CSE 167: Introduction to Computer Graphics Lecture #7: Color and Shading

Jürgen P. Schulze, Ph.D.
University of California, San Diego
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Announcements

- Homework project #3 due this Friday, October 14th
  - To be presented starting 1:30pm in lab 260
- Late submissions for project #2 accepted until this Friday
- Ted problem "Resource Unavailable" solved

Lecture Overview

Color

- Color reproduction on computer monitors
- Perceptually uniform color spaces

Shading

- Introduction
- Local shading models

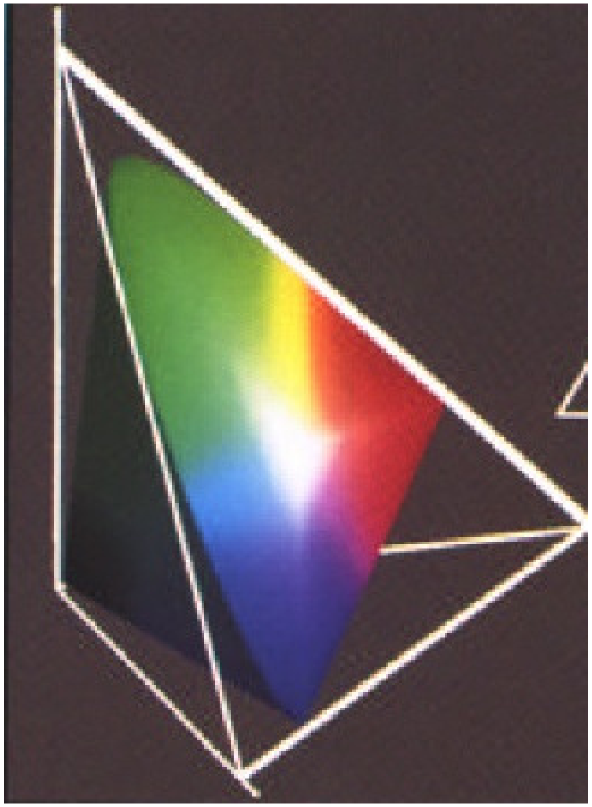
Summary

- 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 trisimulus experiment
- Each distinct color perception has unique coordinates
  - CIE RGB values may be negative
  - CIE XYZ values are always positive

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

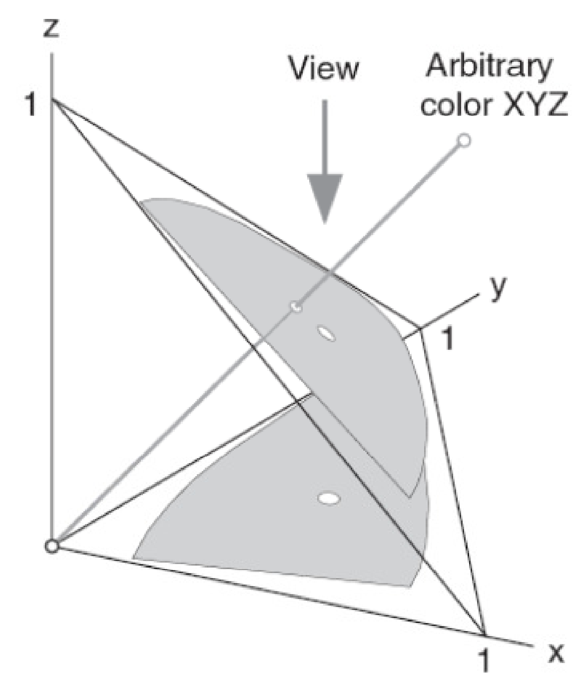


Chromaticity Diagram

- 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

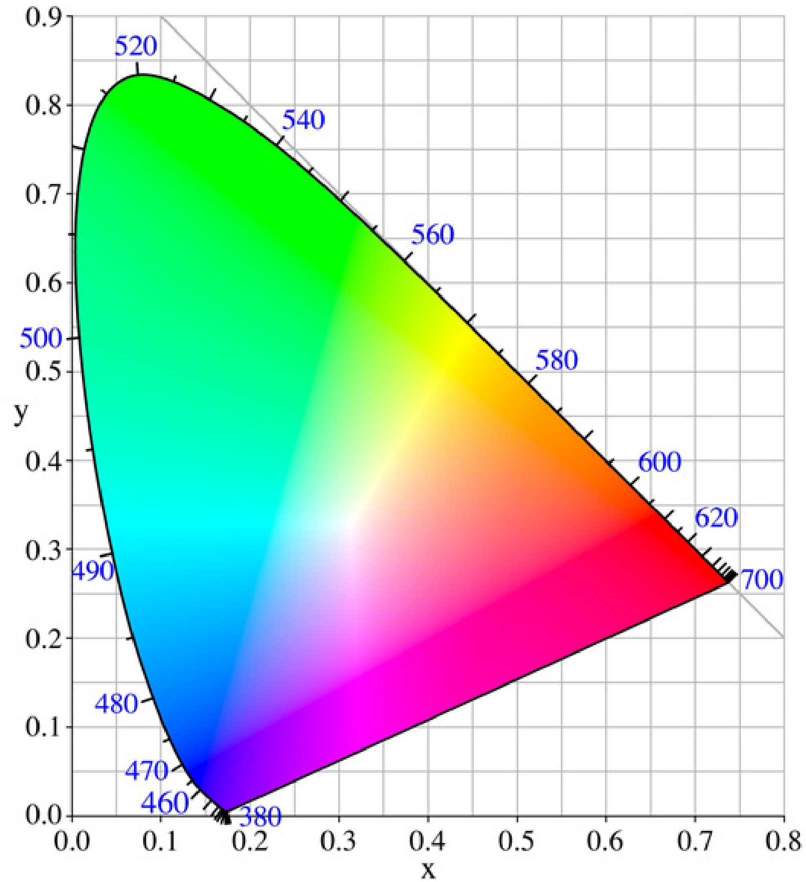
$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad 0 \leq x, y \leq 1$$

  - 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

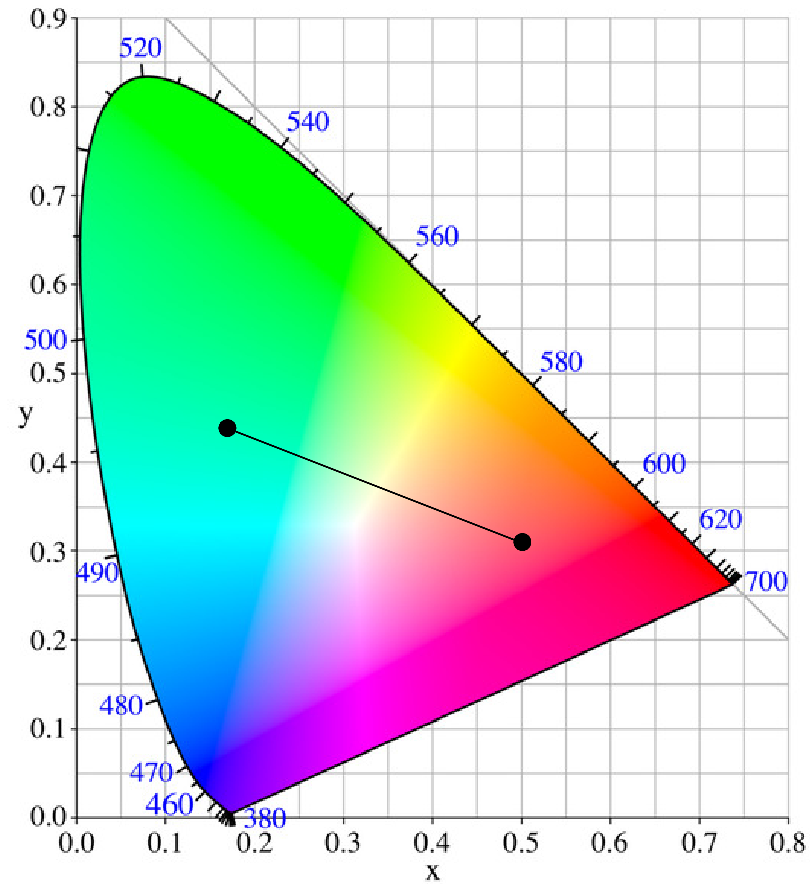
- Visualizes x,y plane (chromaticities)
- Pure spectral colors on boundary



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

Chromaticity Diagram

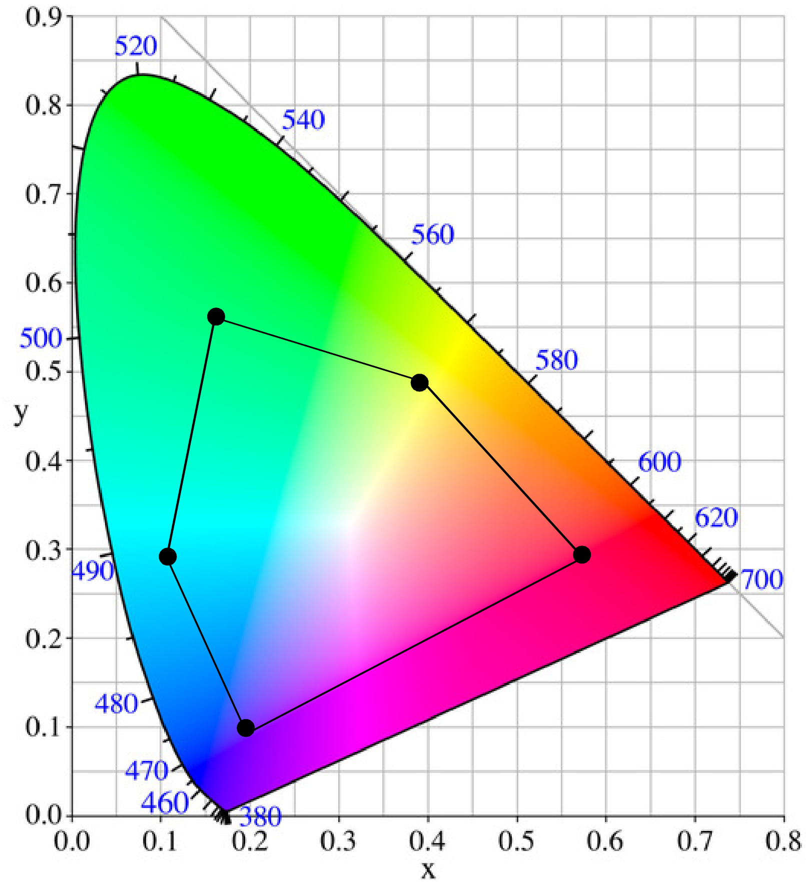
- Visualizes x,y plane (chromaticities)
- Pure spectral colors on boundary
- Weighted sum of any two colors lies on line connecting colors



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

Chromaticity Diagram

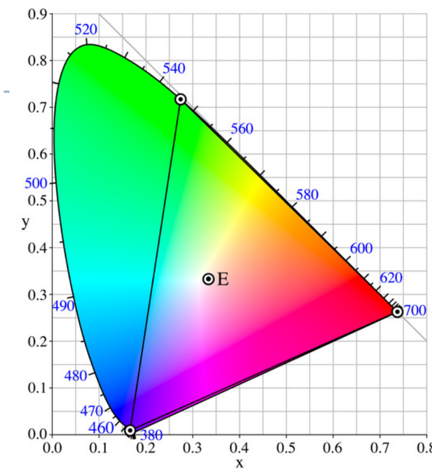
- Visualizes x,y plane (chromaticities)
- Pure spectral colors on boundary
- Weighted sum of any two colors lies on line connecting colors
- Weighted sum of any number of colors lies in convex hull of colors (gamut)



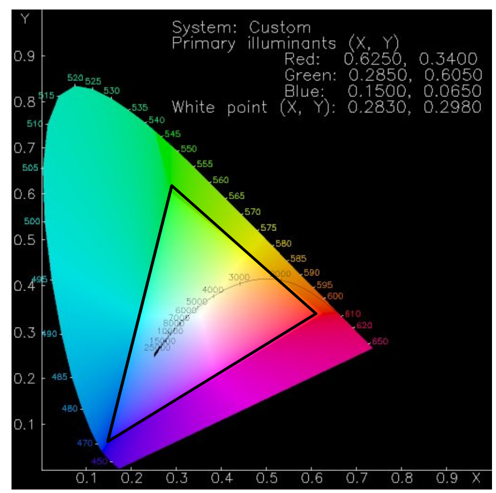
Colors shown do not correspond to colors represented by (x,y) coordinates!

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



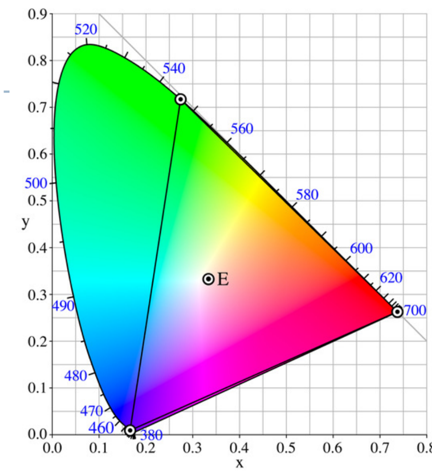
Gamut of CIE RGB primaries



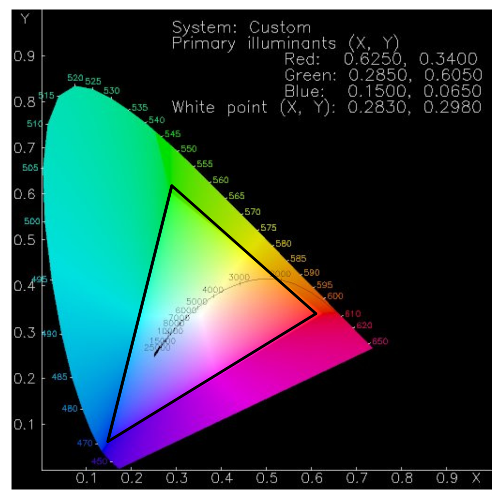
Gamut of typical CRT monitor

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

RGB Monitors

Ideally:

- We know XYZ values for RGB primaries

  $(X_r, Y_r, Z_r)(X_g, Y_g, Z_g)\ (X_b, Y_b, Z_b)$

- Monitor is linear

- RGB signal corresponds to weighted sum of primaries:

$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} = r \begin{bmatrix} X_r \\ Y_r \\ Z_r \end{bmatrix} + g \begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix} + b \begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix}$$

$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

RGB Monitors

- Given desired XYZ values, find rgb values by inverting matrix

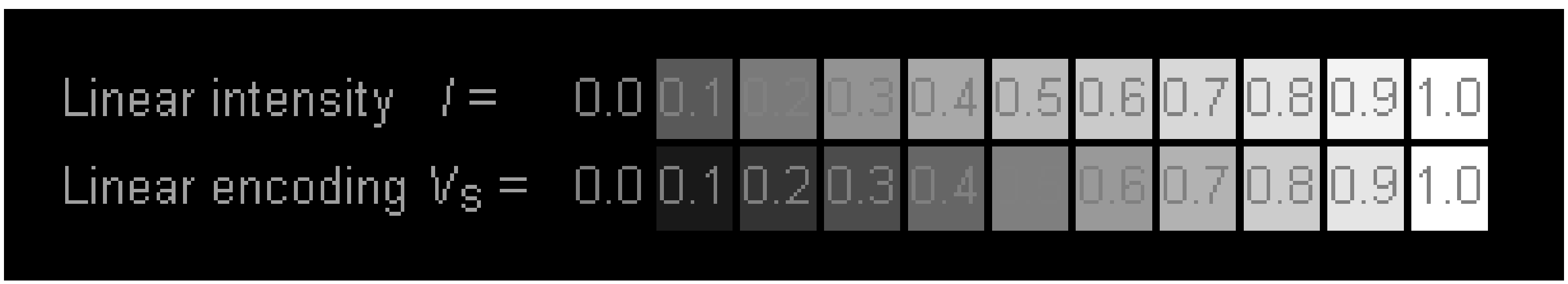
$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}^{-1} = \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

- Similar to change of coordinate systems for 3D points

RGB Monitors

In reality

- XYZ values for monitor primaries are usually not directly specified
  - Monitor brightness is adjustable
- Monitors are not linear



  - For typical CRT monitors $I = V_s^\gamma$

$$\gamma \approx 2.2$$

sRGB

- Standard color space, with standard conversion to CIE XYZ
- Designed to match RGB values of typical monitor under typical viewing conditions
  - If no calibration information available, it is best to interpret RGB values as sRGB
- sRGB is supported by OpenGL 2.0 with the `ARB_framebuffer_sRGB` extension
- For more details and transformation from CIE XYZ to sRGB: http://en.wikipedia.org/wiki/SRGB_color_space

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
  - Consumers do not seem to care
  - Standard for digital publishing, printing, photography

Display calibration

Lecture Overview

Color

- Color reproduction on computer monitors
- Perceptually uniform color spaces

Shading

- Introduction
- Local shading models

Perceptually Uniform Color Spaces

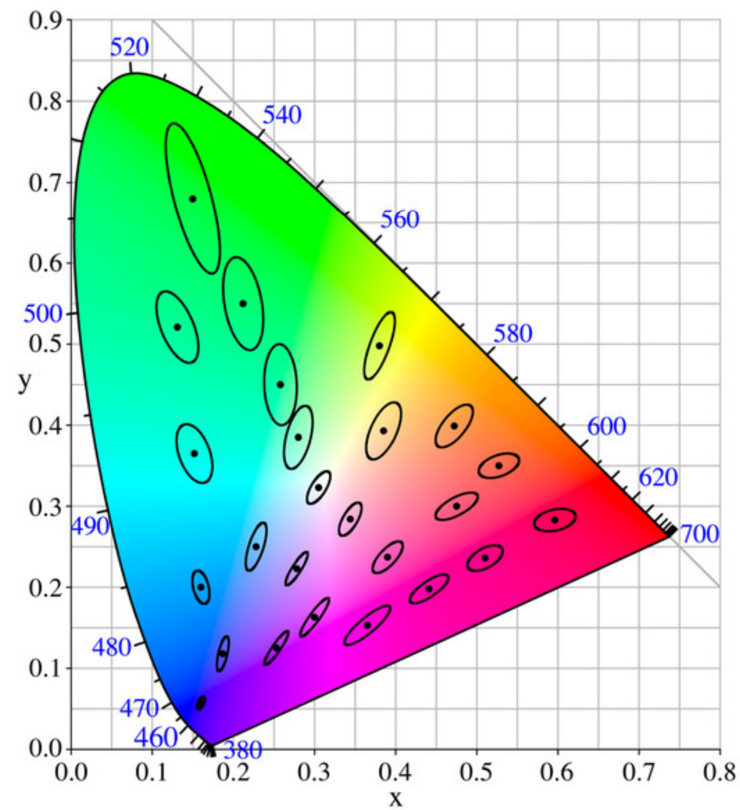
Definition:

Euclidean distance between color coordinates corresponds to perceived difference.

- CIE RGB, XYZ are not perceptually uniform:
  - Euclidean distance between RGB, XYZ coordinates does not correspond to perceived difference

MacAdam Ellipses

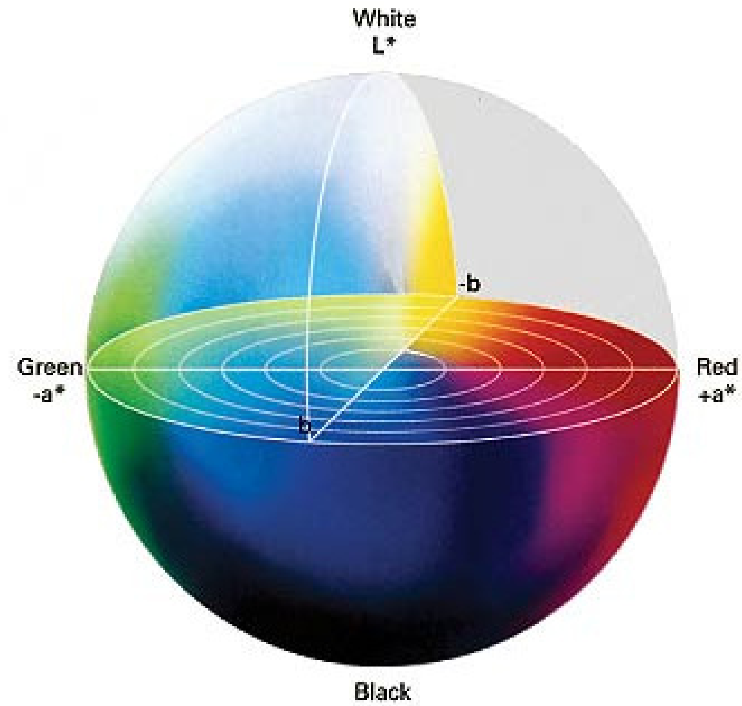
- Experiment (1942) to identify regions in CIE xy color space that are perceived as the same color
- Found elliptical areas, MacAdam ellipses
- In perceptually uniform color space, each point on an ellipse should have the same distance to the center
  - Ellipses become circles



MacAdam ellipses

CIE L*,a*,b* (CIELAB)

- Most common perceptually uniform color space
  - L* encodes lightness
  - a* encodes position between magenta and green
  - b* encodes position between yellow and blue
- Uses asterisk (*) to distinguish from Hunter's Lab color space
- Conversion between CIE XYZ and CIELAB is *non-linear*



CIELAB color space

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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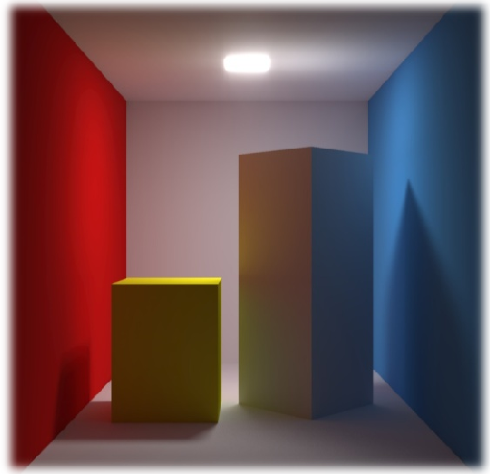
Shading

- 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

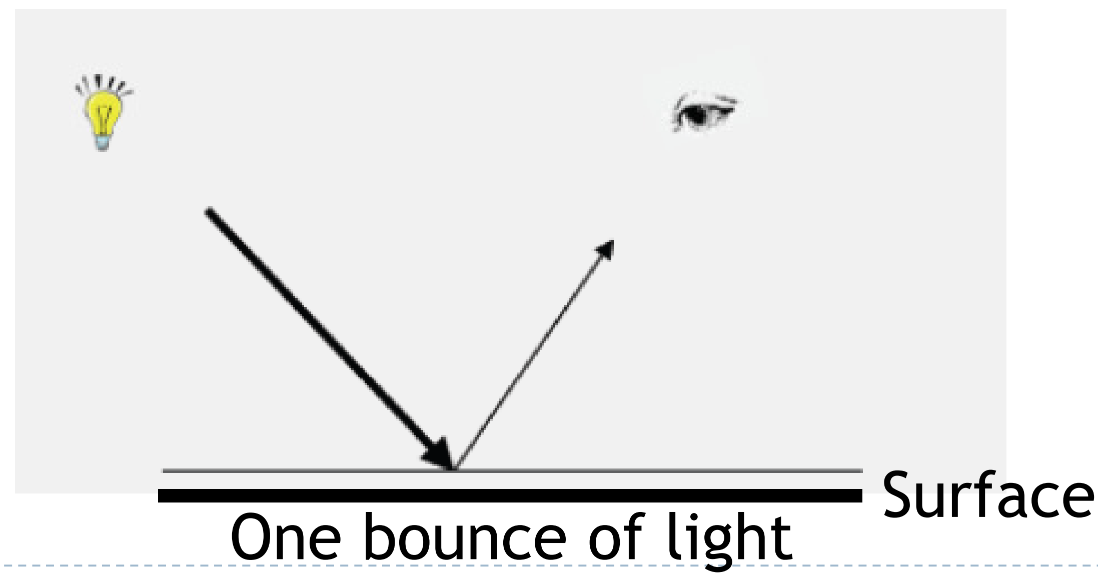
- Covered by CSE168



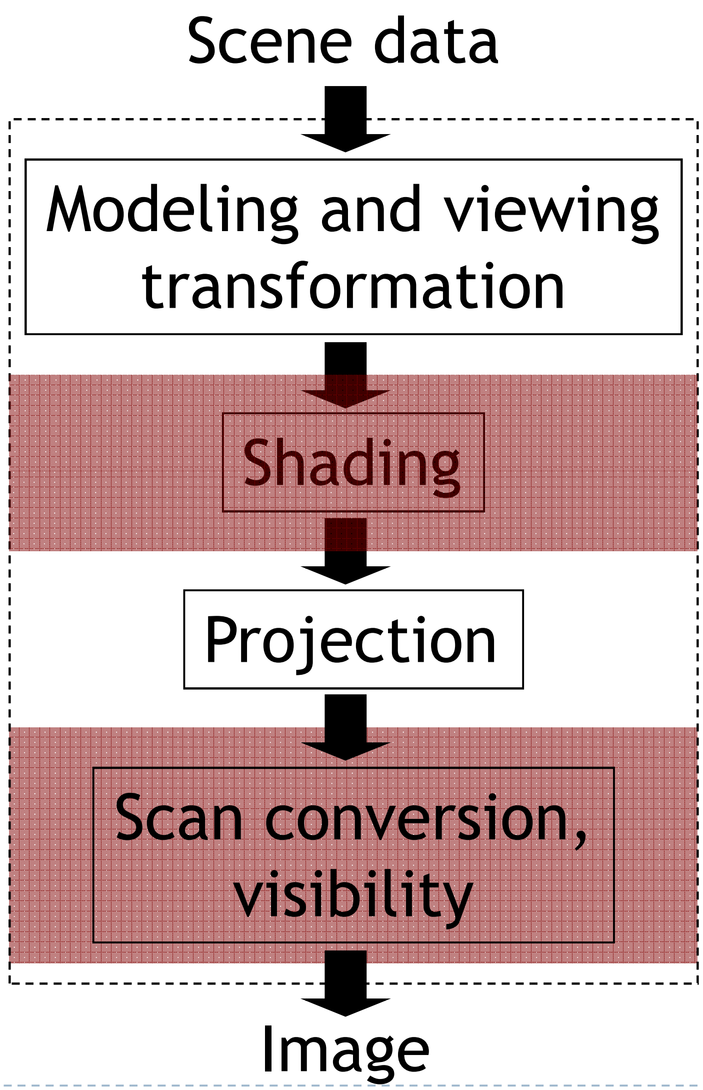
(All non-teapot images courtesy of Prof. Wann Jensen)

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



Rendering Pipeline



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

Lecture Overview

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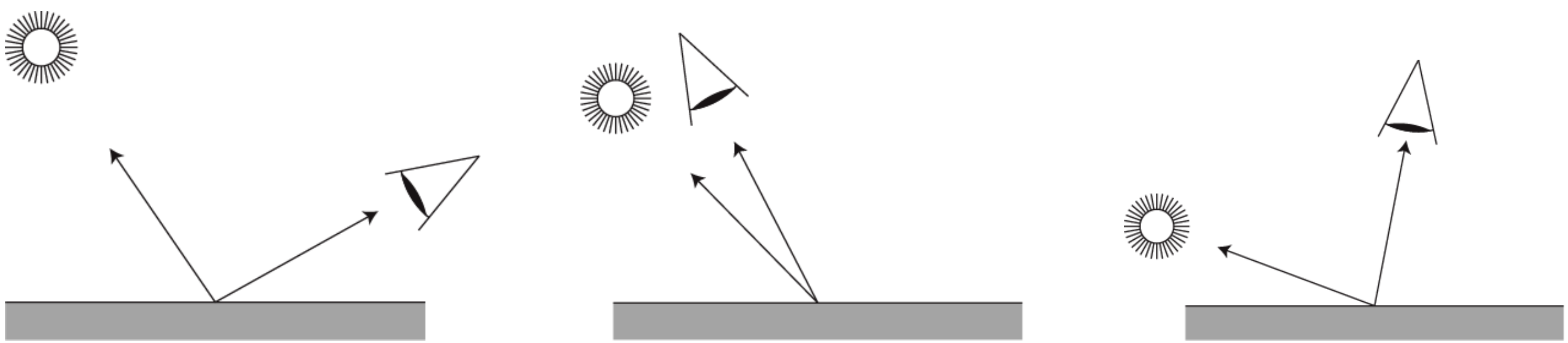
Local Illumination

- 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

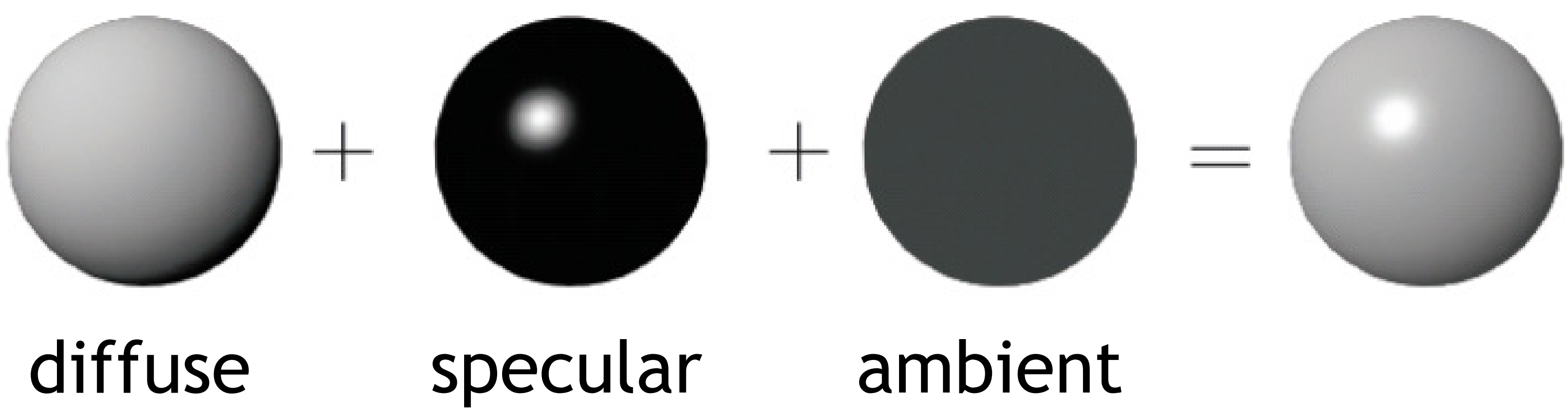
- Model reflection of light at surfaces
  - Assumption: no subsurface scattering
- Bidirectional reflectance distribution function (BRDF)
  - Given light direction, viewing direction, how much light is reflected towards the viewer
  - For any pair of light/viewing directions!



Local Illumination

Simplified model

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



Local Illumination

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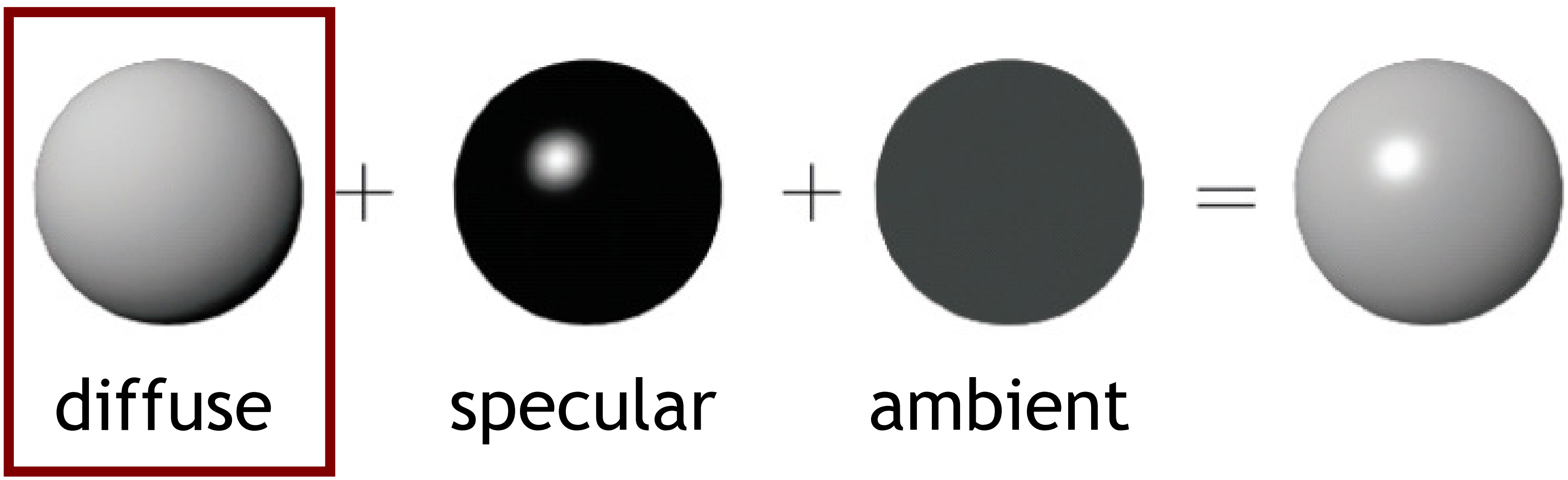
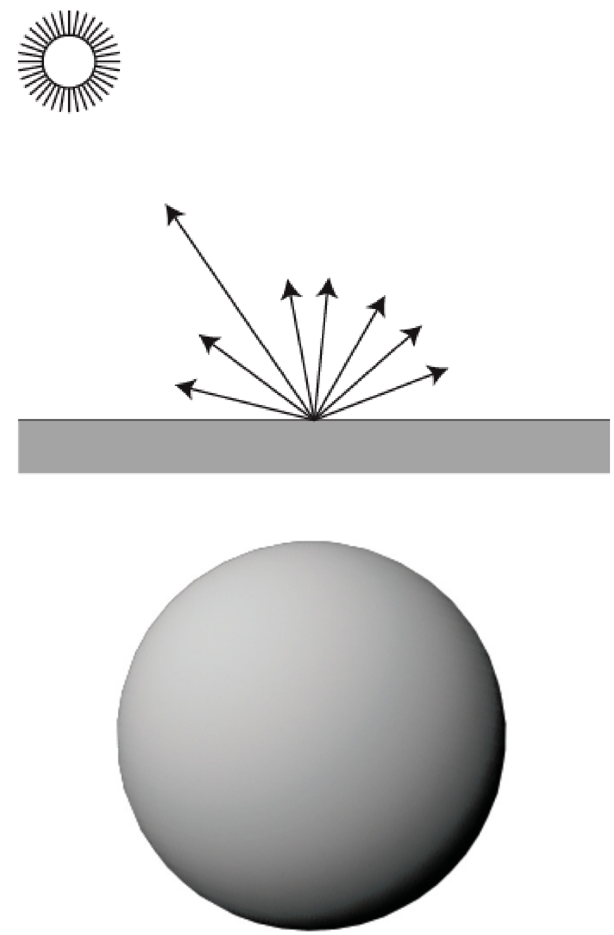


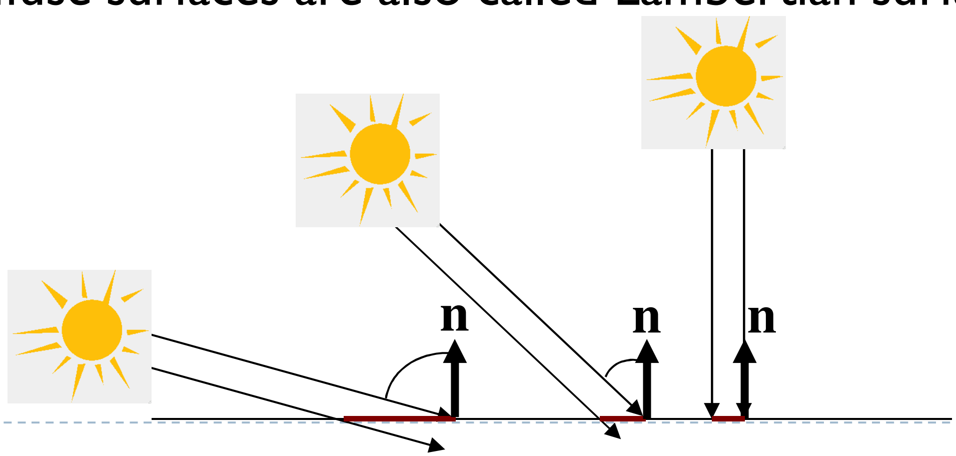
Diffuse Reflection

- 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



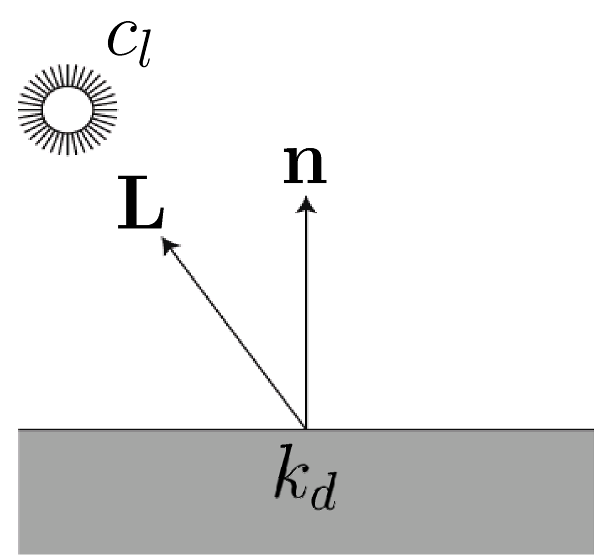
Diffuse Reflection

- 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:

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

Proportional to cosine between normal and light



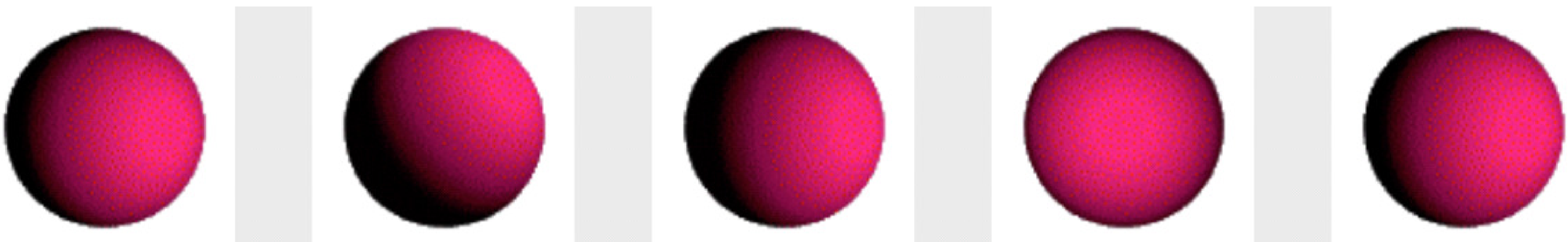
Diffuse Reflection

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

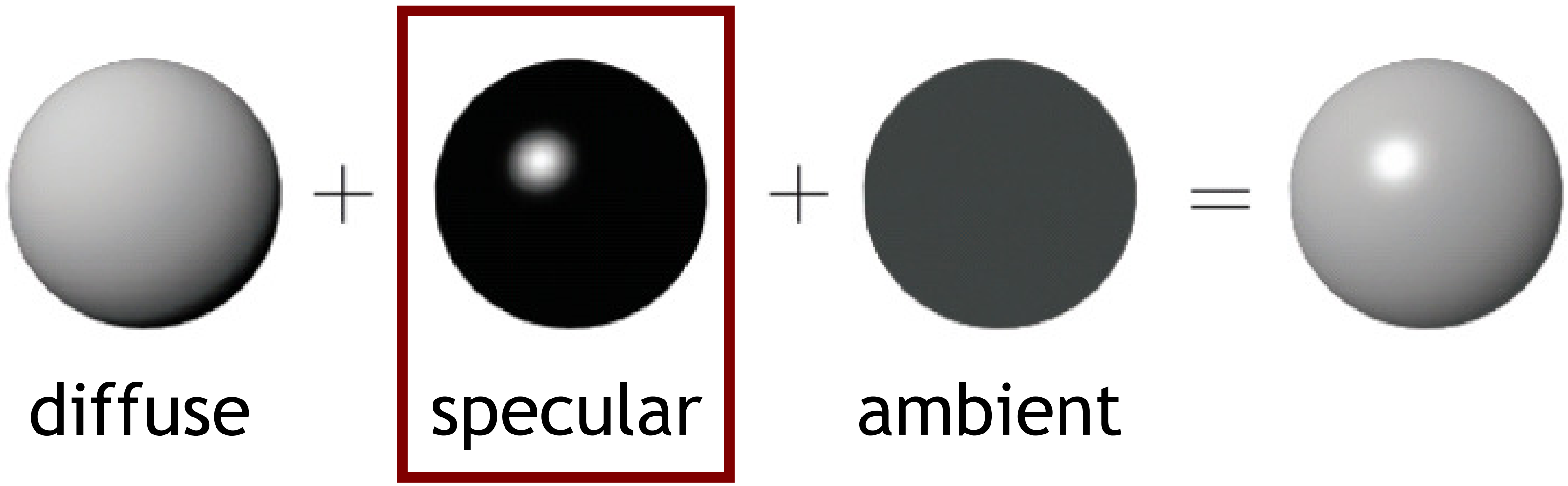
OpenGL

- 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

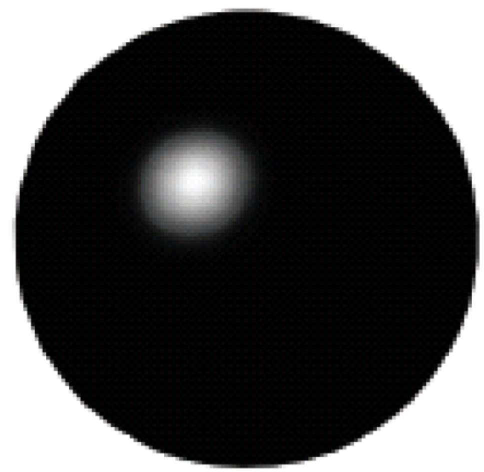
Simplified model

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



Specular Reflection

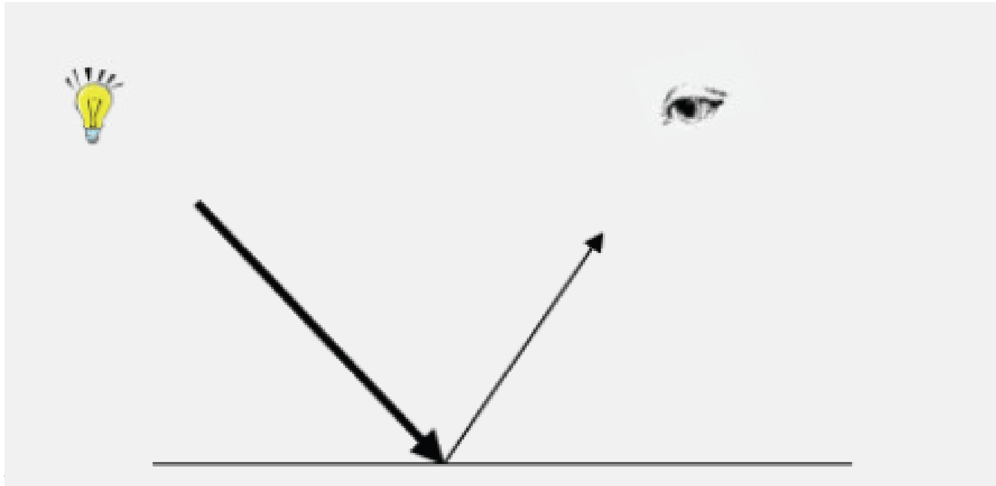
- Shiny surfaces
  - Polished metal
  - Glossy car finish
  - Plastics
- Specular highlight
  - Blurred reflection of the light source
  - Position of highlight depends on viewing direction



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

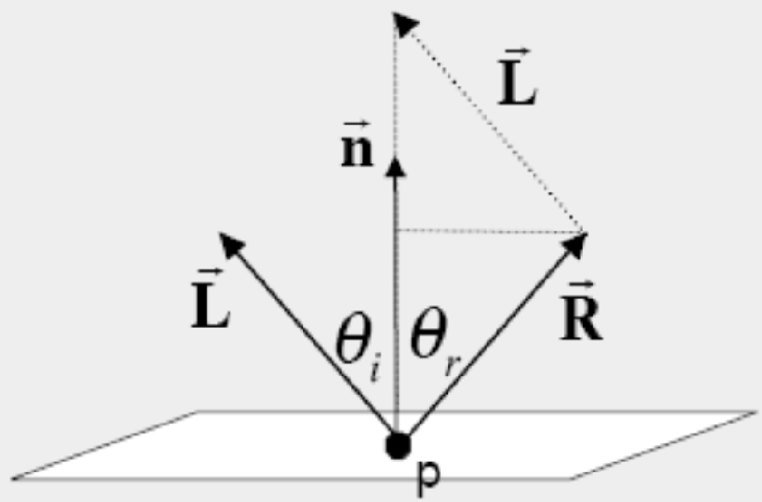


Law of Reflection

- Angle of incidence equals angle of reflection

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

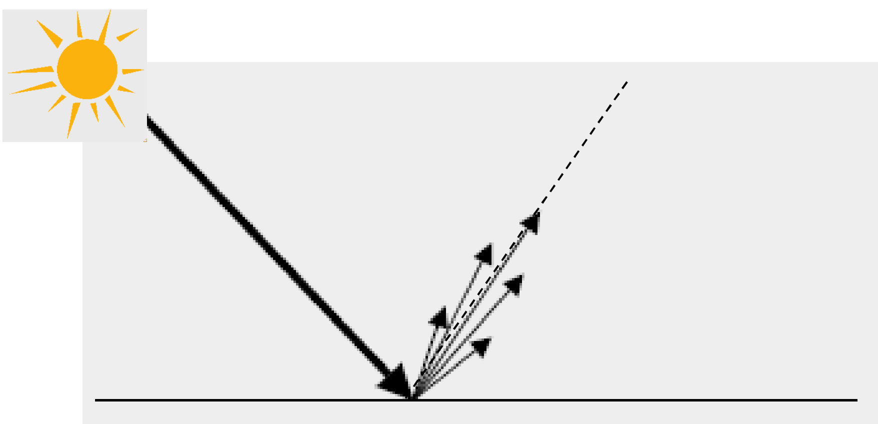
$$\vec{\mathbf{R}} = 2\left(\vec{\mathbf{L}} \cdot \vec{\mathbf{n}}\right)\vec{\mathbf{n}} - \vec{\mathbf{L}}$$



$$\theta_r = \theta_i$$

Specular Reflection

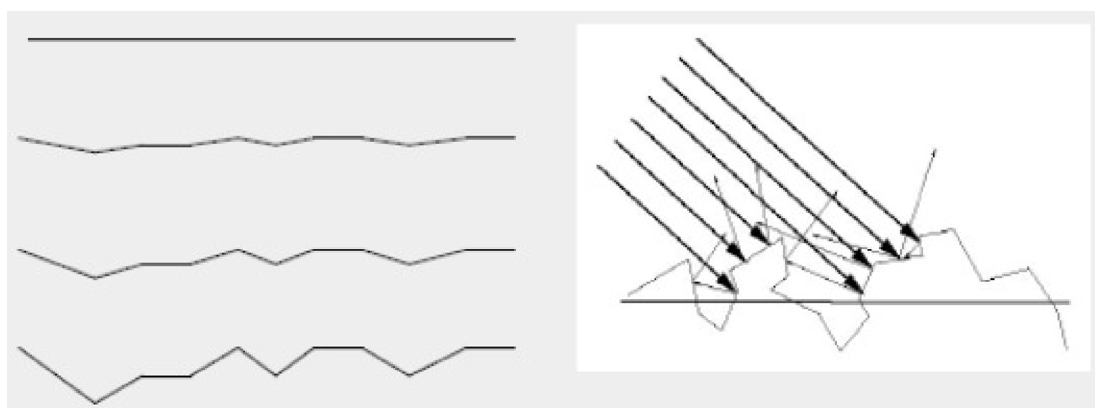
- Many materials are not perfect mirrors
  - Glossy materials



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

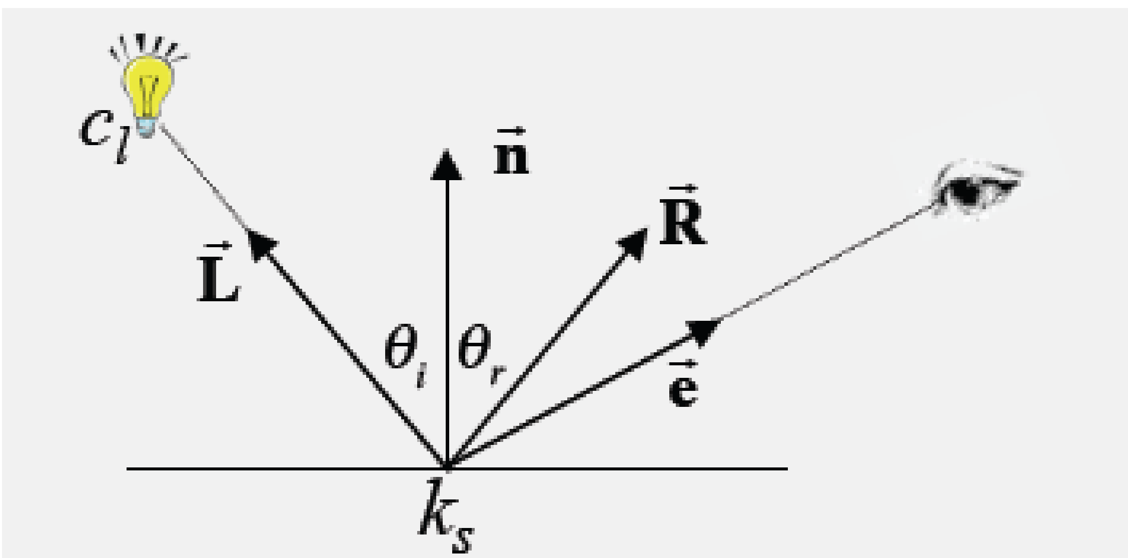
Very rough

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

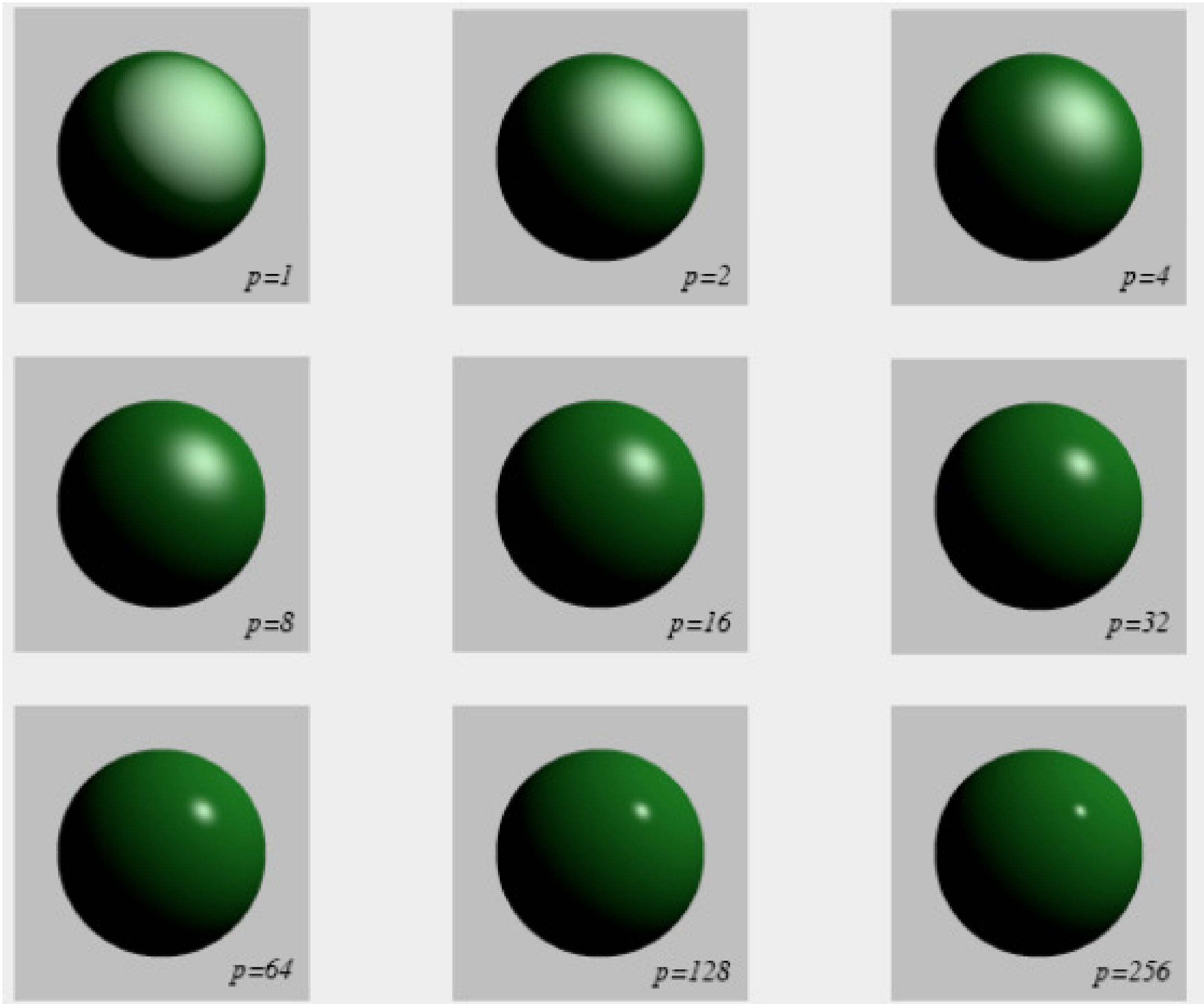
Phong Model (Bui Tuong Phong, 1973)

- 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 Model

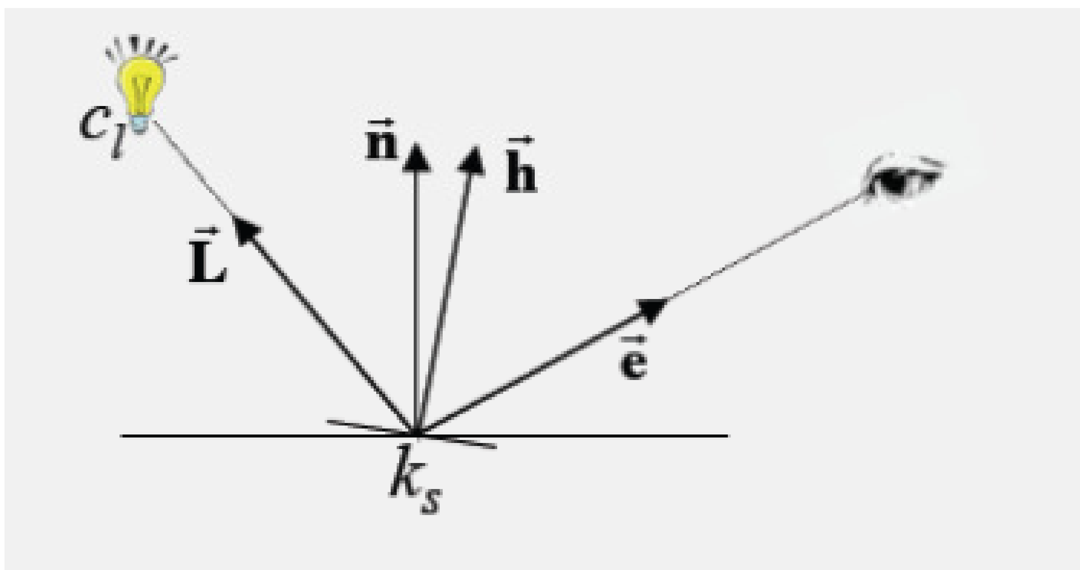


Blinn Model (Jim Blinn, 1977)

- Define unit halfway vector

$$\mathbf{h} = \frac{\mathbf{L}+\mathbf{e}}{\|\mathbf{L}+\mathbf{e}\|}$$

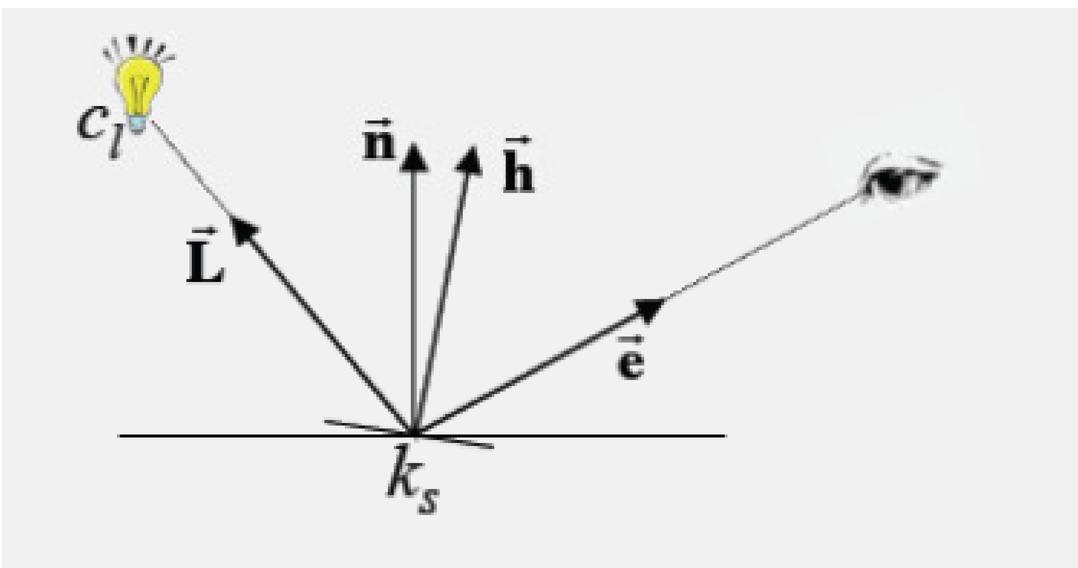
- Halfway vector represents normal of micro-facet that would lead to mirror reflection to the eye



Blinn Model

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

s

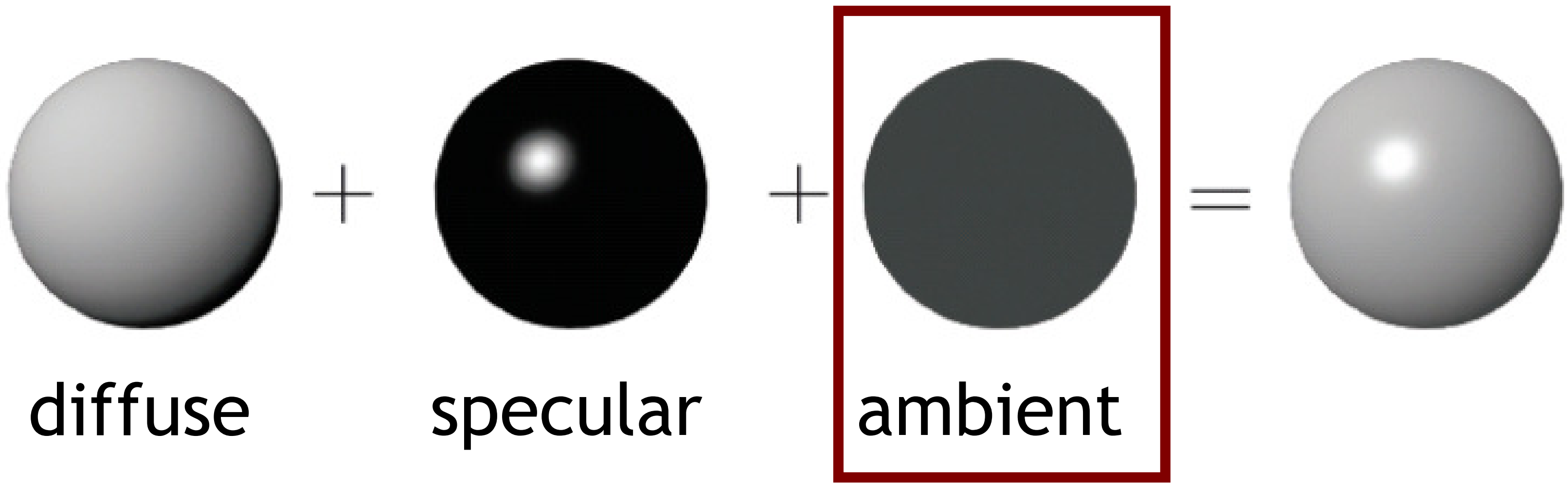


$$c = k_s c_l \left(\mathbf{h} \cdot \mathbf{n}\right)^s$$

Local Illumination

Simplified model

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



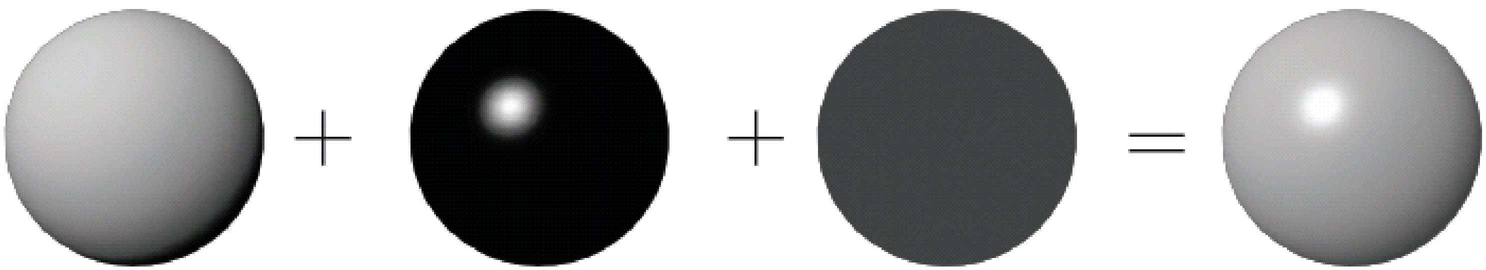
Ambient Light

- 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

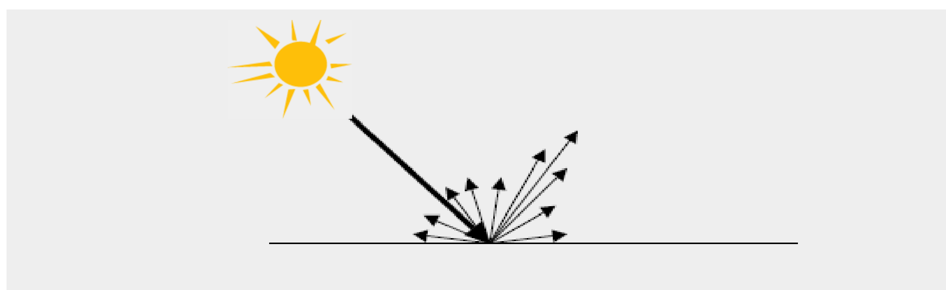
Complete Blinn Model

- Blinn model with several light sources I
- All colors and reflection coefficients have separate values for red, green, blue

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



diffuse specular ambient



BRDFs

- Diffuse, Phong, Blinn models are instances of *bidirectional reflectance distribution functions* (BRDFs)
- For each pair of light directions $\mathbf{L}$, viewing direction $\mathbf{e}$, return fraction of reflected light
- Shading with general BRDF f

$$c = \sum_i c_{l\,i} f(\mathbf{L}_i, \mathbf{e})$$

- Many forms of BRDFs in graphics, often named after inventors
  - Cook-Torrance
  - Ward
  - …

Next Lecture

- Light sources
- Shader programming:
  - Vertex shaders
  - Fragment shaders