Lighting/Illumination/Reflection Model

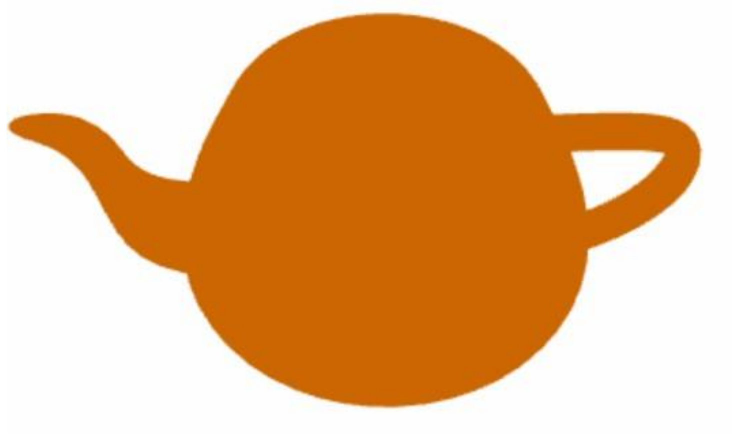
Some of the contents used in this lecture belong to…

- Dr Jon Shiach, Manchester Metropolitan University, “Direct Lighting Model”, https://www.youtube.com/watch?v=7CdS8oOJtVA
- Mr. Jacobson, University of Toronto, “WebGL Phong Shading”, http://www.cs.toronto.edu/~jacobson/phong-demo/ (Online demo)

Basic Terms

- Illumination: the transport of energy from light sources to surfaces & points
  - Local illumination
  - Global illumination
- Lighting model or Illumination model: Express the factors determining a surface's color or luminous intensity (outgoing or reflected light) at a particular 3D point

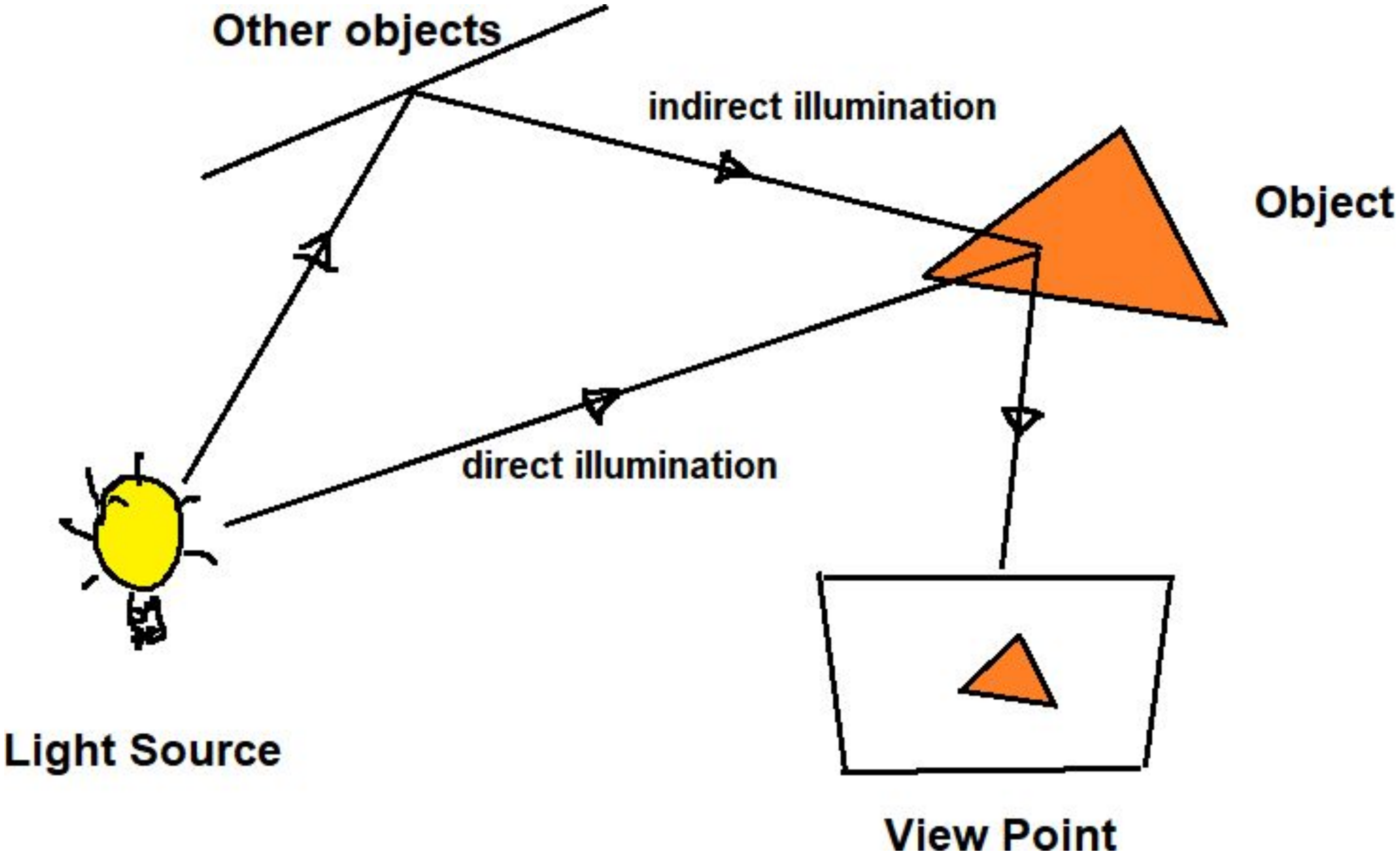
Effects of Lighting



Pixel color only

Pixel colors with lighting

Illumination



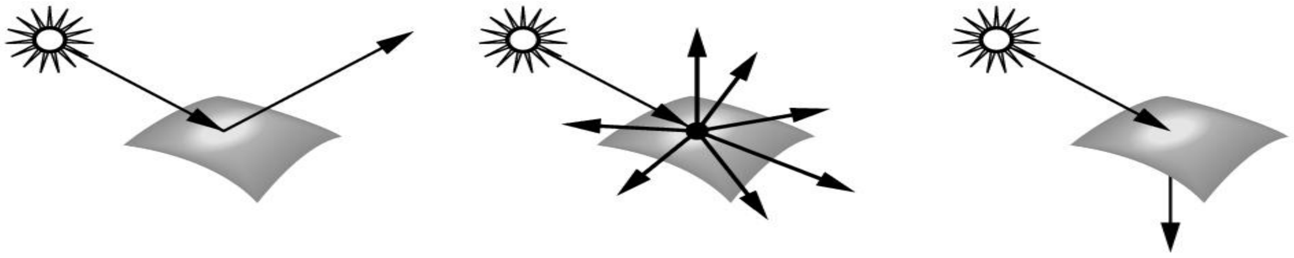
Components of Illumination

- Two components of illumination:
  1. Light sources
  2. Surface properties
- Light source described by a luminance/intensity ‘I’
  - Each color is described separately
  - I = [Ir Ig Ib]
- Types of Light Sources:
  1. Ambient Light
  2. Diffuse Light
  3. Spot Light

Types of Surface

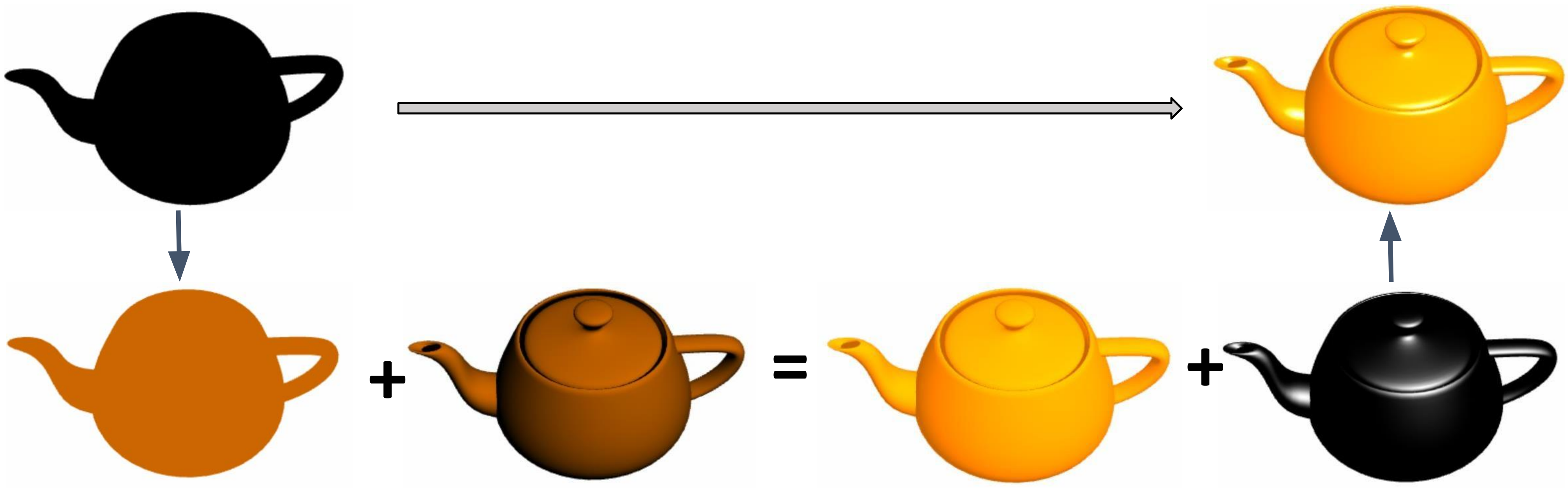
Interaction between light and material can be classified as

- **Specular surfaces** – Ideal mirror
- **Diffuse surfaces** – Reflected light is ideally reflected to all directions uniformly
- **Translucent surfaces** – Allow some lights to penetrate the surface (e.g. refraction in glass, water)



(a) (b) (c)

Phong's Reflection Model



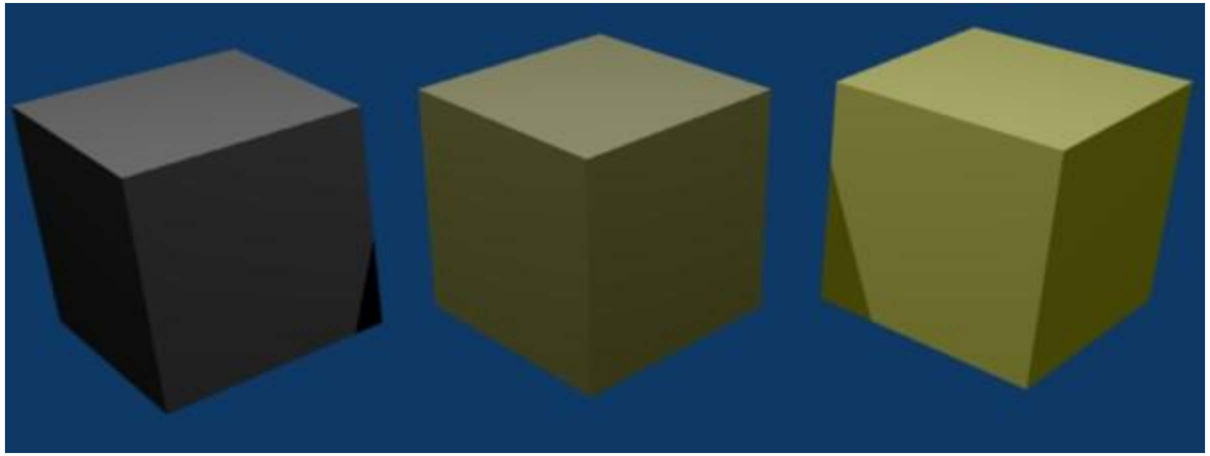
Ambient Light

Diffuse Light

Specular Light

Ambient Light

- No identifiable source or direction
- Product of multiple reflections of light from the many surfaces present in the environment
- Computationally inexpensive



Ambient Light

Categories:

1. Global ambient light
   - Independent of light source
   - Lights entire scene
   - Example: reflection of sunlight from several surfaces
2. Local ambient light
   - Contributed by additional light sources
   - Can be different for each light and primary color
   - Example: Reflection of fluorescent lamps from several surfaces

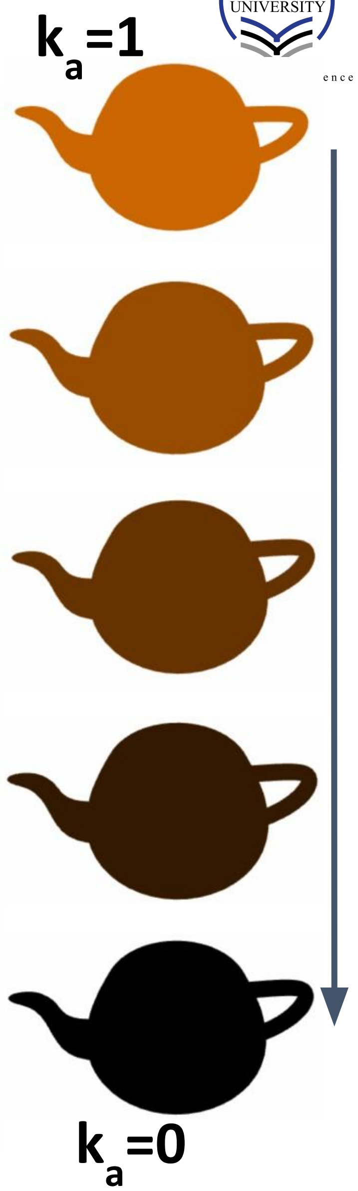
Ambient Reflection

- **Ambient reflection** is the reflection of light that does not come directly from a light source
- Even in a darkened room, we can make out the edges of objects – this is because of light bouncing off of objects
- Since Phong is a **direct** lighting model, we assume that ambient light falls equally on all objects, i.e.,

$$A = I_a k_a$$

  where I_a is the intensity of the ambient light and $k_a \in [0, 1]$ is the **ambient coefficient**

- k_a is set to provide the right amount of ambient light for a scene, e.g., $k \rightarrow 1$ for bright scenes and $k \rightarrow 0$ for dark or nighttime scenes.



Ambient Reflection Coefficient

- Effect of adding ambient light to the diffuse light reflected by a sphere
- Diffuse source intensity is 1.0
  Diffuse reflection coefficient is 0.4
  Ambient source intensity is 1.0
- Moving from left to right the ambient reflection coefficient takes on values: 0.0, 0.1, 0.3, 0.5, and 0.7
  - Too little ambient light makes shadows too deep and harsh
  - Too much makes the picture look washed out and bland

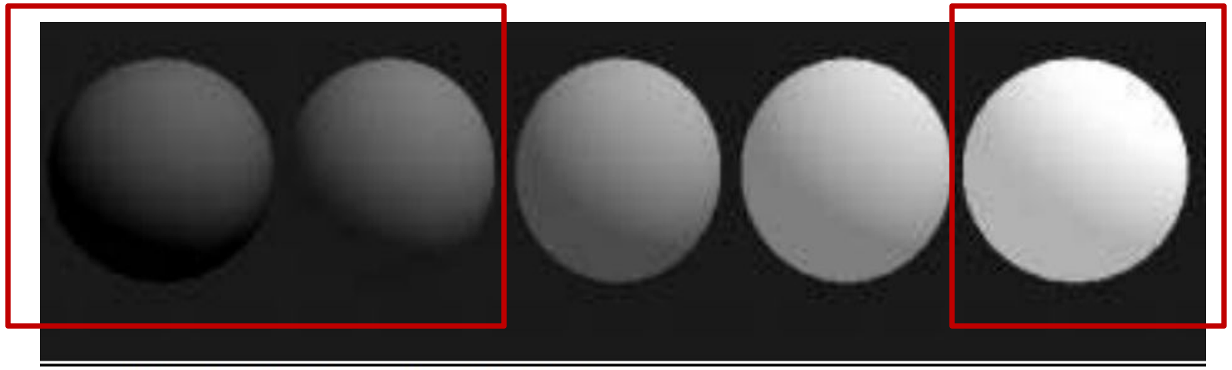
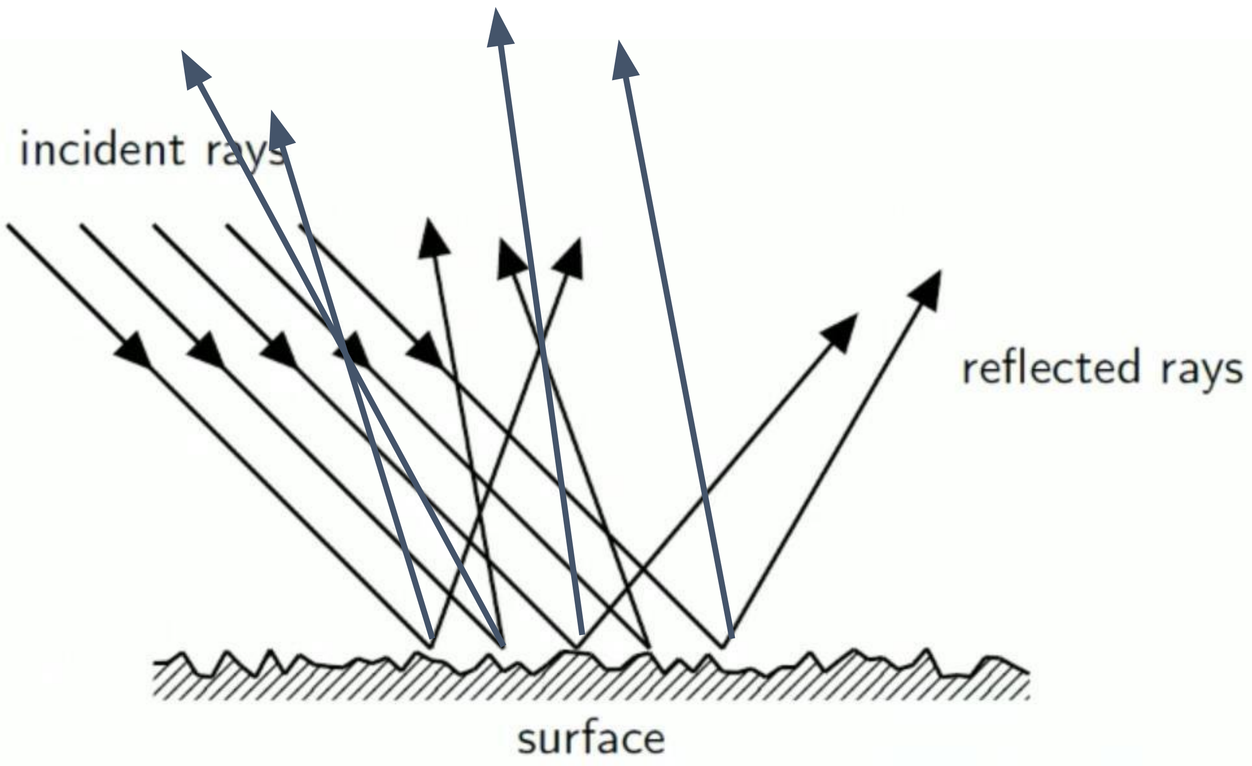


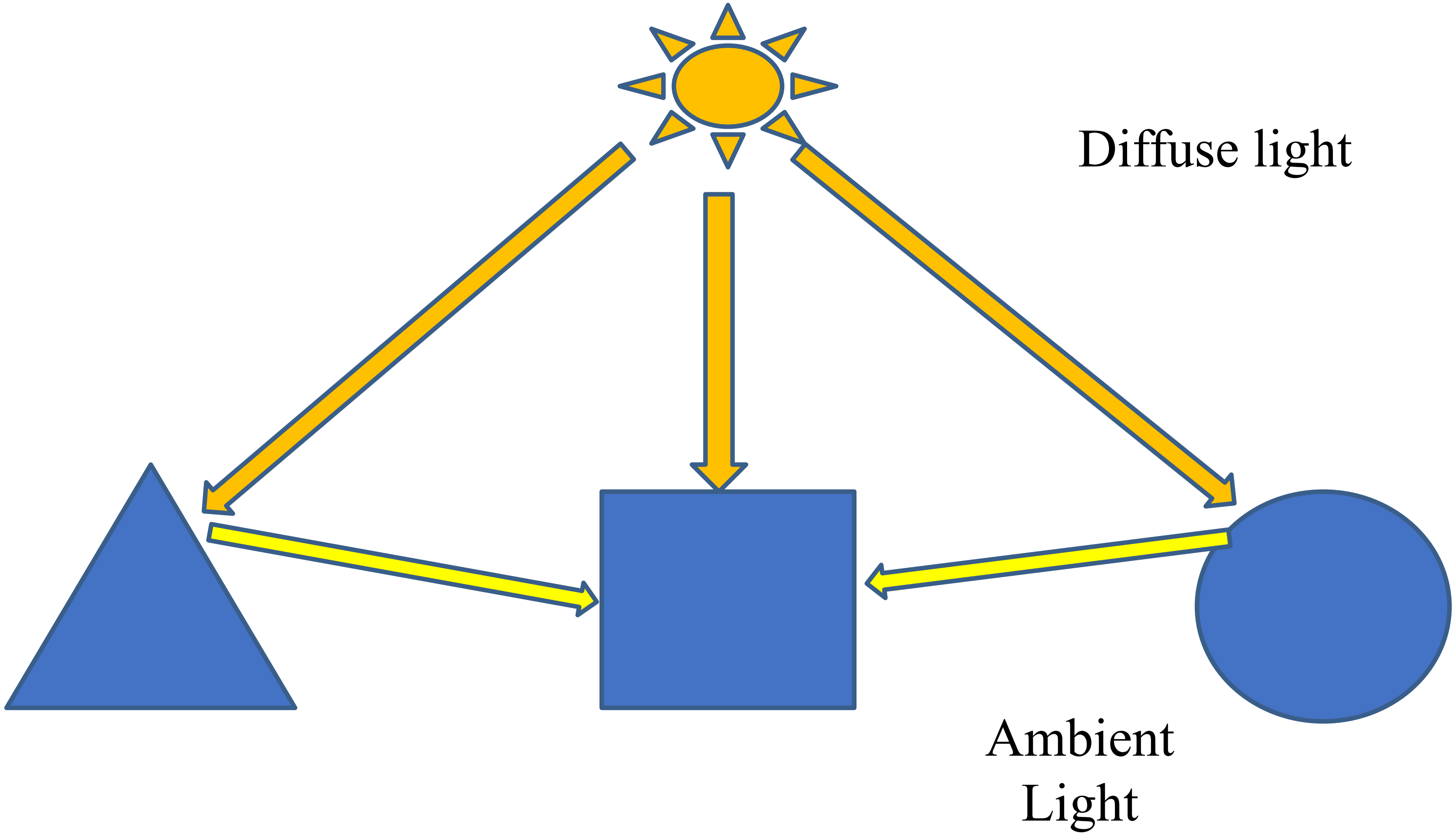
Figure 8.16. On the effect of ambient light.

Diffuse Reflection

- Result of irregular reflection of light
- Light is scattered in all direction. Not all are visible
- Does Not depend on the position of viewpoint

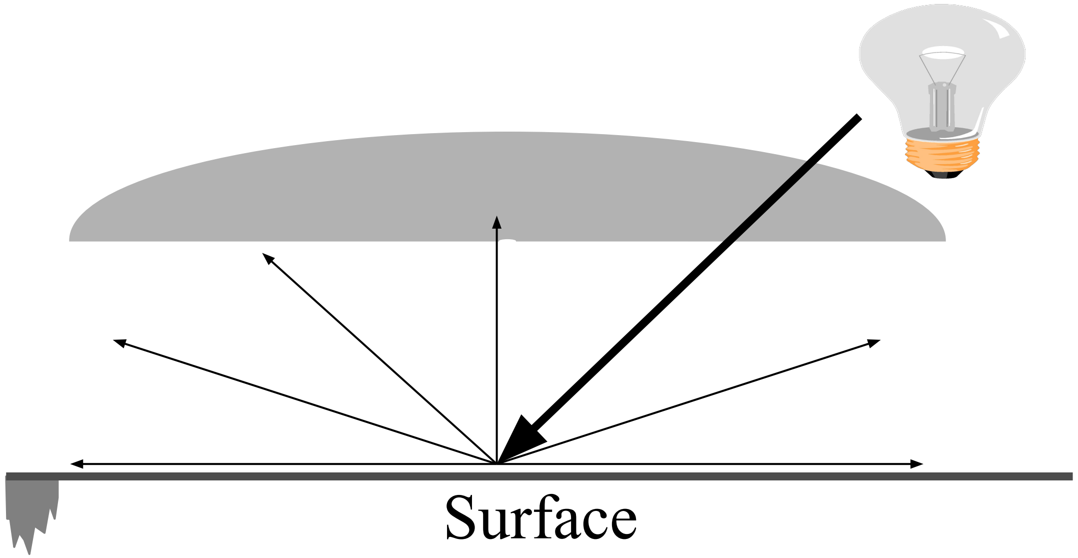


Ambient Light vs Diffuse Light



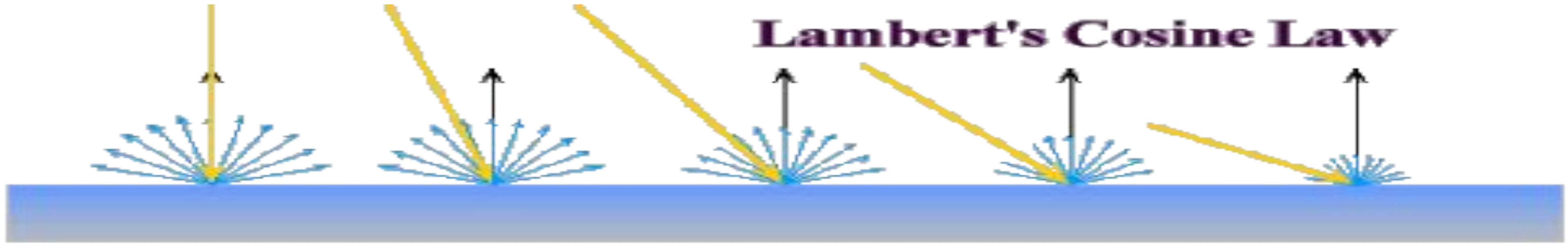
Ideal Diffuse Reflection

- Assumes surface reflects equally in all directions.
- An ideal diffuse surface is, at the microscopic level, a very rough surface.
  - Example: chalk, clay, some paints

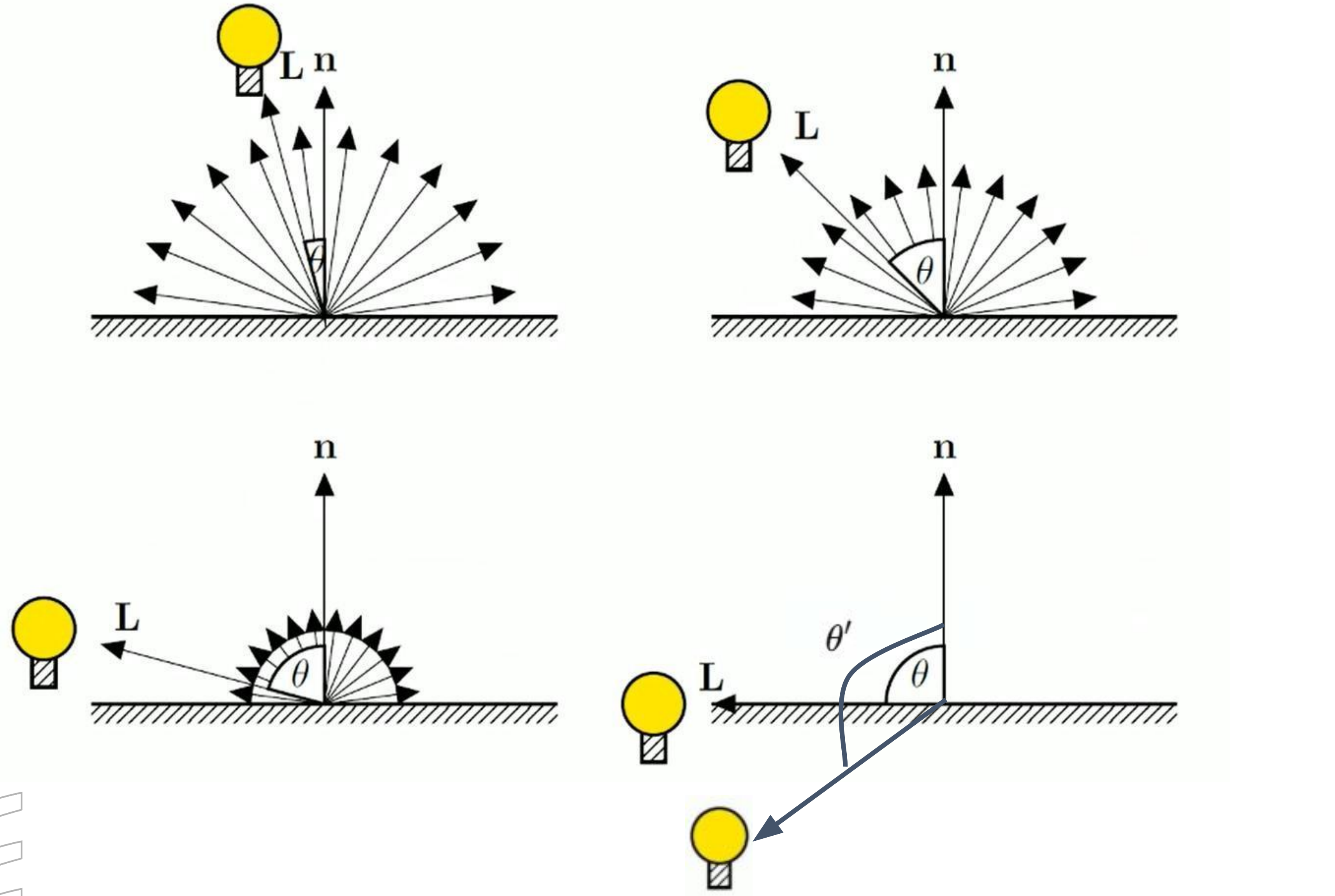


Ideal Diffuse Reflection

- Ideal diffuse reflectors reflect light according to Lambert's cosine law.
- Lambert's law determines how much of the incoming light energy is reflected. The reflected intensity is independent of the viewing direction.
- But reflected light intensity depends on incident angle of light.



Diffuse Reflection (Phong's Model)



- Light reflected equally in all direction.
- Magnitude of reflection depends in incident angle.
- Direction of L reversed? Why?

Diffuse Reflection - Phong’s Model

- Phong’s diffuse reflection model depends upon the position of the light source relative to the surface

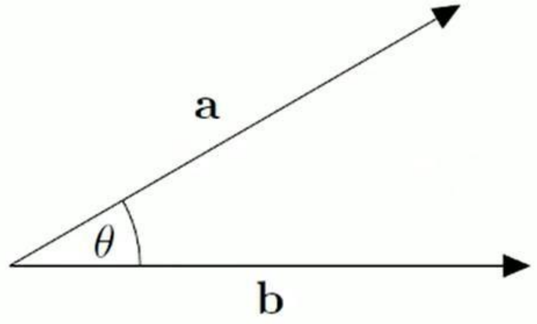
$$D = I_p k_d \max[\underline{\cos(\theta)}, 0]$$

where

  - I_p is the intensity of the point light source
  - $k_d \in [0, 1]$ is the **diffuse coefficient**
  - θ is the angle between the lighting vector and the surface normal

- The $\max[\cos(\theta), 0]$ is used so that no light is reflected if the light source is behind the surface

Diffuse Reflection



- The definition of the dot product is

$$\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}||\mathbf{b}| \cos(\theta)$$

- If $\mathbf{L}$ and $\mathbf{n}$ are unit vectors then

$$\mathbf{L} \cdot \mathbf{n} = \cos(\theta)$$

so we can replace the expensive cosine calculation by an easy dot product, i.e,

$$D = I_p k_d \max(\mathbf{L} \cdot \mathbf{n}, 0)$$

Here L and n are both unit vectors

Diffuse Reflection Coefficient

- $I_d = \max \{I_s k_d \cos\theta, 0\}$
- Source intensity is 1.0
- Background intensity is 0.4
- Sphere reflecting diffuse light, for six reflection coefficients: 0, 0.2, 0.4, 0.6, 0.8, and 1.

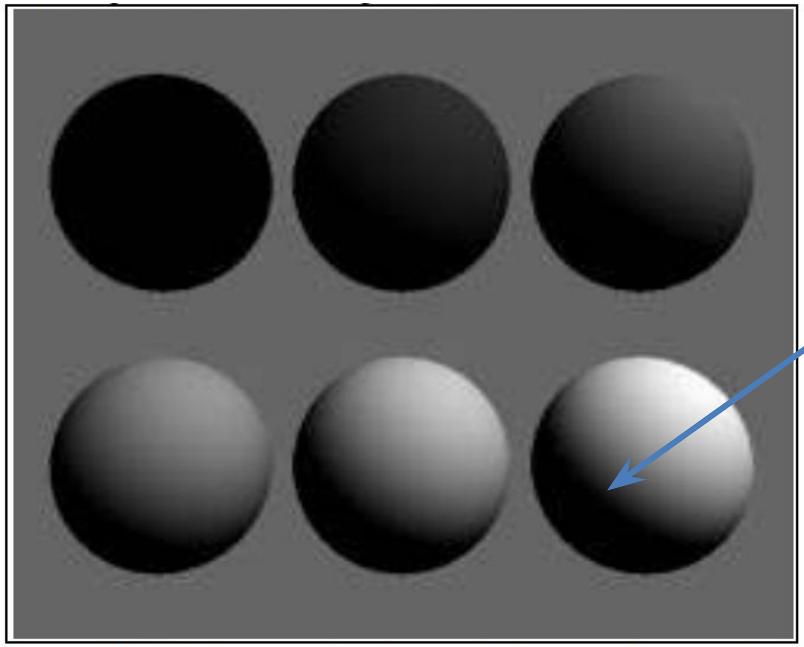
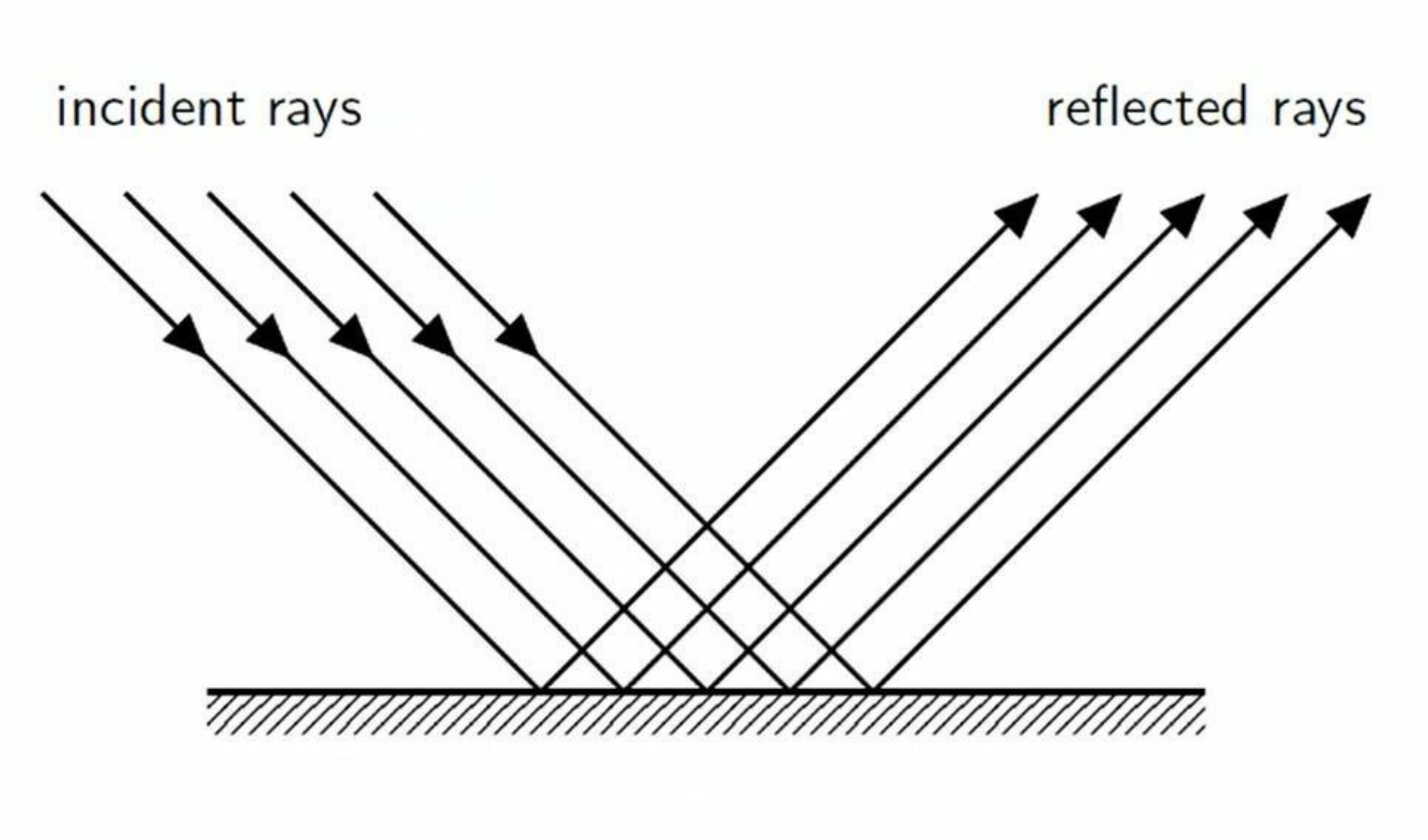


Figure 8.11. Spheres with various reflection coefficients shaded with diffuse light. (file: fig8.11.bmp)

Angle θ between surface normal and incident light is > 90°

- What is the ambient component here?
- What is the specular component?

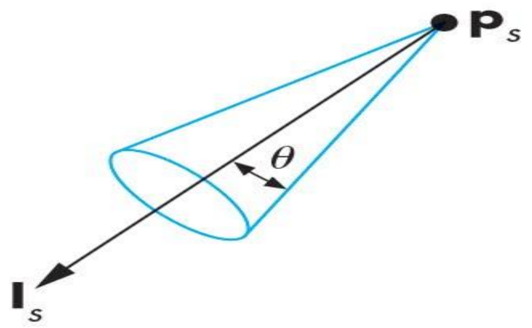
Specular Reflection



Spot Light

- *Spotlight* is a point source that emits light in restricted set of directions,
  - Requires color, point, direction, falloff parameter
  - usually direction boundary forms a cone shape.
  - Here θ is Cut Off Cone. No light is seen at points lying outside Cutoff angle.

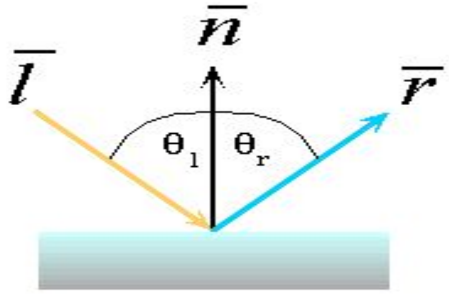
- Intensity falls off directionally



Ideal Specular Reflection

Reflection is only at mirror angle. An ideal mirror is a purely specular reflector.

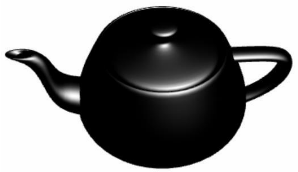
- View dependent reflection. That is, reflected light's intensity varies with viewer's position.
- Intensity of refelcted light is stronger near mirror angle and strongest at mirror angle.
- An Ideal specular reflection follows Snell's Law.

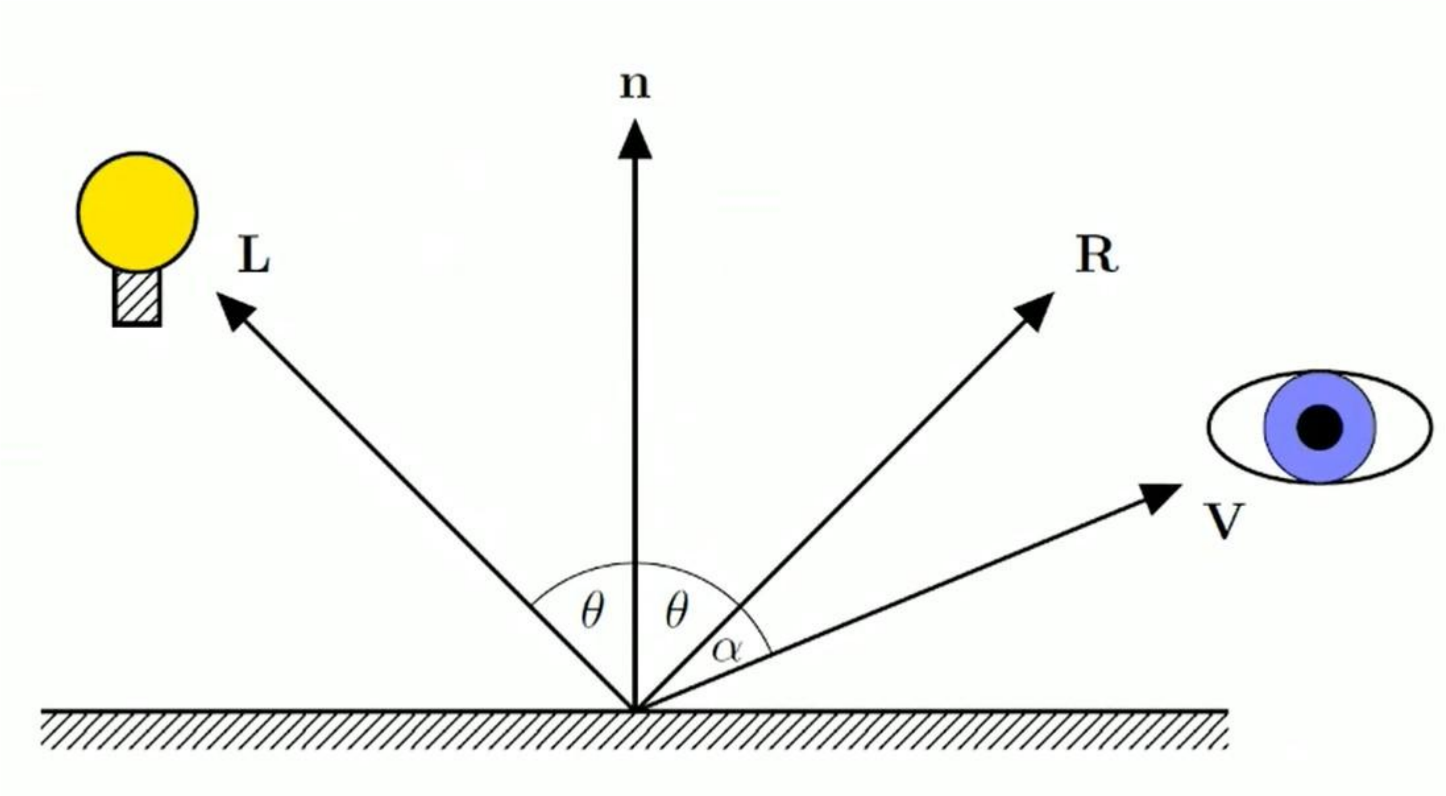


Snell's Laws:

- The incoming ray and reflected ray lie in a plane with the surface normal
- The angle that the reflected ray forms with the surface normal equals the angle formed by the incoming ray and the surface normal

Specular Reflection



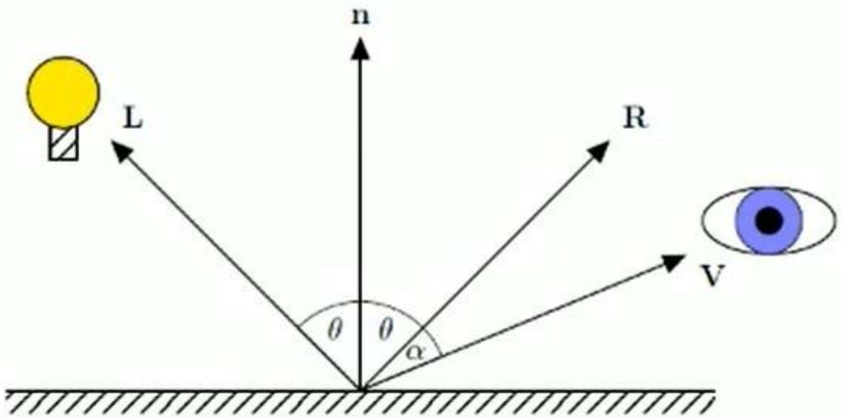


Specular Reflection

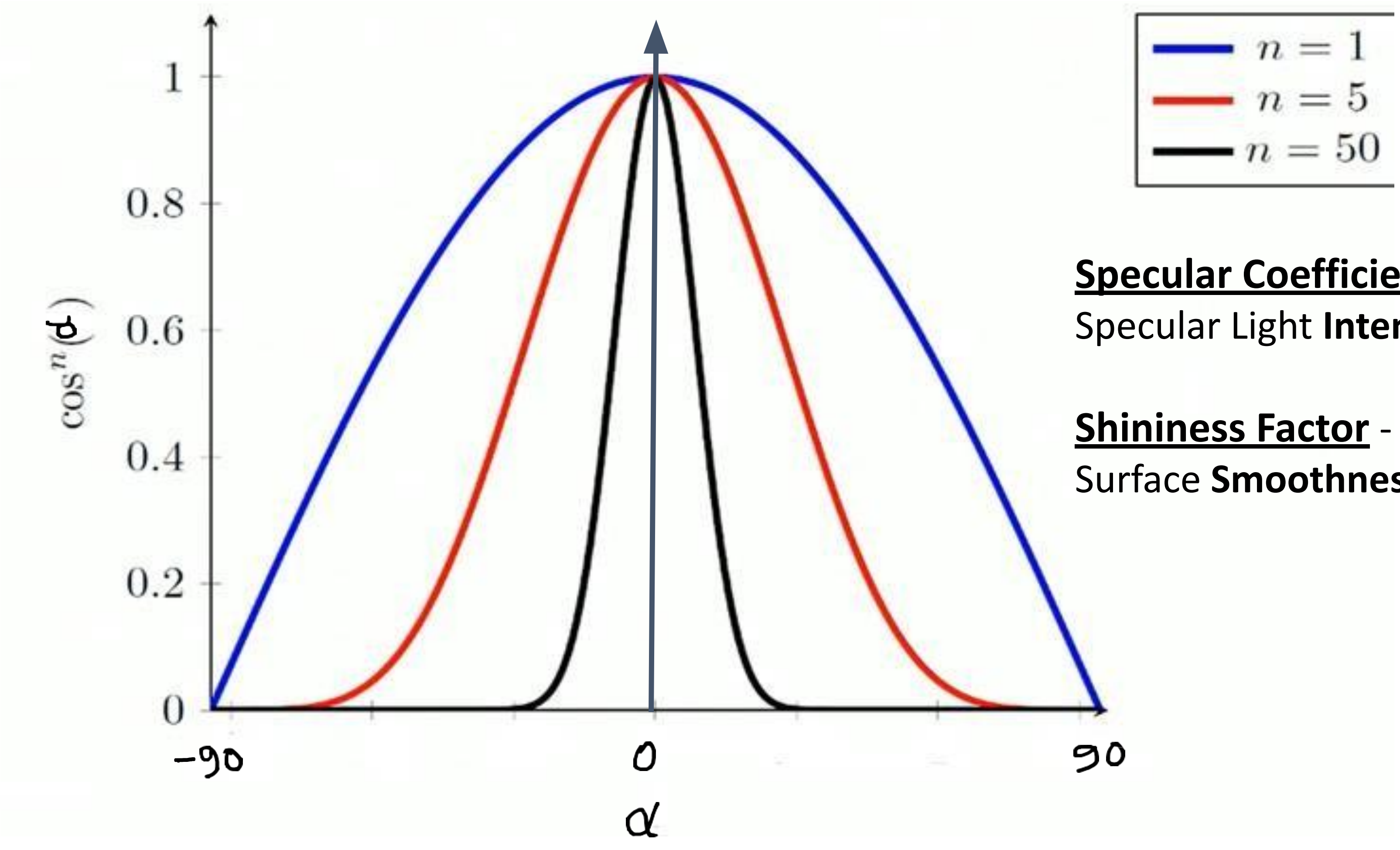
- Phong's specular model is

$$S = I_p k_s \cos^n(\alpha)$$

  where
  - $k_s \in [0, 1]$ is the **specular coefficient**
  - n is the **specular exponent/Shininess**
  - α is the angle between $\mathbf{R}$ and $\mathbf{V}$
- The $\cos^n(\alpha)$ term determines the amount of light that is reflected

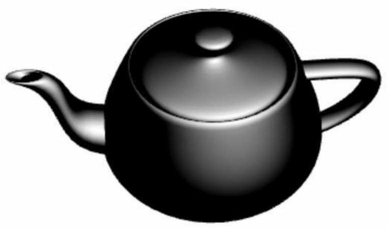


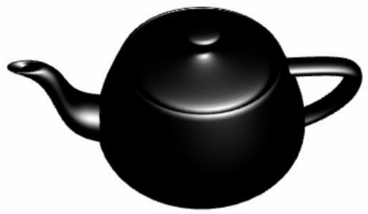
Specular Reflection
Shininess



<u>Specular Coefficient</u> - Determines Specular Light **Intensity**

<u>Shininess Factor</u> - Determines Surface **Smoothness**

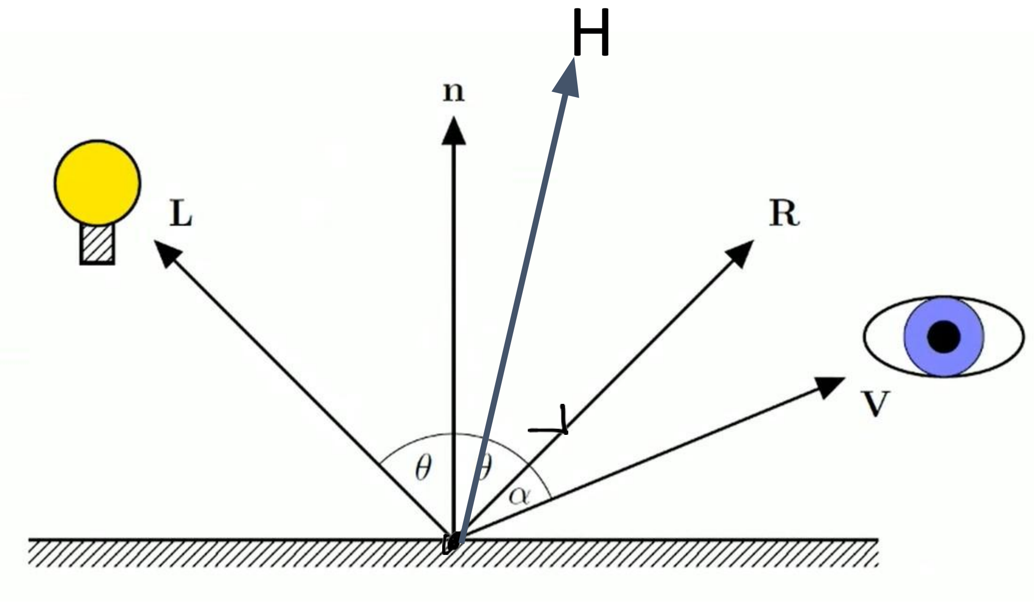




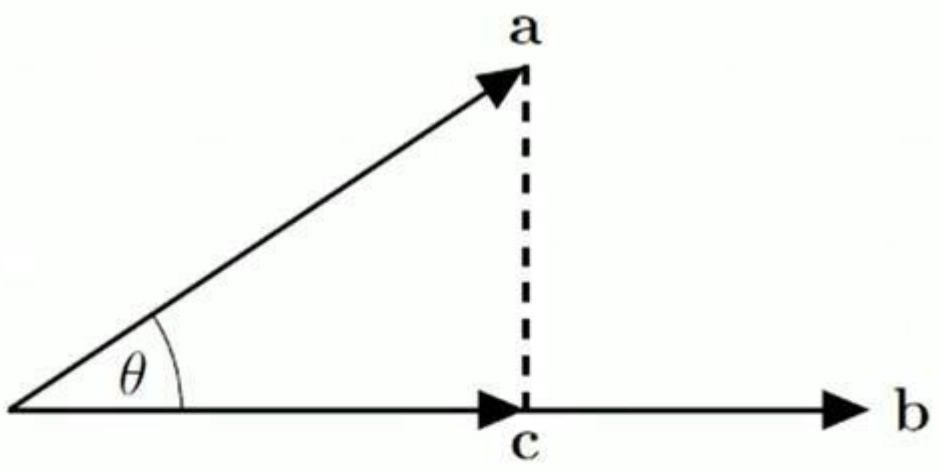
Specular Reflection

$$S = I_p k_s \cos^n(\alpha)$$

Calculate R, $\cos\alpha$



$$\cos\alpha = V \cdot R$$



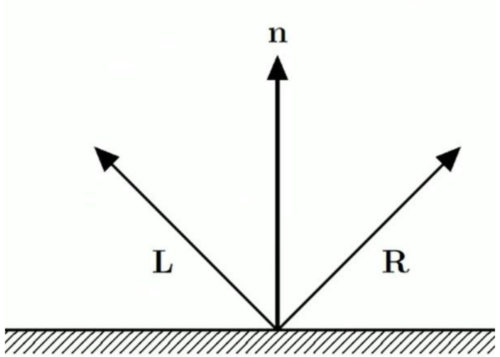
- Using the definition of a dot product

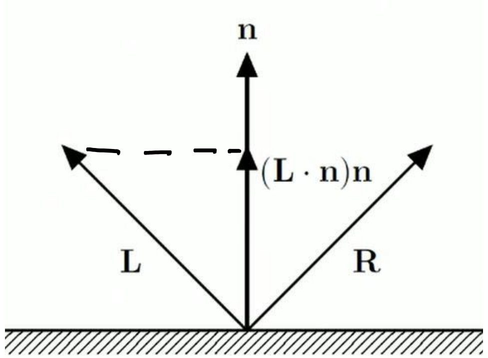
$$\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}||\mathbf{b}| \cos(\theta) = |\mathbf{a}||\mathbf{b}| \frac{|\mathbf{c}|}{|\mathbf{a}|} = |\mathbf{b}||\mathbf{c}|$$

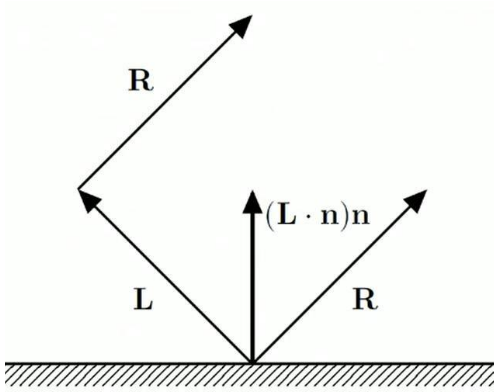
$$\therefore |\mathbf{c}| = \frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{b}|}$$

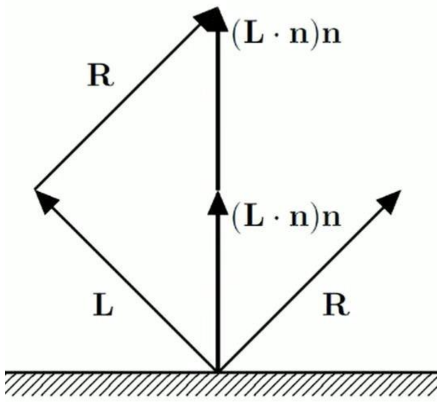
- If $\mathbf{b}$ is a unit vector then $|\mathbf{c}| = \mathbf{a} \cdot \mathbf{b}$ and

$$\mathbf{c} = (\mathbf{a} \cdot \mathbf{b})\mathbf{b}$$









$$\mathbf{L} + \mathbf{R} = 2(\mathbf{L} \cdot \mathbf{n})\mathbf{n}$$

$$\therefore \mathbf{R} = 2(\mathbf{L} \cdot \mathbf{n})\mathbf{n} - \mathbf{L}$$

Here L and n are both unit vectors

Specular Reflection Coefficient

- The ambient and diffuse reflection coefficients are 0.1 and 0.4 for all spheres.
- $I_d = I_s\, k_s\, (\cos \varphi)^k$

More shiny and more highly concentrated along the direction r

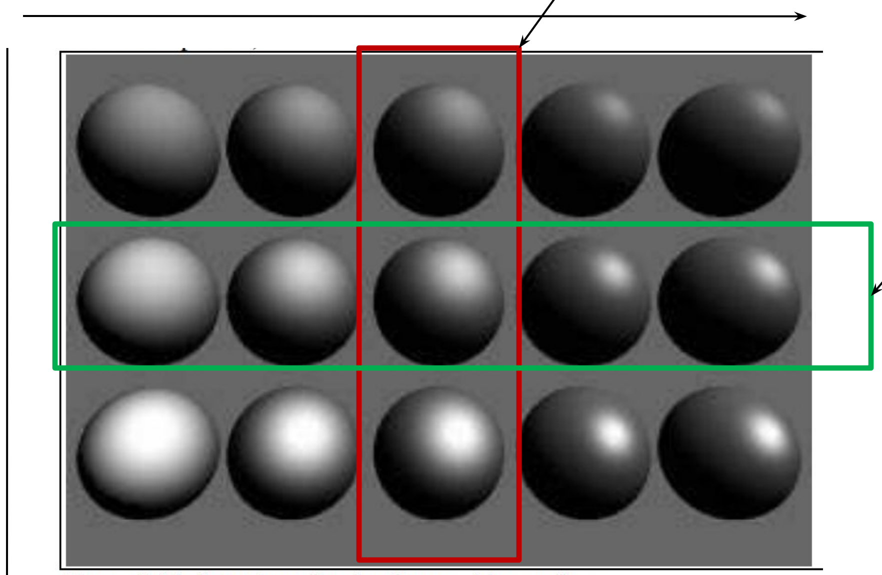


Figure 8.15. Specular reflection from a shiny surface.

More mirror like, more focused reflection with increasing exponent

Blinn and Torrence Variation

- Calculation of **R** is computationally expensive. So in phong model the term **R.V** is sometimes replaced by **N.H** , where **H** is a unit vector that bisect the angle between **L** and **V**.
  - angle between **N** and **H** measures the falloff of intensity.
  - Though calculation of **N.H** is is computationally inexpensive relative to **R.V**, but **N.H** is not always equal to **R.V**. In that case calculation of specular component will be approximate.
    (See Solved Problem 11.11 in Schaum(2nd edition)))

Steps to Calculate H:

1. **Add the light vector L and the view vector V:**

Here L and V are both unit vectors

$$L + V$$

2. **Normalize the resulting vector:**

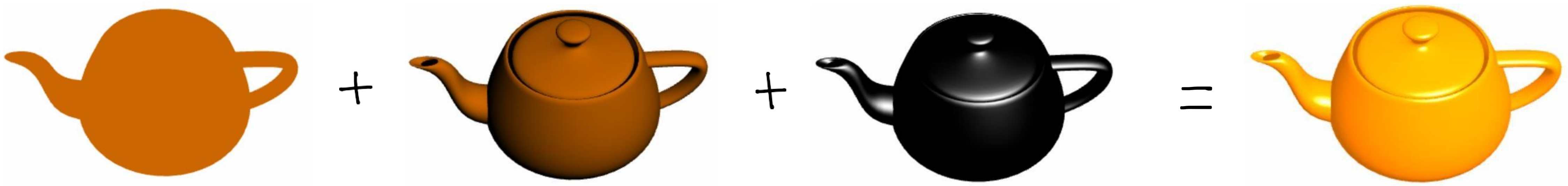
$$H = \frac{L + V}{\|L + V\|}$$

Where $\|L + V\|$ is the magnitude of the vector $L + V$, calculated as:

$$\|L + V\| = \sqrt{(L_x + V_x)^2 + (L_y + V_y)^2 + (L_z + V_z)^2}$$

After computing the magnitude, divide each component of $L + V$ by this magnitude to get the unit vector H.

Phong's Reflection Model



$$I_a k_a + I_p \, [k_d \max\{(L.N),0\} + k_s \max\{(R.V \text{ or } N.H)^k, 0\}] = I$$

Here all are unit vectors

Mathematical Calculation of Phong Model

We need to incorporate the effect light present in environment. Thus total reflected light also includes ambient component.

Ambient Component = $I_a k_a$

Total reflected light intensity from Q,

$$I = \text{Ambient Component} + \text{Diffuse Component} + \text{Specular Component}$$

$$= I_a k_a + I_p\, k_d\, (\mathbf{L}.\mathbf{N}) + I_p\, k_s\, (\mathbf{R}.\mathbf{V})^k$$

More specifically,

$$I = I_a k_a + I_p\, [k_d \max\, \{(\mathbf{L}.\mathbf{N}),0\} + k_s \max\{(\mathbf{R}.\mathbf{V})^k\, ,0\}]$$

Additional Issues

When there are n light sources in the scene, their effects are cumulative: Intensity at Q,

$$I = I_a k_a + \sum_{(i=1 \text{ to } n)} I_{pi} \{k_d (\mathbf{L}.\mathbf{N}) + k_s (\mathbf{R}.\mathbf{V})^k \}$$

The intesnsity of red, green and blue component of reflected light,

$$I_r = I_a k_{ar} + I_{pr} k_{dr} (\mathbf{L}.\mathbf{N}) + I_{pr} k_s (\mathbf{R}.\mathbf{V})^k$$

$$I_g = I_a k_{ag} + I_{pg} k_{dg} (\mathbf{L}.\mathbf{N}) + I_{pg} k_s (\mathbf{R}.\mathbf{V})^k$$

$$I_b = I_a k_{ab} + I_{pb} k_{db} (\mathbf{L}.\mathbf{N}) + I_{pb} k_s (\mathbf{R}.\mathbf{V})^k$$

k_s : coefficient for specular component which is same as the color of light source, not affected by surface color.

Attenuation

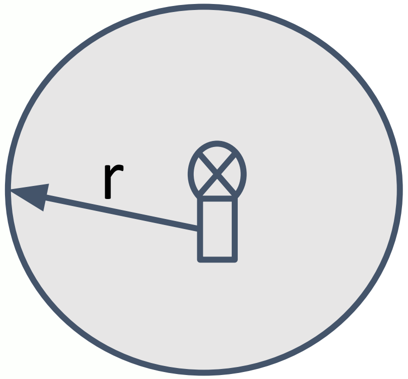
- **Attenuation** is the loss of light energy over space
- In Phong's model attenuation is account for by the variable f_{att} and applied to diffuse and specular components
- Theoretically is should follow the inverse square law, i.e.,

$$f_{att} = \frac{1}{d^2}$$

- In practice this removes too much light, Phong's model uses

$$f_{\text{att}} = \max\left(1 - \left(\frac{d}{r}\right)^2, 0\right)$$

where r is the radius of the light source's sphere of influence



- Combining ambient, diffuse, specular and attenuation models results in Phong's model of reflection

$$I = I_a k_a + I_p \, \mathbf{f}_{\mathbf{att}} [k_d \max \{(\mathbf{L}.\mathbf{N}),0\} + k_s \max\{(\mathbf{R}.\mathbf{V})^k ,0\}]$$

- For multiple light sources, the diffuse and specular components are calculated for each light source and added together, i.e.,

$$I = I_a k_a + \sum_{(i=1 \text{ to } n)} I_{pi} \, \mathbf{f}_{\mathbf{att}} \{k_d (\mathbf{L}.\mathbf{N}) + k_s (\mathbf{R}.\mathbf{V})^k \}$$

Exercise

A light source with **intensity 15** and **radius of influence 80** is **located at (4,2,3)** from which you are called to calculate the illumination of a point on the **xz plane**. The **camera is set at origin** and the light is reflected back from point **(0, 4) of the plane**. The **ambient, diffuse and specular coefficient** is given at **0.4, 0.2, 0.3**.

a. For the above phenomenon, represent the **reflected ray R** in the unit vector.
b. Calculate the **specular reflection intensity** for a **shininess factor of 99**.
c. Calculate the **attenuation factor** for the given point in the above scenario.
d. If the **ambient light** intensity is at **2**, calculate the **total reflected light intensity** at the given point according to **phong's model** with the **attenuation factor.**

Color

- Color is constructed by adding certain amounts of red, green, and blue light
- Light sources have three "types" of color:

- ambient = (I_{ar}, I_{ag}, I_{ab}), diffuse = (I_{dr}, I_{dg}, I_{db}), and specular = $(I_{spr}, I_{spg}, I_{spb})$
  - Ambient reflection coefficient : k_{ar} , k_{ag} , k_{ab}
  - Diffuse reflection coefficient : k_{dr} , k_{dg} , k_{db}
- Color of the specular component is often the same as that of the light source – mirror like, so the specular reflection coefficient:
  k_{sr} , k_{sg} , $k_{sb} = k_s$
  e.g. ***Glossy*** red apple when illuminated by a yellow light is yellow rather than red

Color of an Object

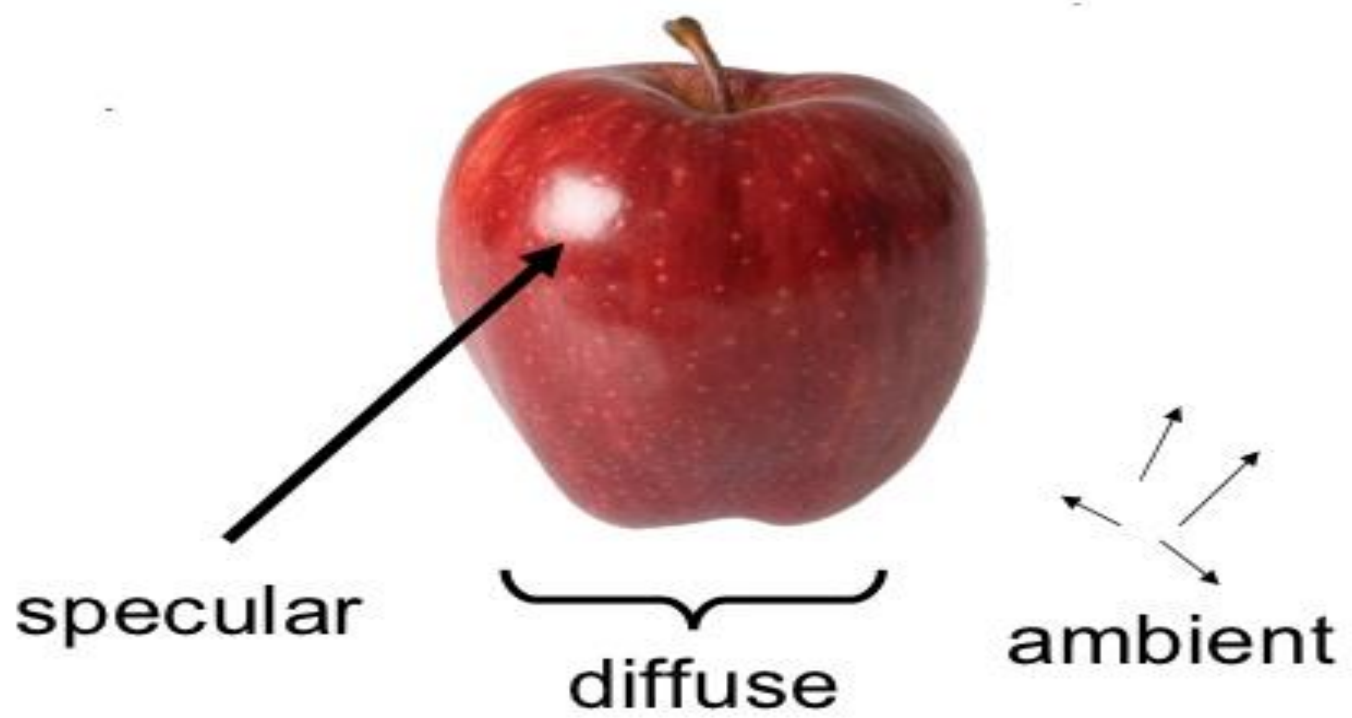


Image synthesis view:

"light, surface, and material interact to reflect light perceived as color, modeled via simplifying assumptions"

Color of an Object

- By “color” of a surface we mean the color that is reflected from it when the illuminated by white light
- The ambient and diffuse reflection coefficients are based on the color of the surface itself.
- The specular reflection coefficient is based on the color of the light source (and the roughness property of the surface)

Color of an Object

- Color of a sphere is 30% red, 45% green, and 25% blue

- Light source in environment:

  Monochrome light (Intensity : $I_{sr} = I_{sg} = I_{sb} = I_s$)

- Sphere's ambient and diffuse reflection coefficients:

  $k_{ar} = k_{dr} = 0.30k$
  $k_{ag} = k_{dg} = 0.45k$
  $k_{ab} = k_{db} = 0.25k$

  here, k is some scaling value

- The individual ambient and diffuse components have intensities

  $I_{ar} = 0.30k\ I_a$, $I_{dr} = 0.30k\ I_s \cos\theta$
  $I_{ag} = 0.45k\ I_a$, $I_{dg} = 0.45k\ I_s \cos\theta$
  $I_{ab} = 0.25k\ I_a$, $I_{ab} = 0.25k\ I_s \cos\theta$

- If the environment is uniformly lighted, $\theta = 0^0$ for sphere!!

Shading

- The process of assigning colors to pixels.

Shading
- Flat Shading
- Smooth Shading
  - Gouraud Shading
  - Phong Shading

Shading Model

- Flat Shading
  - Compute Phong lighting once for entire polygon
- Gouraud Shading
  - Compute Phong lighting at the vertices and interpolate lighting values across polygon
- Phong Shading
  - Interpolate normals across polygon and perform Phong lighting across polygon

Flat Shading

- For each polygon
  - Determines a single intensity value at a chosen point on the polygon
  - Uses that value to shade the entire polygon

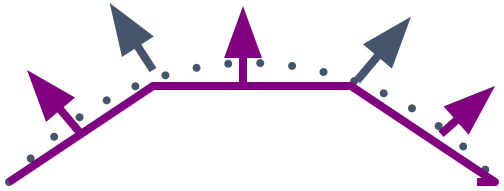
- Assumptions
  - Light source at infinity
  - Viewer at infinity
  - The polygon represents the actual surface being modeled

Problems of Flat Shading

- Specular highlights tends to get lost
- If chosen point on polygon is at location of the light source, then color of the polygon will be significantly distorted.

Smooth Shading

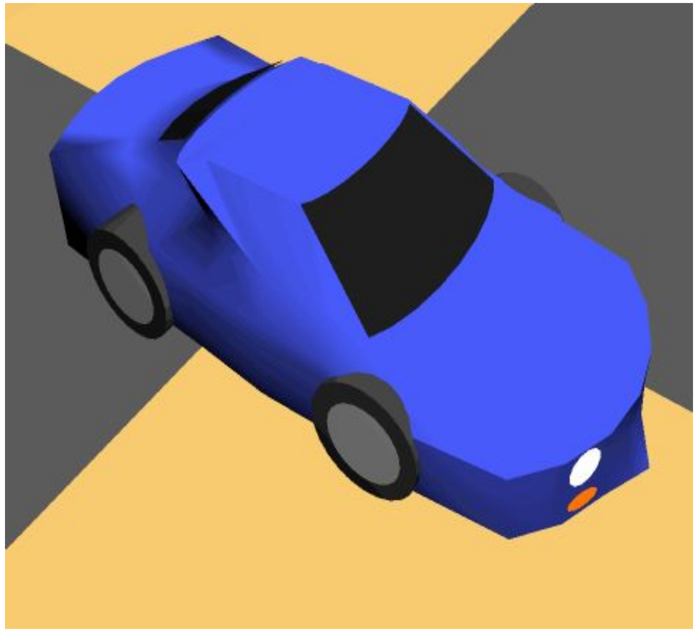
- Introduce vertex normals at each vertex
  – Used only for shading
  – Think of as a better approximation of the real surface that the polygons approximate
  – Finds color value for each point in the polygon individually



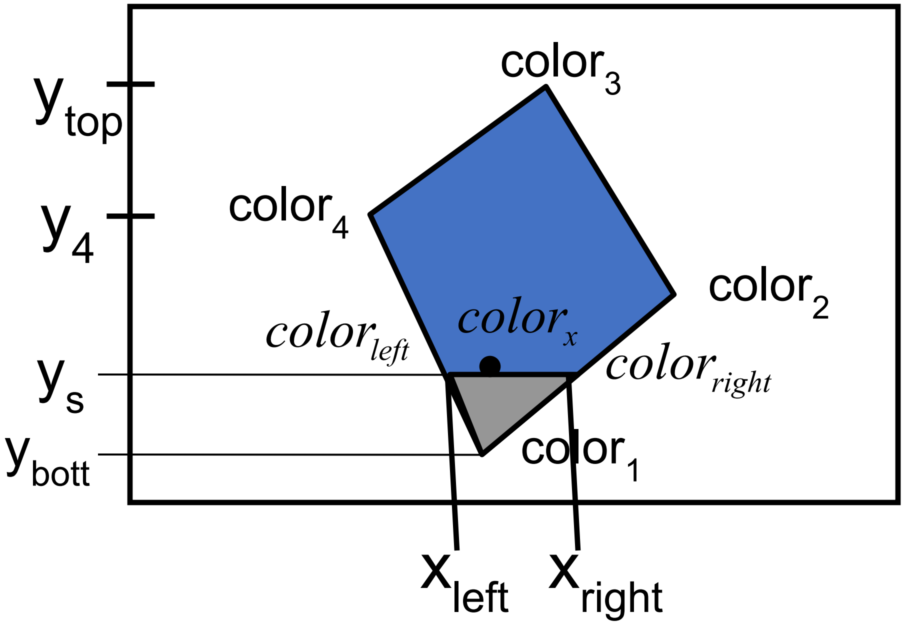
- Two types
  – Gouraud Shading
  – Phong Shading (do not confuse with Phong Lighting Model)

Gouraud Shading

- Most common approach
- Perform Phong lighting at the vertices
- Linearly interpolate the resulting colors over faces
  - Along edges
  - Along scanline



Gouraud Shading

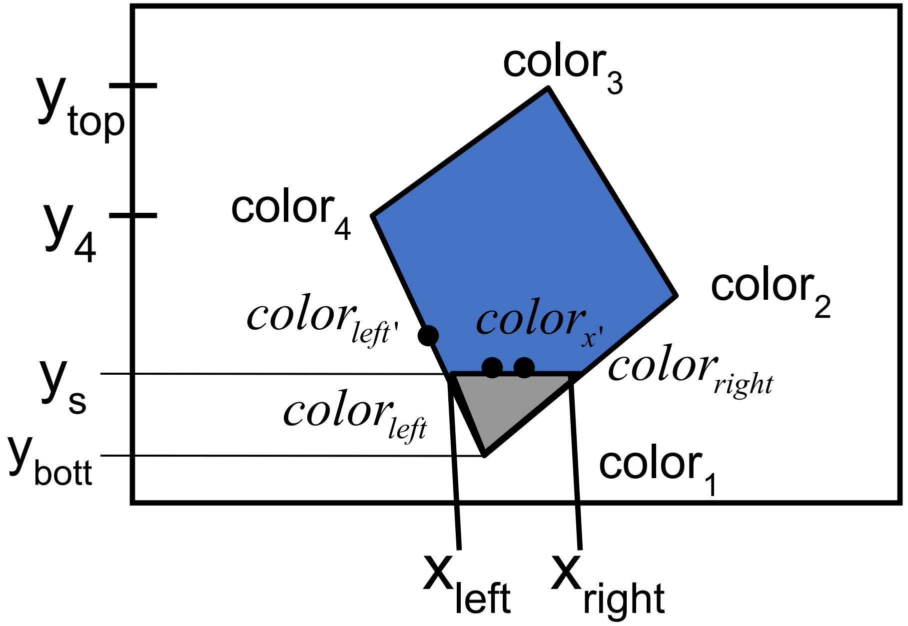


$$color_{left} = color_1 + (color_4 - color_1)\frac{y_s - y_{bott}}{y_4 - y_{bott}}$$

$$color_{right} = color_1 + (color_2 - color_1)\frac{y_s - y_{bott}}{y_2 - y_{bott}}$$

$$color_x = color_{left} + (color_{right} - color_{left})\frac{x - x_{left}}{x_{right} - x_{left}}$$

Gouraud Shading



$$color_x = color_{left} + (color_{right} - color_{left})\frac{x - x_{left}}{x_{right} - x_{left}}$$

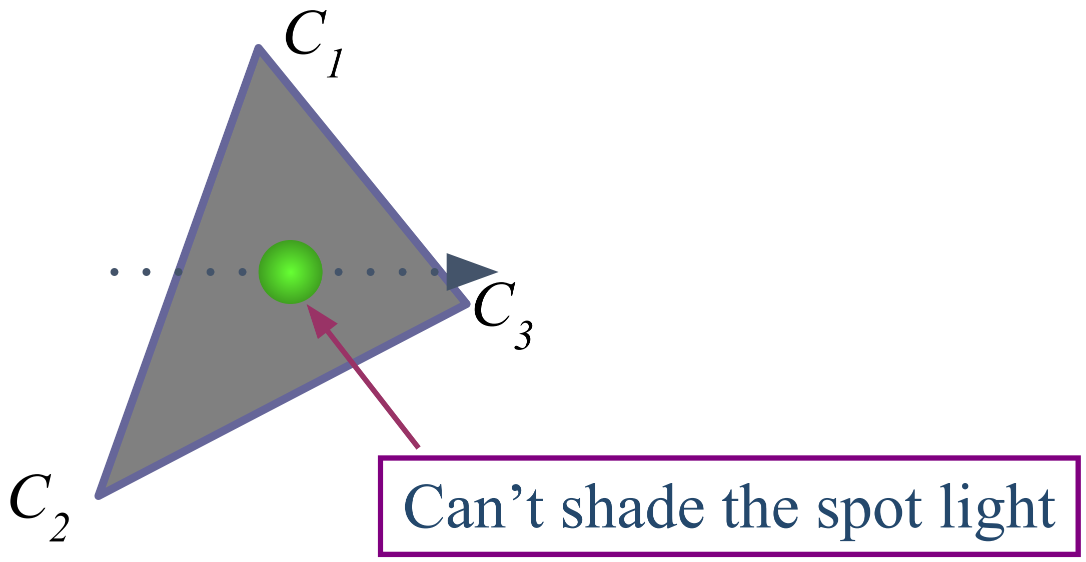
$$color_{x'} = color_x + K\Delta x$$

$$color_{left'} = color_{left} + K'\Delta y$$

Calculate the surface normals along the scan line and the edge using incremental approach

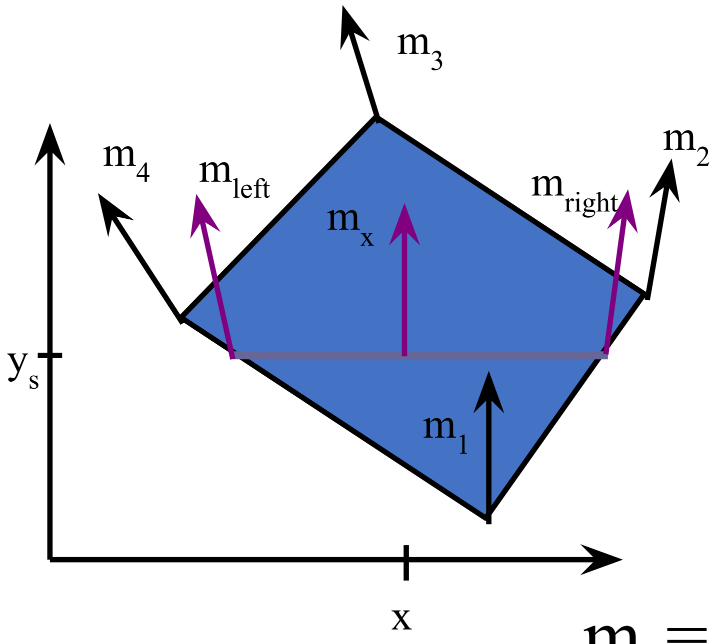
Problem of Gouraud Shading

- Often appears dull
- Lacks accurate specular component



Phong Shading

Interpolate normal vectors of face vertices at each pixel, then perform Phong lighting at each pixel.



$$m_{left} = m_1 + (m_4 - m_1)\frac{y_s - y_1}{Y_4 - y_1}$$

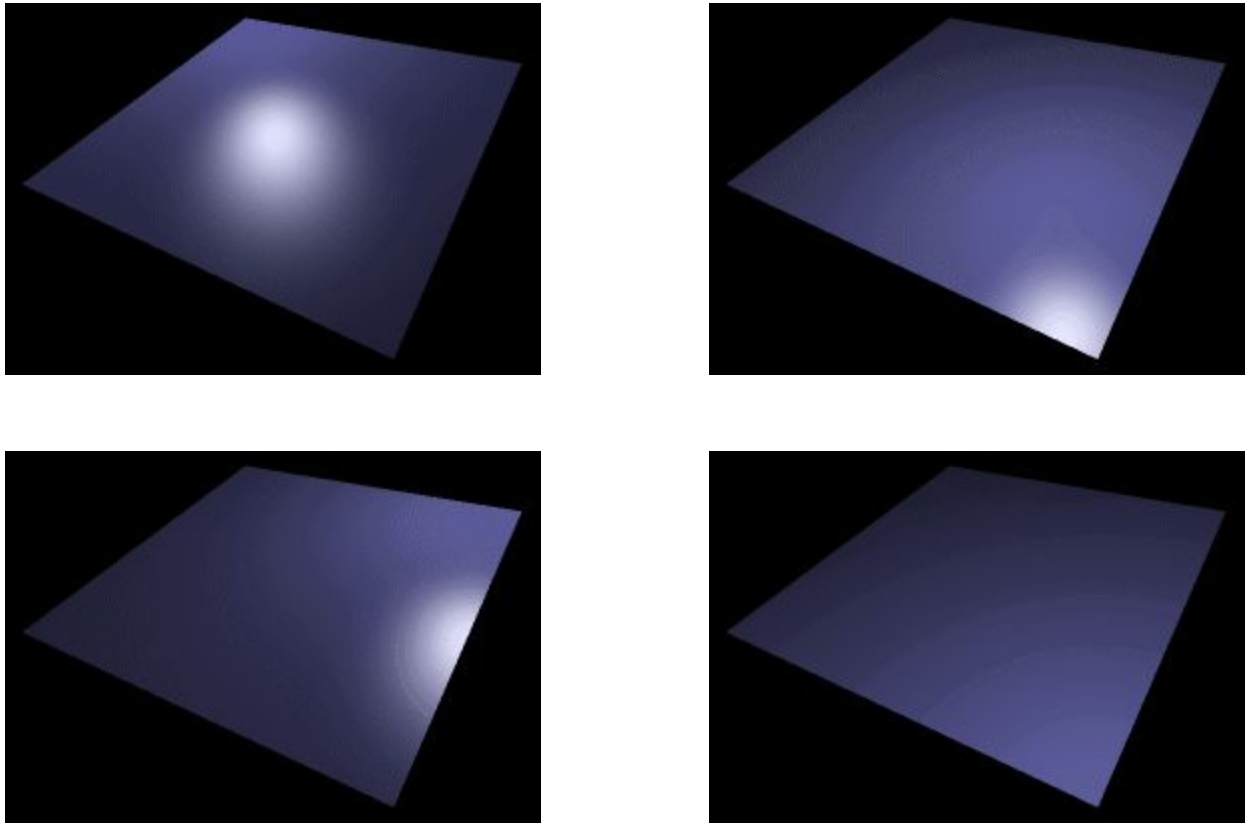
$$m_{right} = m_1 + (m_2 - m_1)\frac{y_s - y_1}{Y_2 - y_1}$$

$$m_x = m_{left} + (m_{right} - m_{left})\frac{x - x_{left}}{x_{right} - x_{left}}$$

Calculate the surface normals along the scan line and the edge using incremental approach

Phong vs Gouraud Shading

- Phong shading is more smooth
- If a highlight does not fall on a vertex, Gouraud shading may miss it completely, but Phong shading does not.



Reference:

Computer Graphics: Principles and Practice: John F. Hughes, James D. Foley, Andries van Dam, Steven K. Feiner (2nd Edition)

Chapter: 16.1.1 - 16.1.4, 16.1.6, 16.2.1 - 16.2.5