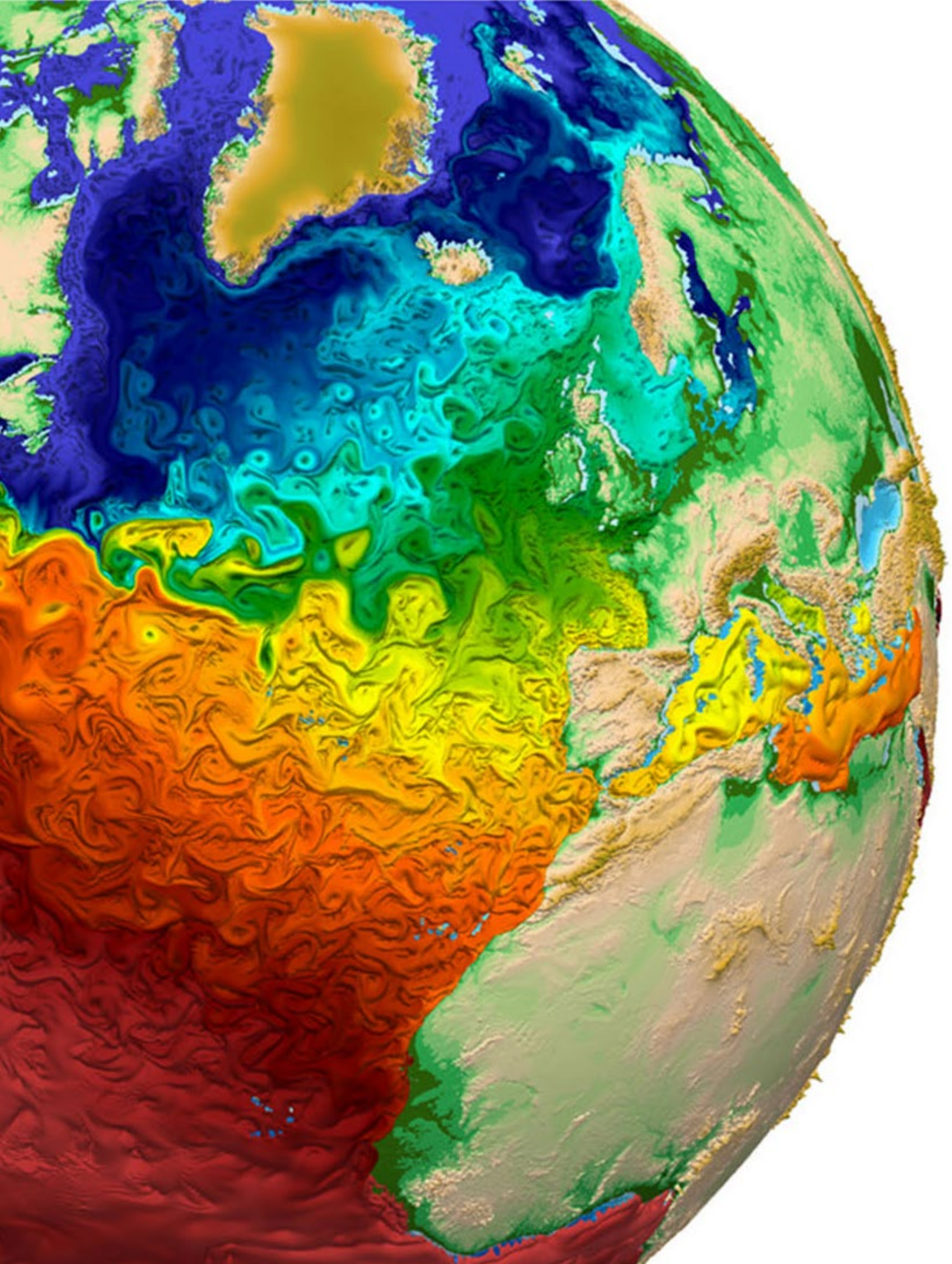

Perceptual Color Spaces

Scientific Visualization

Professor Eric Shaffer

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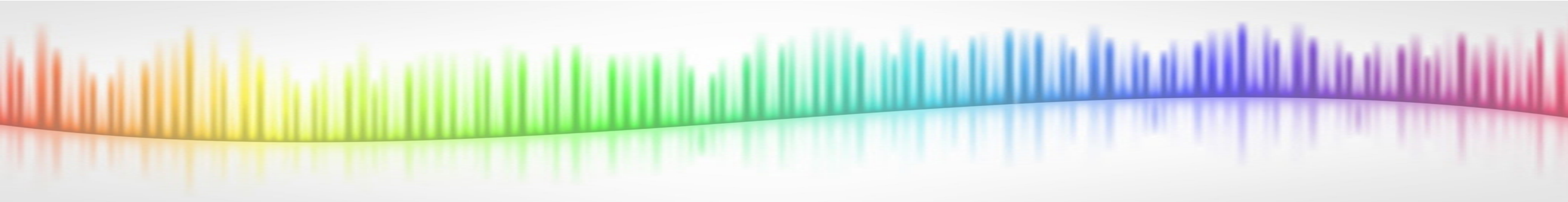
The Most Important Thing to Know About Color



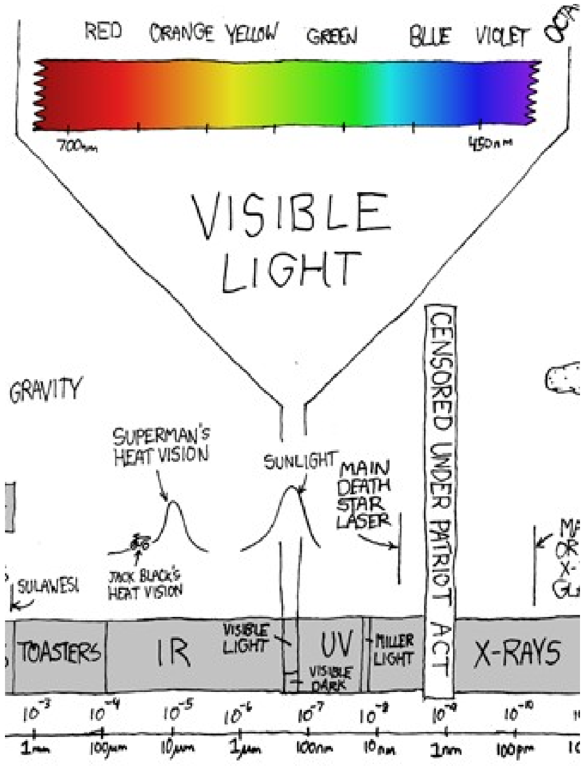
Color is a perceptual phenomenon

It is not a physical property of a material or of light

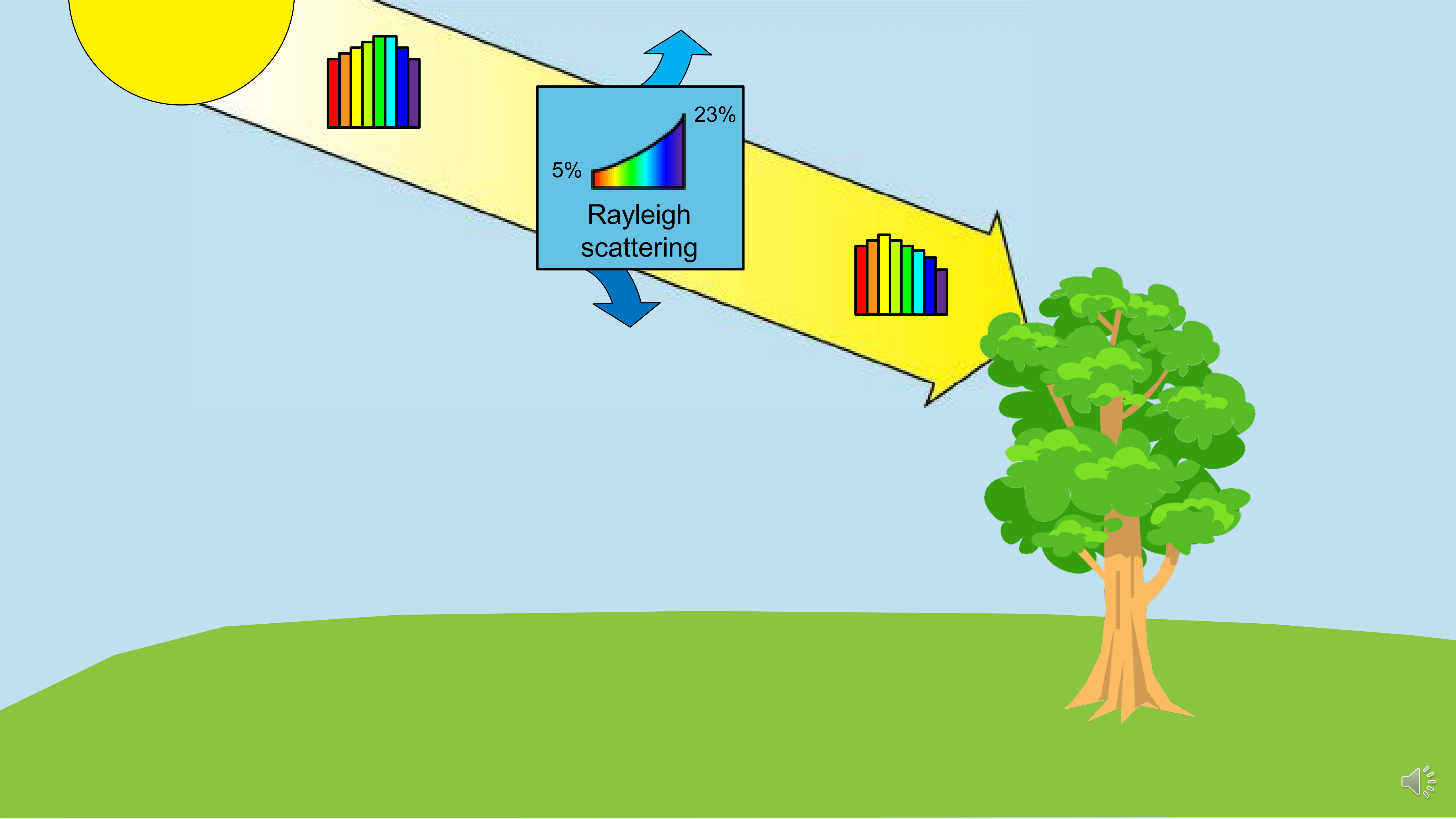
So, how does color perception work?

Light

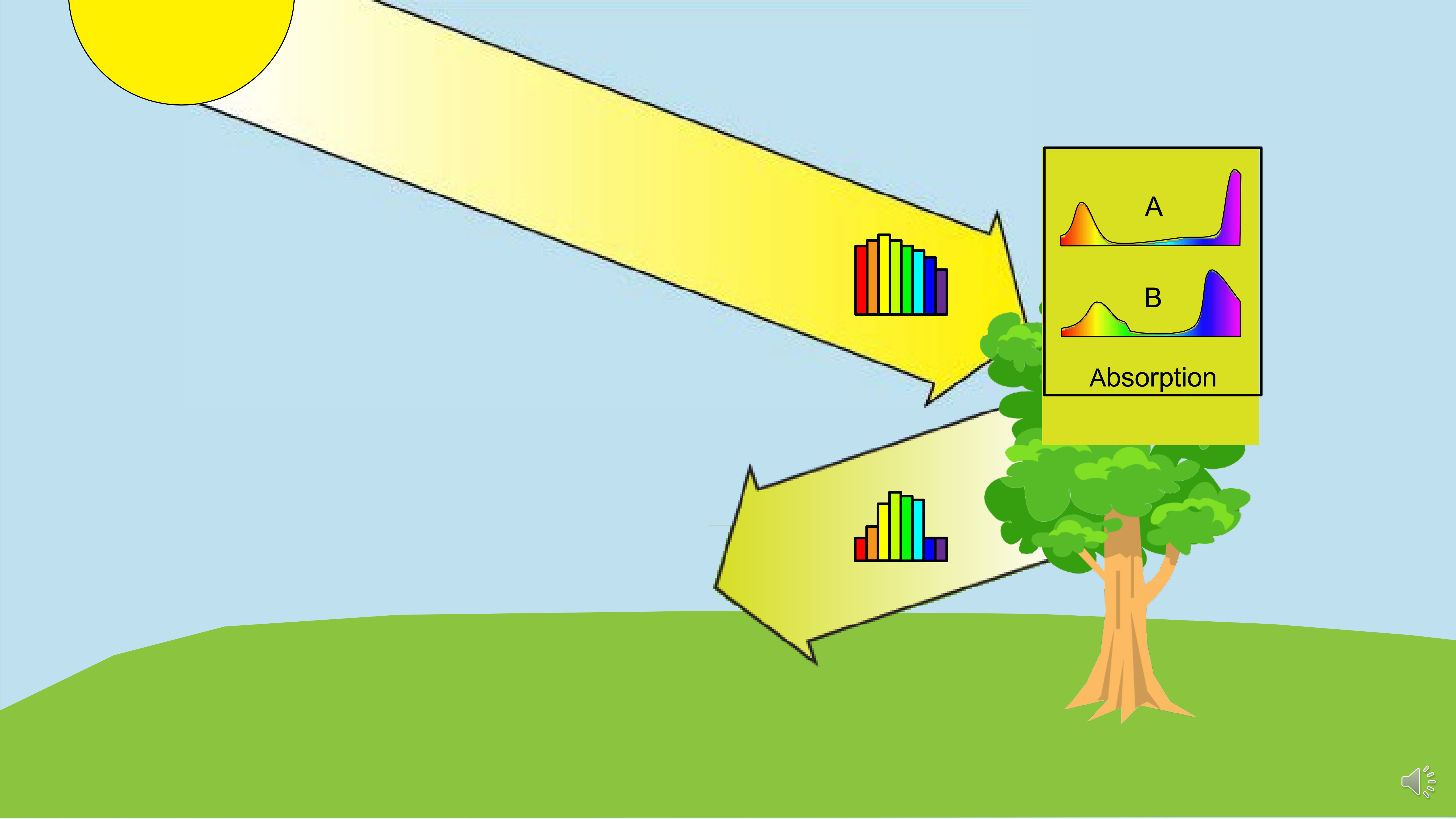
- Human vision senses energy in a portion of the electromagnetic spectrum
- Energy carried by photons
- The energy of each photon is proportional to its frequency
    - Frequency = inverse of wavelength
- The intensity of light is related to the number of photons received

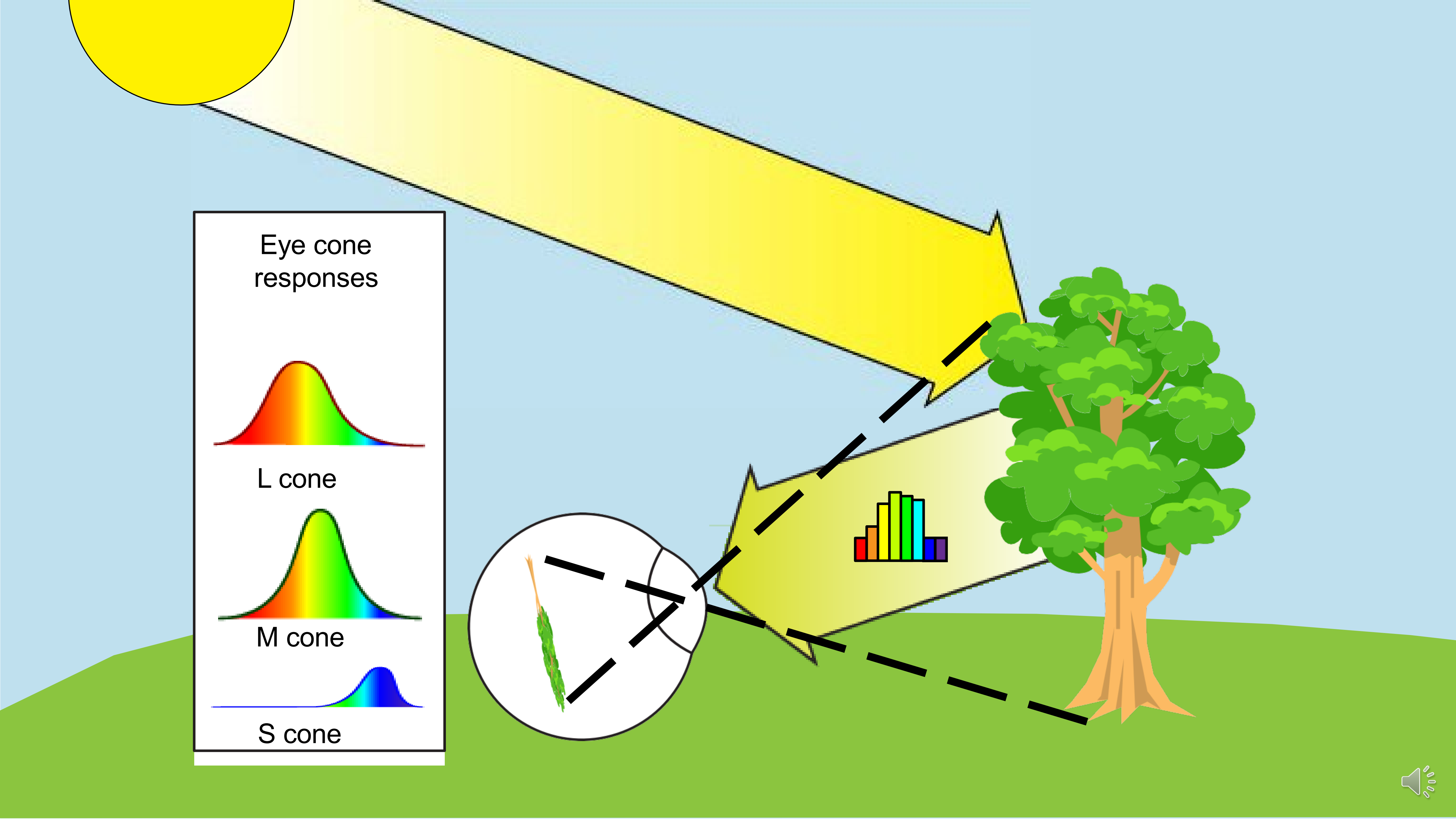


xkcd.com/273



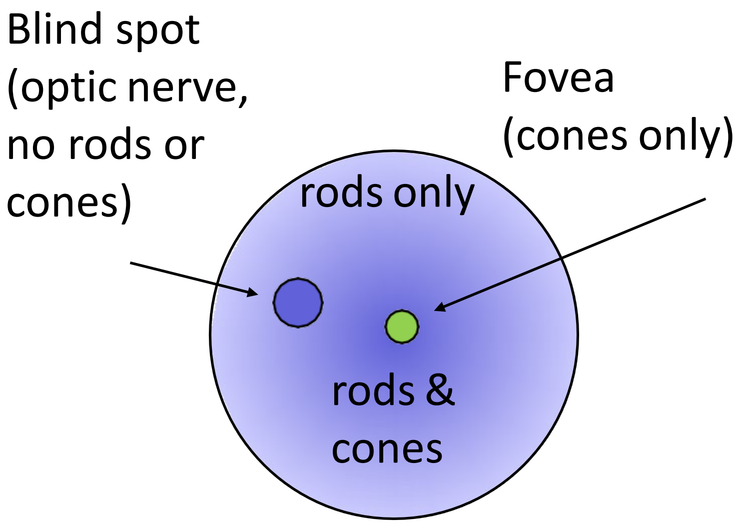
23%
5%
Rayleigh
scattering


A
B
Absorption


Eye cone
responses
L cone
M cone
S cone

Human Visual System: Rod and Cone Cells

- Rods measure intensity
  - 80 million
  - denser away from fovea
  - astronomers learn to glance off to the side of what they are studying
  - sensitive, shut down in daylight
- L,M and S cones
  - 5 million total
  - 100K – 325K cones/mm^2 in fovea
  - 150 hues
- Combined
  - 7 million shades



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Cone Cell Response

V(λ) is the luminosity function

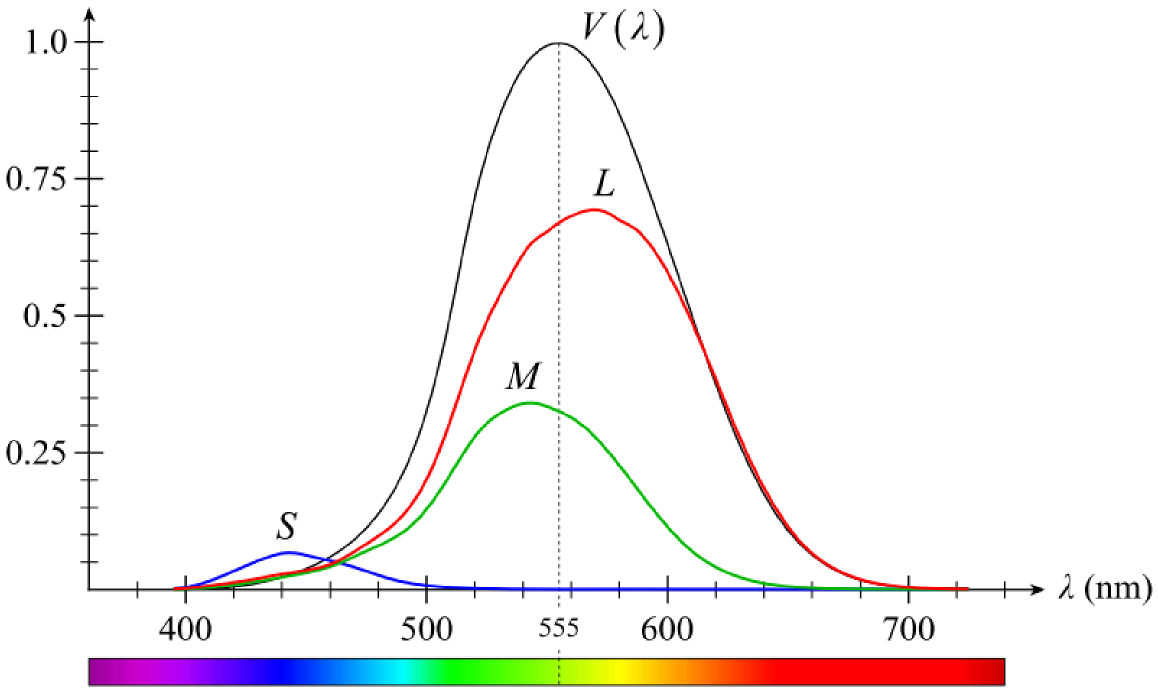
- It indicates perceived brightness

Of total number of cones:

- 63% are L cones
- 31% are M cones
- 6% are S Cones

Luminosity peaks at 555nm

- Green-yellows are perceived as brightest
- Blues are perceived as dark



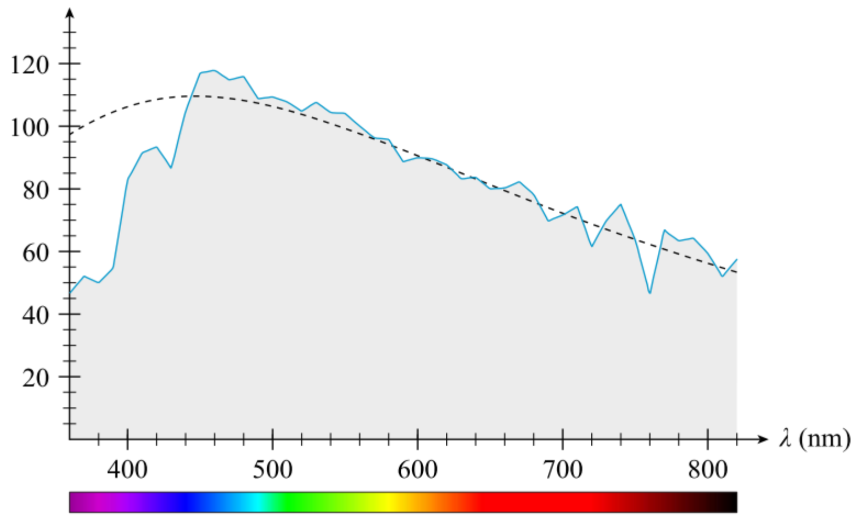
Graph shows relative sensitivity of each type of cone to different wavelengths of light

The Human Visual System

A color corresponds to some amount of stimulus of the cones

Light is usually a mix of wavelengths

- A spectral power distribution
- This distribution is for a “white” light

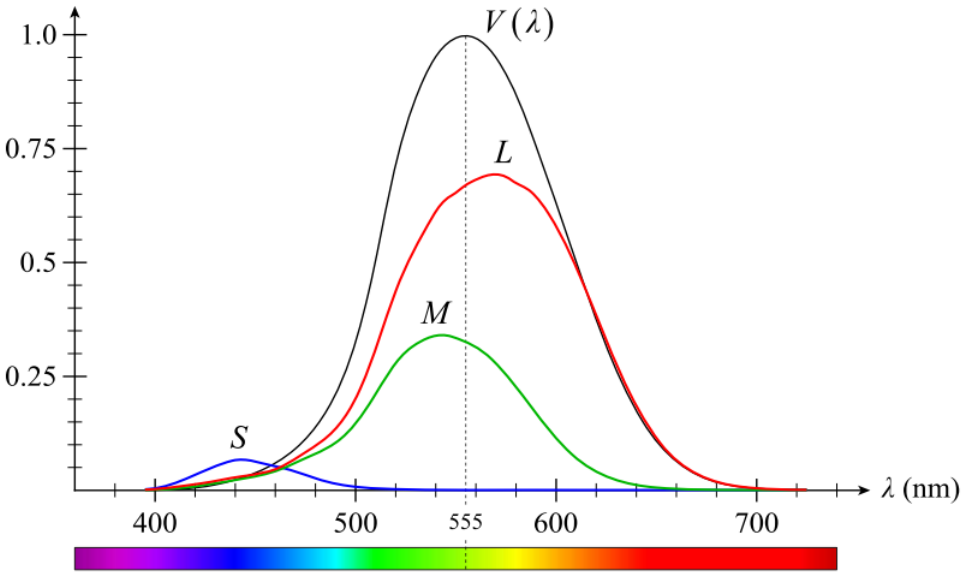


Two different distributions can produce the same stimulus

- Thus they produce the same perceived color
- Different distributions that produce the same color are ***metamers***

Color Spaces

- To create a color image we need a way to specify colors
- A color corresponds to some level of stimulation of the L, M, S cones
  - The set of possible tristimulus values forms a 3D vector space
- The basis vectors for the space are not physical
  - No wavelength of light stimulates only one kind of cone



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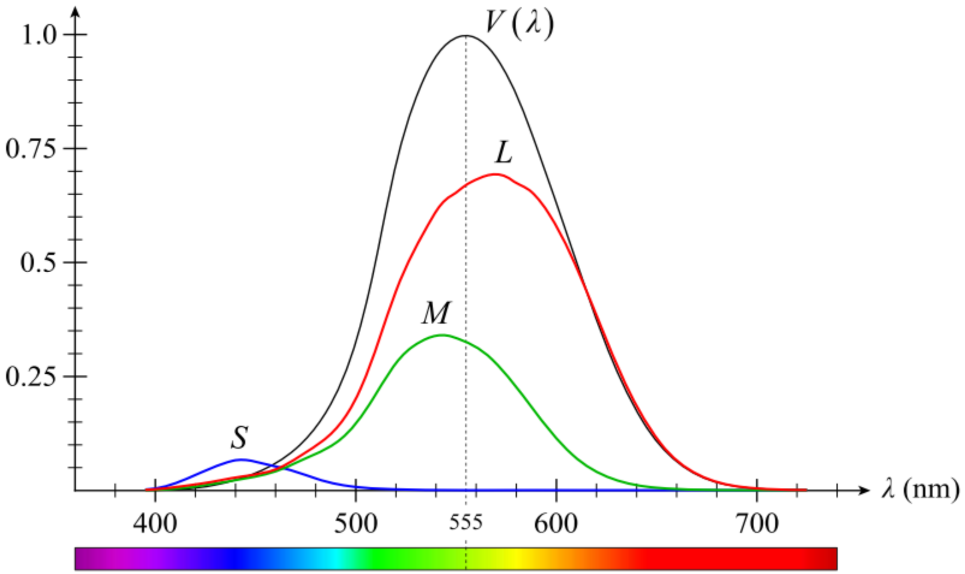
Color Spaces

- To create a color space with a physical meaning
  - We can choose 3 discrete wavelengths which we will call primaries.
- The wavelengths can be mixed at different intensities
  - These spectral distributions correspond to colors defined for some average viewer



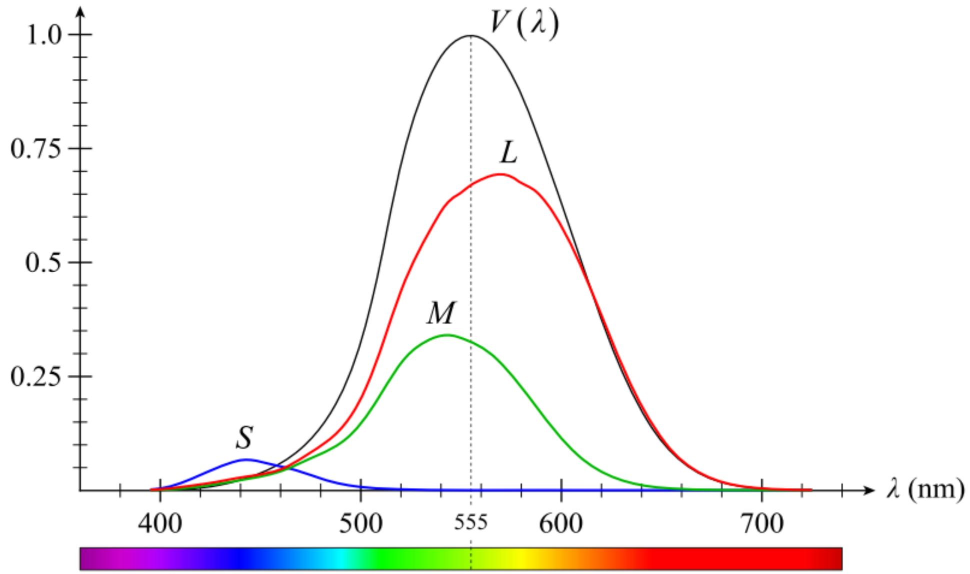
CIE RGB Color Space

CIE RGB Color Space

- Defined in 1931 by the International Commission on Illumination
- CIE is from the French name Commission Internationale de L'éclairage

Used primary wavelengths

- 435.8 nm ("blue")
- 546.1 nm ("green")
- 700 nm ("red")



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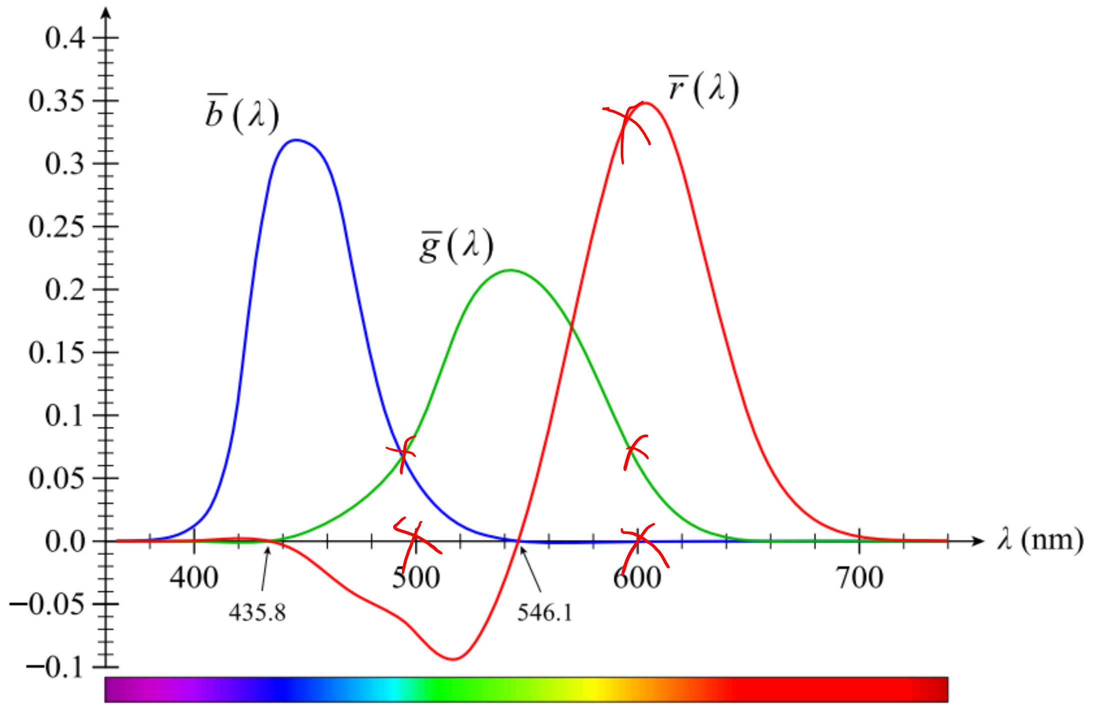
Color Matching Experiments

The Experiment

- A set of viewers were shown a mono-spectral light
- The viewers tried to match the color by mixing the 3 primaries
- This was sometimes impossible
- …but a match could be made by mixing one of primaries with the mono-spectral light
- You can see these events in the graph as negative values



The plot of the functions was created by

- Repeating the experiment for different wavelengths of mono-spectral light
- Averaging/filtering the data from the test subjects

CIE RGB Color Space

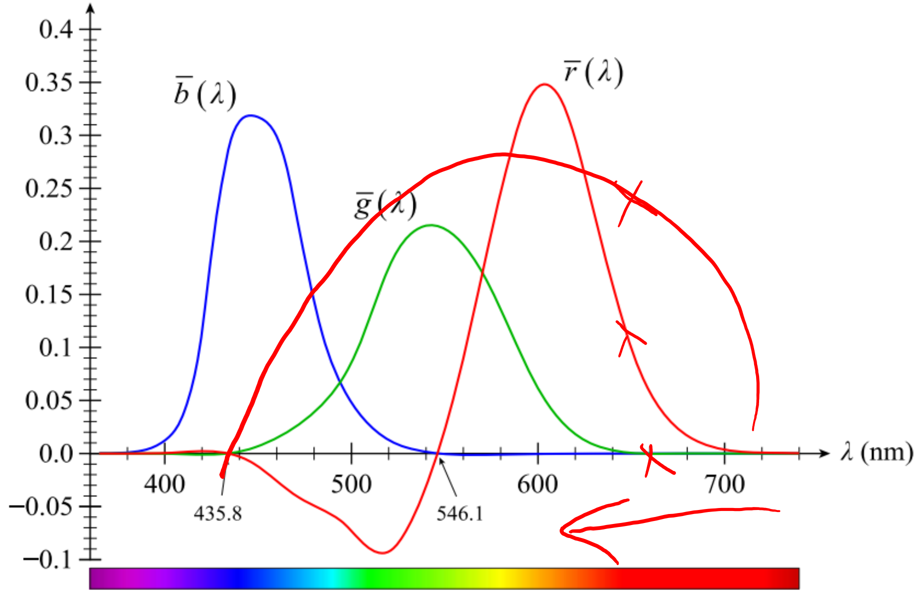
The intensity of the primaries for the CIE RGB color space are computed as follows:
Given a spectral power distribution P(λ)

Compute

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

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

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



This is not the RGB color space you know
It is the basis for it…as we'll see

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CIE XYZ Color Space

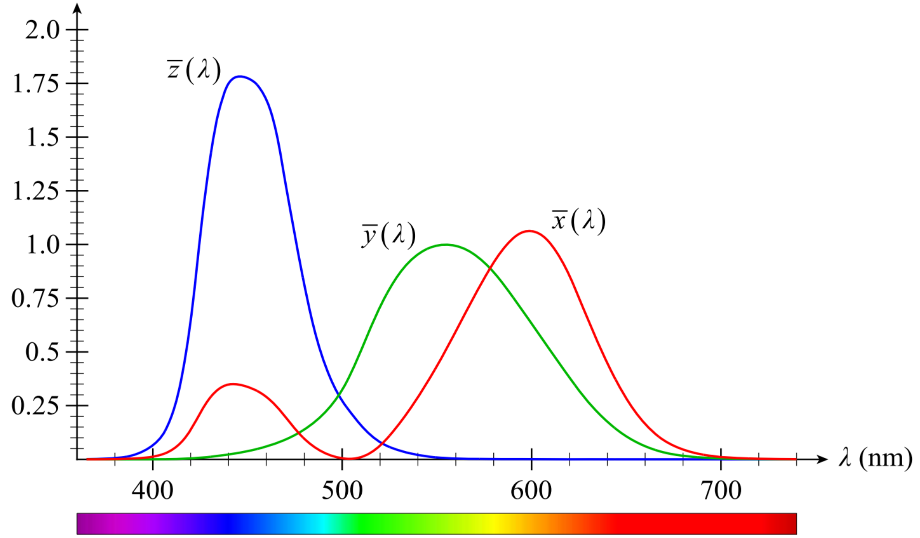
CIE RGB had two problems

- Negative values…people don't like negative values
- It would be useful to separate perceived luminance from chromaticity
  - i.e. separate "brightness" and "hue"

CIE XYZ solves those problems

- Convert from RGB to XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.768892 & 1.751748 & 1.130160 \\ 1 & 4.590700 & 0.060100 \\ 0 & 0.056508 & 5.594292 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



CIE XYZ Color Space

CIE XYZ

- Primaries only take on positive values
- $\bar{y}(\lambda)$ corresponds closely to the values of the luminosity function
  - So Y corresponds to perceived brightness

CIE XYZ

- Primaries only take on positive values
- $\bar{y}(\lambda)$ corresponds closely to the values of the luminosity function
  - So Y corresponds to perceived brightness

xyY Color Space

It can be useful to have normalized chromaticity values

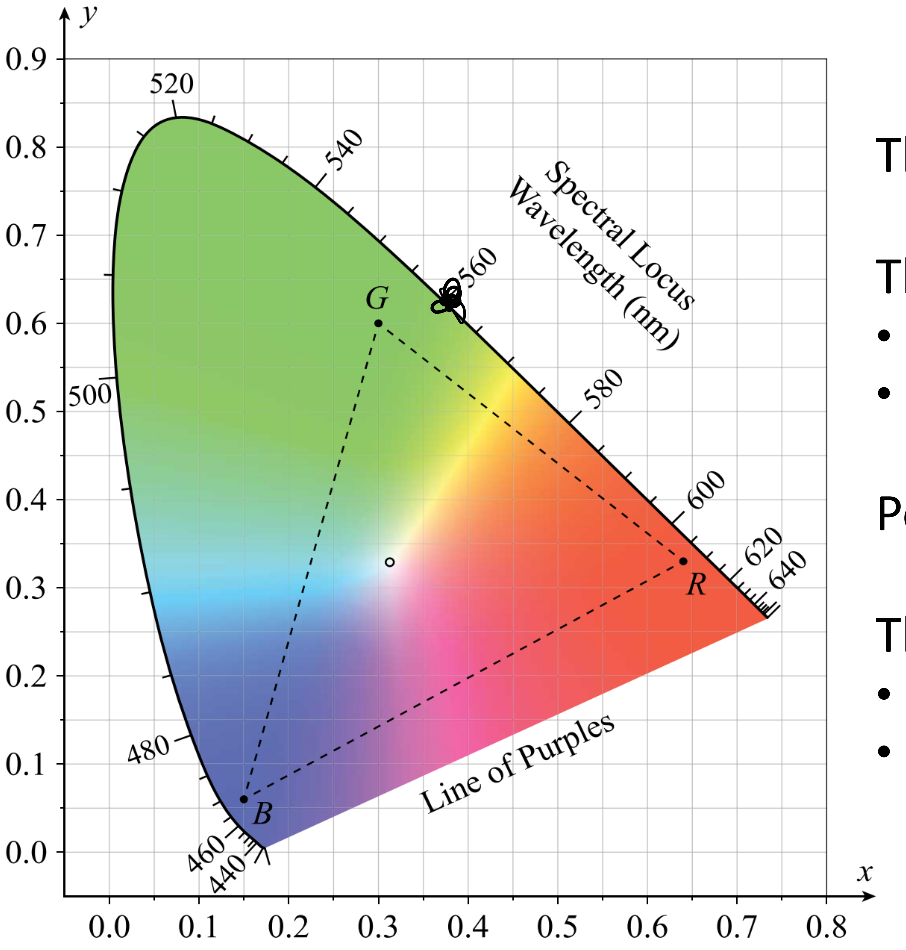
- Fall in range [0,1]
- Do not change with luminance

Standard way to do this is to take

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad \text{and} \quad z = \frac{Z}{X+Y+Z}$$

- Convention is to use x and y to indicate chromaticity
- Combined with the original Y value gives a color in the xyY colorspace

CIE xy Chromaticity Diagram



The diagram depicts all colors visible to an average human

The curved boundary is the spectral locus

- It consists of all the colors associated with a single wavelength
- The bottom line of purples are not single wavelength colors

Points not on the curved boundary are mixture of multiple wavelengths

The standard sRGB color space is defined by 3 points labeled R,G, and B

- All the colors possible in that space lie in the RGB triangle
- The set of producible colors in a space is called the ***gamut***

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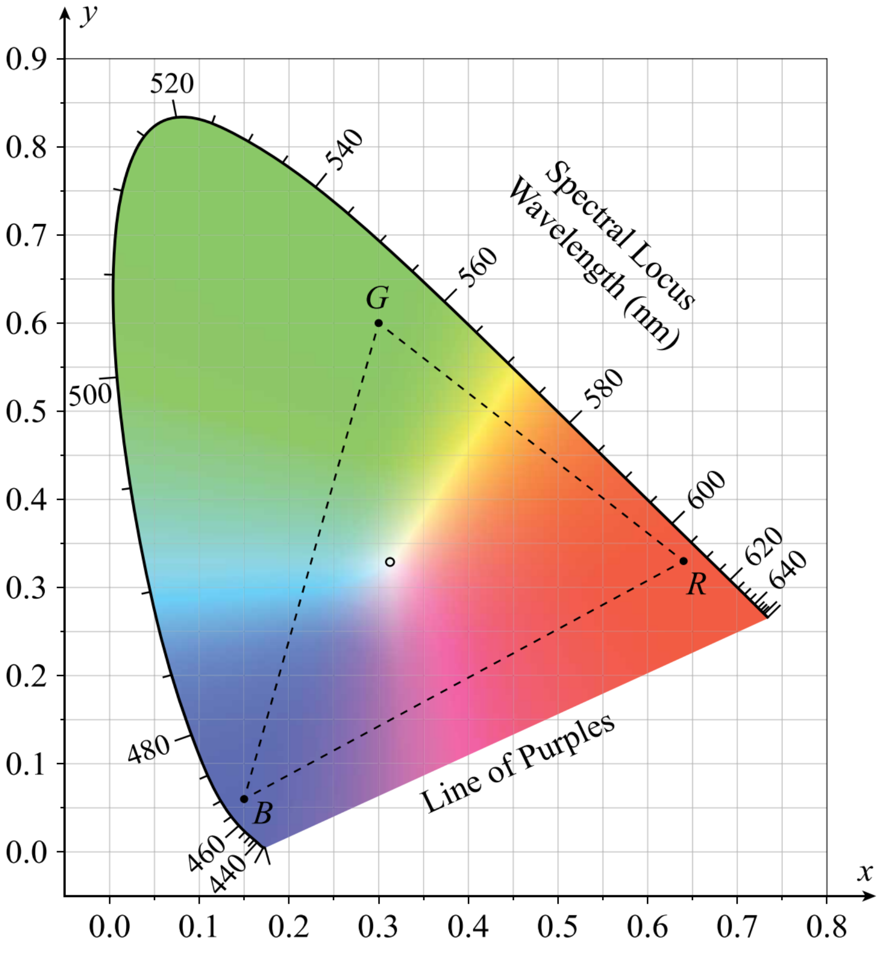
Three Primary Colors Cannot Produce All Possible Colors



The CIE RGB color space includes all possible colors

…at least for most people

No space defined by 3 primary colors can include all colors

….no triangle can cover the horseshoe in the diagram

What about CIE RGB space? It has 3 primaries

The CIE RGB primaries are not colors
The CIE RGB are not physical lights
The CIE RGB primaries are a function of the color-matching curves

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Standard Illuminants

So…what point on the diagram corresponds to white light?

- Perfectly white light occurs at $\left(\frac{1}{3}, \frac{1}{3}\right)$
- This is called standard illuminant E

Most light sources are not perfectly white.

Illuminant D65 is at $(0.3127, 0.2390)$

- Approximates average daylight in most geographic locations
- Defines white light for the sRGB color space
- Has the spectral power distribution shown below