Lecture 8: Color and Illumination Basics

September 19, 2019

Basics: What is Color?

- Eyes, films and CCD/CMOS cameras all convert light into electrical energy
  - More intensity => higher (brighter) value

- This is sufficient for black-and-white (i.e. intensity) images

- What about color?

The Physics View

- Coherent light has a wavelength
  - Visible range typically described as:
  - 380nm (deep purple) to 780 nm (pure red)
- Natural light mixes many frequencies
  - Roughly equal across the spectrum ‘white’
  - Prisms split light by frequency (rainbows)
- Wavelengths ≠ perceptual colors
  - Metamers: wavelength combinations appearing the same to normal human observers

Eye Can See

- Human Receptors 101
- Rods = grayscale
- Cones = color
  - Generally RGB
- Both ‘count’ photons
- Rods highly sensitive
- Cones need a lot of light

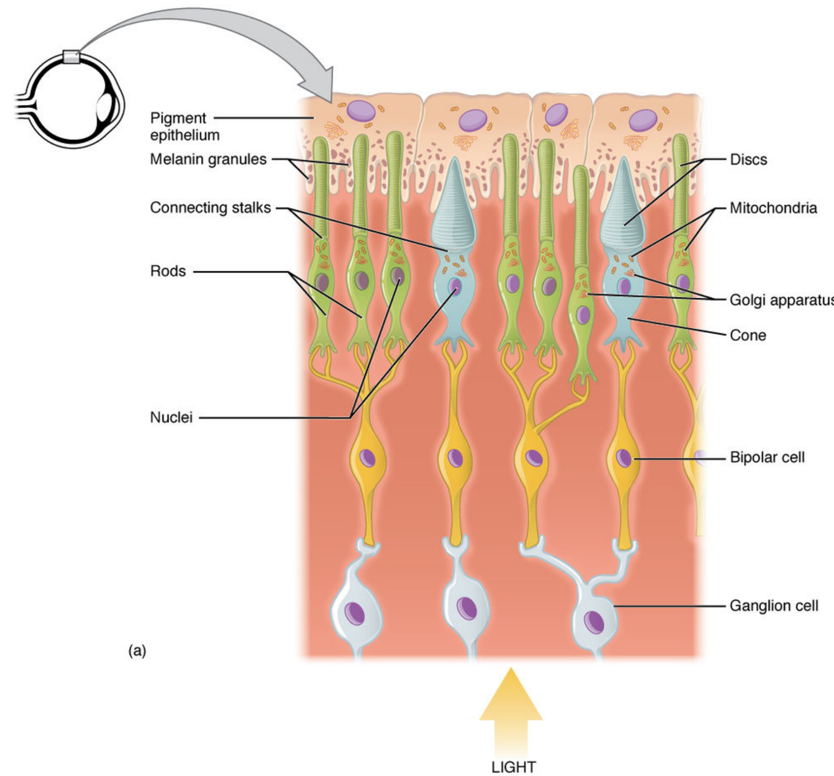


Illustration from Anatomy & Physiology, Connexions via Wikipedia

For Most People – 3 Flavors

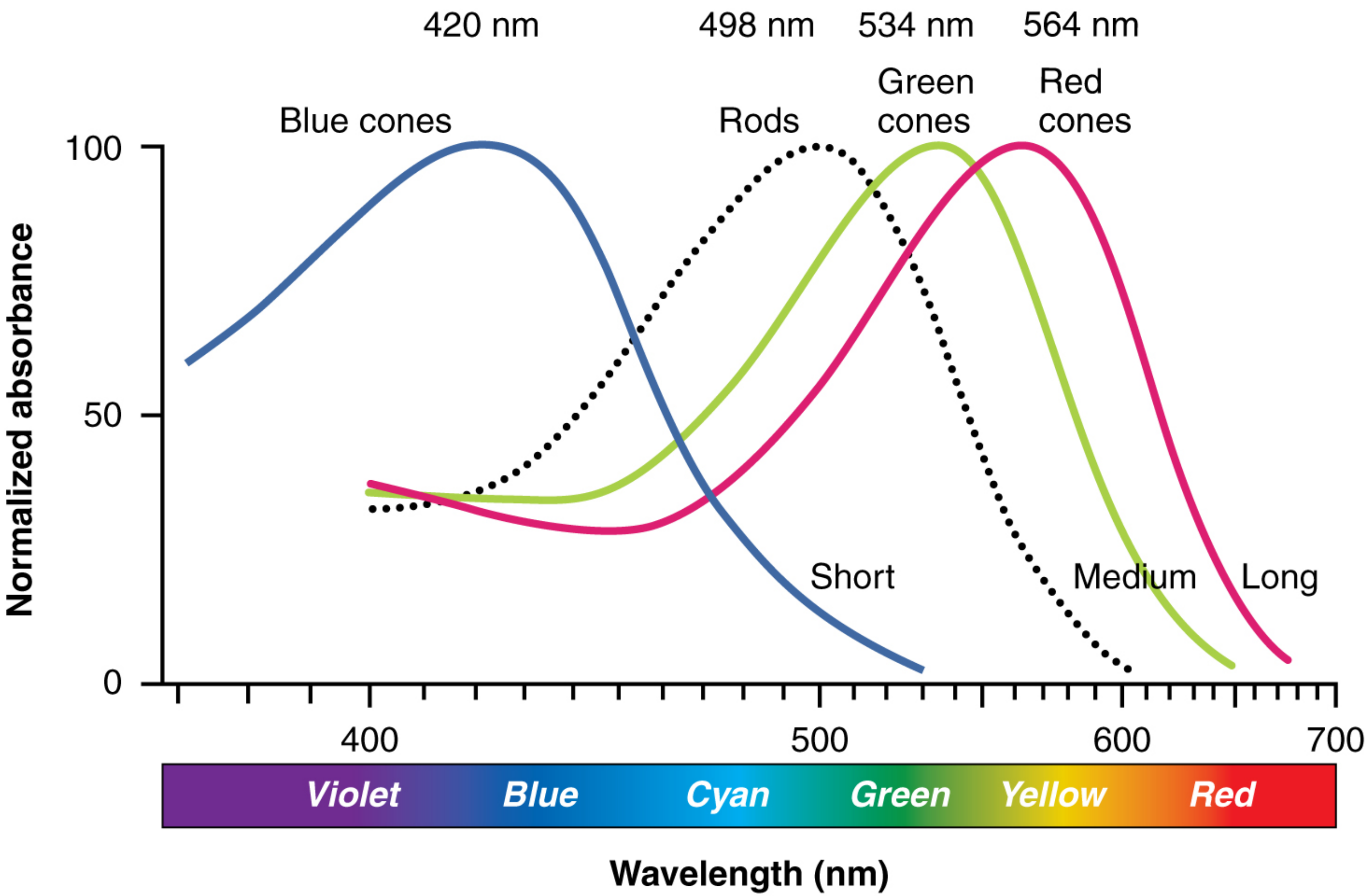


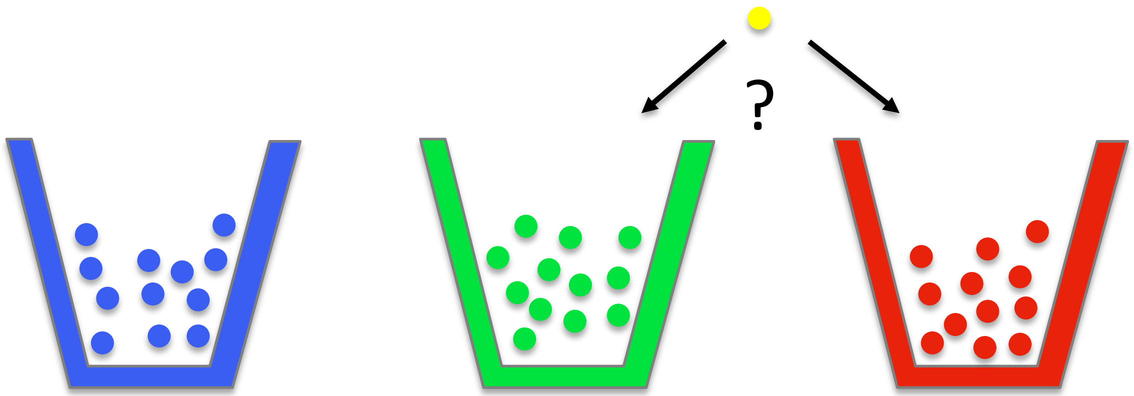
Illustration from OpenStax College - Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/ via Wikipedia

Integration Over Time

Catch photons in a bucket – a metaphor.

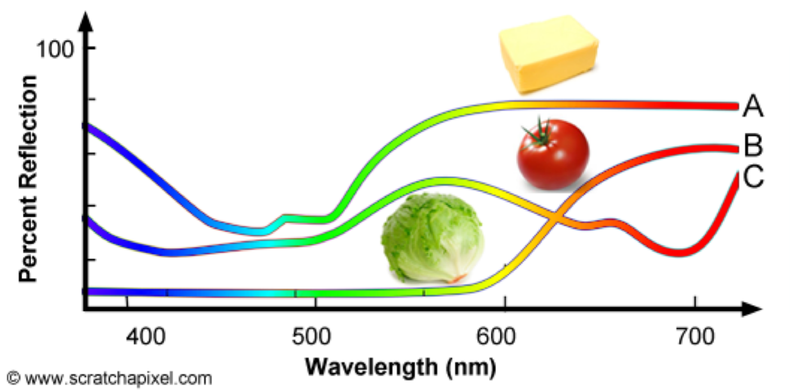
First simple model, photons in 3 flavors

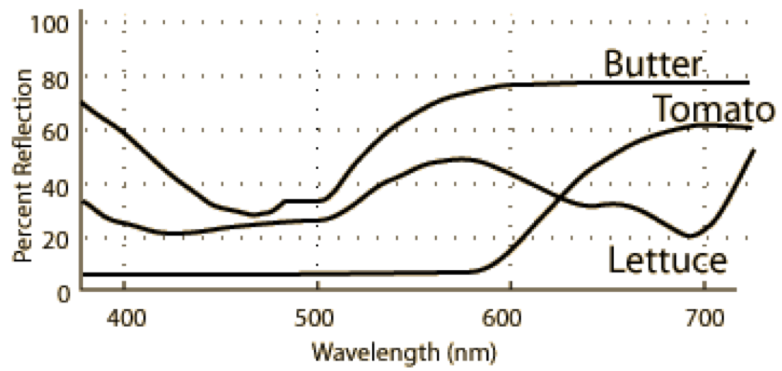
But: what about a 551 nm photon?



Spectral Power Density

- An illuminated object throws off an entire festival of different wavelength photons.



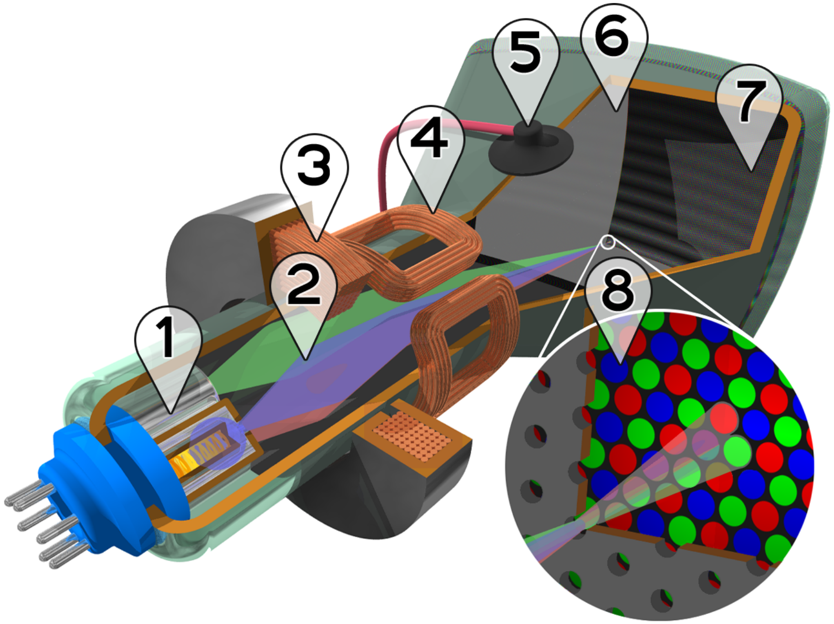


http://www.scratchapixel.com/old/assets/Uploads/Lesson004/l004-spd.png? http://hyperphysics.phy-astr.gsu.edu/hbase/vision/spd.html

Your eye takes all this rich information and transduces it through essentially three accumulators, your RGB cones.

Displays: Clever Fakes?

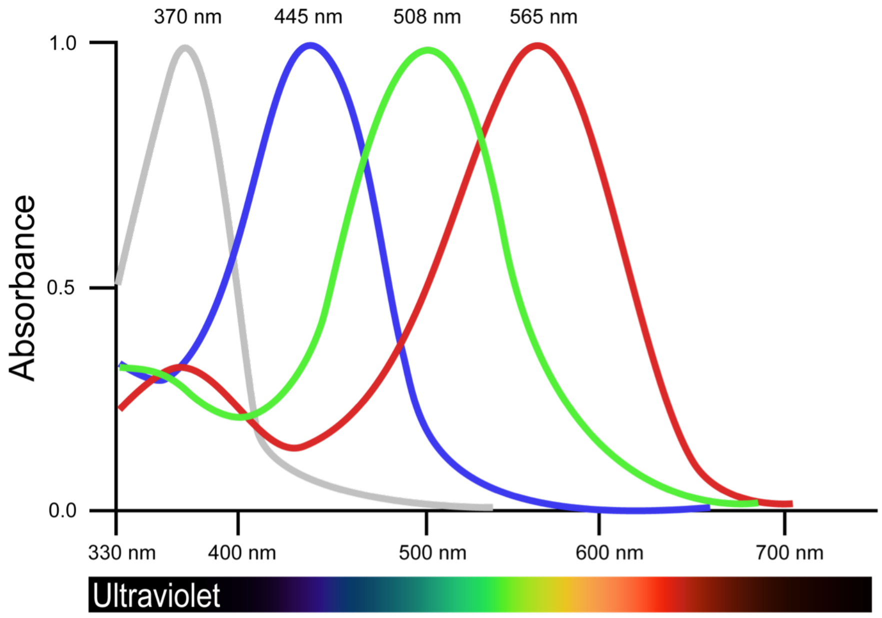
- So how does a display create color images?
  - By stimulating R,G and B cones
- This is(was) easy to explain for TVs



This image and associated numeric key to the right is from wikimedia.
https://commons.wikimedia.org/wiki/File:CRT_color_enhanced.png

1. Electron guns
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating RGB beams
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inside

Do Others Do It Differently?



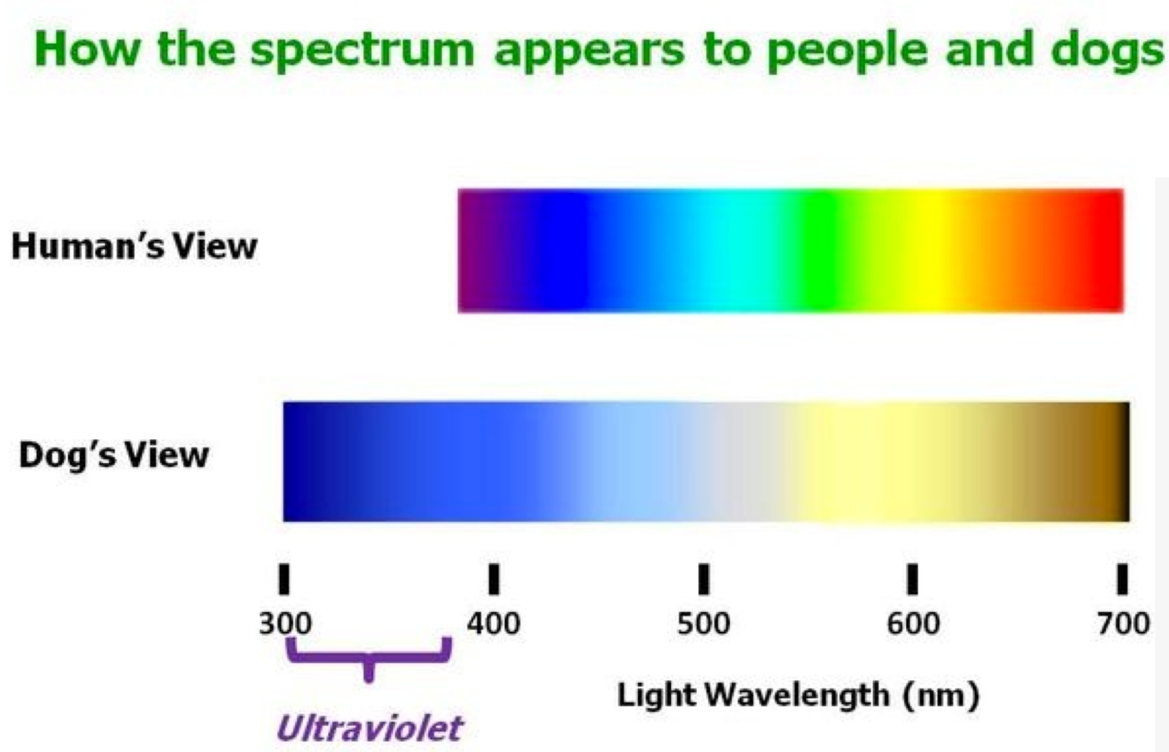
"Uncorrected absorbances of visual pigments of birds based on Pryke, Sarah R. (2007)" from https://commons.wikimedia.org/wiki/File:BirdVisualPigmentSensitivity.svg

Our displays are specifically tuned to fool standard human color perception.

All color perception of this type subject to confusion: Metamers

Dogs are Bichromatic (like most mammals)

But they have a broader visible spectrum than we do….



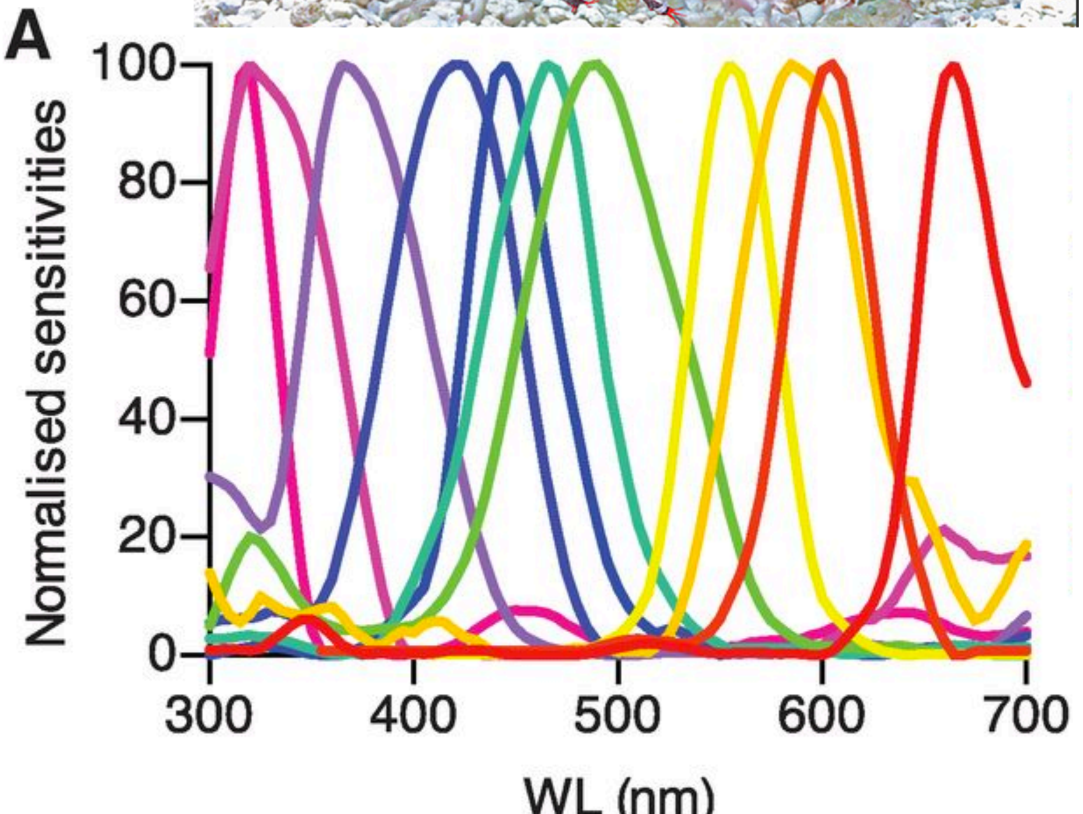
https://www.quora.com/What-colors-can-dogs-see

https://pngtree.com/freepng/dog-wearing-glasses_2224271.html

Mantis Shrimp!

- Between 12 & 16 receptor types
- Some receptors polarized
- Really small central nervous system
- Lives under water (murky)

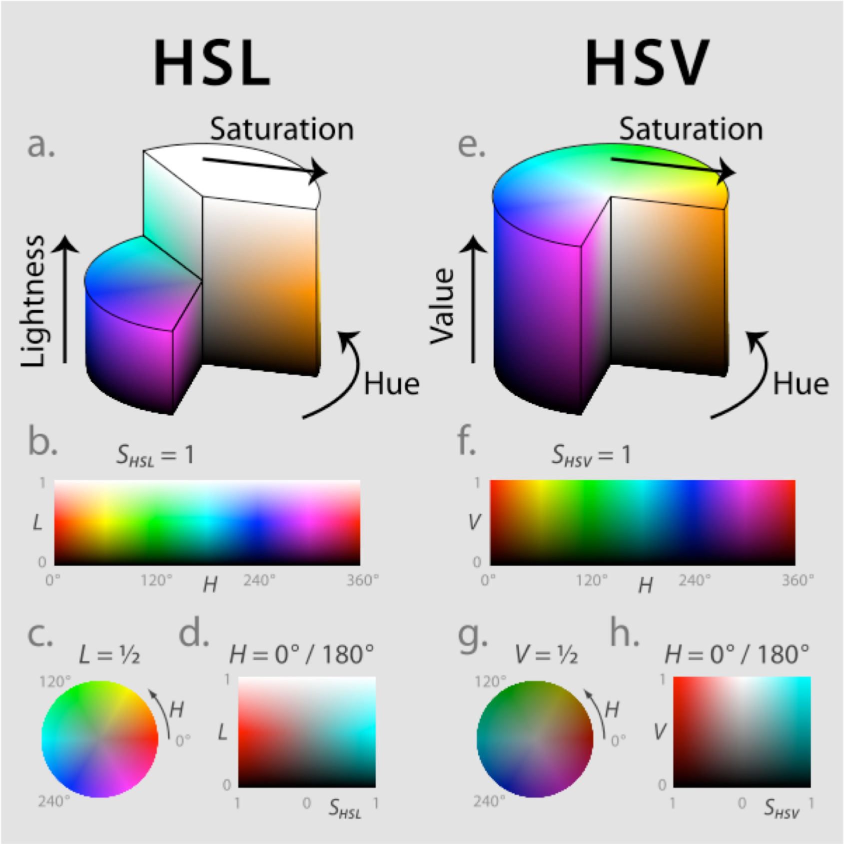
https://www.theinertia.com/environment/the-mantis-shrimp-is-the-oceans-coolest-predator/



Thoen, Hanne H., et al. "A different form of color vision in mantis shrimp." *Science* 343.6169 (2014): 411-413

Color Spaces: HSV

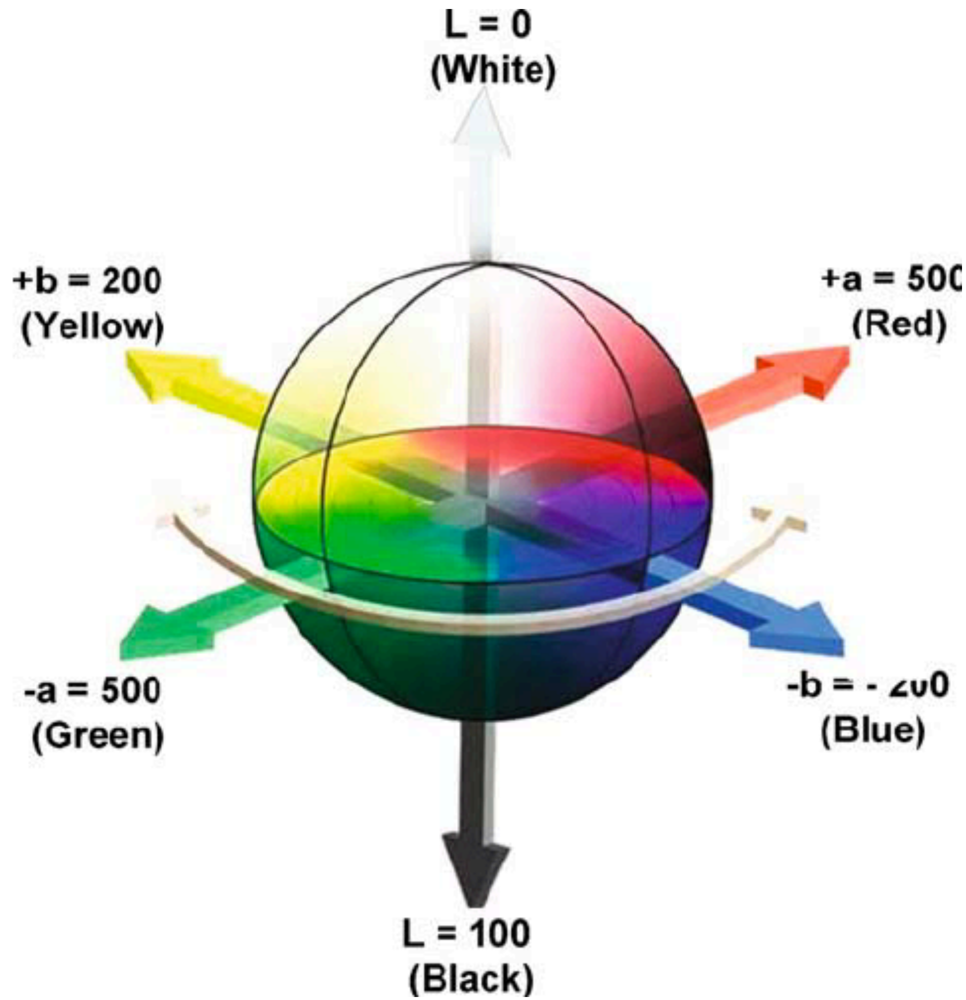
- Perceptual Color
- Described in terms of Hue, Saturation and Intensity (or value)
  – Blue "wraps around" to red
- Broadly used in the art community



http://en.wikipedia.org/wiki/File:Hsl-hsv_models.svg

Color Spaces: Lab

- Lab color space
  - L = Luminance ≈ Intensity
  - a = red – green
  - b = blue – yellow
- Roughly matches human LGN processing



https://www.researchgate.net/figure/The-cubical-CIE-Lab-color-space_fig3_23789543

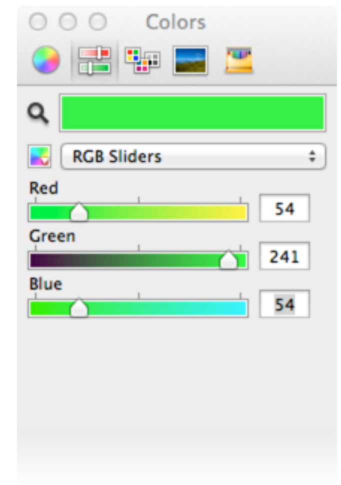
RGB Bits and Hex

- Get used to easily shifting from two views
- 8 bits per color

Red								Green								Blue							
0	0	1	1	0	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	1	1	0

54 241 54

Sample



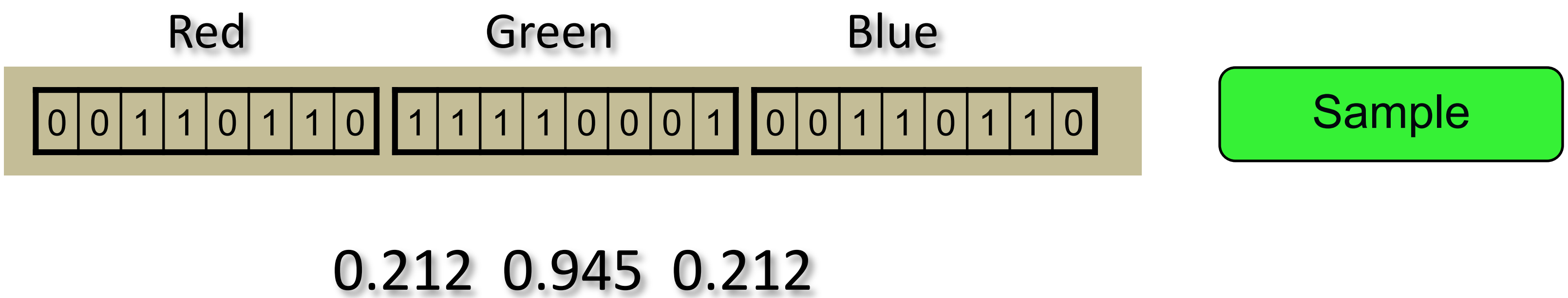
- 2 digit hex number.

Red								Green								Blue							
0	0	1	1	0	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	1	1	0

36 F1 36

RGB values as floats

- When we move to illumination – bits byte ☺
- Want an easier way to blend and combine.
- Shift to floating point numbers.
- Constrained to the range 0.0 to 1.0

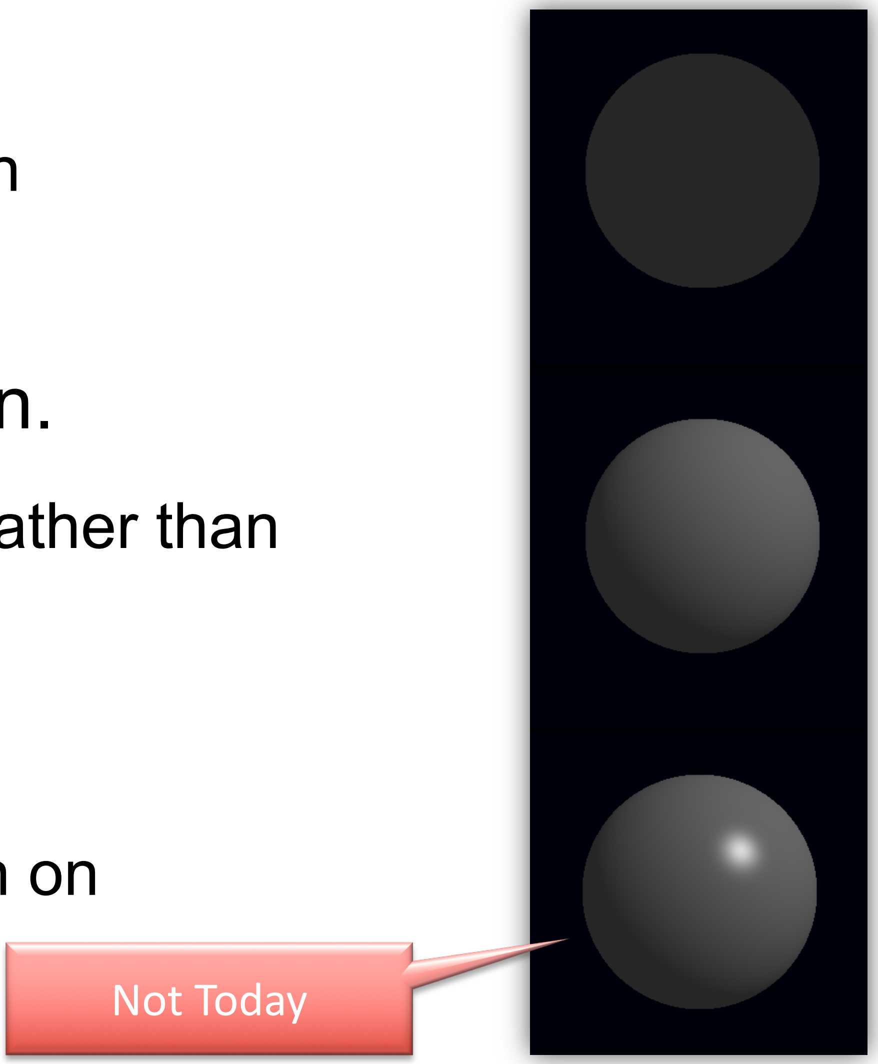


Goals of Reflectance

- Model simple light sources
  - Point light sources
  - Extended light sources
  - Ambient lighting
- Model lighting geometry
  - Angle between light ray and surface normal
  - Angle between surface normal and viewing ray
- Model surface illumination
  - Diffuse (Lambertian) reflection

Reflectance - 3 Kinds

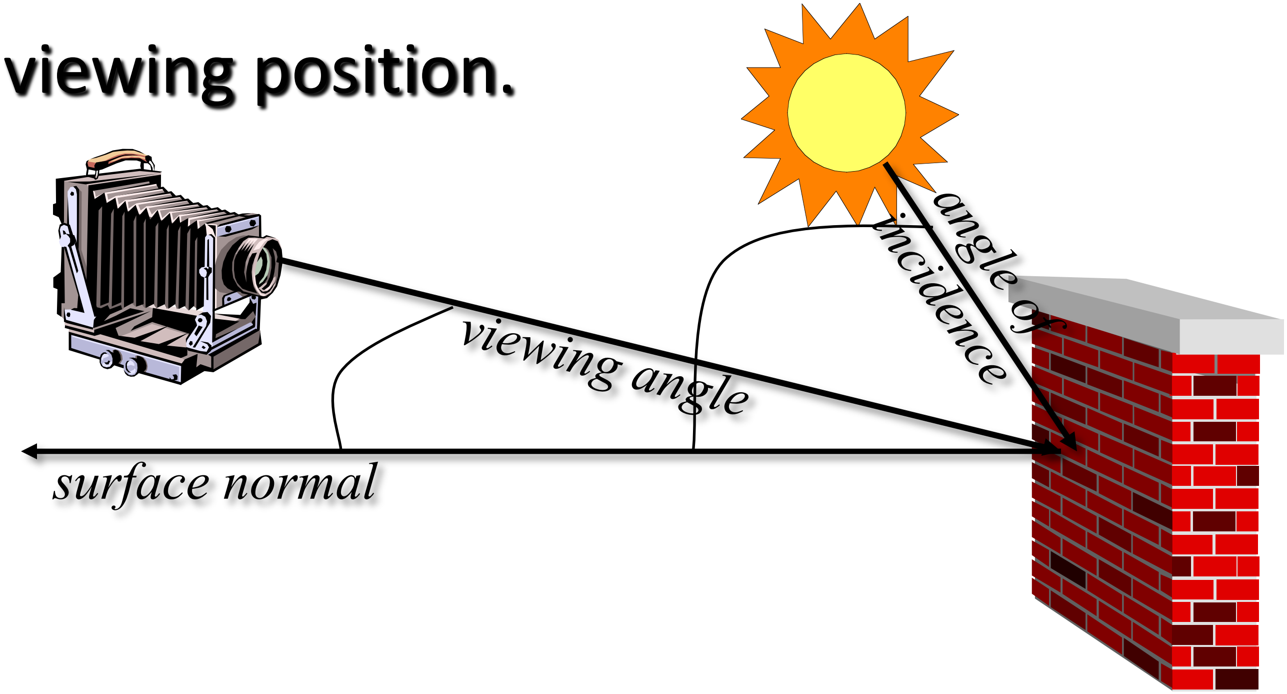
- Ambient reflection.
  - Models perfectly even illumination.
- Lambertian reflection.
  - Matte surfaces, dull rather than shiny.
- Specular reflection.
  - Bright highlights seen on polished surfaces.



Reflectance - Geometry

Reflectance functions are defined in terms of:

- **The position of a (point) light source**
- **The orientation of the reflecting surface**
- **The viewing position.**



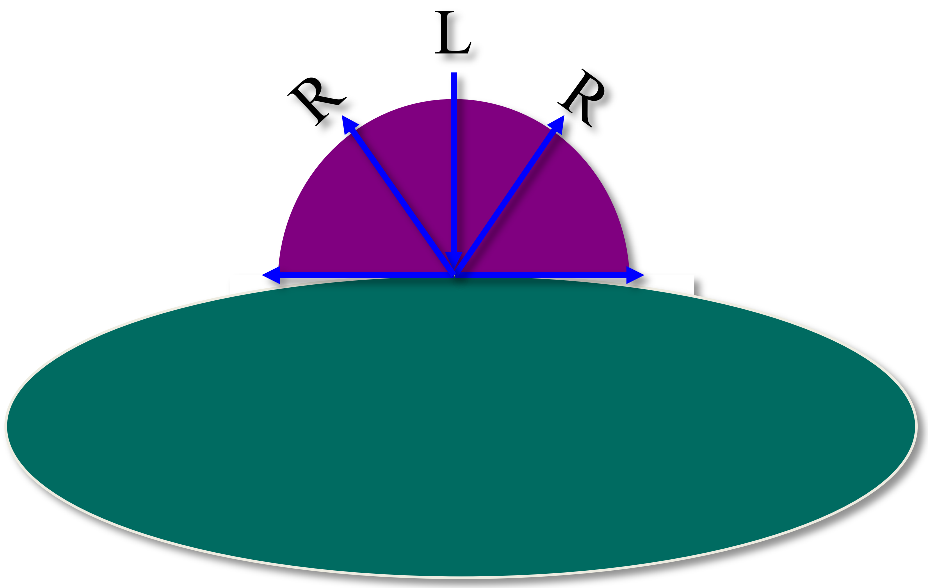
Reflectance Functions (III)

- Light rays, surface normals, and colors are expressed using vectors
  - Light often described as illumination I
  - Three components to illumination:

$$I = \begin{bmatrix} i_r \\ i_g \\ i_b \end{bmatrix}$$

Lambertion Reflection

- Consider a point light source and a Diffuse (Lambertian) Surface.
- Diffuse surfaces reflect light with equal intensity in all directions.



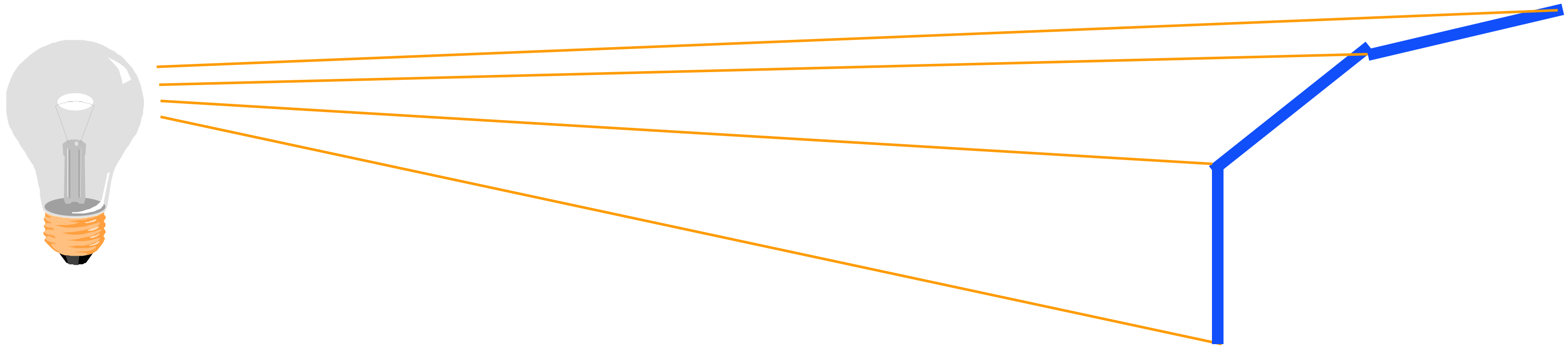
Lambertian Reflection.

The moon is cited as a good example of Lambertion reflection

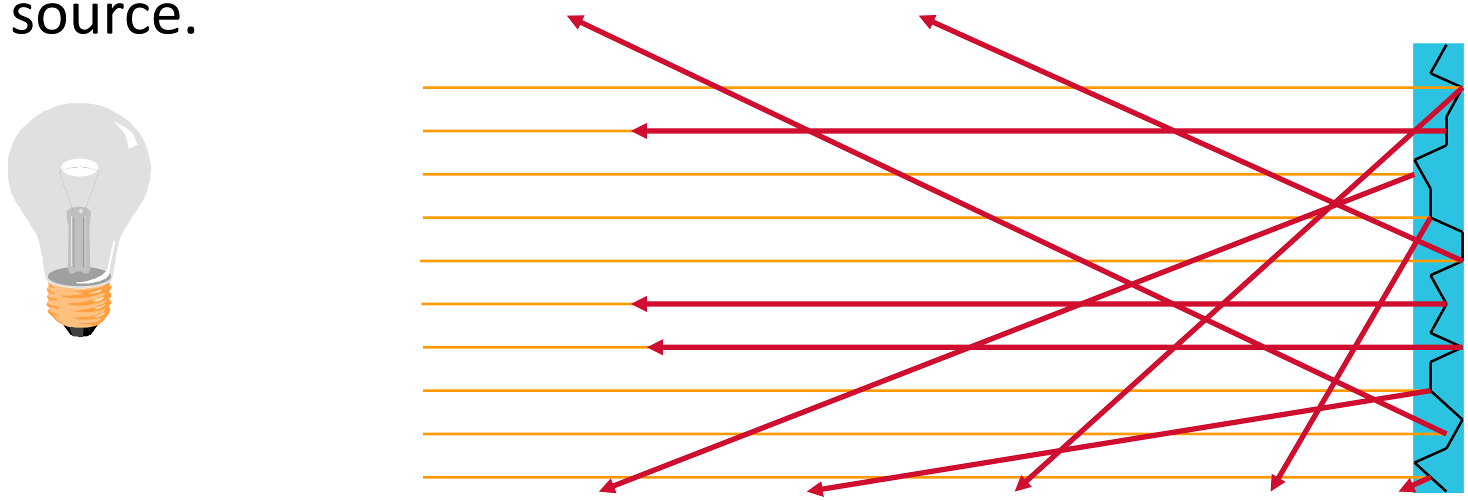
Image by Dmitry, dzz at Morgefile.

Maybe not such a great example … large dark patches …. But you can tell where the sun is …

A Touch of Physics



Light per unit area arriving depends upon angle to light source.



Light leaves in all directions, reflected off micro surfaces.

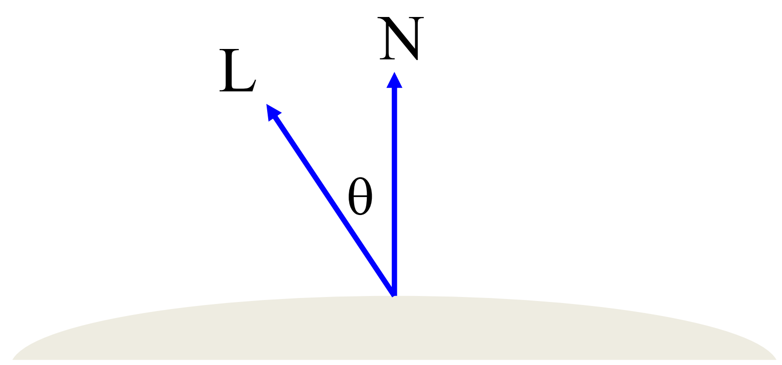
Diffuse Reflection

- Illumination/area drops by θ

$$i_r = b_r \cos\theta \quad i_g = b_g \cos\theta \quad i_b = b_b \cos\theta$$

- Where light L emits light with brightness B:

$$B = \begin{vmatrix} b_r \\ b_g \\ b_b \end{vmatrix}$$



Diffuse Reflection – Parameters

- Diffuse parameters modulate brightness

$$I = \begin{vmatrix} i_r \\ i_g \\ i_b \end{vmatrix} = \begin{vmatrix} k_r & 0 & 0 \\ 0 & k_g & 0 \\ 0 & 0 & k_b \end{vmatrix} \begin{vmatrix} b_r \\ b_g \\ b_b \end{vmatrix} \cos(\theta)$$

- The same statement, but more concise:

$$I_d = K_d B \cos(\theta)$$

The subscript *d* added to indicate diffuse illumination

Rare Case Still Worth Mention

- Use the full power of the 3x3 matrix
  - Comes in red, goes out green

$$I = \begin{vmatrix} i_r \\ i_g \\ i_b \end{vmatrix} = \begin{vmatrix} k_{rr} & k_{rg} & k_{rb} \\ k_{gr} & k_{gg} & k_{gb} \\ k_{br} & k_{bg} & k_{bb} \end{vmatrix} \begin{vmatrix} b_r \\ b_g \\ b_b \end{vmatrix} \cos(\theta)$$

Example of a Non-Diagonal Reflectance Matrix

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/oilfilm.html

- Oil slicks reflect light of one color as another color
- Thin-film interference effect
- Given angles, can be modeled as a non-diagonal Kd matrix

Material Properties (II)

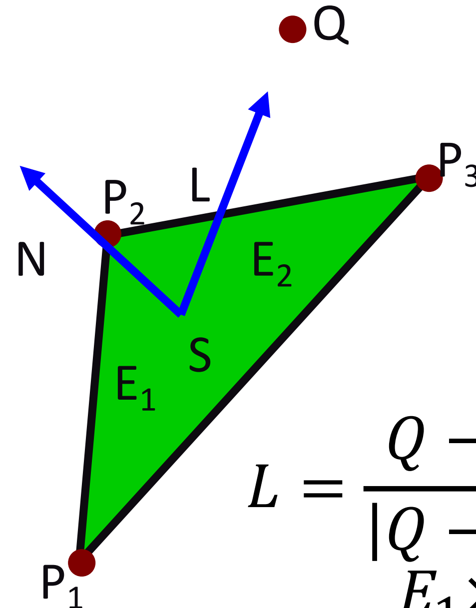
- There are some pragmatic constraints:
  - No term in K may exceed 1.0
  - No term in K may be negative
  - No column may have a sum exceeding 1
- But, …
- These constraints are not always enforced

There is an art to lighting a scene!

Diffuse Reflection – Computation

- The final term in diffuse reflection is cos(θ).
  - Defined by angle between the incoming light ray L and the surface normal N

Symbol	Description
N	Unit Length Surface Normal
L	Unit Length Vector to Light
Q	3D Position of the Light
S	3D Position on Surface
P1, P2 & P3	3D Vertices of the Triangle
E1 & E2	Two 3D Edges of the Triangle



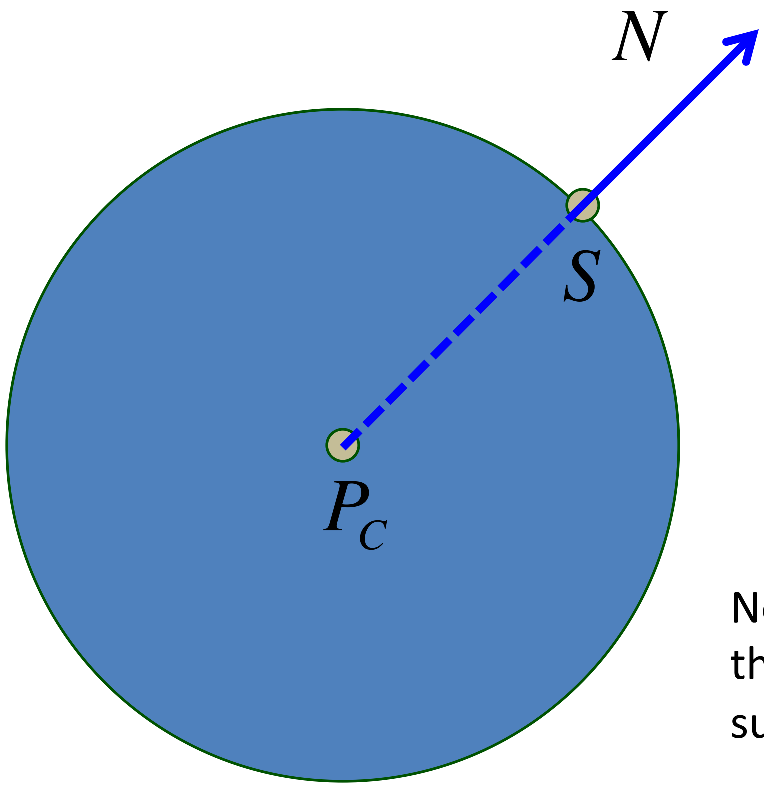
$$L = \frac{Q - S}{|Q - S|}$$

$$N = \frac{E_1 \times E_2}{|E_1 \times E_2|}$$

$$cos(\emptyset) = N \cdot L$$

Surface Normals - Sphere

- What about the surface normal for a sphere?



circle centered at P_C

surface point on sphere S

$$N = \frac{S - P_C}{\left\| S - P_C \right\|}$$

Note: the normal to a polygon is constant across the polygon; for a sphere it is a function of the surface point.

Many Light Sources

- For a single point light source:

$$I = K_d B(N \cdot L)$$

- For m point light sources

$$I = \sum_{i=1,m} K_d B_i (N \cdot L_i)$$

Ambient Reflection

- Ambient reflection is just diffuse reflection of light from the “ambient” light source
- Ambient light models background light
  - It is the same intensity everywhere
  - It is the same color everywhere
  - It comes from every angle
- So…

$$I_a = K_d B_a$$

Ambient plus Diffuse

- Reflectance off a surface point is the sum of:
- Reflection from the ambient light
- Diffuse reflection off of every point light

$$I = K_a B_a + \sum_{i \in lights} \left(K_d B_i \left(L_{ip} \cdot N \right) \right)$$

No ‘Negative’ illumination

- The influence of a light source cannot be negative
  - They are light *emitters*
- We assume $N \cdot V \geq 0$
  - Where V points from surface toward fp
  - Otherwise, flip N
- Therefore, if $L_{ip} \cdot N < 0$, set it to 0
- Similarly, if $V \cdot R_p < 0$, set it to 0
- These situations occur when the light source is behind the surface
  - The light source is shining on the other side of the (opaque) surface