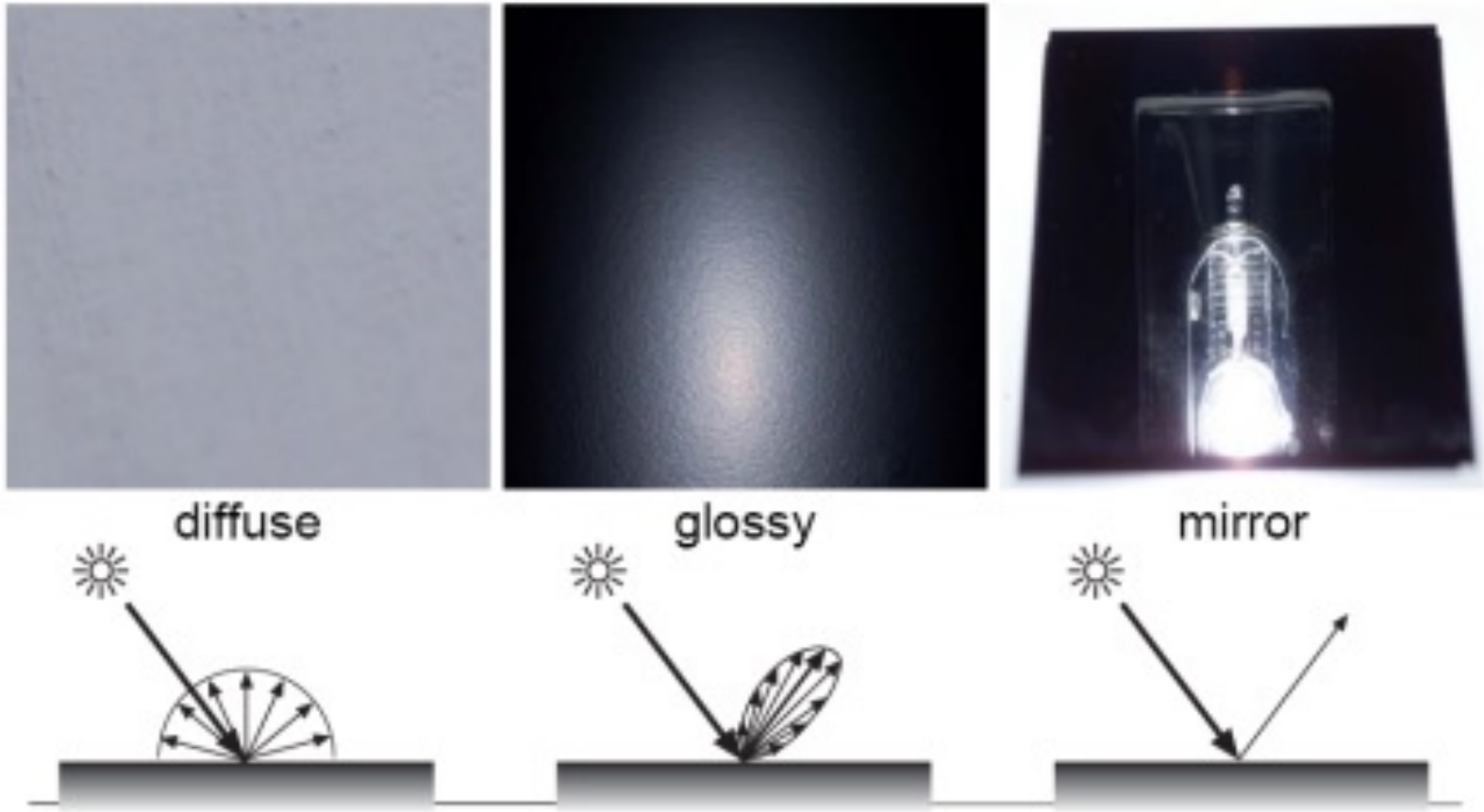
THE BIG PICTURE (BASIC)

- Light: energy in a range of wavelengths
  - White light – all wavelengths
  - Colored (e.g. red) – subset of wavelengths
- Surface “color” – reflected wavelength
  - White – reflects all lengths
  - Black – absorbs everything
  - Colored (e.g. red) absorbs all but the reflected color
- Multiple light sources add (energy sums)

MATERIALS

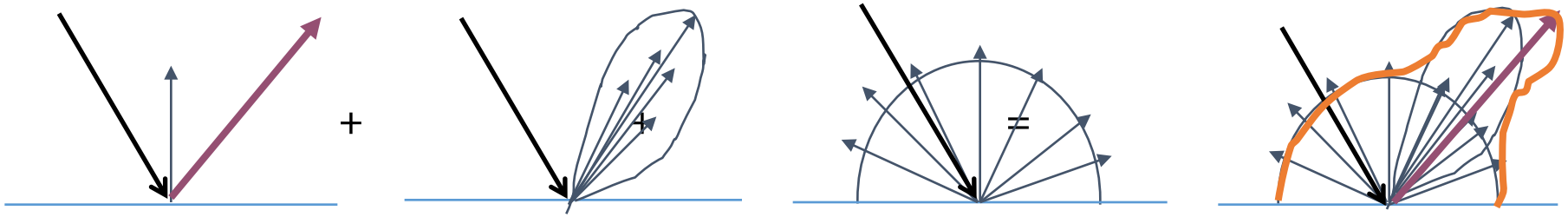
- Surface reflectance:
  - Illuminate surface point with a ray of light from different directions
  - How much light is reflected in each direction?

BASIC TYPES



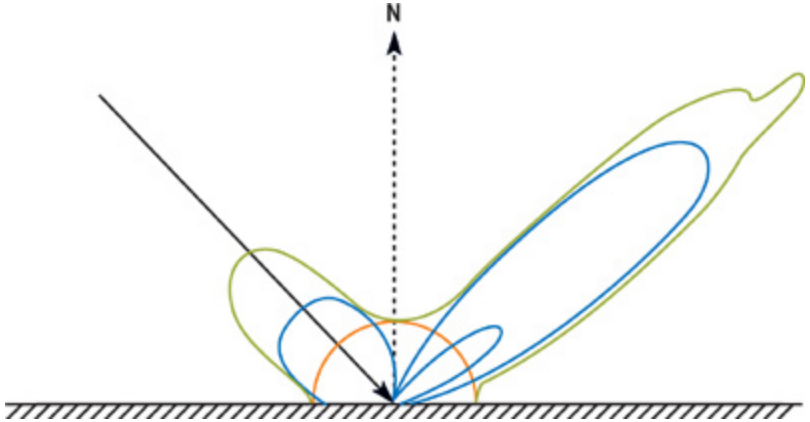
REFLECTANCE DISTRIBUTION MODEL

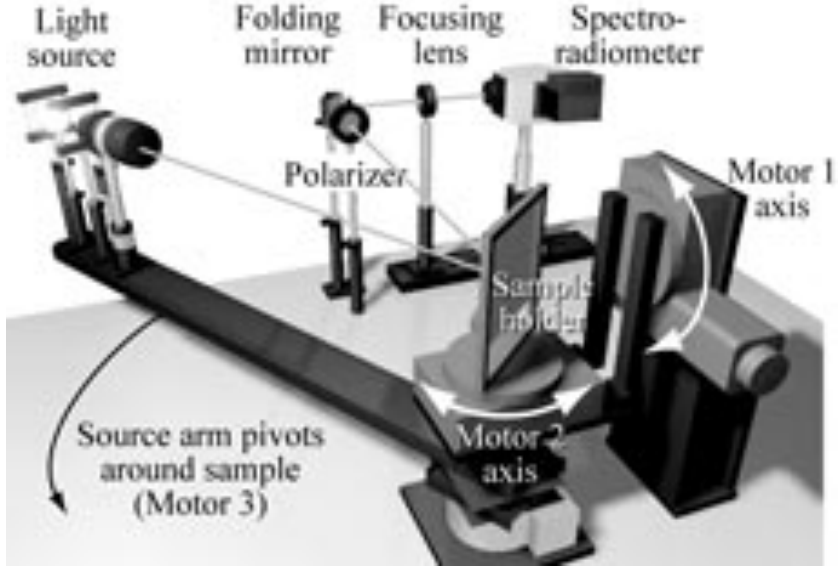
- Most surfaces exhibit complex reflectances
  - Vary with incident and reflected directions.
  - Model with combination – known as BRDF
    - BRDF: *Bidirectional Reflectance Distribution Function*



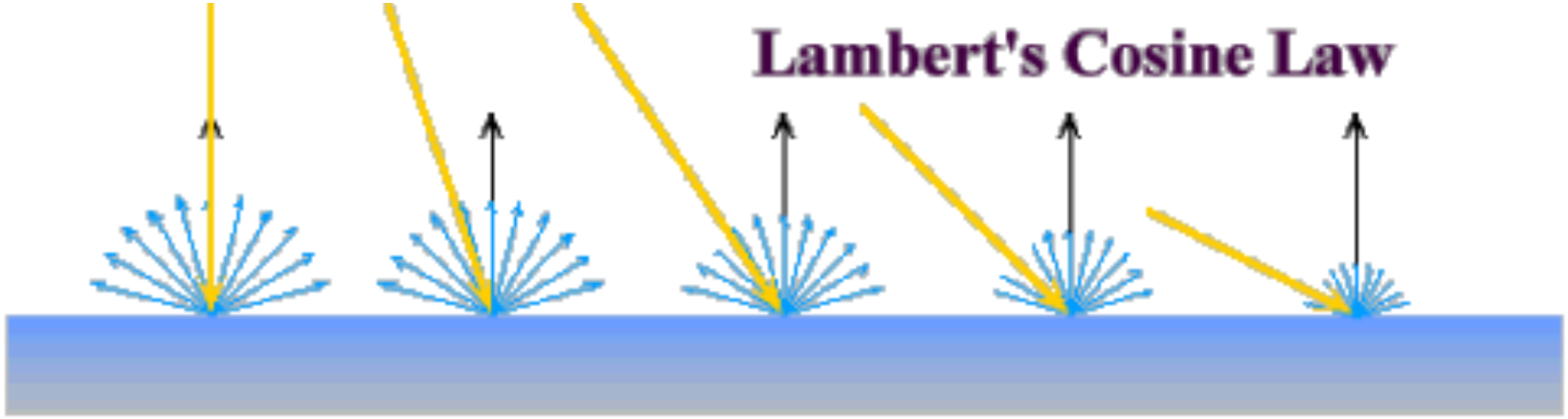
BRDF MEASUREMENTS/PLOTS

2D slice

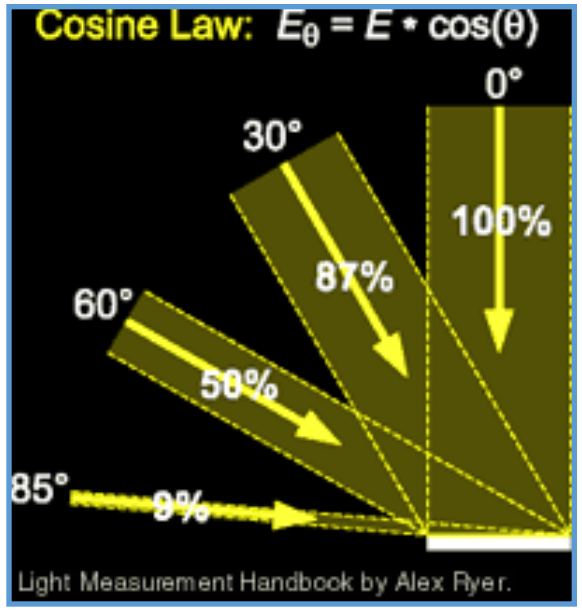




DIFFUSE (LAMBERT)

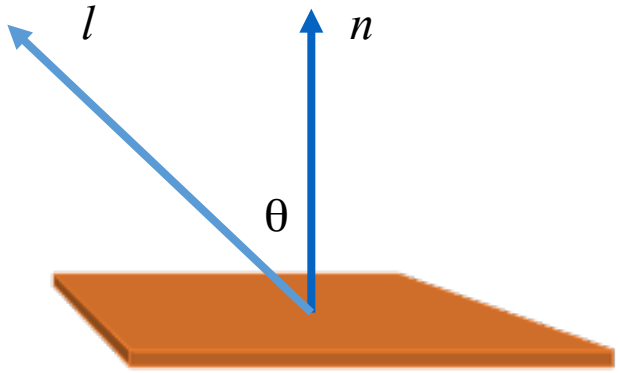


Intuitively: cross-sectional area of the “beam” intersecting an element of surface area is smaller for greater angles with the normal.



COMPUTING DIFFUSE REFLECTION

Depends on angle of incidence: angle between surface normal and incoming light



$$I_{diffuse} = k_d \, I_{light} \, \mathbf{cos}\, \theta$$

In practice use vector arithmetic

$$I_{diffuse} = k_d \, I_{light} \, (\mathbf{n} \bullet \mathbf{l})$$

Scalar (B/W intensity) or 3-tuple (color)

- k_d: diffuse coefficient, surface color
- I_{light}: incoming light intensity
- $I_{diffuse}$: outgoing light intensity (for diffuse reflection)

NB: Always normalize vectors used in lighting

- **n**, **l** should be unit vectors

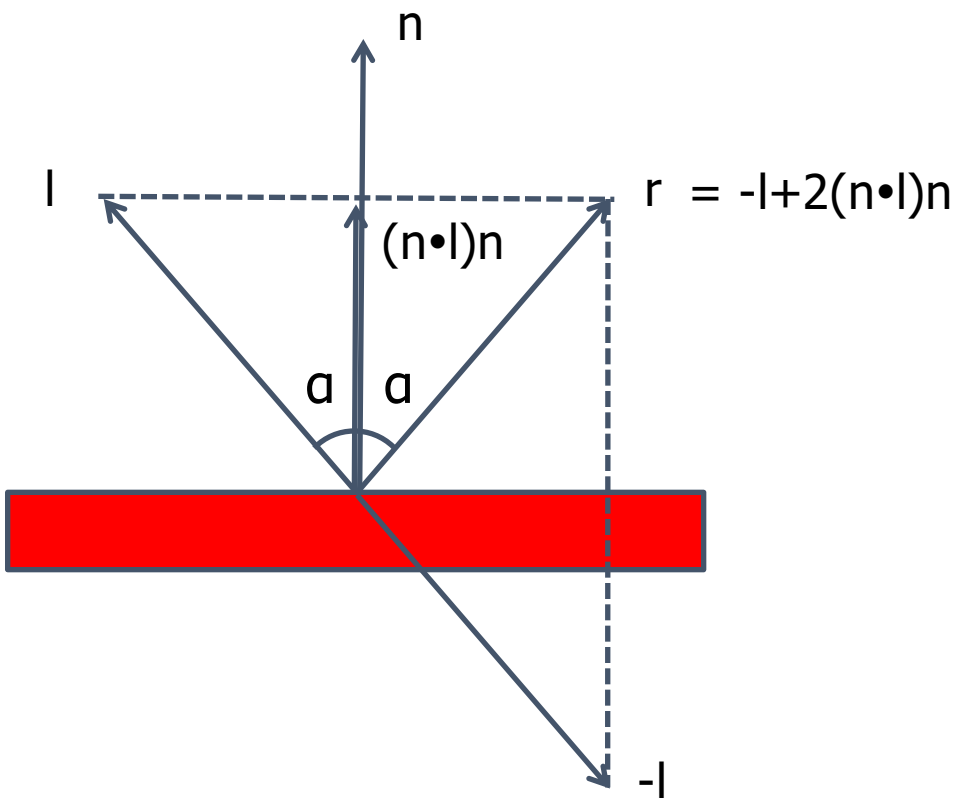
DIFFUSE LIGHTING EXAMPLES

- Lambertian sphere from several lighting angles:

- need only consider angles from 0° to 90°

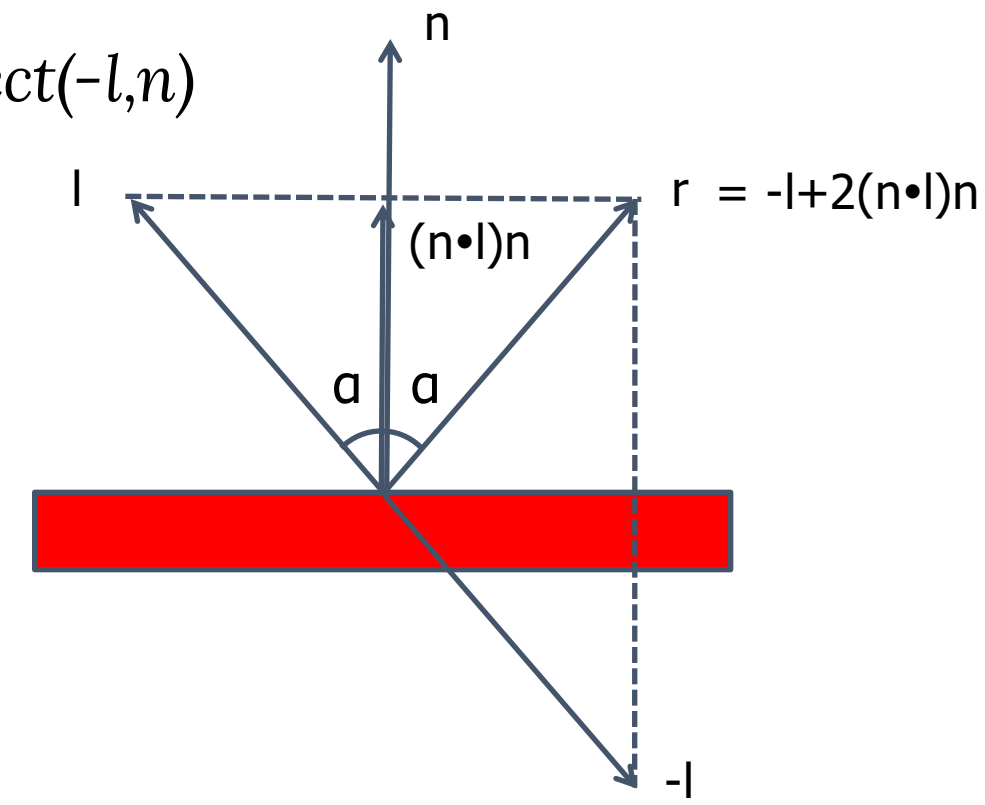
PHYSICS OF SPECULAR REFLECTION

- Geometry of specular (perfect mirror) reflection
  - Snell's law



PHYSICS OF SPECULAR REFLECTION

- Geometry of specular (perfect mirror) reflection
  - Snell's law
  - In GLSL: use *reflect(-l,n)*

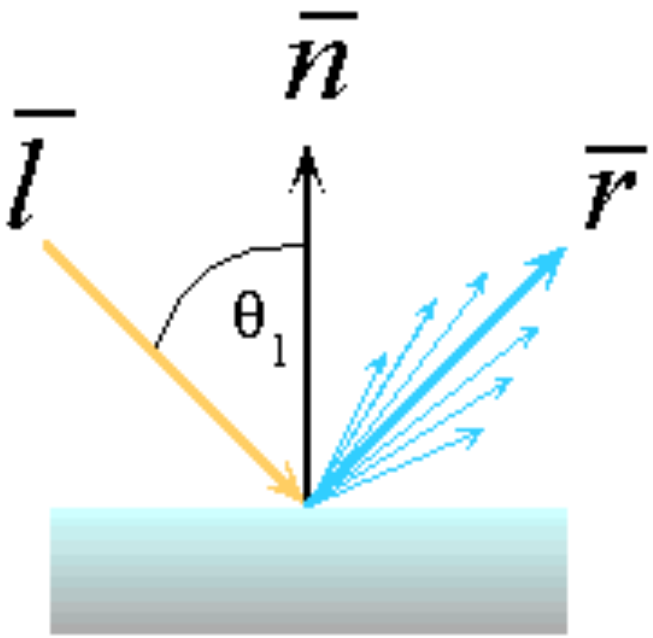


EMPIRICAL APPROXIMATION

- Snell's law = perfect mirror-like surfaces
  - But ..
    - few surfaces exhibit perfect specularity
    - Gaze and reflection directions never EXACTLY coincide
- Expect **most** reflected light to travel in direction predicted by Snell's Law
- But some light may be reflected in a direction slightly off the ideal reflected ray
- As angle from ideal reflected ray increases, we expect less light to be reflected

EMPIRICAL APPROXIMATION

- Angular falloff



- How to model this falloff?

PHONG LIGHTING

Most common lighting model in computer graphics (Phong Bui-Tuong, 1975)

$$\mathbf{I}_{\mathbf{specular}} = \mathbf{k}_{\mathbf{s}}\mathbf{I}_{\mathbf{light}}(\cos\phi)^{n_s}$$

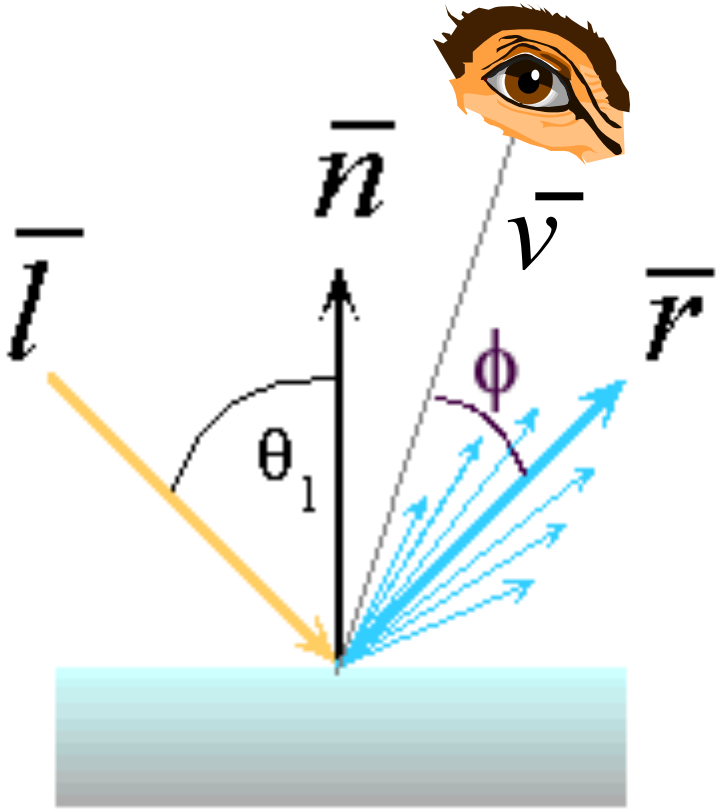
$$\mathbf{I}_{\mathbf{specular}} = \mathbf{k}_{\mathbf{s}}\mathbf{I}_{\mathbf{light}}(\mathbf{v}\bullet\mathbf{r})^{n_s}$$

ϕ: angle between $\mathbf{r}$ and view direction $\mathbf{v}$

n_s : purely empirical constant, varies rate of falloff

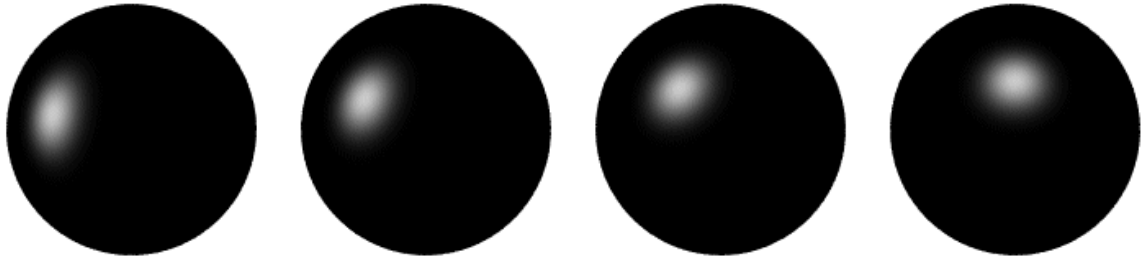
k_s: specular coefficient, highlight color

no physical basis, "plastic" look

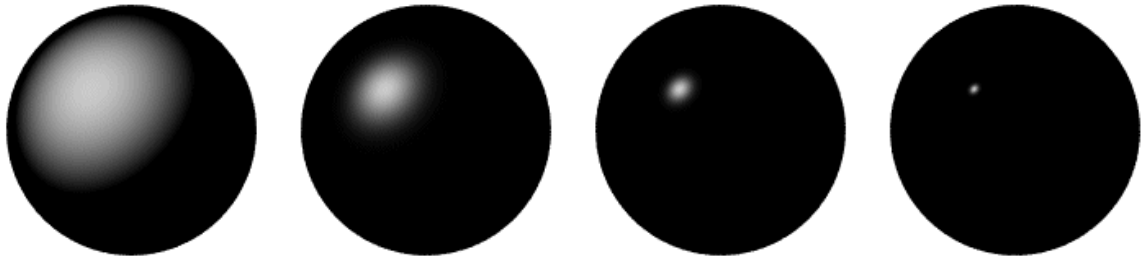


PHONG EXAMPLES

varying light position



varying n_s

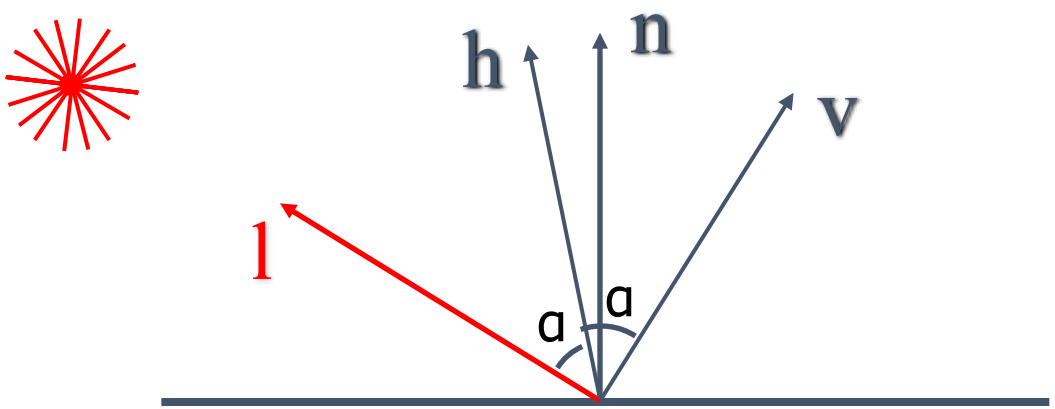


ALTERNATIVE MODEL

Blinn-Phong model (Jim Blinn, 1977)

- Variation with better physical interpretation
  - **h**: halfway vector; r: roughness

$$I_{specular} = k_s \cdot (\mathbf{h} \cdot \mathbf{n})^{1/r} \cdot I_{light}\text{; with } \mathbf{h} = (\mathbf{l} + \mathbf{v})/2$$



MATERIALS (LAST BIT)

- Light is **linear**
  - If multiple rays illuminate the surface point the result is just the sum of the individual reflections for each ray

$$\sum_p I_p(k_d(n \cdot l_p) + k_s(r_p \cdot v)^n)$$

MATERIALS DEMO

- (switch to Maya)

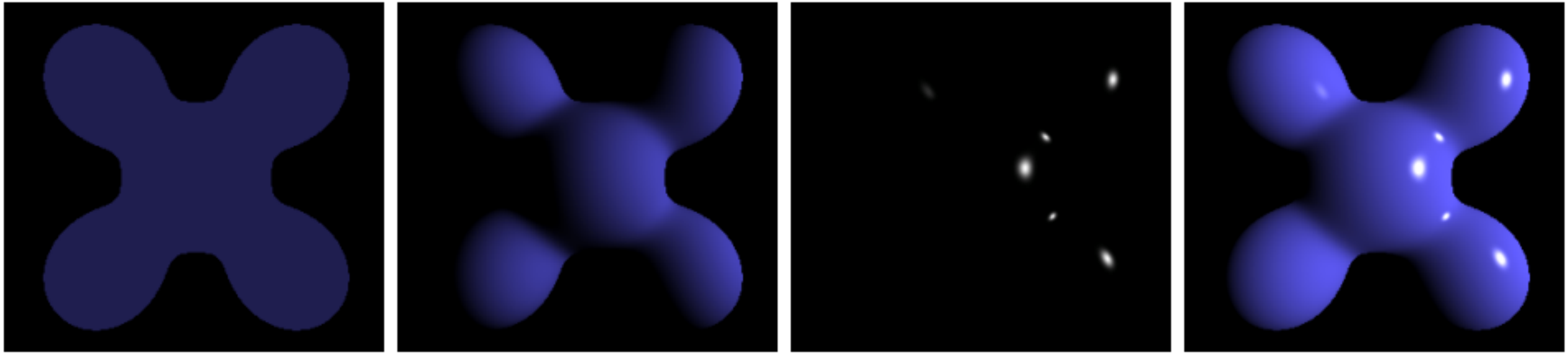
AMBIENT LIGHT

- Non-directional light – environment light
- Object illuminated with same light everywhere
  - Looks like silhouette
- Illumination equation $I = I_a k_a$
  - I_a - ambient light intensity
  - k_a - fraction of this light reflected from surface

ILLUMINATION EQUATION (PHONG)

- If we take the previous formula and add ambient component:

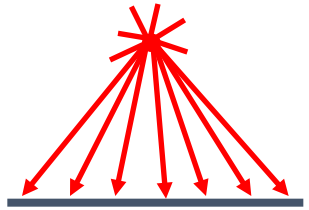
$$I_a k_a + \sum_p I_p \left(k_d \left(n \cdot l_p\right) + k_s \left(r_p \cdot v\right)^n\right)$$



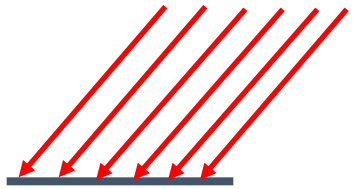
Ambient + Diffuse + Specular = Phong Reflection

LIGHT SOURCE TYPES

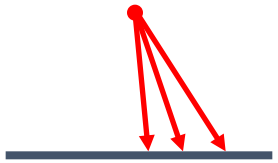
- Point Light
  - light originates at a point
  -



- Directional Light (point light at infinity)
  - light rays are parallel
  - Rays hit a planar surface at identical angles
  -

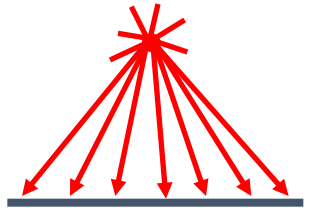


- Spot Light
  - point light with limited angles
  -

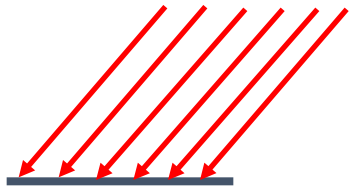


LIGHT SOURCE TYPES

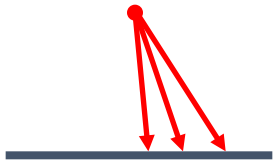
- Point Light
  - light originates at a point
  - defined by **location** only



- Directional Light (point light at infinity)
  - light rays are parallel
  - Rays hit a planar surface at identical angles
  - defined by **direction** only



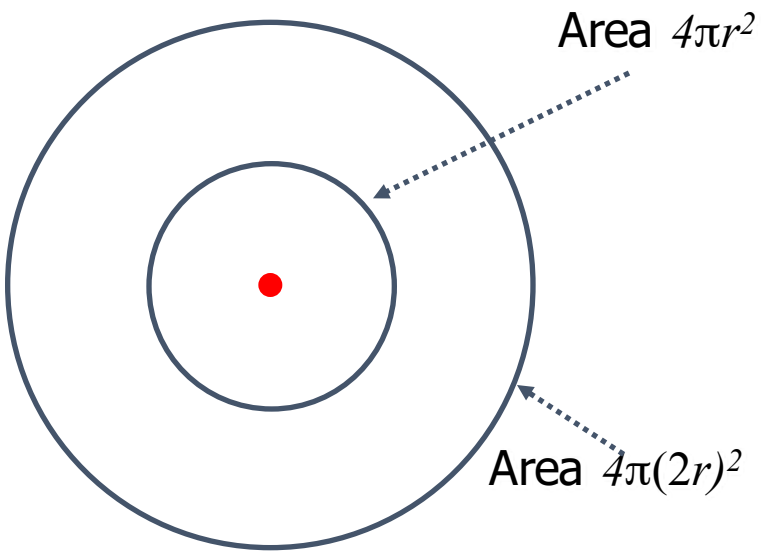
- Spot Light
  - point light with limited angles
  - defined by **location, direction, and angle range**



WHICH LIGHTS/MATERIALS ARE USED HERE?

LIGHT SOURCE FALLOFF

- Quadratic falloff (point- and spot lights)
  - Brightness of objects depends on power per unit area that hits the object
  - The power per unit area for a point or spot light decreases quadratically with distance



ILLUMINATION EQUATION WITH ATTENUATION

- For multiple light sources:

$$I = I_a k_a + \sum_p \frac{I_p}{A(d_p)} (k_d (n \cdot l_p) + k_s (r_p \cdot v)^n)$$

- d_p - distance between surface and light source + distance between surface and viewer, A – attenuation function

LIGHT

- Light has color
- Interacts with object color (r,g,b)

$$I = I_a k_a$$

$$I_a = (I_{ar}, I_{ag}, I_{ab})$$

$$k_a = (k_{ar}, k_{ag}, k_{ab})$$

$$I = (I_r, I_g, I_b) = (I_{ar}k_{ar}, I_{ag}k_{ag}, I_{ab}k_{ab})$$

- Blue light on white surface?
- Blue light on red surface?

LIGHT AND MATERIAL SPECIFICATION

- Light source: amount of RGB light emitted
  - value = intensity per channel

  e.g., (1.0,0.5,0.5)
  - every light source emits ambient, diffuse, and specular light
- Materials: amount of RGB light reflected
  - value represents percentage reflected
    e.g., (0.0,1.0,0.5)
- Interaction: multiply components
  - Red light (1,0,0) x green surface (0,1,0) = black (0,0,0)

WHEN TO APPLY LIGHTING MODEL?

per polygon
"flat shading"

per vertex
"Gouraud shading"

per pixel
"per pixel lighting"
"Phong shading"

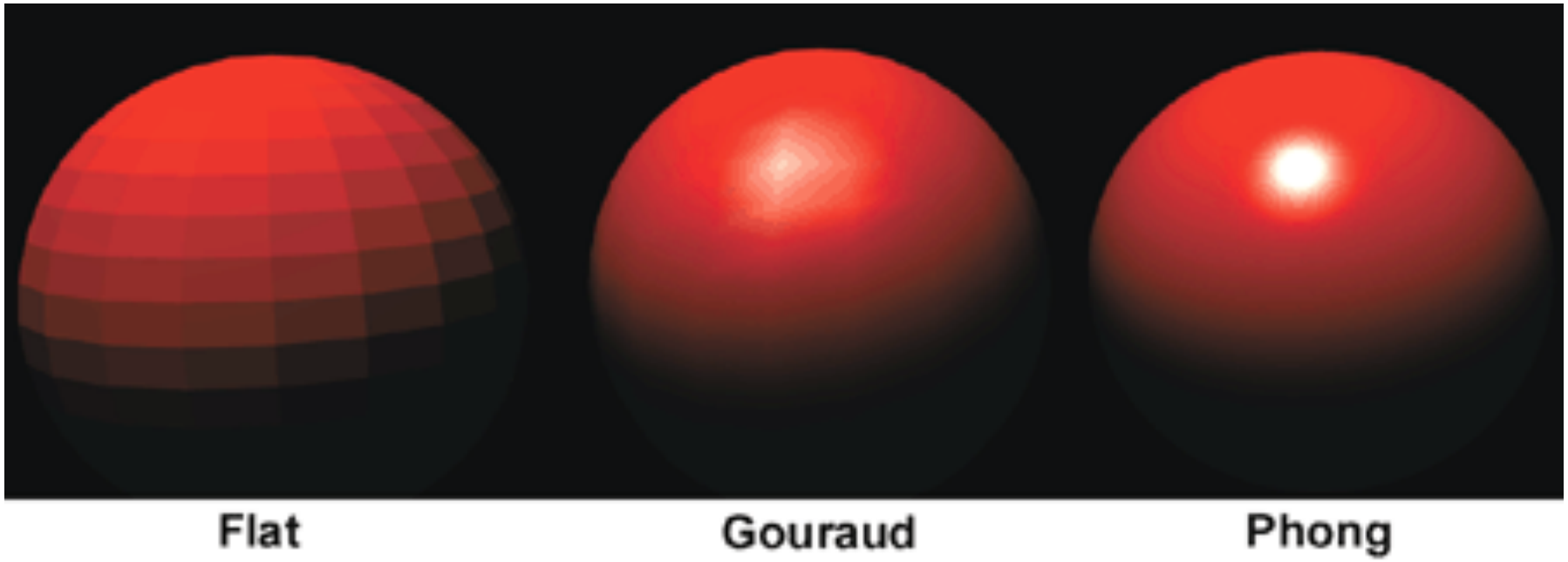
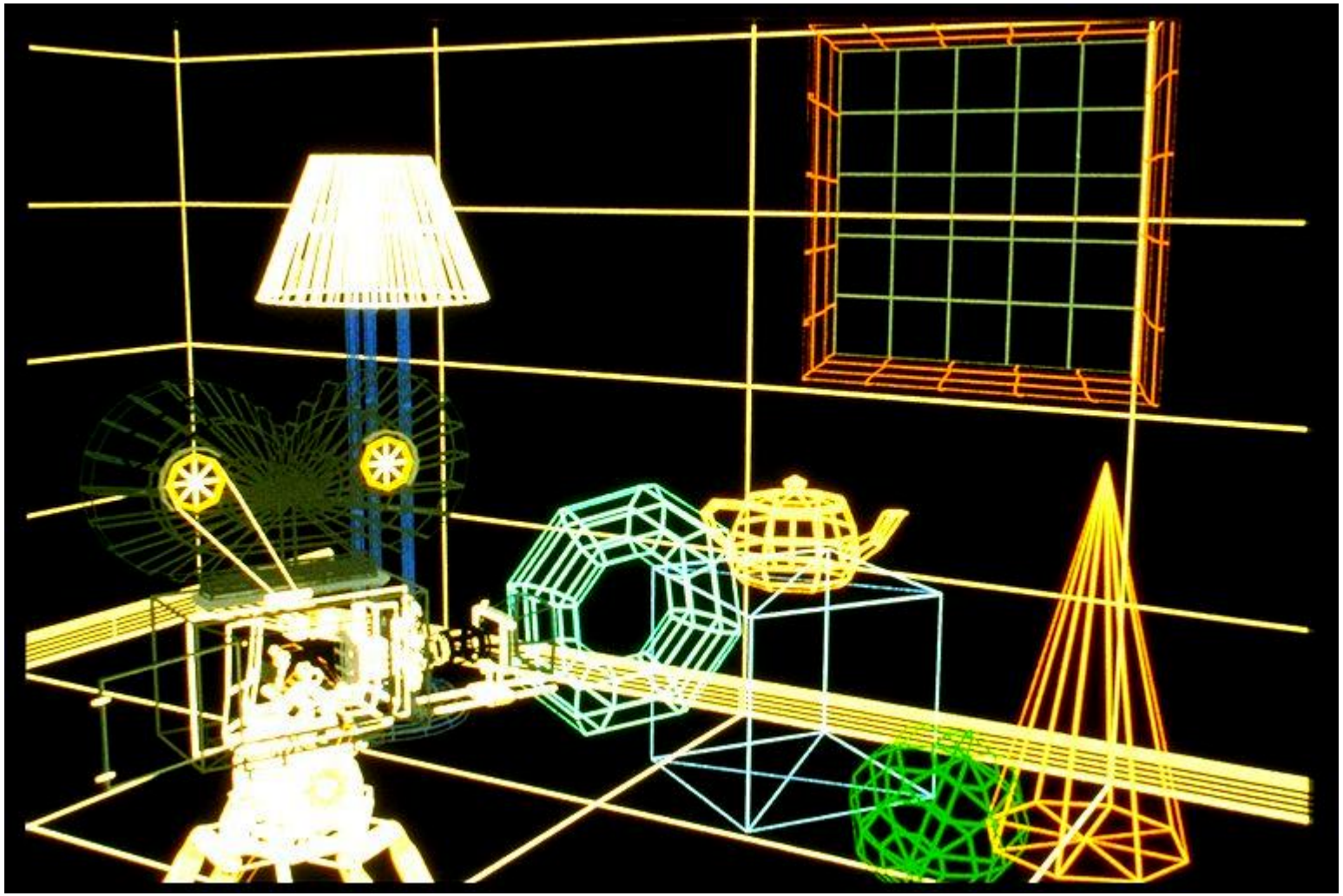


Image © Intergraph Computer Systems

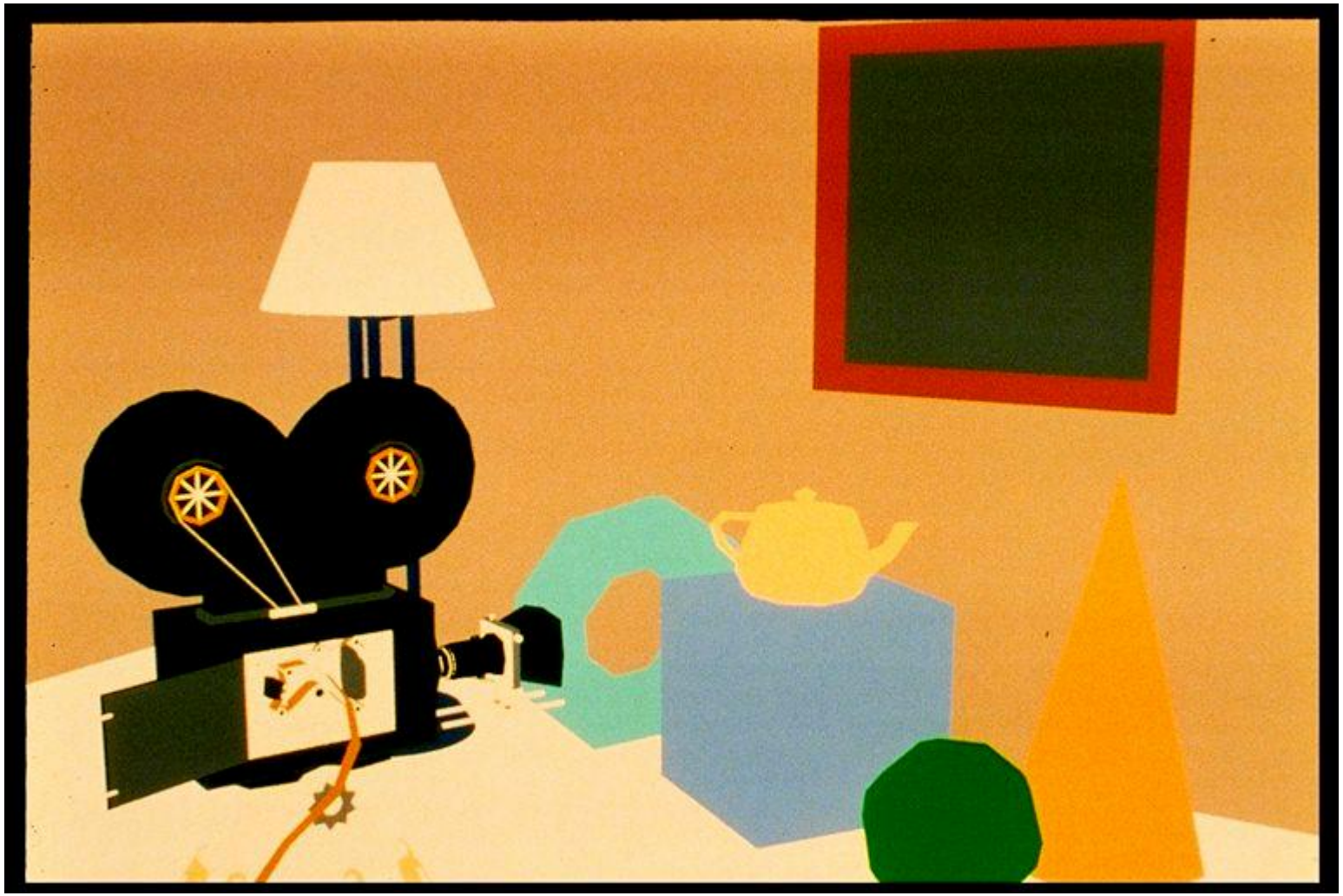
NOTES ON SHADING

- To do all the calculations, we need to choose a coordinate system
- Typically View Coordinate System
- We need to have
  - Vertex Coordinates
  - Normals
  - Light Positions/Directions

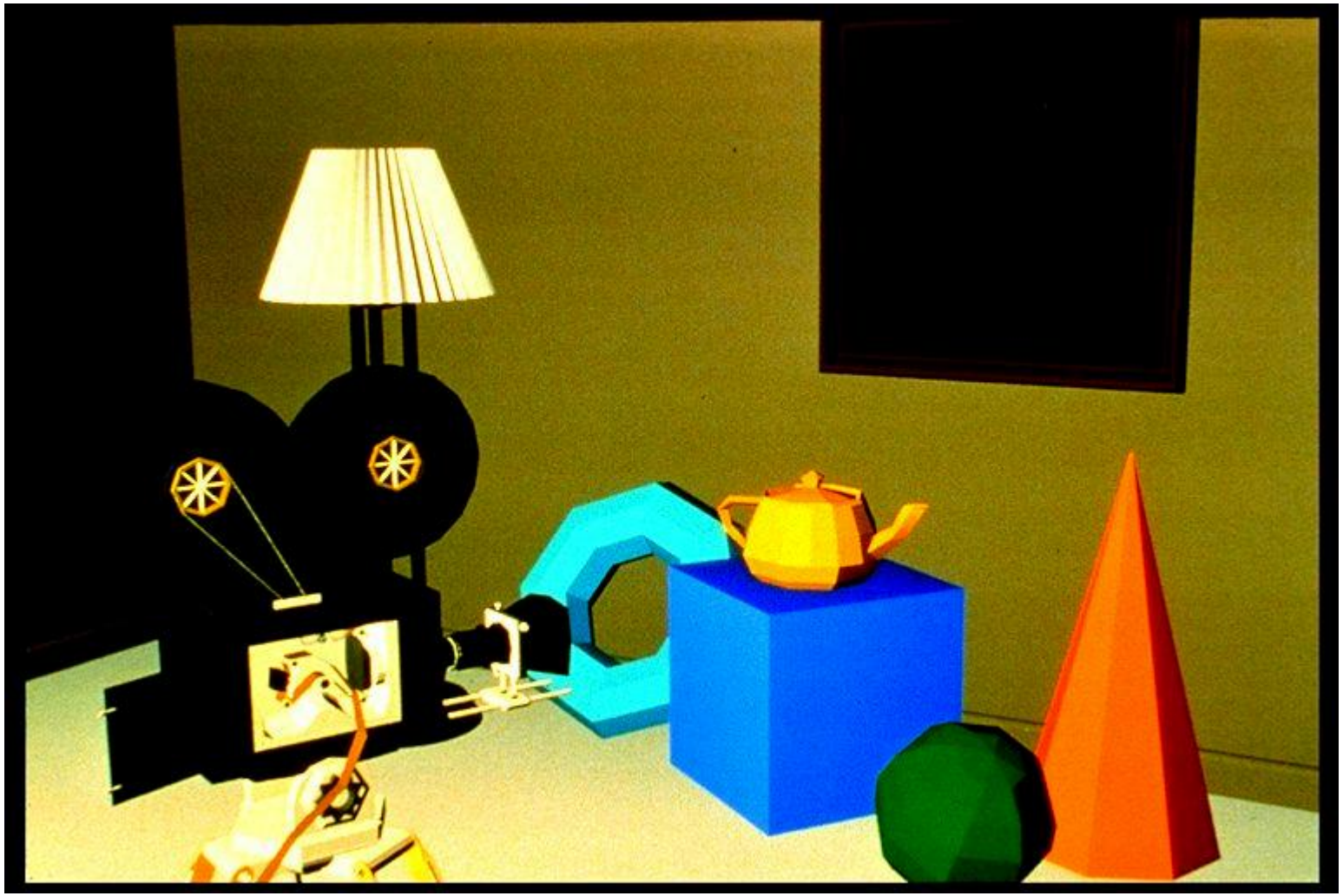
COLORED WIREFRAMES



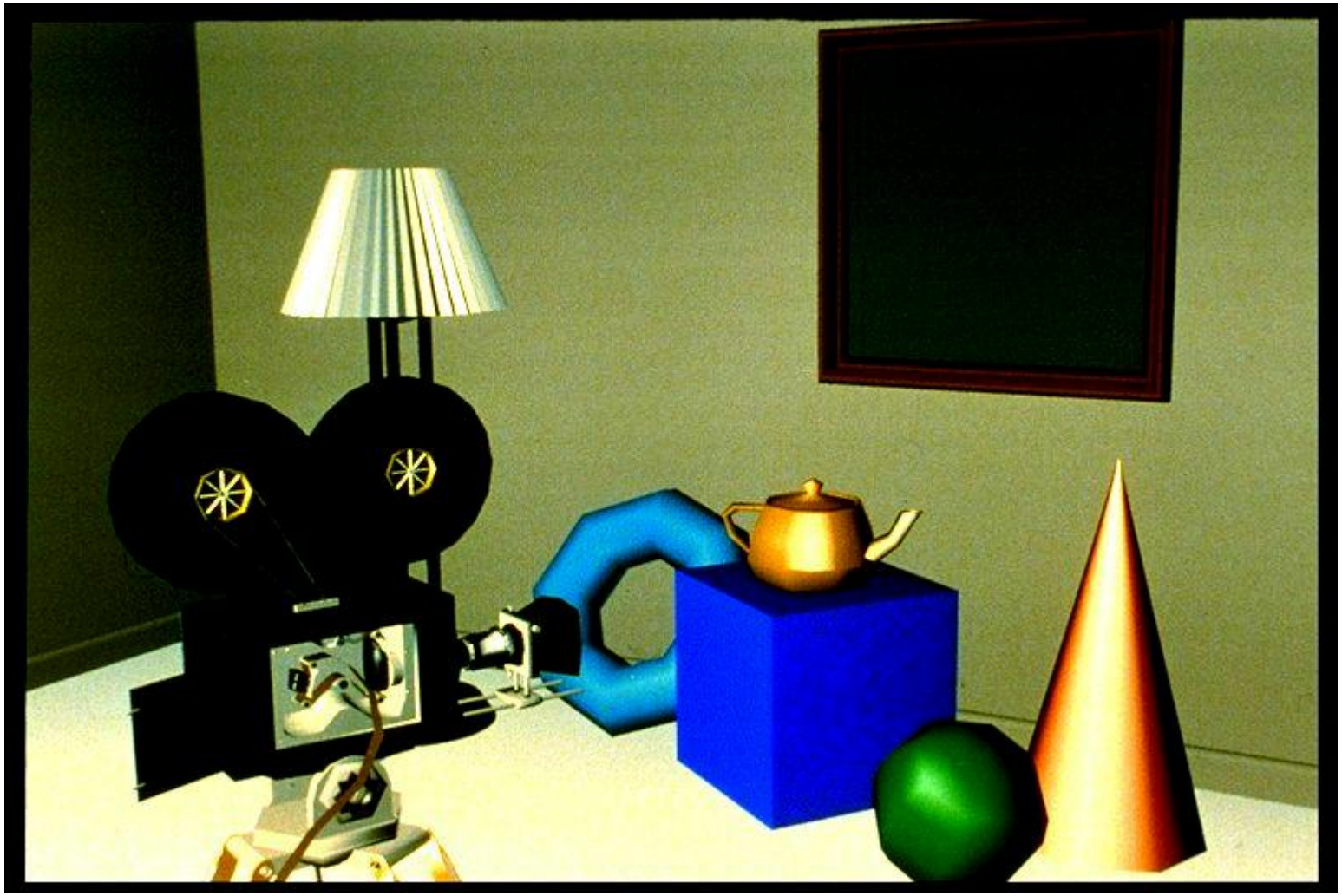
AMBIENT LIGHTING



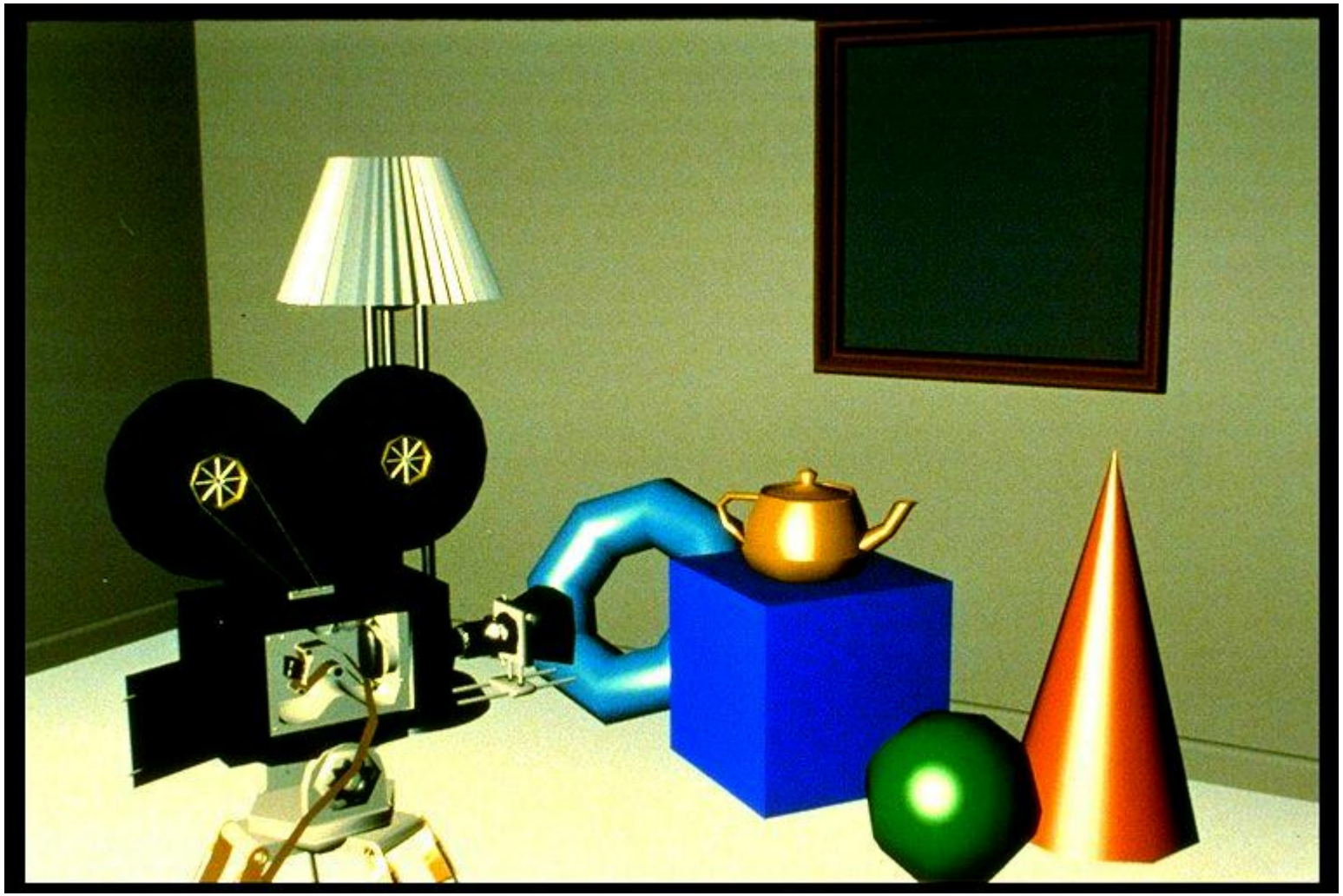
PER-POLYGON SHADING



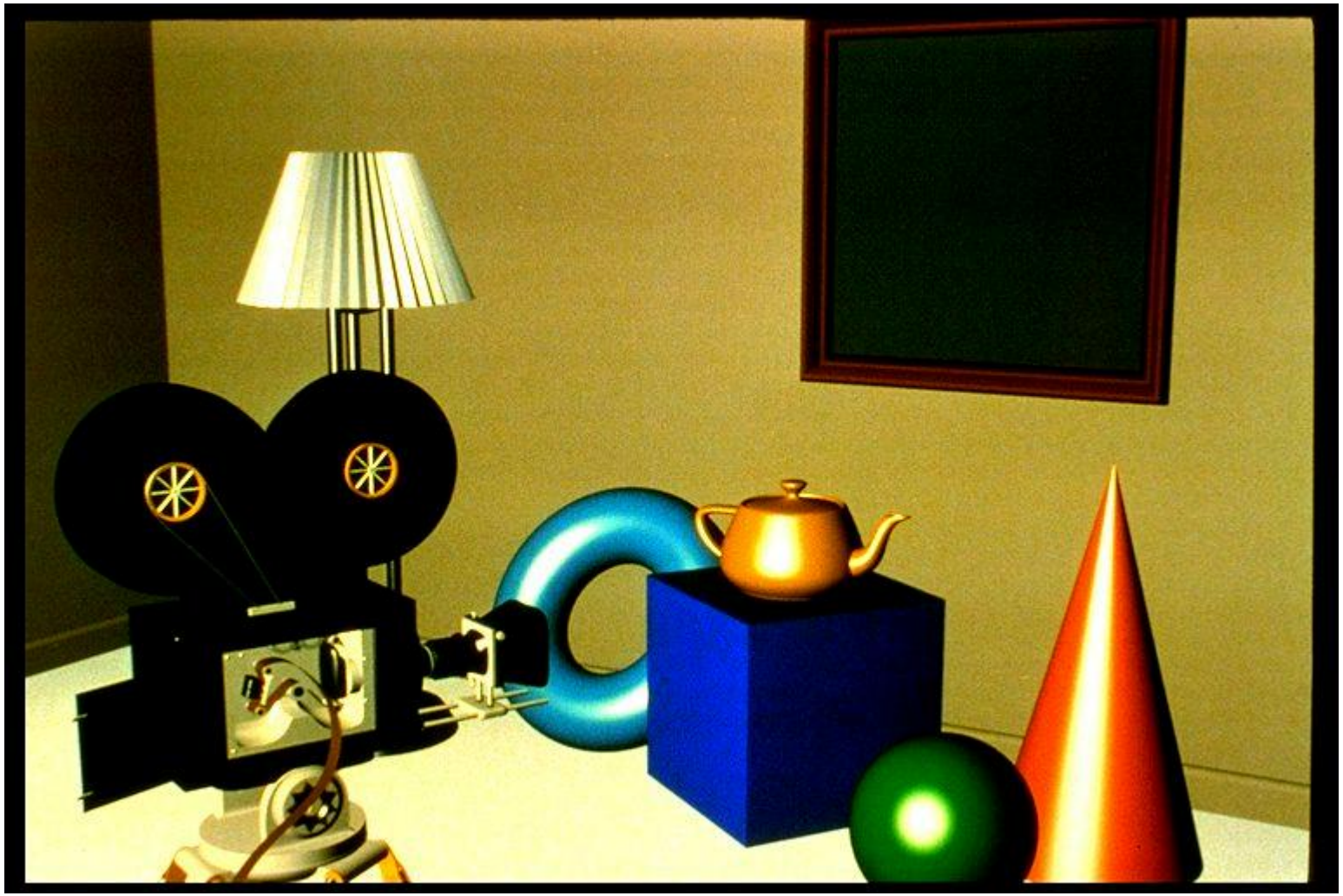
PER VERTEX SHADING



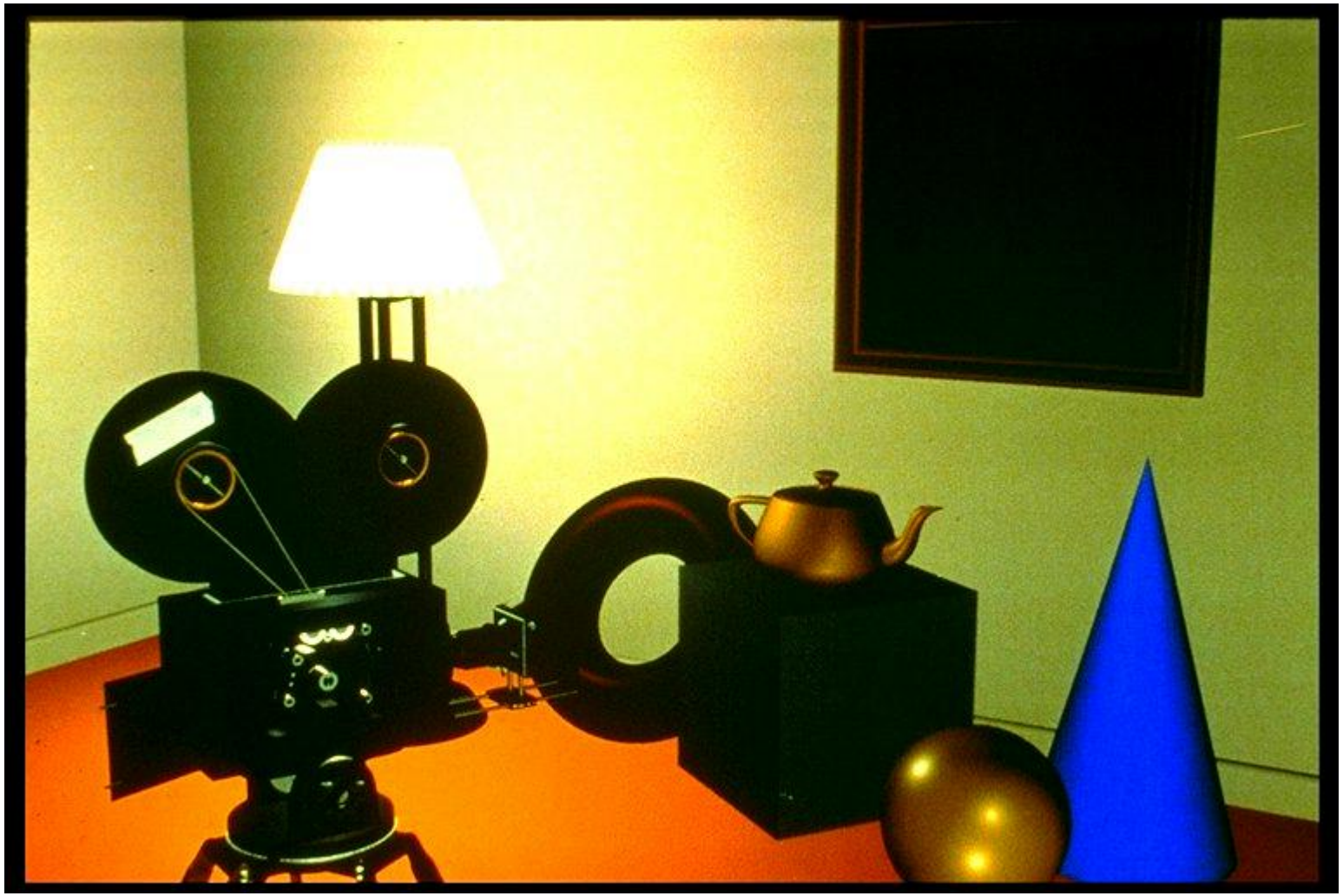
PER PIXEL SHADING



CURVED SURFACES WITH PER-PIXEL SHADING



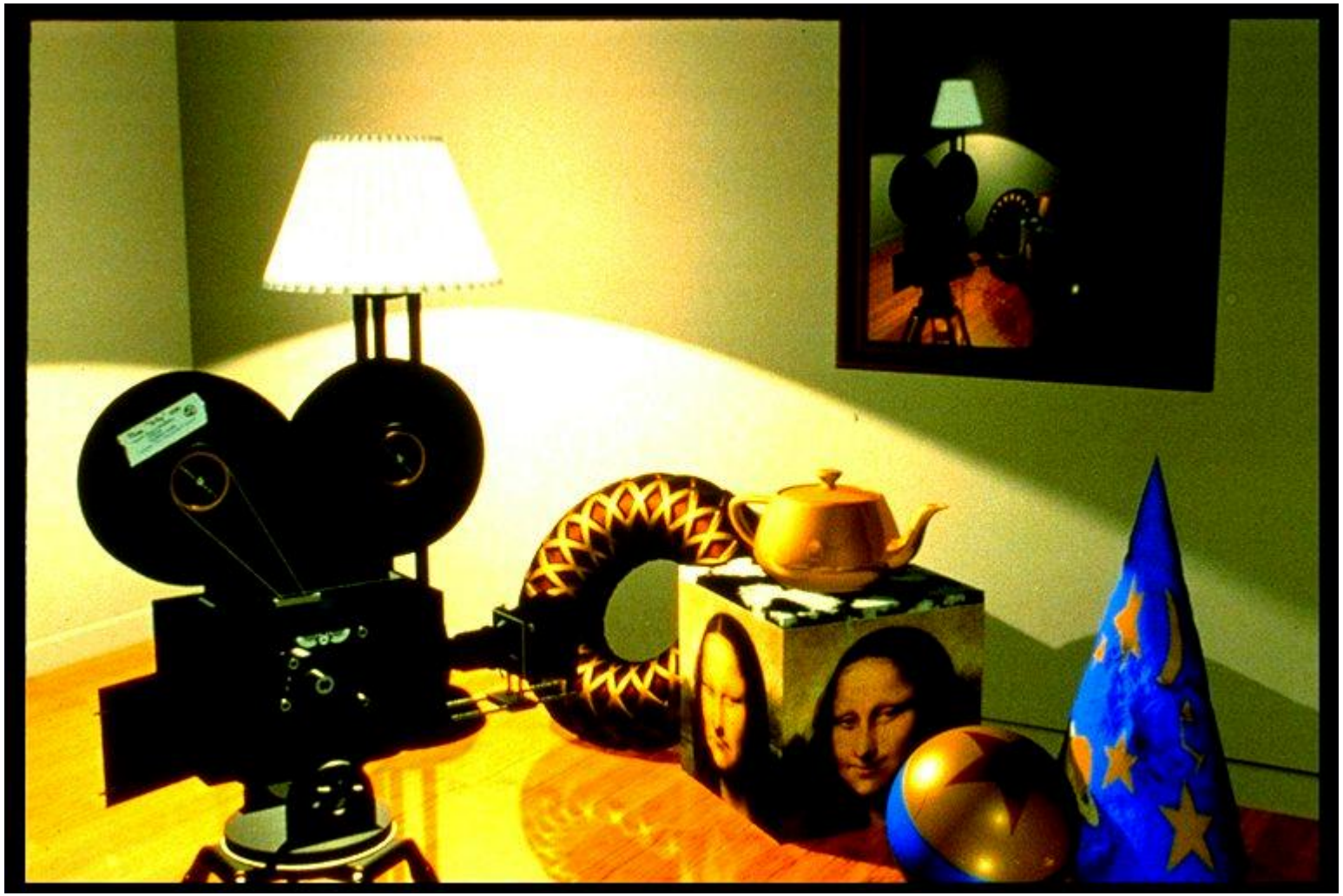
COMPLEX LIGHTING AND SHADING



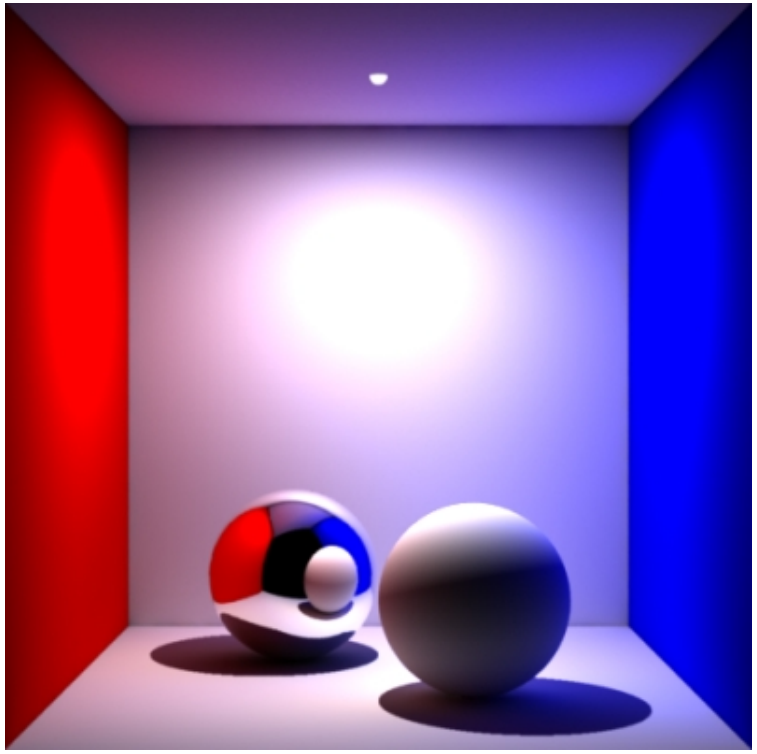
TEXTURE MAPPING

DISPLACEMENT MAPPING

REFLECTION MAPPING



GLOBAL ILLUMINATION

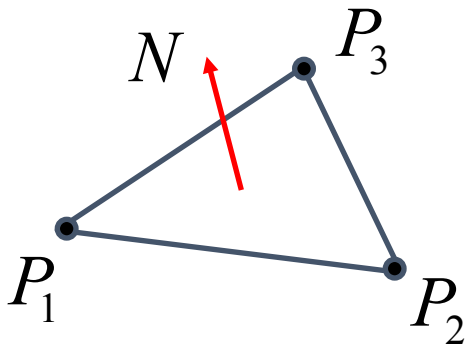


SUBSURFACE SCATTERING

TRANSFORMING NORMALS

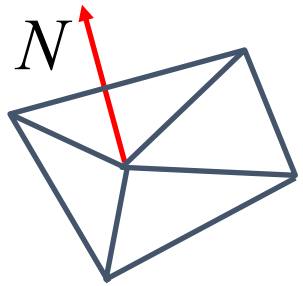
COMPUTING NORMALS

- polygon:



$$N = \frac{(P_2 - P_1) \times (P_3 - P_1)}{\left\| (P_2 - P_1) \times (P_3 - P_1) \right\|}$$

- assume vertices ordered CCW when viewed from visible side of polygon



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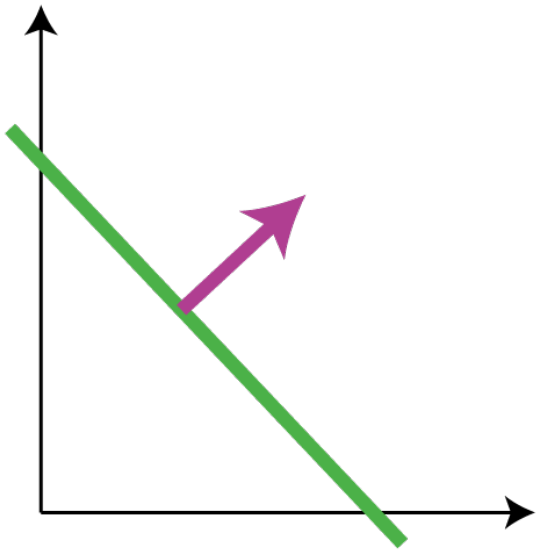
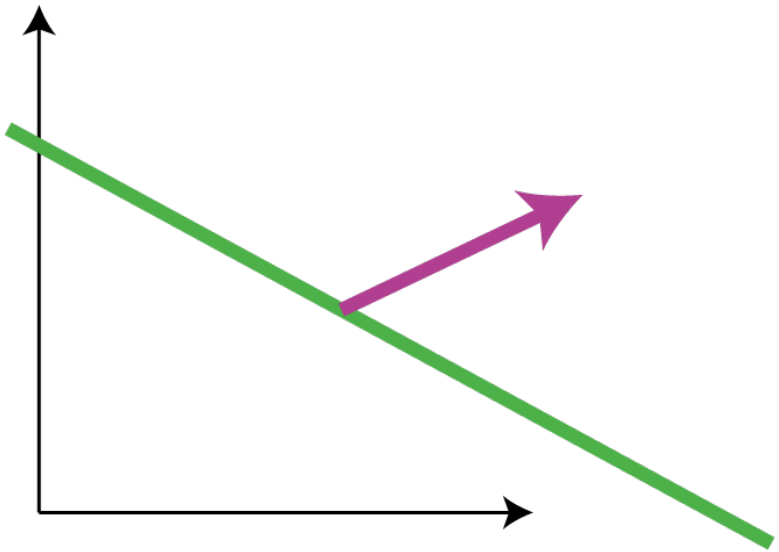
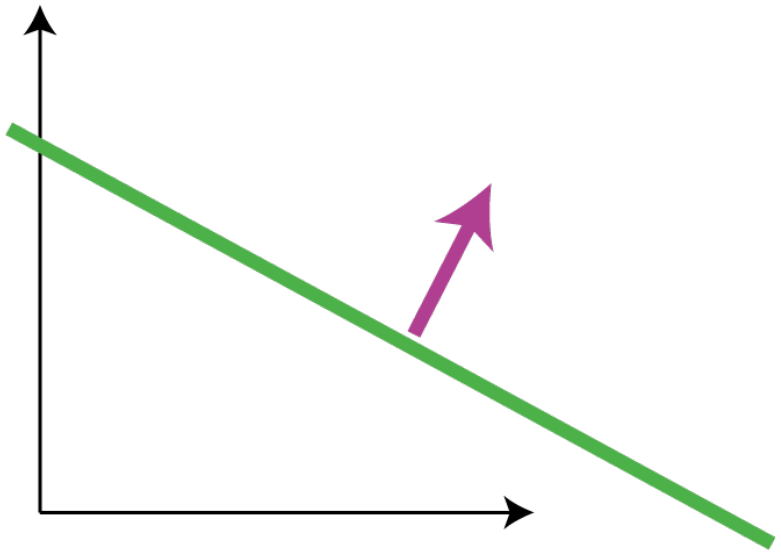


Line + Normal



Transform both by same matrix



Transformed line and correct normal

TRANSFORMING NORMALS

- When transforming triangle(s) can we use the same transformation to transform the normal & avoid re-computation?
- What is a normal?
  - **Vector**
    - Orthogonal (perpendicular) to plane/surface
  - Do standard transformations preserve orthogonality?
    - Or angles in general?

FIRST THINGS FIRST

- Dot product notation: $a \cdot b$
- Matrix notation: $a^T b$
  - Both $\boldsymbol{a}$ and $\boldsymbol{b}$ are columns

PLANES AND NORMALS

Let's take a plane $Ax + By + Cz + D = 0$

And two points on the plane: P_1, P_2

$$(A, B, C, *) \cdot (P_1 - P_2) = 0$$

$$\boldsymbol{n} \cdot (P_1 - P_2) = 0$$

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or, exactly the same:

$$n^T M^{-1} M (P_1 - P_2) = 0$$

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After transformation M:

$$(\boldsymbol{n}')^{\boldsymbol{T}} \ (MP_1 - MP_2) = 0$$

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Let's take a plane $Ax + By + Cz + D = 0$

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$$n^T M^{-1} M (P_1 - P_2) = 0$$

After transformation M:

$$(\boldsymbol{n}')^{\boldsymbol{T}} \ (MP_1 - MP_2) = 0$$

So,

$$n^T M^{-1} = (\boldsymbol{n}')^{\boldsymbol{T}}$$
$$n' = (M^{-1})^T n$$

TRANSFORMING NORMALS

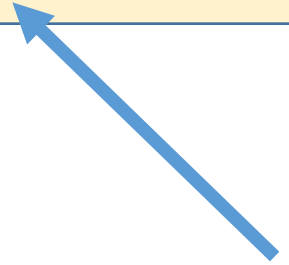
$$n' = (M^{-1})^T n$$

Normals are
transformed by
Transpose of Inverse

IN THREE.JS

- In vertex shader:

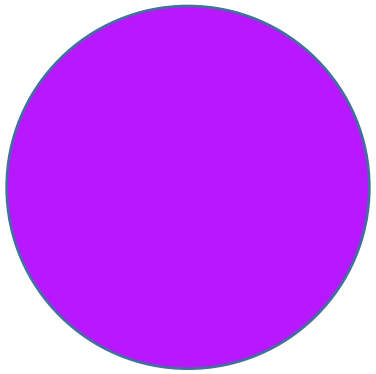
```
pointInVCS = modelViewMatrix * vec4(position, 1.0);
normalInVCS = normalMatrix * normal;
```



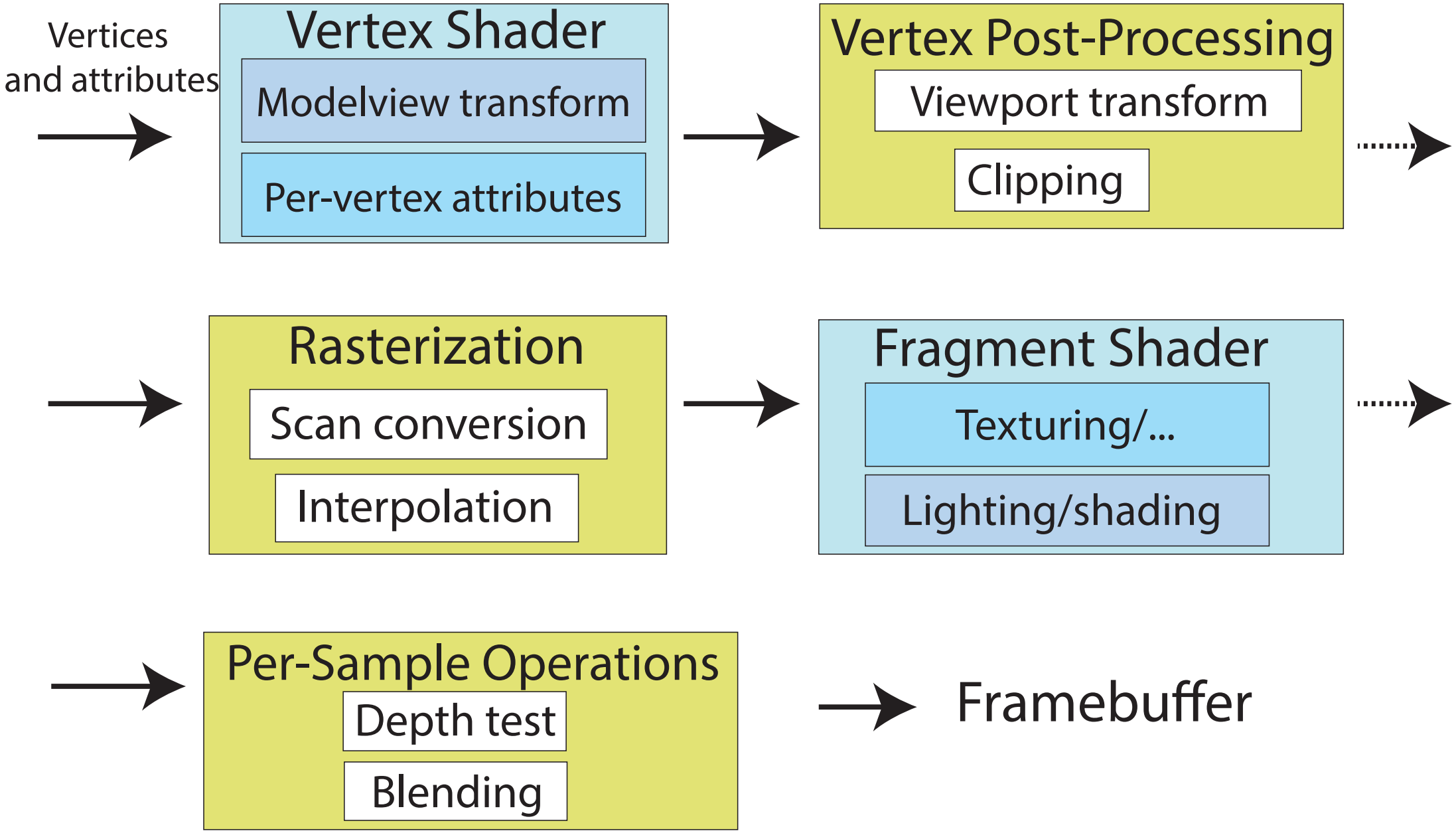
transpose of inverse
of modelViewMatrix

PROBLEMS ON ILLUMINATION

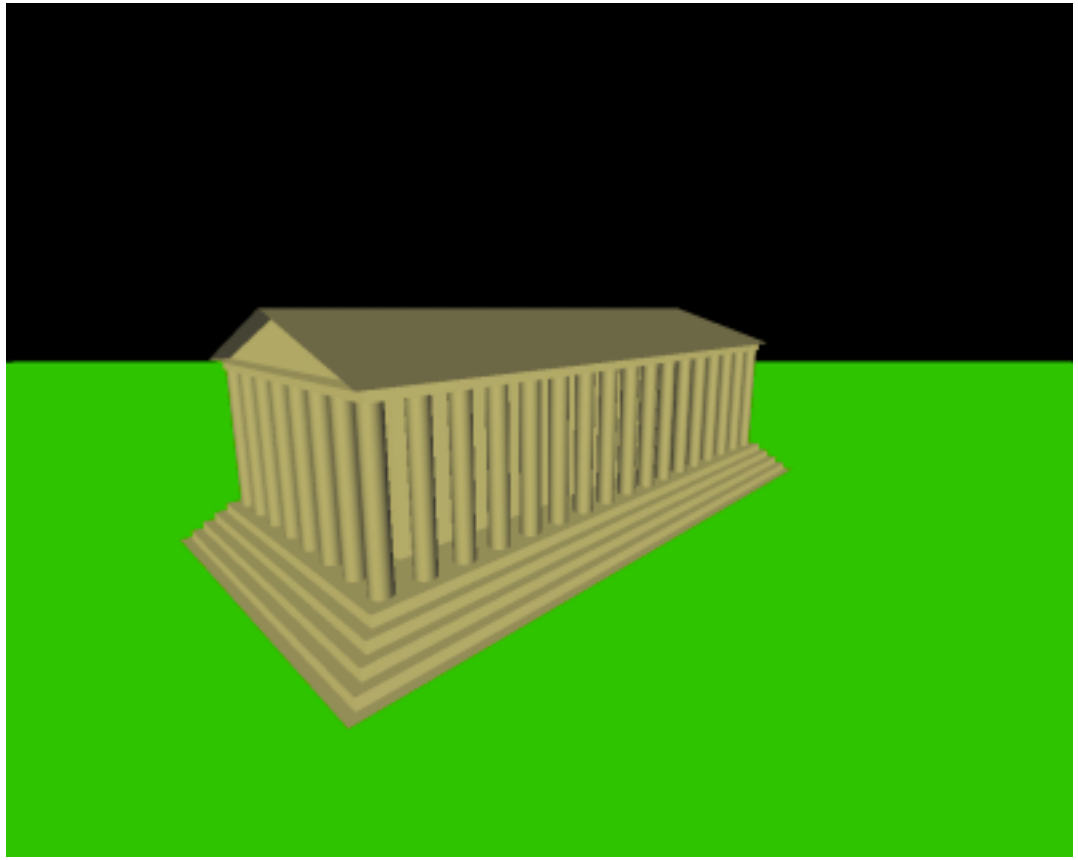
(whiteboard)



THE RENDERING PIPELINE



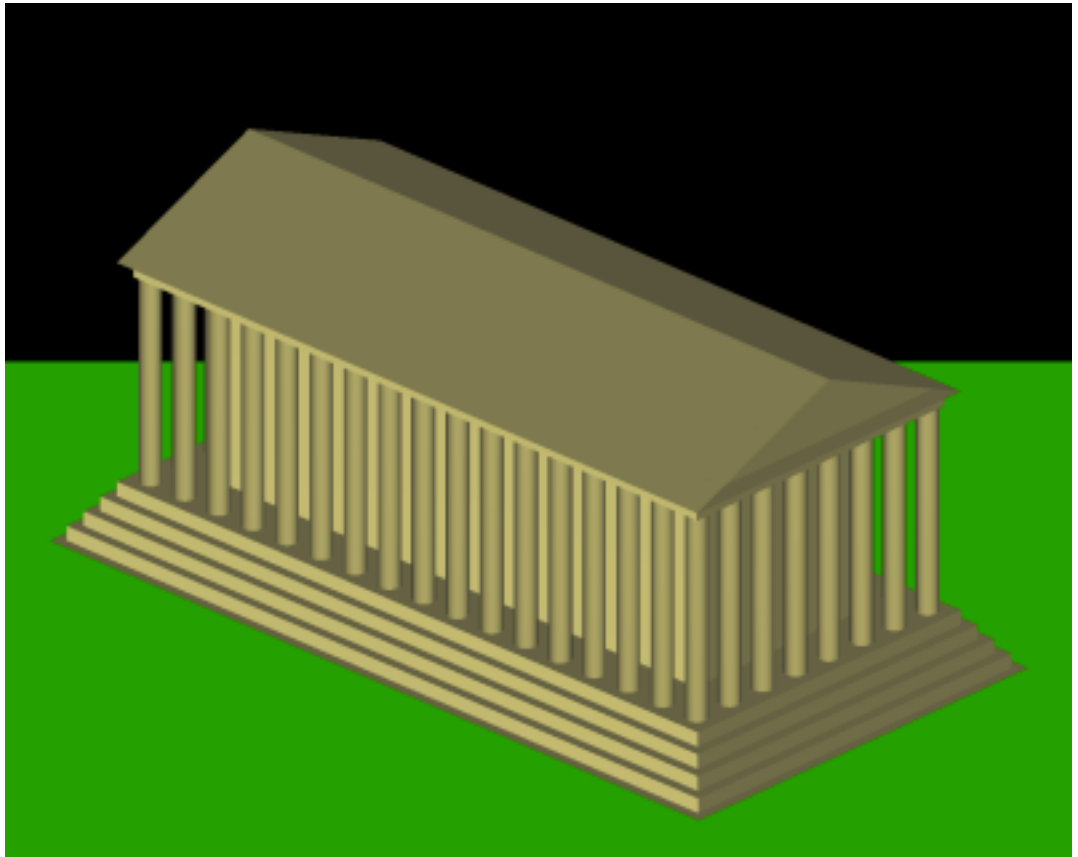
SHADOWS



SHADOWS

Need at least 2 shader passes:

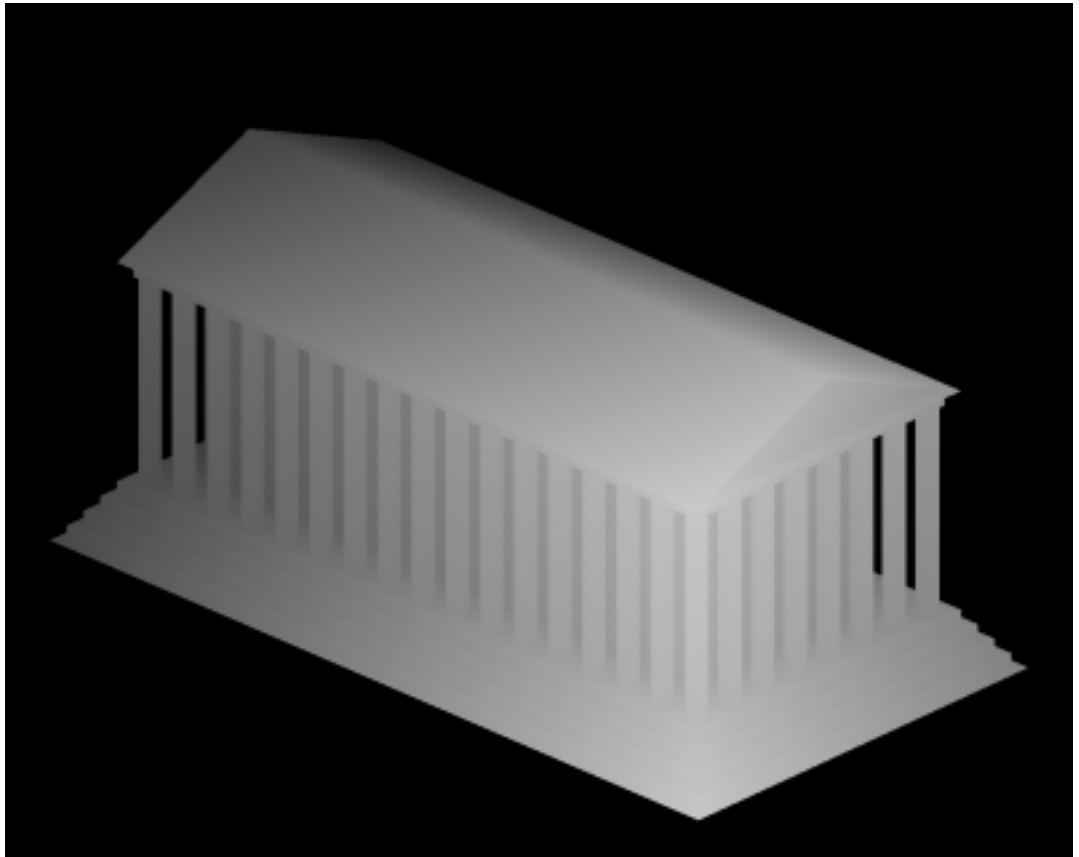
1. Draw everything as it's viewed from the LIGHT SOURCE



SHADOWS

Need at least 2 shader passes:

1. Draw everything as it's viewed from the LIGHT SOURCE
   Depth per pixel ('depth map')



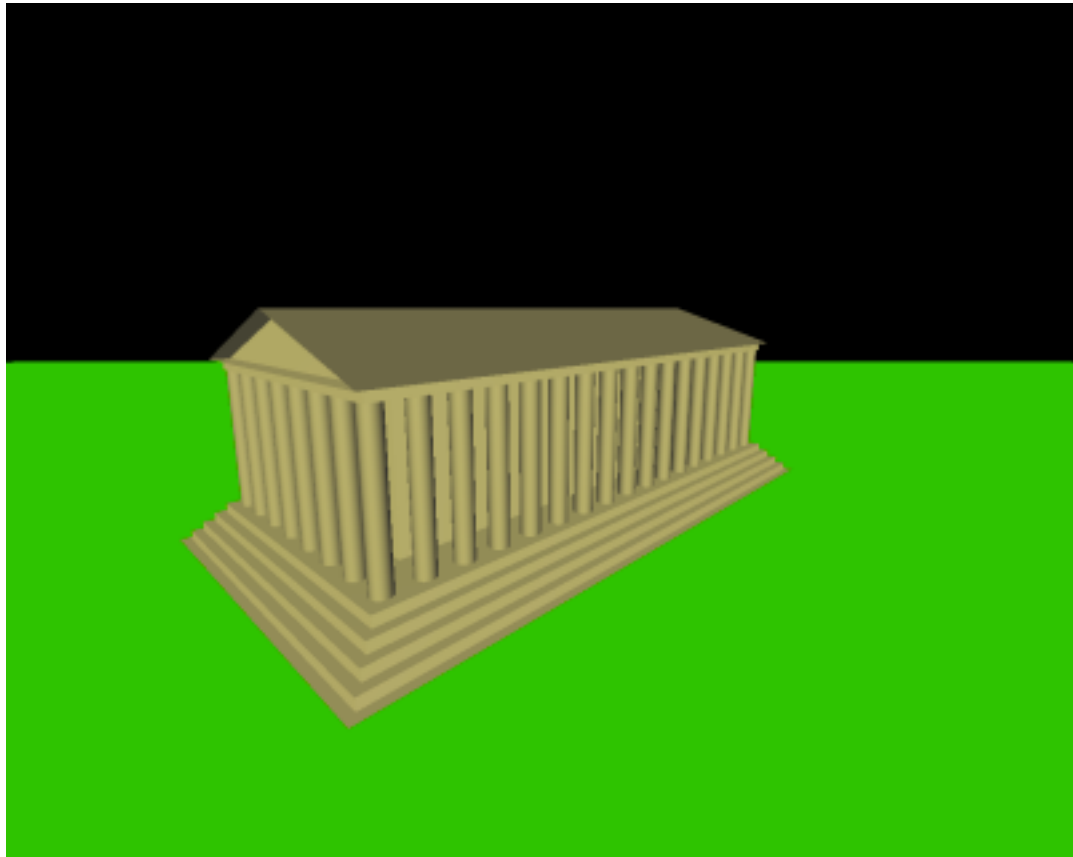
SHADOWS (IDEA)

Need at least 2 shader passes:

1. Draw everything as it's viewed from the LIGHT SOURCE
   Depth per pixel ('depth map').
2. Now draw everything from CAMERA
   When computing color per pixel:

   - Find corresponding depth map pixel:
     D - distance from light source

   - Is distance from me to the camera > D?
     - Yes: I am occluded! I'm in SHADOW.
     - No: I'm LIT!



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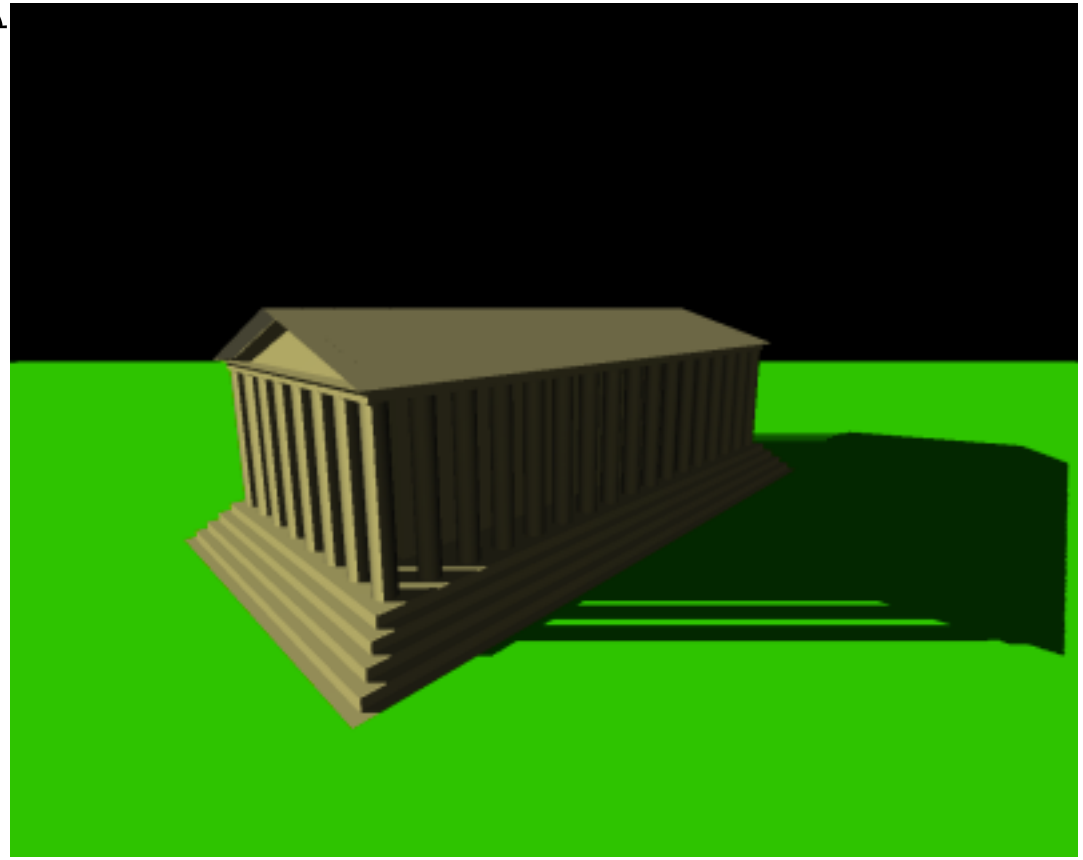

CODING A3 & THEORY A3

- Out tonight
- Coding A3 (*due Nov, 6th*):
  - Lighting & Shading
  - A bit of texturing
- Theory A3 (*due Oct, 30th, in class*):
  - Clipping
  - Rasterization
  - Lighting & Shading

SOME HINTS ON THEORY A3

SHAPES - CURVES/SURFACES

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

SHAPES: EXPLICIT FUNCTIONS

- Curves:
  - y is a function of x:
  - Only works in 2D

$$y := \sin(x)$$

- Surfaces:
  - z is a function of x and y:
  - Cannot define arbitrary shapes in 3D

$$z := \sin(x) + \cos(y)$$

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:

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

HOW TO INTERSECT ?

- Two lines in 2D?
- A line and a plane?
- A line and a sphere?
- (*Whiteboard*)