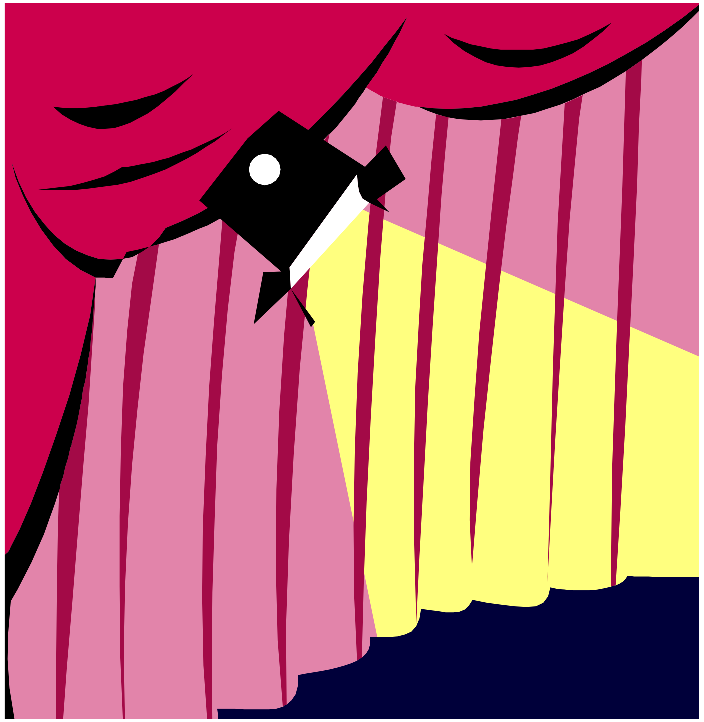
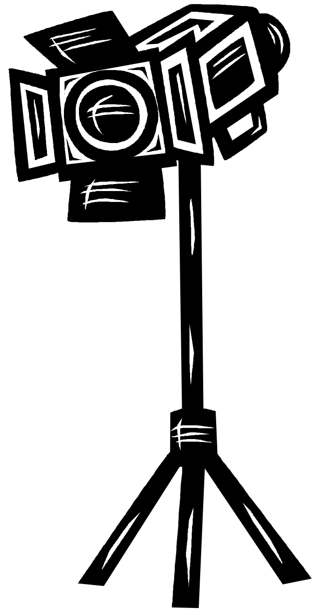
GRAPHICS GROUP

Computer Graphics: Illumination I

Part 2 – Lecture 4

Today's Outline

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

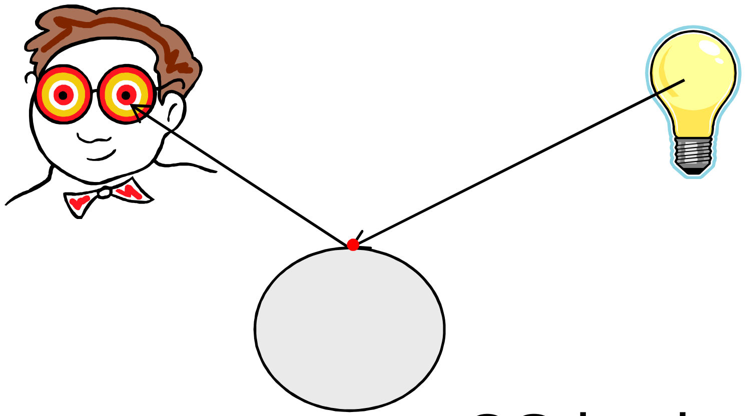
ILLUMINATION AND SHADING

Illumination vs. Shading

NB: Hill doesn't make this distinction

Illumination Model

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



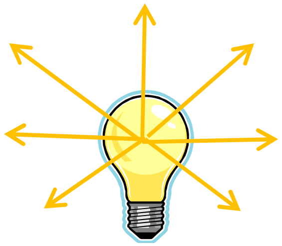
Shading Model

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

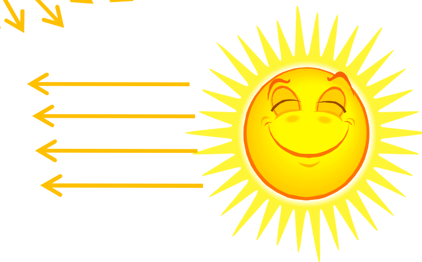
CG is about a trade-off between
visual realism vs. **computing time**

Introduction to Illumination Models

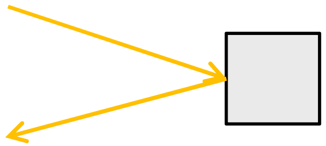
- Where does the light come from? → Light sources
  - **Point sources**
    e.g. lamp, headlight, spotlight



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

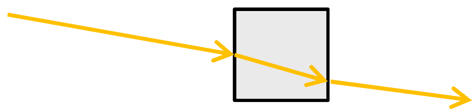


- What happens to the light?
  - **Reflection**: ray bounces off a surface
    (most important for CG)

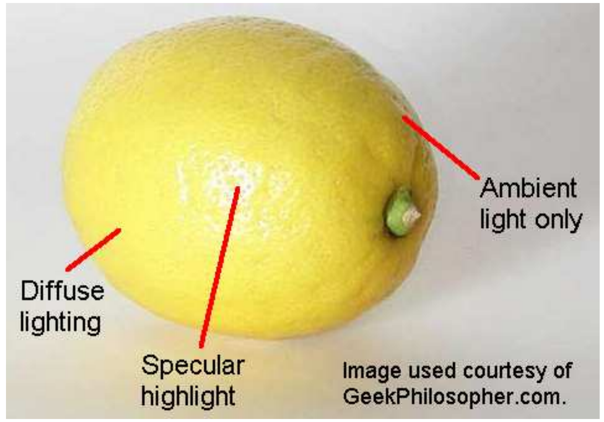


  - **Absorbtion**: ray energy taken up by an object,
    e.g. as heat (not important for CG)

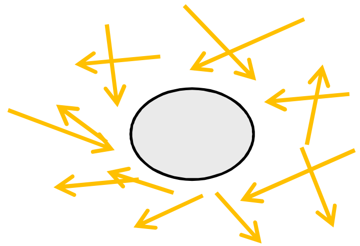
  - **Transmission**: ray passes through an object,
    e.g. water, glass (often not considered in CG)



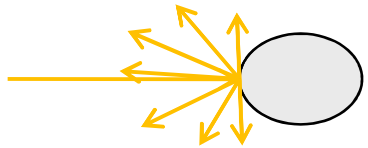
Types of Light Reflection



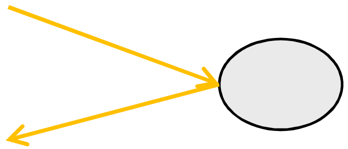
- In the real world:
  - Light reflected unlimited number of times
  - Reflections change the appearance of the light
- In CG we need to keep computation time short:
  - Can often calculate only one reflection per vertex
  - Consider different light appearances as different types of reflection
- **Ambient reflection**: light reflected so many times, it is everywhere (like uniform background illumination)



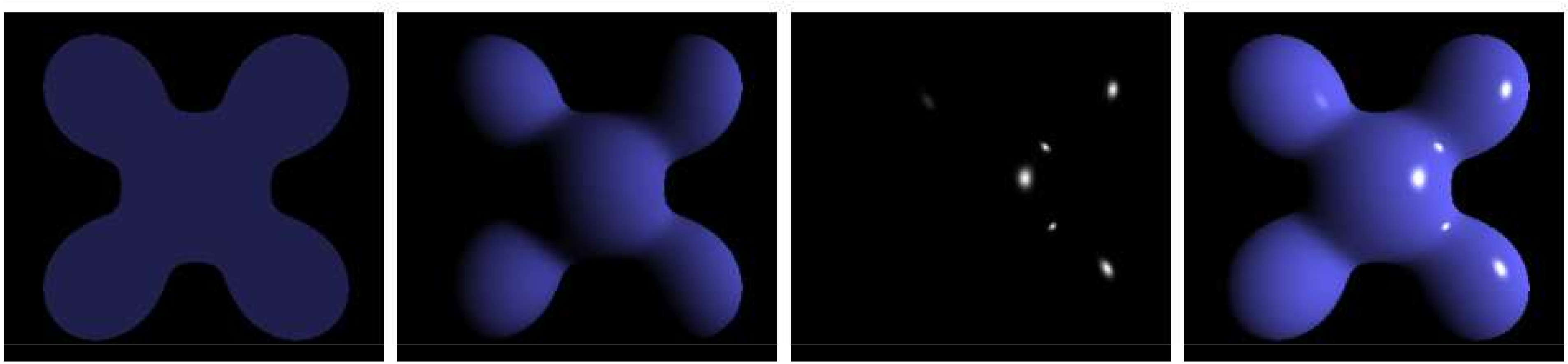
- **Diffuse reflection**: light scattered from one point equally (more or less) into all directions



- **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

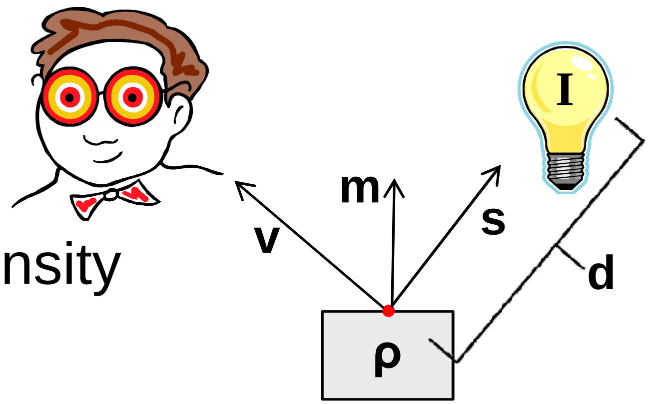


PHONG ILLUMINATION MODEL

Image thanks to Brad Smith

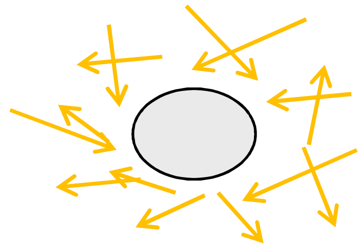
Phong Illumination Model

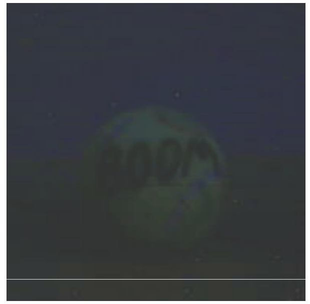
- Invented by Bui Tuong-Phong, PhD at Univ. of Utah 1973
- Idea: calculate intensity **I** (and color) of visible light at a point as the sum of ambient, diffuse and specular reflection
- Variables taken into account:
  - Intensities (and colors) for incident light:
    $\mathbf{I}_a$, $\mathbf{I}_d$,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

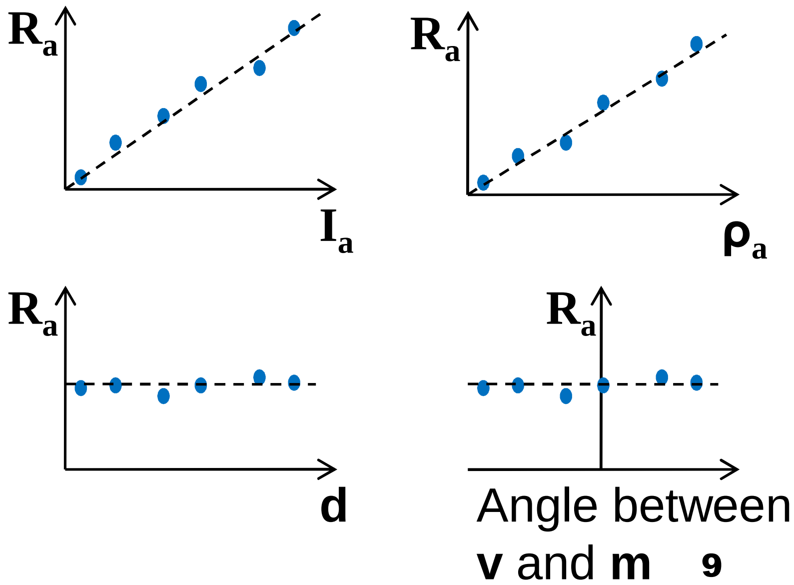


Ambient Reflection

- **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 $\mathbf{R_a}$







Ambient Reflection

We construct an equation for $\mathbf{R_a}$:

$$\mathbf{R_a} = \mathbf{I_a} \, \rho_a$$

Variable	Influence on $\mathbf{R_a}$
$\mathbf{I_a}$	Proportional
$\boldsymbol{\rho}_a$	Proportional
d	No influence
v	No influence

How to deal with colors (RGB)?

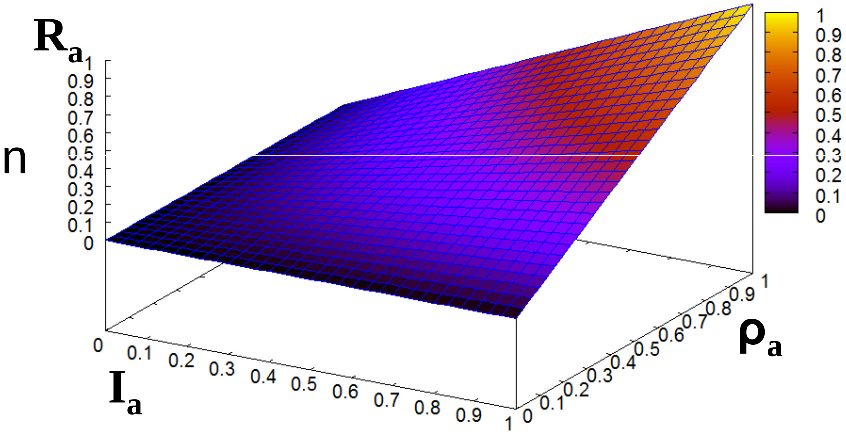
- Instead of just $\mathbf{I_a}$, use $\mathbf{I_{ar}}$, $\mathbf{I_{ag}}$, $\mathbf{I_{ab}}$ $\rightarrow$ colored light
- Instead of just $\boldsymbol{\rho}_a$, use $\boldsymbol{\rho}_{ar}$, $\boldsymbol{\rho}_{ag}$, $\boldsymbol{\rho}_{ab}$ $\rightarrow$ colored materials
- Compute reflected light for each color:

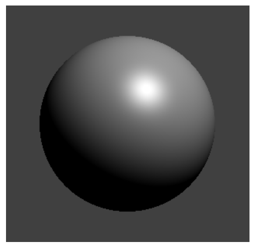
$$\mathbf{R_{ar}} = \mathbf{I_{ar}} \, \rho_{ar}$$

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

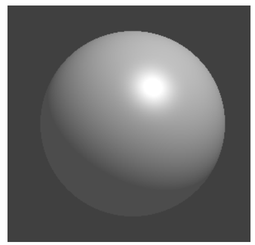
$$\mathbf{R_{ab}} = \mathbf{I_{ab}} \, \rho_{ab}$$

Diffuse Reflection





No ambient light

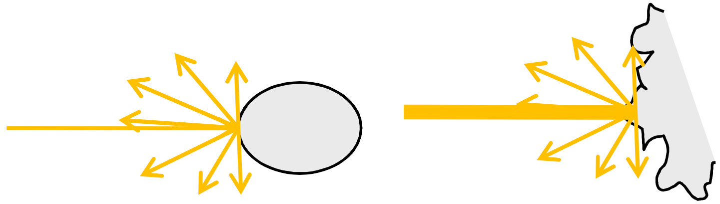


A lot of ambient light

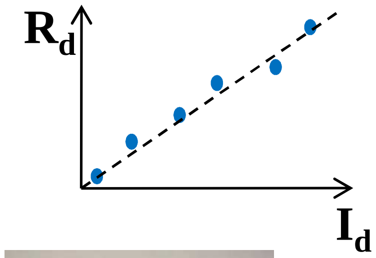
Diffuse Reflection

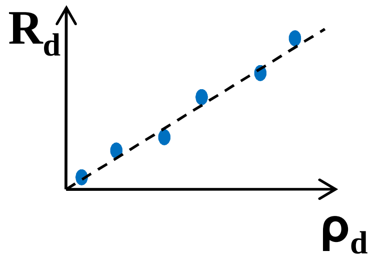
- **Source:** one or more point or directional sources
- **Direction of reflection:** all directions (it is scattered everywhere)
- **Experiment**: turn out room lights
  - Use only “soft” light sources where light is already scattered a little (but not everywhere), e.g. light bulb
  - Shine on rough 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 $\mathbf{R_a}$

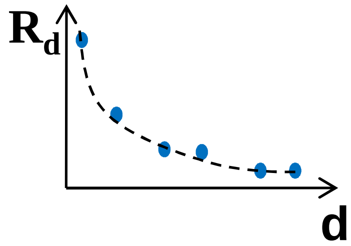
Under microscope:

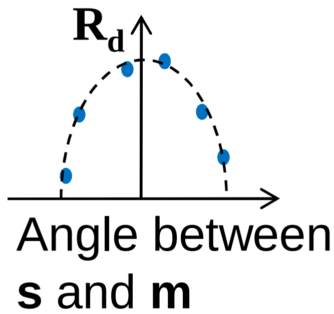


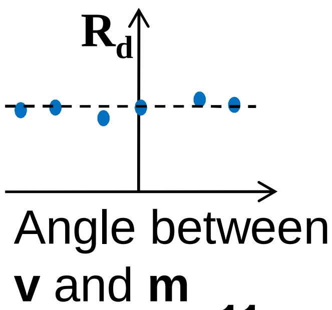
Irregular surface



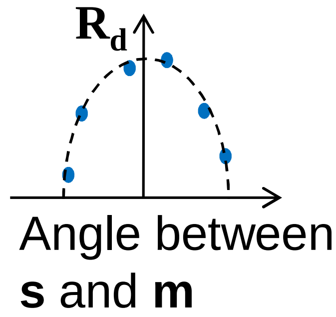






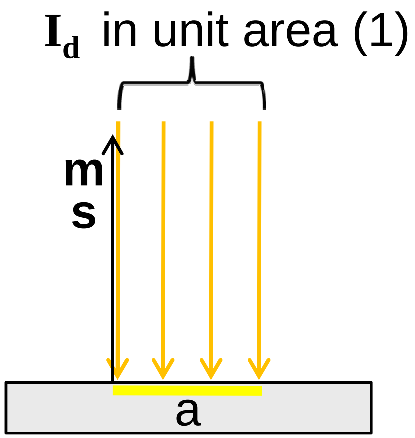


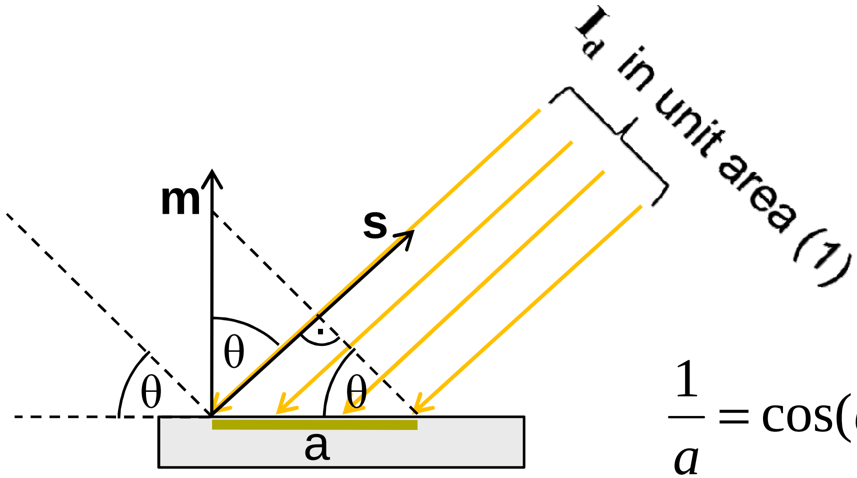
Lambert's Law



Why does $\mathbf{R_d}$ depend on the angle between **s** and **m**?

- $\mathbf{R_d}$ proportional to incoming $\mathbf{I_d}$ **per unit area**
- Rays spread over larger area means less reflection per unit area





$$\frac{1}{a} = \cos(\theta)$$

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

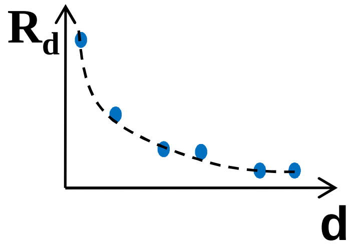
At angle θ between **s** and **m**, rays hit area a of the size 1/cos(θ)

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

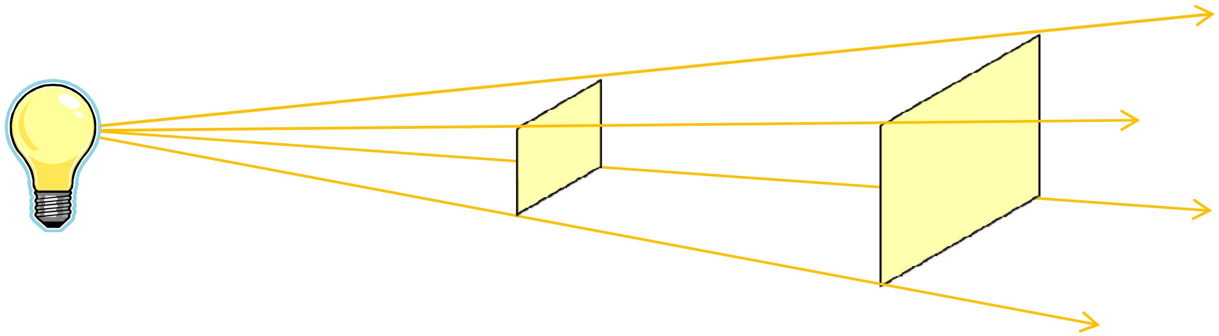
Distance from Light Source

In the real world:

- Intensity of light from a point source decreases quadratically with d, i.e. divide intensity by $\mathbf{d}^2$



- 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

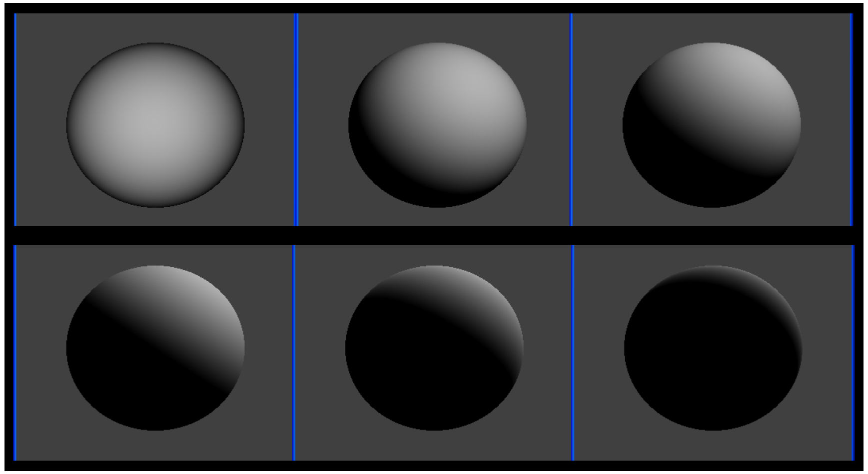
Diffuse Reflection

We construct an equation for $\mathbf{R_d}$:

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

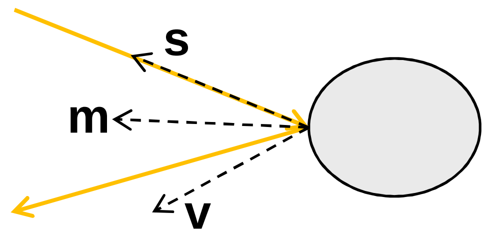
Variable	Influence on $\mathbf{R_d}$
$\mathbf{I_a}$	Proportional
$\boldsymbol{\rho}_\mathbf{d}$	Proportional
s	Lambert's law
d	Divide by ($k_c + k_l d + k_q d^2$)
v	No influence

- Add color by calculating $\mathbf{R_{dr}}$, $\mathbf{R_{dg}}$, $\mathbf{R_{db}}$ using $\mathbf{I_{dr}}$, $\mathbf{I_{dg}}$, $\mathbf{I_{db}}$ and $\boldsymbol{\rho}_\mathbf{dr}$, $\boldsymbol{\rho}_\mathbf{dg}$, $\boldsymbol{\rho}_\mathbf{db}$ instead of just $\mathbf{R_d}$, $\mathbf{I_d}$ and $\boldsymbol{\rho}_\mathbf{d}$

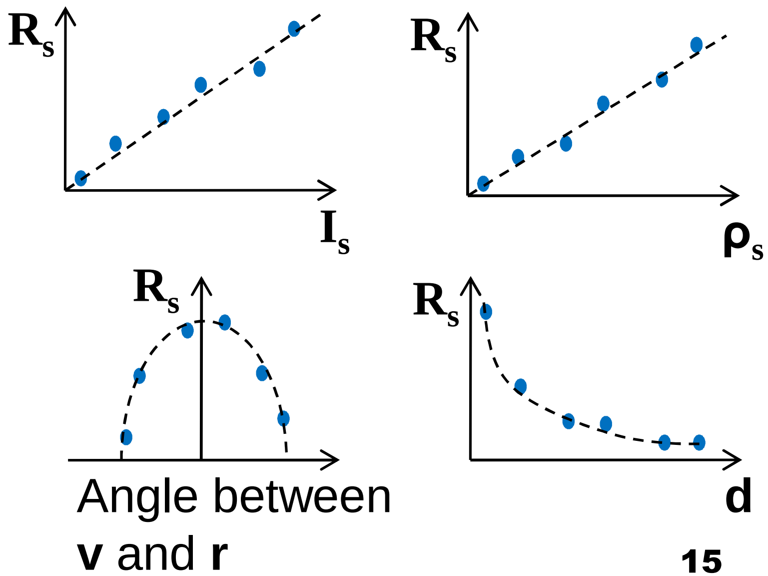


Lambertian spheres
(diffuse reflectors)

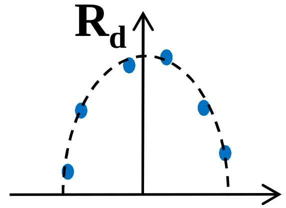
Specular Reflection



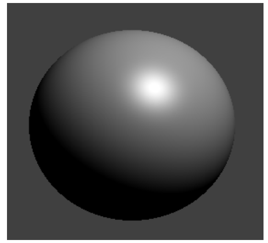
- **Source:** one or more point or directional sources
- **Direction of reflection r:** mostly only one (very little scattering) $\rightarrow$ **r** is calculated from **s** and **m**
- **Experiment**: turn out room lights
  - Use only hard light sources where light is not scattered, e.g. a spotlight
  - 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 **φ** between **v** and **r**

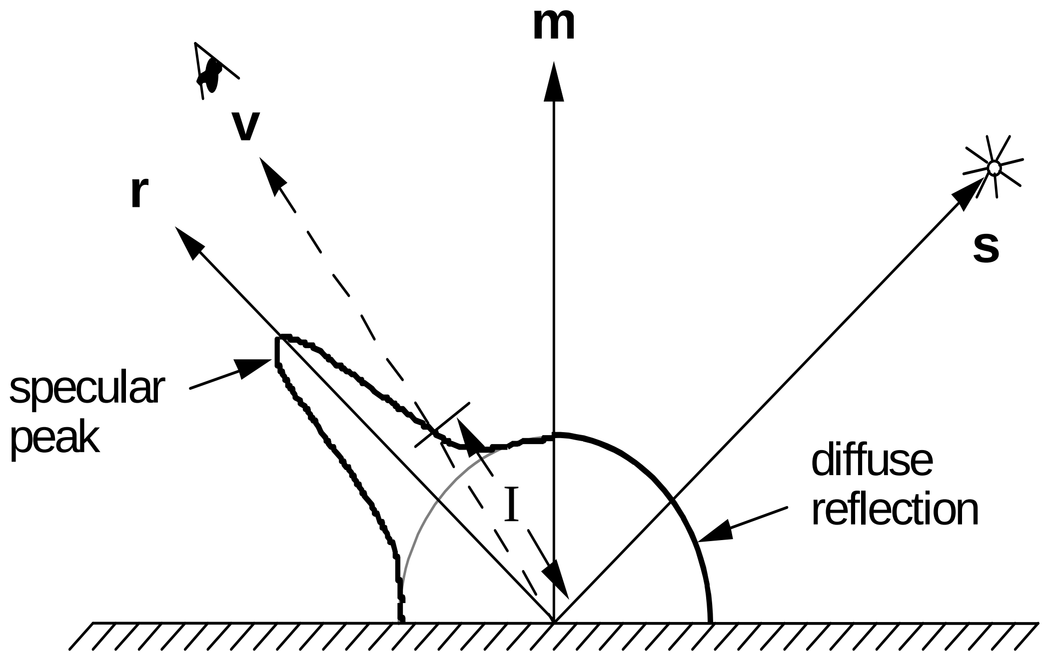


Angle **φ** between **v** and **r**:

- Looking directly into the reflected ray (0°) = very bright
- The farther the reflected ray away from the eye, the darker
- Result: a bright sport where the light is reflected directly into the eye (→ highlight)
- Model as cosine function:

$$\mathbf{R_d} \text{ grows with } \cos(\varphi) = \frac{v \cdot r}{|v||r|}$$

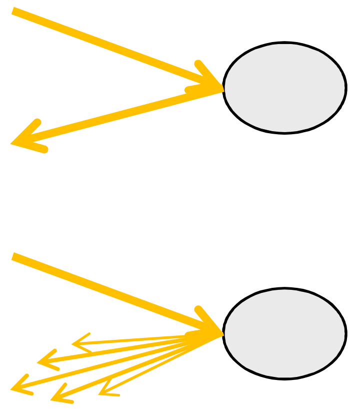
- But $\mathbf{R_d}$ is always positive, so if cos(**φ**) negative set $\mathbf{R_d}$ to 0



Shininess α

Different behaviors of specular surfaces:

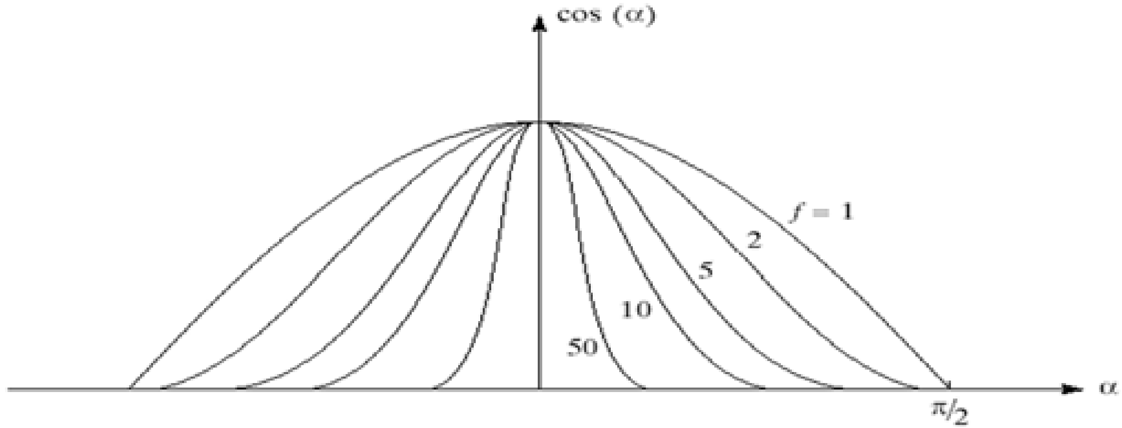
- Some glossy materials reflect perfectly (e.g. a mirror), i.e. one ray is pretty much reflected as one ray
  $\rightarrow$ small highlight (bigger shininess α)
- Other materials scatter incoming rays a little bit, i.e. several outgoing rays close together
  $\rightarrow$ bigger highlight (smaller shininess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



Shininess α of object surface:

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

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



Specular Reflection

We construct an equation for $\mathbf{R_d}$:

(assuming we have calculated **r** from **s** and **m**)

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

Variable	Influence on $\mathbf{R_s}$
$\mathbf{I_s}$	Proportional
$\boldsymbol{\rho_s}$	Proportional
r and **v**	Highlight intensity
α	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 $\boldsymbol{\rho_{sr}}, \boldsymbol{\rho_{sg}}, \boldsymbol{\rho_{sb}}$ instead of just $\mathbf{R_s}$, $\mathbf{I_s}$ and $\boldsymbol{\rho_s}$

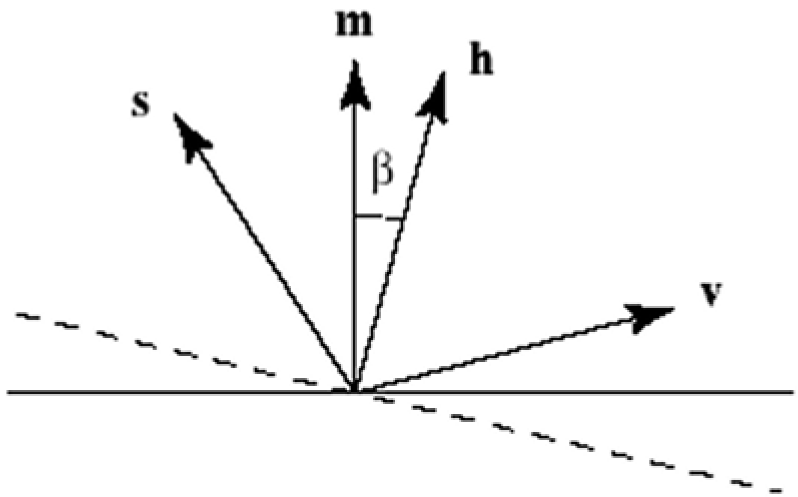
Specular Reflection Optimized

Instead of calculating **r**, use simpler **halfway-vector h** for highlight:

$$\left(\frac{h \cdot m}{|h||m|}\right)^{\alpha}$$

with **h** = normalized (**s** + **v**)
(→ **h** is half way between **s** and **v**)

- Consider angle between **h** and **m** instead of angle between **r** and **v**
  - If **h** is exactly on **m** (0°) then reflection directly into the eye (**r** on **v**)
  - Greater angle between **h** and **m** → greater angle between **r** and **v**
- Not mathematically identical, but same general properties
- Larger highlight for any given α because angle grows slower
- Used by OpenGL



Final Phong Equation

- Achromatic version:

$$\mathbf{R} = \mathbf{I_a}\,\rho_a + (\mathbf{I_d}\,\rho_d \frac{s \cdot m}{|s||m|} + \mathbf{I_s}\,\rho_s \left(\frac{h \cdot m}{|h||m|}\right)^{\alpha}) / (k_c + k_l d + k_q d^2)$$

- Chromatic version (RGB):

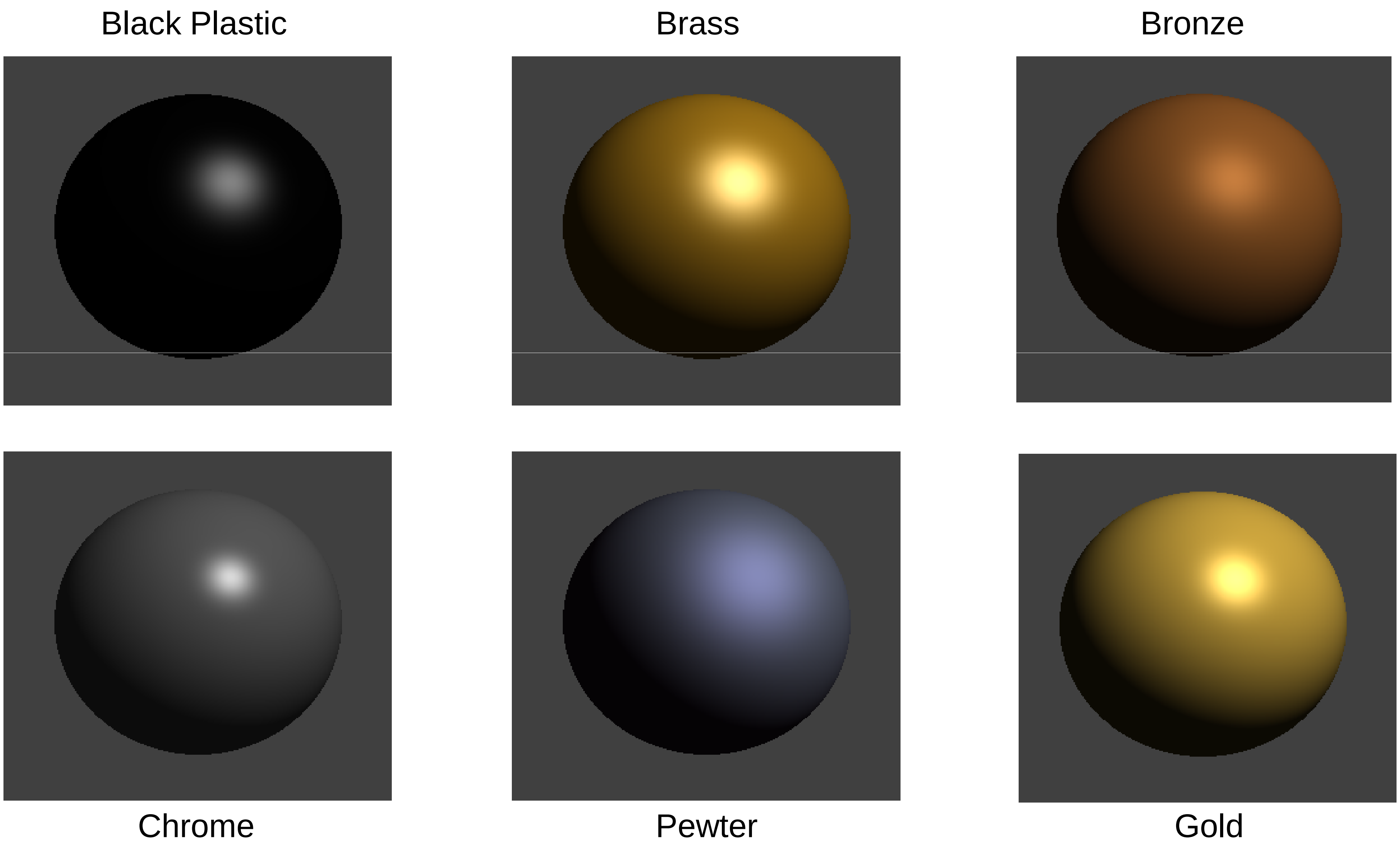
$$\mathbf{R_r} = \mathbf{I_{ar}}\,\rho_{ar} + (\mathbf{I_{dr}}\,\rho_{dr} \frac{s \cdot m}{|s||m|} + \mathbf{I_{sr}}\,\rho_{sr} \left(\frac{h \cdot m}{|h||m|}\right)^{\alpha}) / (k_c + k_l d + k_q d^2)$$

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

$$\mathbf{R_b} = \mathbf{I_{ab}}\,\rho_{ab} + (\mathbf{I_{db}}\,\rho_{db} \frac{s \cdot m}{|s||m|} + \mathbf{I_{sb}}\,\rho_{sb} \left(\frac{h \cdot m}{|h||m|}\right)^{\alpha}) / (k_c + k_l d + k_q d^2)$$

- For multiple light sources: add up the reflected light

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 $\mathbf{I}$ (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

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 α do?