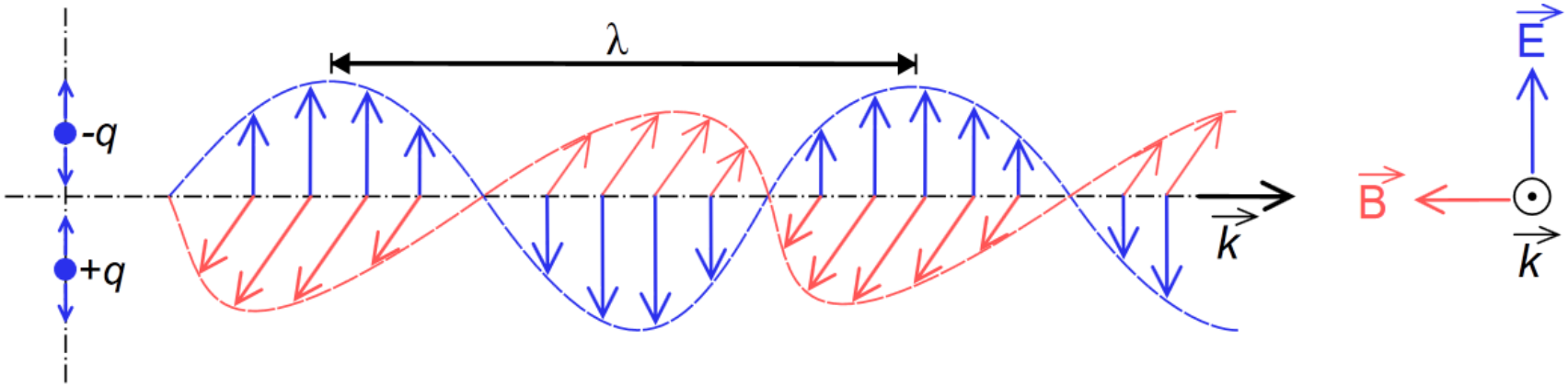
Light and Colors

CS 148: Summer 2016
Introduction of Graphics and Imaging
Zahid Hossain

http://lighthouse8.com/wp-content/uploads/2012/08/true-colors.jpg

What is Light ?



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

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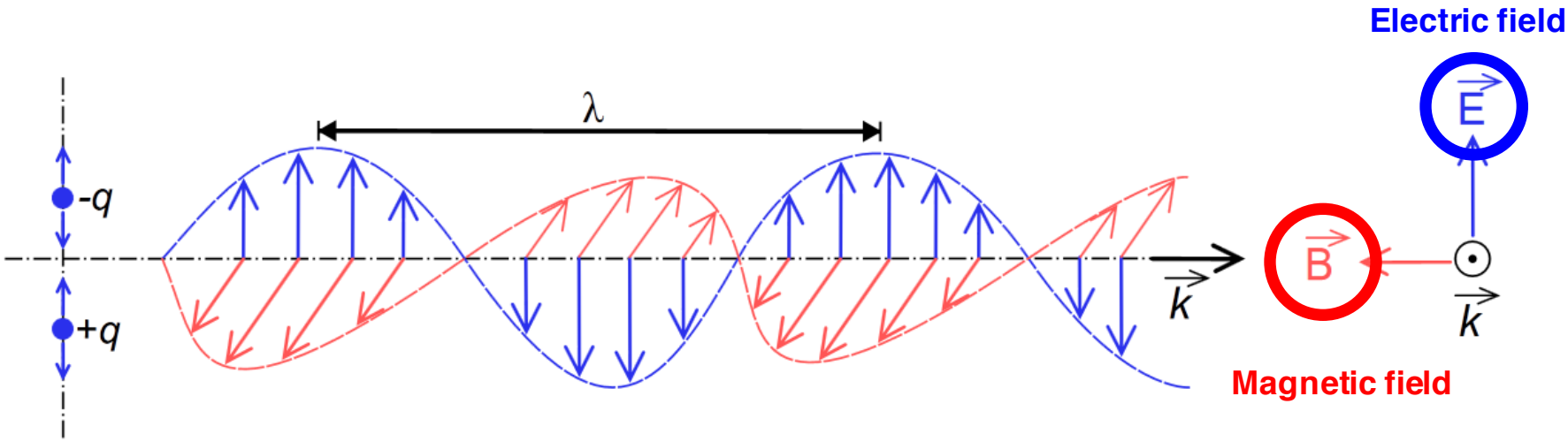

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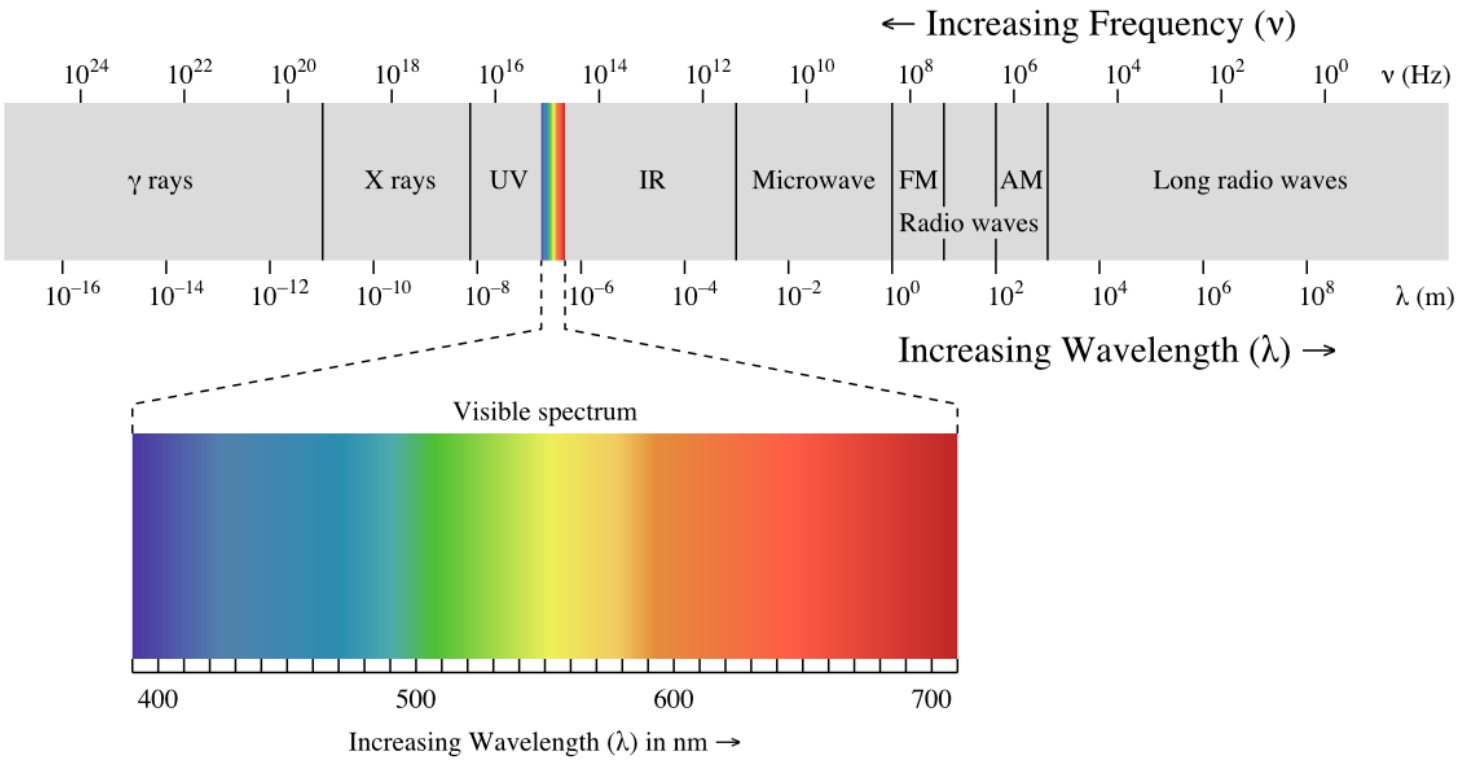

http://en.wikipedia.org/wiki/File:EM_spectrum.svg

Important Facts

C = 299,792,458 m/s **(In 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

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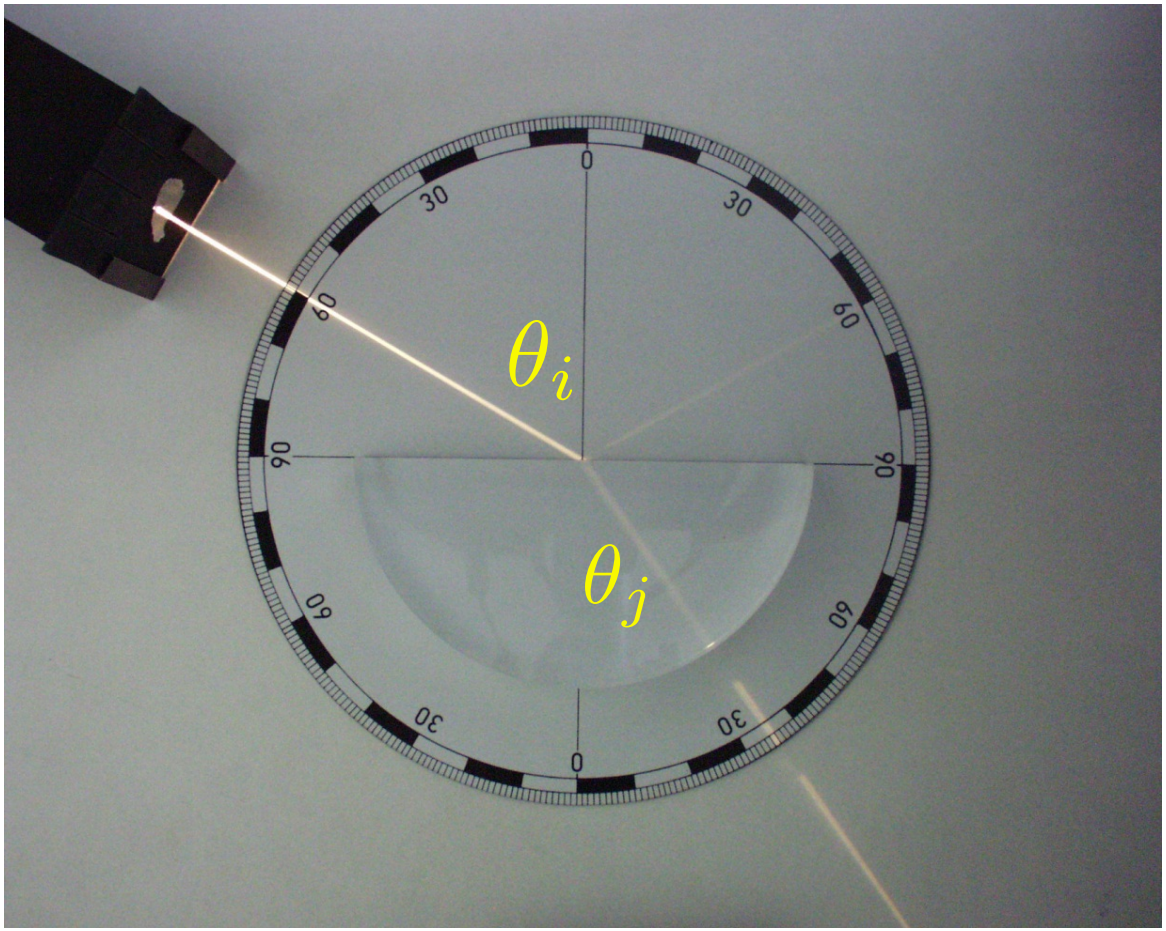
Explains refraction ! & total internal reflection

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

Refraction



$$\frac{\sin(\theta_j)}{\sin(\theta_i)} = \frac{v_j}{v_i}$$

Refractive Index

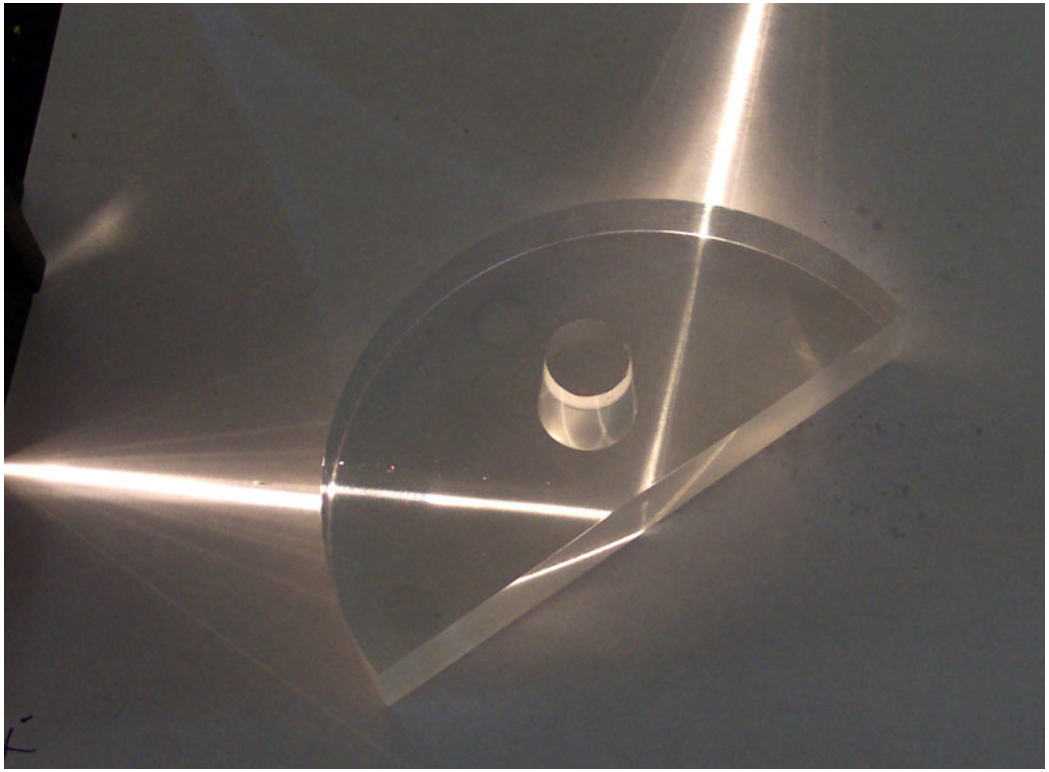
$$\eta_j = \frac{c}{v_j}$$

Snell's Law

$$\eta_j \sin(\theta_j) = \eta_i \sin(\theta_i)$$

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

Total Internal Reflection

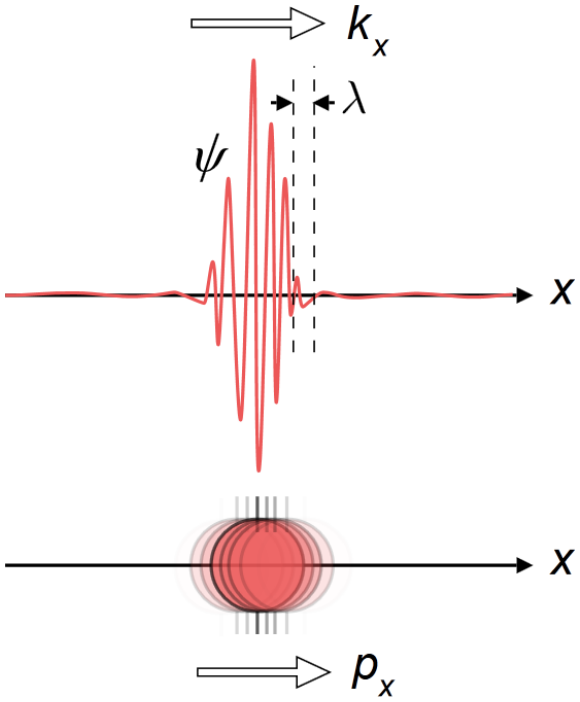


When Light travels from denser medium to a lighter medium, the incident angle above a **critical** angle may cause when:

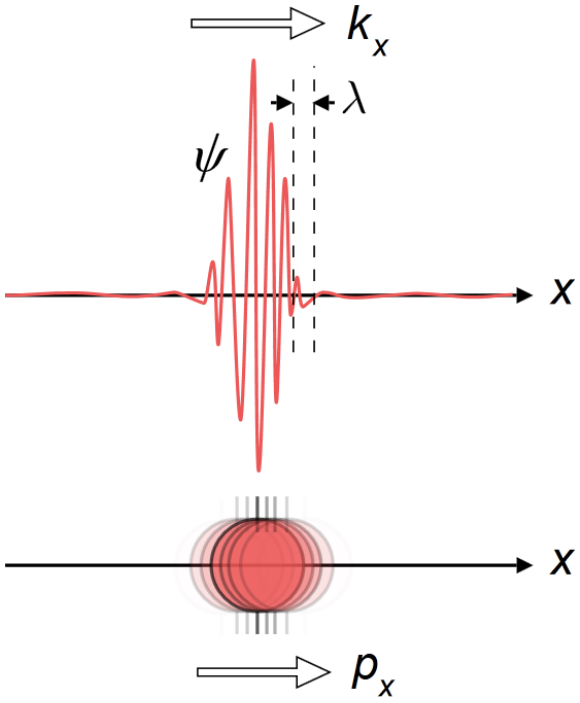
$$\sin\theta_j > 1.0$$

$$\theta_{critical} = \arcsin\left(\frac{n_j}{n_i}\right)$$

Wave Particle Duality



Wave Particle Duality



Assume Particle !

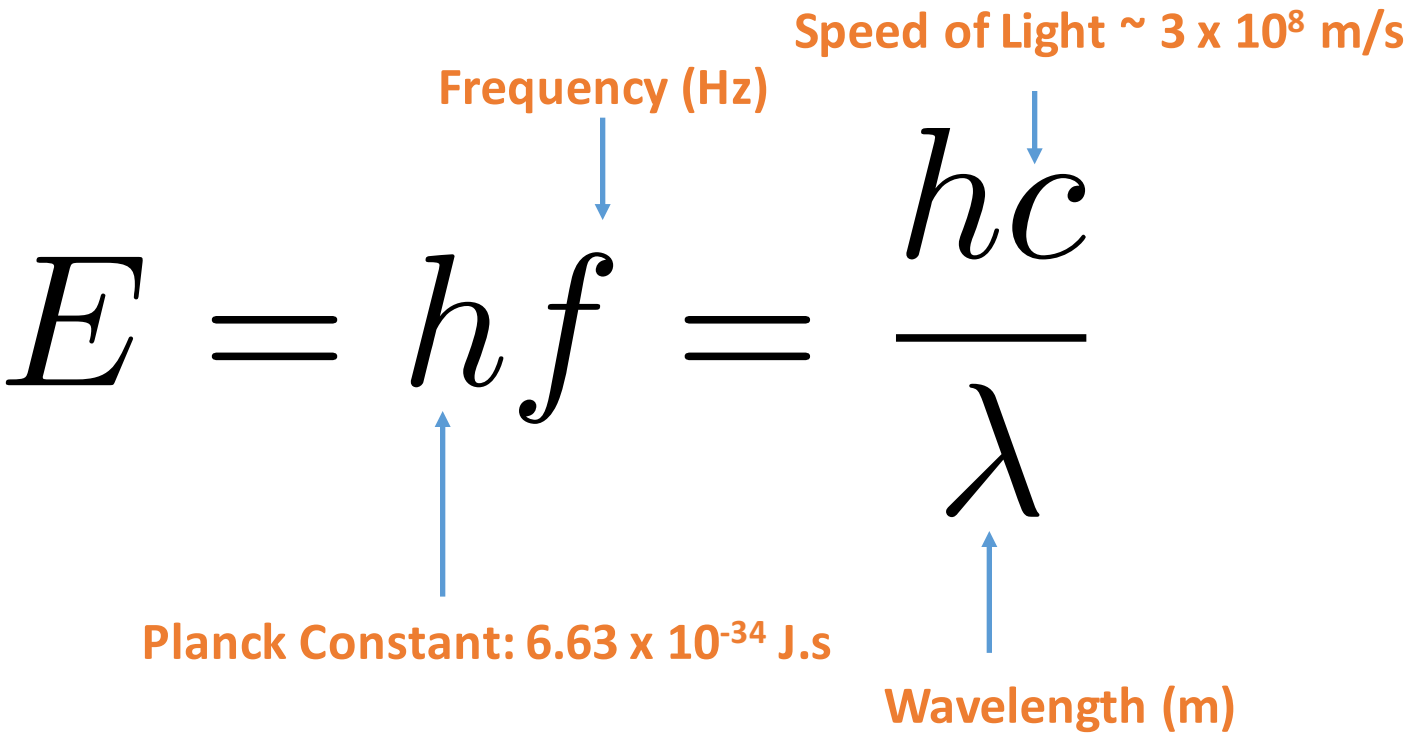
What have we lost ?

- Diffraction
- Polarization
- Interference

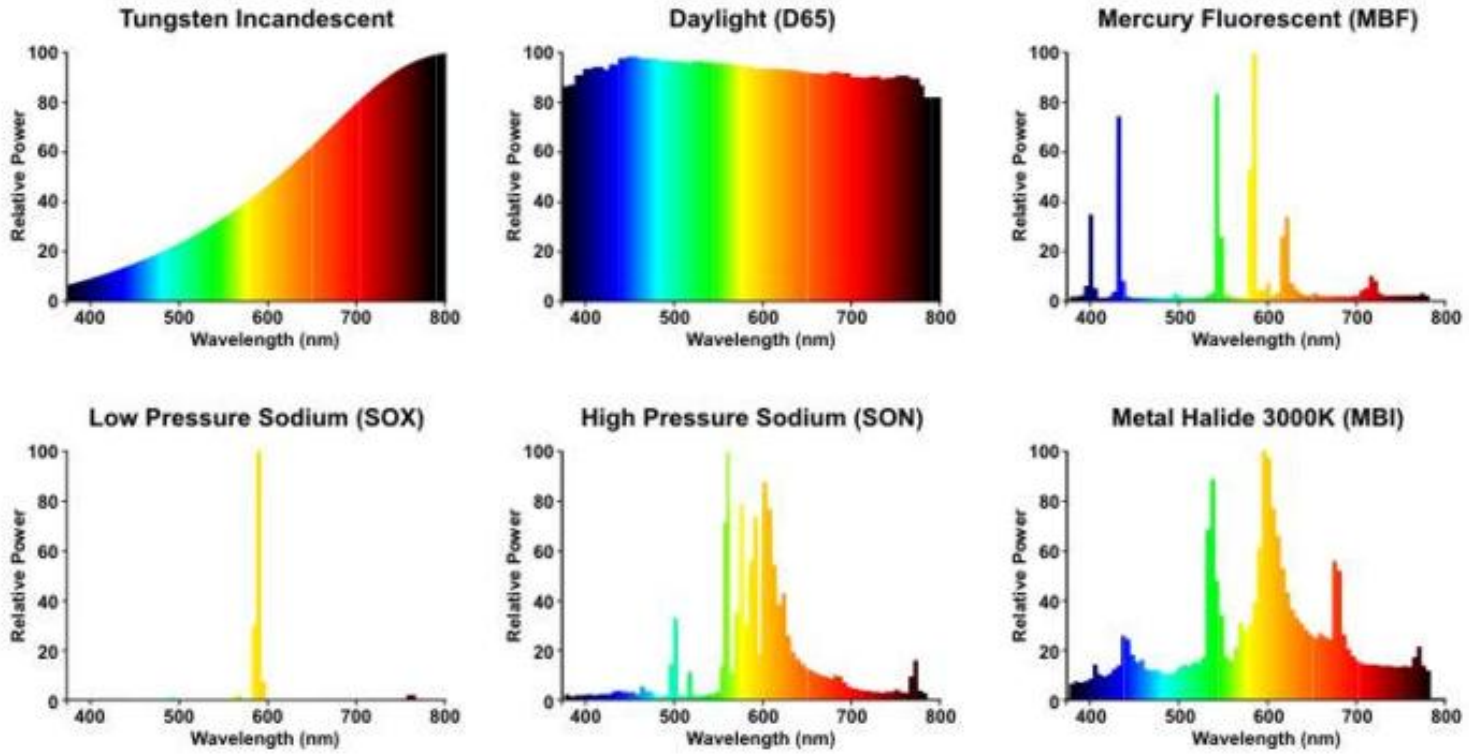
Photon [foh-ton]:

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

Energy Carried by a Photon



Spectral Power Distribution

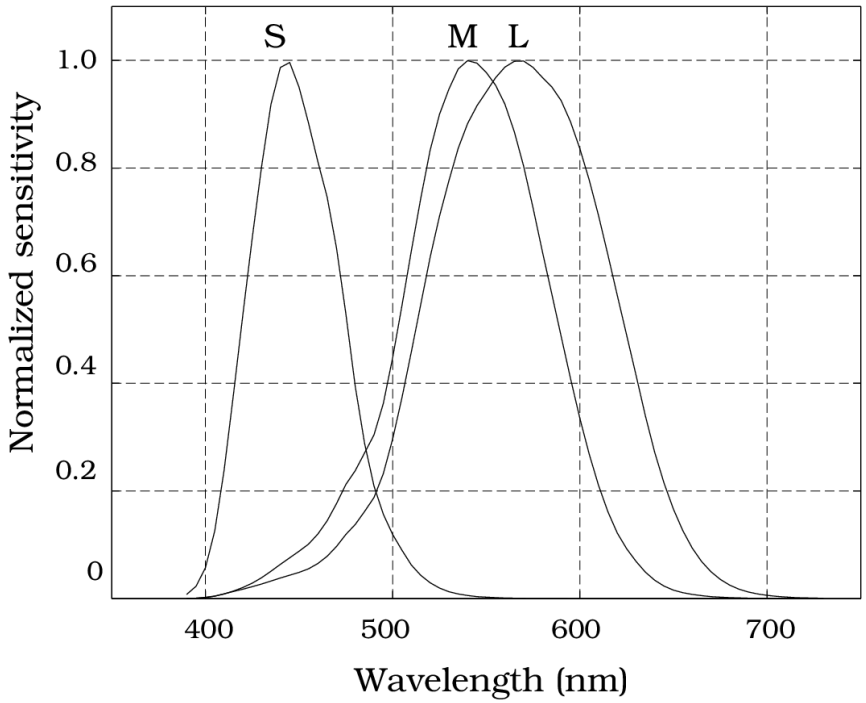


Intuitively: Photons for each wavelength can be counted to give a histogram

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

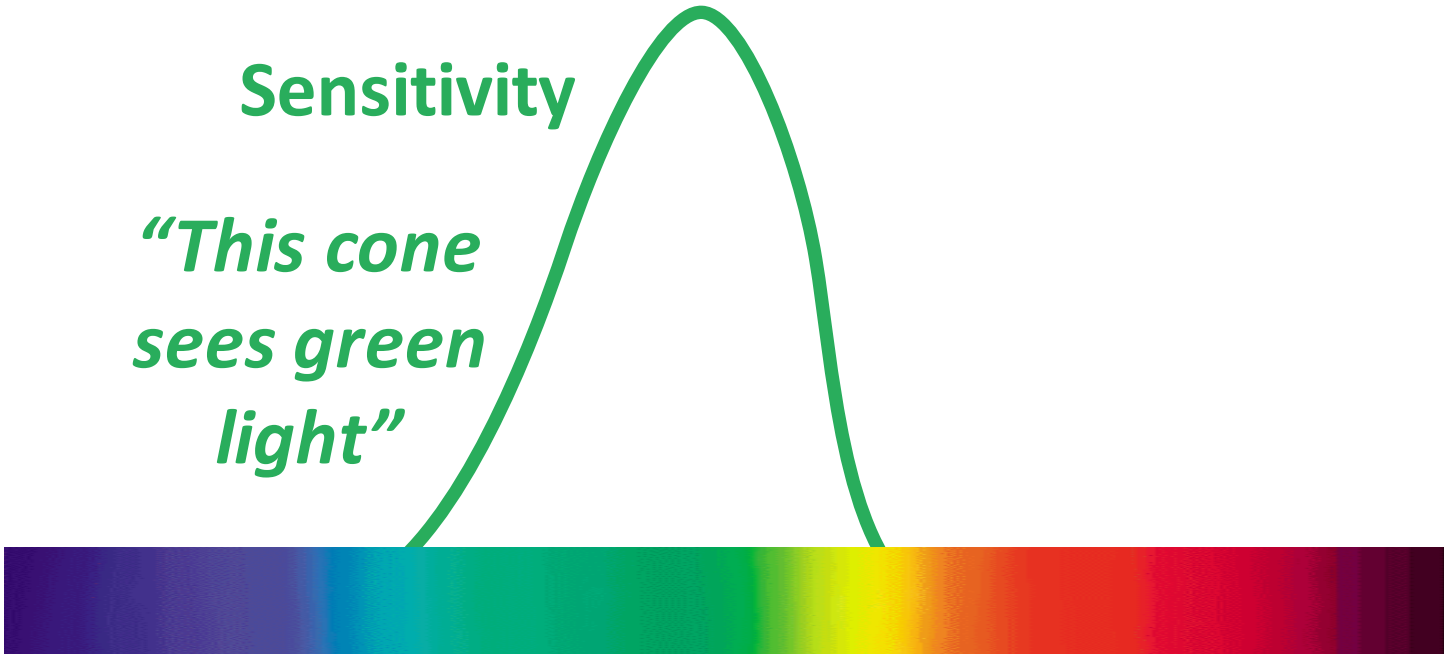
Colors

Types of Cones



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

Measuring Light Perception



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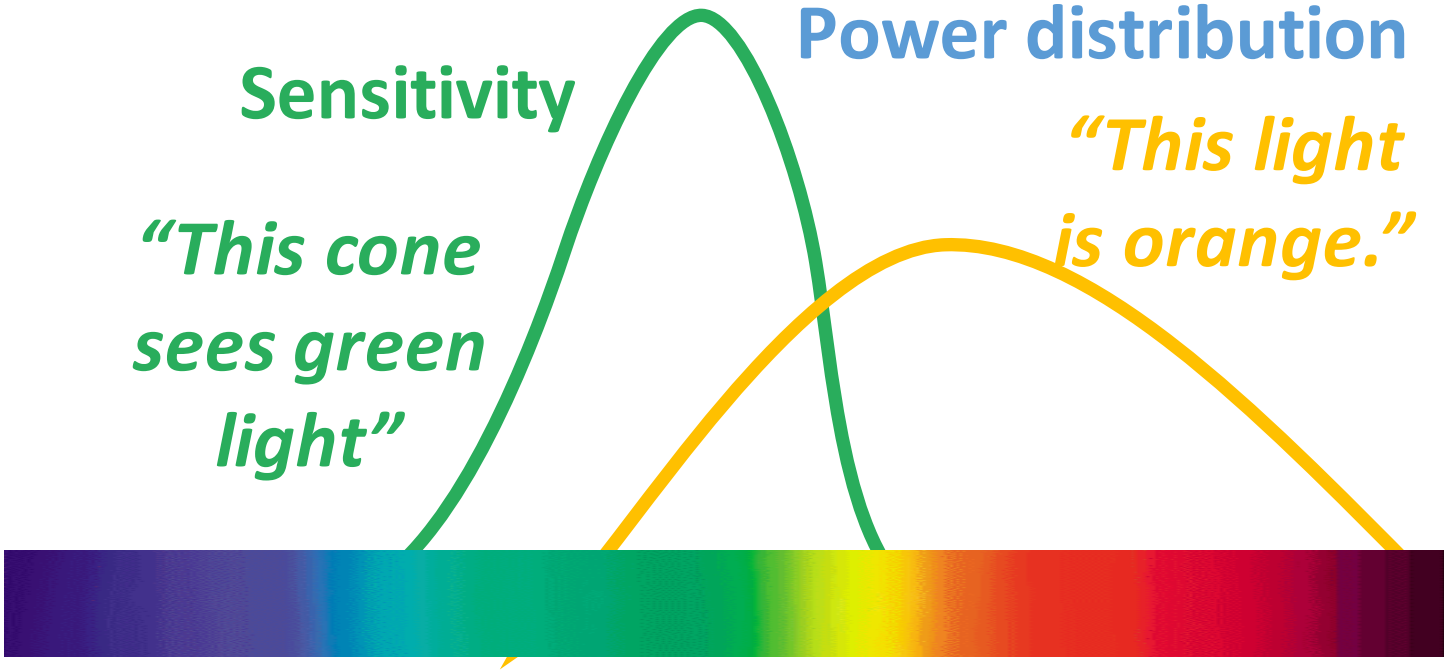

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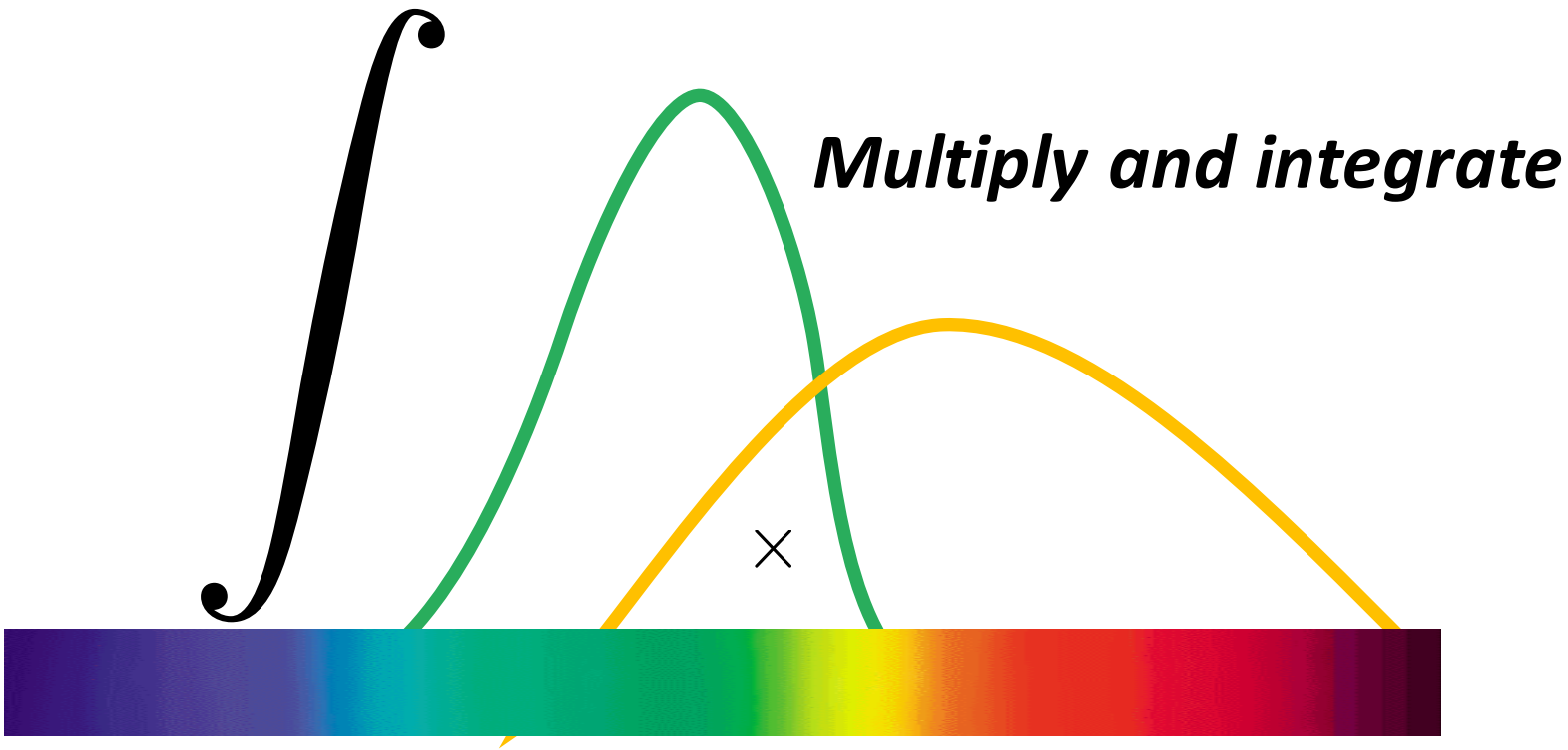

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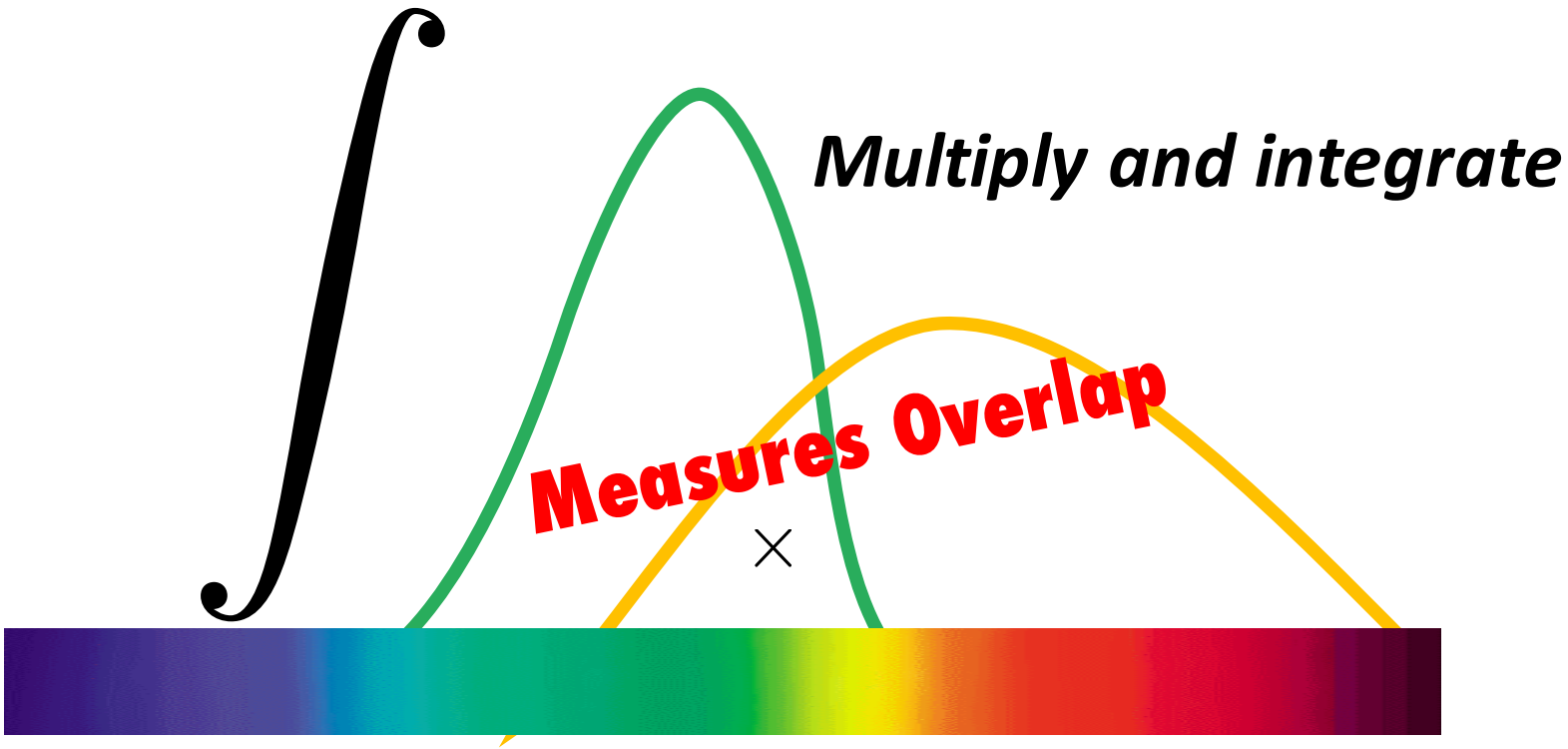


Cone Responses

Power distribution

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

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

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

Cone Responses

Sensitivity

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

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

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

Cone Responses

Tristimulus values

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

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

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

Conclusion

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

Conclusion

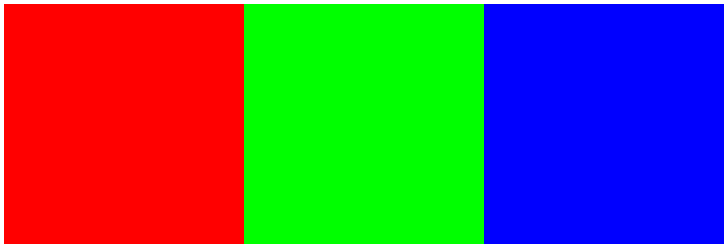
Cones are not single-wavelength detector

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

Metamers [met-uh-mers]

Spectral compositions that create the same tristimulus values.

Implication for Displays

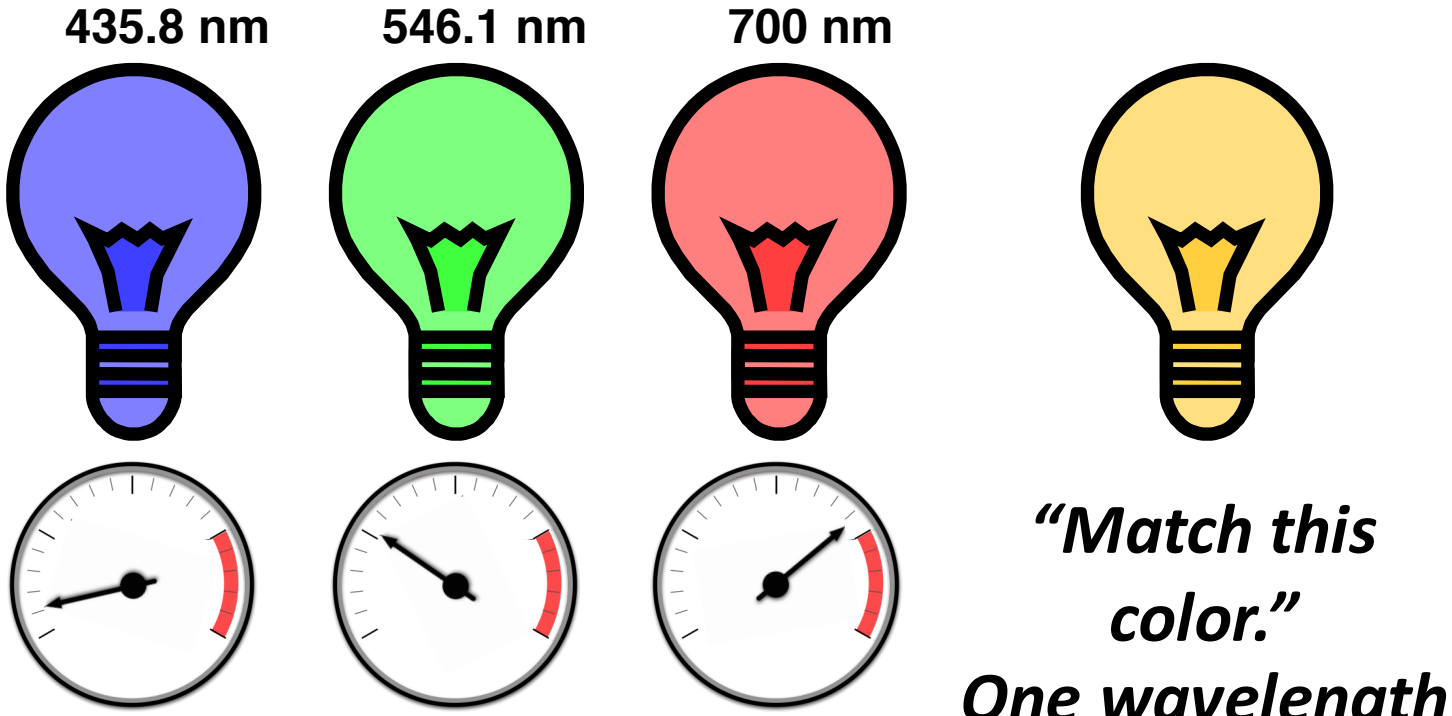


We can simulate visual effects of any wavelength by stimulating cones independently.

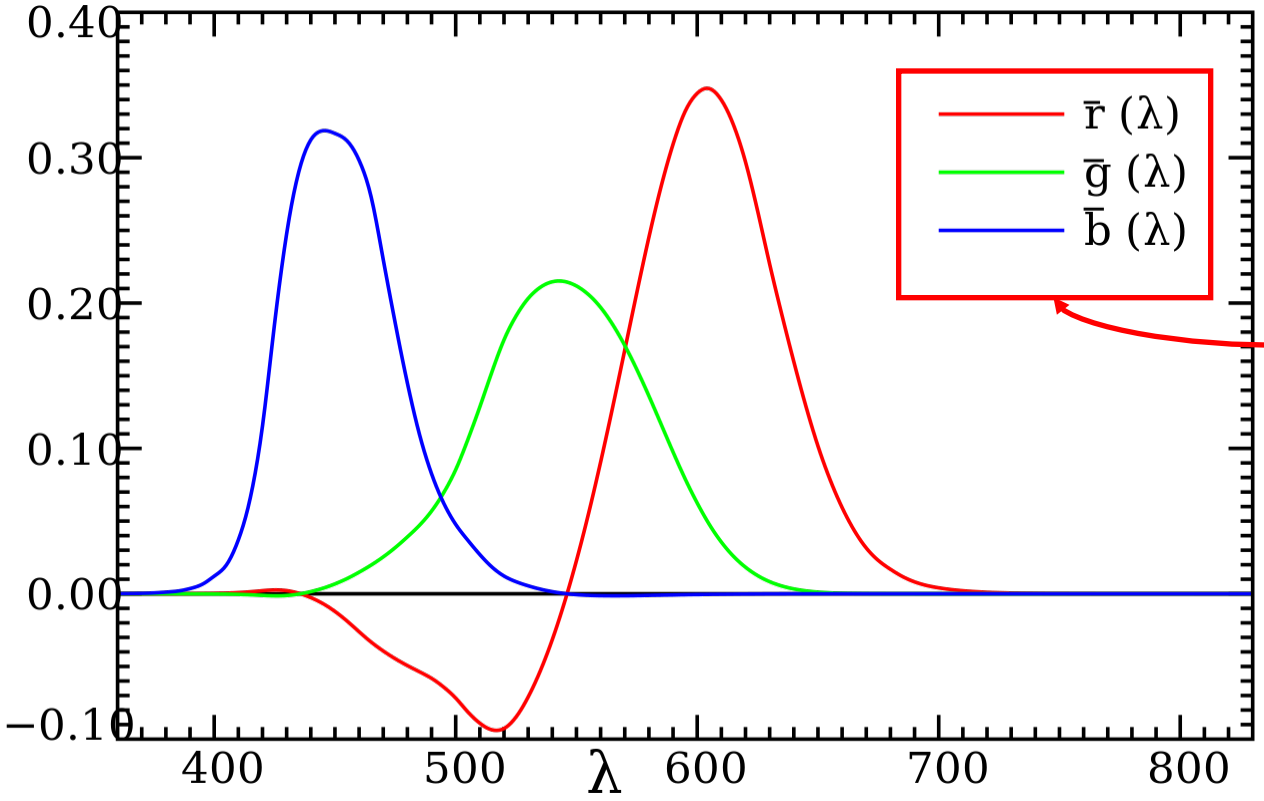
CIE Primaries

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

Color Matching Experiments



CIE RGB Color Matching



Spectral Tristimulus Values

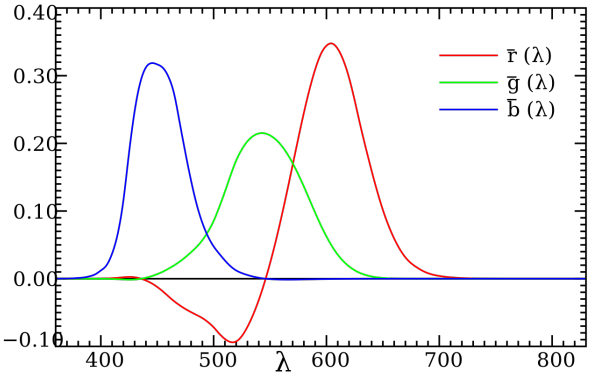
http://en.wikipedia.org/wiki/CIE_1931_color_space

CIE RGB Tristimulus Values

$$R = \int_{\lambda} \phi(\lambda)\bar{r}(\lambda)d\lambda$$

$$G = \int_{\lambda} \phi(\lambda)\bar{g}(\lambda)d\lambda$$

$$B = \int_{\lambda} \phi(\lambda)\bar{b}(\lambda)d\lambda$$



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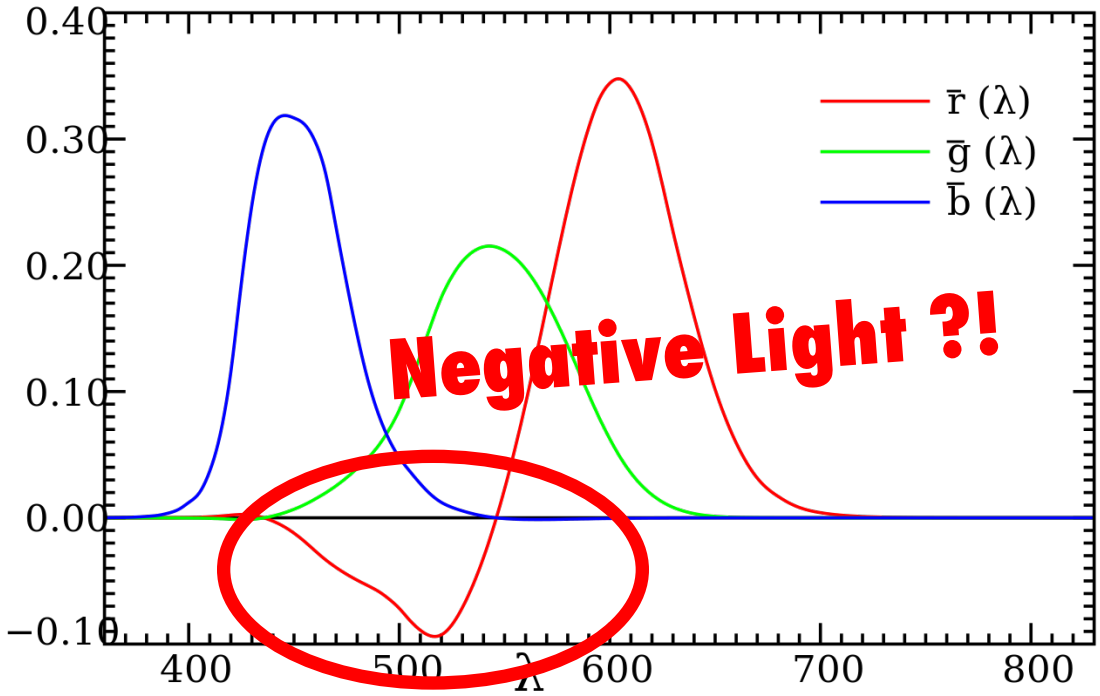

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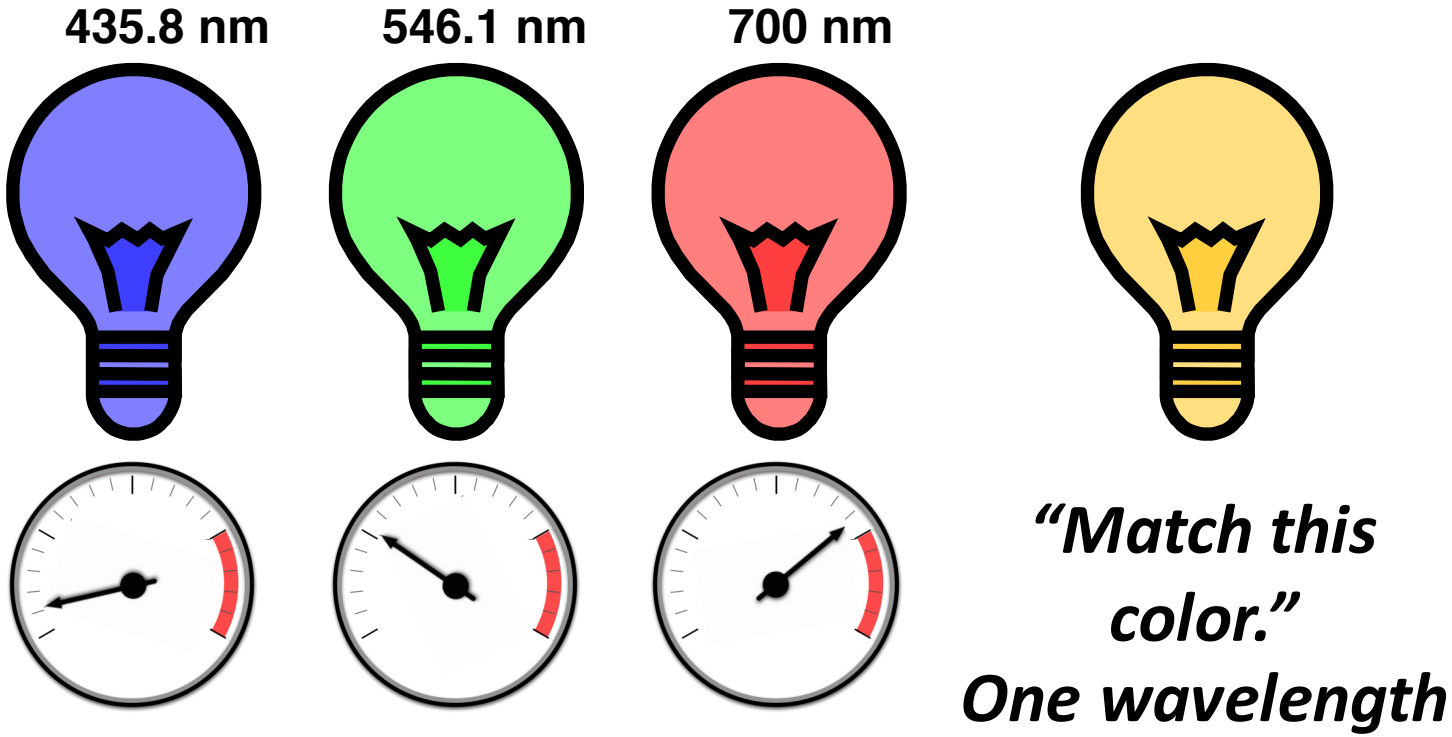
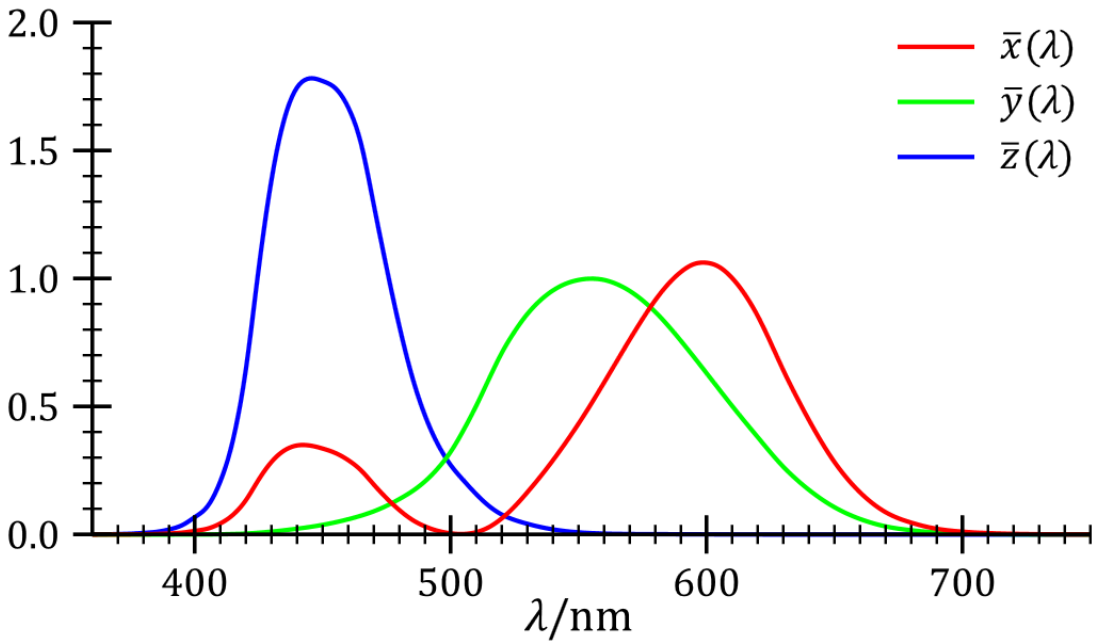


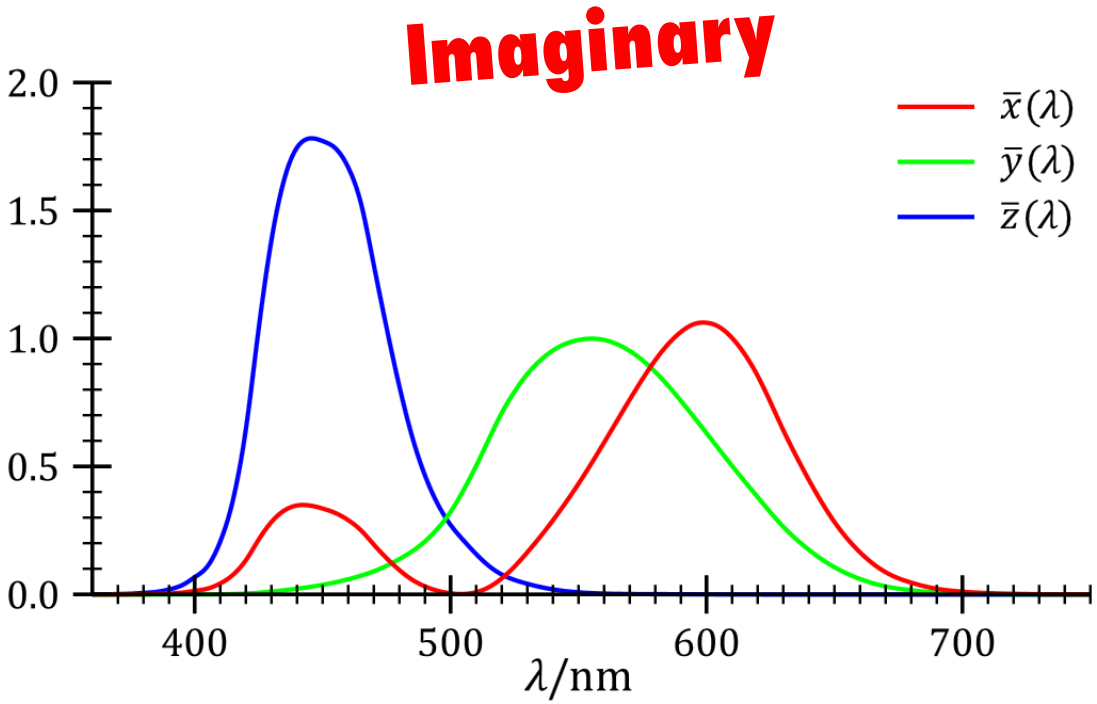
How do you do "Negative Light" ?

CIE XYZ



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

CIE XYZ



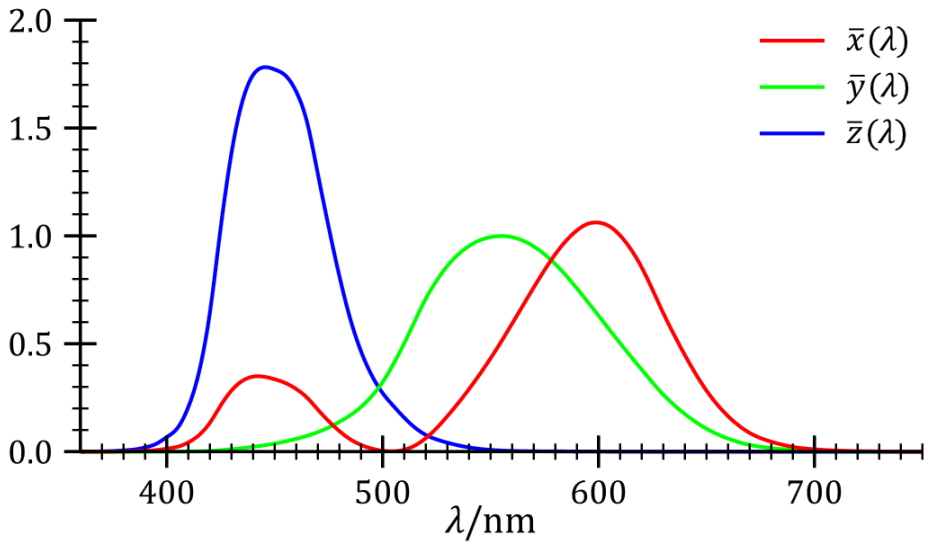
http://upload.wikimedia.org/wikipedia/commons/8/8f/CIE_1931_XYZ_Color_Matching_Functions.svg

CIE XYZ Tristimulus

$$X = \int_\lambda \phi(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int_\lambda \phi(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int_\lambda \phi(\lambda)\bar{z}(\lambda)d\lambda$$



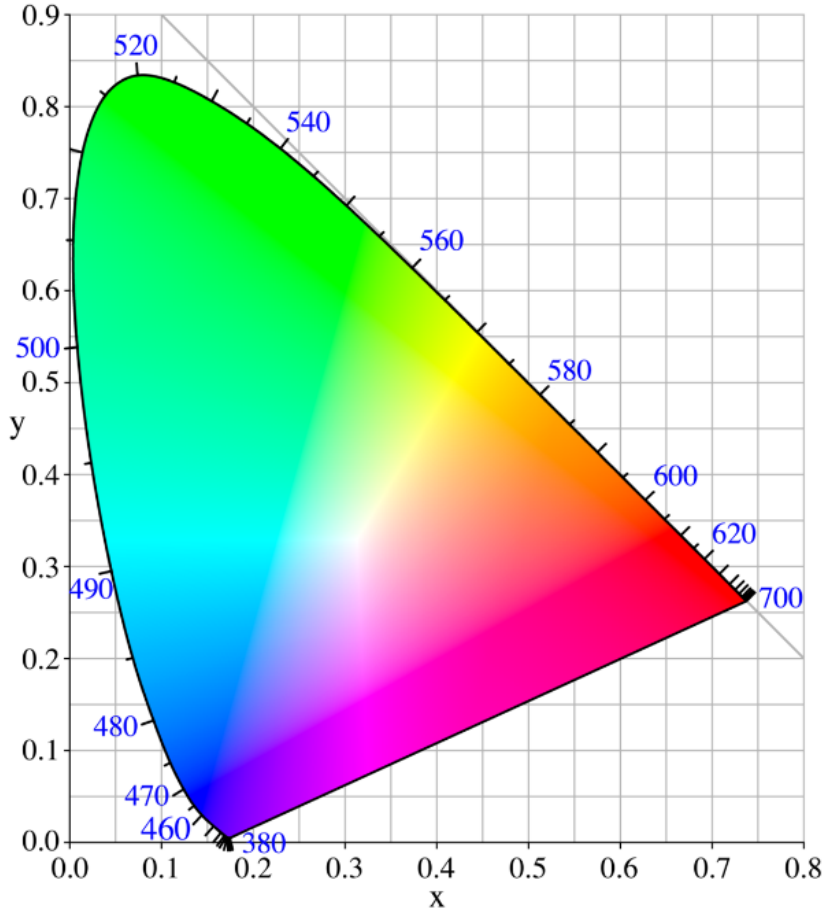
Developed in 1931

CIE RGB to XYZ Conversion

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Positive for visible wavelengths

Chromaticity Diagram



Projection of X,Y,Z on the plane

$$X + Y + Z = 1$$

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

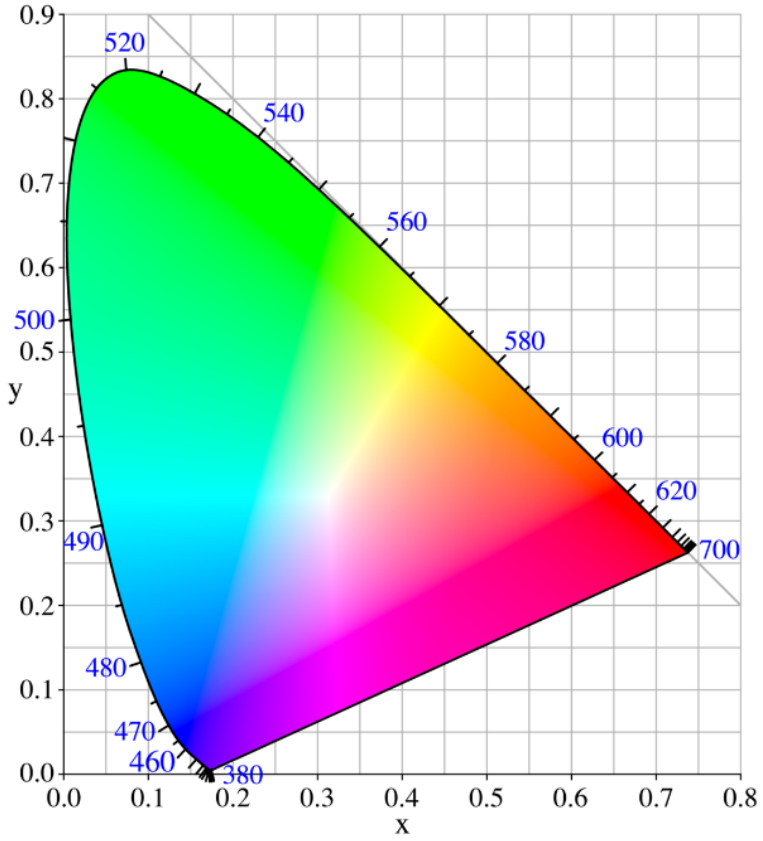
$$y = \frac{Y}{X + Y + Z}$$

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

z is redundant because

$$z = 1 - x - y$$

Chromaticity Diagram

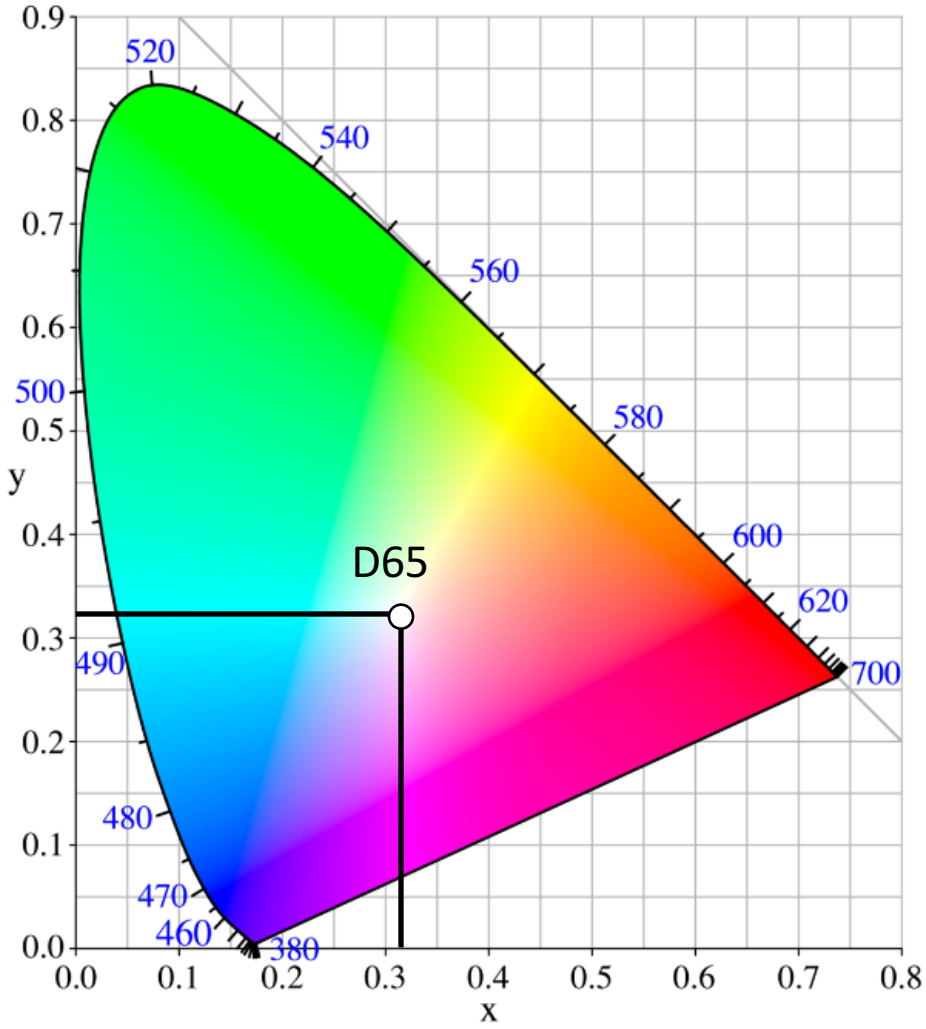


Given x,y and one tristimulus value (typically Y, hence named CIE xyY) one can recover X,Y and Z like the following

$$X = \frac{x}{y}Y$$

$$Z = \frac{1-x-y}{y}Y$$

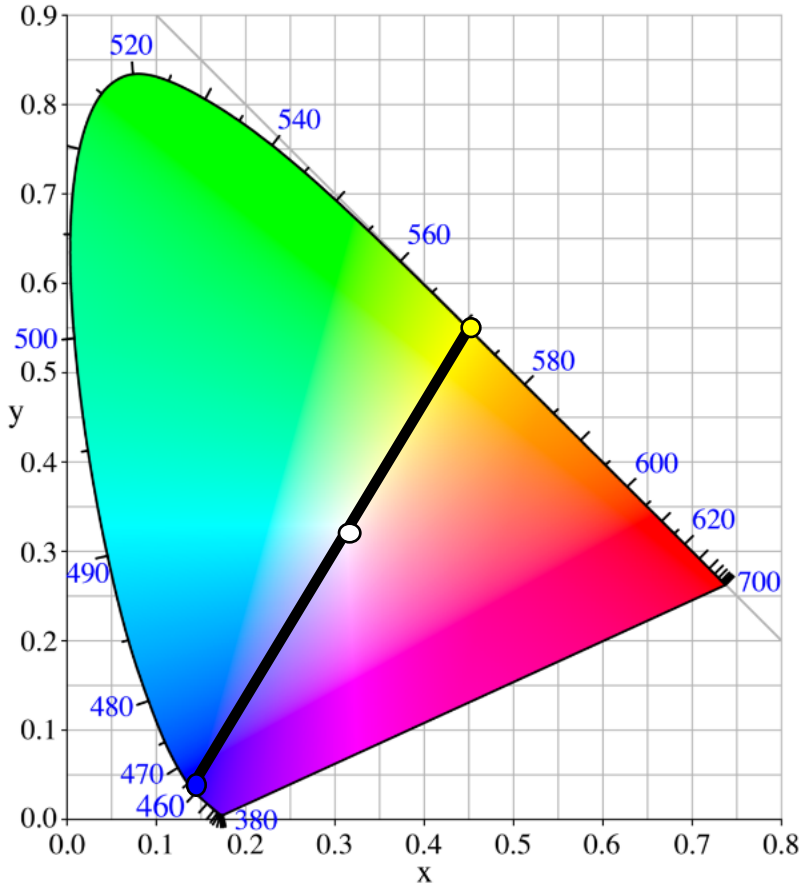
Chromaticity Diagram: D65



D65 – Mid day light
Corresponds to 6500K,
(actually ~6504K.)

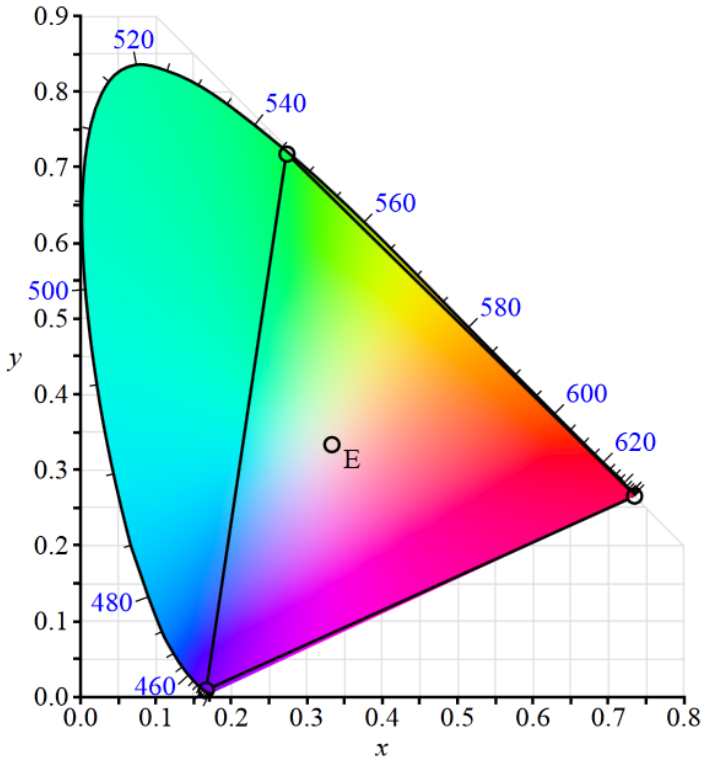
(x,y) = 0.3128, 0.3290)

Chromaticity Diagram: Complementary Color



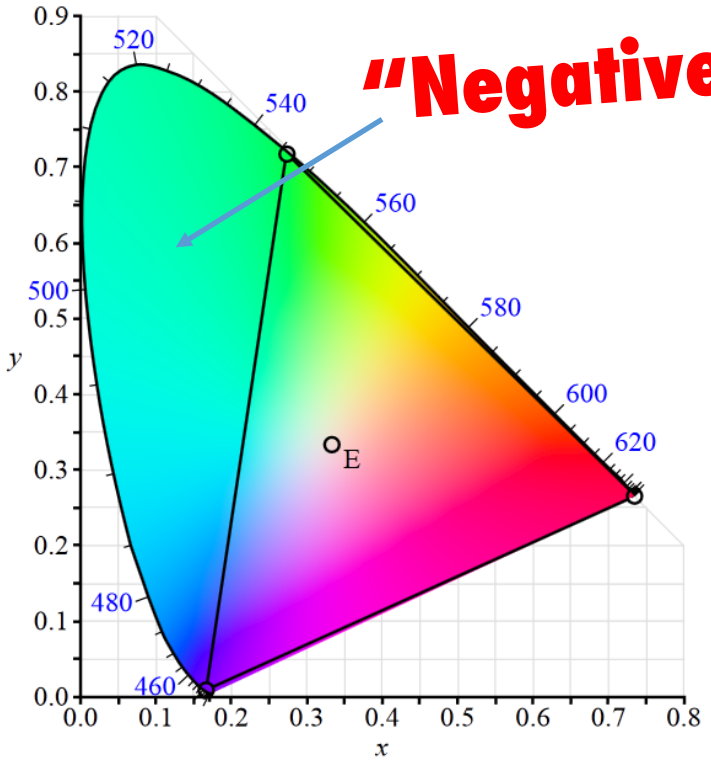
Color A and B are complementary
If Combine(A,B) can produce
White Or Gray

Chromaticity Diagram



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

Chromaticity Diagram



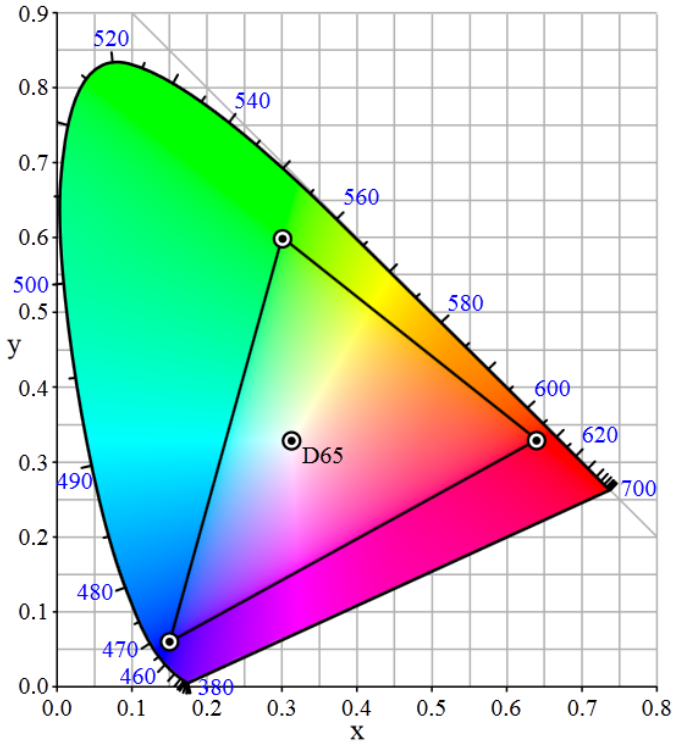
"Negative Light"

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

Gamut [gam-uht]:

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

Describing a Display: HDTV

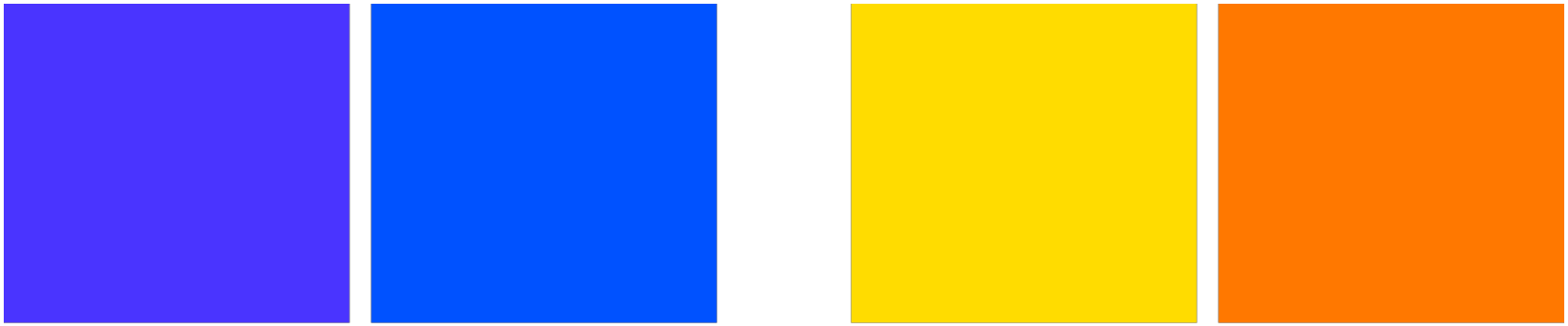


Vertices are primaries, possibilities are inside triangle

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

Preception and Color Spaces

Perception of Color



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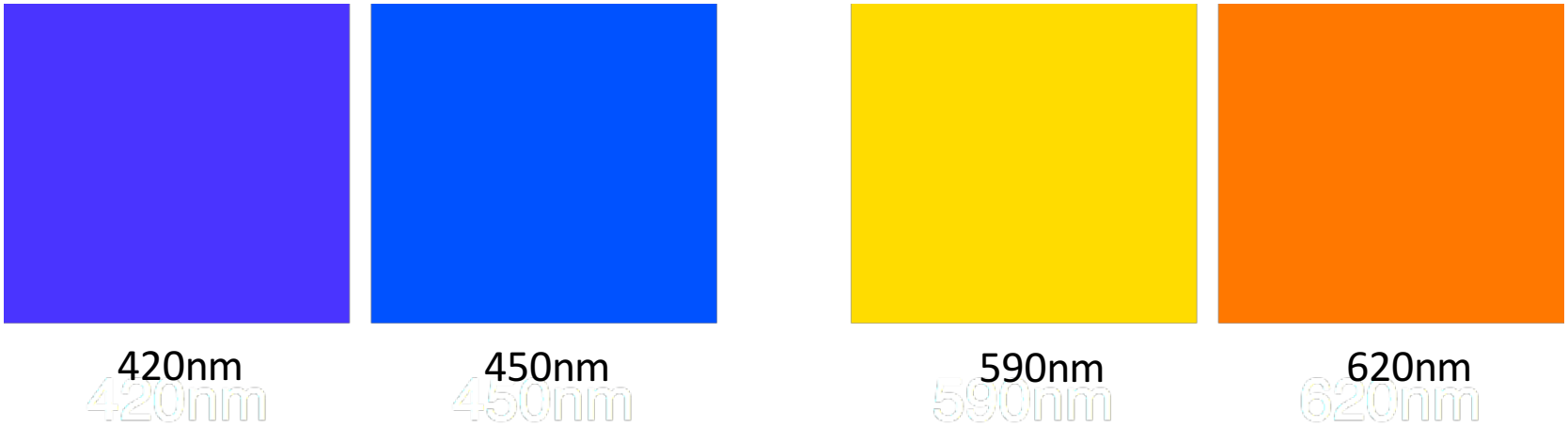


Human are not equally sensitive to all wavelengths

Perceptual Uniformity

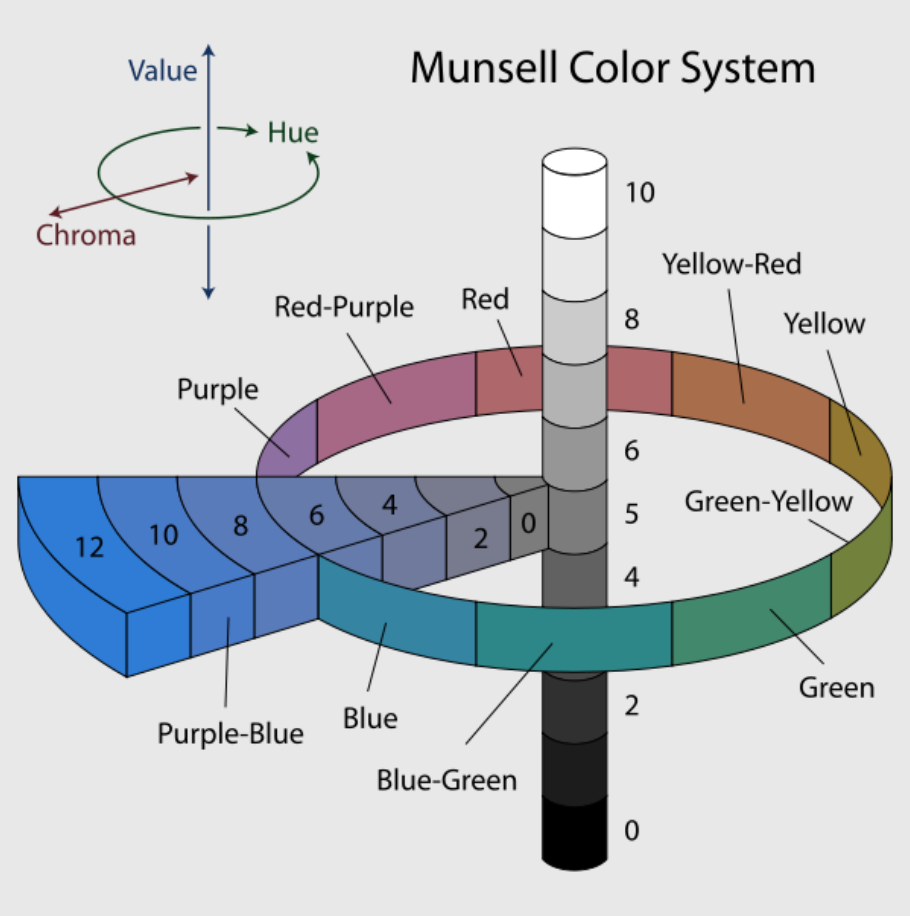
- A distance metric in a perceptually uniform color space would corresponds to the visual difference between colors as perceived by human.

Perceptual Uniformity

- A distance metric in a perceptually uniform color space would corresponds to the visual difference between colors as perceived by human.

Neither RGB nor XYZ are perceptually uniform !!

Perceptually Uniform: Munsell



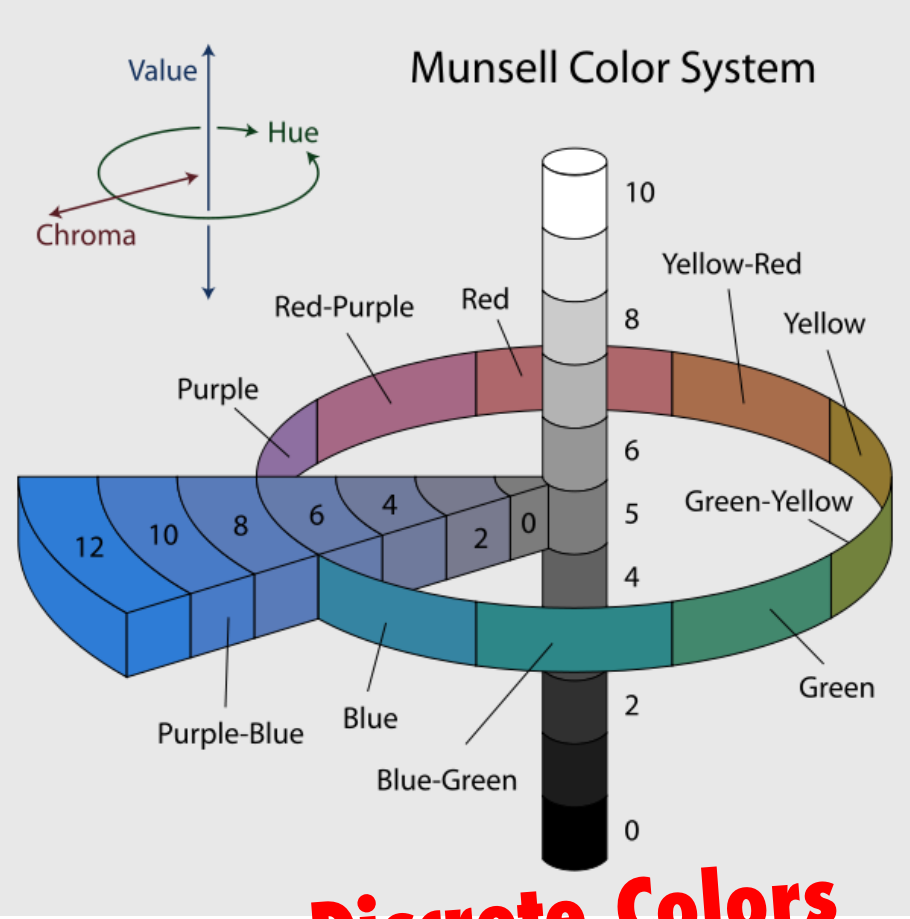
Hue
5 Primary Hues (R,Y,G,B,P)
5 Intermediate Hues (YR, GY, BG, PB, RP)
10 sub-steps = 100 Hues

Value
Black to White

Chroma
Purity of color

Colors on opposite sides of the hue circle can be added to produce gray.

Perceptually Uniform: Munsell



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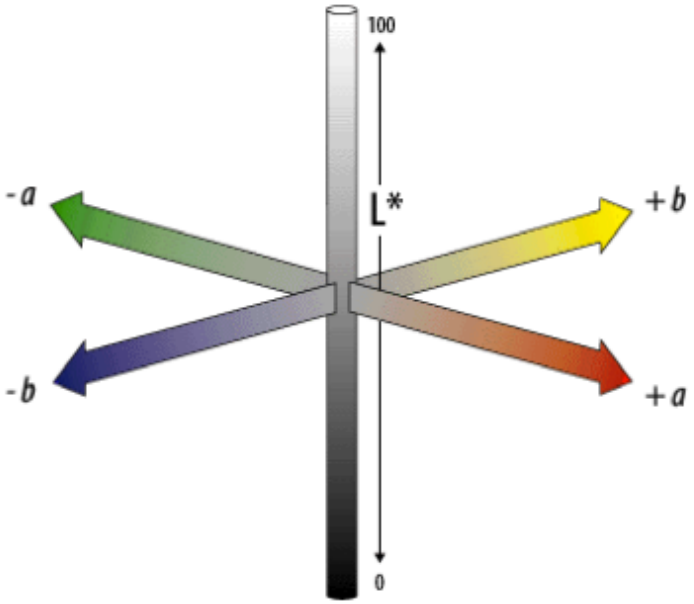
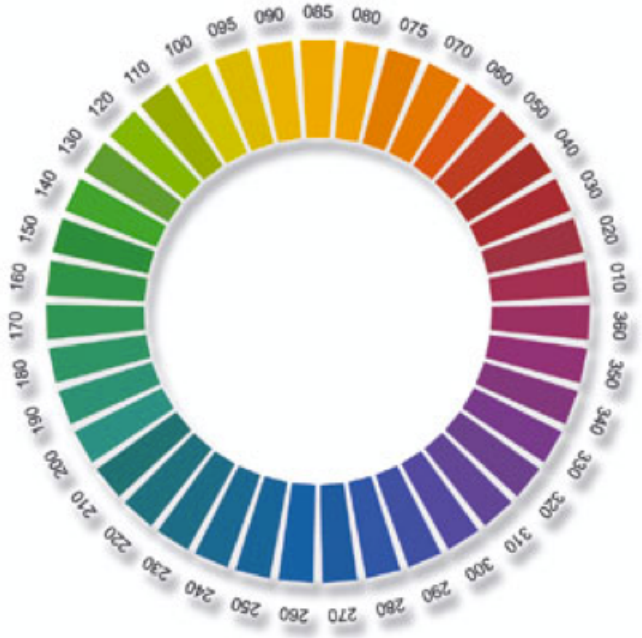
https://en.wikipedia.org/wiki/Munsell_color_system

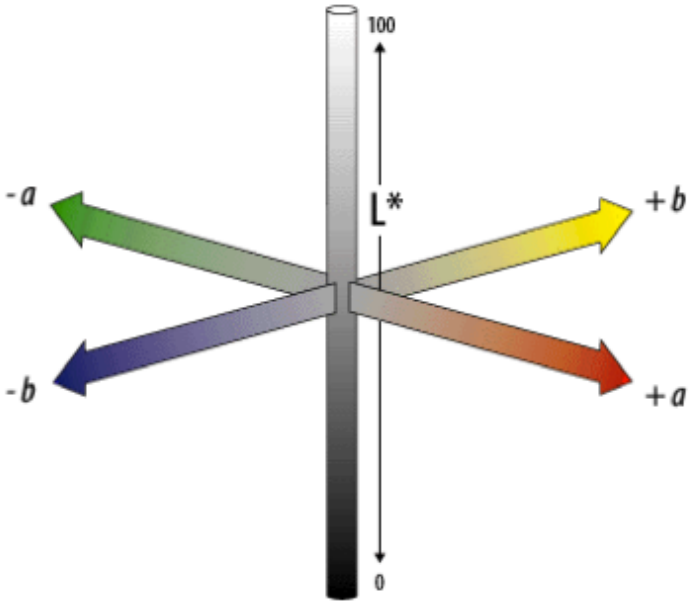
Perceptually Uniform: L*a*b

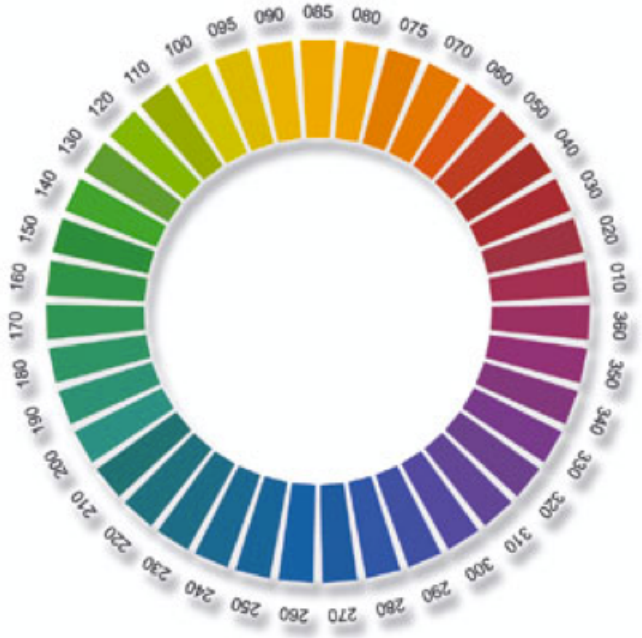




L: Luminance (0-100)
a,b: Color-opponent dimensions (-128..128)

Perceptually Uniform: L*a*b





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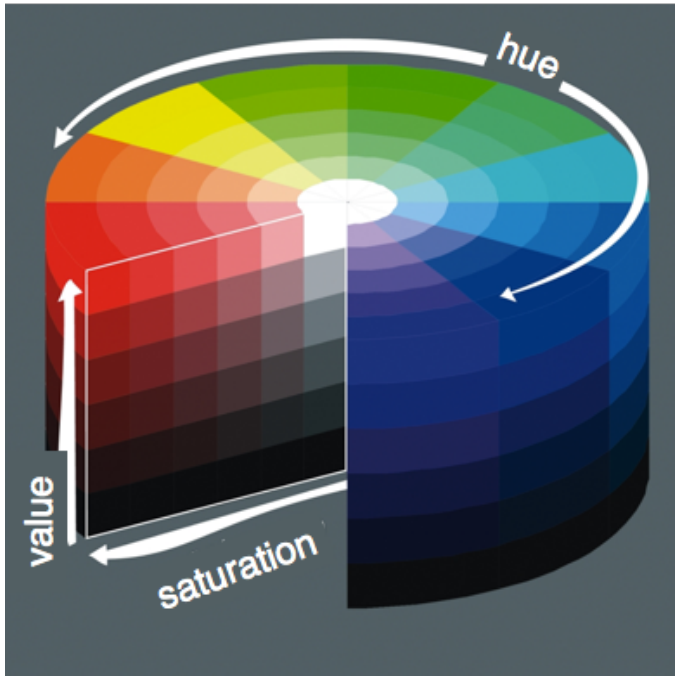
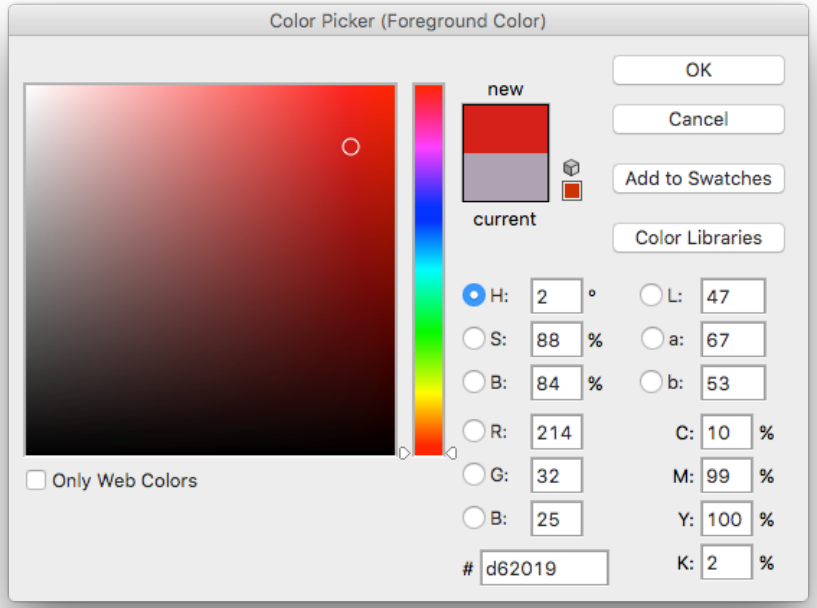
a,b: Color-opponent dimensions (-128..128)

Continuous Colors

Other spaces: HSV

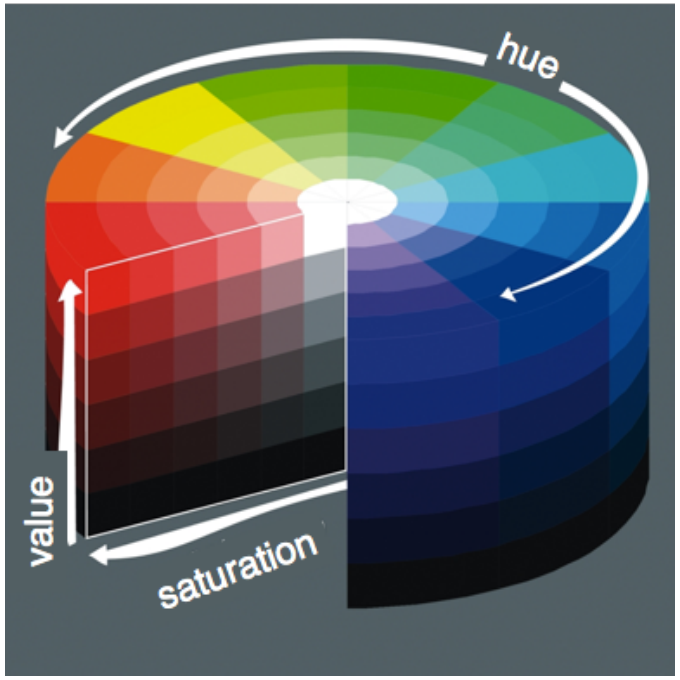


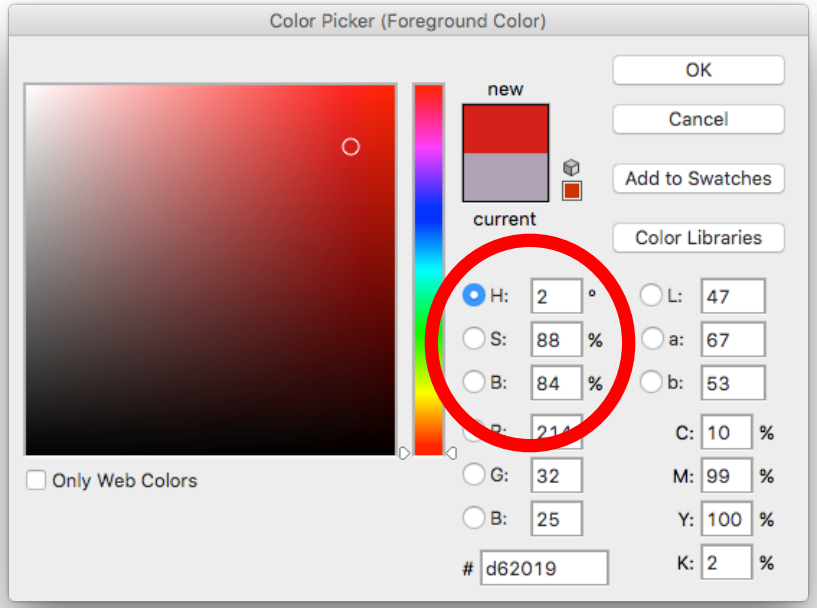


Photoshop color picker

HSV : Hue, Saturation, Value

Other spaces: HSV





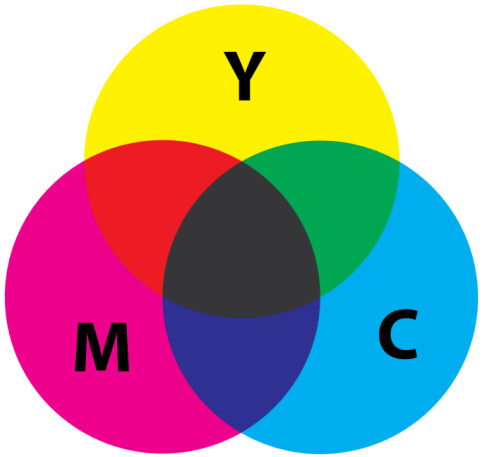
Photoshop color picker

HSV : Hue, Saturation, Value

Color Spaces So Far

Color Space	Continuous	Perceptually Uniform
RGB	Yes	No
XYZ	Yes	No
Munsell	No	Yes
L*a*b	Yes	Yes
HSV	Yes	No

Printing Color Space: CMY



Yellow = White – Blue
Cyan = White – Red
Magenta = White - Green

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

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

Other Spaces: CMYK

No black

Max black

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

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Introduction of Graphics and Imaging
Zahid Hossain

http://lighthouse8.com/wp-content/uploads/2012/08/true-colors.jpg