

# Computer Graphics and Image Processing Illumination I

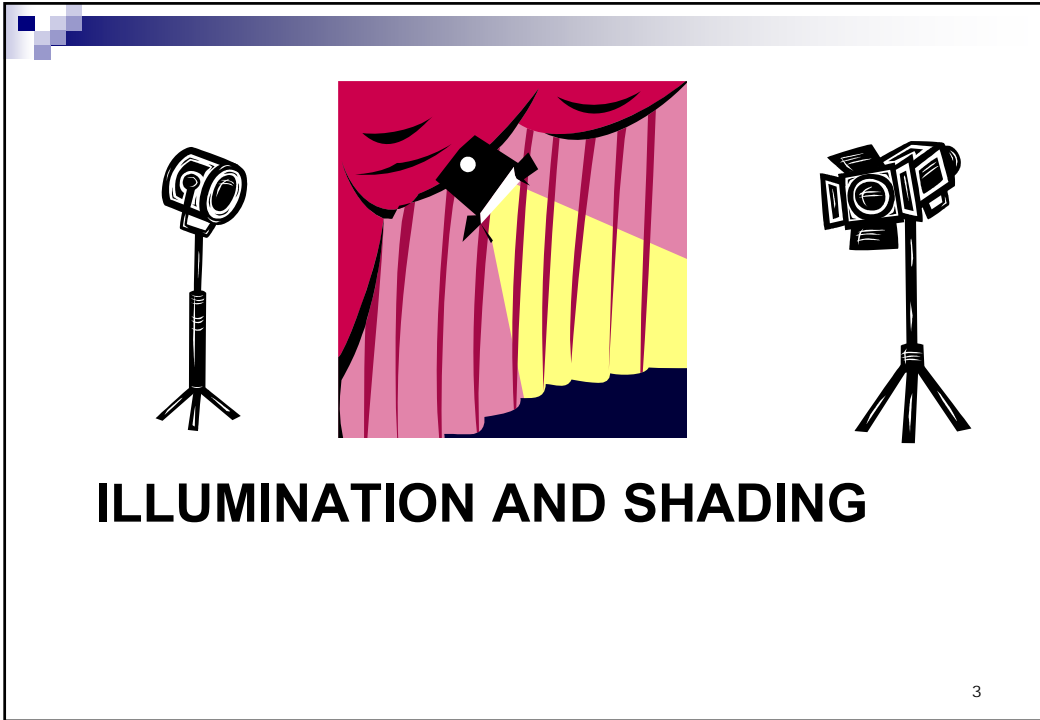
Part 1 – Lecture 7

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## Today's Outline

- Illumination and Shading
- The Phong Illumination Model
  - Ambient Reflection
  - Diffuse Reflection
  - Specular Reflection

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## Illumination vs. Shading

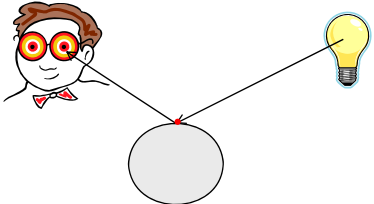
NB: Hill doesn't make this distinction

### Illumination Model


- What color is the surface?  
→ surface reflection model
- Use equations from physics (realistic but time consuming)
- Or use good approximations (much faster to compute!)

### Shading Model

- How do we calculate the color at each pixel?  
→ pixel shading algorithm
- Using exact illumination model for every pixel usually too slow (and often unnecessary)
- Apply the illumination model only sometimes and interpolate



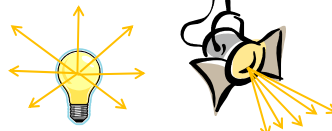
CG is about a trade-off between  
**visual realism vs. computing time**



# Introduction to Illumination Models

- Where does the light come from? → Light sources

- Point sources**  
e.g. lamp, headlight, spotlight

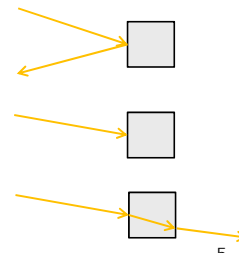


- Directional sources**  
(like a far away point source, rays are parallel)  
e.g. sun



- What happens to the light?

- Reflection:** ray bounces off a surface  
(most important for CG)
  - Absorption:** ray energy taken up by an object,  
e.g. as heat (not important for CG)
  - Transmission:** ray passes through an object,  
e.g. water, glass (often not considered in CG)



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# Types of Light Reflection

- In the real world:
  - Light reflected unlimited number of times
  - Reflections change the appearance of the light
- In CG we need to keep computation time short:
  - Can often calculate only one reflection per vertex
  - Consider different light appearances as different types of reflection
- Ambient reflection:** light reflected so many times, it is everywhere (like uniform background illumination)
- Diffuse reflection:** light scattered from one point equally (more or less) into all directions
- Specular reflection:** light rays bounce off in pretty much only one direction (like from a mirror)
- Type of reflection can depend on light source characteristics and the material of the object

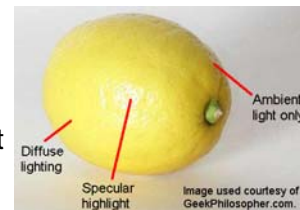
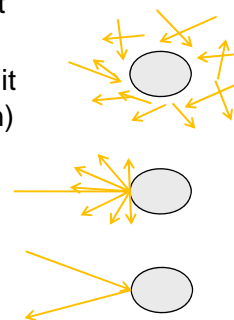
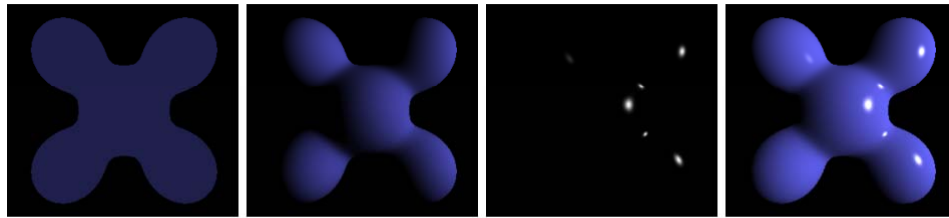


Image used courtesy of GeekPhilosopher.com.



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Ambient + Diffuse + Specular = Phong Reflection

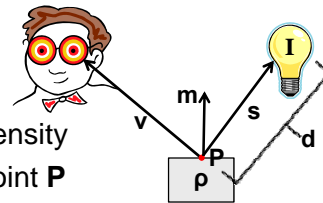
## PHONG ILLUMINATION MODEL

Image thanks to Brad Smith

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## Phong Illumination Model

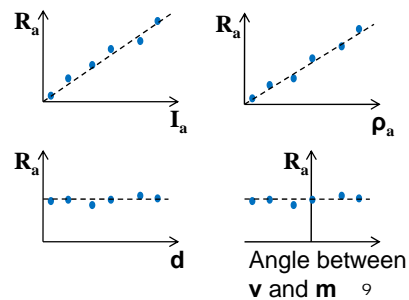
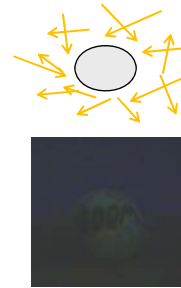
- Invented by Bui Tuong-Phong, PhD at Univ. of Utah 1973
- **Idea:** calculate intensity  $R$  (and color) of visible light at a point as the sum of ambient, diffuse and specular reflection
- Variables taken into account:
  - Intensities (and colors) for incident light:
    - $I_a, I_d, I_s$  for ambient, diffuse and specular intensity
  - Surface normal vector  $\mathbf{m}$  at the illuminated point  $\mathbf{P}$
  - Vector  $\mathbf{s}$  describing the direction to the light source
  - Distance  $d$  to light source
  - Vector  $\mathbf{v}$  describing the direction to the viewer
  - Reflection coefficients of the surface material
    - $\rho_a, \rho_d, \rho_s$  for ambient, diffuse and specular reflection (actually separate coefficients for RGB colors)



$$\begin{aligned} \mathbf{s} &= \text{Light} - \mathbf{P} \\ d &= |\mathbf{s}| \\ \mathbf{v} &= \text{Viewer} - \mathbf{P} \end{aligned}$$

# Ambient Reflection

- **Source:** no single point or directional source  
All the scattered “background” light, e.g. sunlight, lamps, moonlight, star light, ...
- **Direction of reflection:** all directions (it is scattered everywhere)
- **Experiment:** turn out room lights
  - No direct light sources
  - Just some indirect light, e.g. from gap under a door
  - Keeping all other variables constant, we change intensity, view direction, material, etc. and see what happens to the reflected ambient light  $R_a$



# Ambient Reflection

We construct an equation for  $R_a$ :

$$R_a = I_a \rho_a$$

How to deal with colors (RGB)?

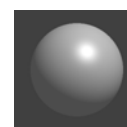
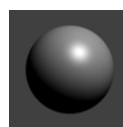
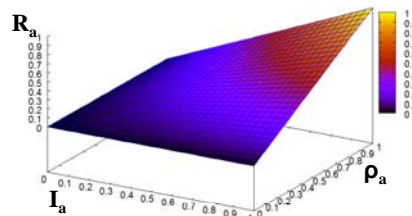
- Instead of just  $I_a$ , use  $I_{ar}, I_{ag}, I_{ab}$   
→ colored light
- Instead of just  $\rho_a$ , use  $\rho_{ar}, \rho_{ag}, \rho_{ab}$   
→ colored materials
- Compute reflected light for each color:

$$R_{ar} = I_{ar} \rho_{ar}$$

$$R_{ag} = I_{ag} \rho_{ag}$$

$$R_{ab} = I_{ab} \rho_{ab}$$

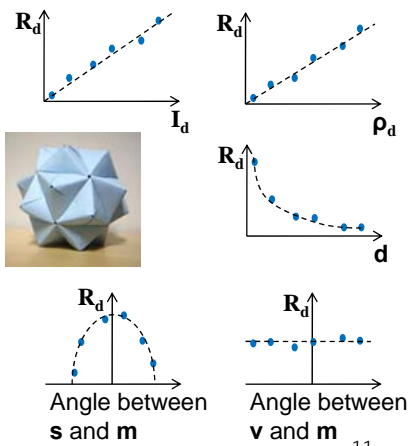
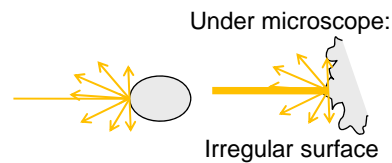
Variable	Influence on $R_a$
$I_a$	Proportional
$\rho_a$	Proportional
$d$	No influence
$v$	No influence



No ambient light    A lot of ambient light

# Diffuse Reflection

- **Source:** one or more point or directional sources
- **Direction of reflection:** all directions (it is scattered everywhere)
- **Experiment:** turn out room lights
  - Use only “soft” light sources where light is already scattered a little (but not everywhere), e.g. light bulb
  - Shine on rough surface, e.g. rough wood, stone or cloth
  - Keeping all other variables constant, we change intensity, view direction, material, etc. and see what happens to the reflected ambient light  $R_d$

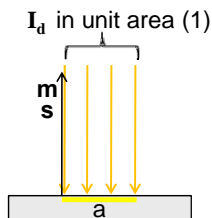
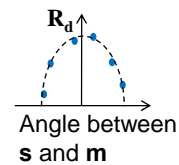


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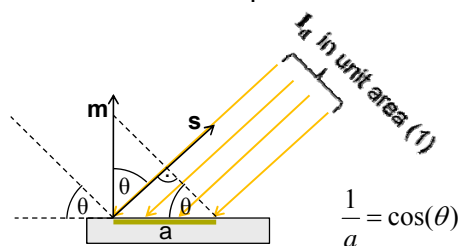
# Lambert's Law

Why does  $R_d$  depend on the angle between  $s$  and  $m$ ?

- $R_d$  proportional to incoming  $I_d$  per unit area
- Rays spread over larger area means less reflection per unit area



At angle 0 between  $s$  and  $m$ , rays hit area of the same size, i.e.  $a=1$  and  $R_d \sim I_d$



At angle  $\theta$  between  $s$  and  $m$ , rays hit area  $a$  of the size  $1/\cos(\theta)$

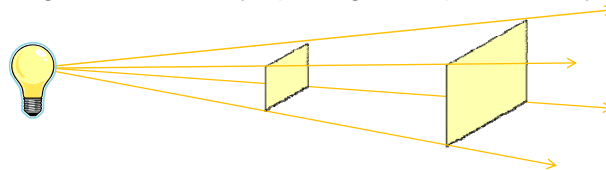
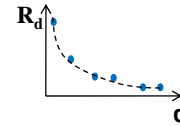
$$R_d \sim \frac{I_d}{1/\cos(\theta)} = I_d \cos(\theta) = I_d \frac{s \cdot m}{|s||m|}$$

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## Distance from Light Source

In the real world:

- Intensity of light from a point source decreases quadratically with  $d$ , i.e. divide intensity by  $d^2$
- Area through which the rays pass grows quadratically with  $d$



In CG:

- Dividing intensity by  $d^2$  would make intensities too small
- CG “hack” is to divide by  $(k_c + k_l d + k_q d^2)$
- $k_c$ ,  $k_l$ ,  $k_q$  are programmer-chosen constants (no real world meaning)
- Typically,  $k_c = 1.0$ ,  $0 < k_l < 1$  and  $k_q = 0$ , but usually they have to be tuned so that it looks good

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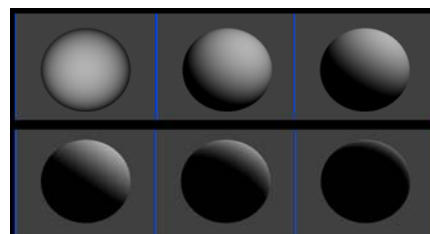
## Diffuse Reflection

We construct an equation for  $R_d$ :

$$R_d = I_d \rho_d \frac{s \cdot m}{|s||m|} / (k_c + k_l d + k_q d^2)$$

- Add color by calculating  $R_{dr}$ ,  $R_{dg}$ ,  $R_{db}$  using  $I_{dr}$ ,  $I_{dg}$ ,  $I_{db}$  and  $\rho_{dr}$ ,  $\rho_{dg}$ ,  $\rho_{db}$  instead of just  $R_d$ ,  $I_d$  and  $\rho_d$

Variable	Influence on $R_d$
$I_d$	Proportional
$\rho_d$	Proportional
$s$	Lambert's law
$d$	Divide by $(k_c + k_l d + k_q d^2)$
$v$	No influence

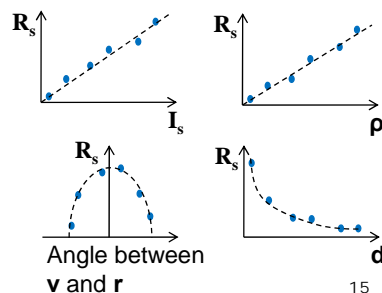
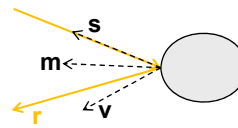


Lambertian spheres  
(diffuse reflectors)

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# Specular Reflection

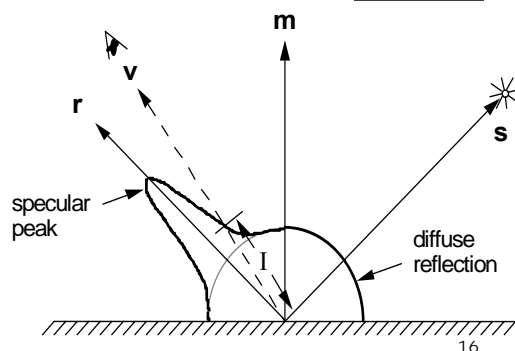
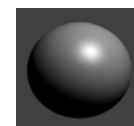
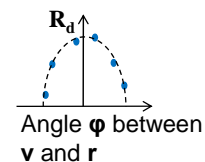
- **Source:** one or more point or directional sources
- **Direction of reflection  $r$ :** mostly only one (very little scattering) →  $r$  is calculated from  $s$  and  $m$
- **Experiment:** turn out room lights
  - Use only hard light sources where light is not scattered, e.g. a spotlight
  - Shine on glossy surface, e.g. polished metal
  - Keeping all other variables constant, we change intensity, view direction, material, etc. and see what happens to the reflected ambient light  $R_a$



# Specular Highlight

Angle  $\phi$  between  $v$  and  $r$ :

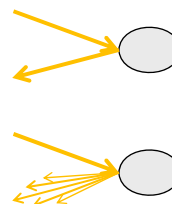
- Looking directly into the reflected ray ( $0^\circ$ ) = very bright
- The farther the reflected ray away from the eye, the darker
- Result: a bright spot where the light is reflected directly into the eye (→ highlight)
- Model as cosine function:
 
$$R_s \text{ grows with } \cos(\phi) = \frac{v \cdot r}{|v||r|}$$
- But  $R_s$  is always positive, so if  $\cos(\phi)$  negative set  $R_s$  to 0



# Shininess $\alpha$

Different behaviors of specular surfaces:

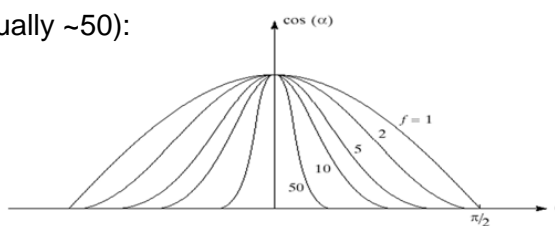
- Some glossy materials reflect perfectly (e.g. a mirror), i.e. one ray is pretty much reflected as one ray → small highlight (bigger shininess  $\alpha$ )
- Other materials scatter incoming rays a little bit, i.e. several outgoing rays close together → bigger highlight (smaller shininess  $\alpha$ )



Shininess  $\alpha$  of object surface (usually ~50):

- “Focus” of specular reflection
- Use as exponent of our cosine specular reflection formula:

$$\cos(\varphi)^\alpha = \left( \frac{\mathbf{v} \cdot \mathbf{r}}{\|\mathbf{v}\| \|\mathbf{r}\|} \right)^\alpha$$



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# Specular Reflection

We construct an equation for  $\mathbf{R}_s$ :

(assuming we have calculated  $\mathbf{r}$  from  $\mathbf{s}$  and  $\mathbf{m}$ )

$$\mathbf{R}_s = \mathbf{I}_s \rho_s \left( \frac{\mathbf{v} \cdot \mathbf{r}}{\|\mathbf{v}\| \|\mathbf{r}\|} \right)^\alpha / (k_c + k_l d + k_q d^2)$$

Variable	Influence on $\mathbf{R}_s$
$\mathbf{I}_s$	Proportional
$\rho_s$	Proportional
$\mathbf{r}$ and $\mathbf{v}$	Highlight intensity
$\alpha$	Highlight size
$d$	Divide by $(k_c + k_l d + k_q d^2)$

- Add color by calculating  $\mathbf{R}_{sr}$ ,  $\mathbf{R}_{sg}$ ,  $\mathbf{R}_{sb}$  using  $\mathbf{I}_{sr}$ ,  $\mathbf{I}_{sg}$ ,  $\mathbf{I}_{sb}$  and  $\rho_{sr}$ ,  $\rho_{sg}$ ,  $\rho_{sb}$  instead of just  $\mathbf{R}_s$ ,  $\mathbf{I}_s$  and  $\rho_s$



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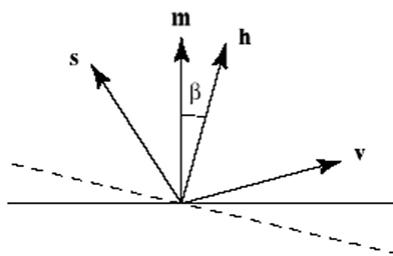
# Specular Reflection Optimized

Instead of calculating  $\mathbf{r}$ , use simpler **halfway-vector**  $\mathbf{h}$  for highlight:

$$\left( \frac{\mathbf{h} \cdot \mathbf{m}}{|\mathbf{h}| |\mathbf{m}|} \right)^\alpha \quad \text{with}$$

$\mathbf{h} = \text{normalized}(\text{normalized}(\mathbf{s}) + \text{normalized}(\mathbf{v}))$   
 ( $\rightarrow \mathbf{h}$  is half way between  $\mathbf{s}$  and  $\mathbf{v}$ )

- Consider angle between  $\mathbf{h}$  and  $\mathbf{m}$  instead of angle between  $\mathbf{r}$  and  $\mathbf{v}$ 
  - If  $\mathbf{h}$  is exactly on  $\mathbf{m}$  ( $0^\circ$ ) then reflection directly into the eye ( $\mathbf{r}$  on  $\mathbf{v}$ )
  - Greater angle between  $\mathbf{h}$  and  $\mathbf{m} \rightarrow$  greater angle between  $\mathbf{r}$  and  $\mathbf{v}$
- Not mathematically identical, but same general properties
- Larger highlight for any given  $\alpha$  because angle grows slower
- Used by OpenGL



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# Final Phong Equation

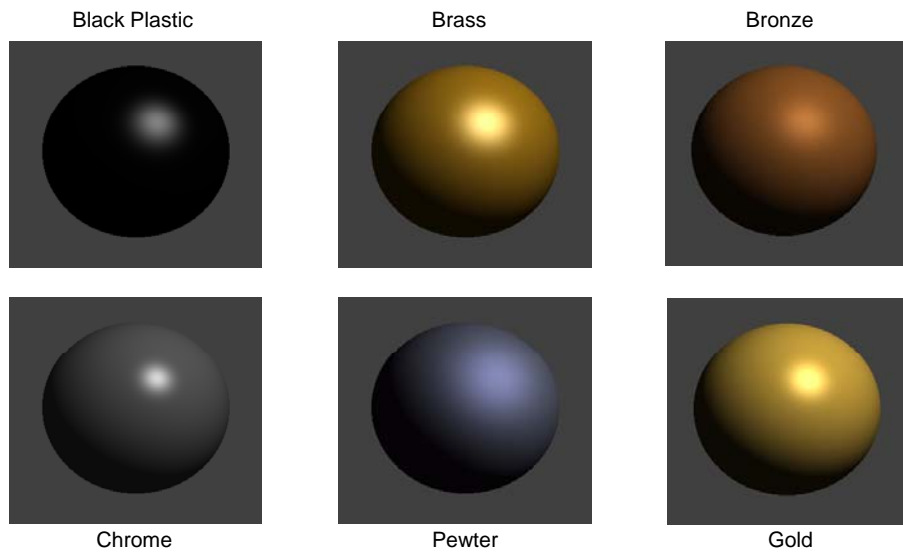
- Achromatic version:
 
$$\mathbf{R} = \mathbf{I}_a \rho_a + \left( \mathbf{I}_d \rho_d \frac{\mathbf{s} \cdot \mathbf{m}}{|\mathbf{s}| |\mathbf{m}|} + \mathbf{I}_s \rho_s \left( \frac{\mathbf{h} \cdot \mathbf{m}}{|\mathbf{h}| |\mathbf{m}|} \right)^\alpha \right) / (k_c + k_l d + k_q d^2)$$
- Chromatic version (RGB):
 
$$\mathbf{R}_r = \mathbf{I}_{ar} \rho_{ar} + \left( \mathbf{I}_{dr} \rho_{dr} \frac{\mathbf{s} \cdot \mathbf{m}}{|\mathbf{s}| |\mathbf{m}|} + \mathbf{I}_{sr} \rho_{sr} \left( \frac{\mathbf{h} \cdot \mathbf{m}}{|\mathbf{h}| |\mathbf{m}|} \right)^\alpha \right) / (k_c + k_l d + k_q d^2)$$

$$\mathbf{R}_g = \mathbf{I}_{ag} \rho_{ag} + \left( \mathbf{I}_{dg} \rho_{dg} \frac{\mathbf{s} \cdot \mathbf{m}}{|\mathbf{s}| |\mathbf{m}|} + \mathbf{I}_{sg} \rho_{sg} \left( \frac{\mathbf{h} \cdot \mathbf{m}}{|\mathbf{h}| |\mathbf{m}|} \right)^\alpha \right) / (k_c + k_l d + k_q d^2)$$

$$\mathbf{R}_b = \mathbf{I}_{ab} \rho_{ab} + \left( \mathbf{I}_{db} \rho_{db} \frac{\mathbf{s} \cdot \mathbf{m}}{|\mathbf{s}| |\mathbf{m}|} + \mathbf{I}_{sb} \rho_{sb} \left( \frac{\mathbf{h} \cdot \mathbf{m}}{|\mathbf{h}| |\mathbf{m}|} \right)^\alpha \right) / (k_c + k_l d + k_q d^2)$$
- For multiple light sources: add up the reflected light

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# Phong Shading Examples



Hill, Fig. 8.17



**SUMMARY**

## Summary

- **Illumination models:** what color does a surface have?
- **Shading models:** how to calculate the color of each pixel?
- **Phong illumination model:**  
calculate intensity  $\mathbf{R}$  (and color) of visible light at a point as the sum of ambient, diffuse and specular reflection
  - Ambient reflection: light scattered everywhere (background illumination)
  - Diffuse reflection: light reflected into all directions on rough surface
  - Specular reflection: light reflected directly into the eye

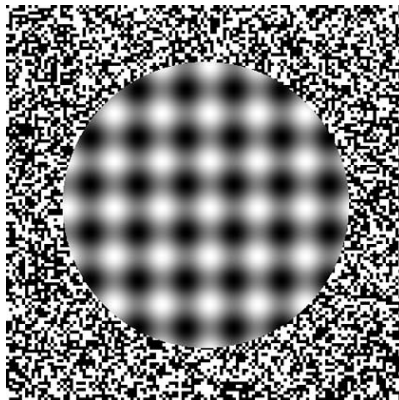
### References:

- Phong Illumination Model: Hill, Chapter 8.2, pp. 381-391

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## Quiz

1. Why does the view direction not matter for diffusely reflected light?
2. What does Lambert's law say? Where do we use it?
3. What does the shininess parameter  $\alpha$  do?



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