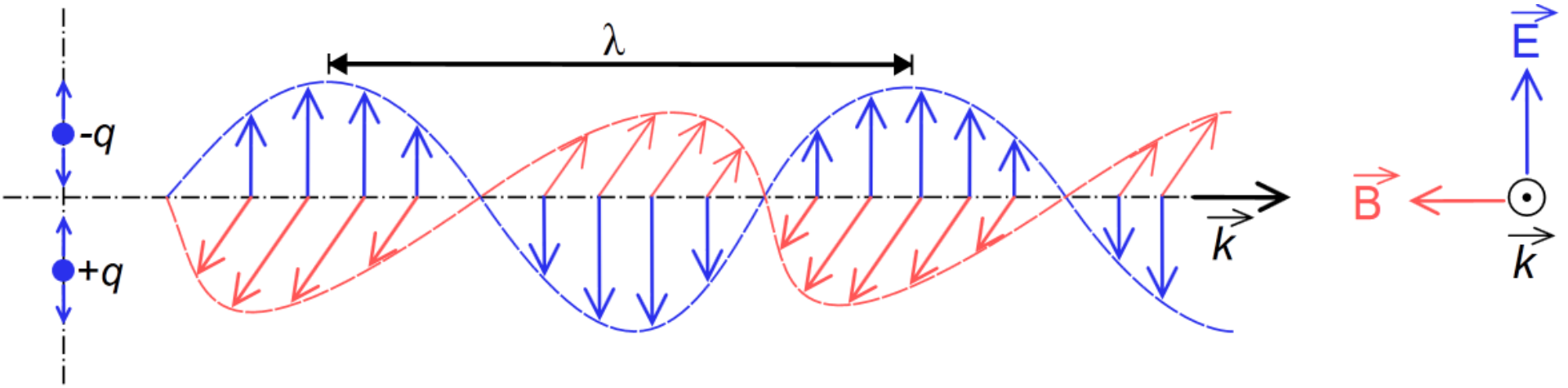
http://www.kewlwallpapers.com/wallpaper/Light-beam-passing-through-jungle-trees/

Light and Color

CS 148, Summer 2012
Introduction to Computer Graphics and Imaging

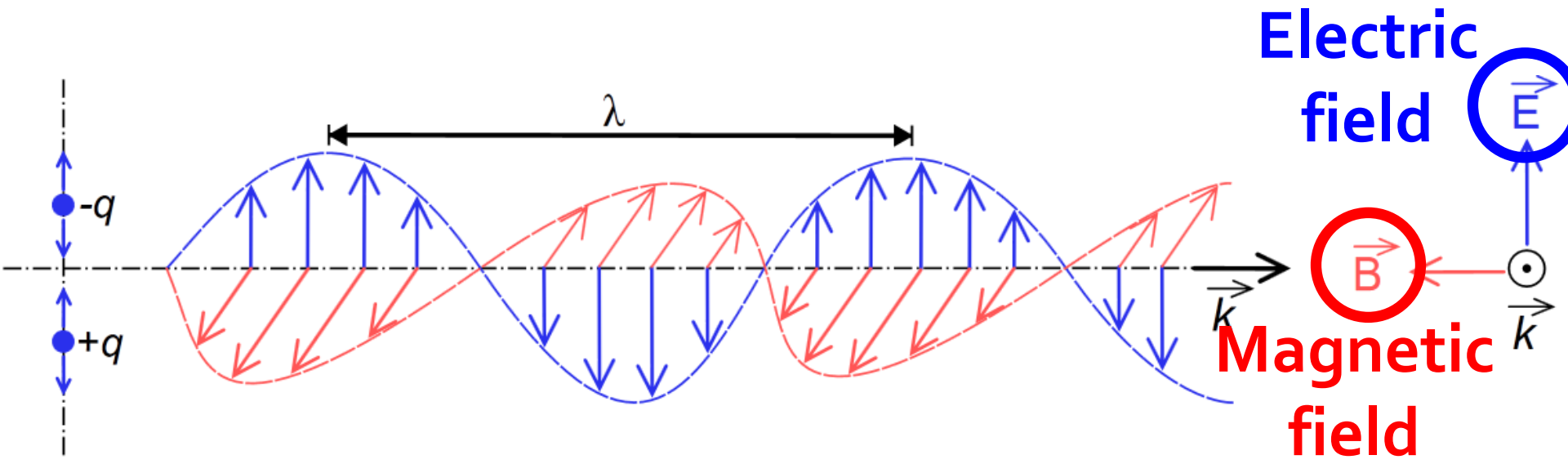
What is Light?



http://en.wikipedia.org/wiki/Electromagnetic_radiation

Visible electromagnetic radiation

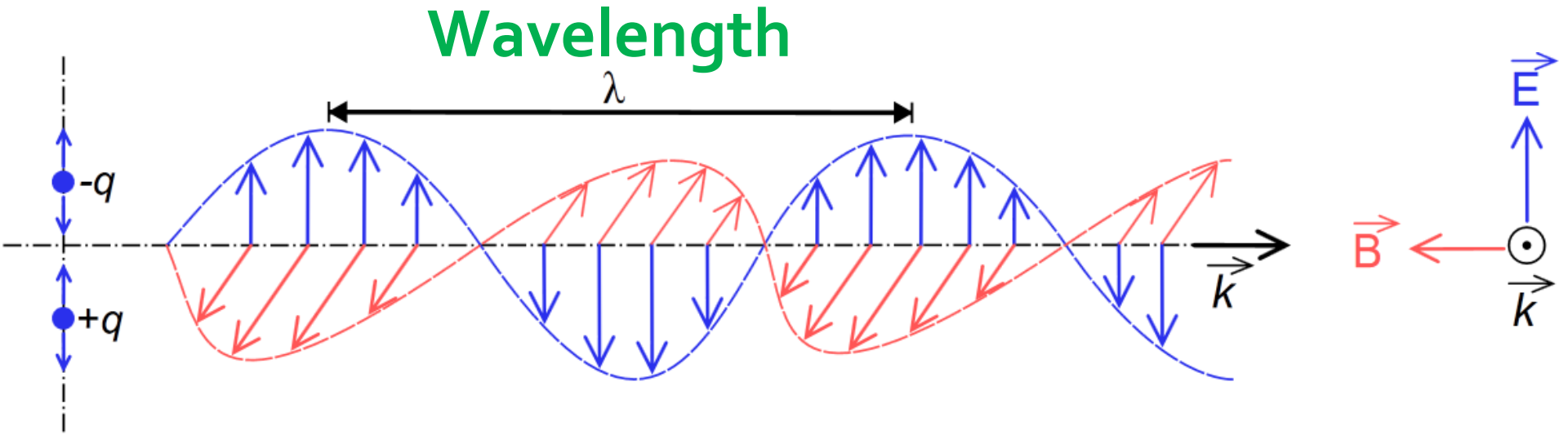
What is Light?



http://en.wikipedia.org/wiki/Electromagnetic_radiation

Visible electromagnetic radiation

What is Light?



http://en.wikipedia.org/wiki/Electromagnetic_radiation

Visible electromagnetic radiation

Important Facts

$$c = 299,792,458 \text{ m/s}$$

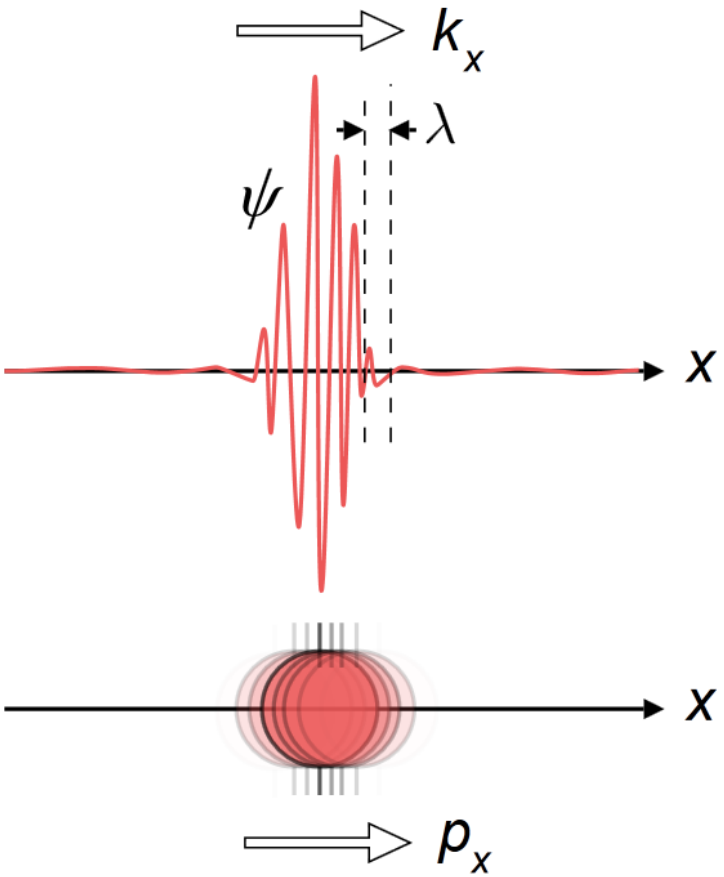
in a vacuum

Material	Speed (multiple of *c*)
Air	0.9997
Water	0.75
Fused quartz	0.686
Crown glass	0.658
Dense flint glass	0.60
Diamond	0.41

http://wiki.answers.com/Q/What_is_the_velocity_of_light_in_space_and_in_different_materials

Constant propagation speed

Important Facts



http://en.wikipedia.org/wiki/Wave%E2%80%93particle_duality

"Both" wave and particle

Photon [**foh**-ton]:

A quantum of light that has a position, a direction of propagation, and a wavelength.

Radiometry

[rey-dee-**om**-i-tree]:

Techniques for the measurement of light.

Energy Carried by a Photon

Planck's constant

$$q = hf = \frac{hc}{\lambda}$$

Frequency

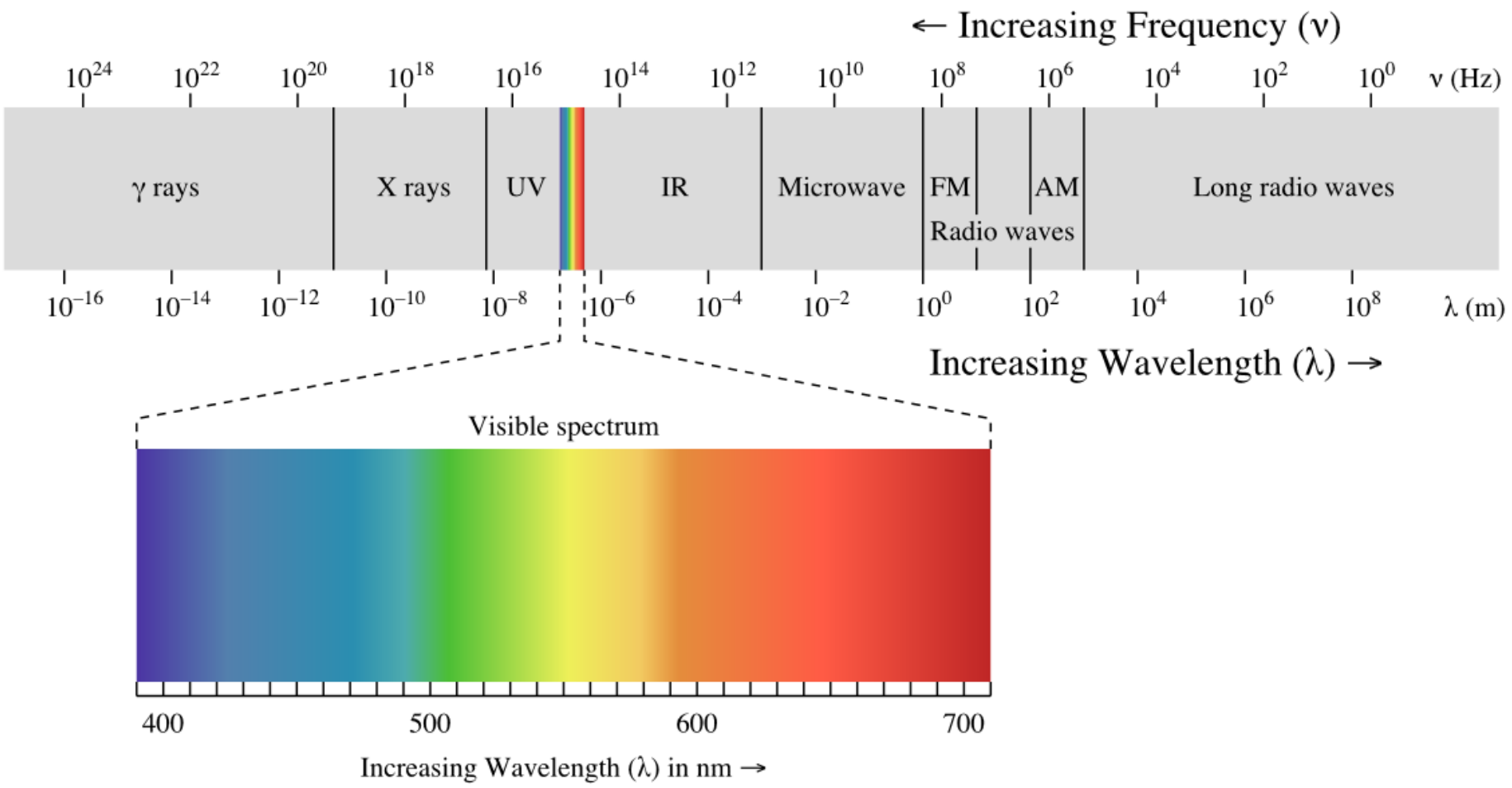
Wavelength

Radiant Flux(Power)

$$\Phi \propto \text{energy}/\text{time}$$

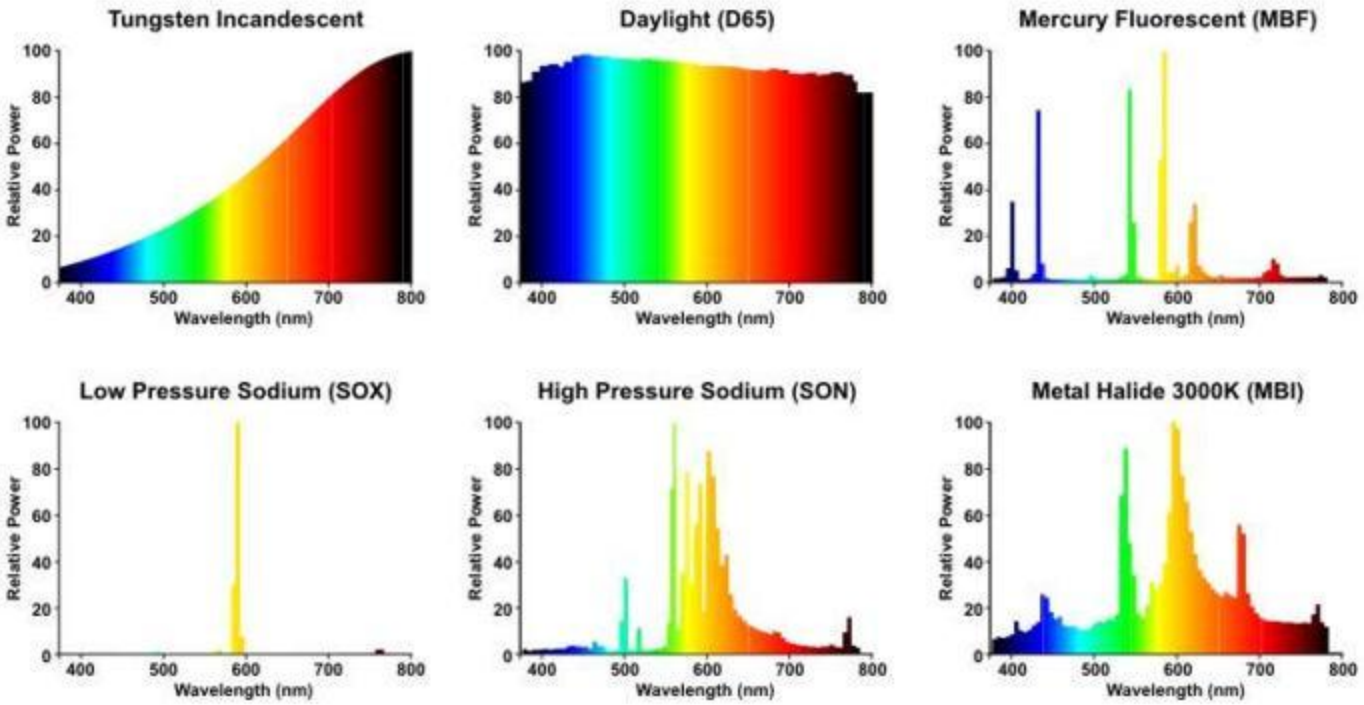
Photon energy released by a light source

Electromagnetic Spectrum



http://en.wikipedia.org/wiki/File:EM_spectrum.svg

Spectral Power Distribution



$$\frac{d\Phi}{d\lambda}$$

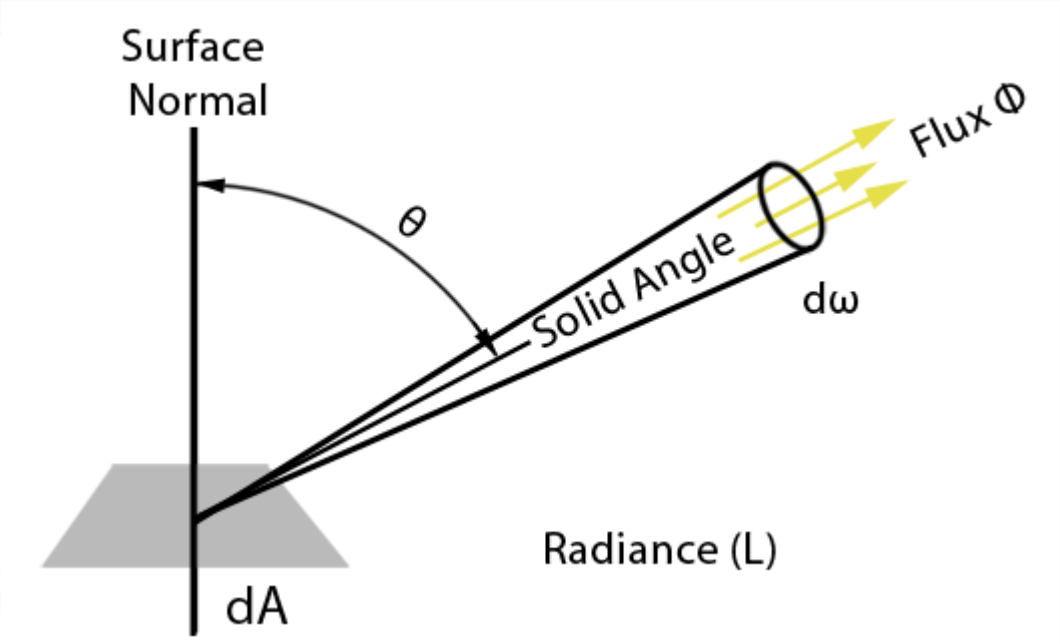
http://www.lamptech.co.uk/Images/Illustrations/SO%20SPD%27s.jpg

More Radiometric Vocabulary

- **Radiance**: flux per solid angle (directional quantity)
- **Irradiance**: incident flux per area of surface

Radiance

Measures amount of radiation through a given direction/area



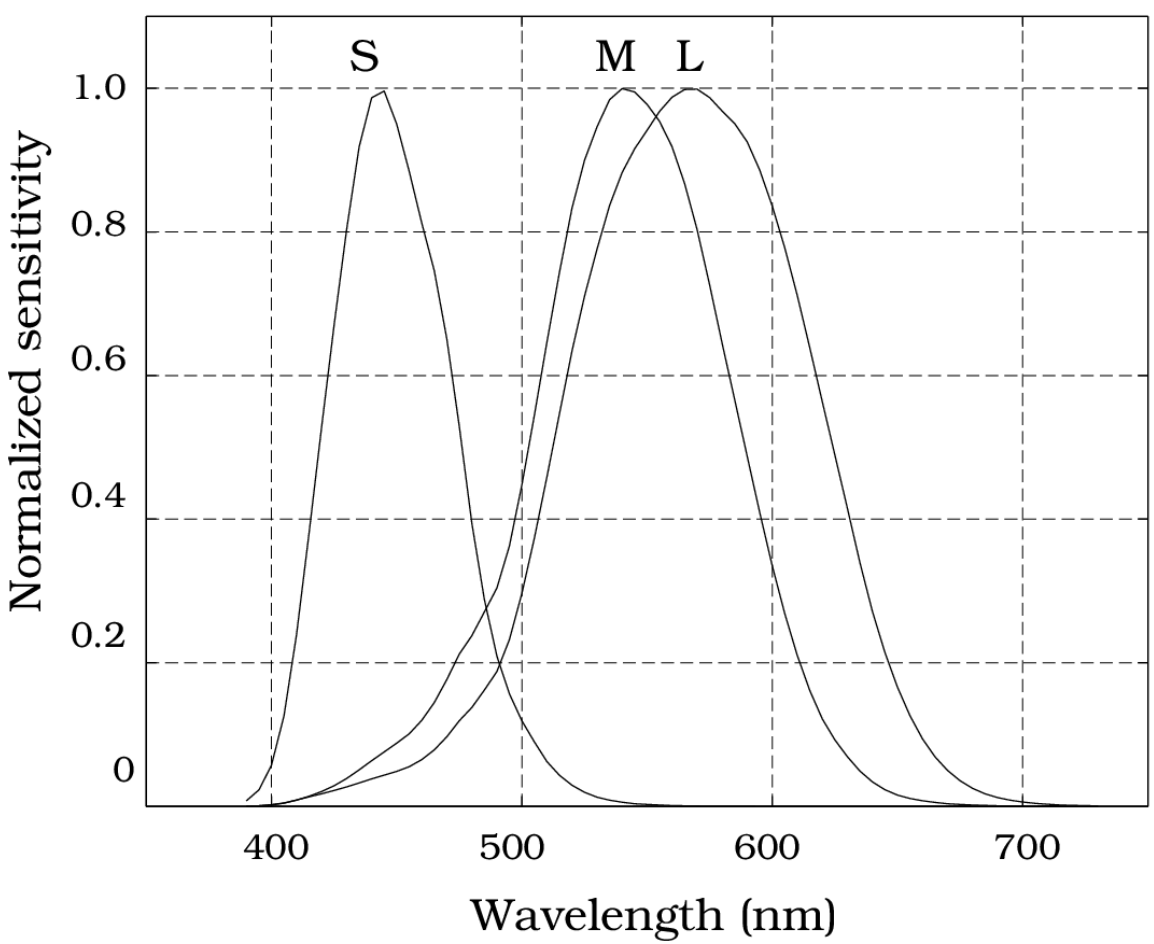
http://www.scratchapixel.com/assets/Uploads/Lighting%20Pipeline/lp-solidangle.png

Photometry

[foh-**tom**-i-tree]:

Measurement of light in terms of its perceived brightness to humans.

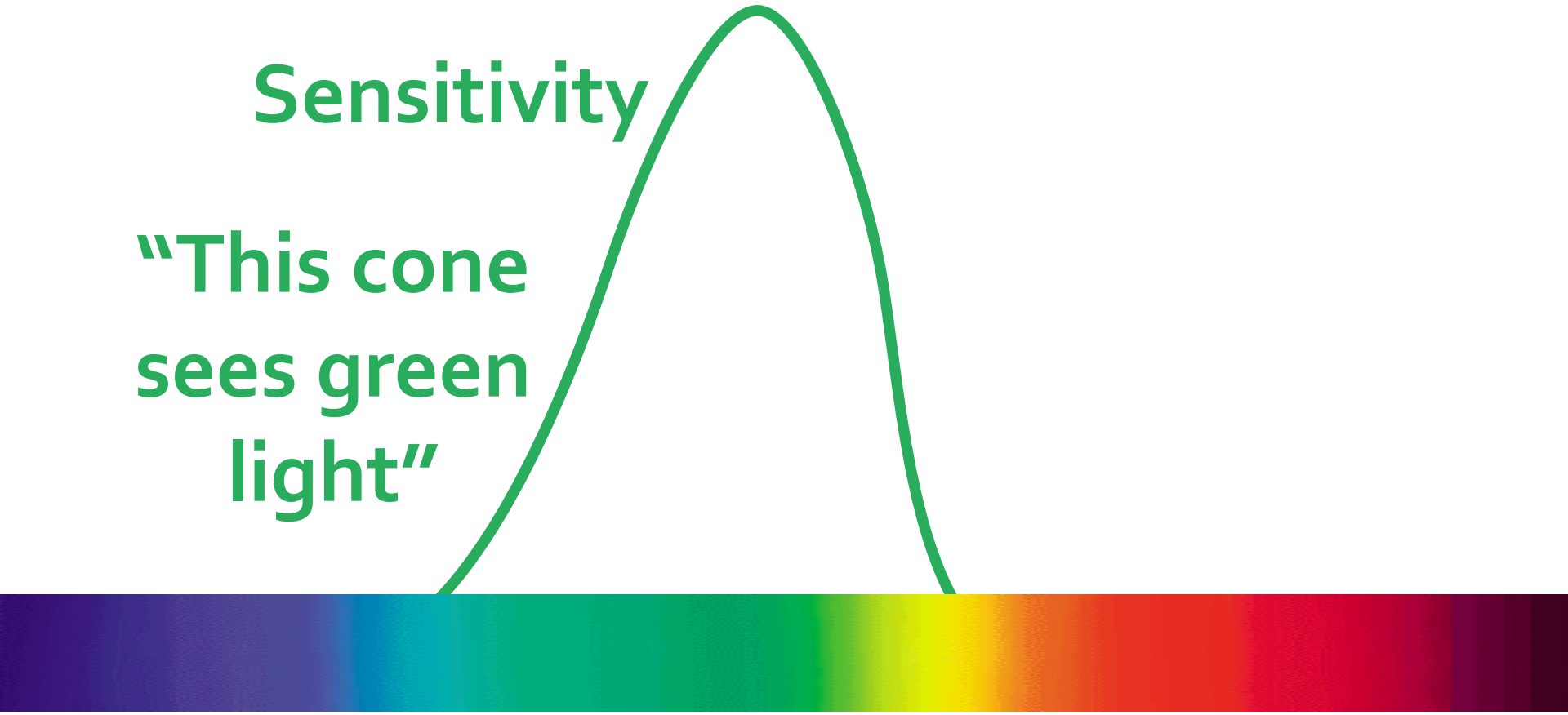
Types of Cones



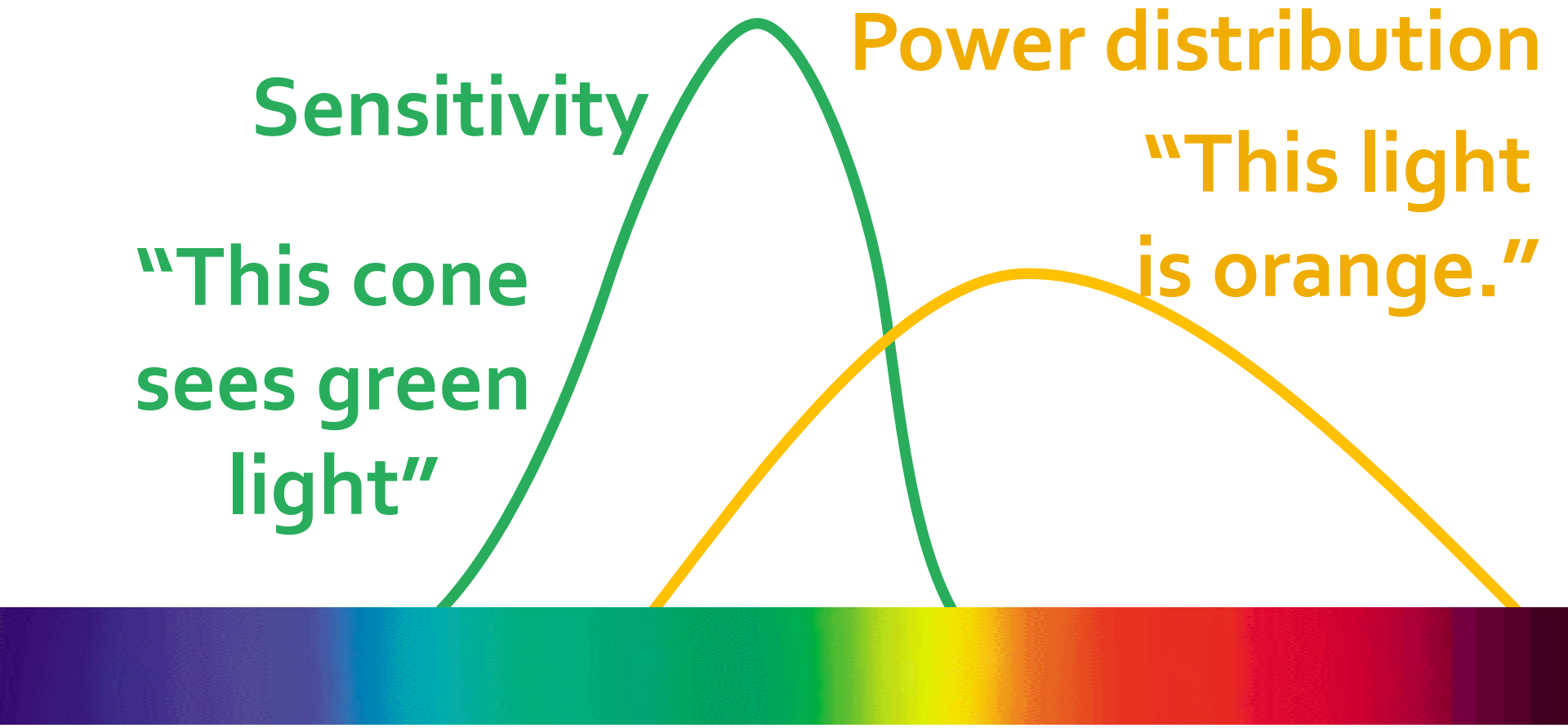
Recall!

http://www.stanford.edu/group/vista/cgi-bin/FOV/wp-content/uploads/2012/02/rec.spec_.sens_.png

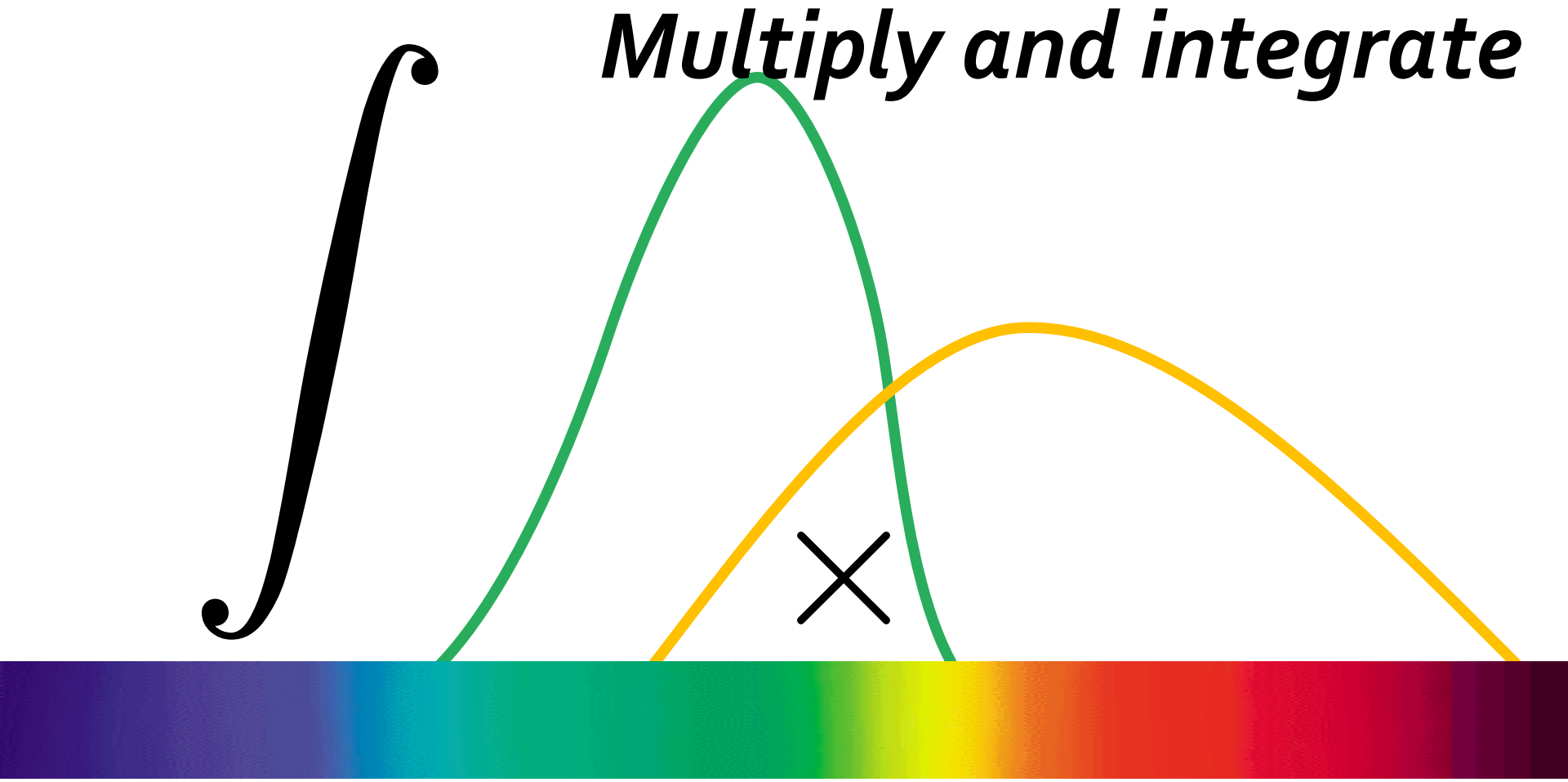
Measuring Light Perception



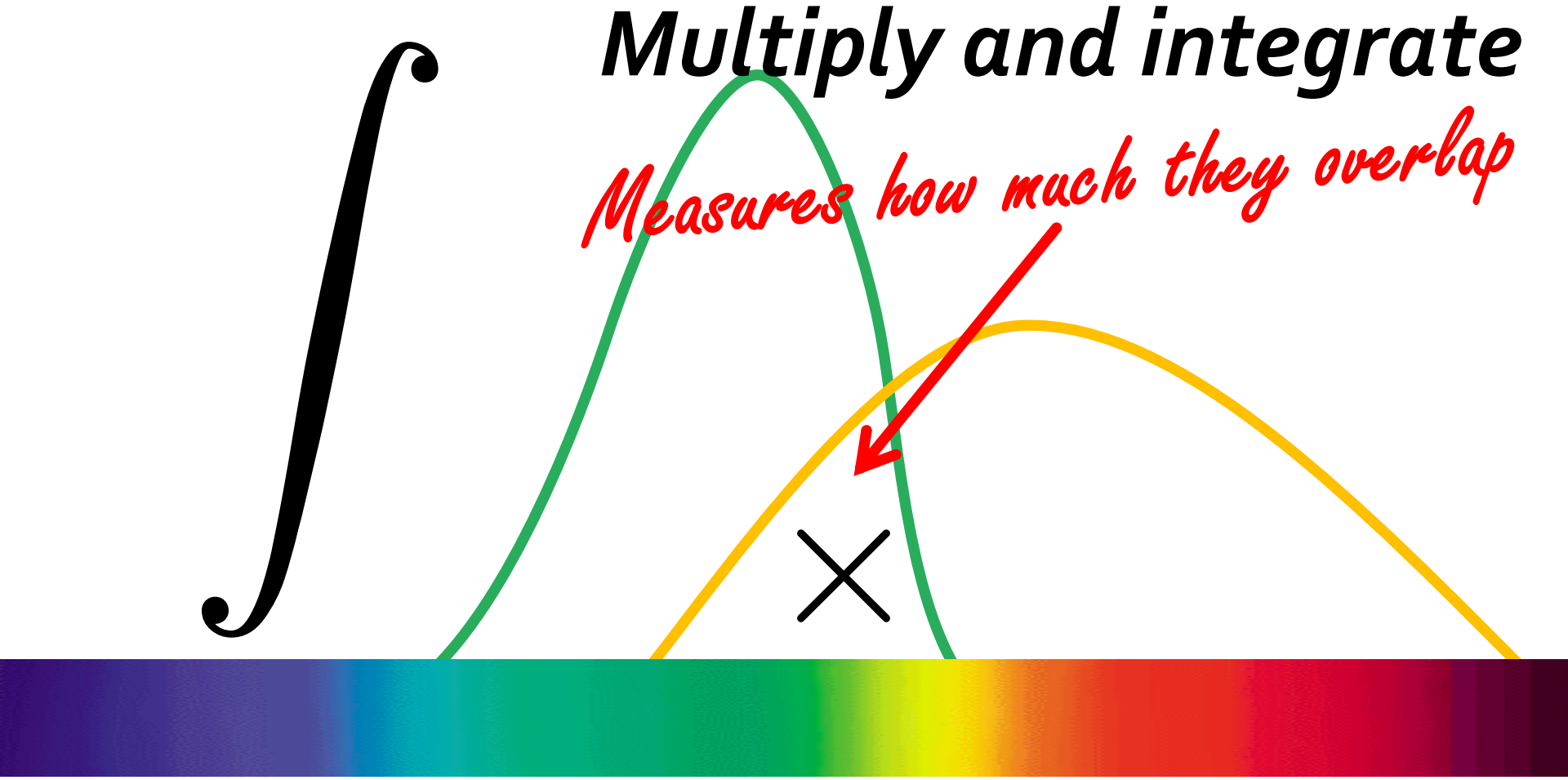
Measuring Light Perception



Measuring Light Perception



Measuring Light Perception



Cone Responses

$$L = \int_{\lambda} \Phi(\lambda) L(\lambda)\ d\lambda$$

$$M = \int_{\lambda} \Phi(\lambda) M(\lambda)\ d\lambda$$

$$S = \int_{\lambda} \Phi(\lambda) S(\lambda)\ d\lambda$$

Sensitivity

Tristimulus Values

Cone Responses

Power distribution

$$L = \int_\lambda \Phi(\lambda) L(\lambda)\ d\lambda$$

$$M = \int_\lambda \Phi(\lambda) M(\lambda)\ d\lambda$$

$$S = \int_\lambda \Phi(\lambda) S(\lambda)\ d\lambda$$

Tristimulus Values

Conclusion

There is an **infinite** number of wavelengths, but we only see **three** integral values.

Conclusion

Cones are not single-wavelength detectors!

There is an **infinite** number of wavelengths, but we only see **three** integral values.

Conclusion

There is an infinite number of wavelengths, but we only see three integral values.

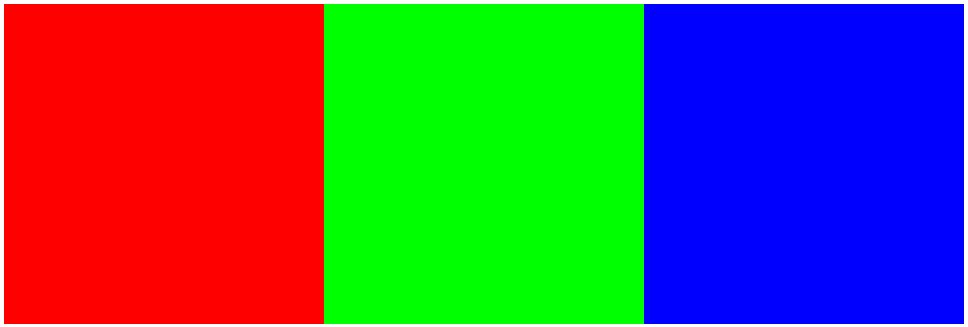
Tristimulus values

Metamers

[**met**-*uh*-mers]:

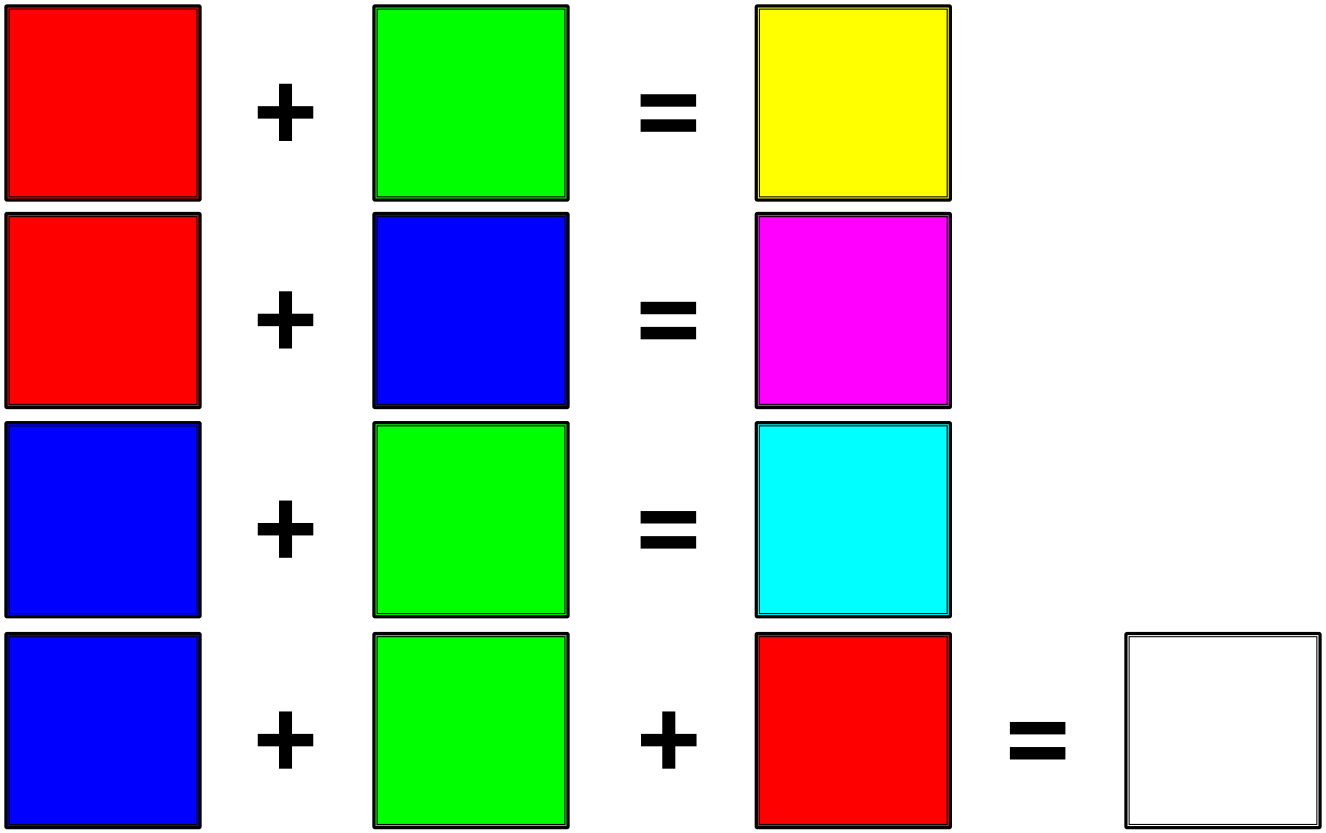
Spectral compositions that create the same tristimulus values.

Implication for Displays



We can simulate visual effects of any wavelength by stimulating cones independently.

Grassman's "Law"



Chromatic sensation is linear

CIE Primaries

- **Red**: 700 nm
- **Green**: 546.1 nm
- **Blue**: 435.8 nm

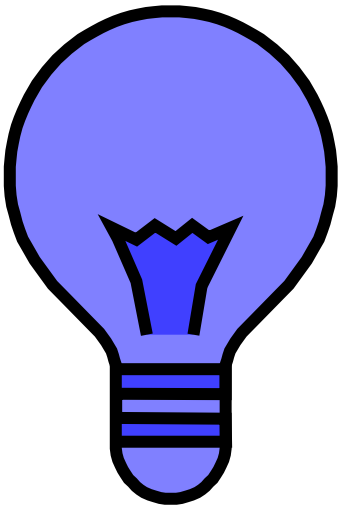
Reproduce all visible wavelengths when combined.

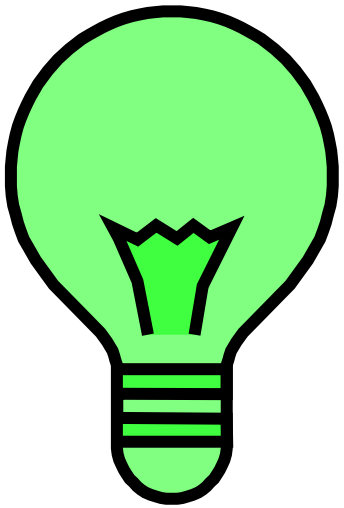
Specifying a Color

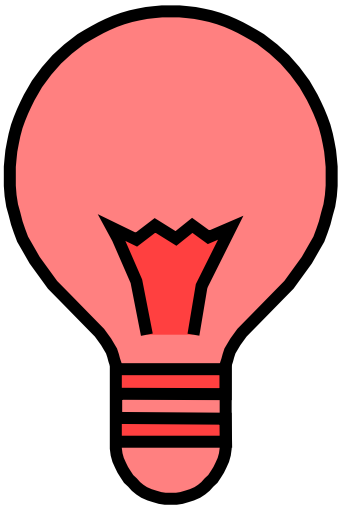
$$(R, G, B) \in \mathbb{R}^3$$

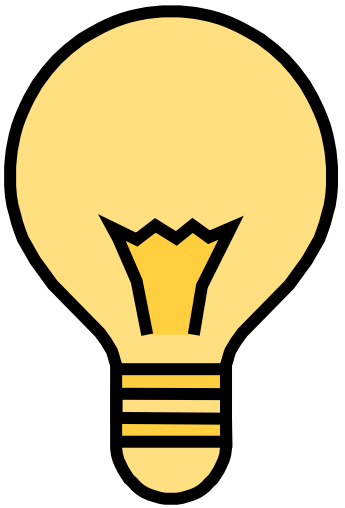
Linear combination of primaries

Color Matching Experiments





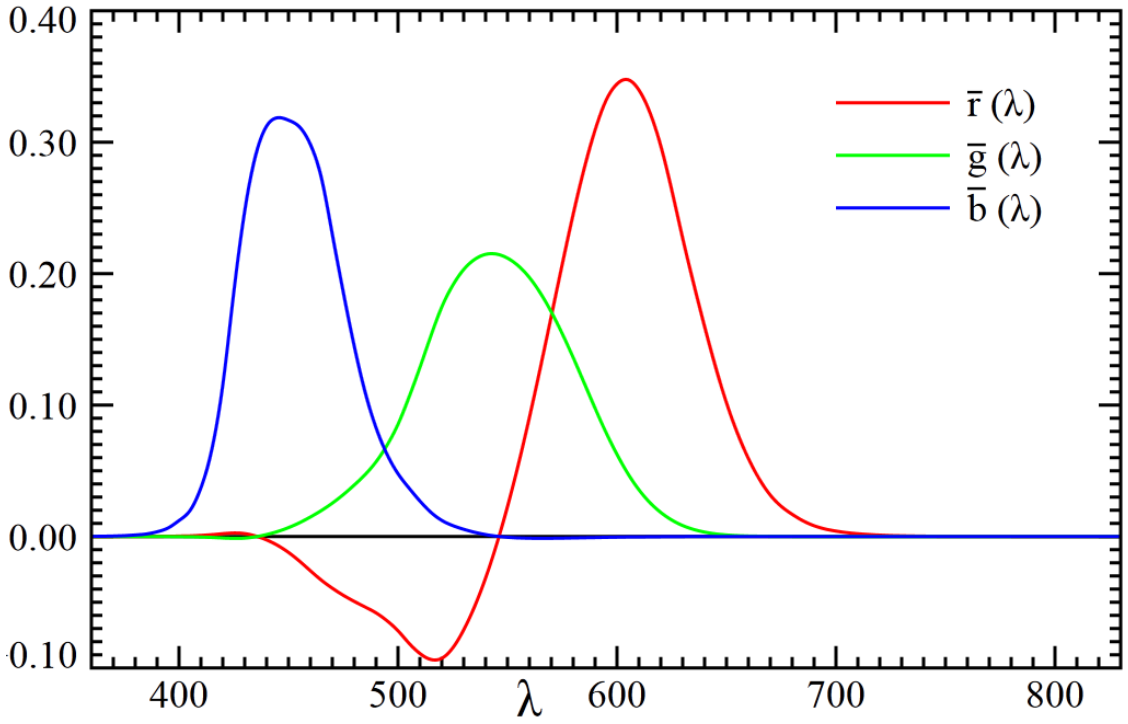




"Match this color."

One wavelength

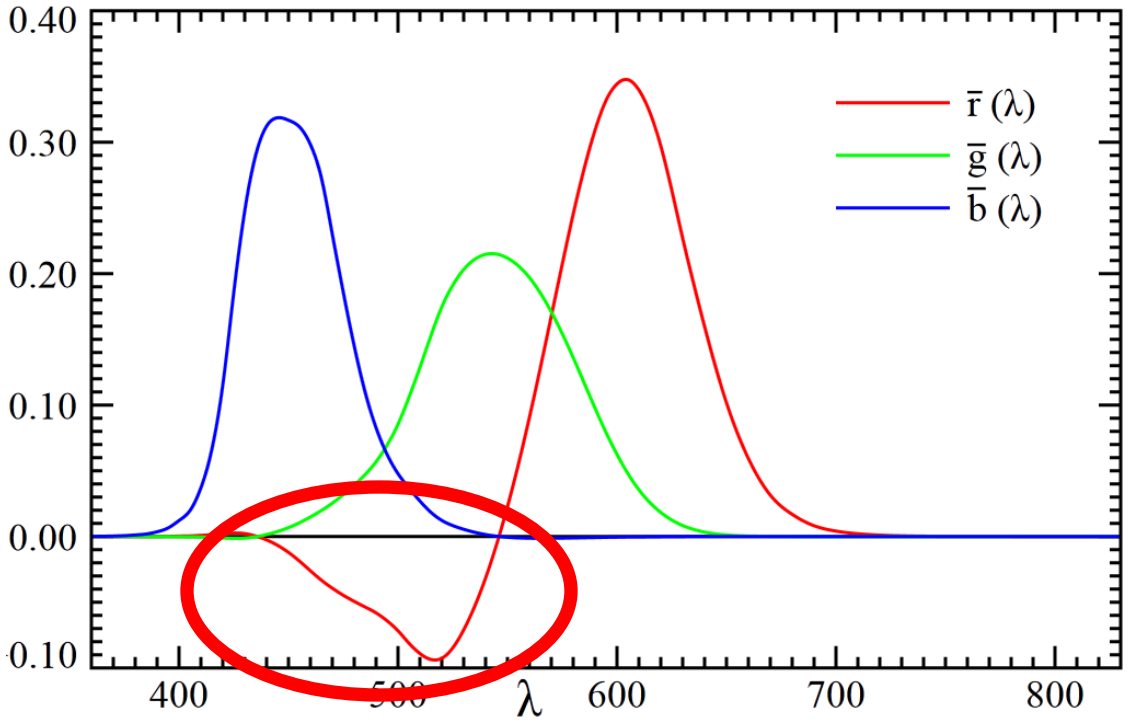
CIE RGB Color Matching



http://en.wikipedia.org/wiki/CIE_1931_color_space

How to combine primaries to mimic each visible wavelength

CIE RGB Color Matching



Negative light?!

http://en.wikipedia.org/wiki/CIE_1931_color_space

How to combine primaries to mimic each visible wavelength

CIE Primaries

- **Red**: 700 nm
- **Green**: 546.1 nm
- **Blue**: 435.8 nm

This problem cannot be solved by changing 'real' primaries.

CIE XYZ

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{0.17697} \begin{pmatrix} 0.49 & 0.31 & 0.2 \\ 0.17697 & 0.8124 & 0.01063 \\ 0 & 0.01 & 0.99 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Map rgb to xyz values, which are positive for visible wavelengths

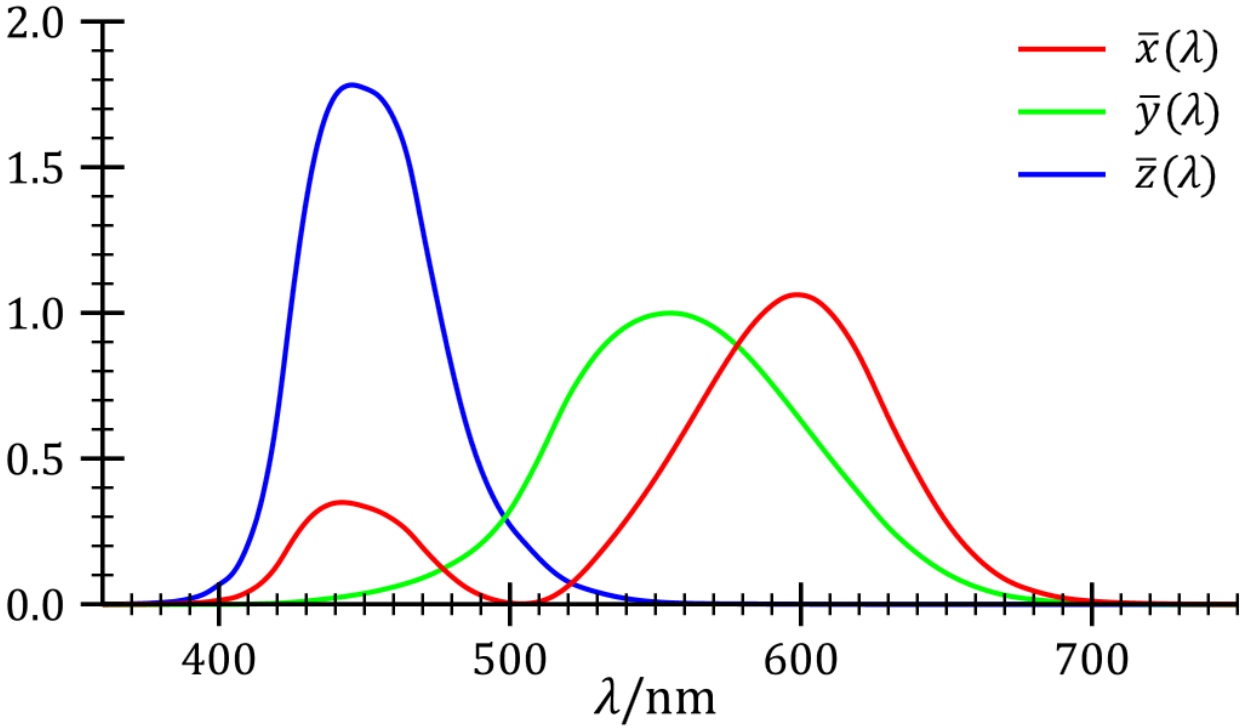
CIE XYZ

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{0.17697} \begin{pmatrix} 0.49 & 0.31 & 0.2 \\ 0.17697 & 0.8124 & 0.01063 \\ 0 & 0.01 & 0.99 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

No longer corresponds to a single wavelength

Map rgb to xyz values, which are positive for visible wavelengths

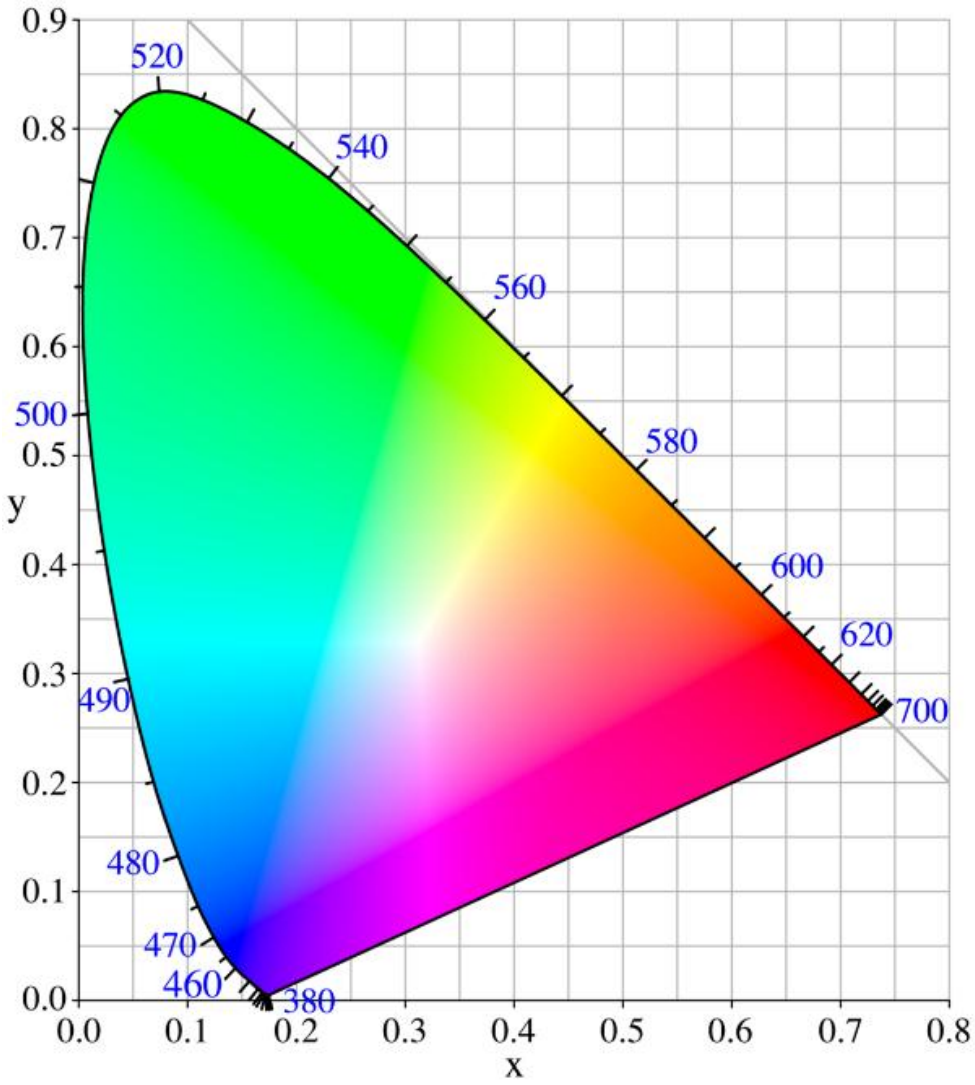
CIE XYZ



http://upload.wikimedia.org/wikipedia/commons/8/8f/CIE_1931_XYZ_Color_Matching_Functions.svg

Map rgb to xyz values, which are positive for visible wavelengths

Chromaticity Diagram



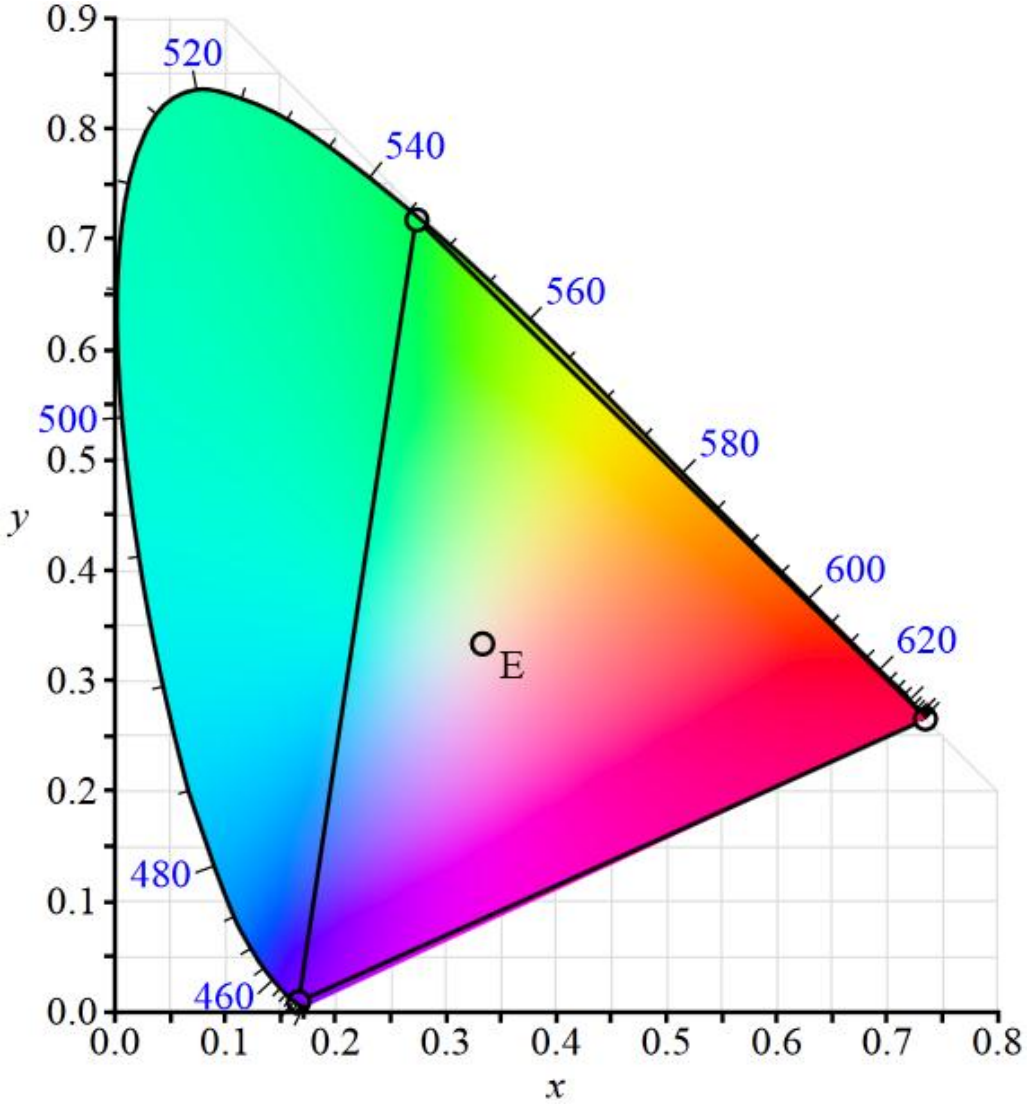
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

Divide out luminance

http://upload.wikimedia.org/wikipedia/commons/b/bo/CIExy1931.png

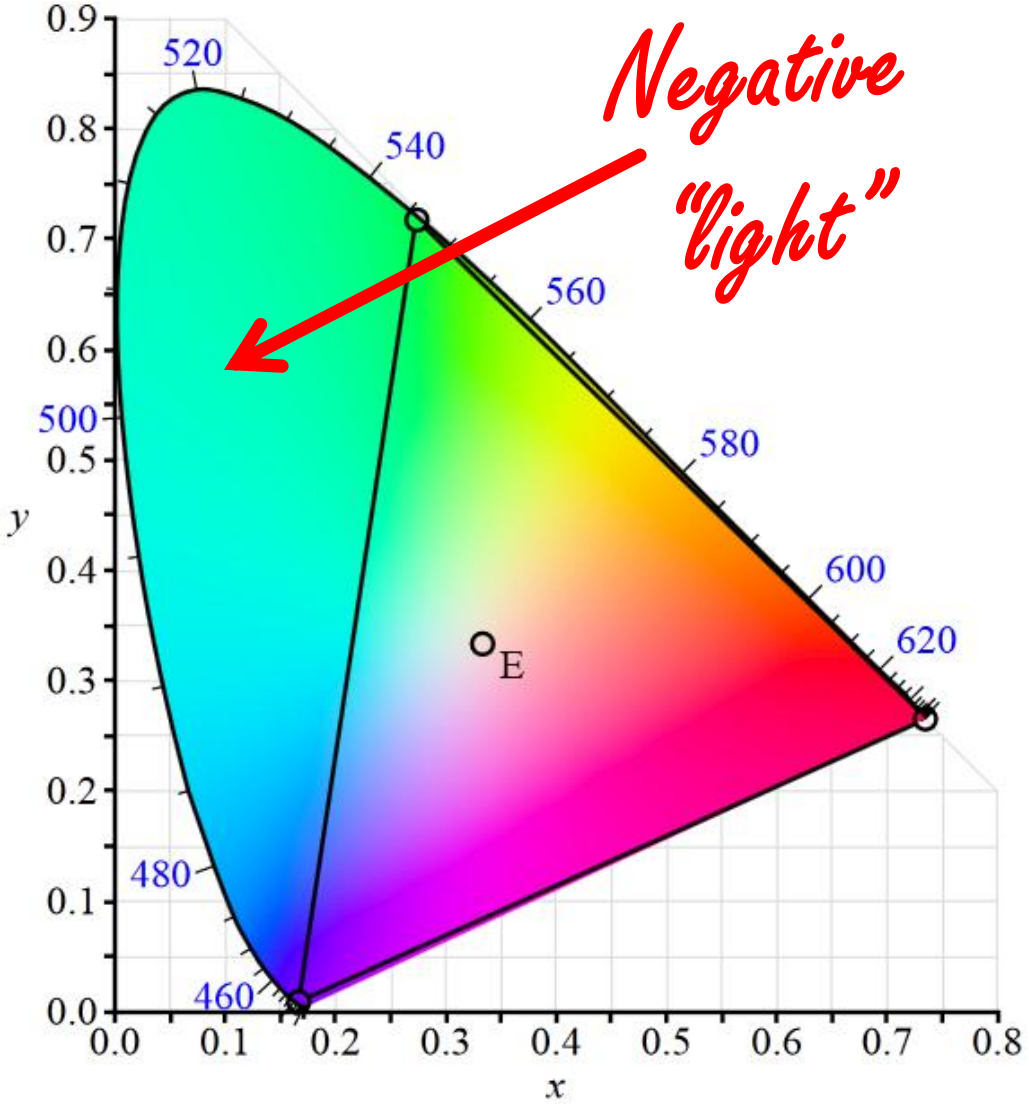
CIE Primaries



RGB are vertices; can achieve colors inside the triangle by combining them

http://upload.wikimedia.org/wikipedia/commons/6/60/CIE1931xy_CIERGB.svg

CIE Primaries



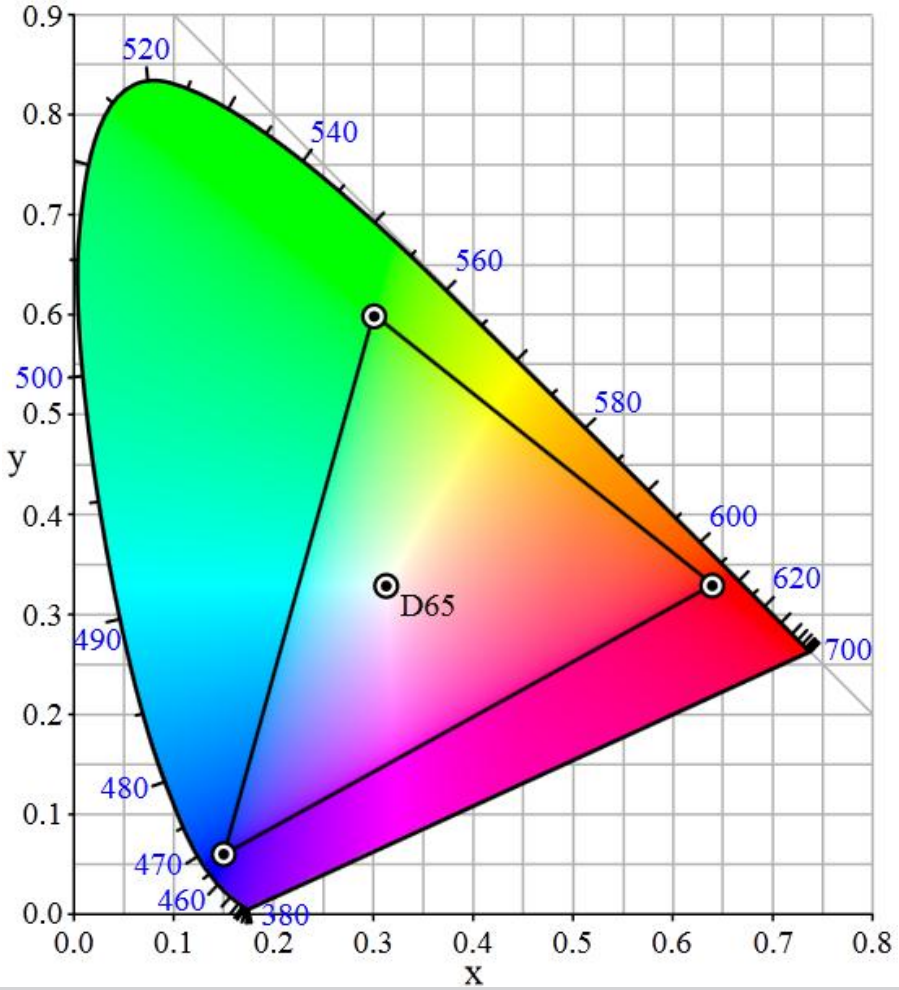
RGB are vertices; can achieve colors inside the triangle by combining them

http://upload.wikimedia.org/wikipedia/commons/6/60/CIE1931xy_CIERGB.svg

Gamut [**gam**-*uh*t]:

The set of colors representable using a particular display device or color space.

Describing a Display



sRGB

-HDTV

http://upload.wikimedia.org/wikipedia/commons/8/8f/CIExy1931_sRGB.svg

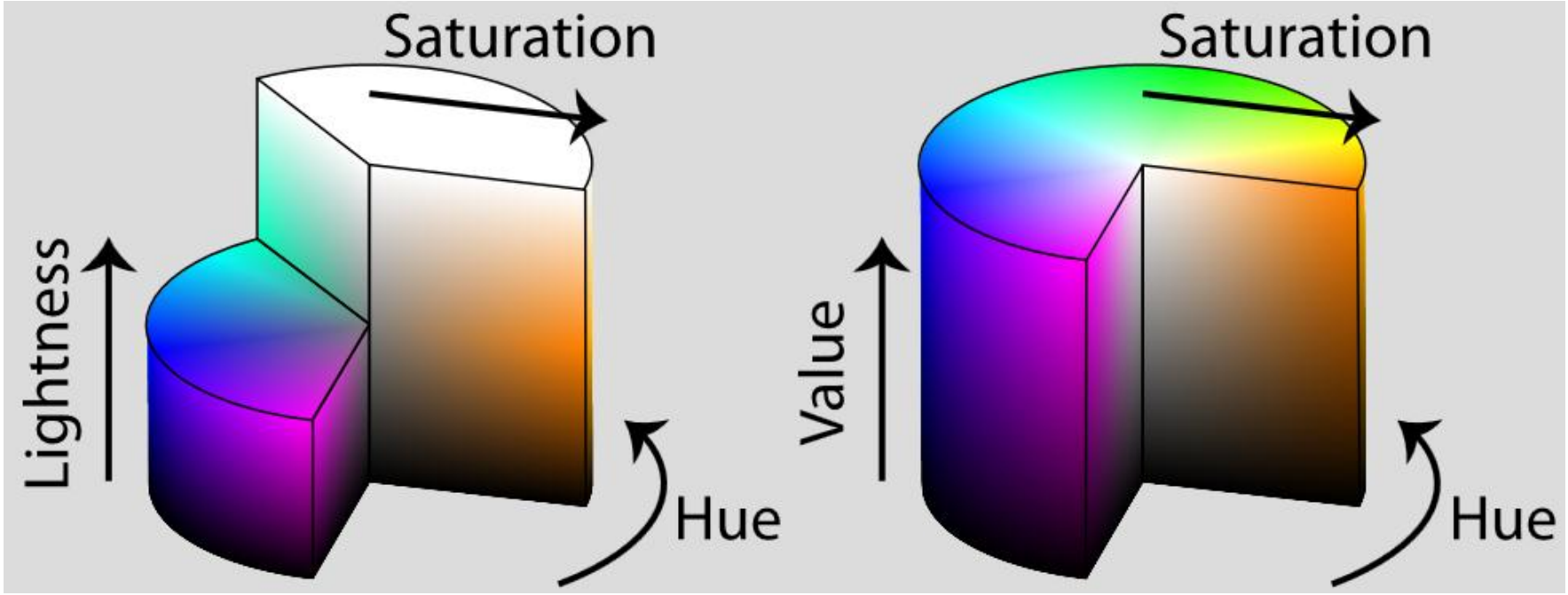
Vertices are primaries, possibilities are inside triangle

Alternative Color Spaces

So far we have:

- **CIE RGB**
  Can have negative numbers
- **CIE XYZ**
  Nonnegative, no physical realization
- **Display-dependent RGB**
  Values saying how much to light each pixel

Alternative Color Spaces



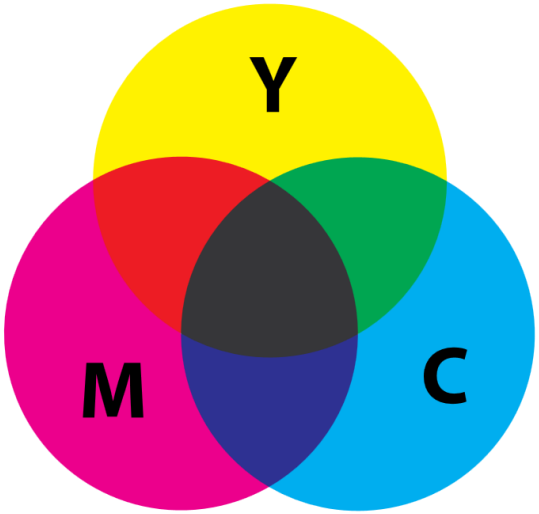
Designed to be more intuitive

http://upload.wikimedia.org/wikipedia/commons/a/ao/Hsl-hsv_models.svg

HSV (HSL):

Hue, Saturation, Value (Luminance)

Subtractive Color



What matters is the color of a pigment does *not* absorb!

http://en.wikipedia.org/wiki/CMYK_color_model

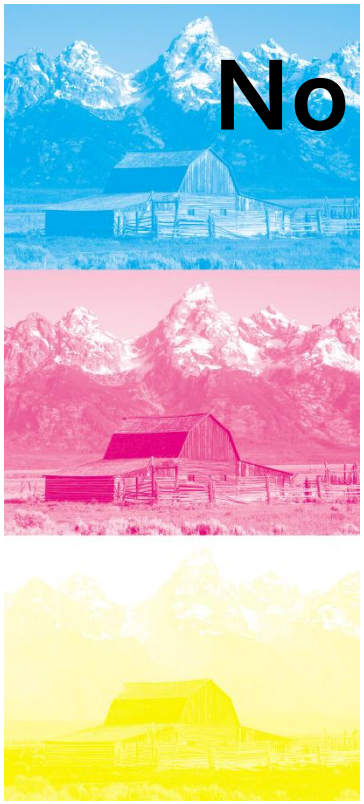
CMYK:

Cyan, Magenta, Yellow, Black

CMYK is Nonunique

Four primaries!

No black

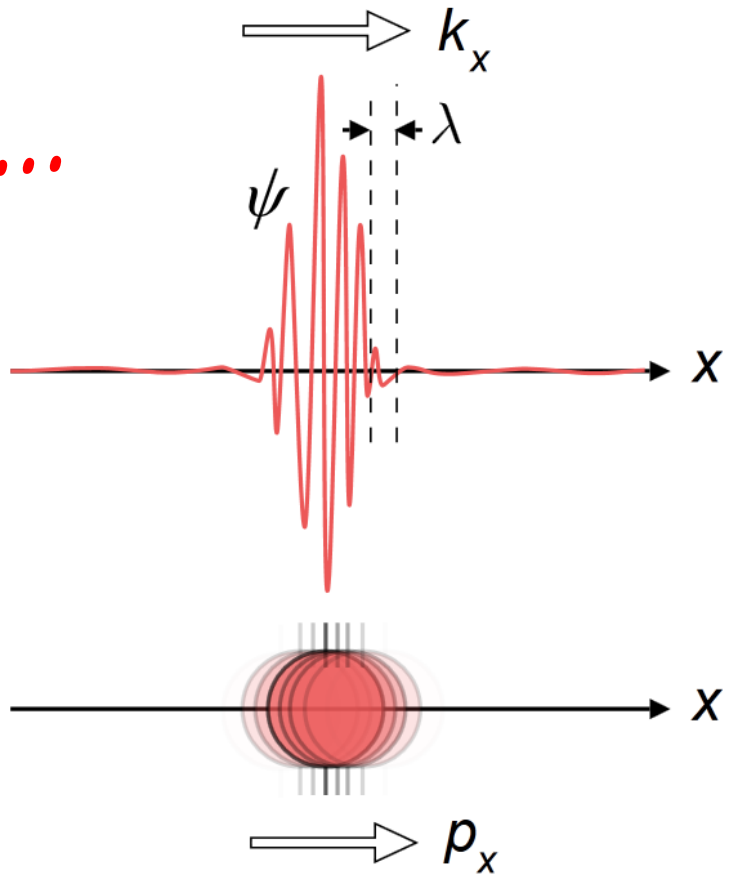


Max black

http://en.wikipedia.org/wiki/CMYK_color_ model

Important Facts

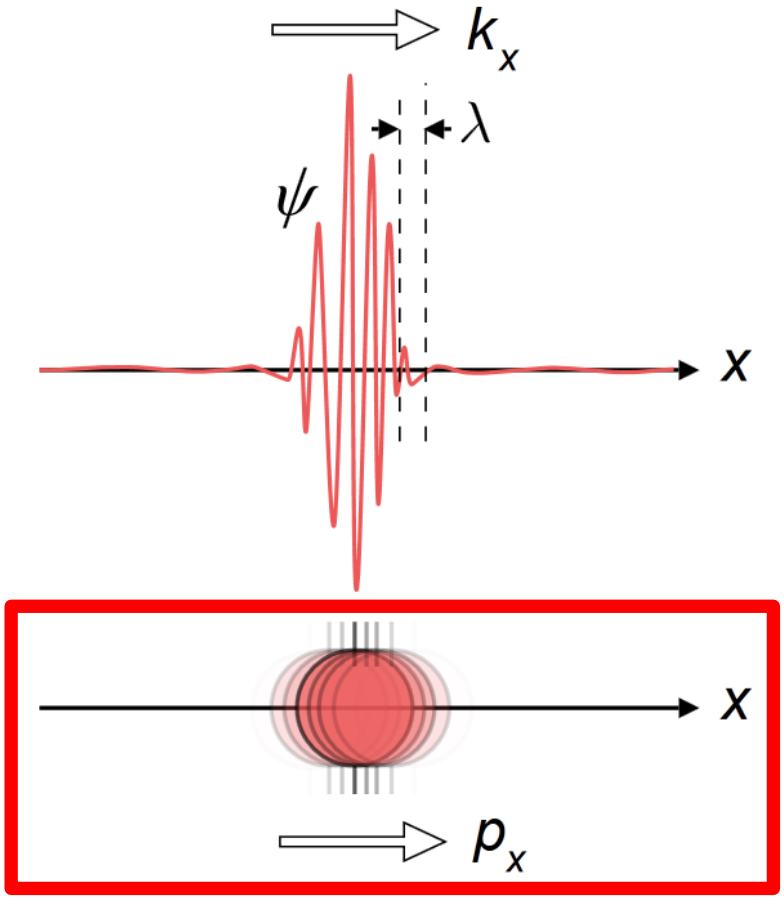
So far...



http://en.wikipedia.org/wiki/Wave%E2%80%93particle_duality

"Both" wave and particle

Important Facts



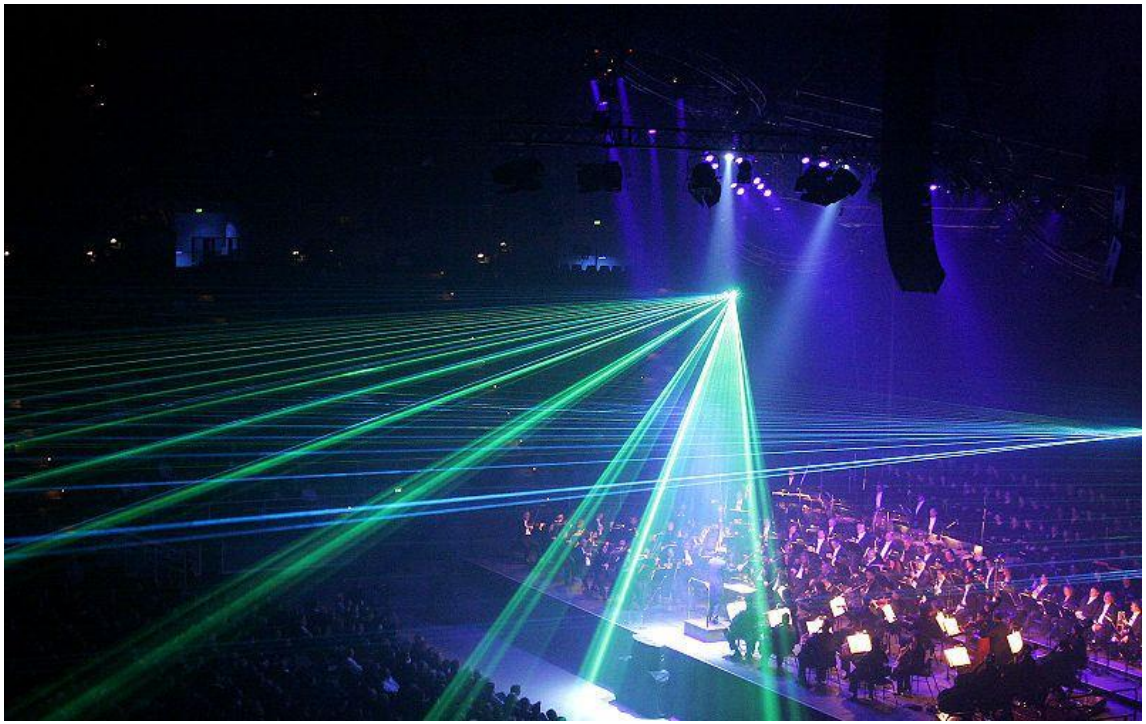
http://en.wikipedia.org/wiki/Wave%E2%80%93particle_duality

"Both" wave and particle

Fermat's Principle

The path taken between two points by a ray of light is the path that can be traversed in least time.

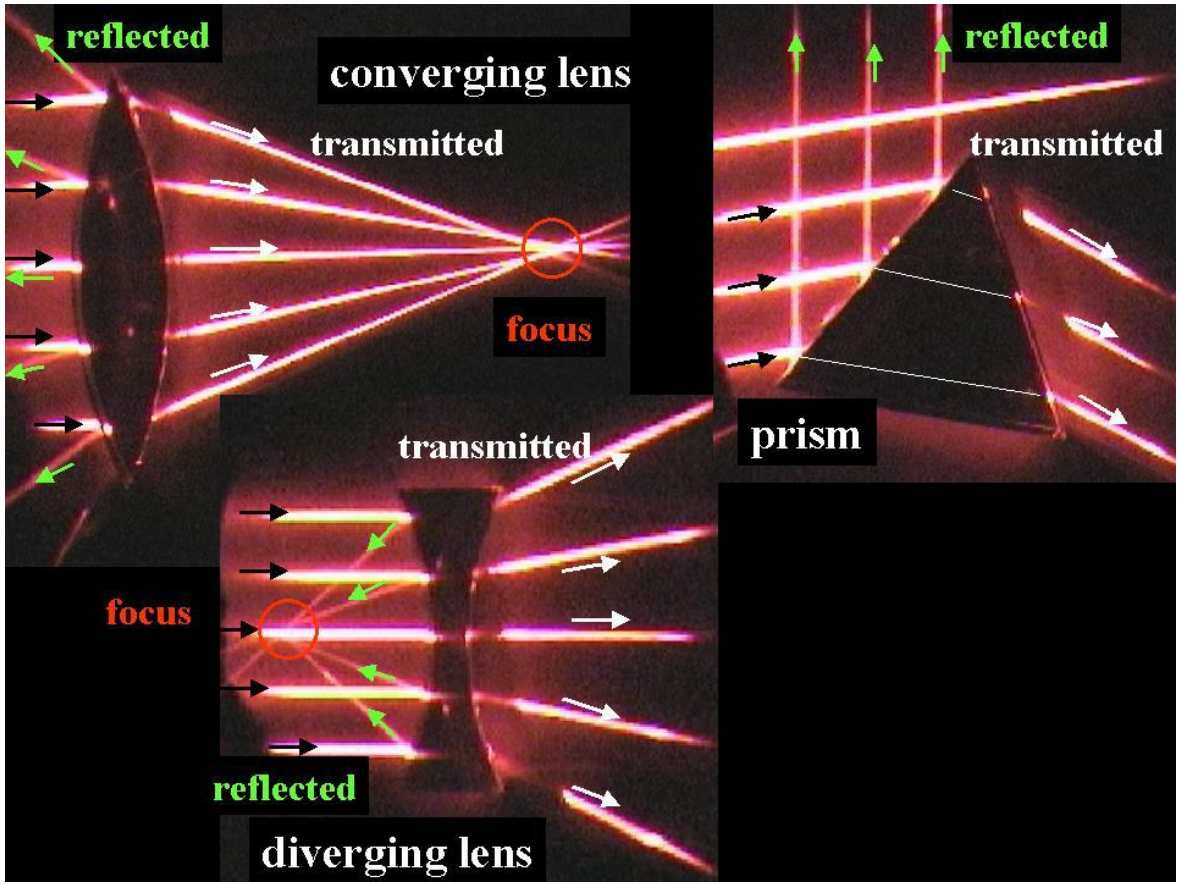
Conclusion



http://www.nidokidos.org/userpix/38570_3__Ibn_alHaytham_proved_that_light_travels_in_straight_lines_using_the_scientific_method_in_his_Book_of_Optics__1.jpg

In uniform material, light travels in a straight line!

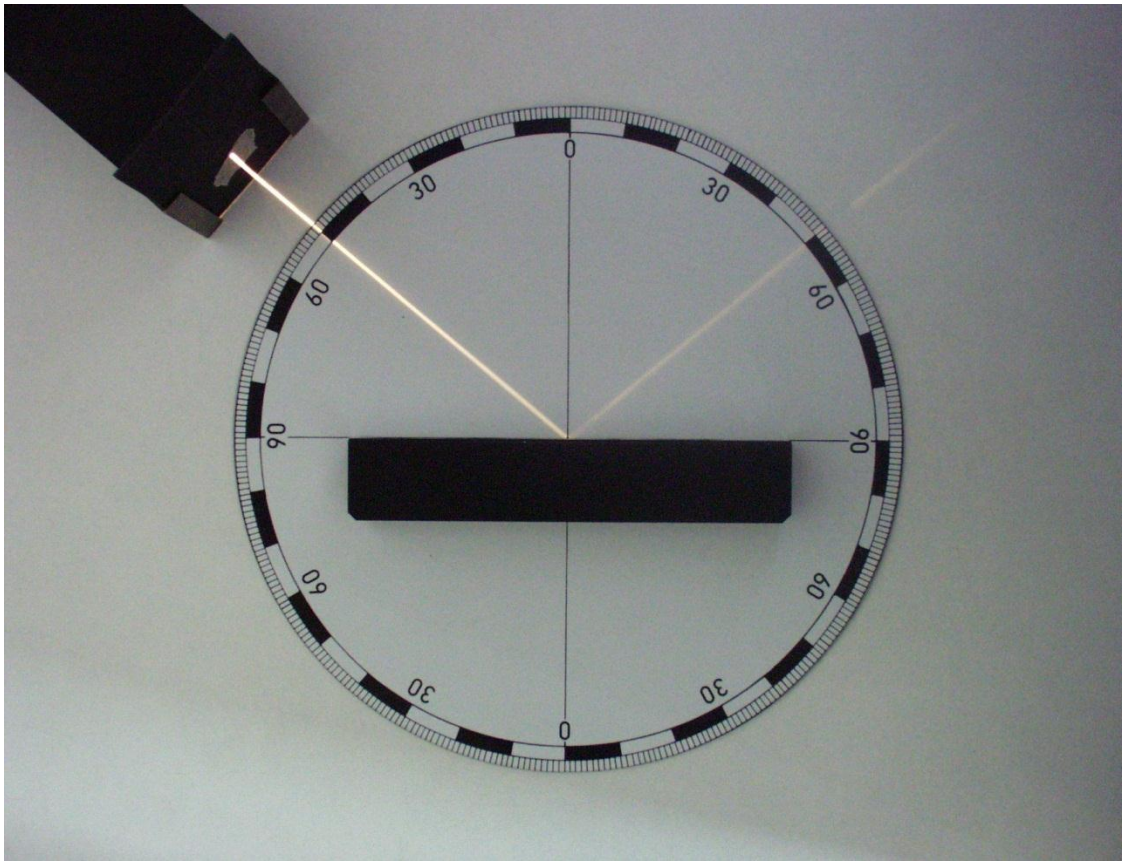
Ray Tracing Optics

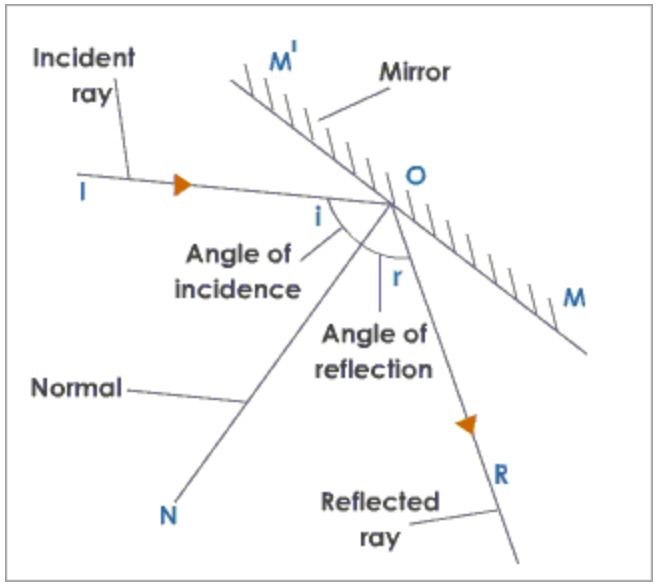


http://www.physics.rutgers.edu/~croft/divconvprism.jpg

Optics as tracing paths of light

Ways to Modify Path

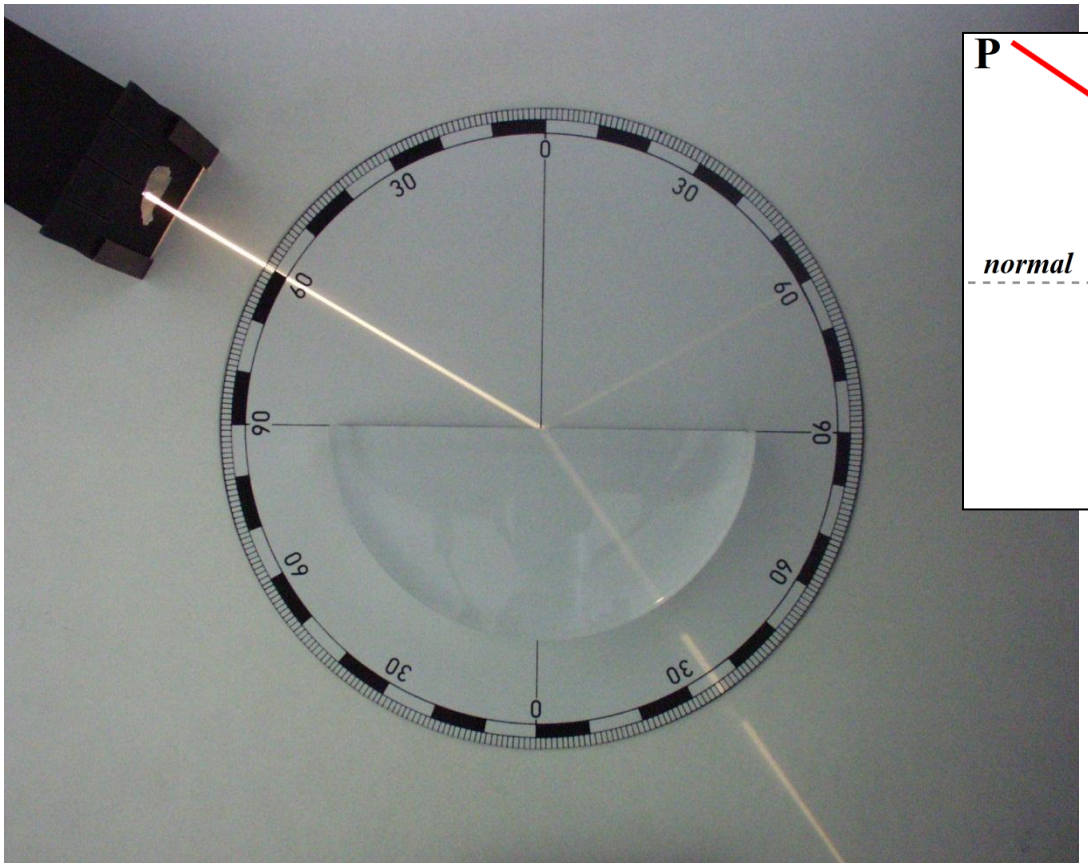


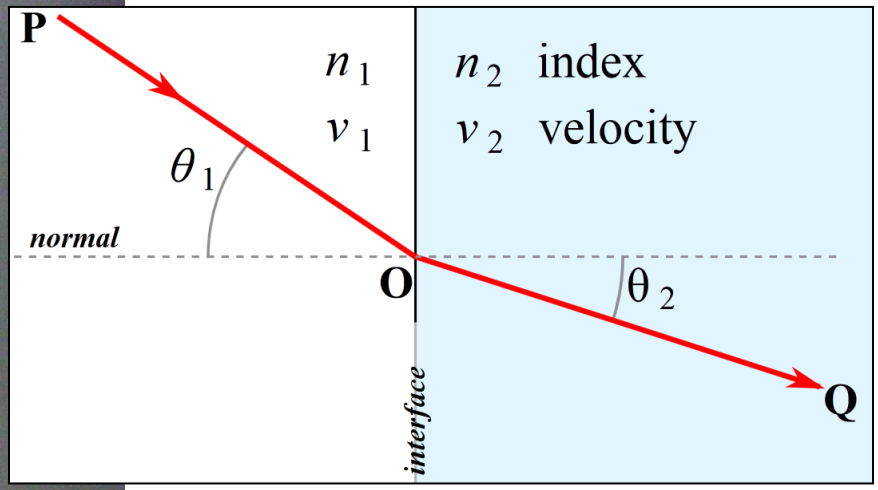


http://upload.wikimedia.org/wikipedia/commons/e/e3/F%C3%A9nyvisszaver%C5%91d%C3%A9s.jpg
http://www.miniphysics.com/wp-content/uploads/2012/07/light-reflection-plane-mirror.gif

Reflection

Ways to Modify Path

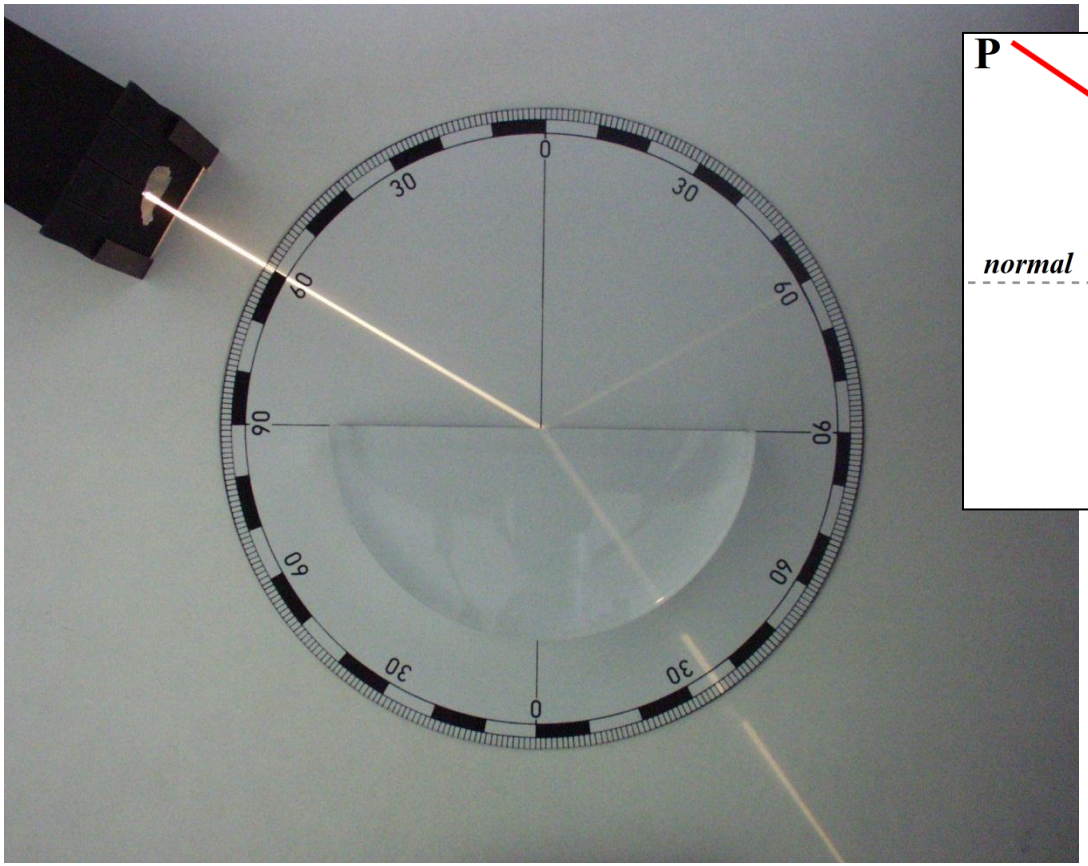


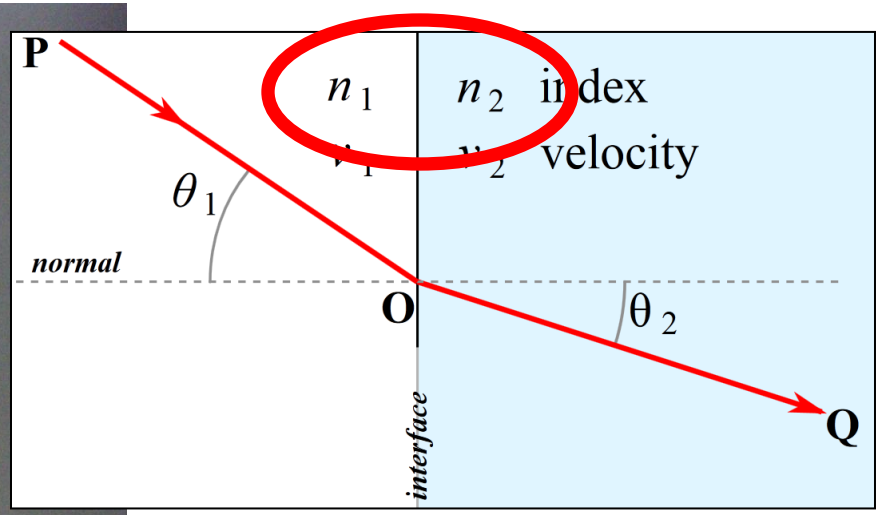


http://upload.wikimedia.org/wikipedia/commons/1/13/F%C3%A9nyt%C3%B6r%C3%A9s.jpg
http://upload.wikimedia.org/wikipedia/commons/d/d1/Snells_law.svg

Refraction

Ways to Modify Path



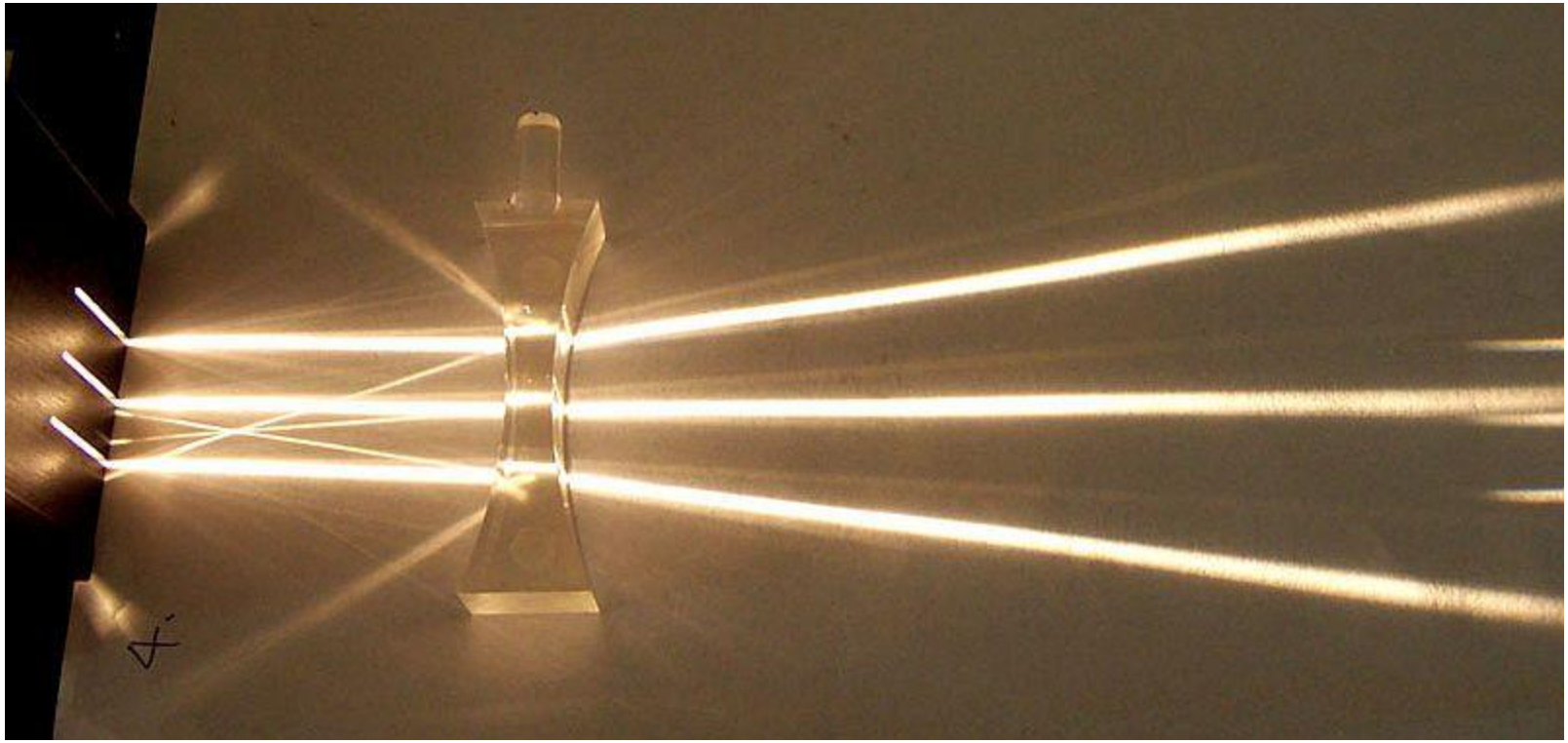


Index of refraction (property of material)

http://upload.wikimedia.org/wikipedia/commons/1/13/F%C3%A9nyt%C3%B6r%C3%A9s.jpg
http://upload.wikimedia.org/wikipedia/commons/d/d1/Snells_law.svg

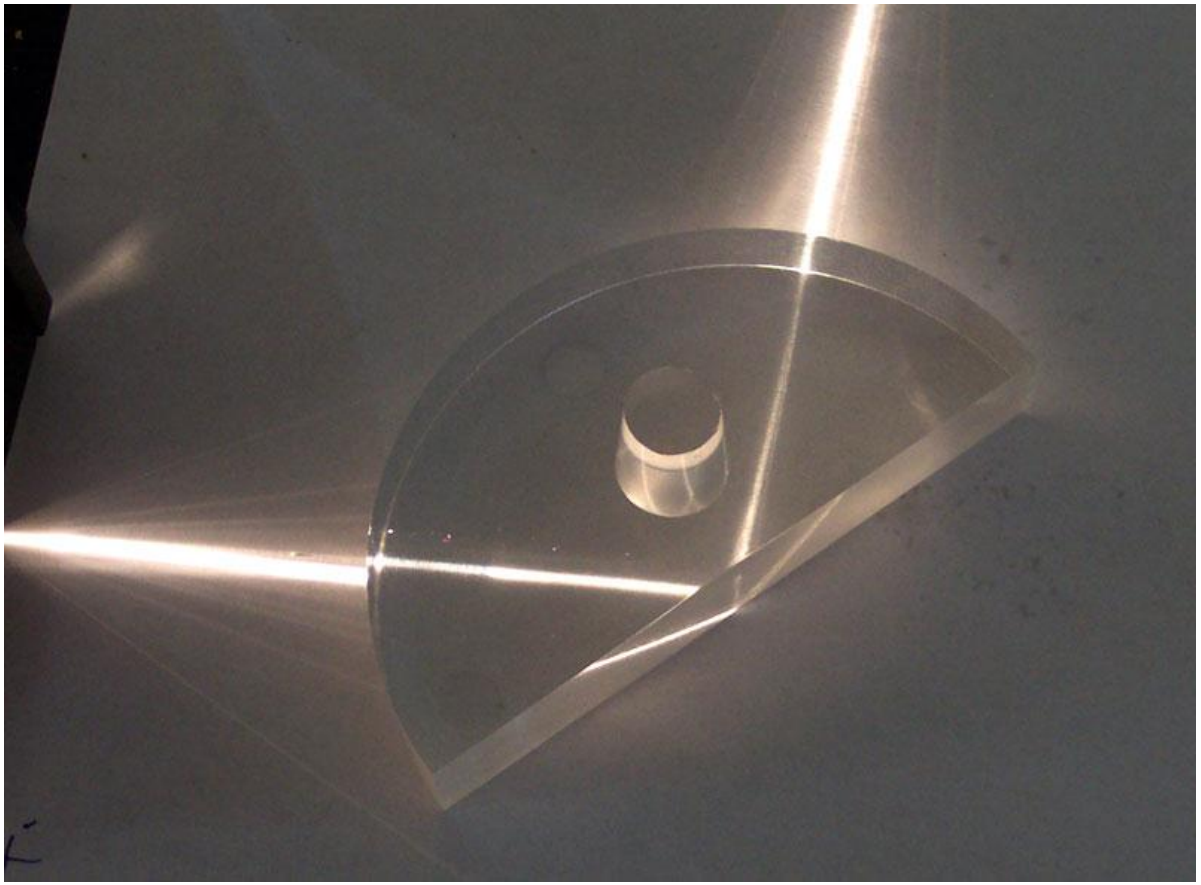
Refraction

Lens: Application of Refraction



http://upload.wikimedia.org/wikipedia/commons/3/32/Concave_lens.jpg

Total Internal Reflection



http://upload.wikimedia.org/wikipedia/commons/e/ec/Total_internal_reflection.jpg

Refraction becomes reflection

http://www.kewlwallpapers.com/wallpaper/Light-beam-passing-through-jungle-trees/

Light and Color

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Introduction to Computer Graphics and Imaging