CSE 167:
Introduction to Computer Graphics
Lecture #6: Color

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Announcements

- Homework project #3 due this Friday, October 18th
  - Starts at 1:30pm as usual.
  - Grading in order of names on white board in labs 260 and 270.
- Last day for late submissions of project #2: this Friday
- Next Monday:
  - No new homework assignment,
    but midterm review session in Center Hall 105 at 3pm

Lecture Overview

Color

- Color spaces
- Color reproduction on computer monitors

Shading

- Introduction
- Local shading models

Color Reproduction

- How can we reproduce, represent color?
  - One option: store full spectrum
- Representation should be as compact as possible
- Any pair of colors that can be distinguished by humans should have two different representations

Color Spaces

- Set of parameters describing a color sensation
- "Coordinate system" for colors
- Three types of cones, expect three parameters to be sufficient
- Why not use L,M,S cone responses?

Color Spaces

- Set of parameters describing a color sensation
- “Coordinate system” for colors
- Three types of cones
  - We expect three parameters to be sufficient

Trichromatic Theory

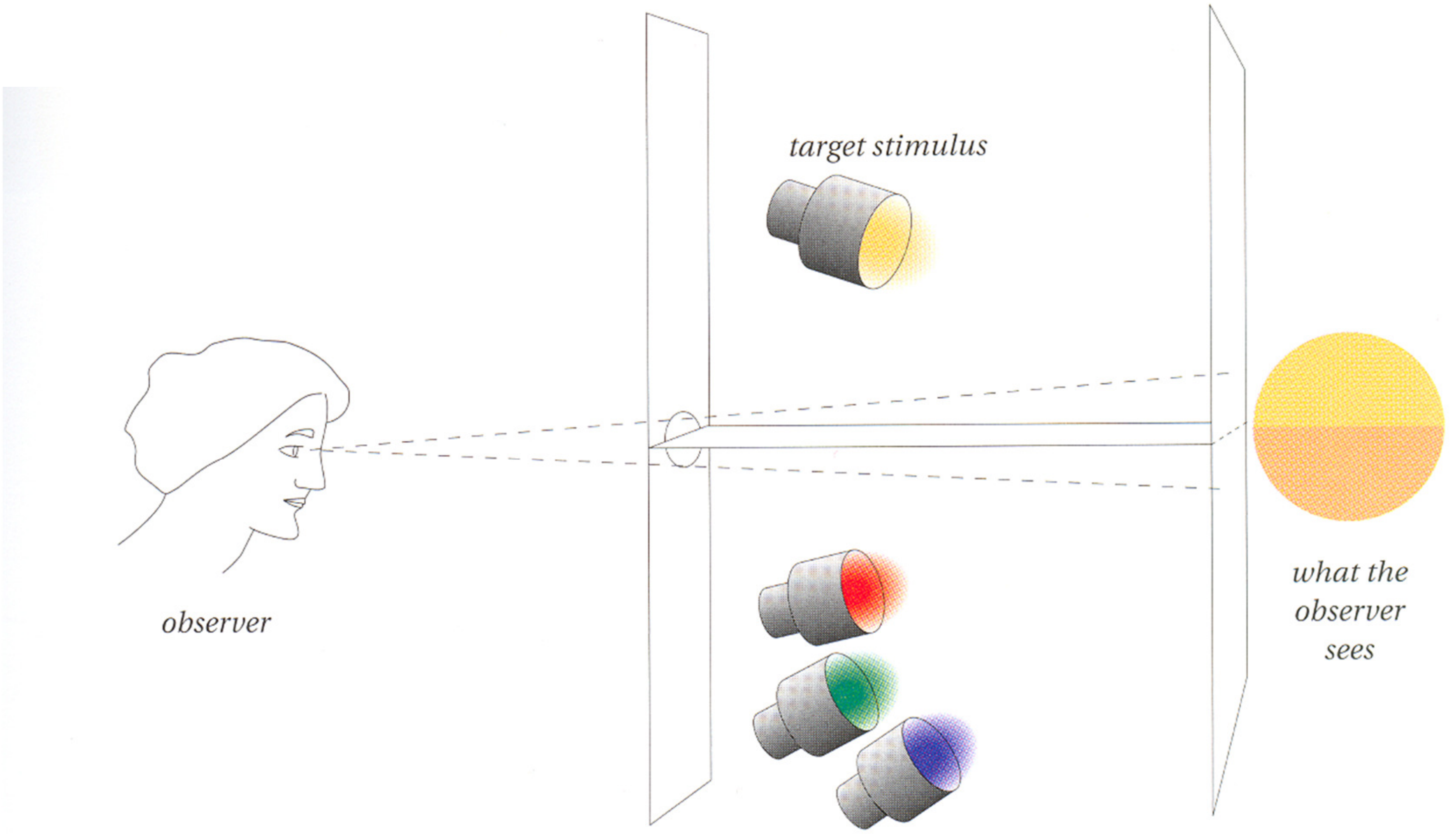
- Claims that any color can be represented as a weighted sum of three primary colors
- Proposes red, green, blue as primaries
- Developed in 18th and 19th century, before discovery of photoreceptor cells (Thomas Young, Hermann von Helmholtz)

Tristimulus Experiment

- Given arbitrary color, we want to know the weights for the three primaries
- Yields tristimulus values
- Experimental solution
  - CIE (Commission Internationale de l'Eclairage, International Commission on Illumination), circa 1920

Tristimulus Experiment

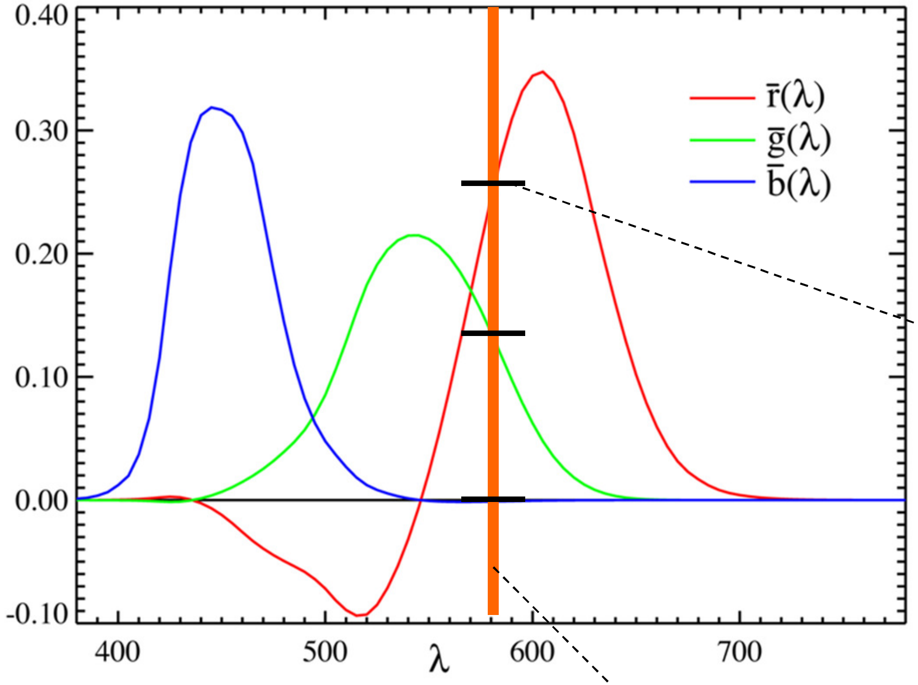
- Determine tristimulus values for spectral colors experimentally



The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

Tristimulus Experiment

- Spectral primary colors were chosen
  - Blue (435.8nm), green (546.1nm), red (700nm)
- Matching curves for monochromatic target



Weight for red primary

Target (580nm)

- Negative values!

Tristimulus Experiment

Negative values

- Some spectral colors could not be matched by primaries in the experiment
- “Trick”
  - One primary could be added to the source (stimulus)
  - Match with the other two
  - Weight of primary added to the source is considered negative

Photoreceptor response and matching curves are different!

Tristimulus Values

- Matching values for a sum of spectra with small spikes are the same as sum of matching values for the spikes
- Monochromatic matching curves $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$
- In the limit (spikes are infinitely narrow)

$$R = \int \bar{r}(\lambda) L(\lambda) d\lambda$$
$$G = \int \bar{g}(\lambda) L(\lambda) d\lambda$$
$$B = \int \bar{b}(\lambda) L(\lambda) d\lambda$$

CIE Color Spaces

- Matching curves $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ define CIE RGB color space
  - CIE RGB values are color "coordinates"
- CIE was not satisfied with range of RGB values for visible colors
- Defined CIE XYZ color space
  - Most commonly used color space today

CIE XYZ Color Space

- Determined coefficients such that
  - Y corresponds to an experimentally determined brightness
  - No negative values in matching curves
  - White is XYZ=(1/3,1/3,1/3)

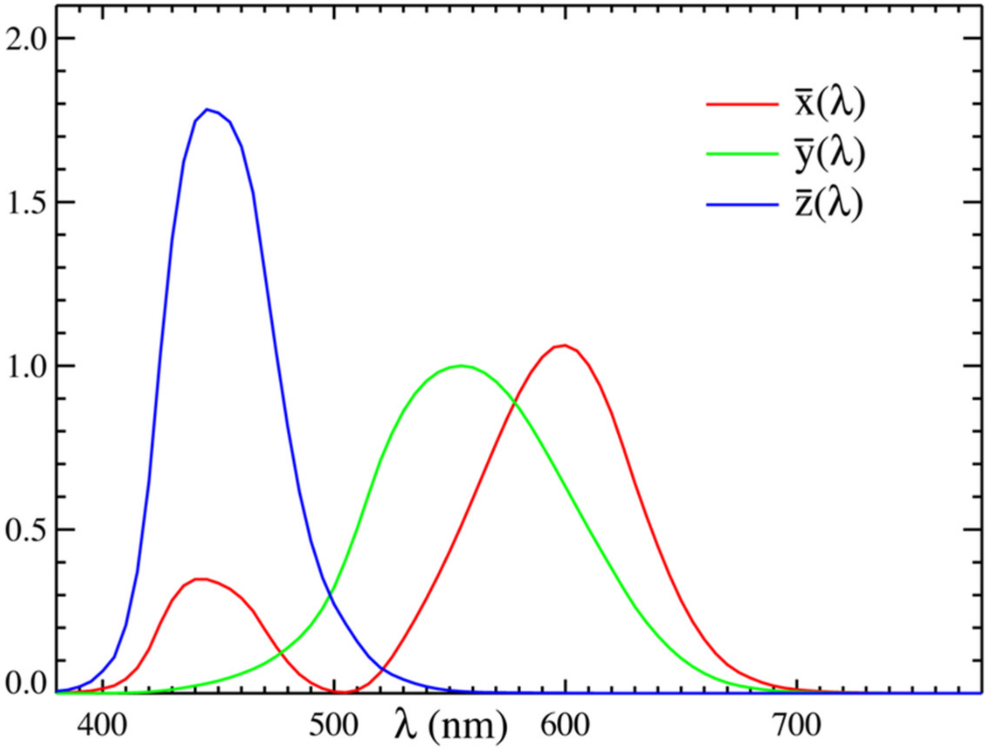
- Linear transformation of CIE RGB:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{b_{21}} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE XYZ Color Space

Matching curves

- No corresponding physical primaries



Tristimulus values

- Always positive!

$$X = \int \bar{x}(\lambda)L(\lambda)d\lambda$$

$$Y = \int \bar{y}(\lambda)L(\lambda)d\lambda$$

$$Z = \int \bar{z}(\lambda)L(\lambda)d\lambda$$

Summary

- CIE color spaces are defined by matching curves
  - At each wavelength, matching curves give weights of primaries needed to produce color perception of that wavelength
  - CIE RGB matching curves determined using tristimulus experiment
- Each distinct color perception has unique coordinates
  - CIE RGB values may be negative
  - CIE XYZ values are always positive

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CIE XYZ Color Space

Visualization

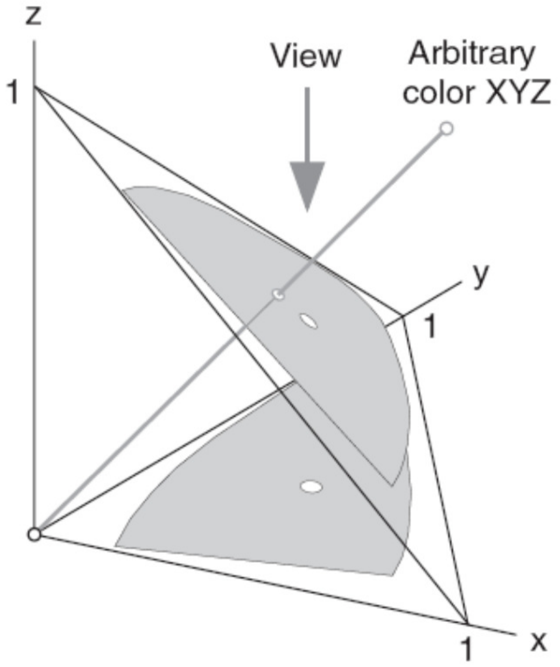
- Interpret XYZ as 3D coordinates
- Plot corresponding color at each point
- Many XYZ values do not correspond to visible colors

Chromaticity Diagram

- Project from XYZ coordinates to 2D for more convenient visualization

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z}$$

- Drop z-coordinate



Chromaticity Diagram

- Factor out luminance (perceived brightness) and chromaticity (hue)
  - x,y represent chromaticity of a color

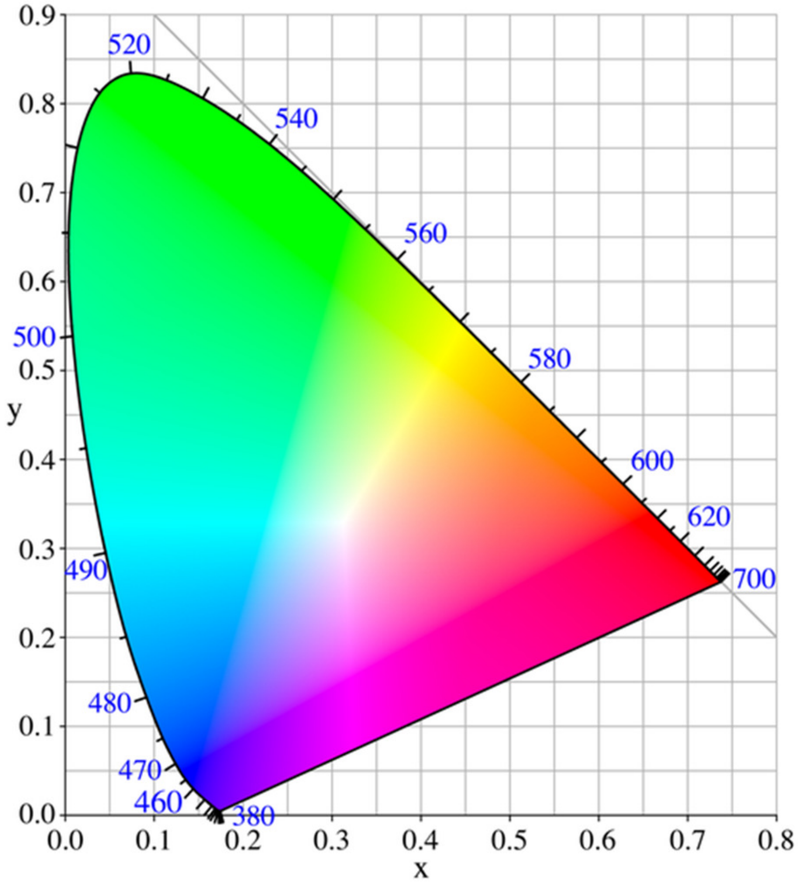
$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad 0 \le x, y \le 1$$

  - Y is luminance
- CIE xyY color space
- Reconstruct XYZ values from xyY

$$X = \frac{Y}{y}x \qquad Z = \frac{Y}{y}(1 - x - y)$$

Chromaticity Diagram

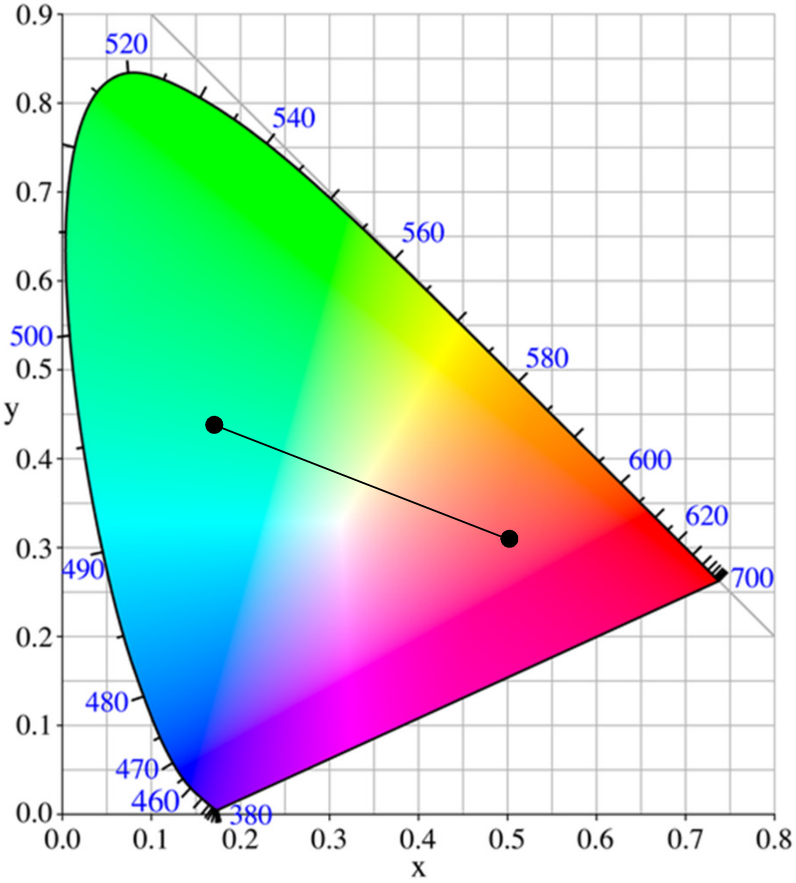
- Visualizes x,y plane (chromaticities)
- Pure spectral colors on boundary



Colors shown do not correspond to colors represented by (x,y) coordinates!

Chromaticity Diagram

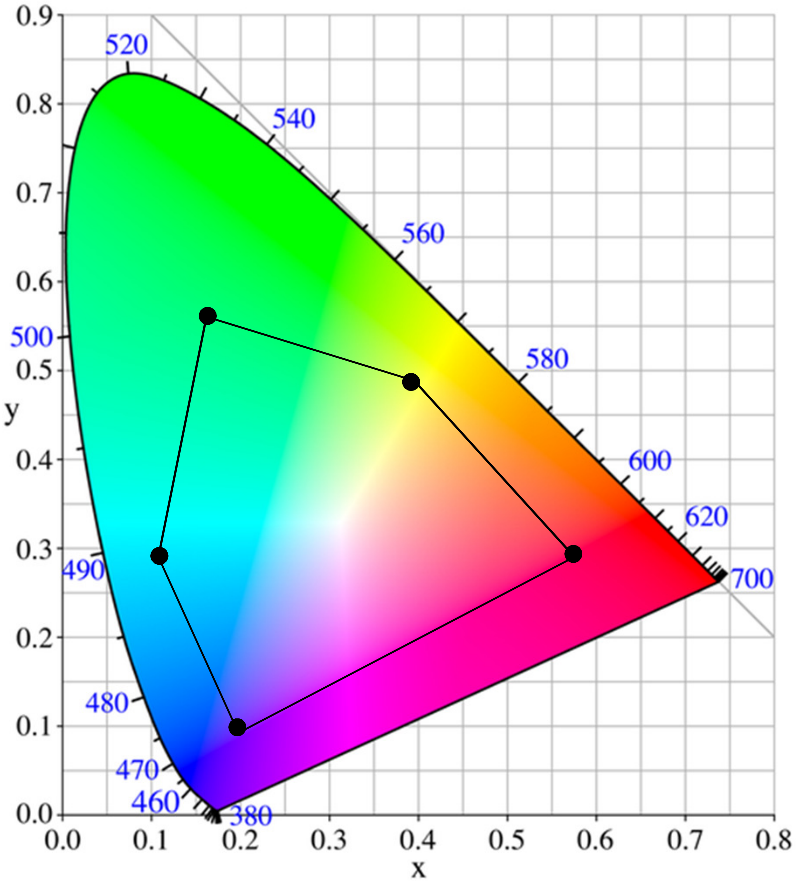
- Visualizes x,y plane (chromaticities)
- Pure spectral colors on boundary
- Weighted sum of any two colors lies on line connecting colors



Colors shown do not correspond to colors represented by (x,y) coordinates!

Chromaticity Diagram

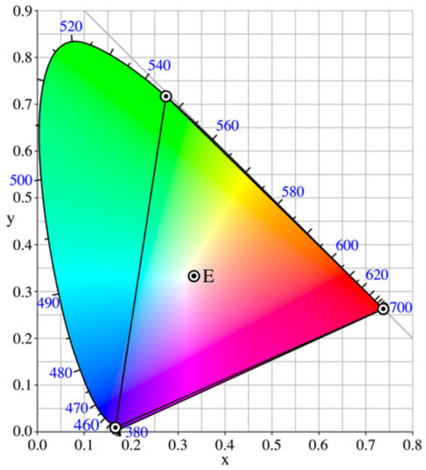
- Visualizes x,y plane (chromaticities)
- Pure spectral colors on boundary
- Weighted sum of any two colors lies on line connecting colors
- Weighted sum of any number of colors lies in convex hull of colors (gamut)



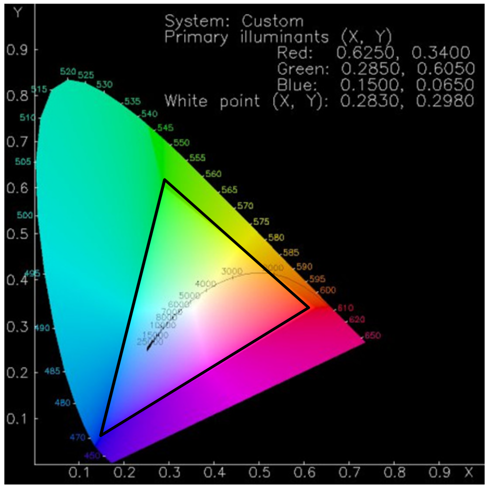
Colors shown do not correspond to colors represented by (x,y) coordinates!

Gamut

- Any device based on three primaries can only produce colors within the triangle spanned by the primaries
- Points outside gamut correspond to negative weights of primaries



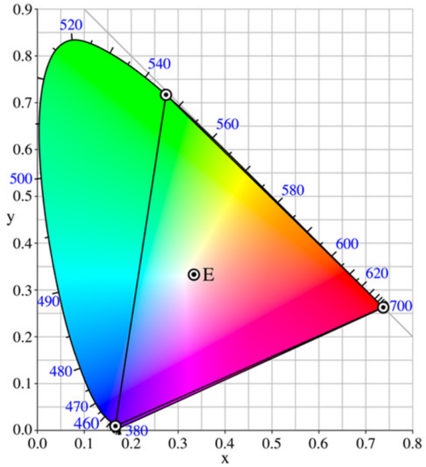
Gamut of CIE RGB primaries



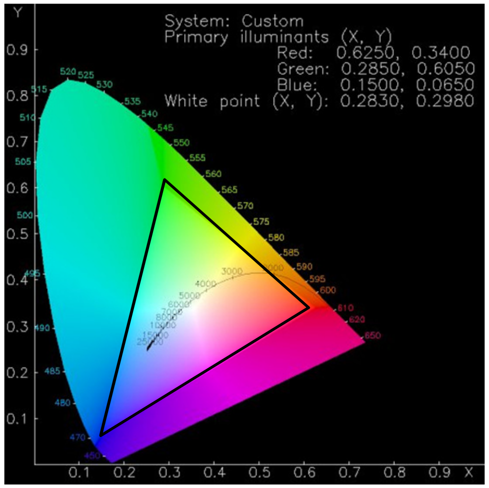
Gamut of typical CRT monitor

RGB Monitors

- Given red, green, blue (RBG) values, what color will your monitor produce?
  - I.e., what are the CIE XYZ or CIE RGB coordinates of the displayed color?
  - How are OpenGL RGB values related to CIE XYZ, CIE RGB?
- Often you don't know!
  - OpenGL RGB ≠ CIE XYZ, CIE RGB



Gamut of CIE RGB primaries



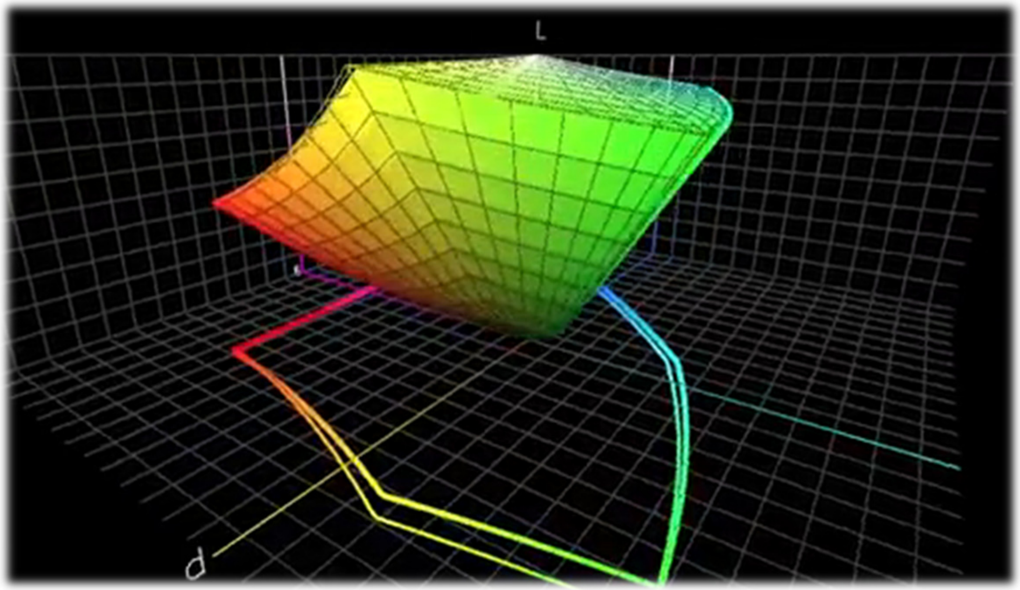
Gamut of typical CRT monitor

sRGB

- Standard color space, with standard conversion to CIE XYZ
- Designed to match RGB values of typical monitor under typical viewing conditions (dimly lit office)
  - If no calibration information available, it is best to interpret RGB values as sRGB
- sRGB roughly corresponds to 2.2 gamma correction
- sRGB is supported by OpenGL as
  - sRGB textures (since OpenGL 2.1)
  - sRGB framebuffers (since OpenGL 3.0)

Video: Gamut Comparison

- Macbook Pro/Retina display compared to sRGB
  - http://www.youtube.com/watch?v=mIFnztUehP4
  - sRGB: solid line, Macbook Pro: wireframe



Conclusions

- Color reproduction on consumer monitors is less than perfect
  - The same RGB values on one monitor look different than on another
  - Given a color in CIE XYZ coordinates, consumer systems do not reliably produce that color
- Need color calibration
  - But no selling point for consumers
  - Standard for digital publishing, printing, photography

Display calibration

Further Reading

- Wikipedia pages
  - http://en.wikipedia.org/wiki/CIE_1931_color_space
  - http://en.wikipedia.org/wiki/CIELAB
- More details:
  - CIE Color Space: http://www.fho-emden.de/~hoffmann/ciexyz29082000.pdf

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Shading

- Compute interaction of light with surfaces
- Requires simulation of physics
- “Global illumination”
  - Multiple bounces of light
  - Computationally expensive, minutes per image
  - Used in movies, architectural design, etc.

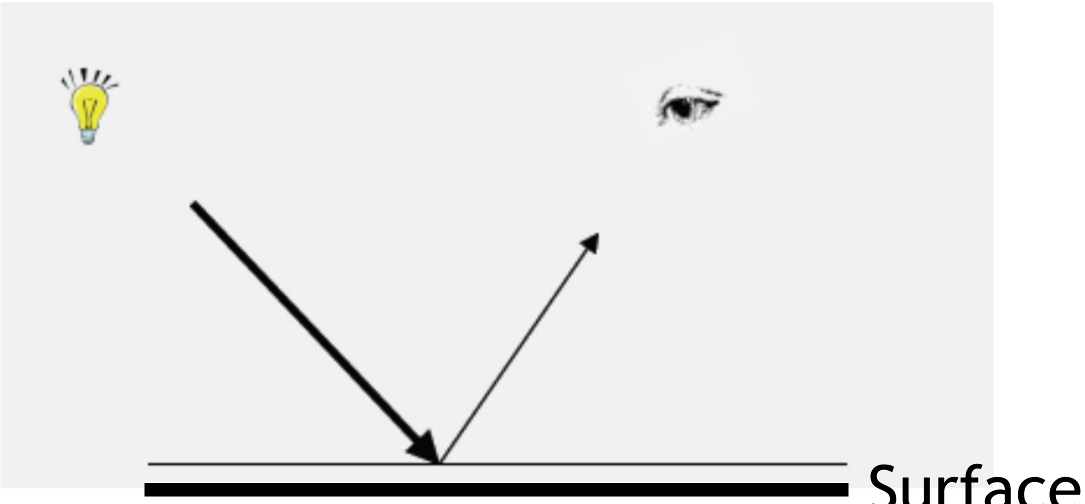
Global Illumination

- Covered by CSE168

(All non-teapot images courtesy of Prof. Wann Jensen)

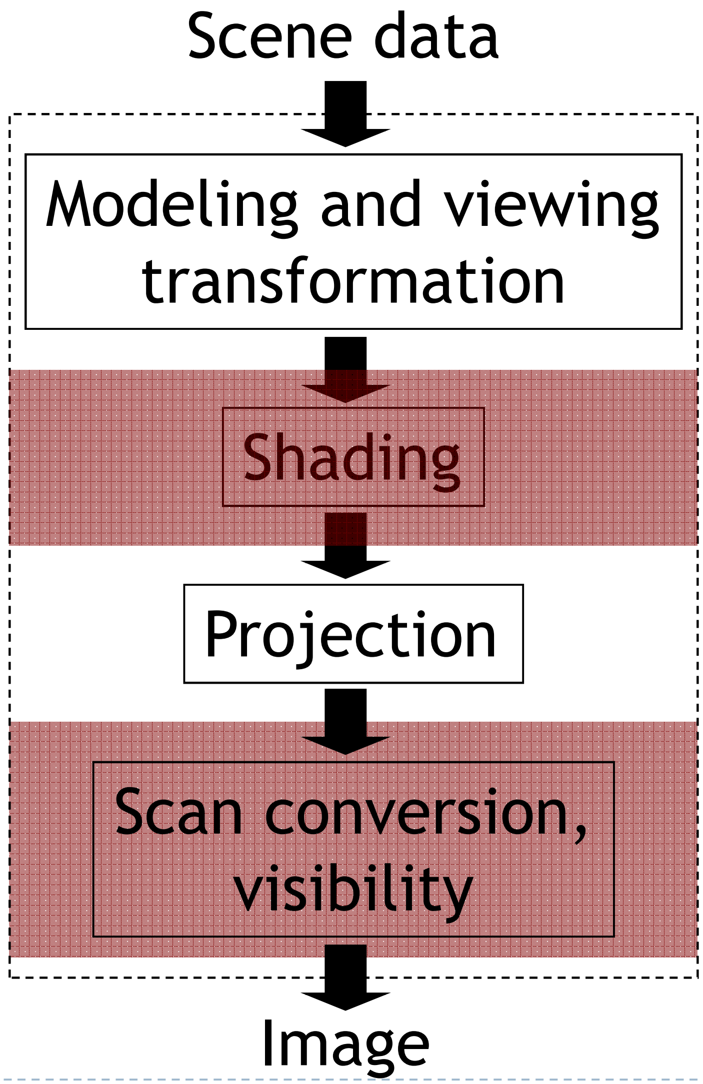
Interactive Applications

- No physics-based simulation
- Simplified models
- Reproduce perceptually most important effects
- Local illumination
  - Only one bounce of light between light source and viewer



One bounce of light

Rendering Pipeline



Scene data

Modeling and viewing transformation

Shading

Projection

Scan conversion, visibility

Image

- Position object in 3D
- Determine colors of vertices
  - Per vertex shading
- Map triangles to 2D
- Draw triangles
  - Per pixel shading

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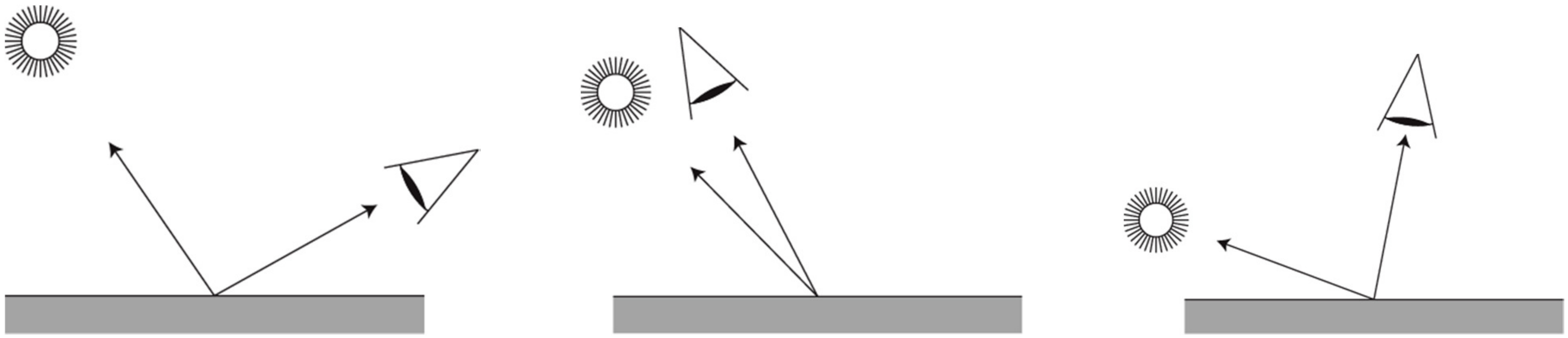
Local Illumination

- What gives a material its color?
- How is light reflected by a
  - Mirror
  - White sheet of paper
  - Blue sheet of paper
  - Glossy metal

Local Illumination

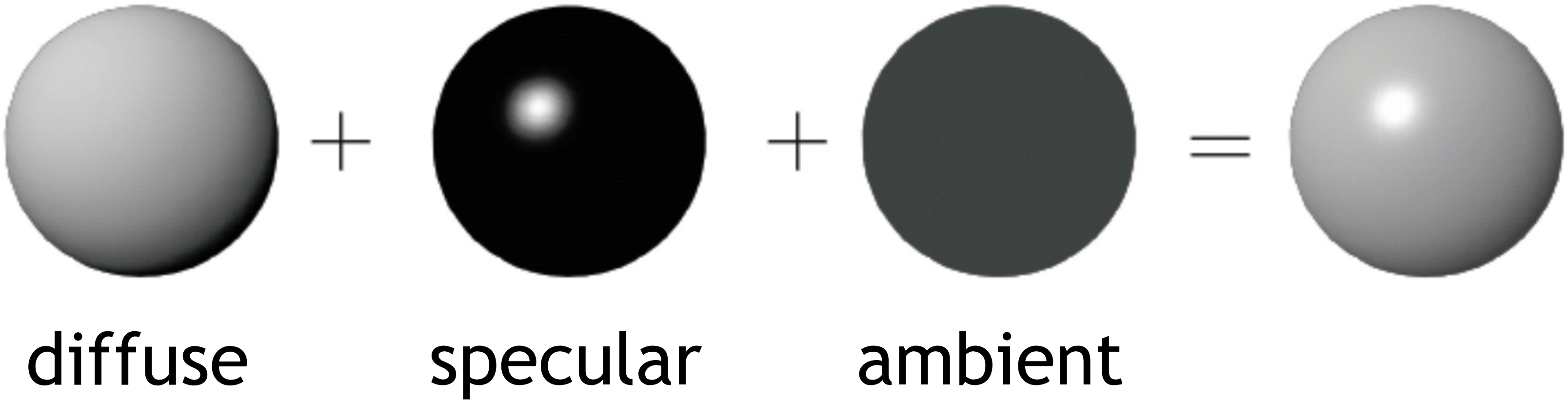
- Model reflection of light at surfaces
  - Assumption: no subsurface scattering
- Bidirectional reflectance distribution function (BRDF)
  - Given light direction, viewing direction, how much light is reflected towards the viewer
  - For any pair of light/viewing directions!



Local Illumination

Simplified model

- Sum of 3 components
- Covers a large class of real surfaces



Local Illumination

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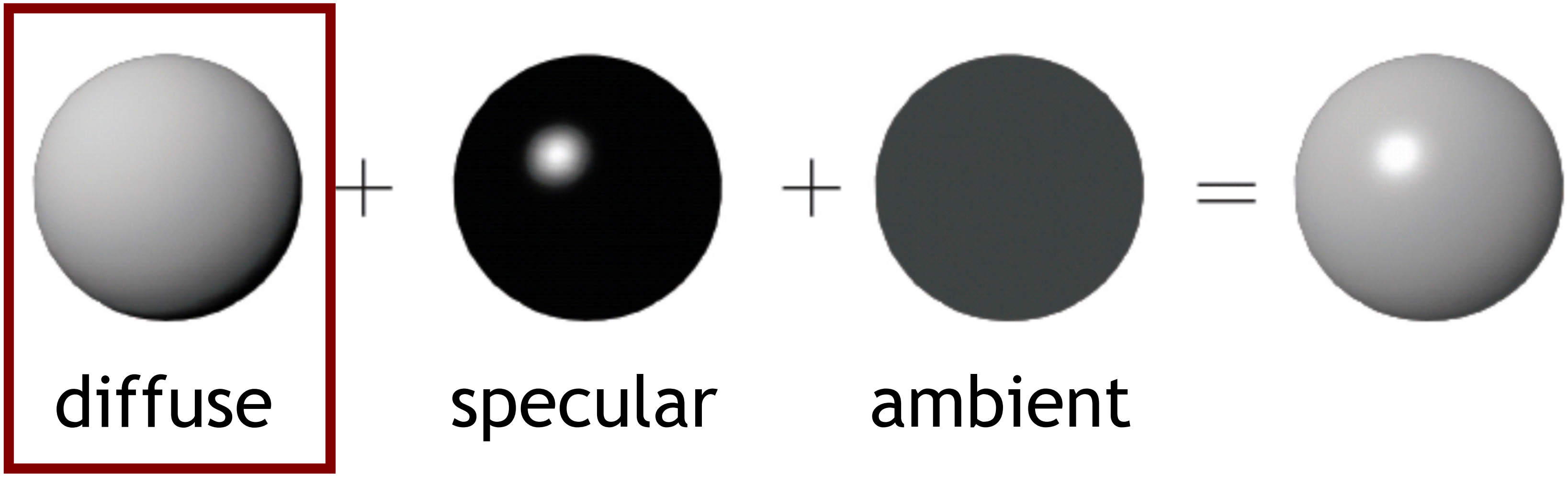
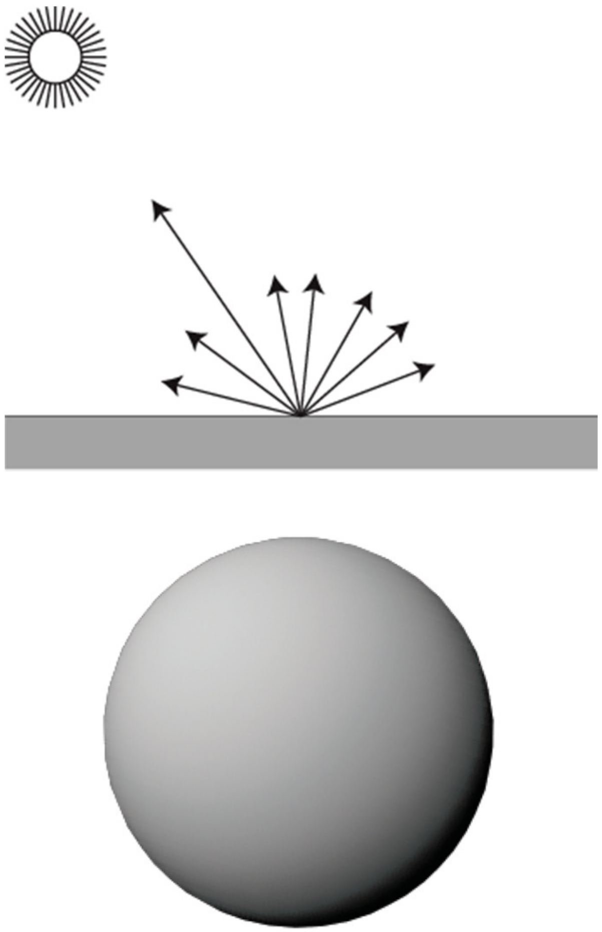


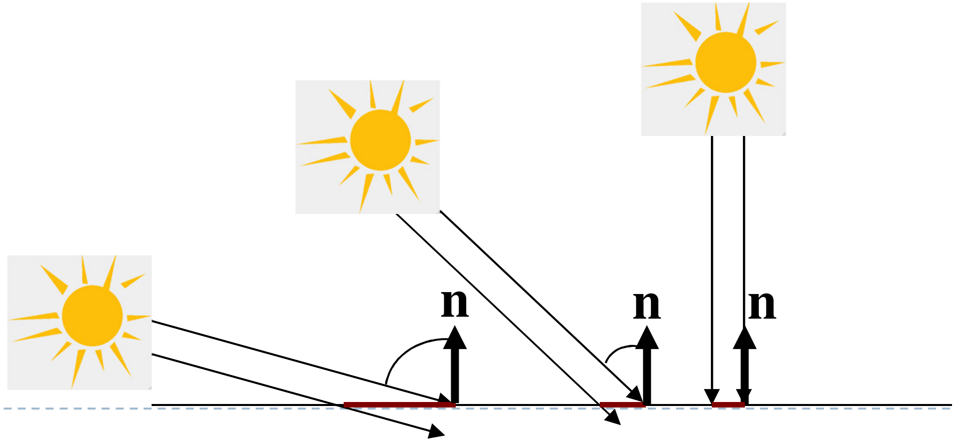
Diffuse Reflection

- Ideal diffuse material reflects light equally in all directions
- View-independent
- Matte, not shiny materials
  - Paper
  - Unfinished wood
  - Unpolished stone



Diffuse Reflection

- Beam of parallel rays shining on a surface
  - Area covered by beam varies with the angle between the beam and the normal
  - The larger the area, the less incident light per area
  - Incident light per unit area is proportional to the cosine of the angle between the normal and the light rays
- Object darkens as normal turns away from light
- Lambert's cosine law (Johann Heinrich Lambert, 1760)
- Diffuse surfaces are also called Lambertian surfaces



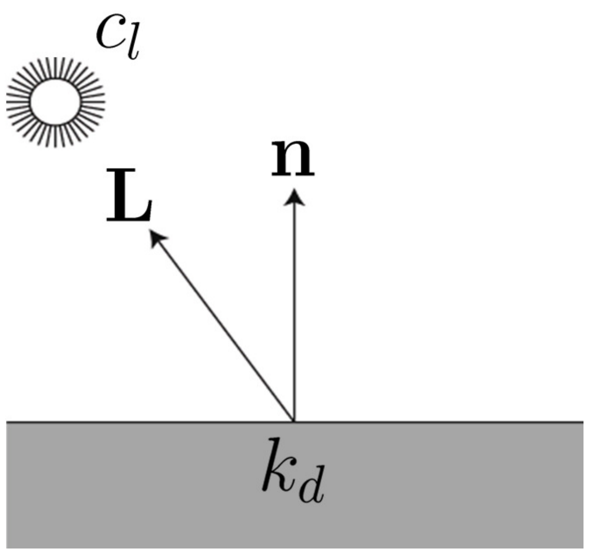
Diffuse Reflection

- Given
  - Unit surface normal **n**
  - Unit light direction **L**
  - Material diffuse reflectance (material color) k_d
  - Light color (intensity) c_l

- Diffuse color c_d is:

$$c_d = c_l k_d \underbrace{(\mathbf{n} \cdot \mathbf{L})}_{}$$

Proportional to cosine between normal and light



Diffuse Reflection

Notes

- Parameters k_d, c_l are r,g,b vectors
- Need to compute r,g,b values of diffuse color c_d separately
- Parameters in this model have no precise physical meaning
  - c_l: strength, color of light source
  - k_d: fraction of reflected light, material color

Diffuse Reflection

- Provides visual cues
  - Surface curvature
  - Depth variation

Lambertian (diffuse) sphere under different lighting directions

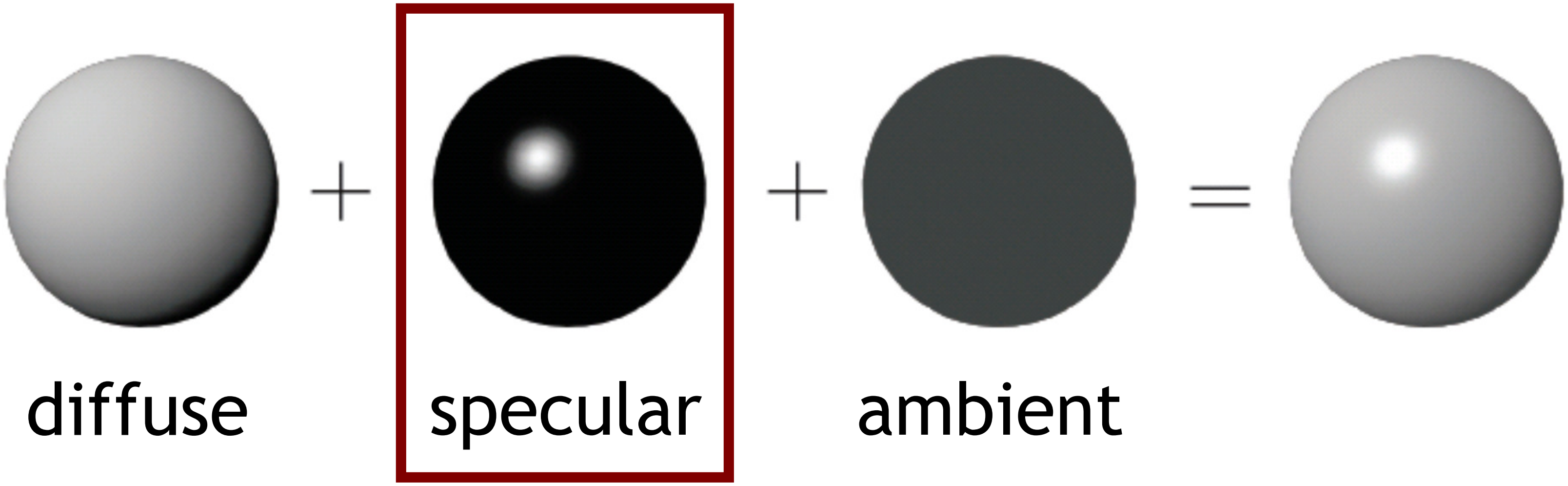
OpenGL

- Lights (glLight*)
  - Values for light: $(0,0,0) \leq c_l \leq (1,1,1)$
  - Definition: (0,0,0) is black, (1,1,1) is white
- OpenGL
  - Values for diffuse reflection
  - Fraction of reflected light: $(0,0,0) \leq k_d \leq (1,1,1)$
- Consult OpenGL Programming Guide (Red Book)
  - See course web site

Local Illumination

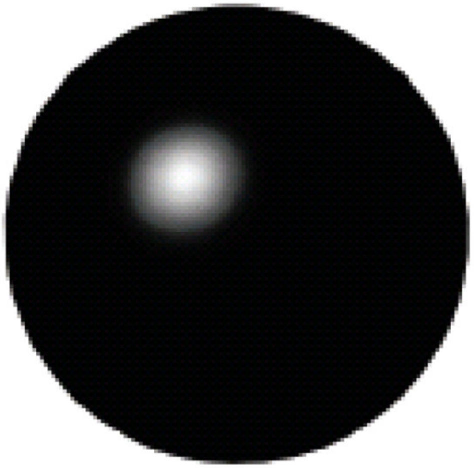
Simplified model

- Sum of 3 components
- Covers a large class of real surfaces



Specular Reflection

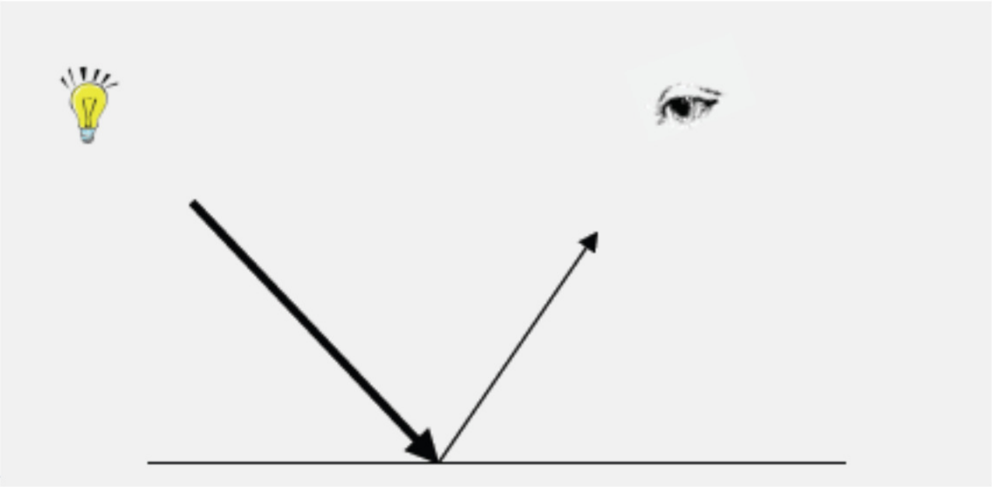
- Shiny surfaces
  - Polished metal
  - Glossy car finish
  - Plastics
- Specular highlight
  - Blurred reflection of the light source
  - Position of highlight depends on viewing direction



Specular highlight

Specular Reflection

- Ideal specular reflection is mirror reflection
  - Perfectly smooth surface
  - Incoming light ray is bounced in single direction
  - Angle of incidence equals angle of reflection

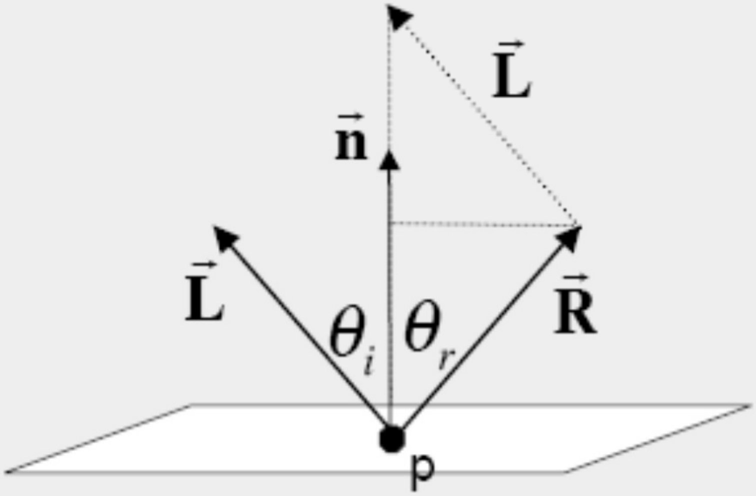


Law of Reflection

- Angle of incidence equals angle of reflection

$$\vec{\mathbf{R}} + \vec{\mathbf{L}} = 2\cos\theta\ \vec{\mathbf{n}} = 2\left(\vec{\mathbf{L}} \cdot \vec{\mathbf{n}}\right)\vec{\mathbf{n}}$$

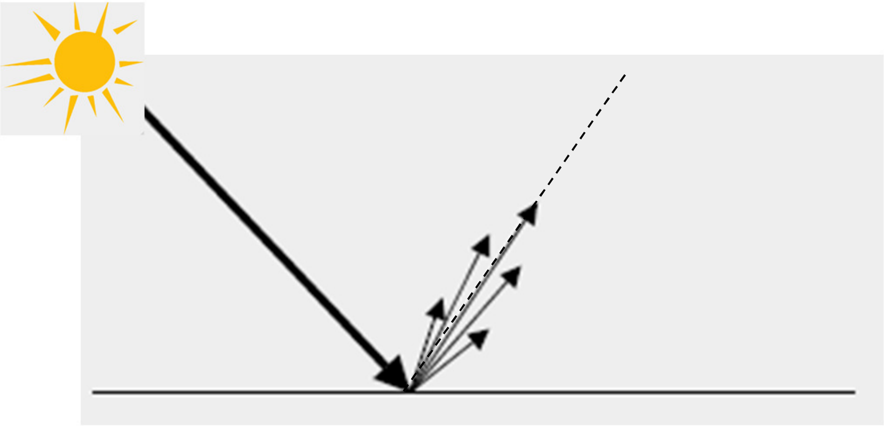
$$\vec{\mathbf{R}} = 2\left(\vec{\mathbf{L}} \cdot \vec{\mathbf{n}}\right)\vec{\mathbf{n}} - \vec{\mathbf{L}}$$



$$\theta_r = \theta_i$$

Specular Reflection

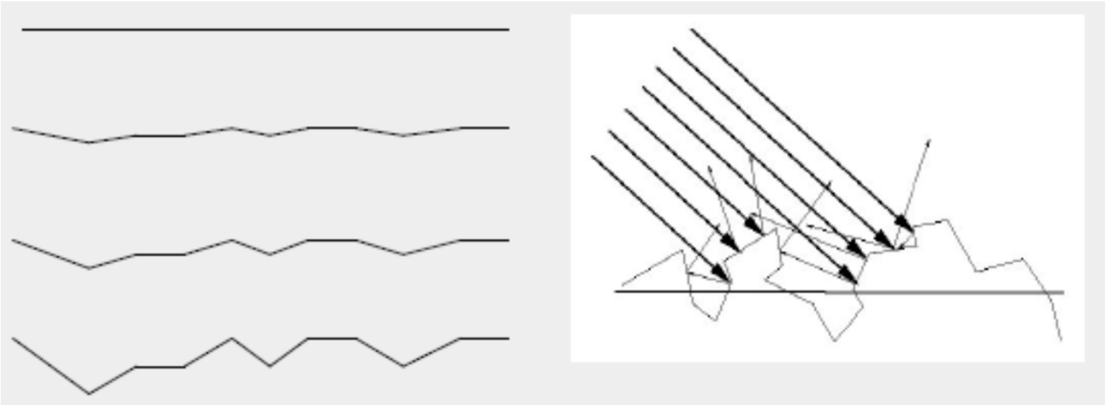
- Many materials are not perfect mirrors
  - Glossy materials



Glossy teapot

Glossy Materials

- Assume surface composed of small mirrors with random orientation (micro-facets)
- Smooth surfaces
  - Micro-facet normals close to surface normal
  - Sharp highlights
- Rough surfaces
  - Micro-facet normals vary strongly
  - Blurry highlight



Polished

Smooth

Rough

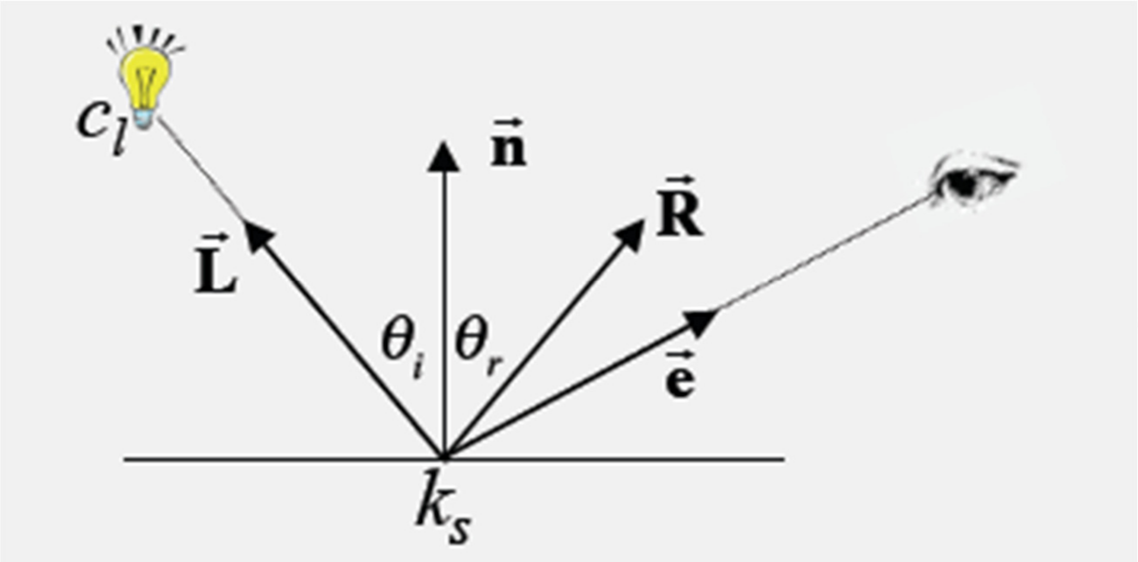
Very rough

Glossy Surfaces

- Expect most light to be reflected in mirror direction
- Because of micro-facets, some light is reflected slightly off ideal reflection direction
- Reflection
  - Brightest when view vector is aligned with reflection
  - Decreases as angle between view vector and reflection direction increases

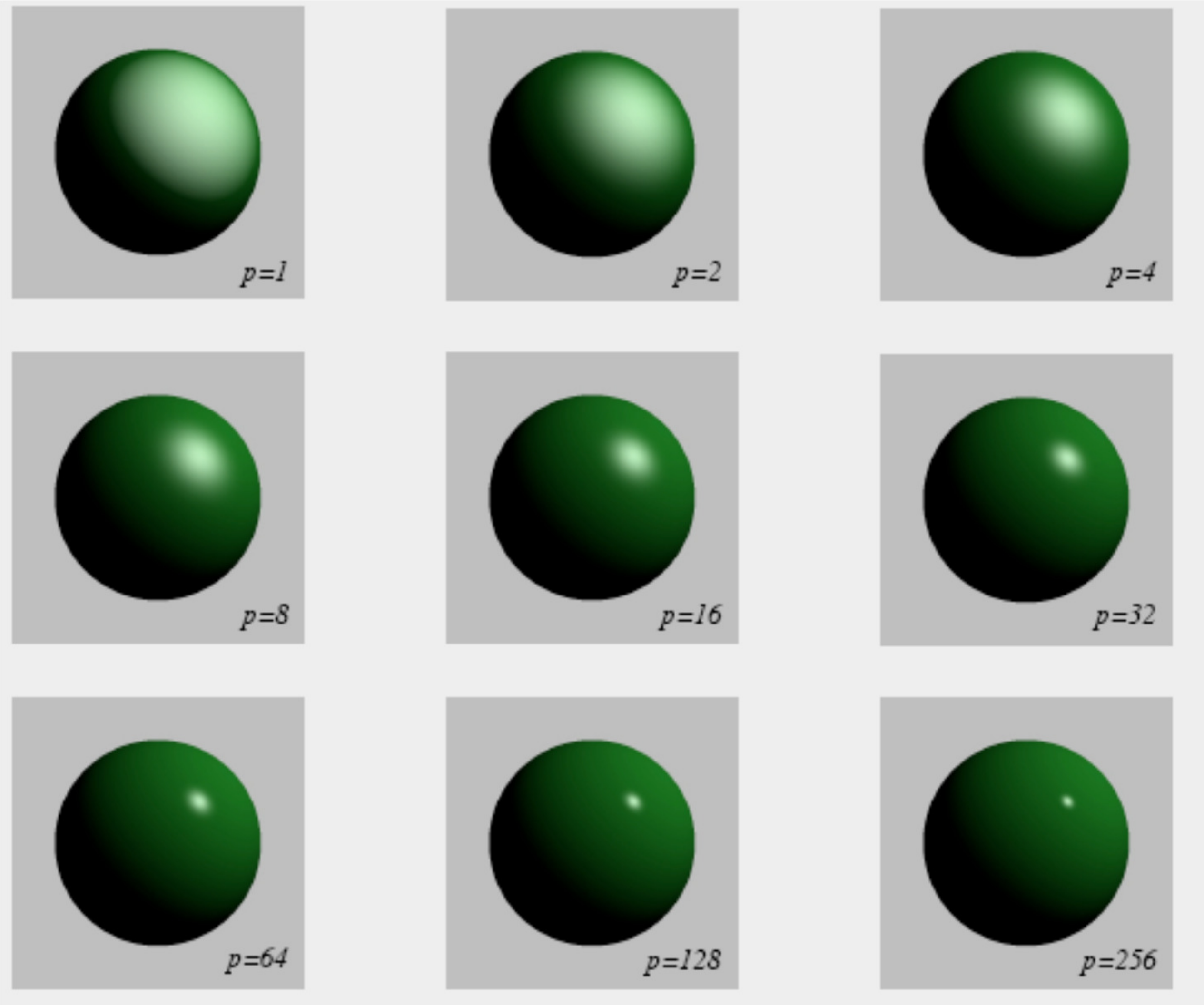
Phong Shading Model

- Developed by Bui Tuong Phong in1973
- Specular reflectance coefficient k_s
- Phong exponent p
  - Greater p means smaller (sharper) highlight



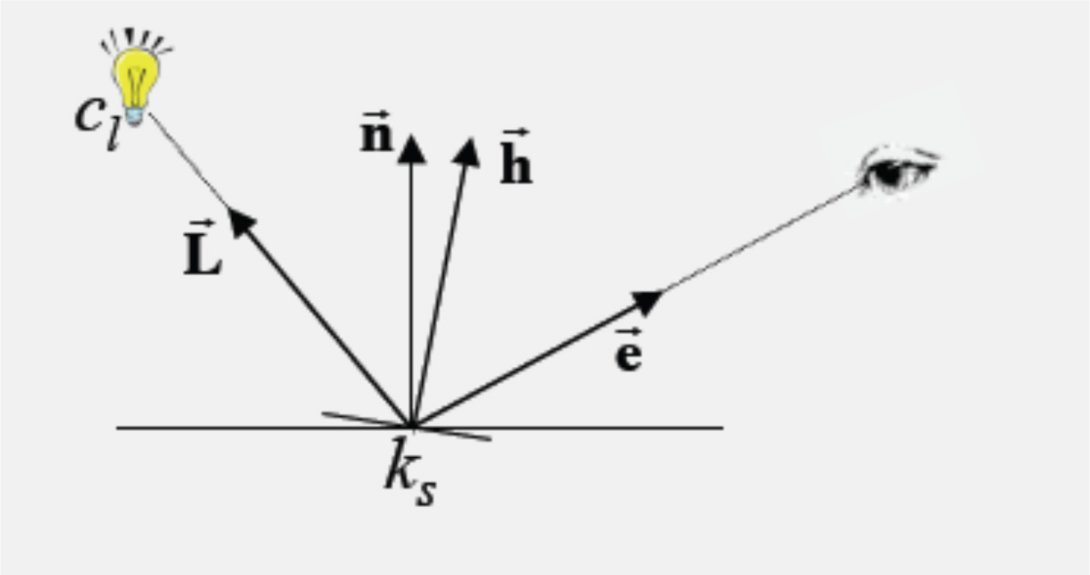
$$c = k_s c_l \left(\mathbf{R} \cdot \mathbf{e}\right)^p$$

Phong Shading Model



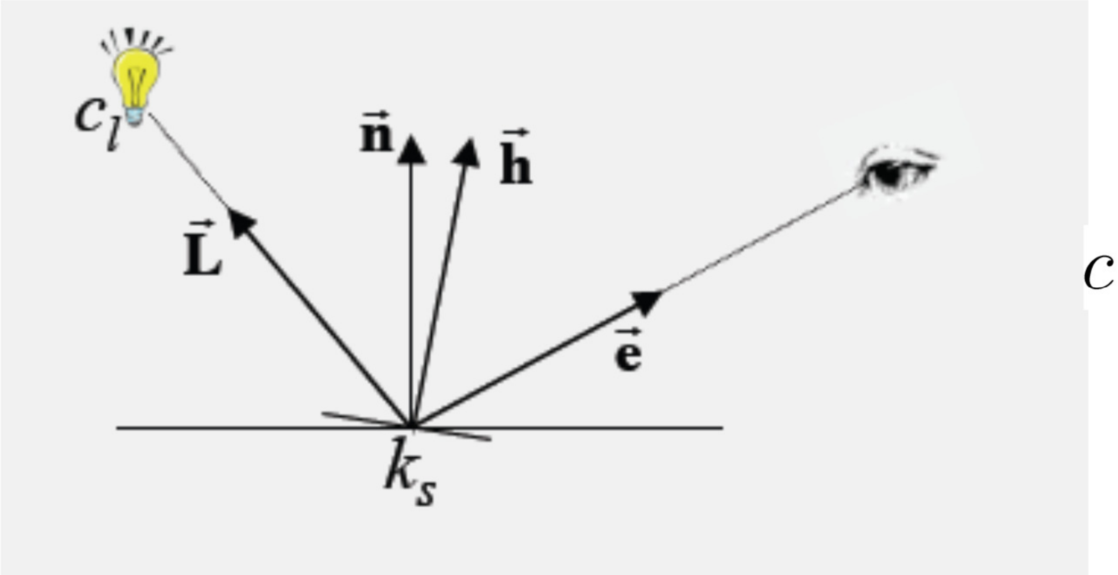
Blinn Shading Model (Jim Blinn, 1977)

- Modification of Phong Shading Model
- Defines unit halfway vector $\mathbf{h} = \frac{\mathbf{L}+\mathbf{e}}{\|\mathbf{L}+\mathbf{e}\|}$
- Halfway vector represents normal of micro-facet that would lead to mirror reflection to the eye



Blinn Shading Model

- The larger the angle between micro-facet orientation and normal, the less likely
- Use cosine of angle between them
- Shininess parameter *s*
- Very similar to Phong Model

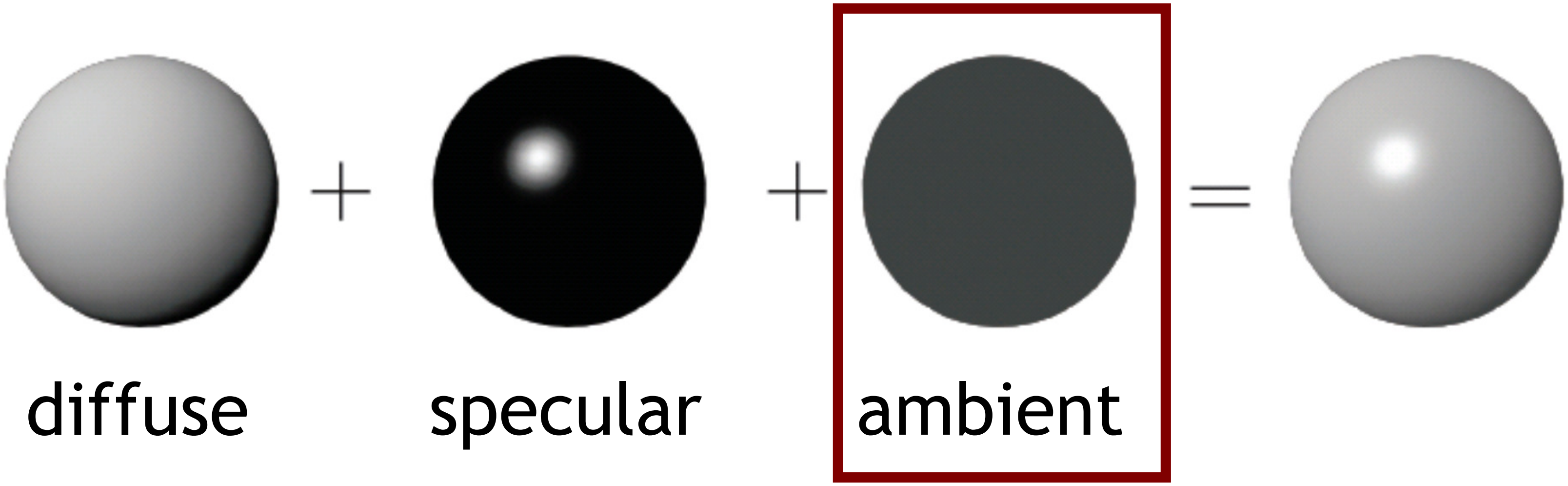


$$c = k_s c_l \left(\mathbf{h} \cdot \mathbf{n}\right)^s$$

Local Illumination

Simplified model

- Sum of 3 components
- Covers a large class of real surfaces



Ambient Light

- In real world, light is bounced all around scene
- Could use global illumination techniques to simulate
- Simple approximation
  - Add constant ambient light at each point: $k_a c_a$
  - Ambient light color: c_a
  - Ambient reflection coefficient: k_a
- Areas with no direct illumination are not completely dark

Complete Blinn-Phong Shading Model

- Blinn-Phong model with several light sources I
- All colors and reflection coefficients are vectors with 3 components for red, green, blue

$$c = \sum_i c_{l_i} \left(k_d \left(\mathbf{L}_i \cdot \mathbf{n} \right) + k_s \left(\mathbf{h}_i \cdot \mathbf{n} \right)^s \right) + k_a c_a$$