CPSC 314
17 – LIGHTING AND SHADING

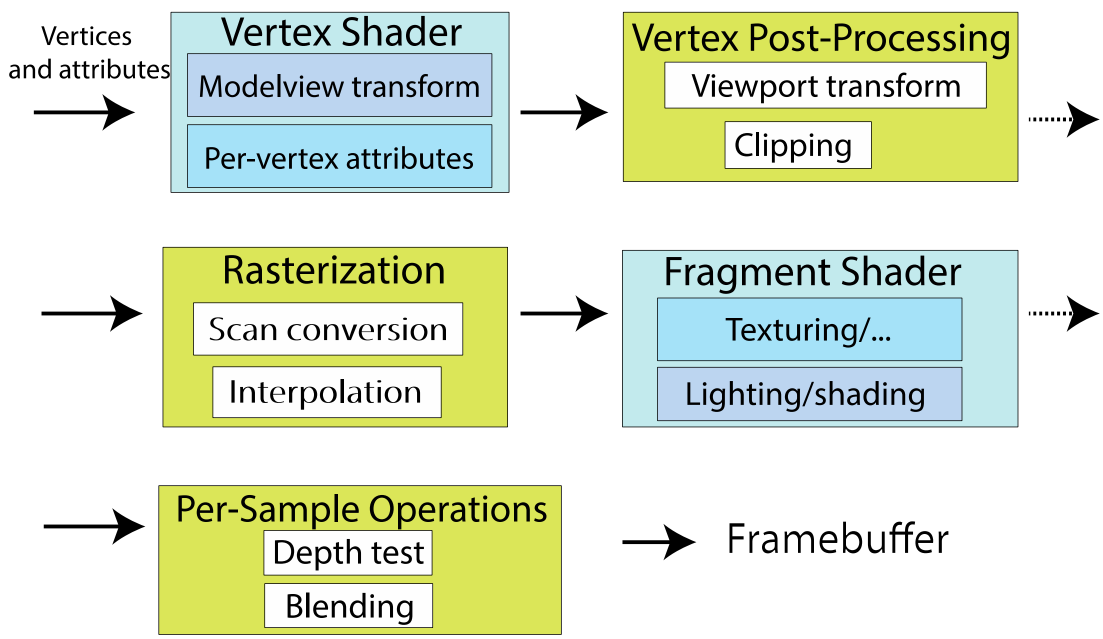
Textbook: 14

UGRAD.CS.UBC.CA/~CS314

Alla Sheffer

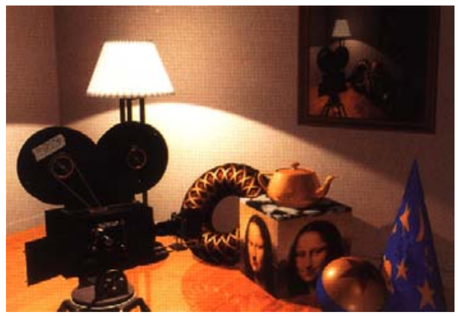
2016

THE RENDERING PIPELINE



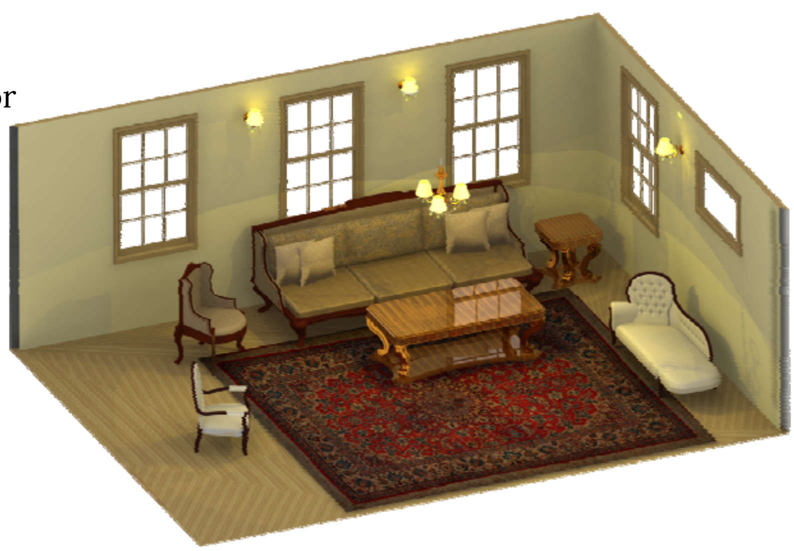
LIGHTING/SHADING

- 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
(More) Physically based
Interactions between objects

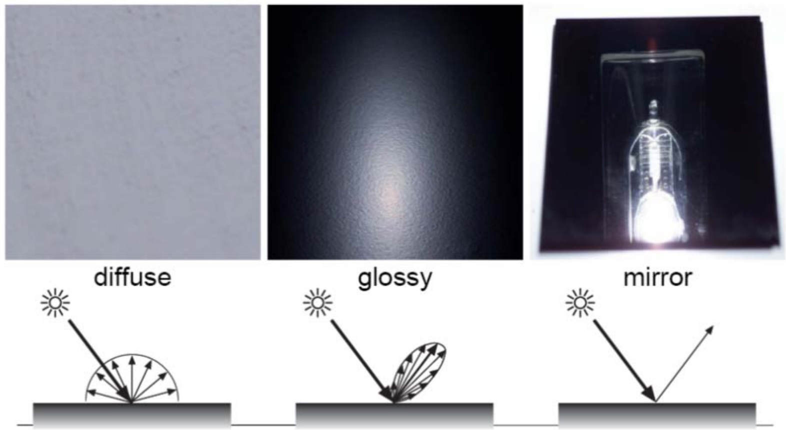
THE BIG PICTURE (BASIC)

- 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

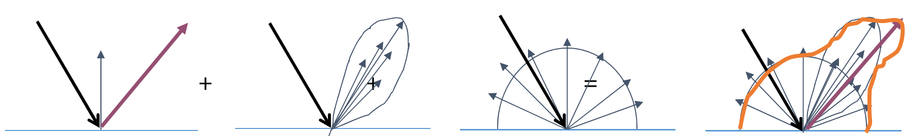
- Surface reflectance:
  - Illuminate surface point with a ray of light from different directions
  - How much light is reflected in each direction?

BASIC TYPES



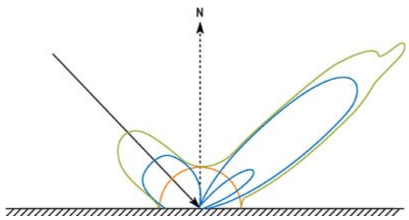
REFLECTANCE DISTRIBUTION MODEL

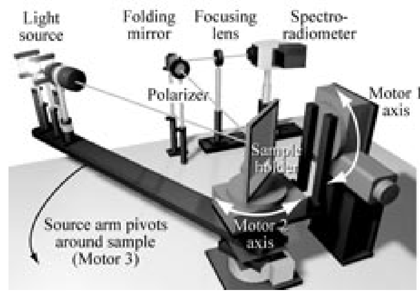
- Most surfaces exhibit complex reflectances
  - Vary with incident and reflected directions.
  - Model with combination – known as BRDF
    - BRDF: *Bidirectional Reflectance Distribution Function*



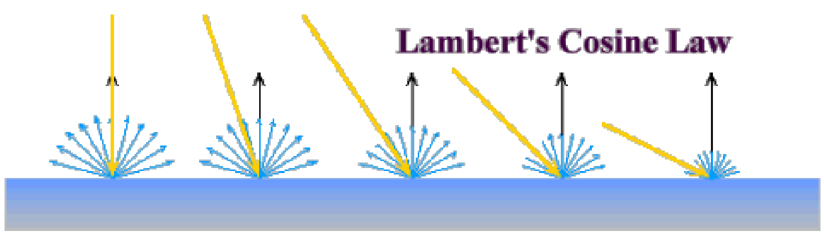
BRDF MEASUREMENTS/PLOTS

2D slice

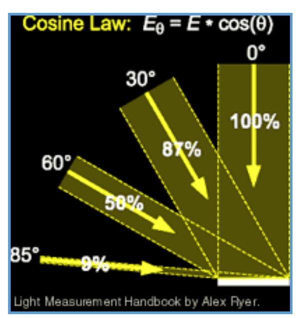




DIFFUSE (LAMBERT)

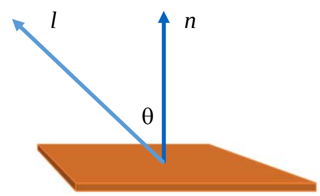


Intuitively: cross-sectional area of the "beam" intersecting an element of surface area is smaller for greater angles with the normal.



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

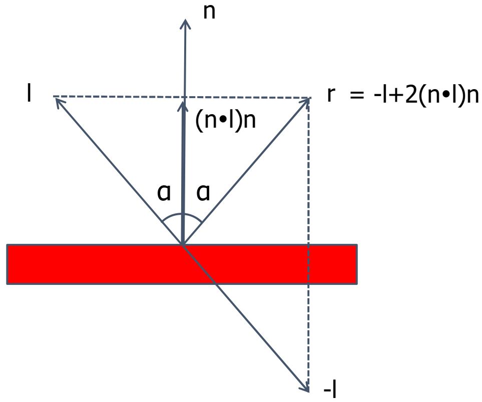
DIFFUSE LIGHTING EXAMPLES

- Lambertian sphere from several lighting angles:

- need only consider angles from 0° to 90°

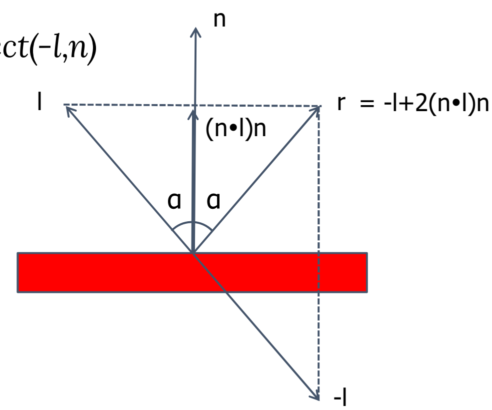
PHYSICS OF SPECULAR REFLECTION

- 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)*

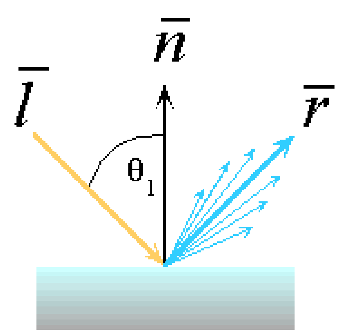


EMPIRICAL APPROXIMATION

- 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)

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

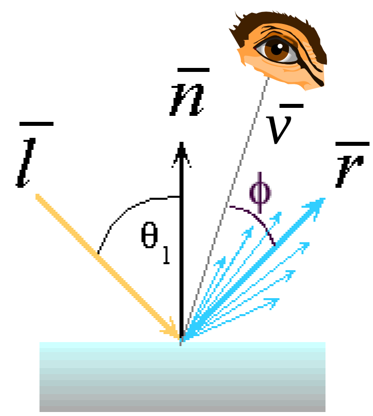
$$\mathbf{I}_{\mathbf{specular}} = \mathbf{k}_s \mathbf{I}_{\mathbf{light}} (\mathbf{v} \bullet \mathbf{r})^{n_s}$$

ϕ: angle between r and view direction v

n_s : purely empirical constant, varies rate of falloff

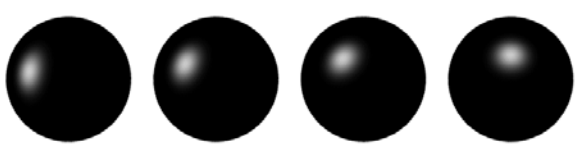
k_s: specular coefficient, highlight color

no physical basis, "plastic" look



PHONG EXAMPLES

varying light position



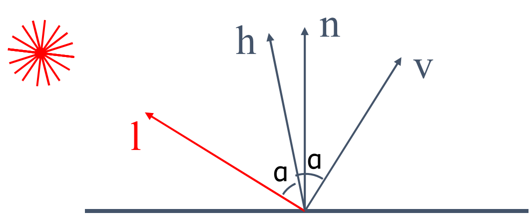
varying n_s

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

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

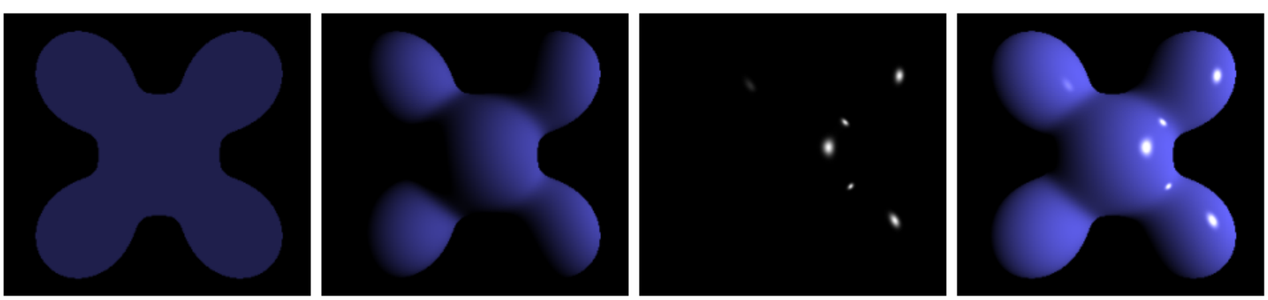
AMBIENT LIGHT

- 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:

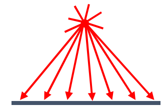
$$I_a k_a + \sum_p I_p\left(k_d\left(n \cdot l_p\right) + k_s\left(r_p \cdot v\right)^n\right)$$

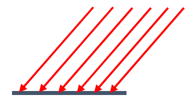


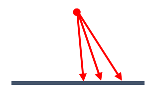
Ambient + Diffuse + Specular = Phong Reflection

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
  -

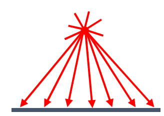


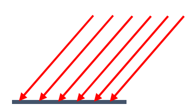


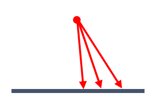


LIGHT SOURCE TYPES

- 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**



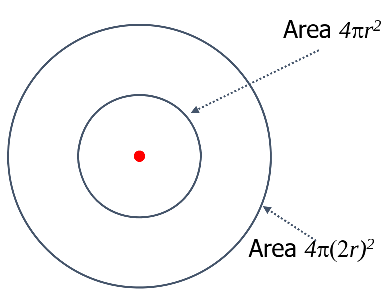




WHICH LIGHTS/MATERIALS ARE USED HERE?

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

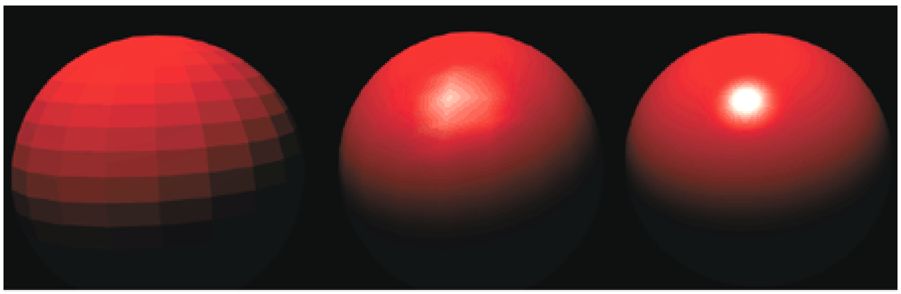
- Light source: amount of RGB light emitted
  - value = intensity per channel
  e.g., (1.0,0.5,0.5)
  - every light source emits ambient, diffuse, and specular light
- Materials: amount of RGB light reflected
  - value represents percentage reflected
    e.g., (0.0,1.0,0.5)
- Interaction: multiply components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

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

WHEN TO APPLY LIGHTING MODEL? OR WHERE DO NORMAL COME FROM?

per polygon	per vertex	per pixel
"flat shading"	"Gouraud shading"	"per pixel lighting" "Phong shading"

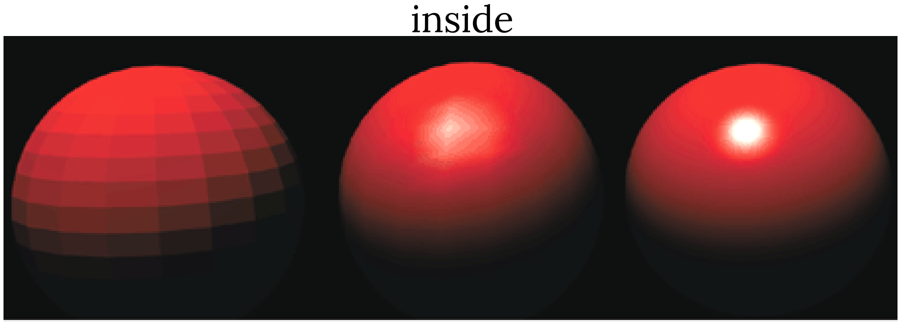


Flat Gouraud Phong

Image © Intergraph Computer Systems

WHEN TO APPLY LIGHTING MODEL? OR WHERE DO NORMAL COME FROM?

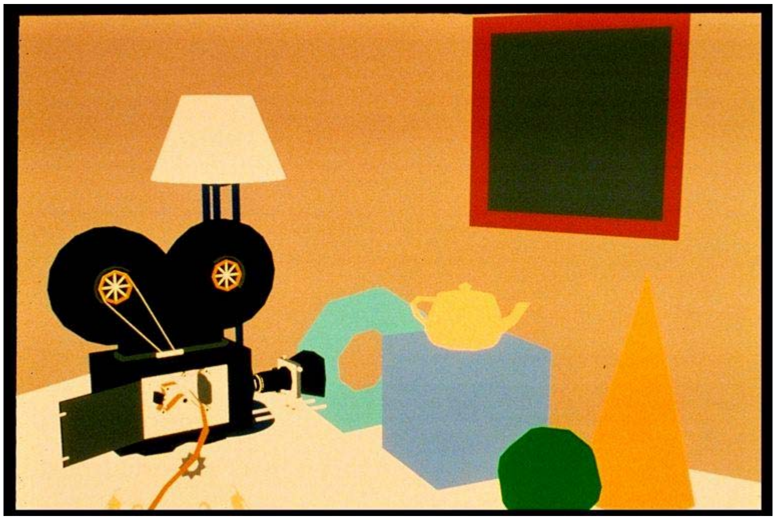
"flat" =	"Gouraud" = use	"per pixel/Phong" =
constant *face normal*	*vertex normal*, interpolate vertex color inside	*interpolate normal*, compute equation per pixel



Flat Gouraud Phong

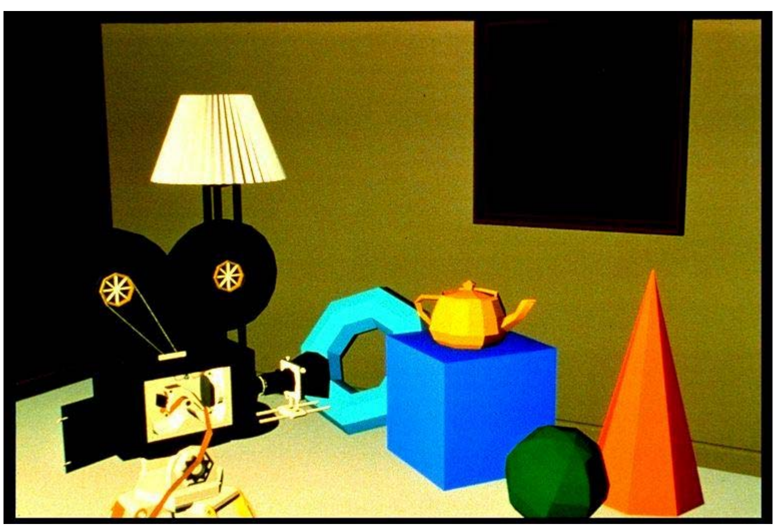
Image © Intergraph Computer Systems

AMBIENT LIGHTING



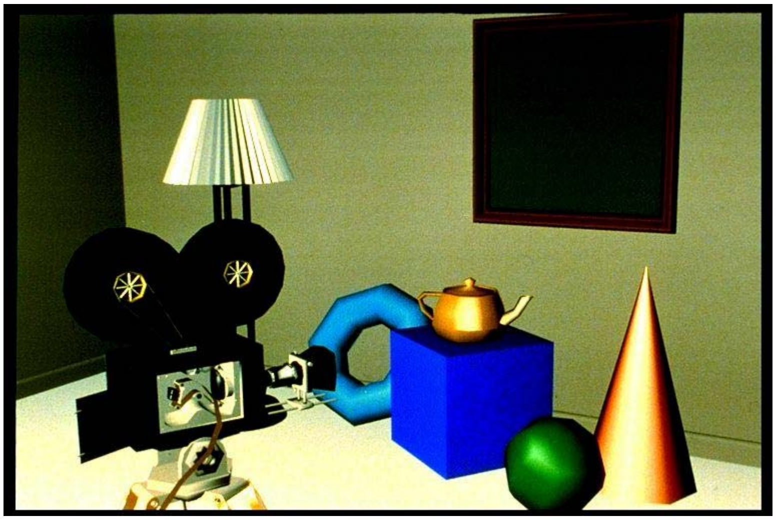
37

PER-POLYGON SHADING

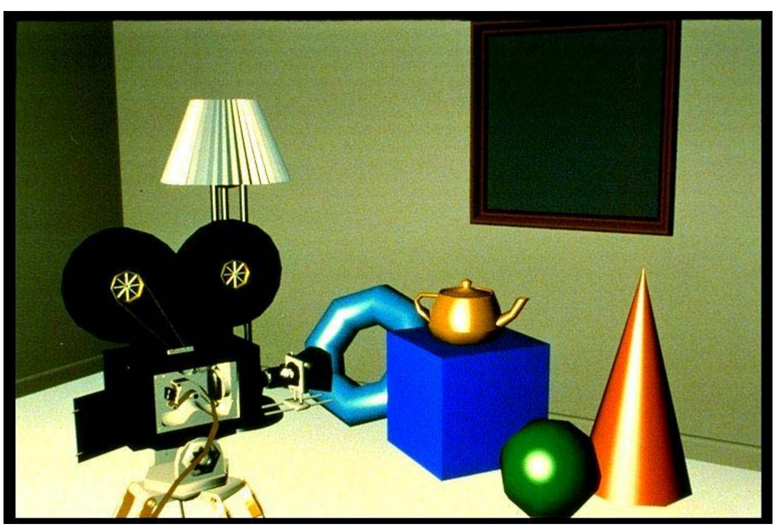


38

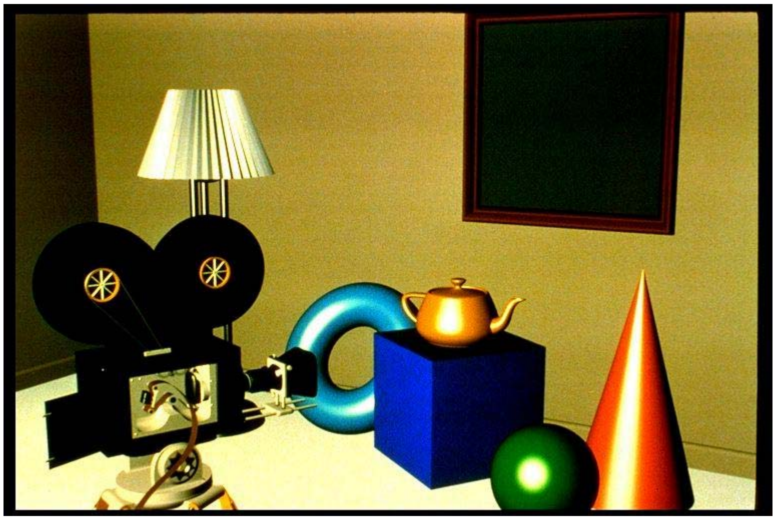
PER VERTEX SHADING



PER PIXEL SHADING



CURVED SURFACES WITH PER-PIXEL SHADING



41

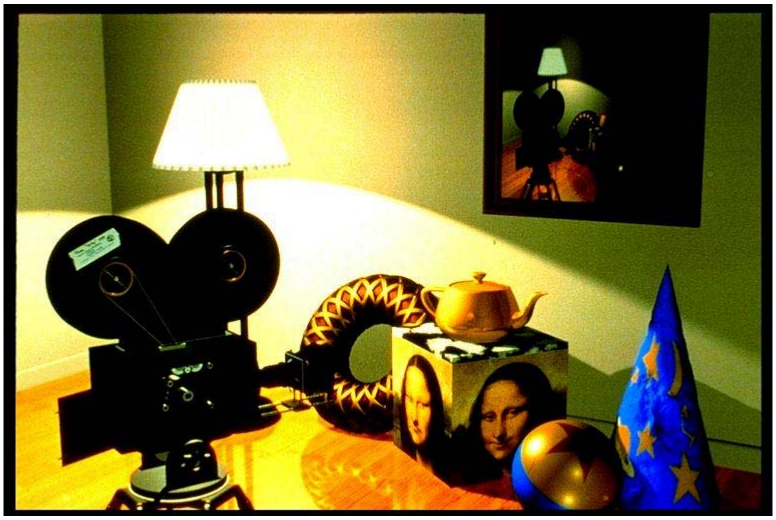
COMPLEX LIGHTING AND SHADING

42

TEXTURE MAPPING

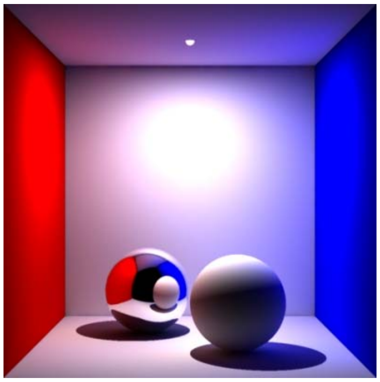
DISPLACEMENT MAPPING

REFLECTION MAPPING



45

GLOBAL ILLUMINATION

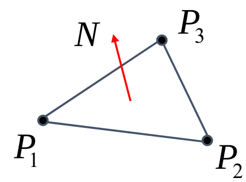


SUBSURFACE SCATTERING

TRANSFORMING NORMALS

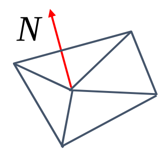
COMPUTING NORMALS

- polygon:

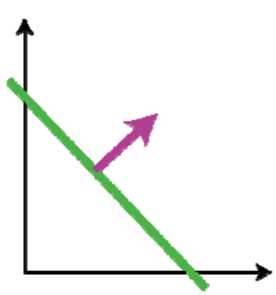


$$N = \frac{(P_2 - P_1) \times (P_3 - P_1)}{\left\| (P_2 - P_1) \times (P_3 - P_1) \right\|}$$

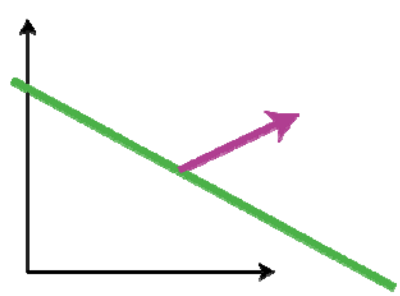
- assume vertices ordered CCW when viewed from visible side of polygon



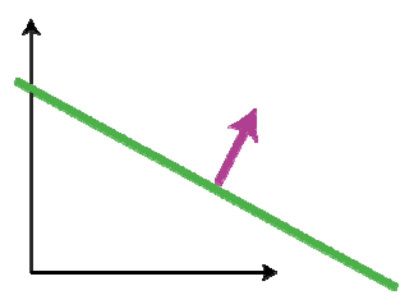
TRANSFORMING NORMALS



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

$$(A, B, C, *) \cdot (P_1 - P_2) = 0$$
$$\boldsymbol{n} \cdot (P_1 - P_2) = 0$$

PLANES AND NORMALS

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

And two points on the plane: P_1, P_2

$$(A, B, C, *) \cdot (P_1 - P_2) = 0$$
$$\boldsymbol{n} \cdot (P_1 - P_2) = 0$$

or, exactly the same:

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

PLANES AND NORMALS

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

And two points on the plane: P_1, P_2

$$(A, B, C, *) \cdot (P_1 - P_2) = 0$$
$$\boldsymbol{n} \cdot (P_1 - P_2) = 0$$

or, exactly the same:

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

After transformation M:

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

PLANES AND NORMALS

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

And two points on the plane: P_1, P_2

$$(A, B, C, *) \cdot (P_1 - P_2) = 0$$
$$\boldsymbol{n} \cdot (P_1 - P_2) = 0$$

or, exactly the same:

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

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

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)*