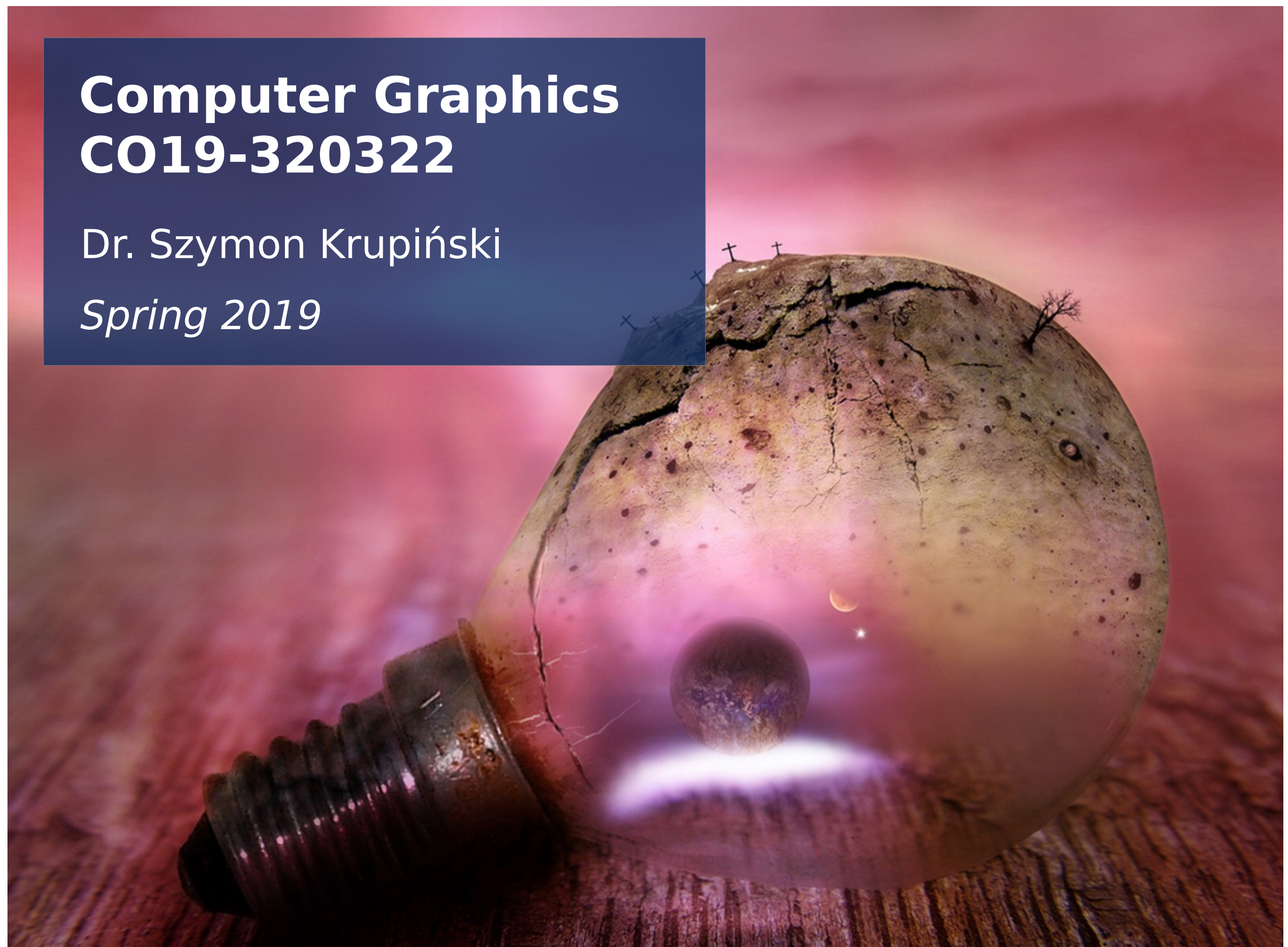
Lecture 13: Light and color

JACOBS UNIVERSITY



Computer Graphics
CO19-320322

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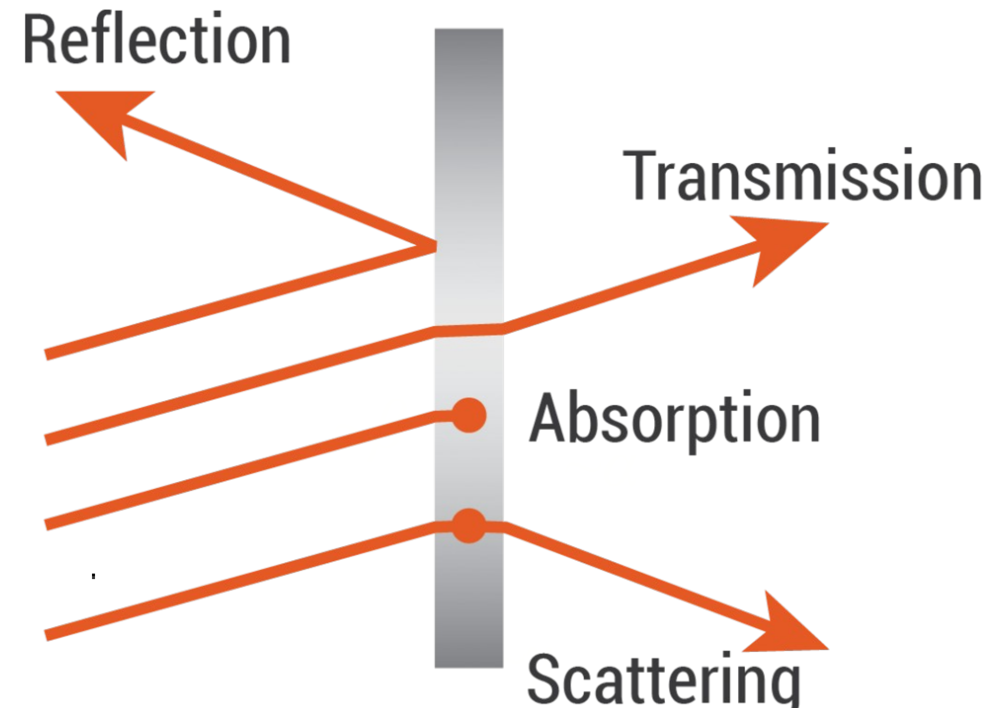
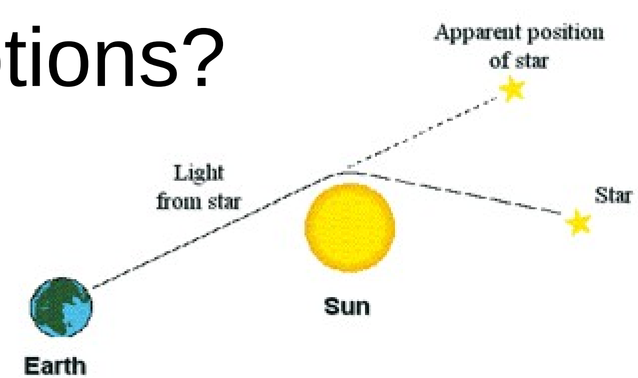
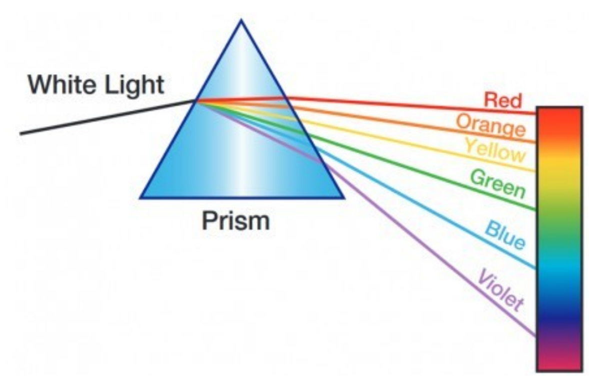
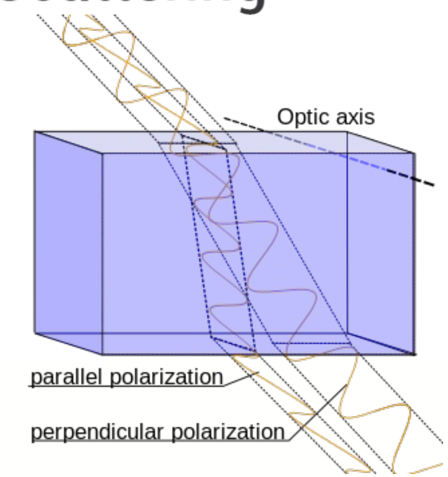
Light interaction with objects

- What happens to a light ray when it impinges on a surface?
  - It depends!
  - Reflection
  - Transmission
  - Absorption
  - Scattering
- Are these all options?
  - Not really...



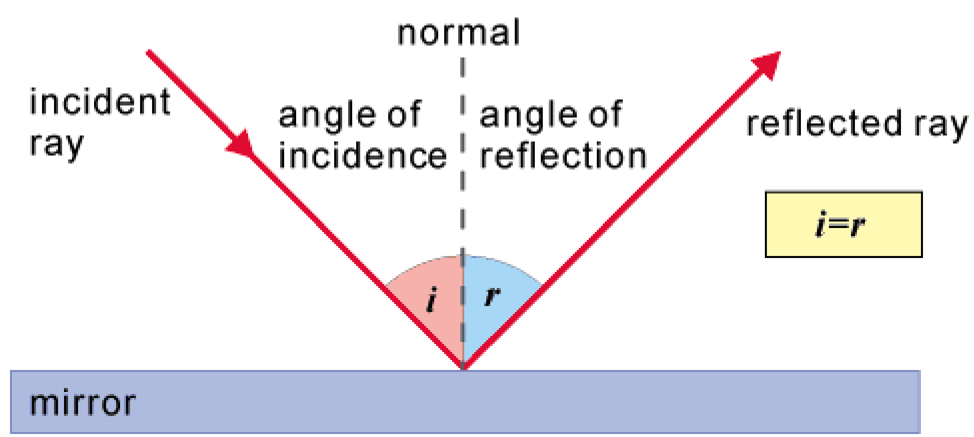






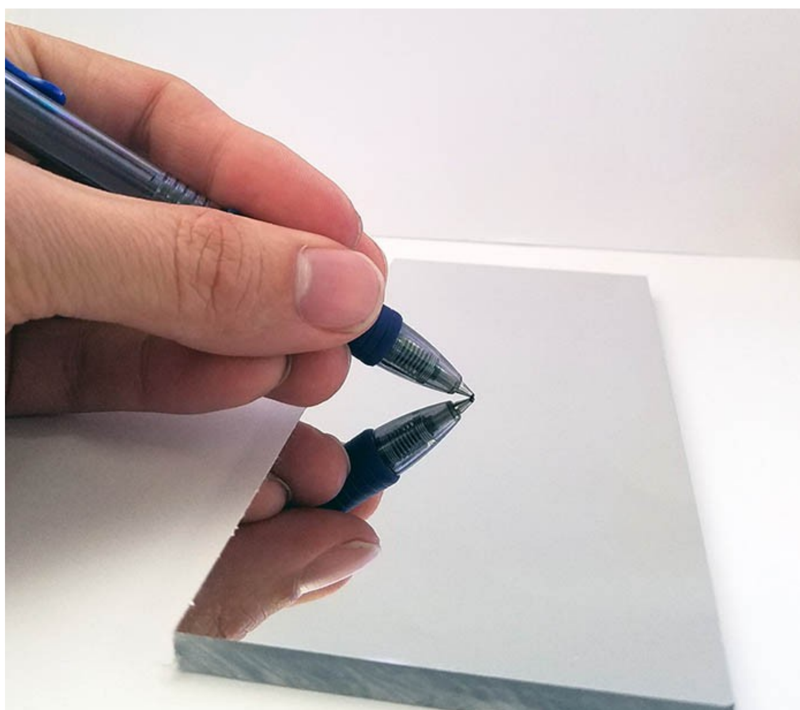
Reflections

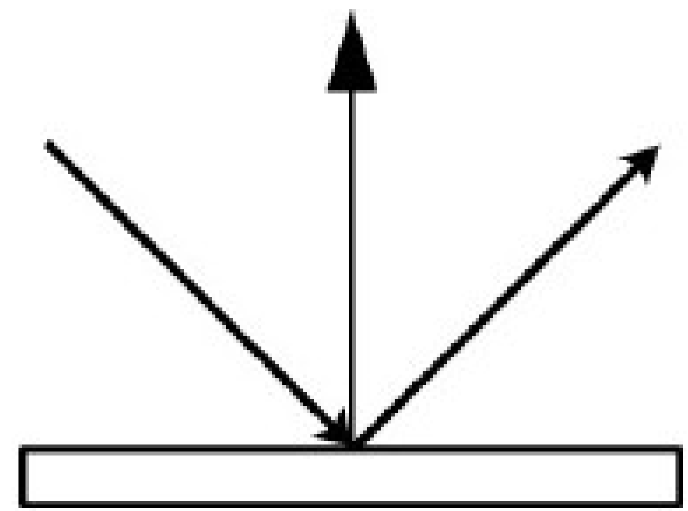
- The general rule of reflection: angle of incidence w.r.t. the normal = angle of reflection w.r.t. the normal to the surface
  - We need to know the normal!



Reflections

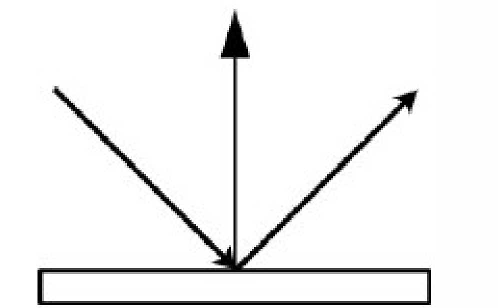
- Ideal specular
  - Perfect mirror



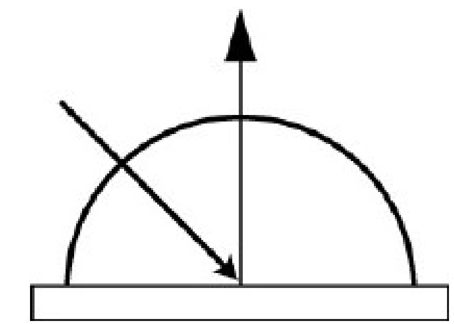


Non-ideal reflections

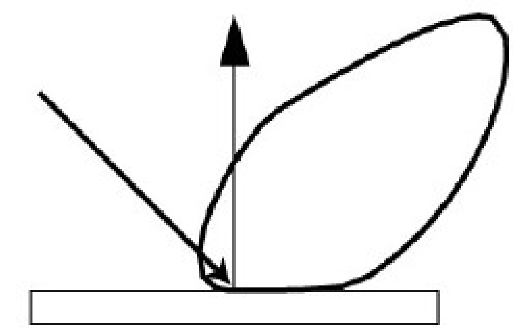
- Ideal specular
  - Perfect mirror



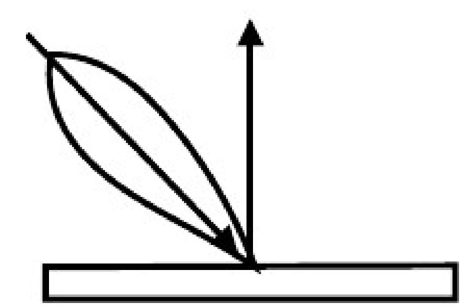
- Ideal diffuse
  - Uniform reflection in all directions



- Glossy specular
  - Majority of light distributed in reflection direction

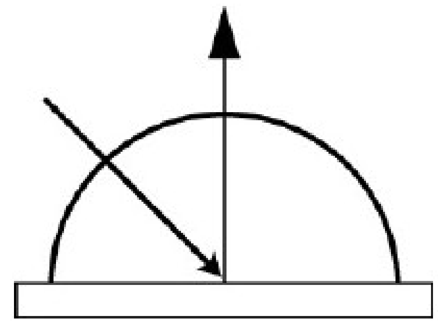


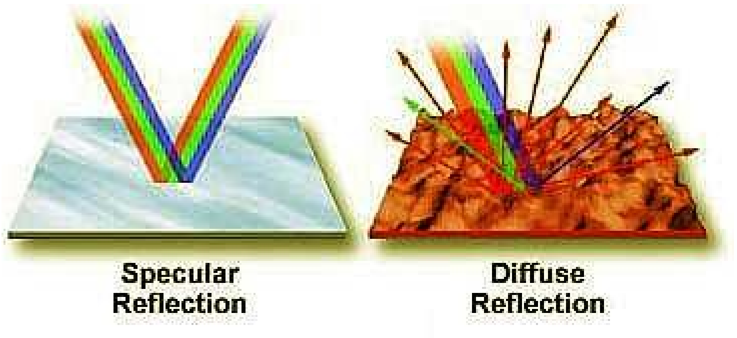
- Retro-reflective
  - Reflects light back toward source



Non-ideal reflections

- Ideal diffuse (a.k.a Lambertian reflection)



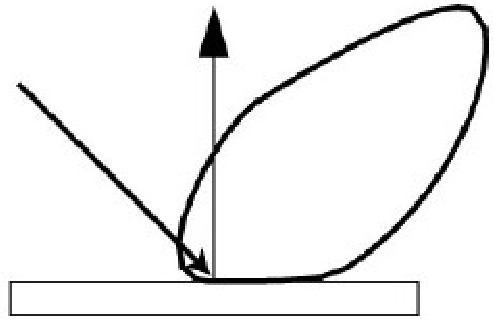


$$
\begin{aligned}
L_o(\omega_o) &= \int_{H^2} f_r \, L_i(\omega_i) \, \cos\theta_i \, \mathrm{d}\omega_i \\
&= f_r \int_{H^2} L_i(\omega_i) \, \cos\theta_i \, \mathrm{d}\omega_i \\
&= f_r E
\end{aligned}
$$

$$f_r = \frac{\rho}{\pi}$$

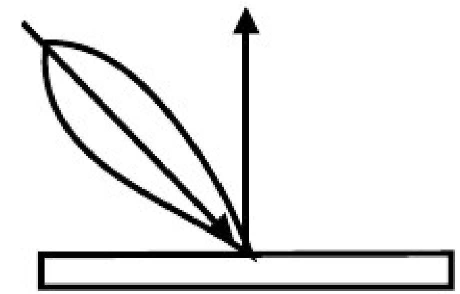
Non-ideal reflections

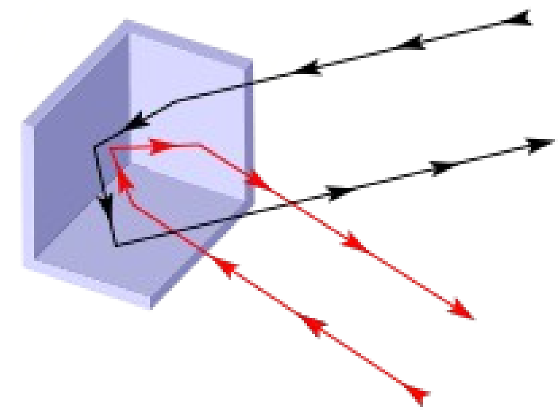
- Glossy specular



Non-ideal reflections

- Retro-reflective

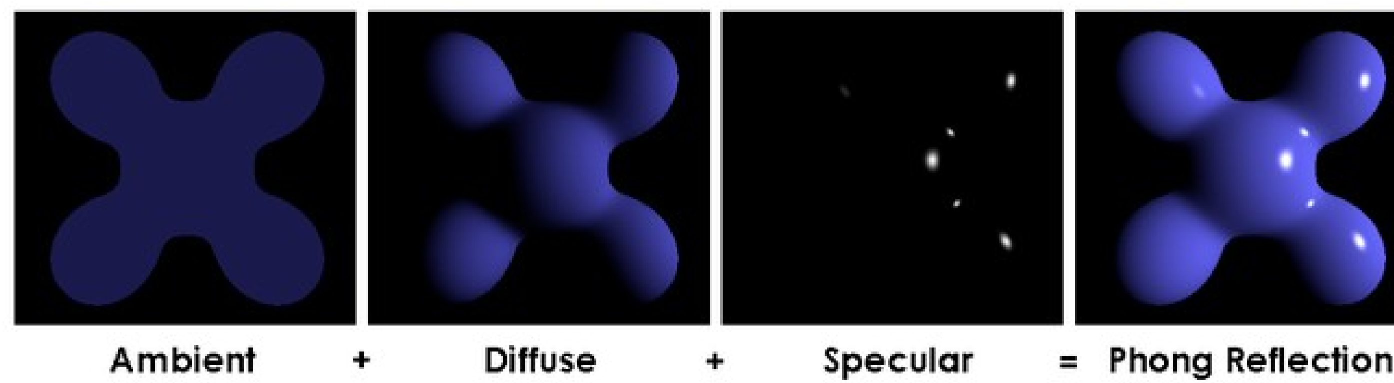




Phong reflection model

- The Phong model describes (some of) these illumination phenomena quantitatively for fast CG applications

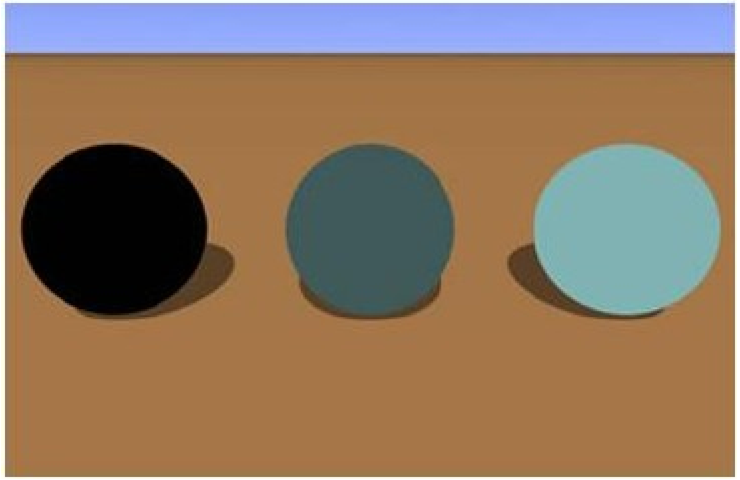
- It includes 3 components:
  - Ambient reflection
  - Diffuse reflection
  - Specular reflection

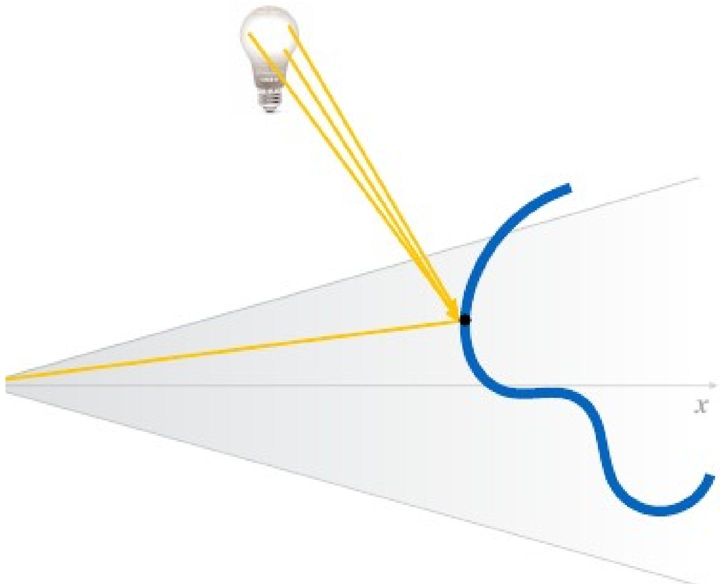


- It estimates the result of light reflection for a given point

Phong reflection model

- Ambient reflection takes into account the general light intensity homogeneously distributed across the scene, assumed to come from an infinitely big source
  - The ambient light is supposed to be undirected, so single material, single texture object will appear as an uniform silhouette
- The other two components are assumed to come from one point source





The lighting equation

- If we want to apply it to one point but include all points of lights in the scene:

$$L = \sum_{j \epsilon lights} L_i^j \left(k_a + k_d(\hat{\mathbf{N}} \cdot \omega_i^j)_+ + k_s(\hat{\mathbf{N}} \cdot \hat{\mathbf{H}}_i^j)_+^s\right)$$

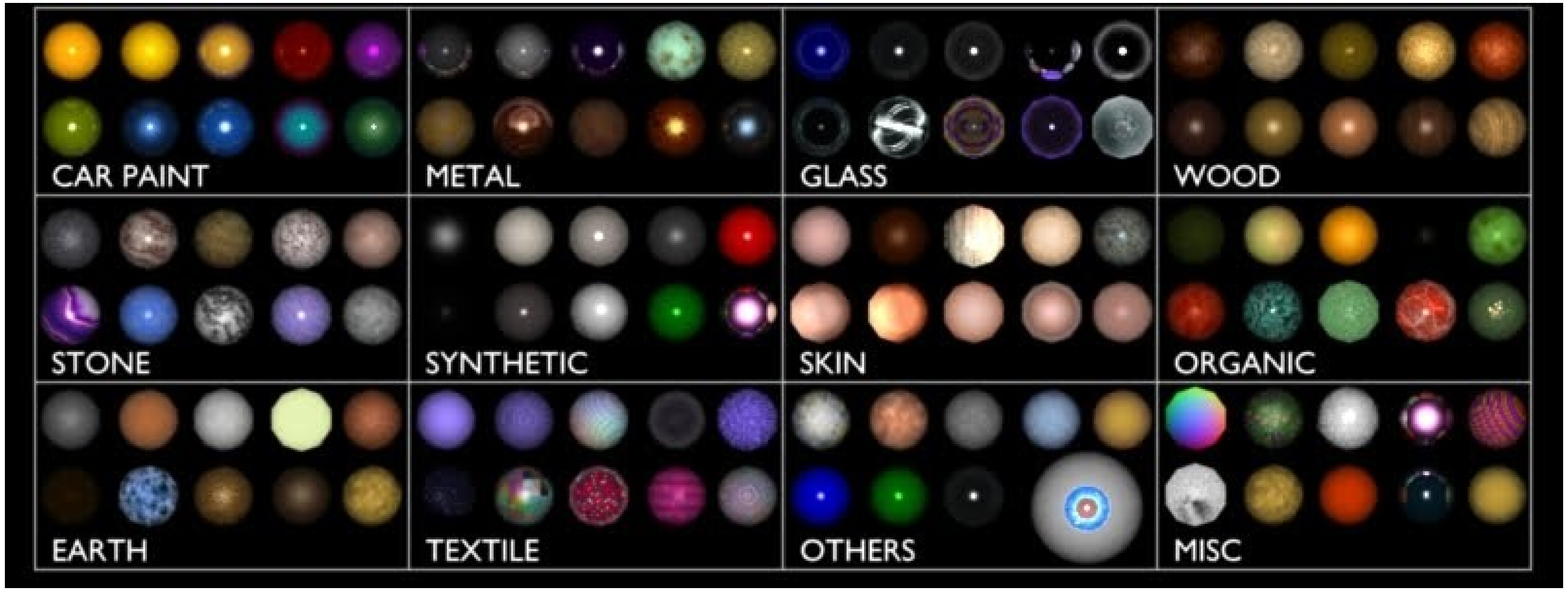
ambient diffuse specular

sum all lights

- Intensity (luminance) of light L^i_j
- Phong coefficients: k_a, k_d, k_s
- Can easily implement on a GPU
- Can easily use all the cores on a CPU
- Can easily use many machines across a network, or on the cloud

Material

- The notion of material serves to define how the surface of the object will interact with simulated light (or even produce it)
- It does not replace texture- it complements it!
- The objective: to define a set of parameters relevant to and capable of representing all real life materials which will guide the calculations



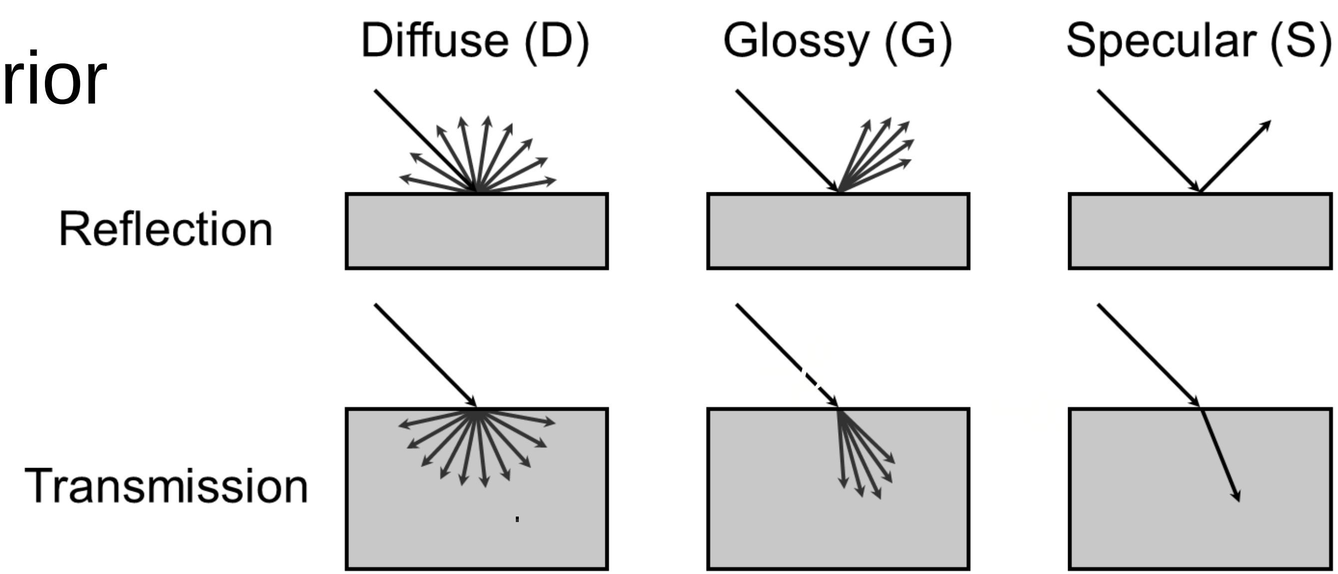
The lighting problem

- Light at a point may not just come directly from light sources:
  - Light can bounce off other objects (reflection)
  - Light can pass through objects (transparency/refraction)
- Trace more rays to look for more lighting information
  - Send secondary rays from the intersection point
  - Recursively compute the color for these secondary rays and sum them onto the primary ray
- Lighting equation becomes:

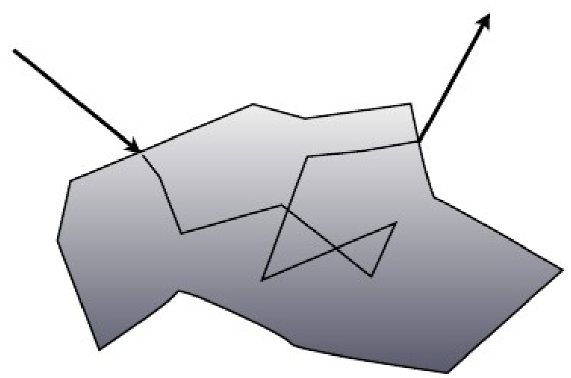
$$L = \underbrace{\sum_{j \epsilon lights} L_i^j (k_a + k_d(\hat{\mathbf{N}} \cdot \omega_i^j)_+ + k_s(\hat{\mathbf{N}} \cdot \hat{\mathbf{H}}_i^j)_+^s)}_{\text{standard direct illumination}} + \underbrace{k_r L_{reflected}}_{\text{recursively computed reflection}} + \underbrace{k_t L_{transmitted}}_{\text{recursively computed refraction}}$$

Transmission

- The same phenomena can take place towards the interior of the material



- Visual characteristics of many surfaces caused by light entering at different points than it exits

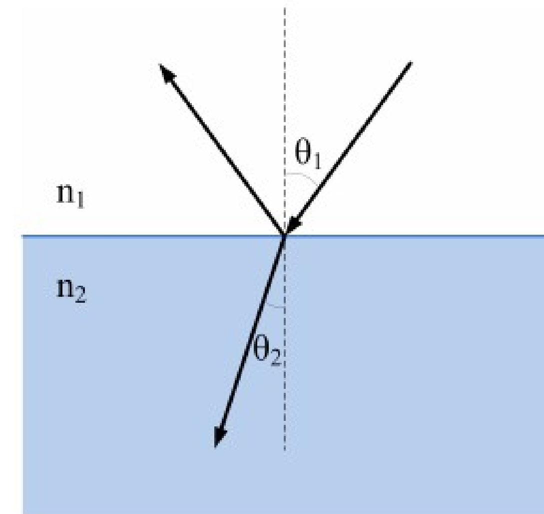


Transmission

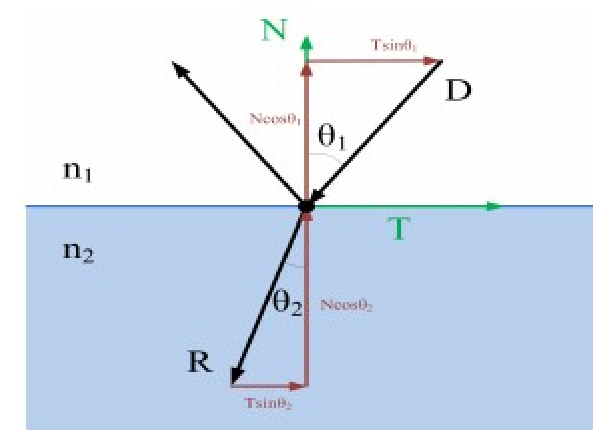
- Has some easy to see consequences for many real-life materials

Ideal transmission

- The relationship between the angle of incidence and angle of refraction/transmission for light passing through a boundary between two different isotropic media is described by Snell's law



$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

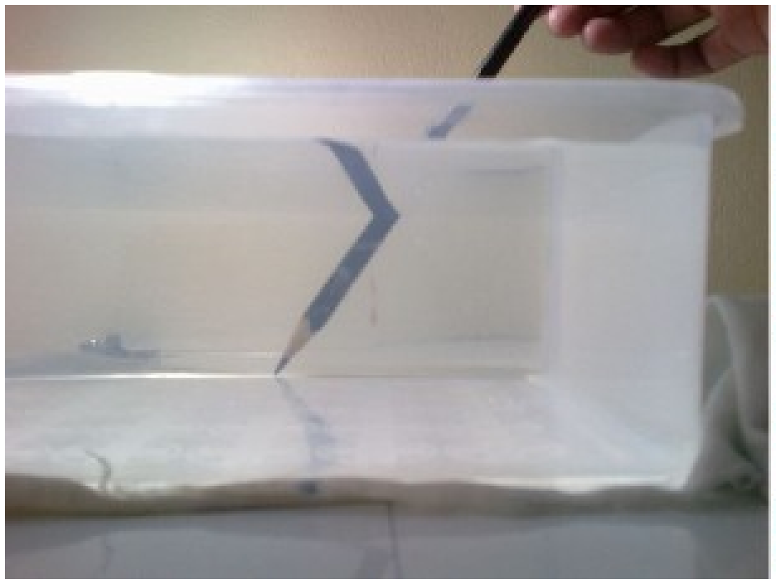


- Deciding how much will be transmitted and how much will be reflected is a tougher matter

$$\begin{aligned} \boldsymbol{R} &= -\boldsymbol{T}\sin\theta_2 - \boldsymbol{N}\cos\theta_2 \\ &= \boldsymbol{D}\frac{n_1}{n_2} - \boldsymbol{N}\left(\frac{n_1}{n_2}\boldsymbol{D}\bullet\boldsymbol{N} + \sqrt{1-\frac{n_1^{\,2}}{n_2^{\,2}}\left(1-(\boldsymbol{D}\bullet\boldsymbol{N})^2\right)}\right) \end{aligned}$$

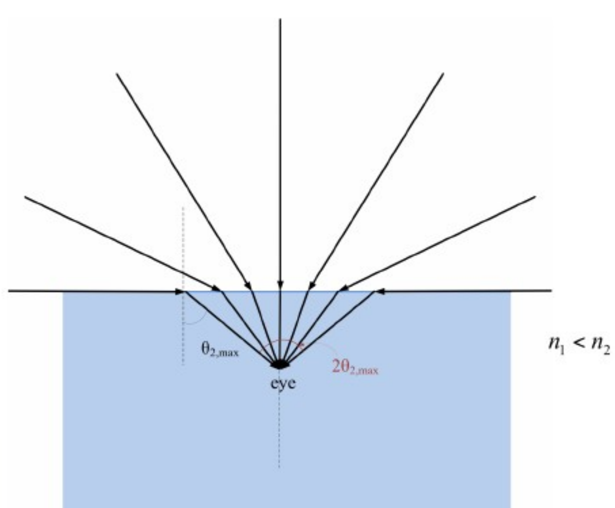
If the number under the square root is negative, there is no refracted/transmitted ray and all of the light is reflected (total internal reflection)

Total internal reflection and Snell's window



Total reflection makes the appearance of liquids very special

Snell's window

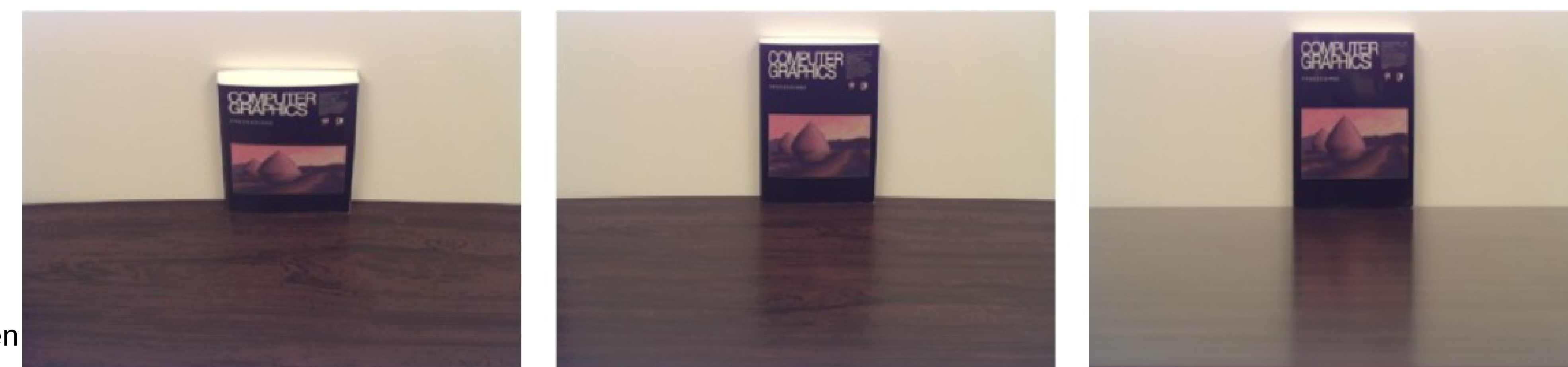


Reflection or transmission?

- The proportion of reflection versus transmission gradually increases as the viewing angle goes from perpendicular to a parallel (grazing)

Transparent material

Opaque material



Attenuation

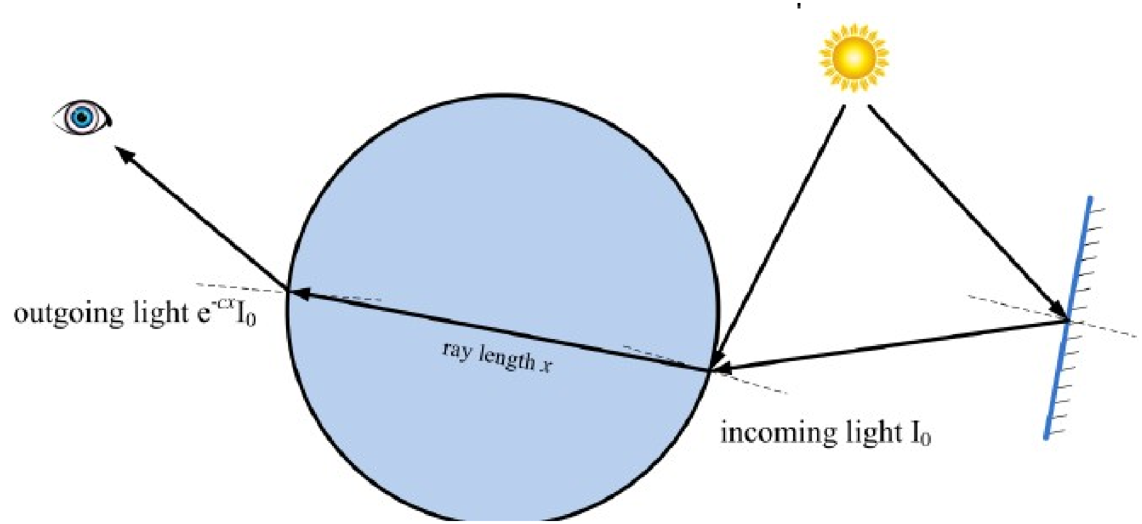
- Light is attenuated as it travels through media
- The attenuation effect from the media is stronger over longer distances
- Different colors attenuate with different rates
  - Shallow water is clear (almost no attenuation)
  - Deeper water attenuates all the red light and looks blue-green
  - Even deeper water also attenuates all the green light and looks blue
  - Eventually all the light attenuates, and the color ranges from blackish-blue to black

Attenuation

- If the media is homogeneous, the attenuation along the ray can be described using Beer's Law:

$$\frac{dI}{dx} = -cI \quad \Rightarrow \quad I(x) = I_0 e^{-cx}$$

where *I* is the light intensity, x is the distance along the ray, and c is the attenuation constant (which varies based on color/wavelength)

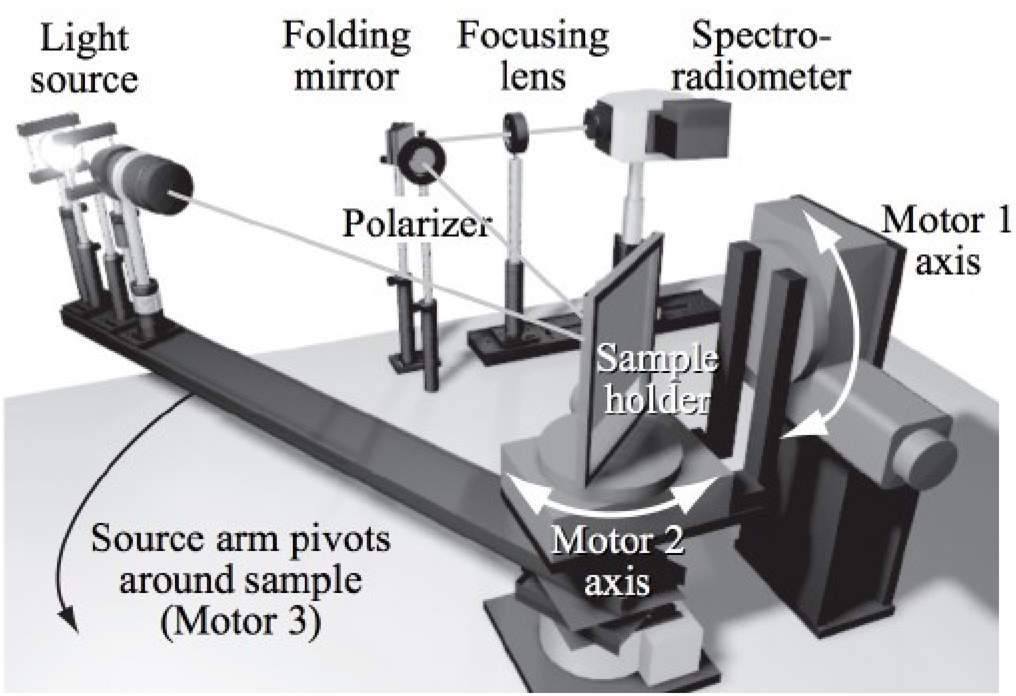


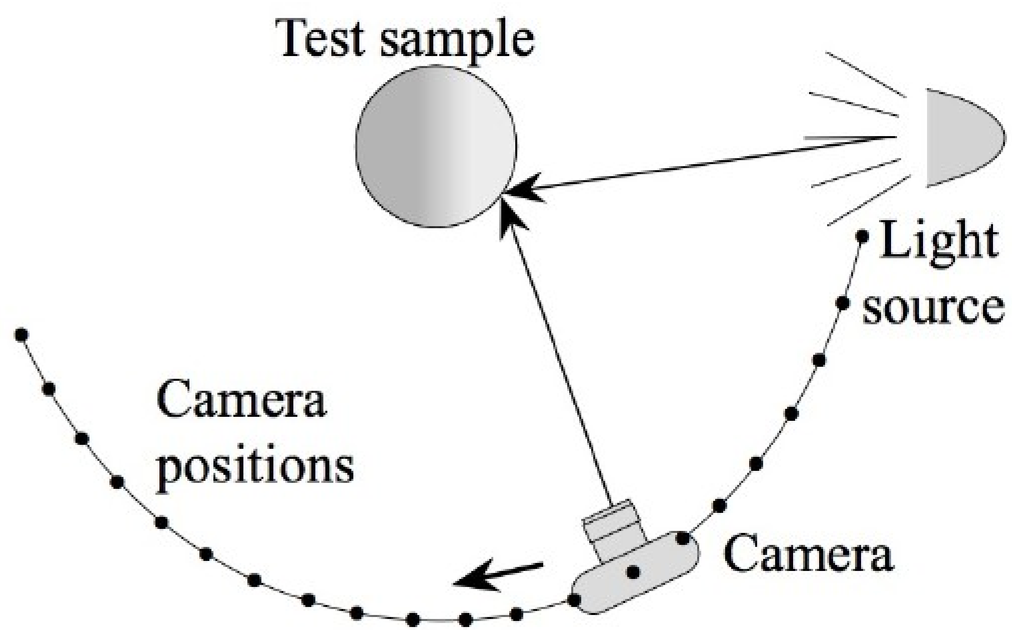
Global illumination

- Given the complexity of the problem, it asks to be solved “globally”
- More faithfully (less hacks) tracking the physical process:
  - Emit light from light sources
  - Follow the light from the light sources throughout the scene
  - Account for all reflection and absorption along the way
  - Follow the light through the aperture into the camera
  - Record the final pixel colors when the light hits the virtual film
- Using physically justified description: Bidirectional reflectance distribution function (BRDF)

BRDF

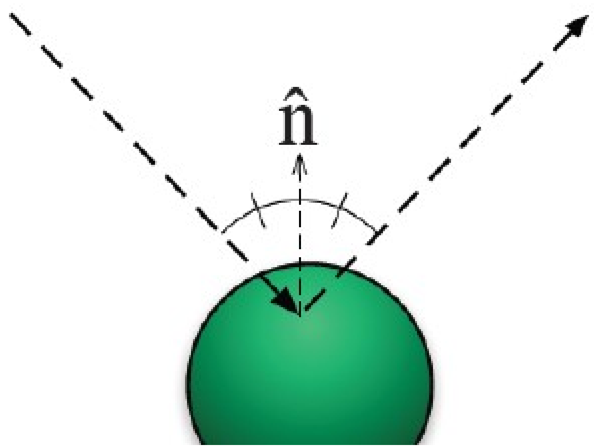
- Physical methods can be used to measure the properties of materials

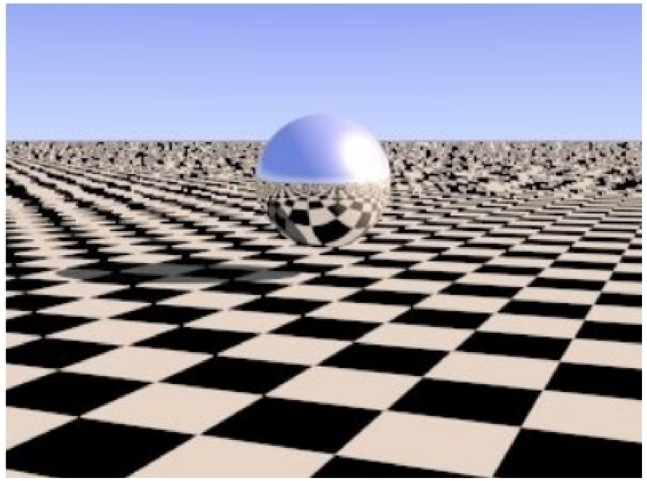




And practically..?

- Play around with the settings of the material until it “looks right”
- Shade recursively
  - Treat reflected rays like primary rays from the camera
  - Shade the reflected ray and return its color
  - Multiply by the reflection coefficient k_r
  - Add the resulting color to the shading at the original point





Thank you!

- Questions?