Computer Graphics (CS 543)
Lecture 6 (Part 3): Lighting, Shading and Materials (Part 3)

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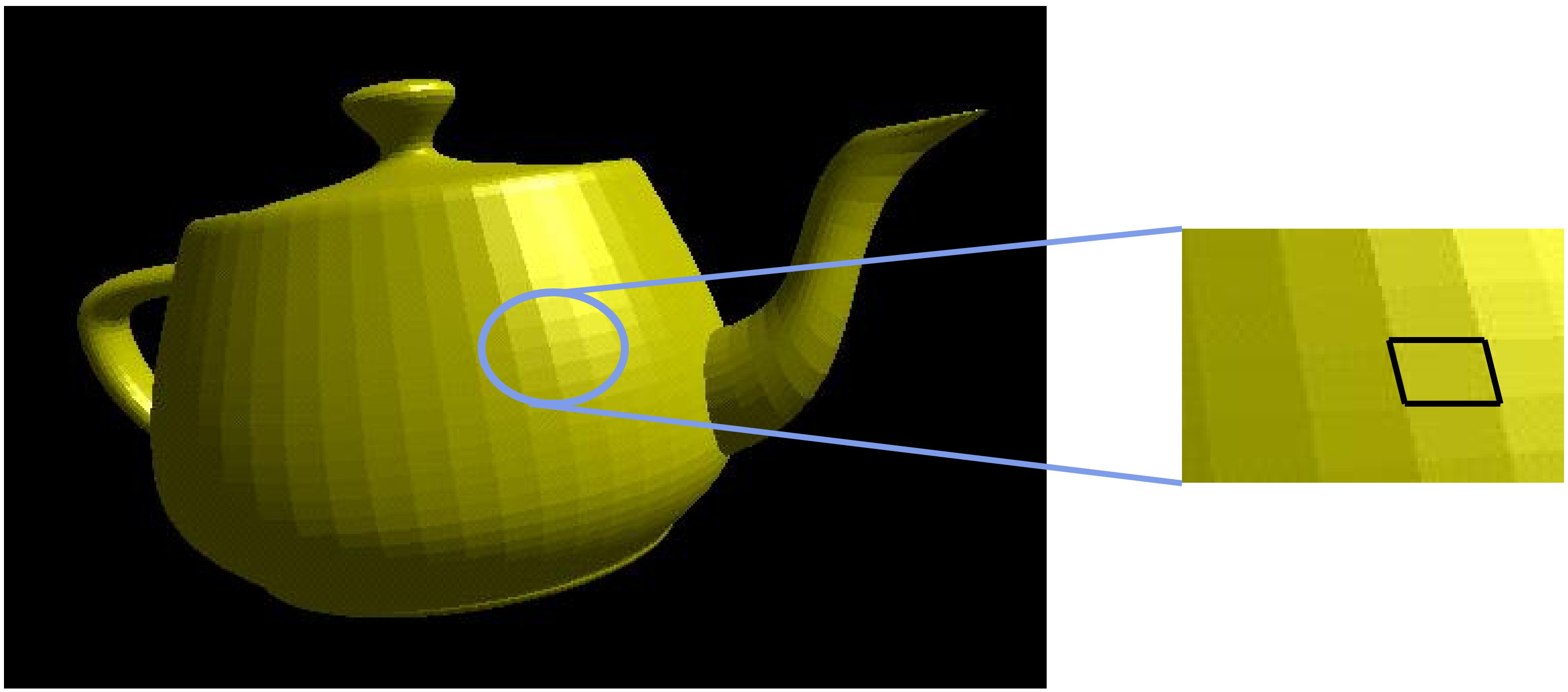
Recall: Flat Shading

- compute lighting once for each face, assign color to whole face

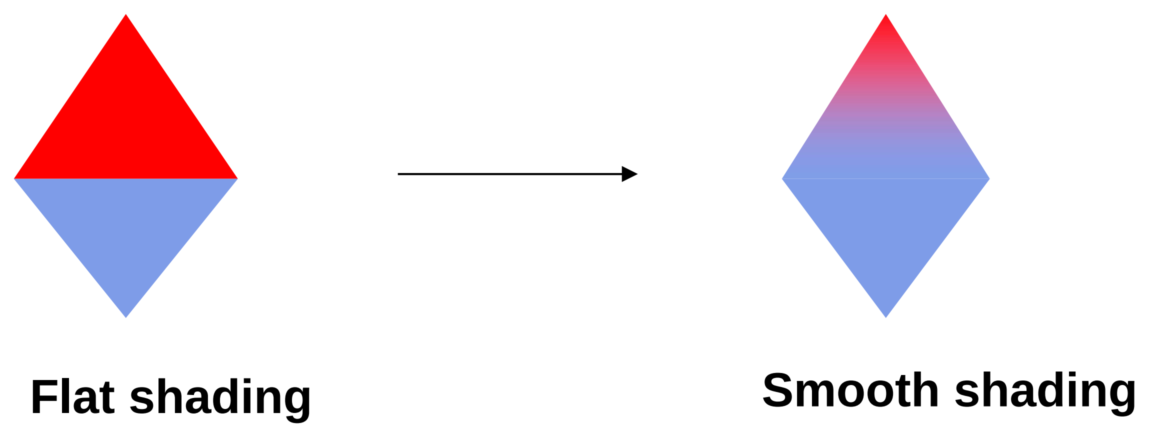


Recall: Flat Shading Implementation

```
flat out vec4 color;      //vertex shader
 ……
  color = ambient + diffuse + specular;
   color.a = 1.0;

flat in vec4 color;    //fragment shader

void main() {
   gl_FragColor = color;
}
```

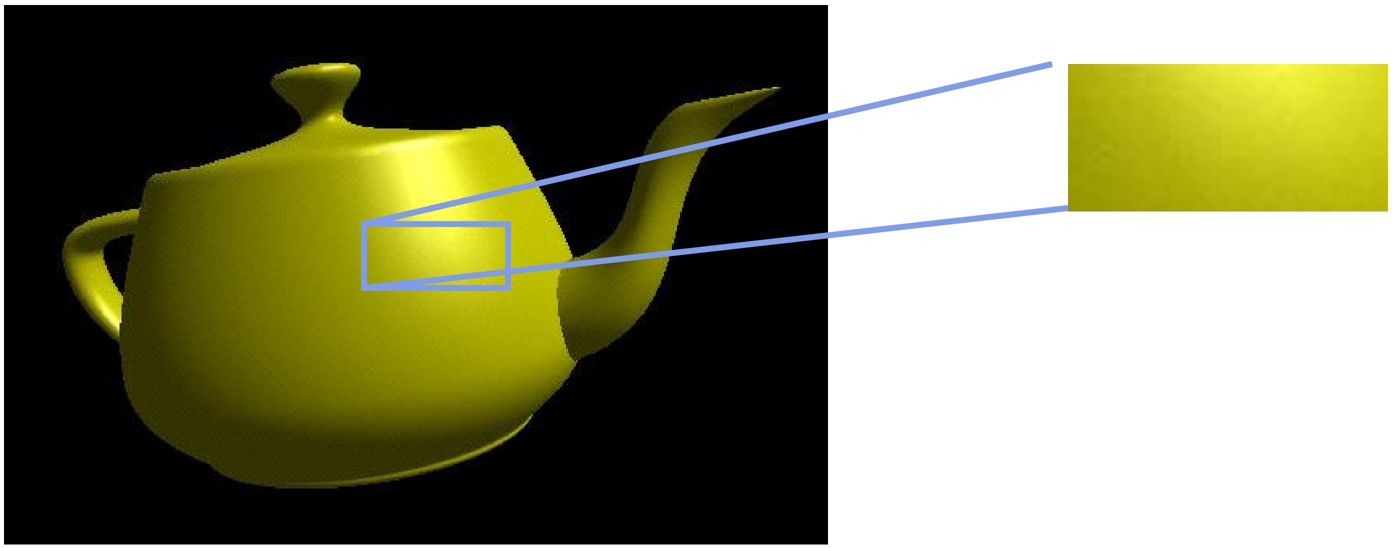
Recall: Smooth shading

- 2 popular methods:
  - Gouraud shading
  - Phong shading



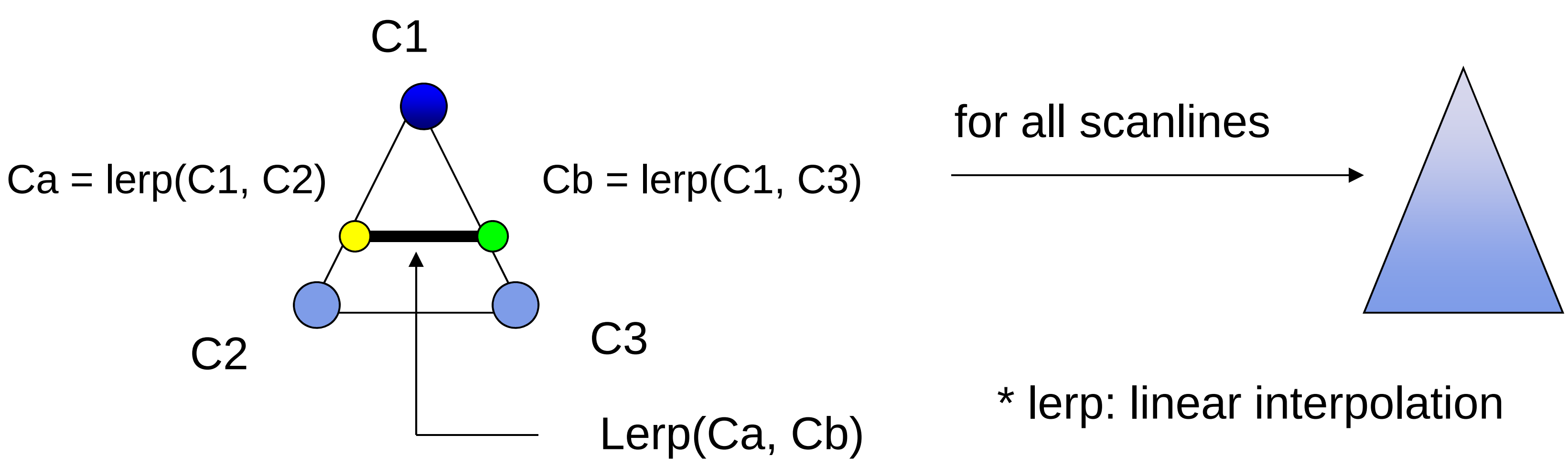
Recall: Gouraud Shading

- **Vertex shader:** lighting calculated for each vertex
- Default shading. Just suppress keyword **flat**
- Colors interpolated for interior pixels
- **Interpolation?** Assume linear change from one vertex color to another



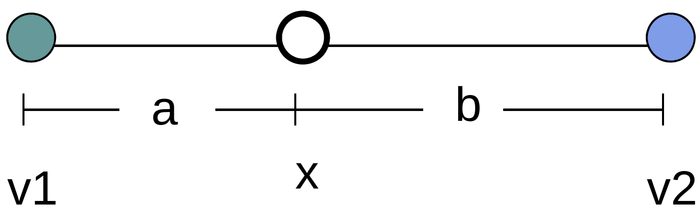
Gouraud Shading

- Compute vertex color in vertex shader
- Shade interior pixels: vertex color **interpolation**



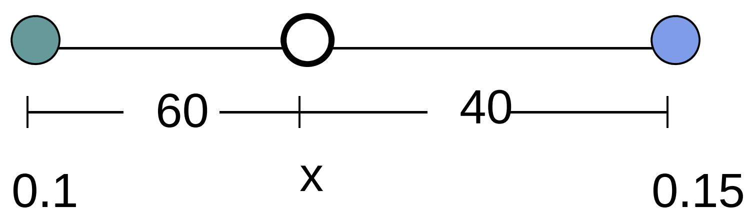
* lerp: linear interpolation

Linear interpolation Example



$$x = \frac{b}{(a+b)} * v1 + \frac{a}{(a+b)} * v2$$

- If a = 60, b = 40
- RGB color at v1 = (0.1, 0.4, 0.2)
- RGB color at v2 = (0.15, 0.3, 0.5)
- Red value of v1 = 0.1, red value of v2 = 0.15

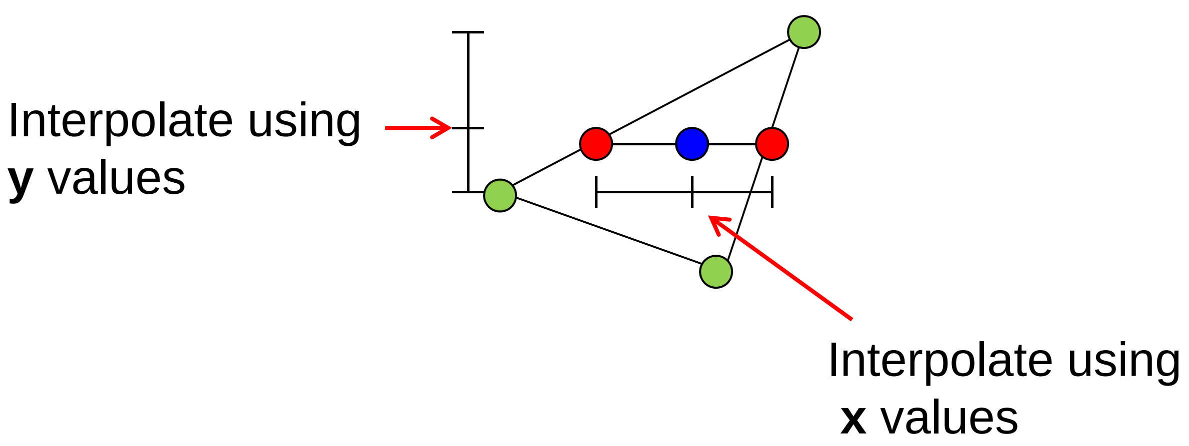


Red value of x = 40 /100 * 0.1 + 60/100 * 0.15
= 0.04 + 0.09 = 0.13

Similar calculations for Green and Blue values

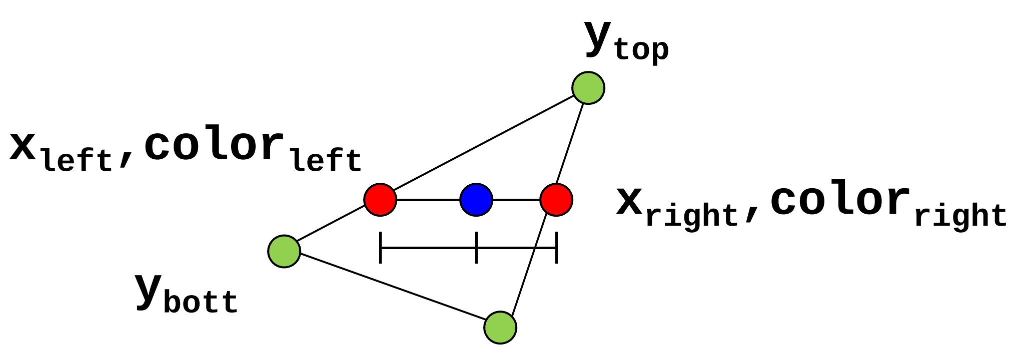
Gouraud Shading

- Interpolate triangle color
  1. Interpolate **y distance** of end points (green dots) to get color of two end points in scanline (red dots)
  2. Interpolate **x distance** of two ends of scanline (red dots) to get color of pixel (blue dot)



Gouraud Shading Function (Pg. 433 of Hill)

```
for(int y = y_bott; y < y_top; y++) // for each scan line
{
   find x_left  and x_right
   find color_left  and color_right
   color_inc = (color_right - color_left)/ (x_right - x_left)
   for(int x = x_left, c = color_left; x < x_right; x++, c+ = color_inc)
   {
        put c into the pixel at (x, y)
   }
}
```

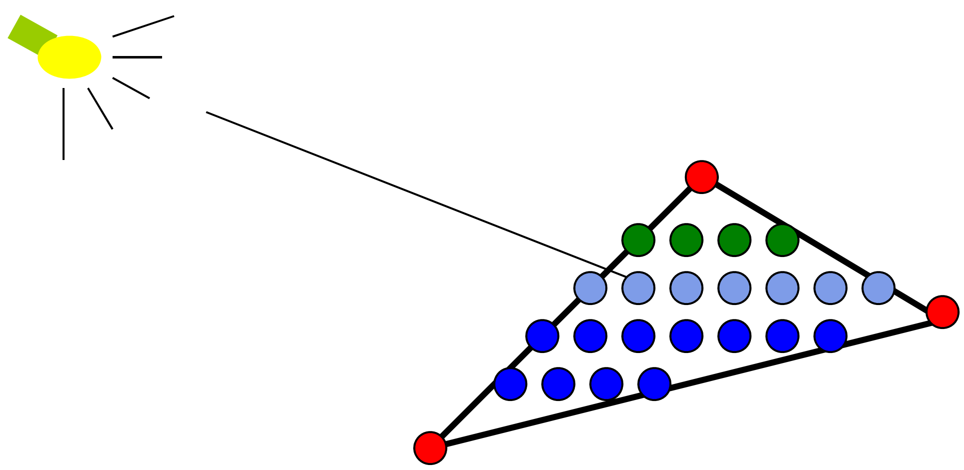


Gouraud Shading Implemenation

- Vertex lighting interpolated across entire face pixels if passed to fragment shader in following way
  1. **Vertex shader:** Calculate output color in vertex shader, Declare output vertex color as **out**

$$I = k_d I_d \; \mathbf{l} \cdot \mathbf{n} + k_s I_s (\mathbf{n} \cdot \mathbf{h})^{\beta} + k_a I_a$$

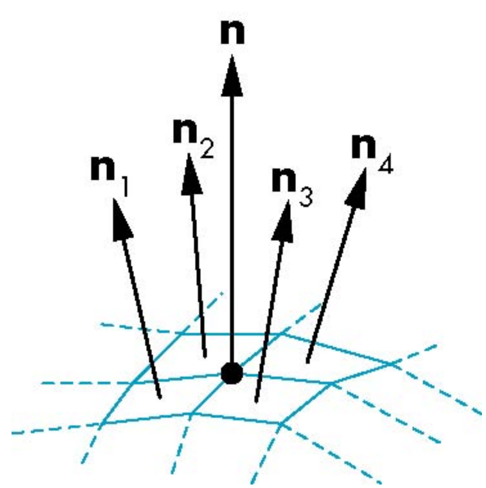
  2. **Fragment shader:** Declare color as **in,** use it, already interpolated!!



Calculating Normals for Meshes

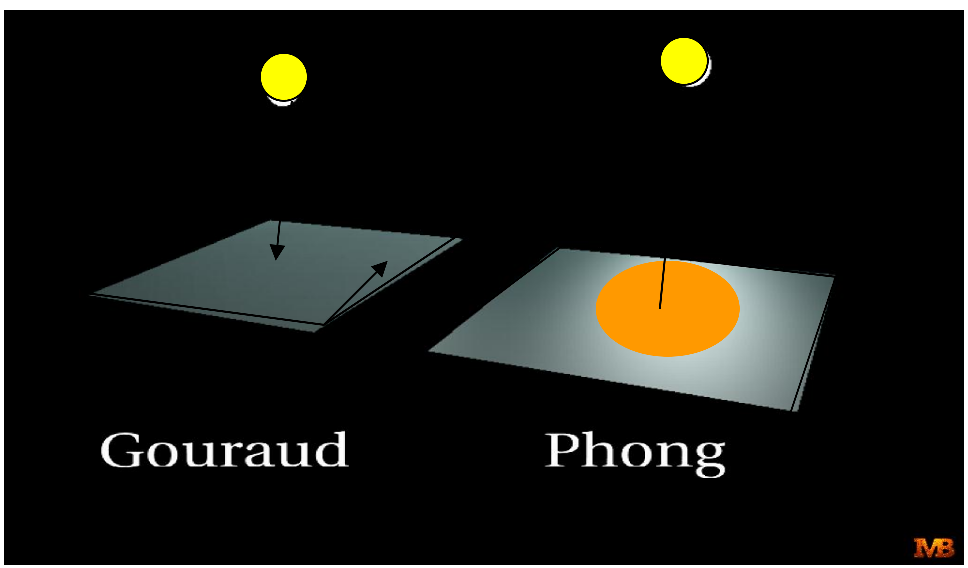
- For meshes, already know how to calculate face normals (e.g. Using Newell method)
- For polygonal models, Gouraud proposed using average of normals around a mesh vertex

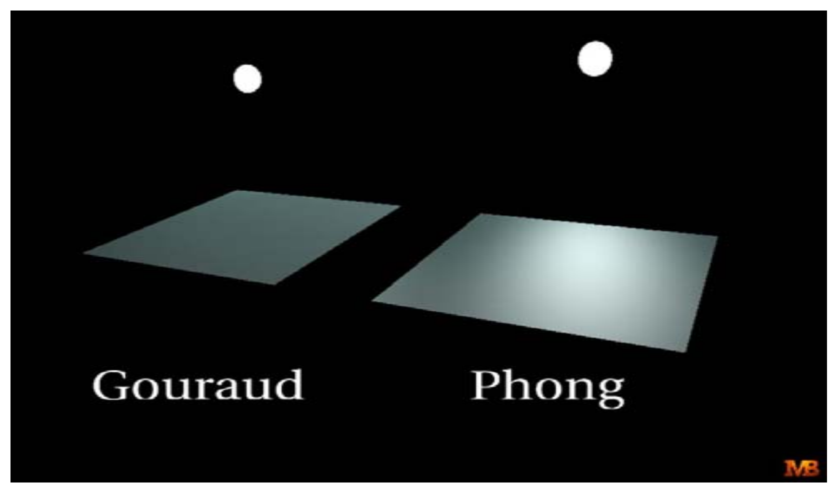
$$\mathbf{n} = (\mathbf{n}_1+\mathbf{n}_2+\mathbf{n}_3+\mathbf{n}_4)/\ |\mathbf{n}_1+\mathbf{n}_2+\mathbf{n}_3+\mathbf{n}_4|$$



Gouraud Shading Problem

- If polygon mesh surfaces have high curvatures, Gouraud shading may show edges
- Lighting in the polygon interior can be inaccurate
- Phong shading may look smooth



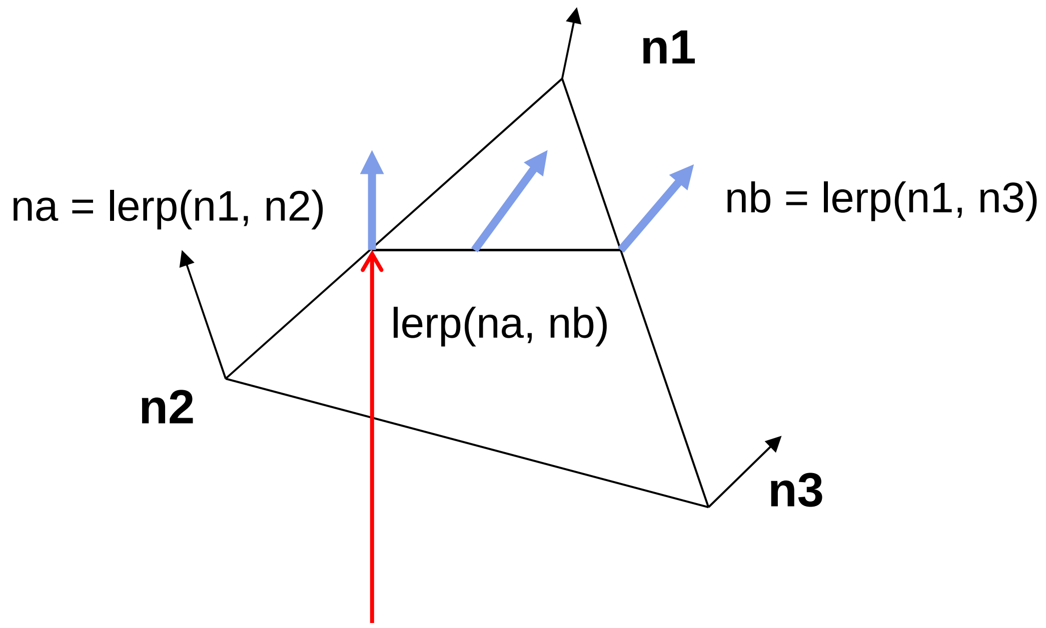


Phong Shading

- Need normals for all pixels – not provided by user
- Instead of interpolating vertex color
  - Interpolate **vertex normal and vectors** to calculate normal (and vectors) at each ***each pixel*** inside polygon
  - Use pixel normal to calculate Phong at pixel (**per pixel lighting**)
- Phong shading algorithm interpolates normals and compute lighting in fragment shader

Phong Shading (Per Fragment)

- Normal interpolation



At each pixel, need to interpolate
Normals (n) and vectors v and l

Gouraud Vs Phong Shading Comparison

- Phong shading more work than Gouraud shading
  - Move lighting calculation to fragment shaders
  - Just set up vectors (l,n,v,h) in vertex shader

a. Gouraud Shading

- Set Vectors (l,n,v,h)
- Calculate vertex colors

→ **Hardware Interpolates Vertex color** →

- Read/set fragment color
- (Already interpolated)

b. Phong Shading

- Set Vectors (l,n,v,h)

→ **Hardware Interpolates Vectors (l,n,v,h)** →

- Read in vectors (l,n,v,h)
- (interpolated)
- Calculate fragment lighting

Per-Fragment Lighting Shaders I

```
// vertex shader
in vec4 vPosition;
in vec3 vNormal;

// output values that will be interpolatated per-fragment
out vec3 fN;
out vec3 fE;
out vec3 fL;

uniform mat4 ModelView;
uniform vec4 LightPosition;
uniform mat4 Projection;
```

Declare variables **n, v, l** as **out** in vertex shader

Per-Fragment Lighting Shaders II

```
void main()
{
   fN = vNormal;
   fE = -vPosition.xyz;
   fL = LightPosition.xyz;

   if( LightPosition.w != 0.0 ) {
         fL = LightPosition.xyz - vPosition.xyz;
   }

   gl_Position = Projection*ModelView*vPosition;
}
```

Set variables **n, v, l** in vertex shader

Per-Fragment Lighting Shaders III

```
// fragment shader

// per-fragment interpolated values from the vertex shader
in vec3 fN;
in vec3 fL;
in vec3 fE;

uniform vec4 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform vec4 LightPosition;
uniform float Shininess;
```

Declare vectors n, v, l as **in** in fragment shader
(**Hardware interpolates these vectors**)

Per=Fragment Lighting Shaders IV

```
void main()
{
   // Normalize the input lighting vectors

   vec3 N = normalize(fN);
   vec3 E = normalize(fE);
   vec3 L = normalize(fL);

   vec3 H = normalize( L + E );
   vec4 ambient = AmbientProduct;
```

Use interpolated variables n, v, l in fragment shader

$$I = k_d I_d \; \mathbf{l} \cdot \mathbf{n} + k_s I_s (\mathbf{n} \cdot \mathbf{h})^{\beta} + k_a I_a$$

Per-Fragment Lighting Shaders V

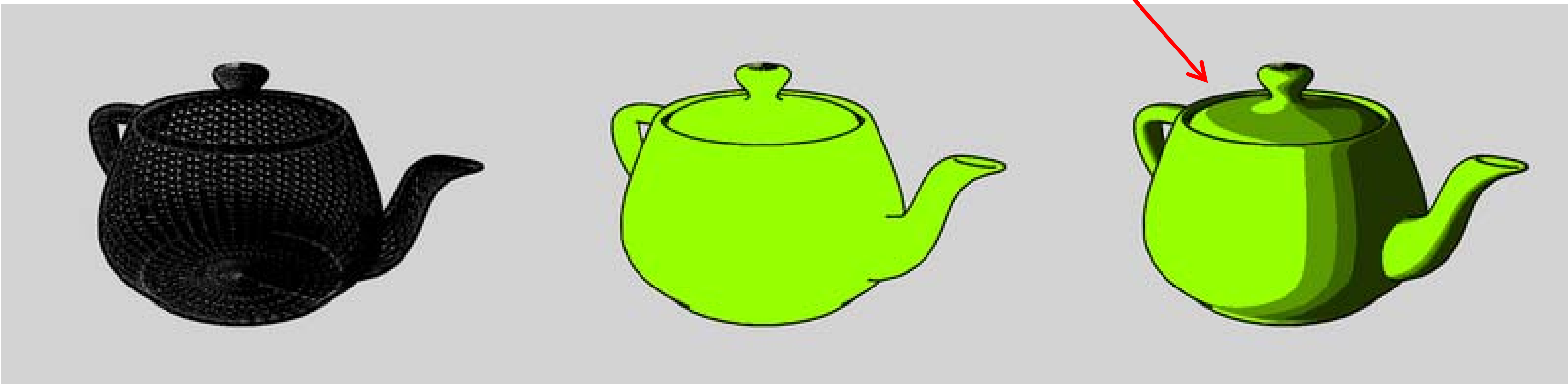
```
float Kd = max(dot(L, N), 0.0);
   vec4 diffuse = Kd*DiffuseProduct;

   float Ks = pow(max(dot(N, H), 0.0), Shininess);
   vec4 specular = Ks*SpecularProduct;

   // discard the specular highlight if the light's behind the vertex
   if( dot(L, N) < 0.0 )
         specular = vec4(0.0, 0.0, 0.0, 1.0);

   gl_FragColor = ambient + diffuse + specular;
   gl_FragColor.a = 1.0;
}
```

Use interpolated variables n, v, l in fragment shader

$$I = k_d I_d \; \mathbf{l} \cdot \mathbf{n} + k_s I_s (\mathbf{n} \cdot \mathbf{h})^{\beta} + k_a I_a$$

Toon (or Cel) Shading

- Non-Photorealistic (NPR) effect
- Shade in bands of color



Toon (or Cel) Shading

- How?
- Consider **(l · n)** diffuse term (or cos Θ) term

$$I = k_d I_d \; \mathbf{l} \cdot \mathbf{n} + k_s I_s (\mathbf{n} \cdot \mathbf{h})^{\beta} + k_a I_a$$

- Clamp values to ranges to get toon shading effect

l · n	**Value used**
Between 0.75 and 1	0.75
Between 0.5 and 0.75	0.5
Between 0.25 and 0.5	0.25
Between 0.0 and 0.25	0.0

BRDF Evolution

- BRDFs have evolved historically
- 1970's: Empirical models
  - Phong's illumination model
- 1980s:
  - Physically based models
  - Microfacet models (e.g. Cook Torrance model)
- 1990's
  - Physically-based appearance models of specific effects (materials, weathering, dust, etc)
- Early 2000's
  - Measurement & acquisition of static materials/lights (wood, translucence, etc)
- Late 2000's
  - Measurement & acquisition of time-varying BRDFs (ripening, etc)

Physically-Based Shading Models

- Phong model produces pretty pictures
- Cons: empirical (fudged?) ($cos^{\alpha}\phi$), plastic look
- Shaders can implement better lighting/shading models
- Big trend towards Physically-based lighting models
- Physically-based?
  - Based on physics of how light interacts with actual surface
  - Apply Optics/Physics theories
- Classic: Cook-Torrance shading model (TOGS 1982)

Cook-Torrance Shading Model

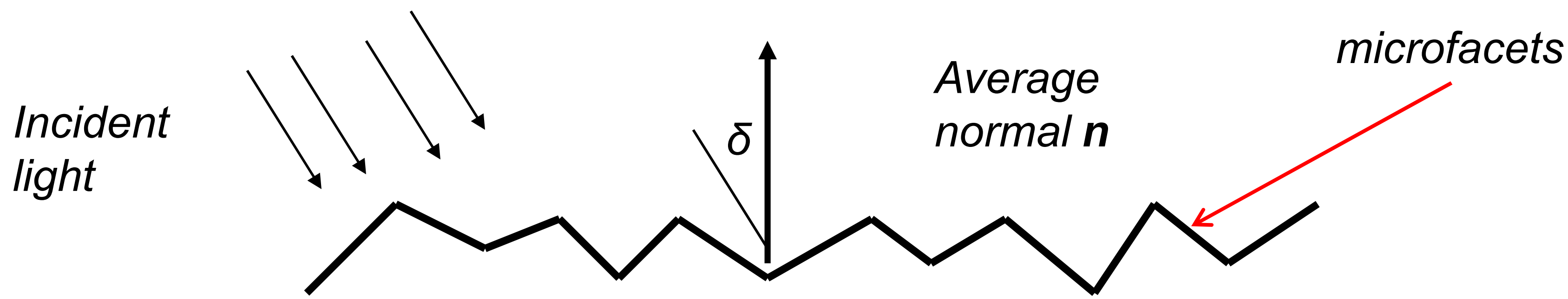
- Same ambient and diffuse terms as Phong
- New, better specular component than ($cos^{\alpha}\phi$),

$$\cos^{\alpha}\phi \rightarrow \frac{F(\phi,\eta)DG}{(\mathbf{n}\cdot\mathbf{v})}$$

- Where
  - D - Distribution term
  - G – Geometric term
  - F – Fresnel term

Distribution Term, D

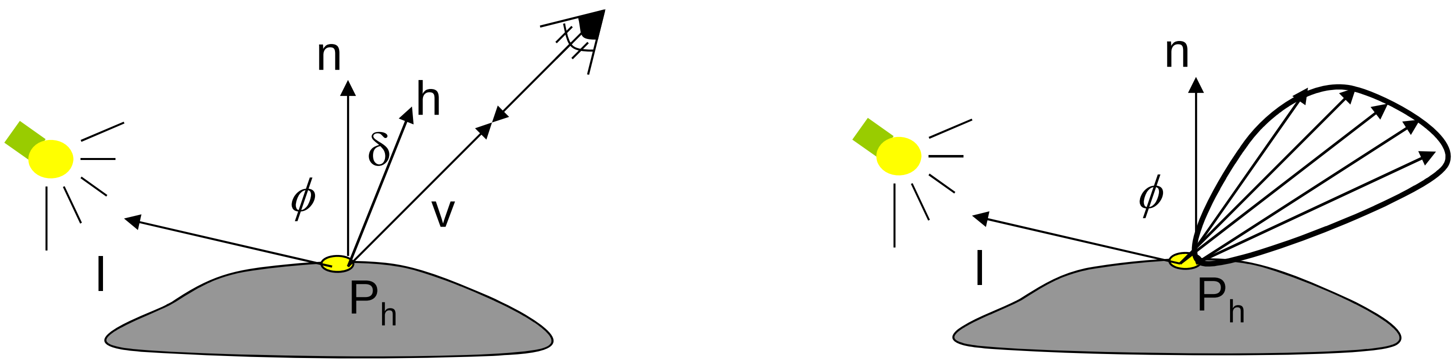
- **Idea:** surfaces consist of small V-shaped **microfacets (grooves)**



- Many grooves at each surface point
- Grooves facing a direction contribute
- D(δ) term: what fraction of grooves facing each angle δ
- E.g. half of grooves at hit point face 30 degrees, etc

Cook-Torrance Shading Model

- Define angle δ as deviation of **h** from surface normal
- Only microfacets with pointing along halfway vector, **h = s + v**, contributes



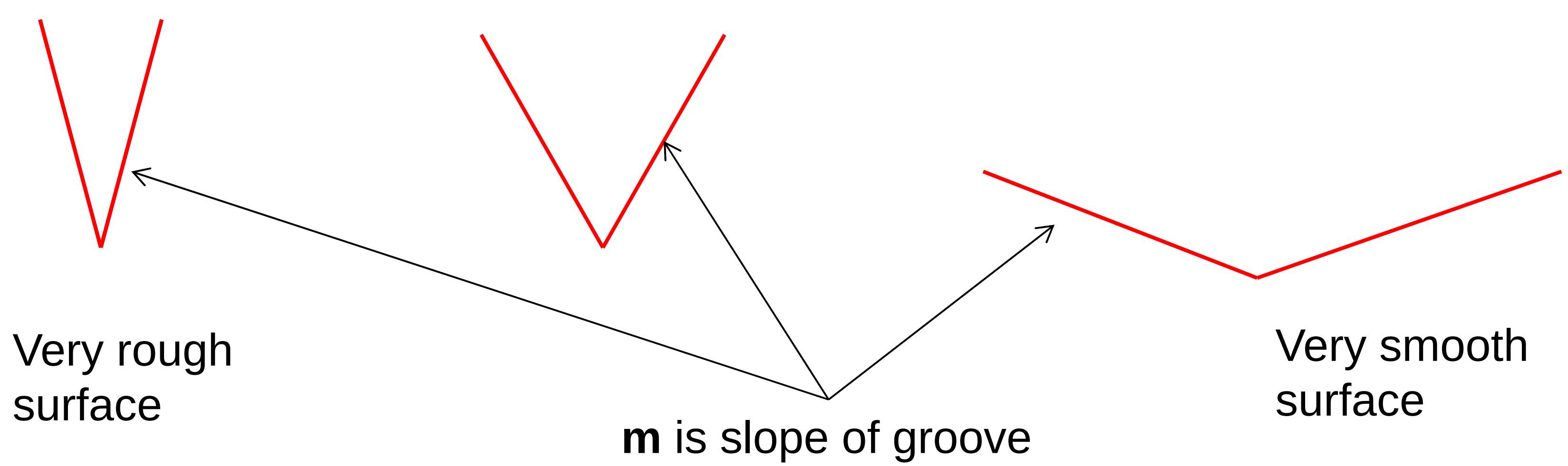
- Can use old Phong cosine ($cos^n \phi$), as D
- Use Beckmann distribution instead

$$D(\delta) = \frac{1}{4\mathbf{m}^2 \cos^4(\delta)} e^{-\left(\frac{\tan(\delta)}{\mathbf{m}}\right)^2}$$

- **m** expresses roughness of surface. How?

Cook-Torrance Shading Model

- **m** is Root-mean-square (RMS) of **slope** of V-groove
- m = 0.2 for nearly smooth
- m = 0.6 for very rough

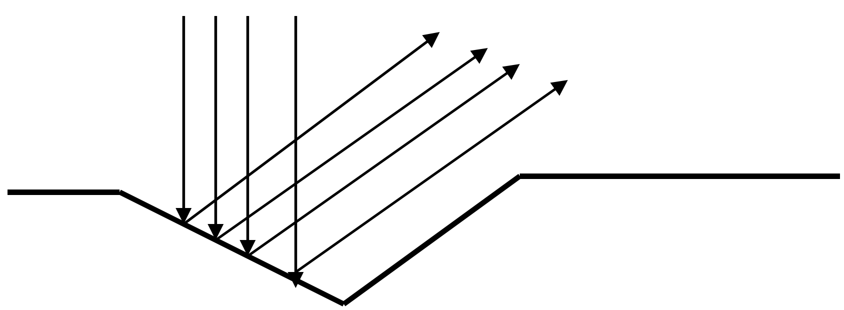


Self-Shadowing (G Term)

- Some grooves on extremely rough surface may block other grooves

Geometric Term, G

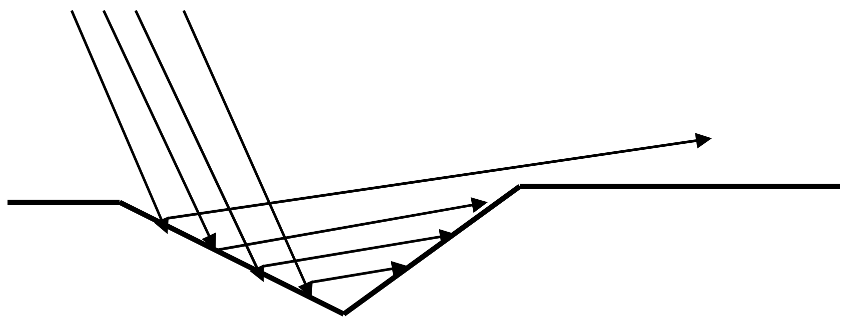
- Surface may be so rough that interior of grooves is blocked from light by edges
- Self blocking known as **shadowing** or **masking**
- Geometric term G accounts for this
- Break G into 3 cases:
- G, case a: No self-shadowing (light in-out unobstructed)



- Mathematically, G = 1

Geometric Term, G

- G_m, case b: No blocking on entry, blocking of exitting light **(masking)**



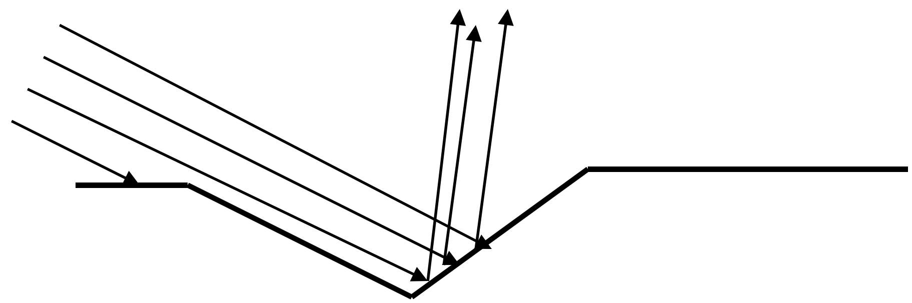
- Mathematically,

$$G_m = \frac{2(\mathbf{n} \cdot \mathbf{h})(\mathbf{n} \cdot \mathbf{s})}{\mathbf{h} \cdot \mathbf{s}}$$

Geometric Term, G

- G_s, case c: blocking of incident light, no blocking of exitting light (**shadowing)**
- Mathematically,

$$G_s = \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{\mathbf{h}\cdot\mathbf{s}}$$



- G term is minimum of 3 cases, hence

$$G = \left(1, G_m, G_s\right)$$

Fresnel Term, F

- So, again recall that specular term

$$spec = \frac{F(\phi,\eta)DG}{(\mathbf{n}\cdot\mathbf{v})}$$

- Microfacets not perfect mirrors
- F term, $F(\phi, \eta)$ gives fraction of incident light reflected

$$F = \frac{1}{2}\frac{(g-c)^2}{(g+c)^2}\left\{1+\left(\frac{c(g+c)-1}{c(g-c)-1}\right)^2\right\}$$

F is function of material and incident angle

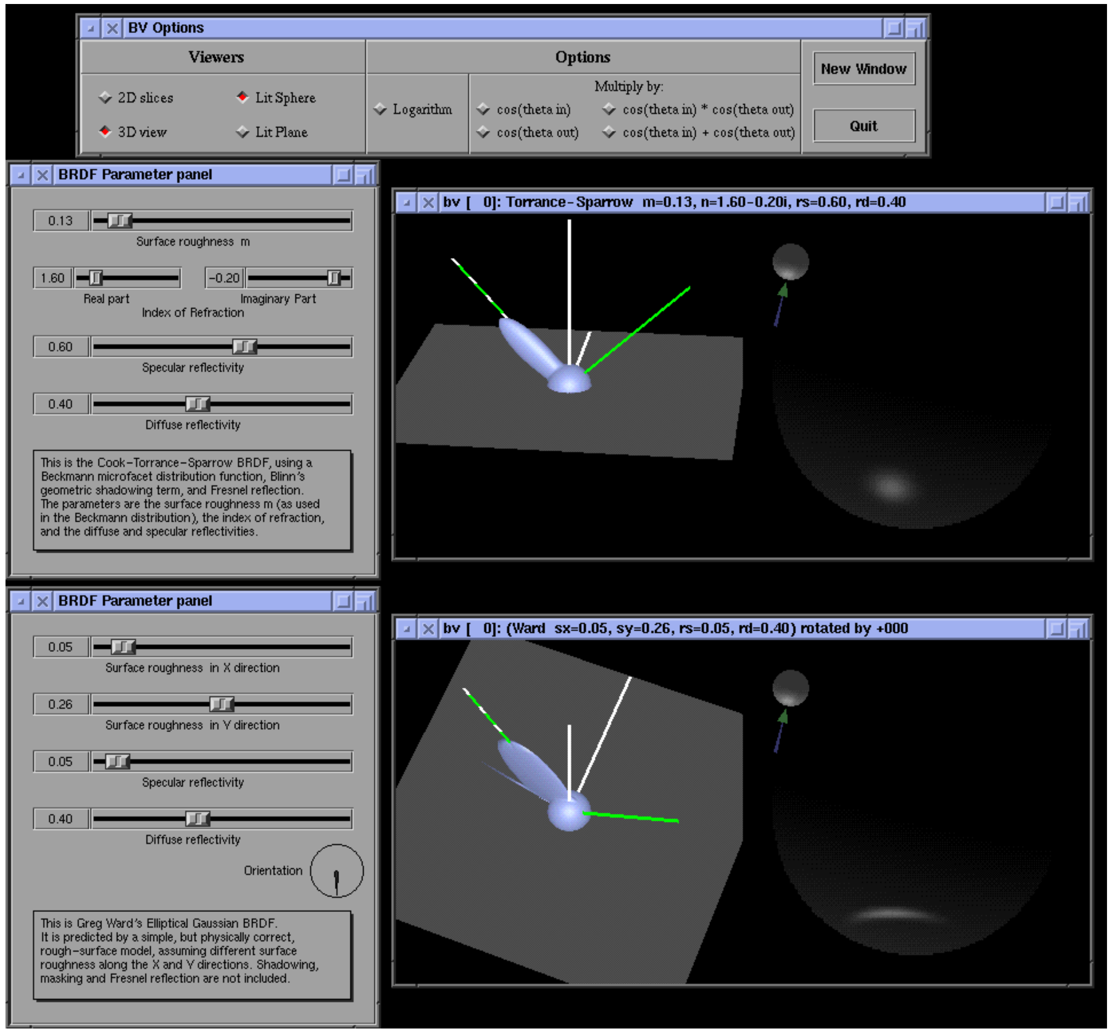
- where c = cos(ϕ) = **n.s** and $g^2 = \eta^2 + c^2 + 1$
- ϕ is incident angle, η is refractive index of material

Other Physically-Based BRDF Models

- Oren-Nayar – Diffuse term changed not specular
- Aishikhminn-Shirley – Grooves not v-shaped. Other Shapes
- Microfacet generator (Design your own microfacet)

BV BRDF Viewer

BRDF viewer (View distribution of light bounce)



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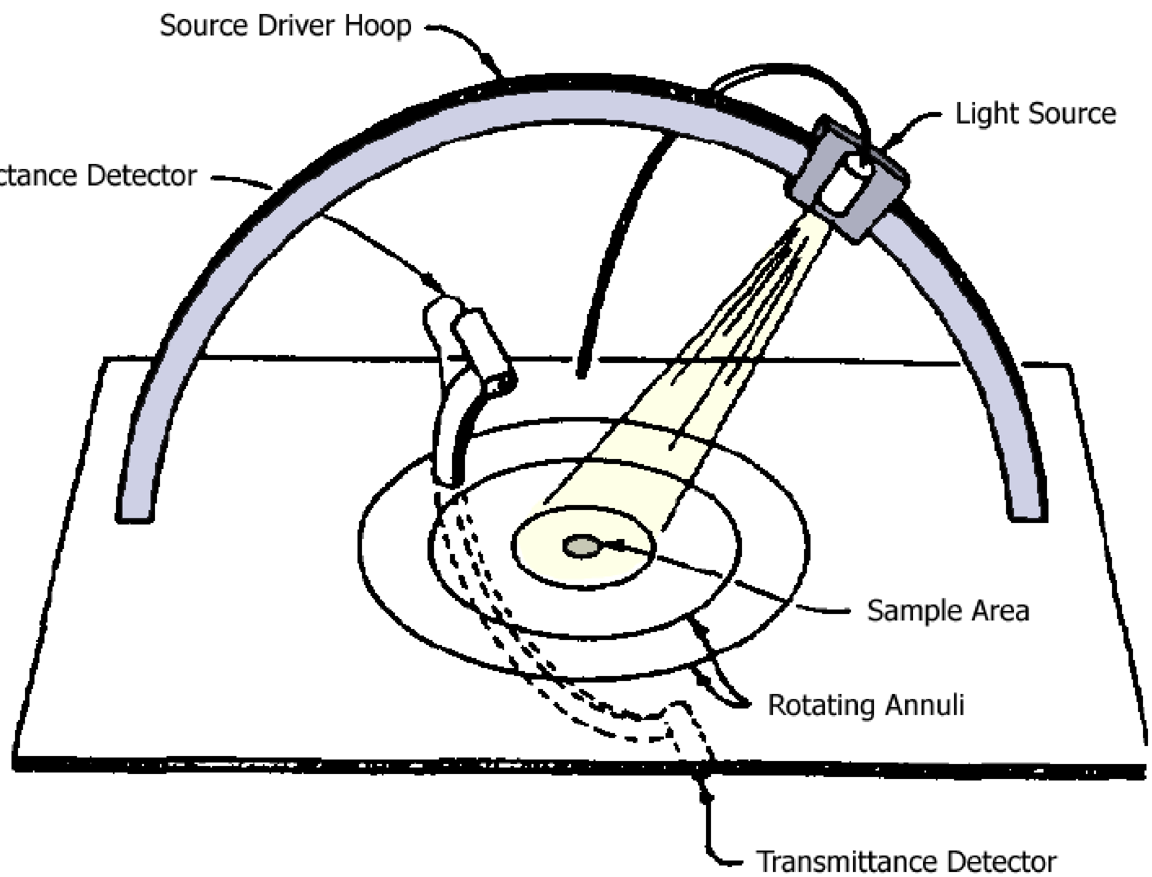
Measuring BRDFs



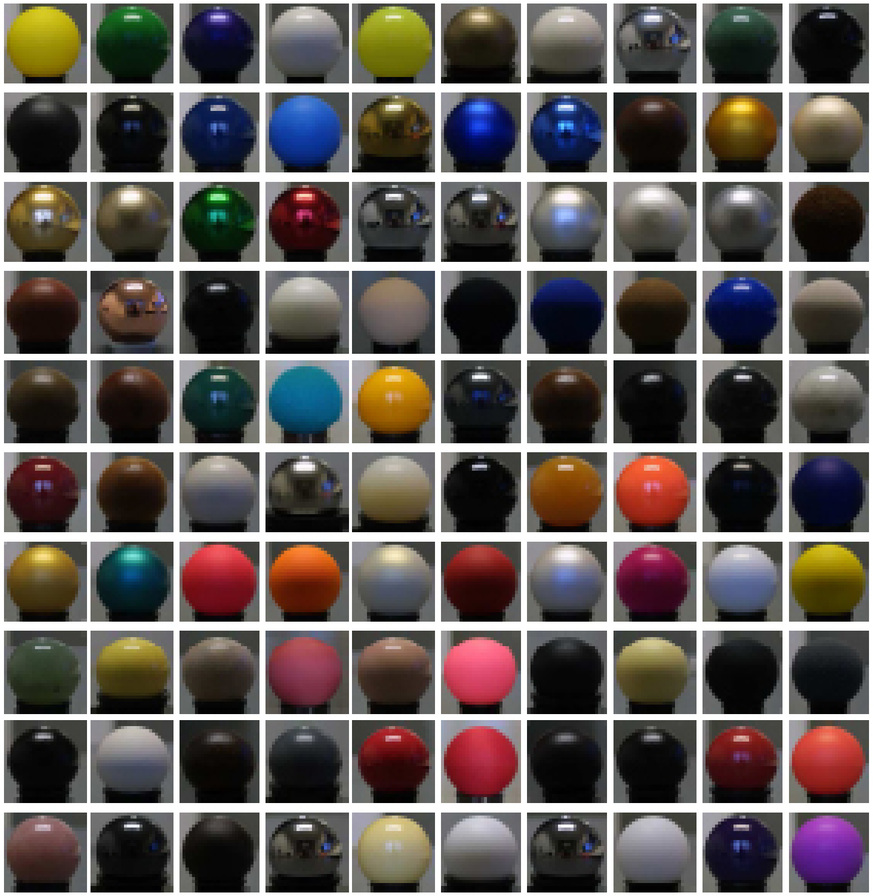
Murray-Coleman and Smith Gonioreflectometer. (Copied and Modified from [Ward92]).

Measured BRDF Samples

- Mitsubishi Electric Research Lab (MERL)

http://www.merl.com/brdf/

- Wojciech Matusik
- MIT PhD Thesis
- 100 Samples



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Time-varying BRDF

- BRDF: How different materials reflect light
- Time varying?: how reflectance changes over time
- 

References

- Interactive Computer Graphics (6th edition), Angel and Shreiner
- Computer Graphics using OpenGL (3rd edition), Hill and Kelley