CG – T8 – Colour and Light

L:CC, MI:ERSI

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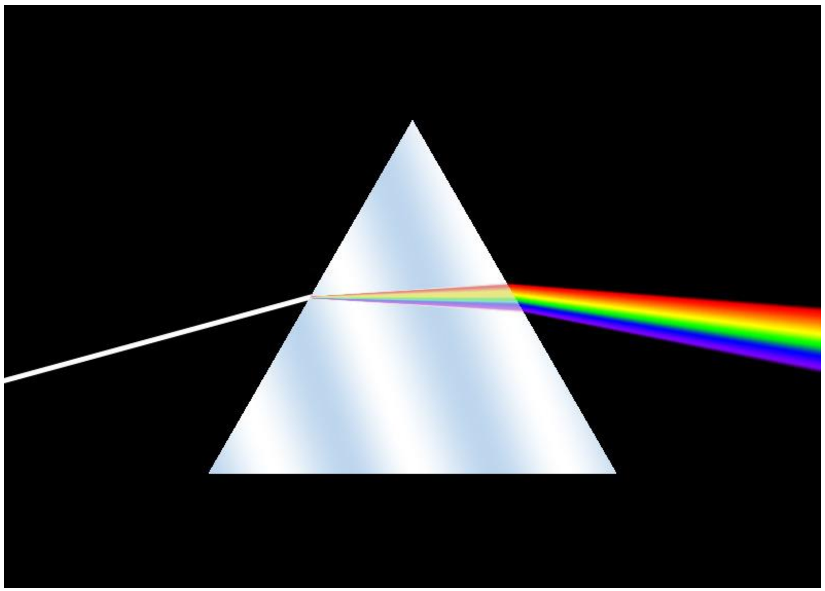
(course and slides designed by Verónica Costa Orvalho)

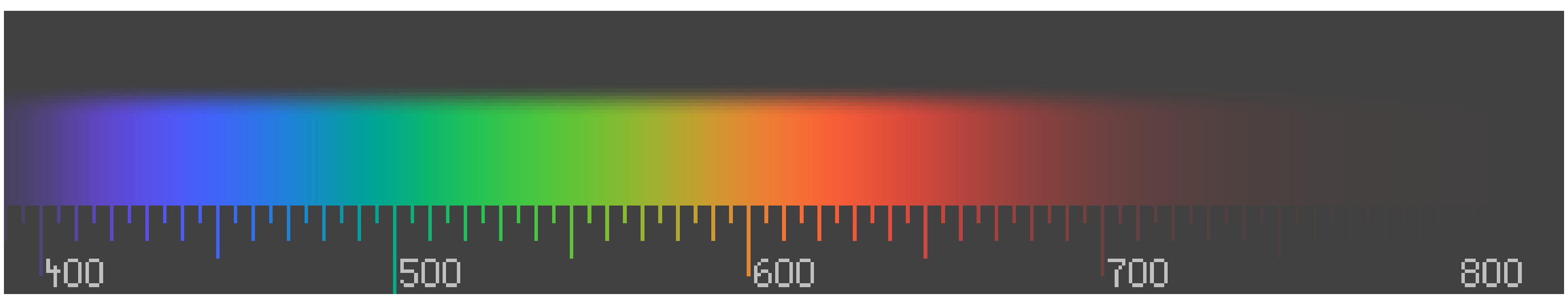
What is colour?

Light is electromagnetic radiation

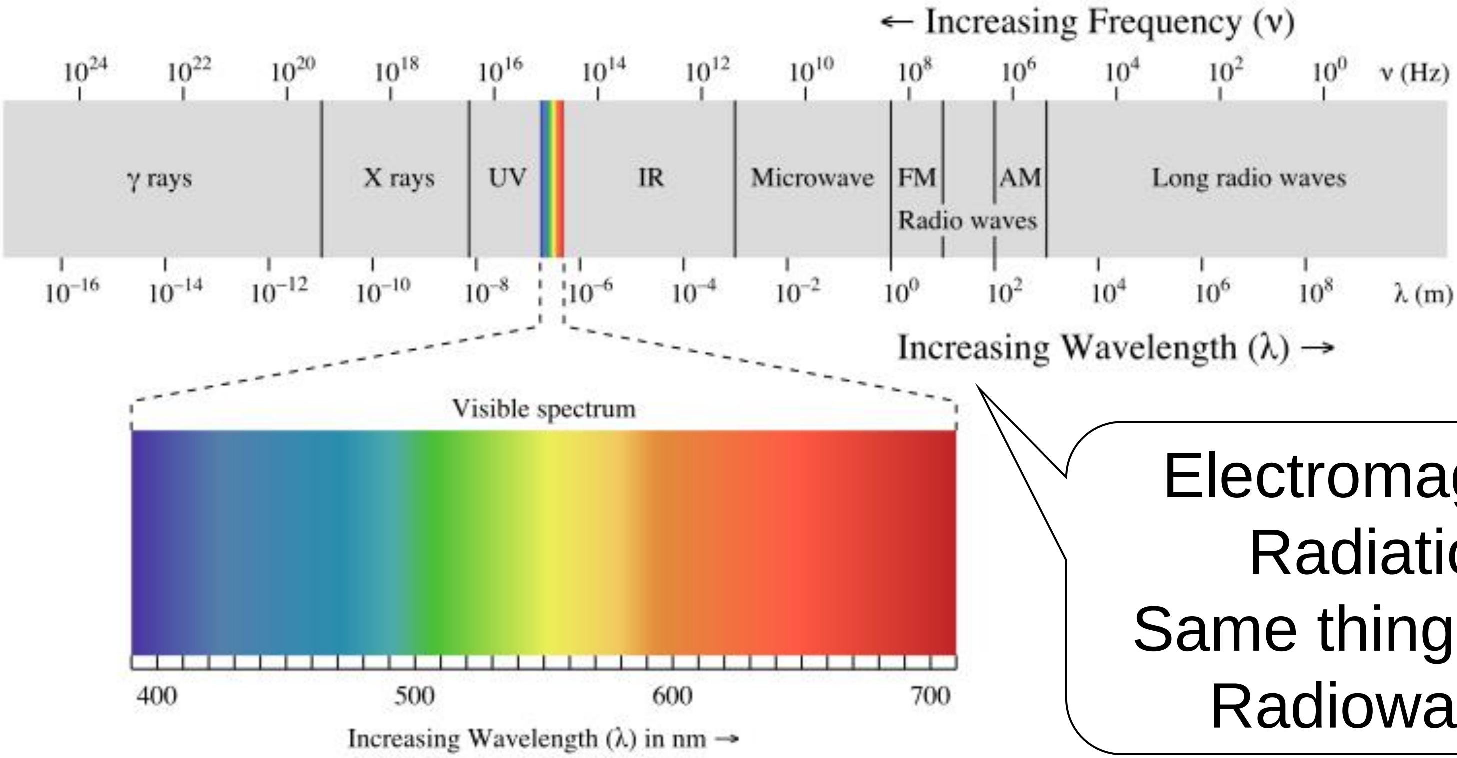


Optical Prism dispersing light

Visible colour spectrum



Visible Spectrum

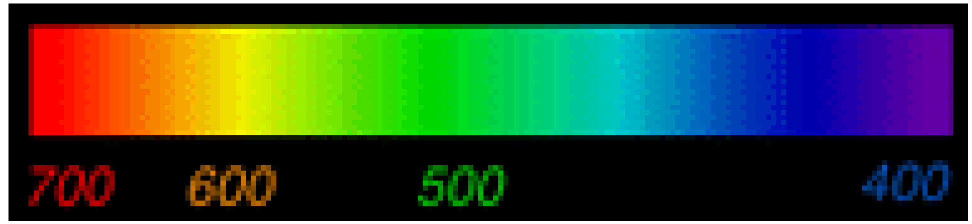


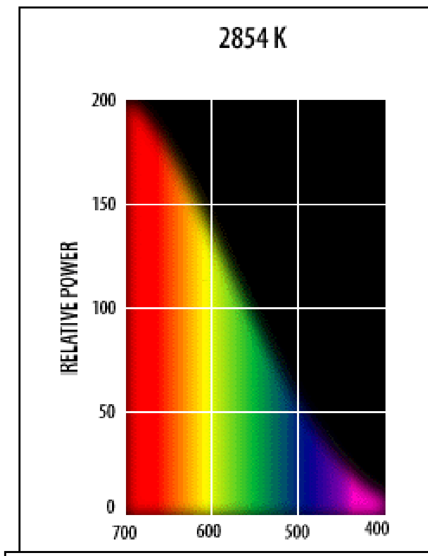
Electromagnetic Radiation.
Same thing as FM Radiowaves!

http://science.howstuffworks.com/light.htm

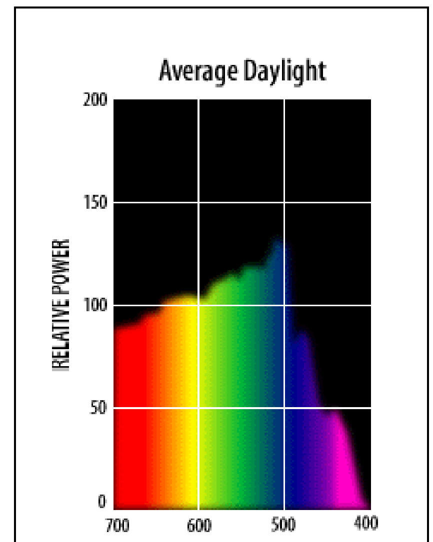
Colour Spectrum

- ‘Pure’ colour
  - Energy concentrated into a unique frequency of the visible spectrum
- Composite colour
  - Energy spread among various frequencies
  - This is what happens in reality





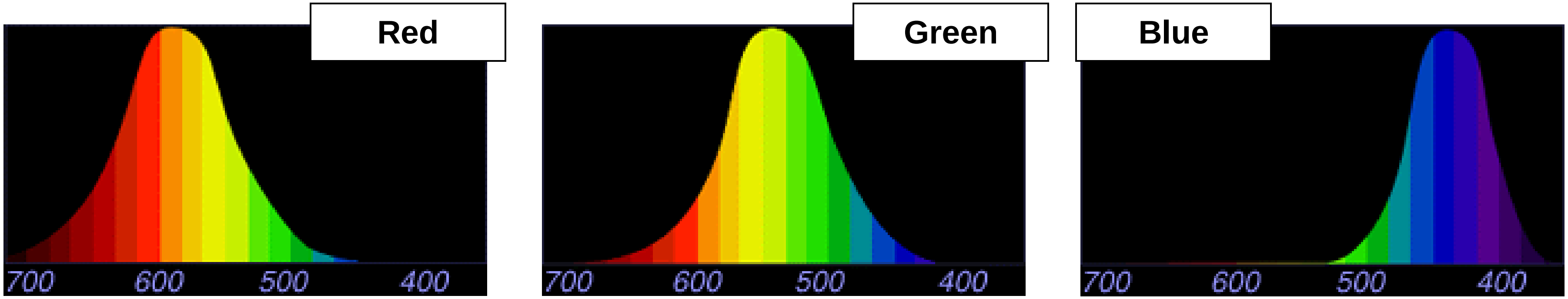
Incandescent Light



Sunlight

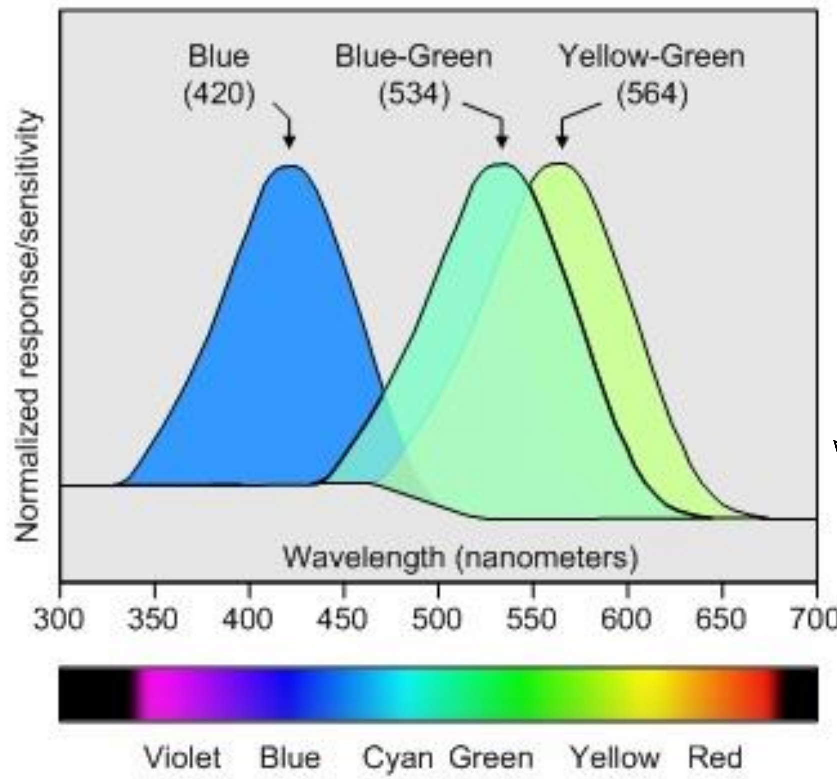
How do we see colour?

- Cones
  - We have three types of cones in our retina



We also typically model digital images using three colour primitives

Colour is a human creation



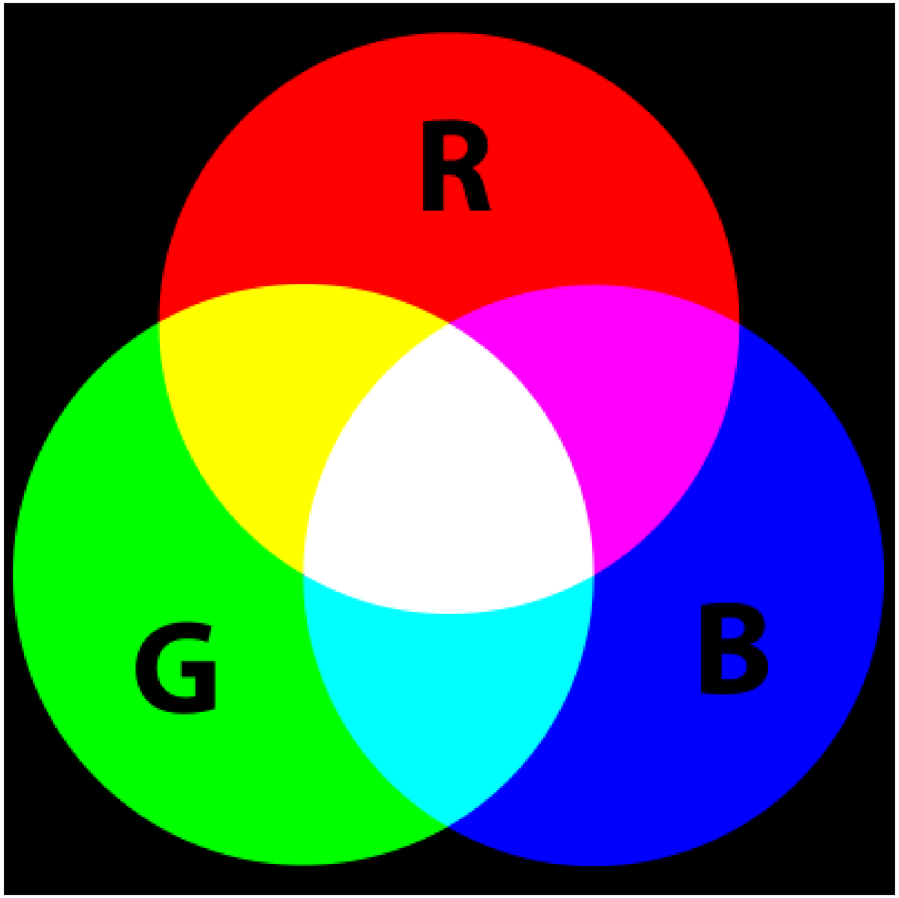
Typical humans are trichromats
(three color cone/pigment types – blue, blue-green, and yellow-green)

Human
Colour
Sensors:
Cones

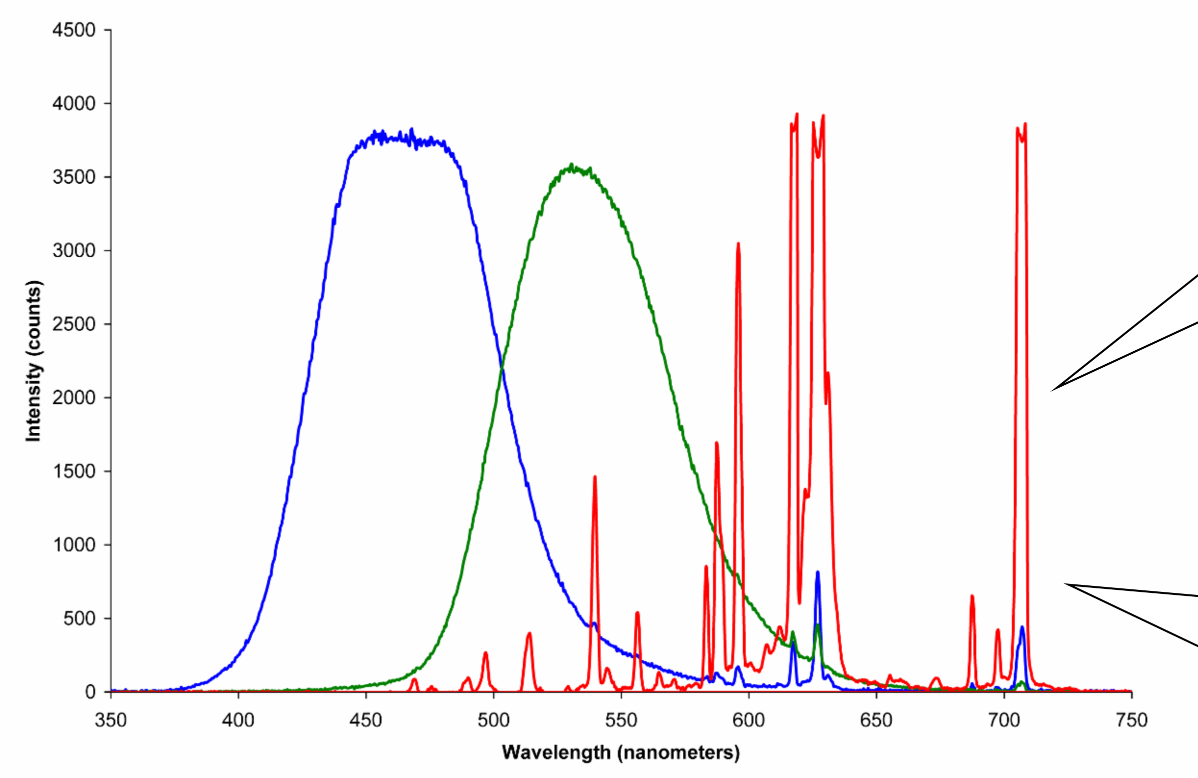
65% ‘Red’ cones
33% ‘Green’ cones
2%’Blue’ cones

Primary Colours

- Not a fundamental property of light
- Based on the physiological response of the human eye
- Form an additive colour system



Example: Television



Three types of phosphors very close together

The components are added to create a final colour

http://www.howstuffworks.com/tv.htm

Colour Space

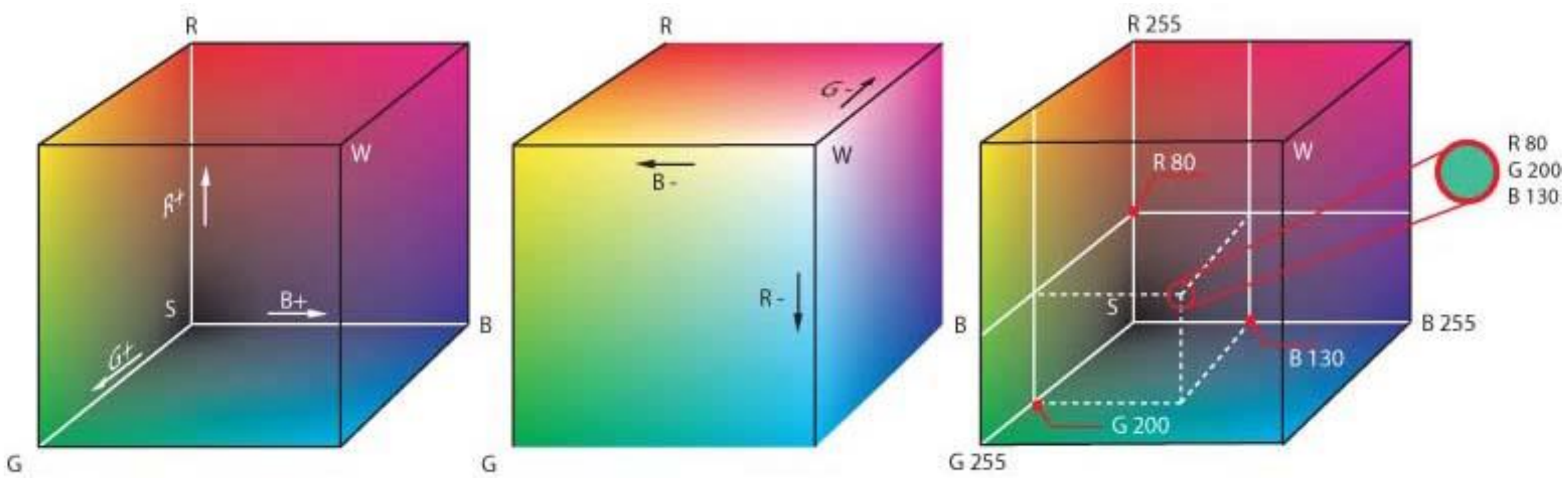
- "The purpose of a color model is to facilitate the specification of colours in some standard, generally accepted way"

  Gonzalez & Woods

- Colour space
  - Coordinate system
  - Subspace: One colour -> One point

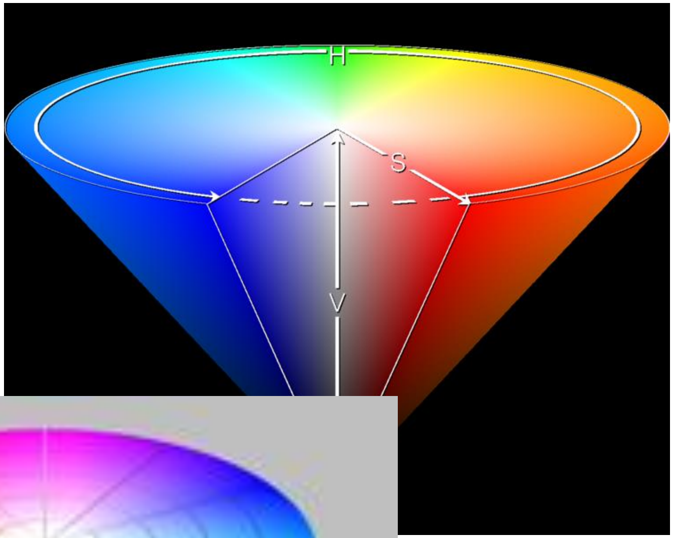
RGB

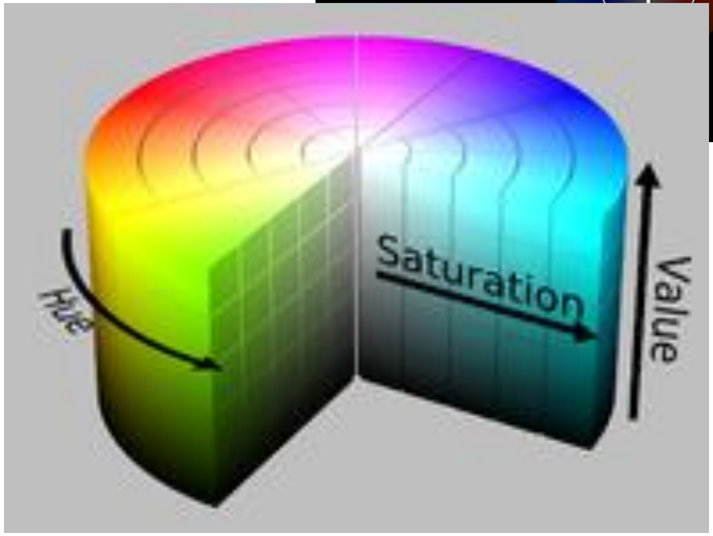
- Red Green Blue
- Defines a colour cube.
- Additive components.
- Great for image capture.
- Great for image projection.
- Poor colour description.



HSI

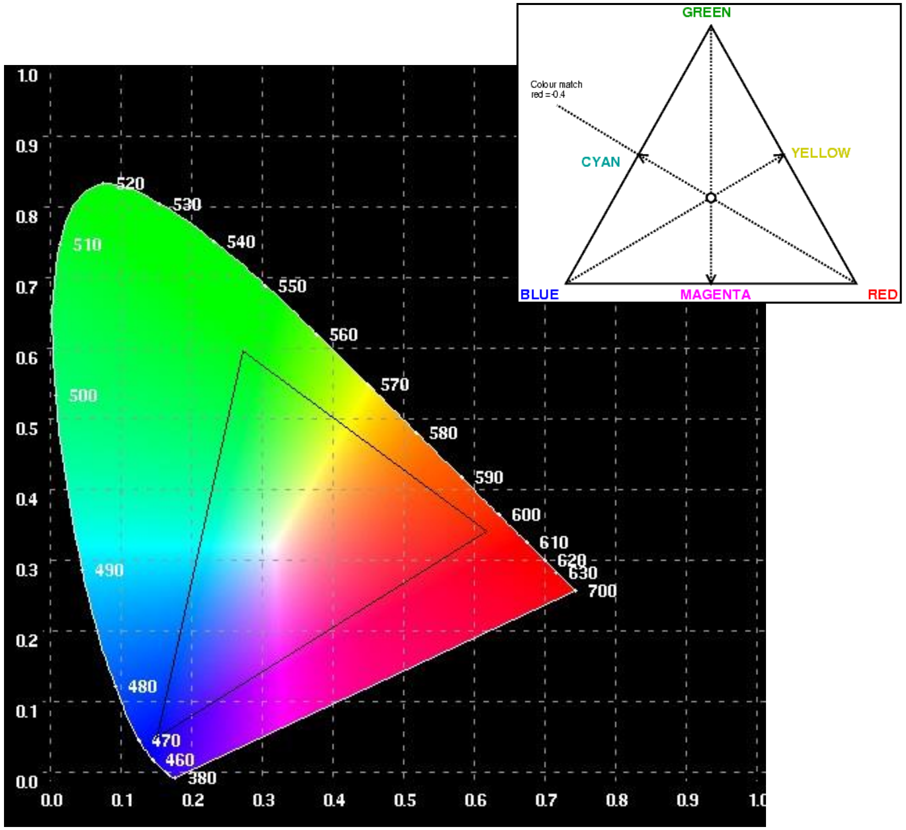
- Hue Saturation Intensity
- Defines a colour cone
- Great for colour description.





Chromaticity Diagram

- Axis:
  - Hue
  - Saturation
- Outer line represents our visible spectrum.
- No three primaries can create all colours!

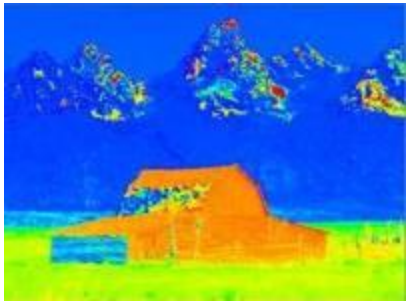


http://www.cs.rit.edu/~ncs/color/a_chroma.html

RGB to HSI

Hue:

$$H = \begin{cases} \theta & \Leftarrow B \le G \\ 360 - \theta & \Leftarrow B > G \end{cases}$$



$$\theta = \cos^{-1}\left\{ \frac{\frac{1}{2}\left[(R-G)+(R-B)\right]}{\left[(R-G)^2+(R-B)(G-B)\right]^{1/2}} \right\}$$

Saturation

$$S = 1 - \frac{3}{(R+G+B)}\left[\min(R,G,B)\right]$$

Intensity

$$I = \frac{1}{3}(R+G+B)$$

HSI to RGB

- Depends on the 'sector' of H

0 <= H < 120

$$B = I(1-S)$$

$$R = I\left[1 + \frac{S\cos H}{\cos(60^{o} - H)}\right]$$

$$G = 3I - (R + B)$$

120 <= H < 240

$$H = H - 120^{o}$$

$$R = I(1-S)$$

$$G = I\left[1 + \frac{S\cos H}{\cos(60^{o} - H)}\right]$$

$$B = 3I - (R + B)$$

240 <= H < 360

$$H = H - 240^{o}$$

$$G = I(1-S)$$

$$B = I\left[1 + \frac{S\cos H}{\cos(60^{o} - H)}\right]$$

$$R = 3I - (R + B)$$

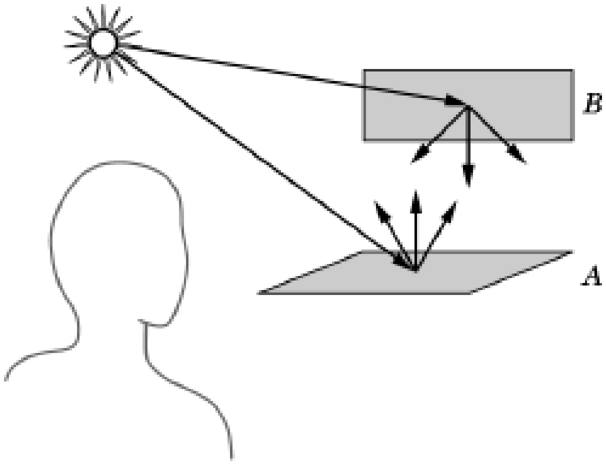
What determines illumination?

Illumination: main concepts

light sources **<u>emit light</u>**

. color spectrum

. position and direction



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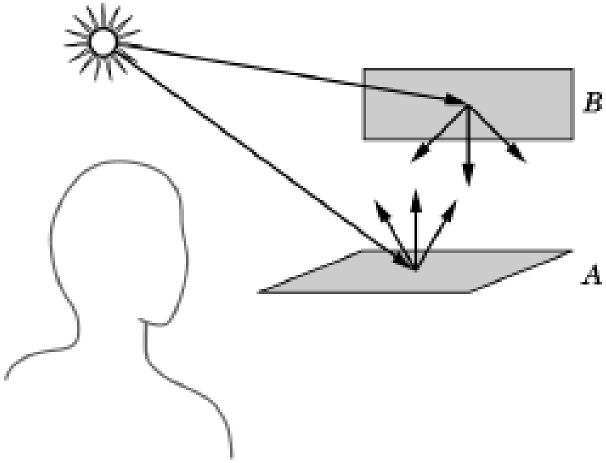


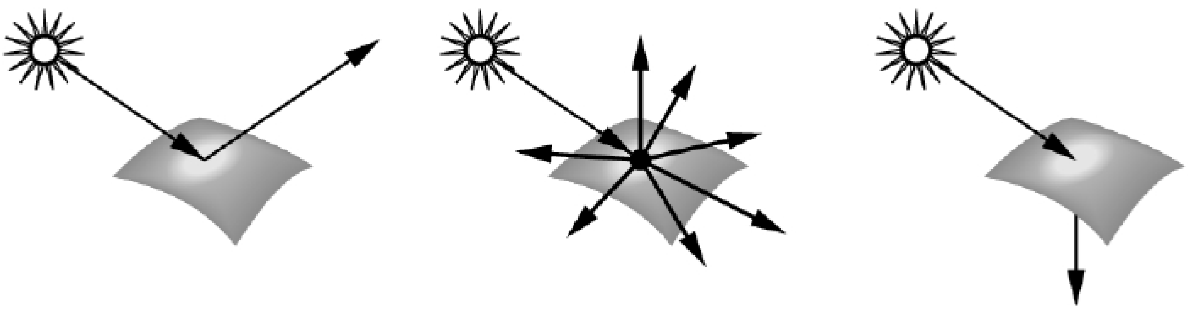
surfaces **reflect light**

. reflectance

. geometry

. transmission

. absortion



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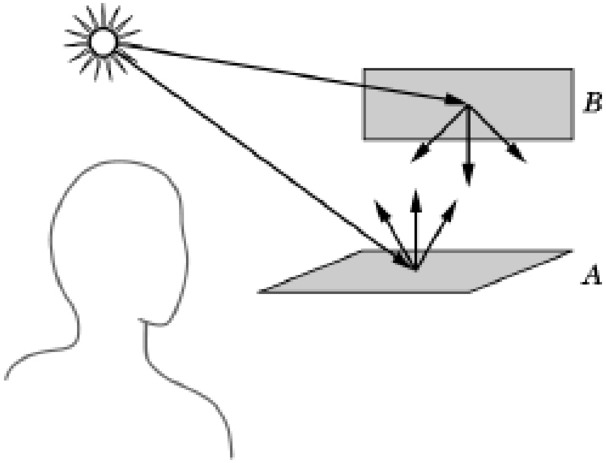

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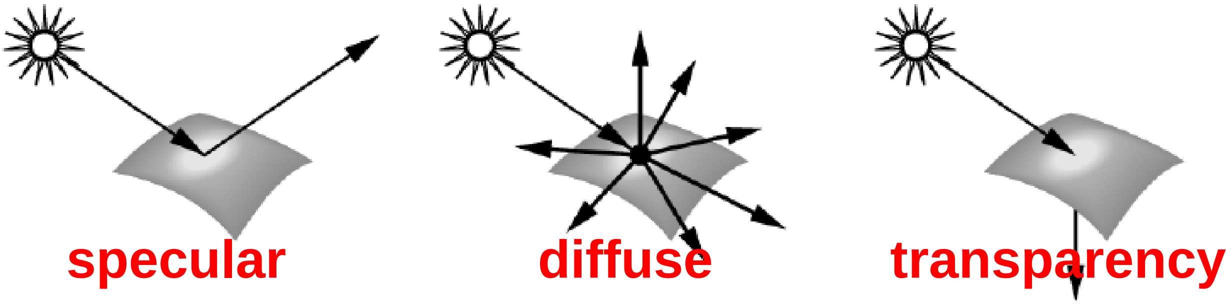


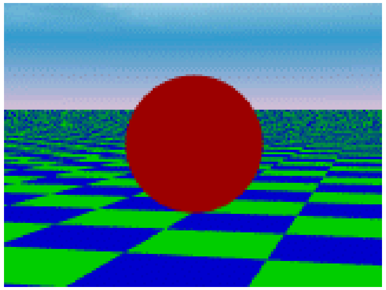
Illumination: main concepts

Illumination determined by the interaction of the

light source + **the surface**

Illumination: types of lights

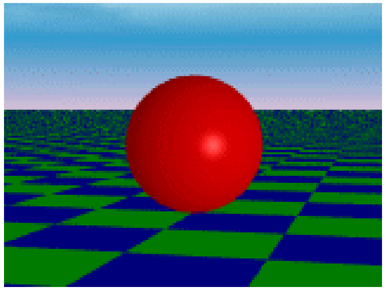
ambient



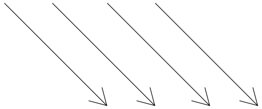
indirect

illumination

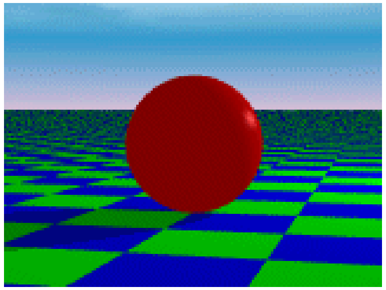
directional



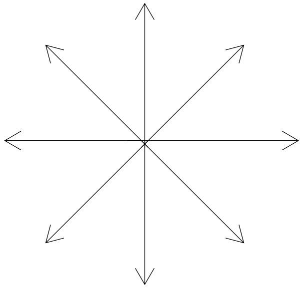
sun



point



light bulb

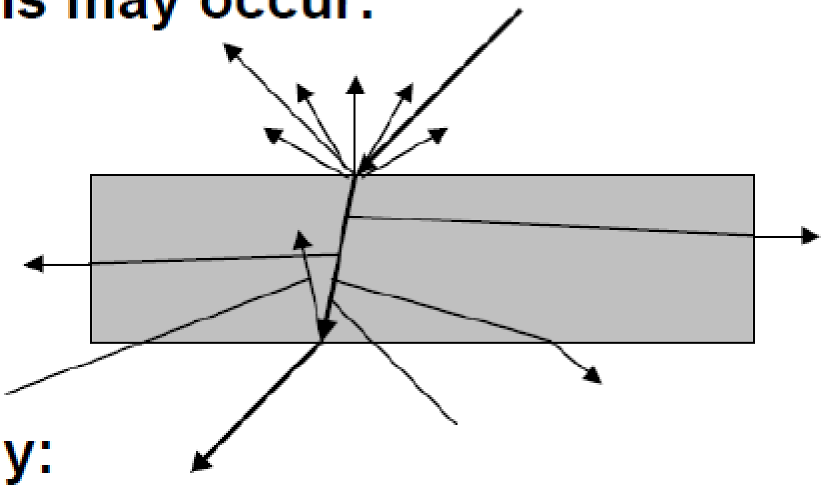


How does light interact with a surface?

Three types of interactions

When light makes contact with a material, three types of interactions may occur:

- **Reflection**
- **Absorption**
- **Transmittance**



From conservation of energy:

$$\text{light incident at surface} = \text{light reflected} + \text{light absorbed} + \text{light transmitted}$$

Opaque object: the majority of incident light is either reflected or absorbed – transmitted light≈0

Translucent object: significant light transmission

Slide by Ron Fedkiw, Stanford University

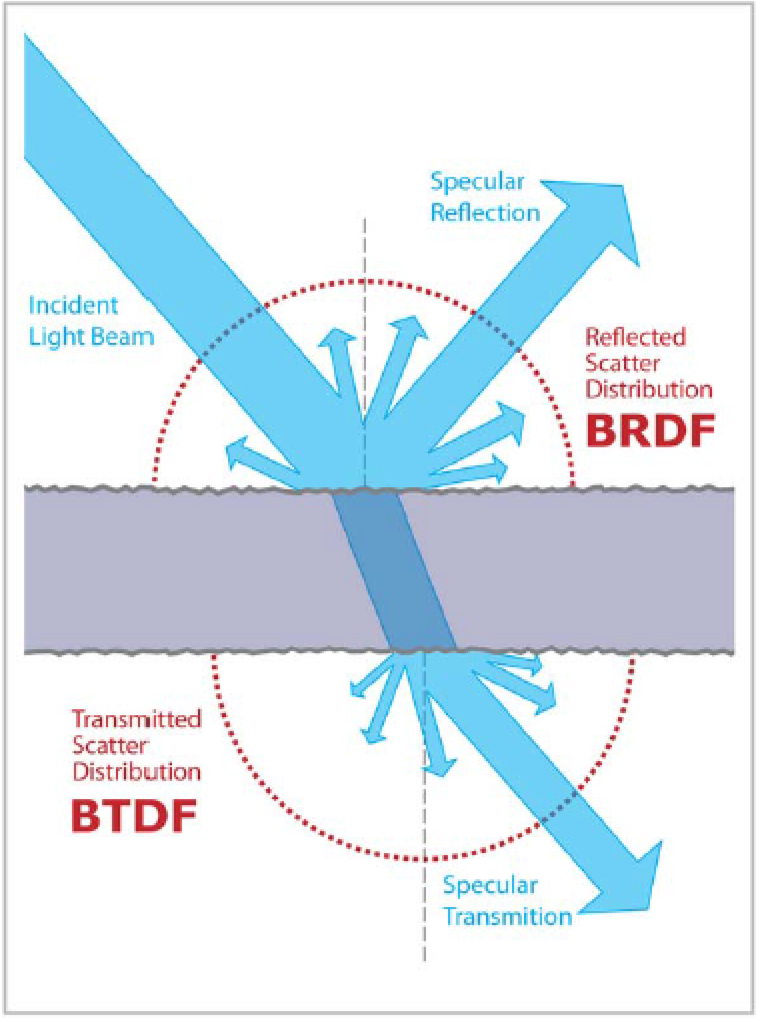
Bidirectional Reflectance Distribution Function (BRDF)

A BRDF describes how much light is reflected when light makes contact with a certain material

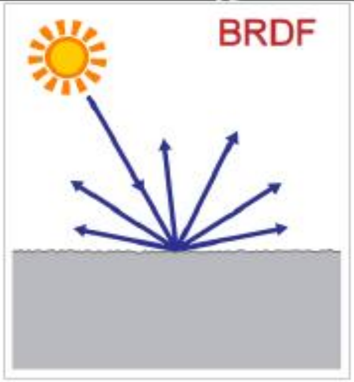
If our object is opaque, we can ignore transmission and a BRDF is all we need to model its macroscopic material property

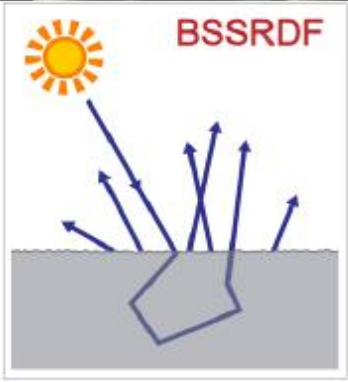
In order to model translucency, in addition to the BRDF, we would also need a BTDF (Bidirectional Transmittance Distribution Function)

Or we can model the transmission and reflection together as a BSSRDF(BSurfaceScatteringRDF)



Opaque vs Translucent





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Paint vs. Milk

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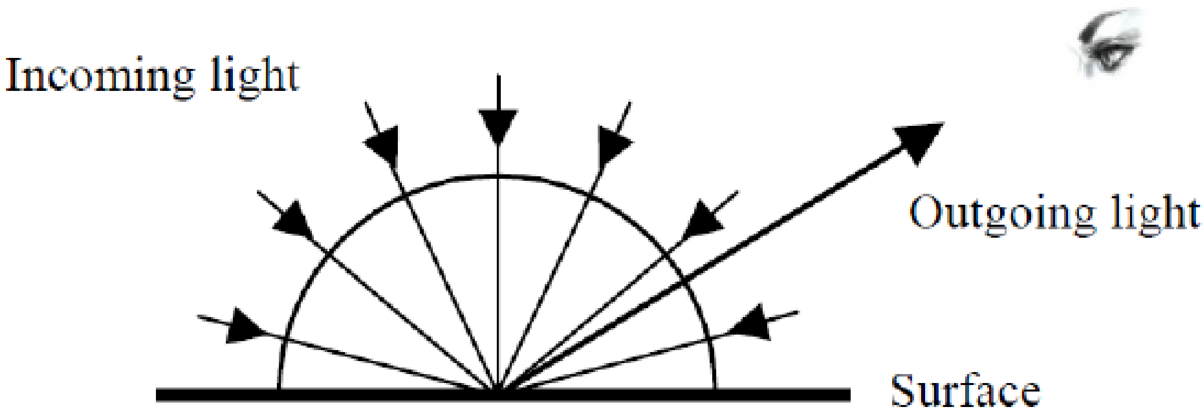
The lighting equation

In the real world, the entire environment surrounding a surface in a scene contributes to the illumination of every surface point



The amount of light reflected in an outgoing direction is the integral of the amount of light reflected in that direction due to light from every incoming direction. Discretely put, we have $L_o = \sum_{i \in \text{in}} L_{o\,\text{due to}\,i}(\omega_i, \omega_o)$

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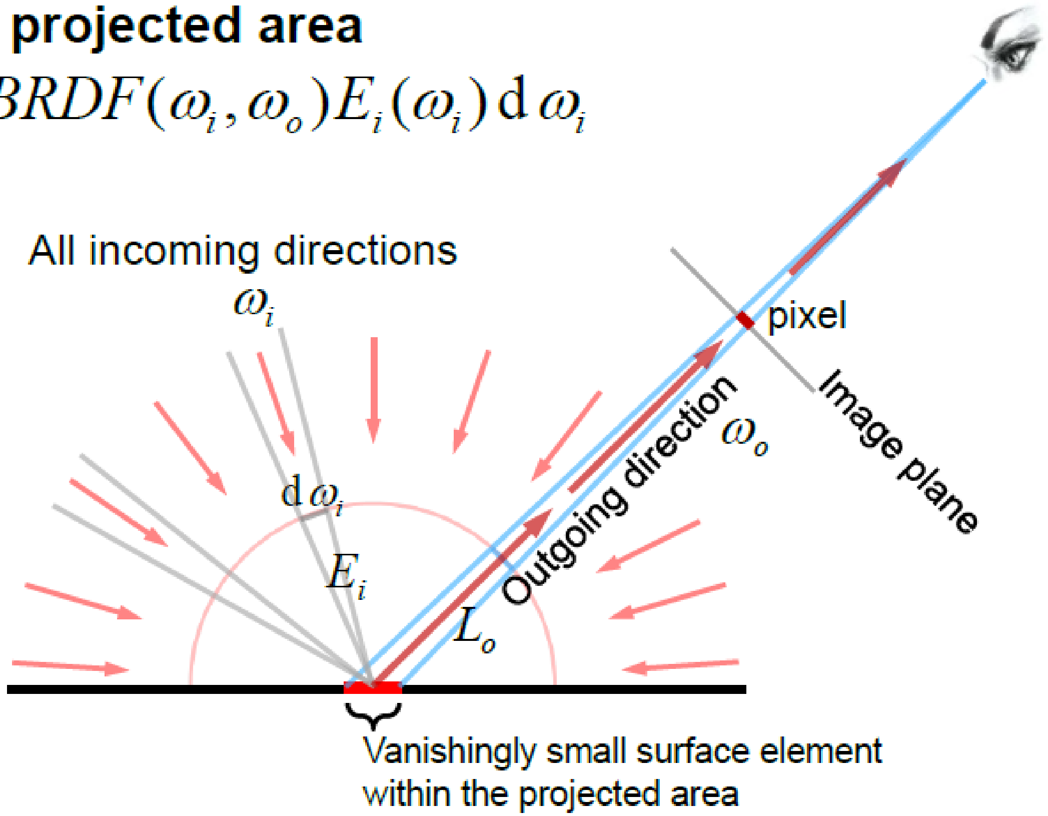
How to colour a pixel?

For each pixel in the image plane, need to integrate the BRDF across all incoming directions for every point in the projected area

$$L_o = \int_{i \in \text{in}} BRDF(\omega_i, \omega_o) E_i(\omega_i) \, \mathrm{d}\,\omega_i$$



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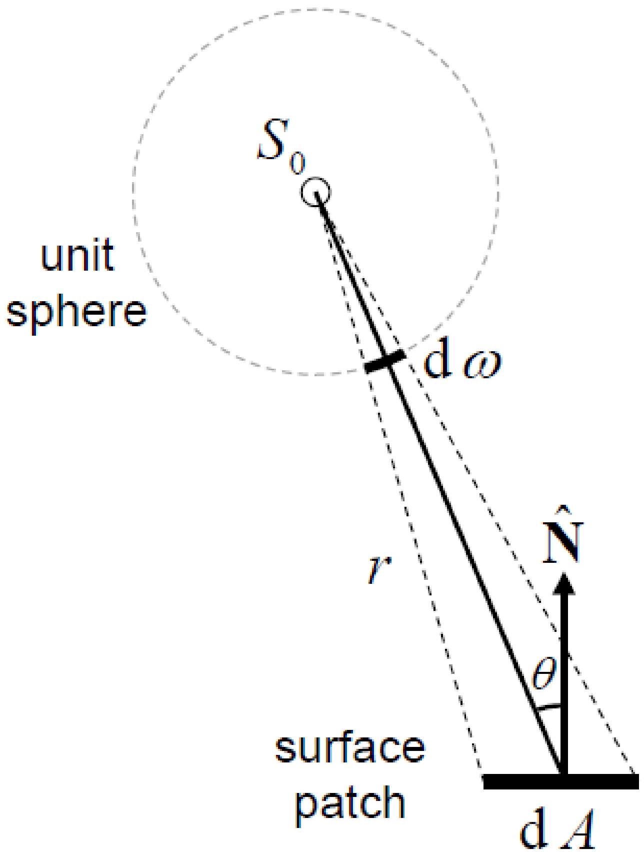
Light energy

No energy can flow through a point, must go through either a solid angle or an area (interchangeable)

Total light power per unit <u>solid angle</u> → Radiant Intensity
- **This gives a measure of how strong a point light source is**

Total light power per unit <u>area</u> → Irradiance
- **This gives measure of how much light hits a surface, and varies based on the distance to the light and the angle of the surface (the farther away and more tilted, the smaller the solid angle is)**

Solid Angle vs. Area



The relation between solid angle and area:

$$\mathrm{d}\,\omega = \frac{\mathrm{d}\,A \cos\theta}{r^2}$$

where $\mathrm{d}\,A\cos\theta$ **is the area of the orthogonal cross section**

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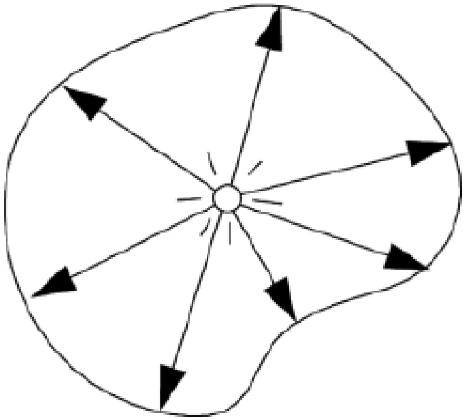
Radiant Intensity

Power per unit **solid angle**



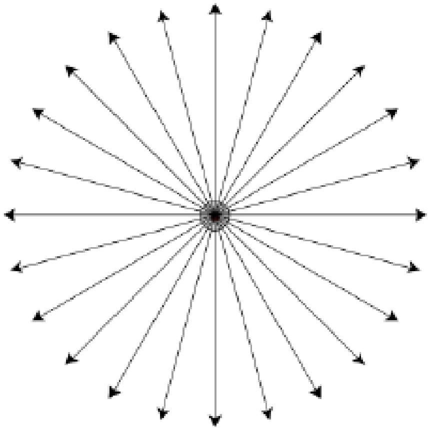
$$I(\omega) \equiv \frac{\mathrm{d}\,\Phi}{\mathrm{d}\,\omega}$$

where Φ is the power

Note: I is a function of ω for anisotropic light emission

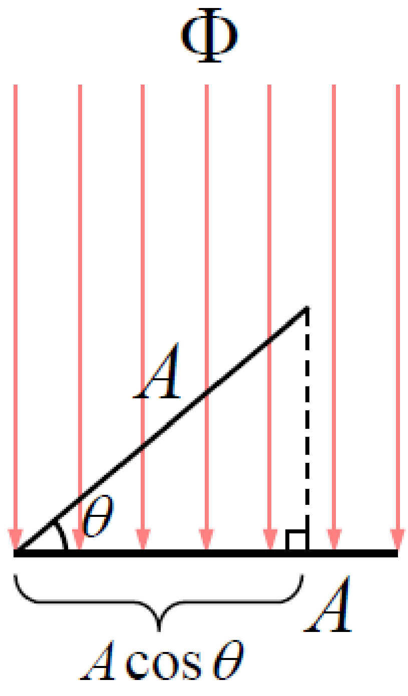
The relation between power and radiant intensity for an isotropic point light source:

$$\Phi = \int_{\text{sphere}} I \,\mathrm{d}\,\omega = 4\pi I$$

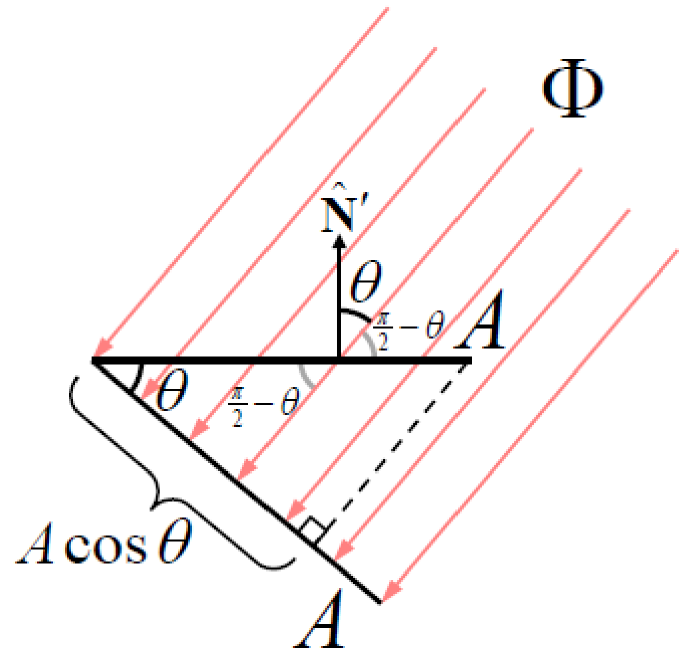


Irradiance

Power per unit **surface area** $E \equiv \frac{d\Phi}{dA}$



$$E_{\text{tilted}} = \frac{\left(\frac{A\cos\theta}{A}\right)\Phi}{A} = \frac{\Phi\cos\theta}{A} = E\cos\theta$$



Note how the irradiance decreases as you tilt the object, since it fits into a smaller solid angle

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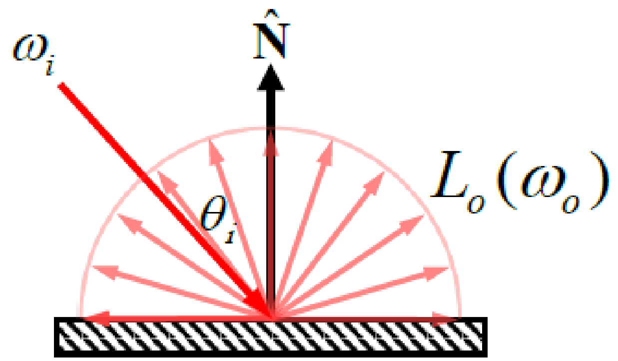
Phong Reflection Model - Diffuse



The reflection of an ideally diffuse / dull / matte surface can be modeled by a constant BRDF

$$BRDF(\omega_i, \omega_o) = k_d$$

$$L_o = BRDF(\omega_i, \omega_o) L_i \cos\theta_i = k_d L_i \cos\theta_i$$

The cosine can be computed by $\cos\theta_i = (\omega_i \cdot \hat{\mathbf{N}})_+ \equiv \max(0, \omega_i \cdot \hat{\mathbf{N}})$

Since the light only comes in a hemisphere of directions, the back face is not lit

Outgoing radiance L_o is constant in all directions ω_o on the hemisphere surrounding the surface

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Phong Reflection Model - Ambient

Motivation: for local illumination such as diffuse reflection, regions in complete shadow are totally black

Ambient lighting models a constant illumination independent of the incident light angle θ_i. Thus we drop the $\cos\theta_i$ term from the BRDF lighting equation and get

$$L_o = k_a \sum_j L_i^j \quad \text{or} \quad L_o = \sum_j k_a^j L_i^j$$

where k_a is the ambient reflectivity for each object, optionally different for each light source j

Ambient lighting is a crude approximation of the total effect of all indirect lighting in the real world

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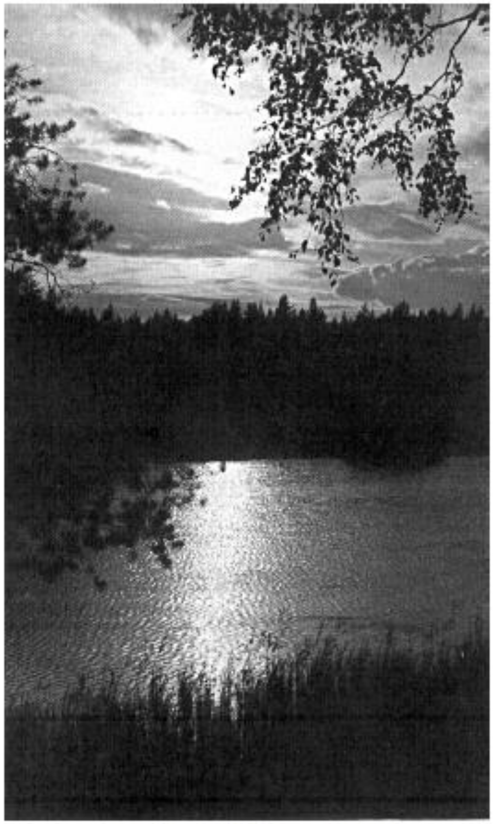
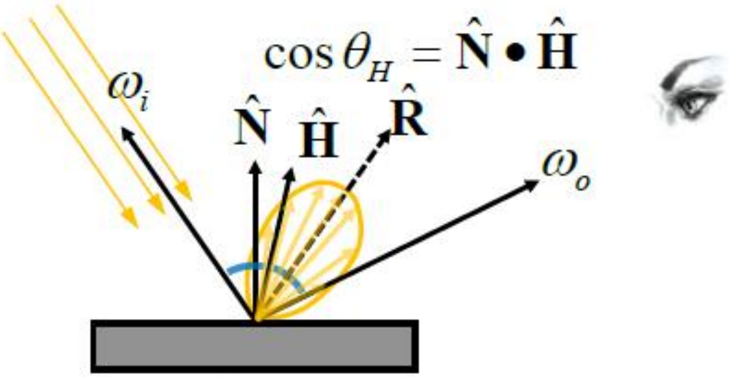
Phong Reflection Model - Specular



Minnaert p. 28



For a mirror, the outgoing radiance is

$$L_o(\omega_o) = \begin{cases} k_s L_i(\omega_i), & \text{if } \dfrac{\omega_i + \omega_o}{|\omega_i + \omega_o|} = \hat{\mathbf{N}} \\ 0, & \text{otherwise} \end{cases}$$

For a glossy but rough surface, due to the microscopic spatial variation of normal directions, the impulse function is smoothed into a lobe

$$L_o(\omega_o) = k_s \left(\hat{\mathbf{N}} \cdot \frac{\omega_i + \omega_o}{|\omega_i + \omega_o|} \right)_+^s L_i(\omega_i)$$

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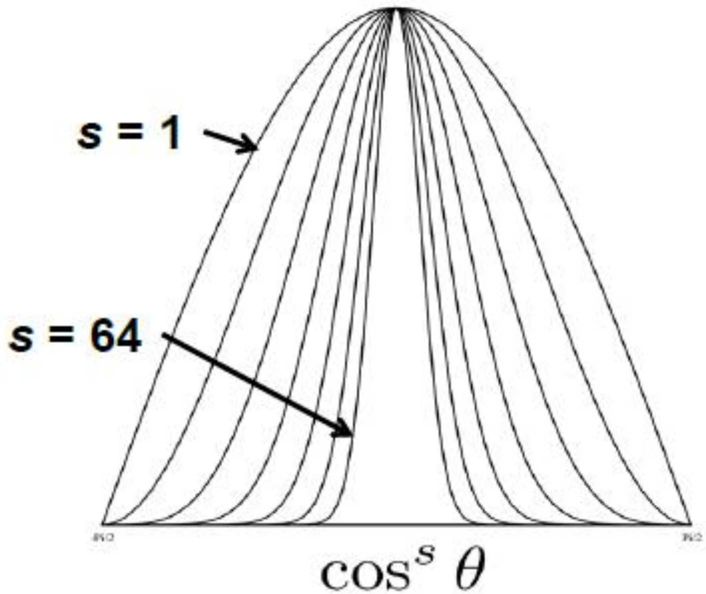
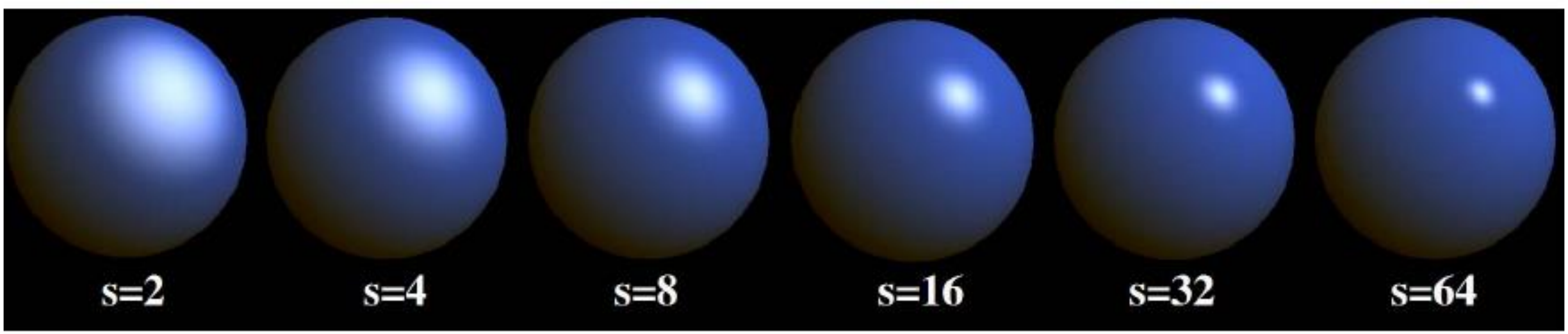
Specular Shininess



The larger the value s, the narrower the highlight

Converges to mirror reflection as $s \rightarrow \infty$



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Next class: Simpler models for illumination in CG

Summary

- Light is electromagnetic radiation
- "Colour" is a human creation describing the frequency components of light
- We can describe colours using colour spaces
- Illumination is determined by the interaction of the light source with the surface
  - Reflection, absorption, transmittance
- Complex physics lead to model simplifications for CG
  - Diffuse, ambient, specular, etc.