Computer Graphics

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Fall 2016

http://www.cs.pdx.edu/~fliu/courses/cs447/

09/28/2016

Announcement

- Class mailing list
  https://groups.google.com/d/forum/cs447-fall-2016

Last Time

- Course introduction
- Digital images
  - The difference between an image and a display
  - Ways to get them
  - Raster vs. Vector
  - Digital images as discrete representations of reality
  - Human perception in deciding resolution and image depth
- Homework 1 – due Oct. 6 in class

Today

- Color
- Tri-Chromacy
- Digital Color
- Programming Tutorial 1

About Color

- So far we have only discussed intensities, so called *achromatic light* (shades of gray)
- On the order of 10 color names are widely recognized by English speakers - other languages have fewer/more, but not much more

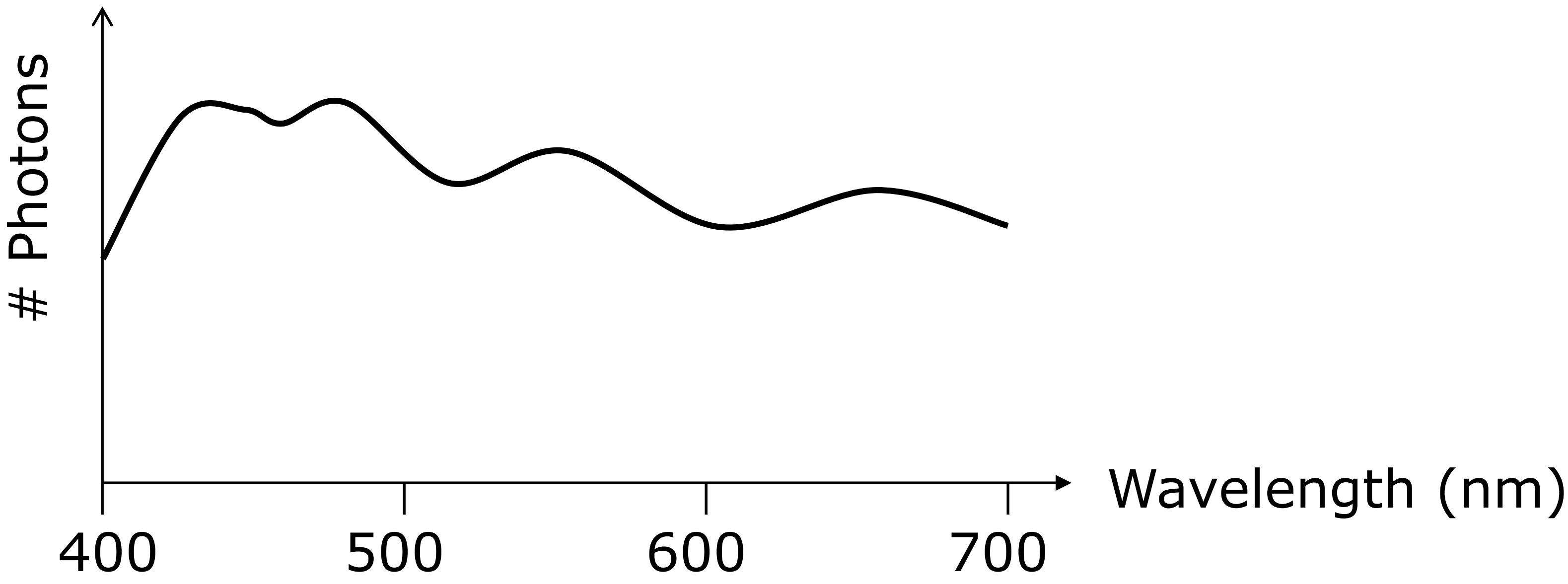
About Color

- So far we have only discussed intensities, so called *achromatic light* (shades of gray)
- On the order of 10 color names are widely recognized by English speakers - other languages have fewer/more, but not much more
- Accurate color reproduction is commercially valuable - e.g. painting a house, producing artwork
- E-commerce has accentuated color reproduction issues, as has the creation of digital libraries
- Color consistency is also important in user interfaces, eg: what you see on the monitor should match the printed version

Light and Color

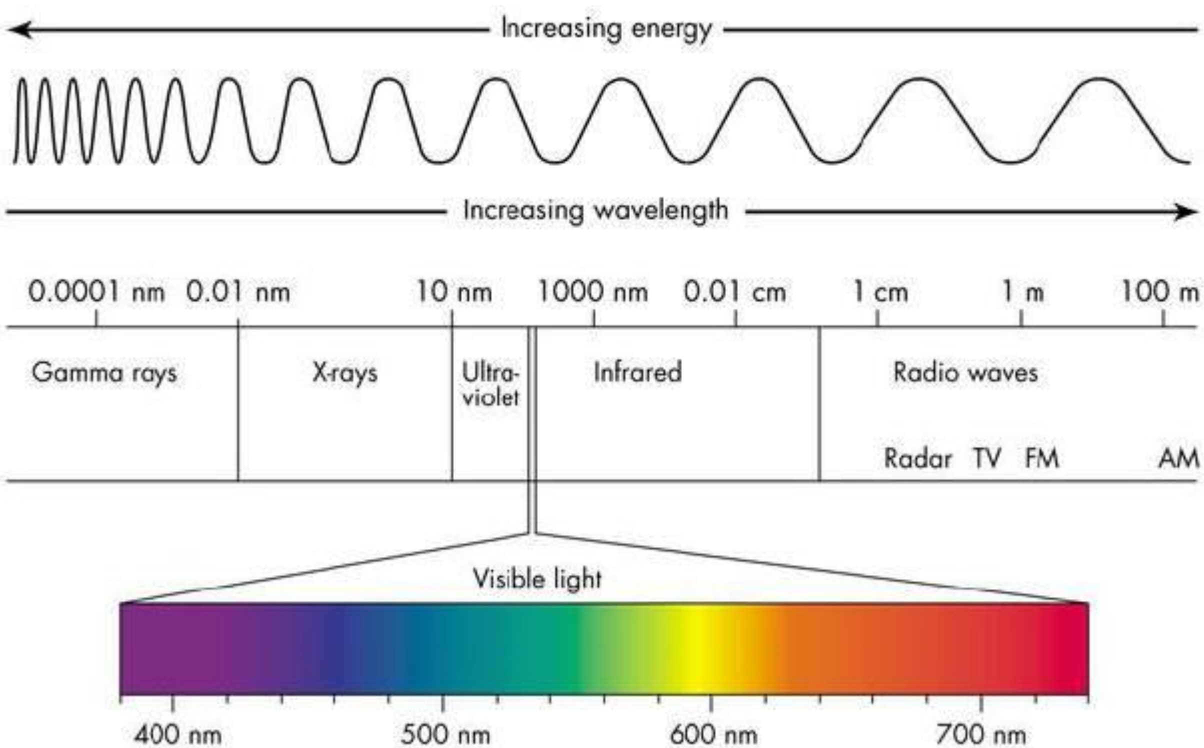
- The frequency, ζ, of light determines its “color”
  - Wavelength, κ, is related:
  - Energy also related
- Describe incoming light by a *spectrum*
  - Intensity of light at each frequency
  - A graph of intensity vs. frequency
- We care about wavelengths in the visible spectrum: between the infra-red (700nm) and the ultra-violet (400nm)

Normal Daylight

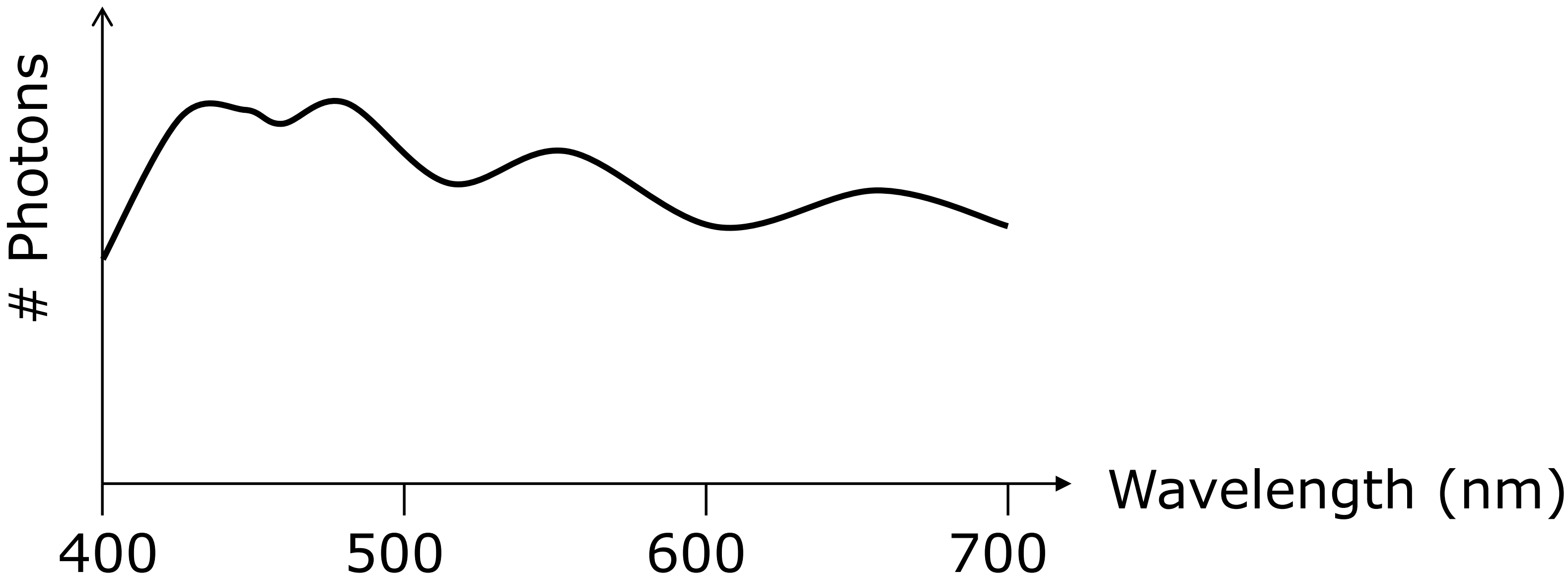


- Note the hump at short wavelengths - the sky is blue

Color and Wavelength



Normal Daylight



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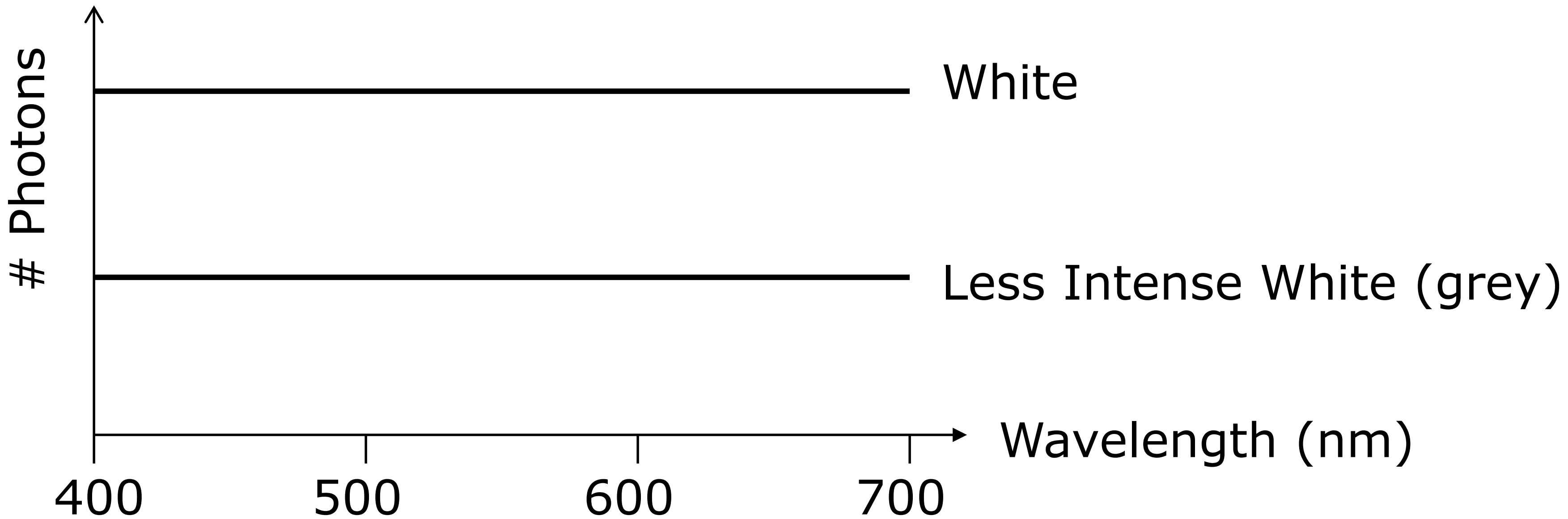
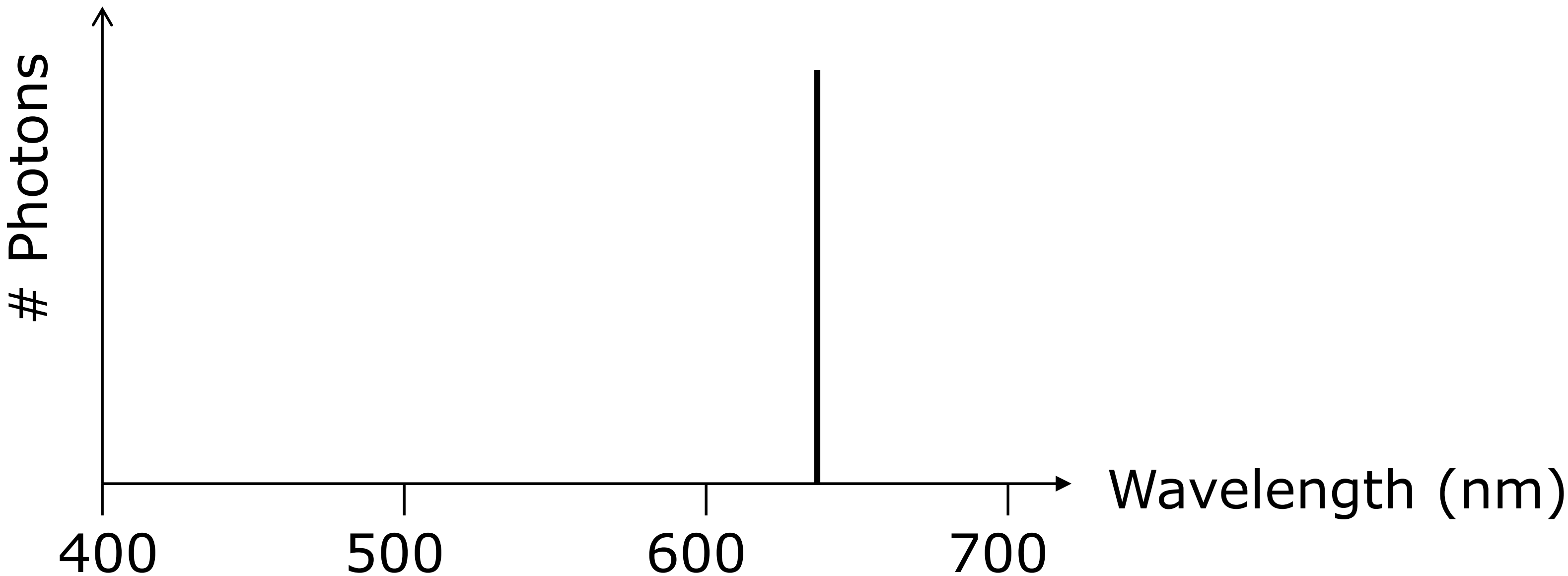
White



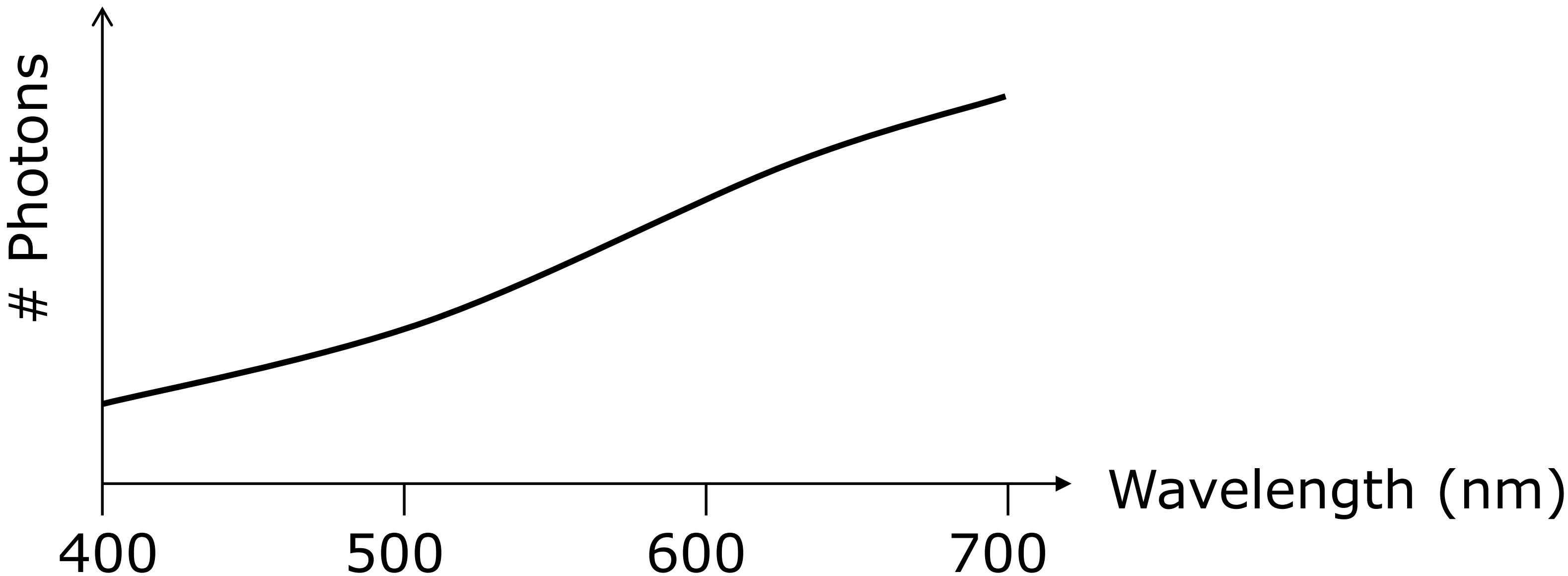
- Note that **color** and **intensity** are technically two different things
- However, in common usage we use color to refer to both
  - White = grey = black in terms of color
- You will have to use context to extract the meaning

Helium Neon Laser



- Lasers emit light at a single wavelength, hence they appear colored in a very “pure” way

Tungsten Lightbulb

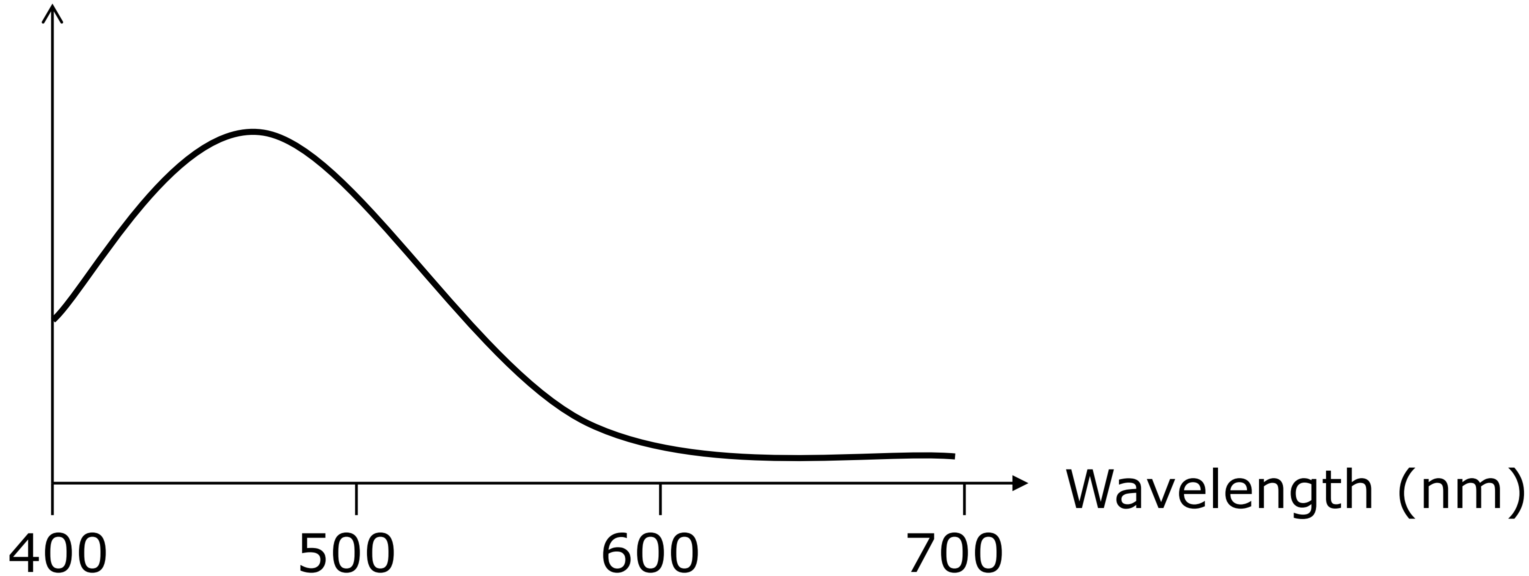


- Most light sources are not anywhere near white
- It is a major research effort to develop light sources with particular properties

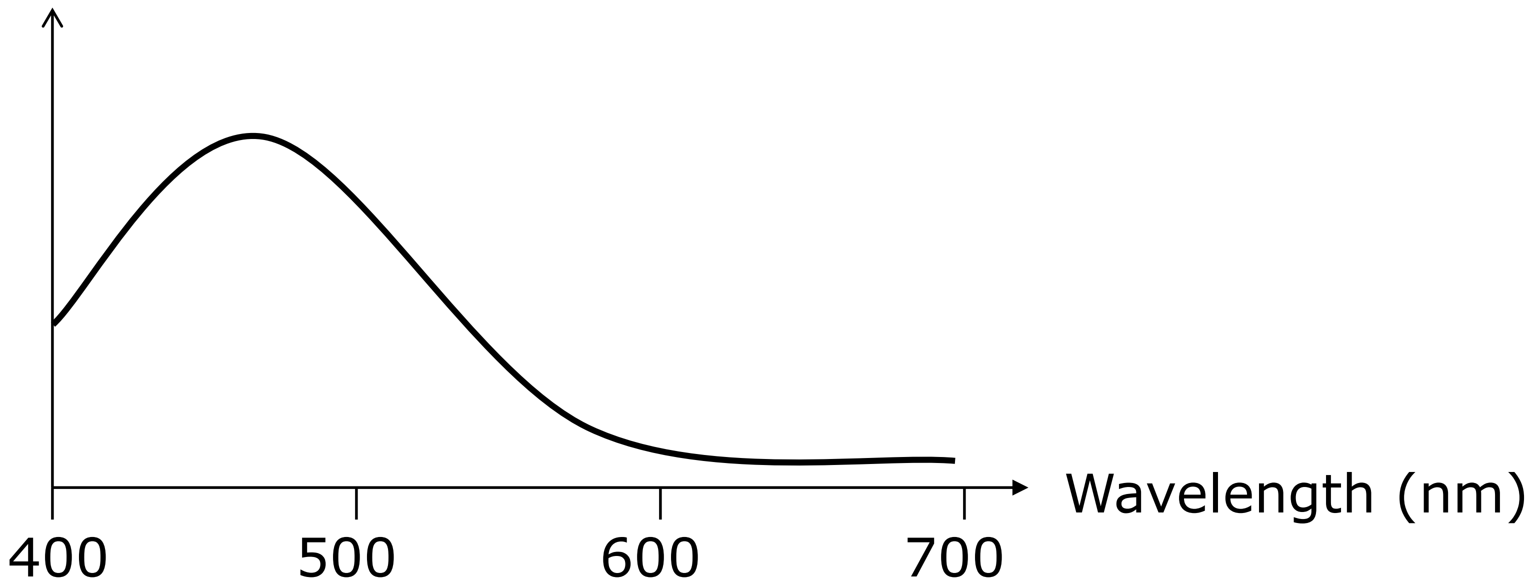
Emission vs. Adsorption

- Emission is what light sources do
- Adsorption is what paints, inks, dyes etc. do
- Emission produces light, adsorption removes light
- We still talk about spectra, but now is it the *proportion* of light that is removed at each frequency
  - Note that adsorption depends on such things as the surface finish (glossy, matte) and the substrate (e.g. paper quality)
  - The following examples are qualitative at best

Adsorption Spectra



Adsorption Spectra: Red Paint



- Red paint absorbs green and blue wavelengths, and reflects red wavelengths, resulting in you seeing a red appearance

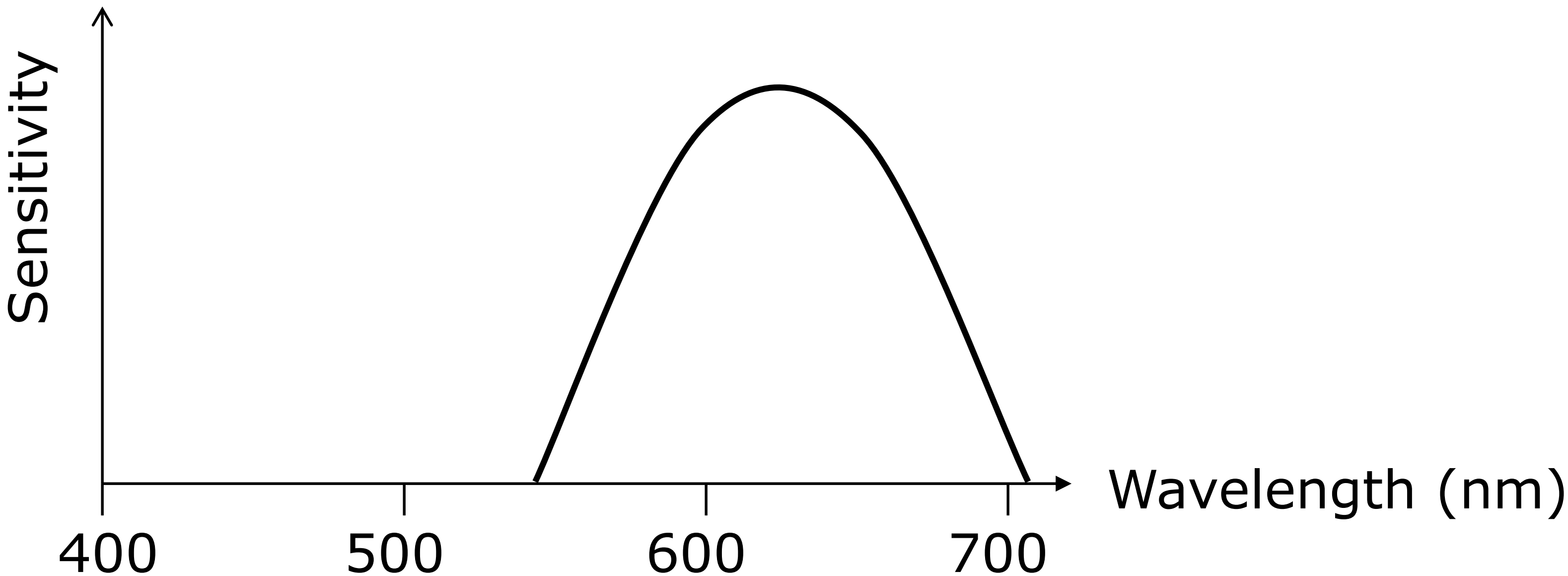
Representing Color

- Our task with digital images is to represent color
- You probably know that we use three channels: R, G and B
- We will see why this is perceptually sufficient for display and why it is computationally an approximation
- First, how we measure color

Sensors

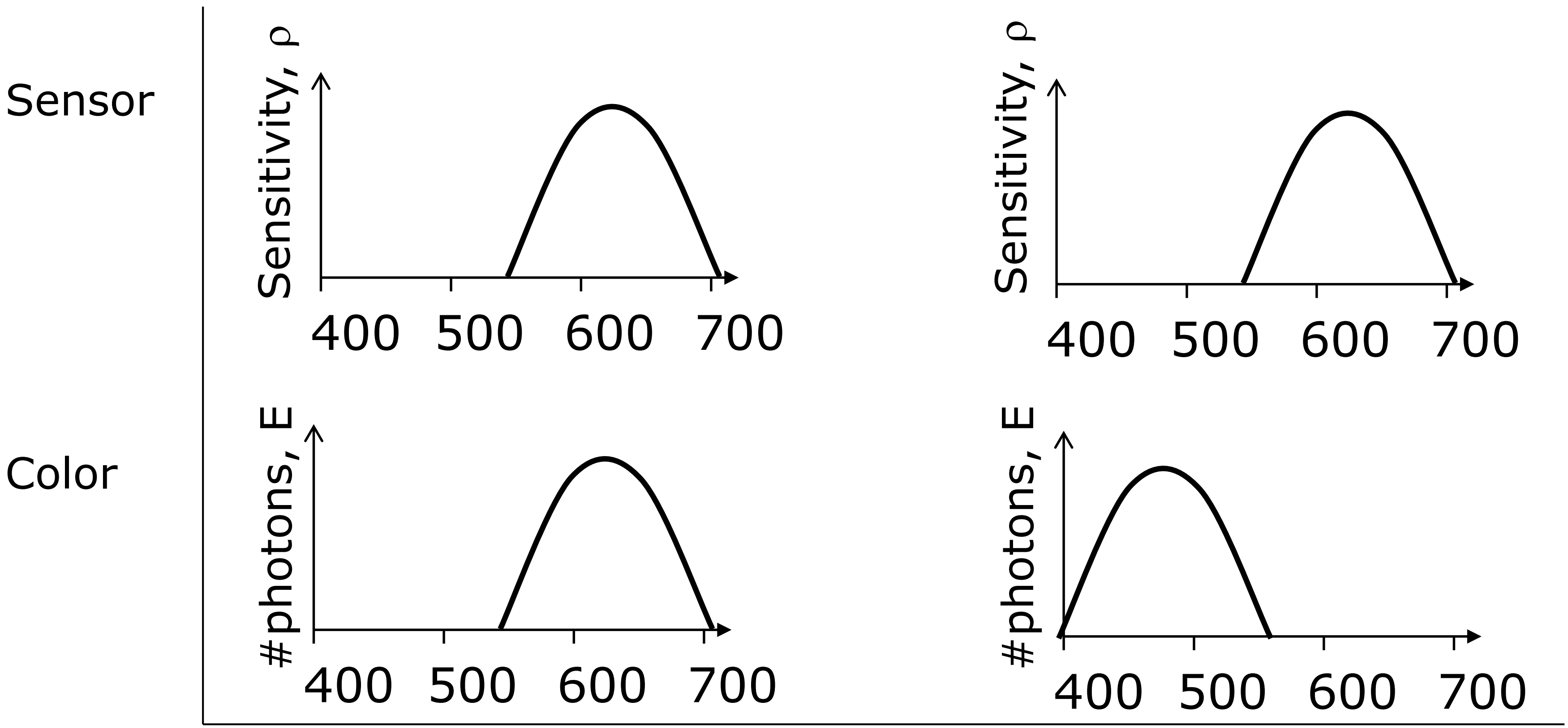
- Any *sensor* is defined by its *response* to a frequency distribution
- Expressed as a graph of sensitivity vs. wavelength, $\rho(\lambda)$
  - For each unit of energy at the given wavelength, how much voltage/impulses/whatever the sensor provides
- To compute the response, take the integral $\int \rho(\lambda) E(\lambda) d\lambda$
  - E(λ) is the incoming energy at the particular wavelength
  - The integral multiplies the amount of energy at each wavelength by the sensitivity at that wavelength, and sums them all up

A “Red” Sensor



- This sensor will respond to red light, but not to blue light, and a little to green light

The “Red” Sensor Response



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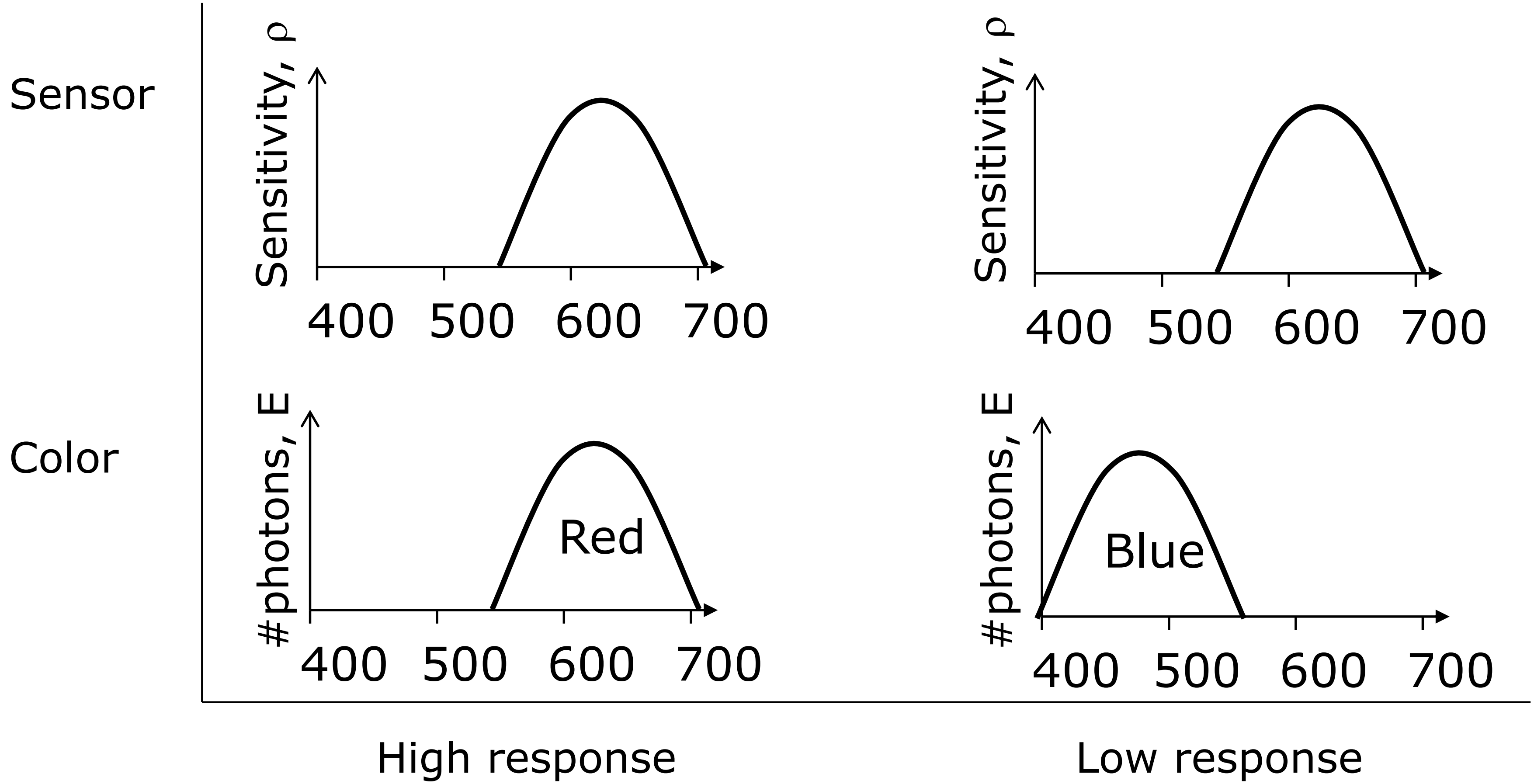
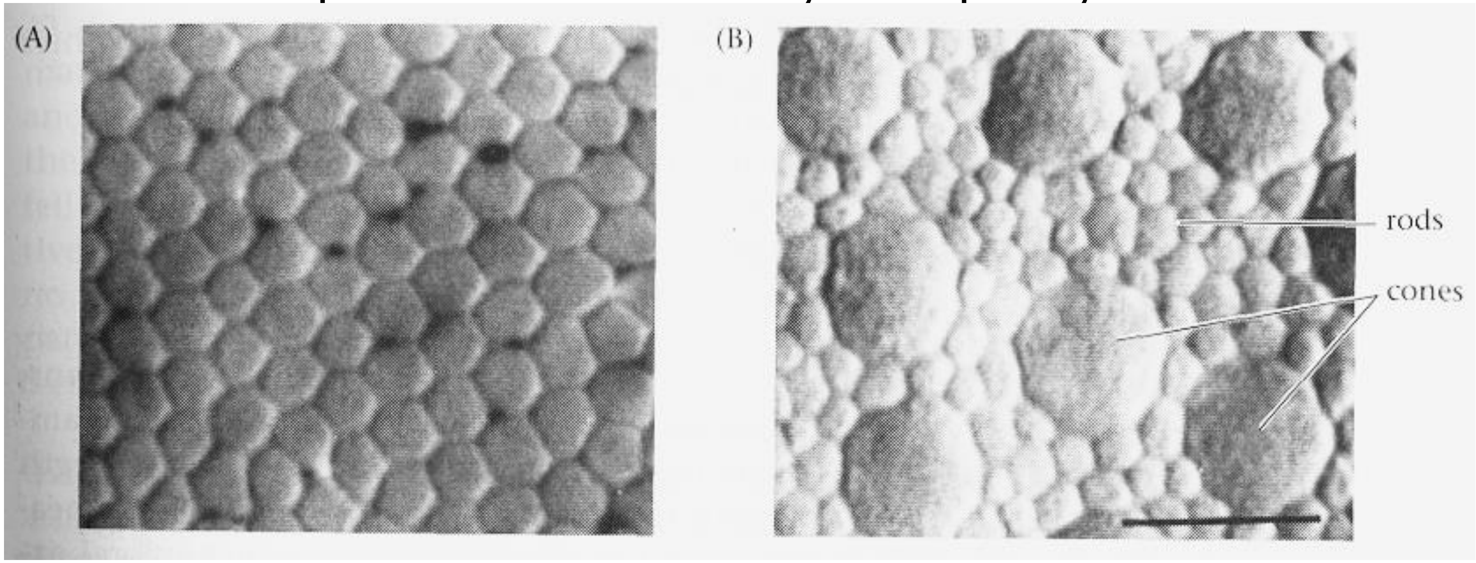


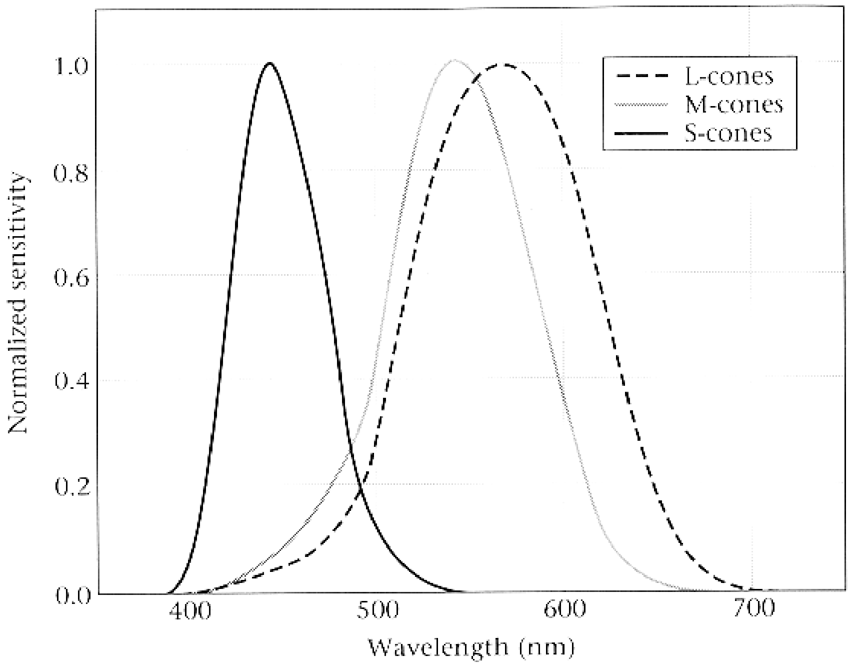
Seeing in Color

- The eye contains *rods* and *cones*
  - Rods work at low light levels and do not see color
    - That is, their response depends only on how many photons, not their wavelength
  - Cones come in three types (experimentally and genetically proven), each responds in a different way to frequency distributions



Color receptors

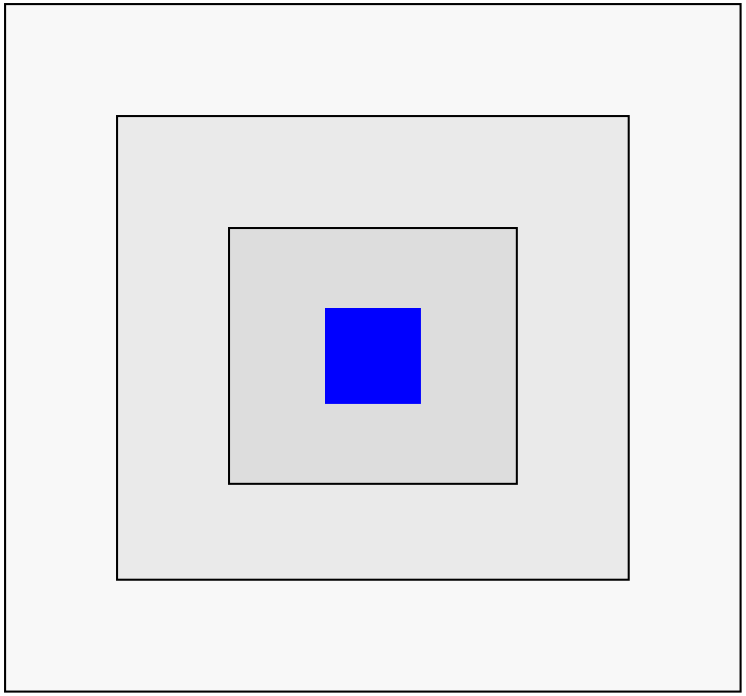
- Each cone type has a different sensitivity curve
  - Experimentally determined in a variety of ways
- For instance, the L-cone responds most strongly to red light
- "Response" in your eye means nerve cell firings
- How you interpret those firings is not so simple …

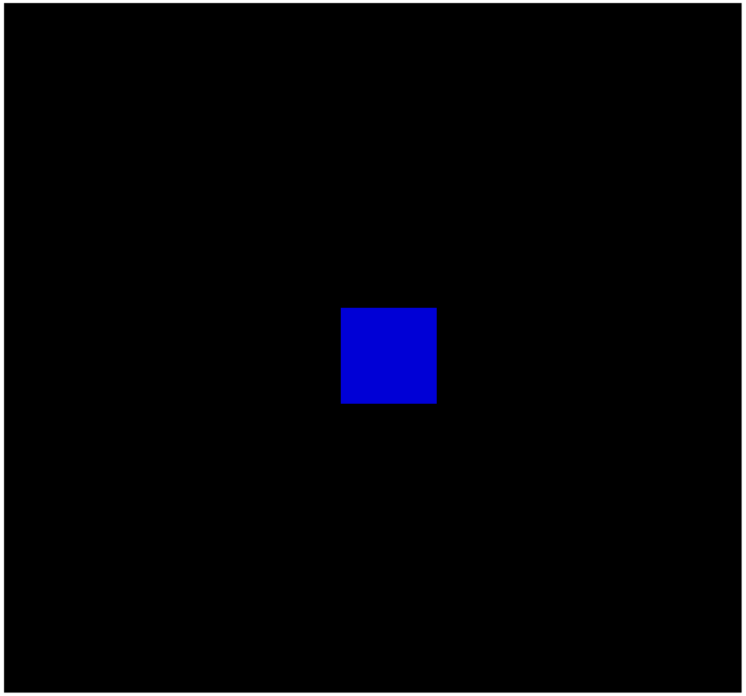


Color Perception

- How your brain interprets nerve impulses from your cones is an open area of study, and deeply mysterious
- Colors may be perceived differently:
  - Affected by other nearby colors
  - Affected by adaptation to previous views
  - Affected by “state of mind”
- Experiment:
  - Subject views a colored surface through a hole in a sheet, so that the color looks like a film in space
  - Investigator controls for nearby colors, and state of mind

The Same Color?





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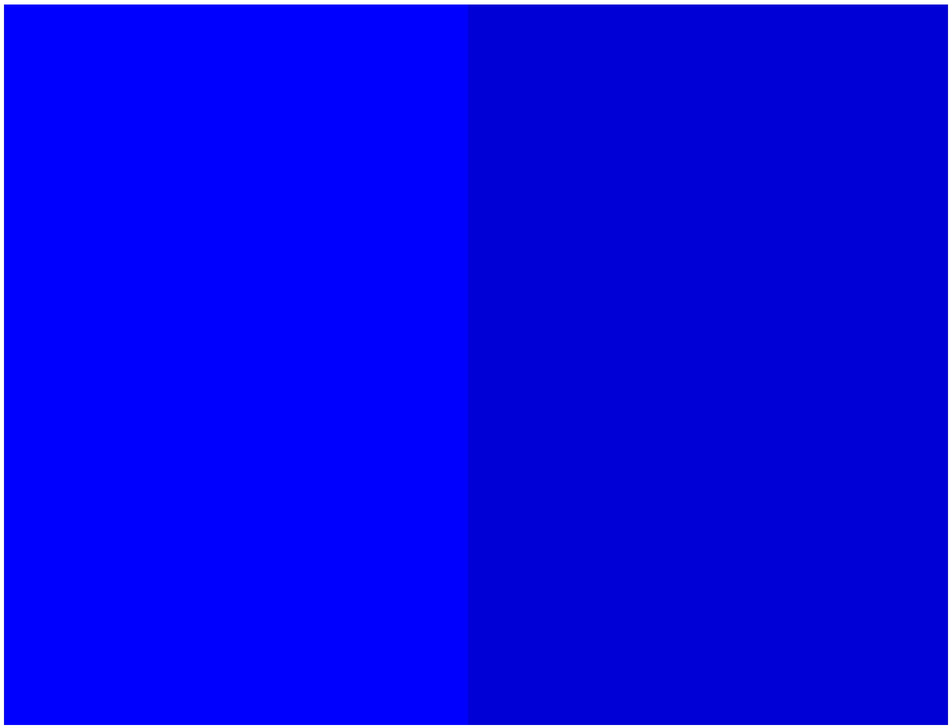
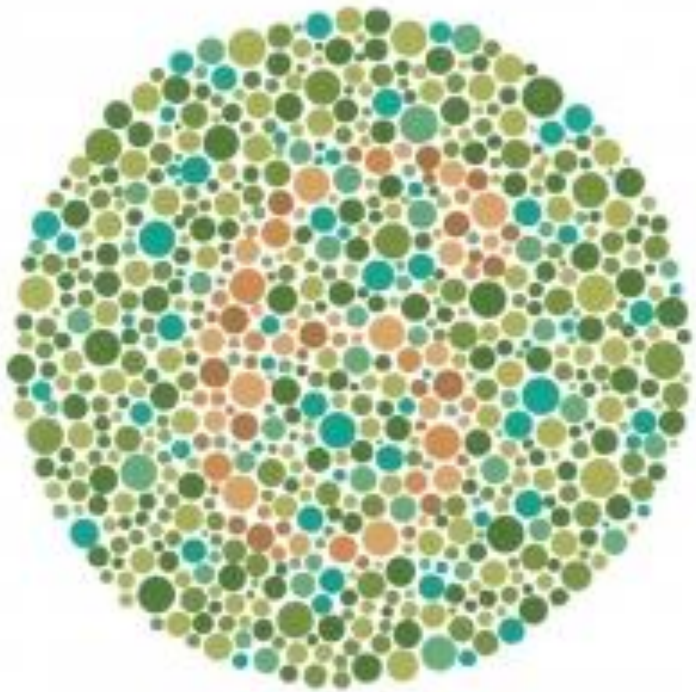


Color Deficiency

- Some people are missing one type of receptor
  - Most common is red-green color blindness in men
  - Red and green receptor genes are carried on the X chromosome - most red-green color blind men have two red genes or two green genes
- Other color deficiencies
  - Anomalous trichromacy, Achromatopsia, Macular degeneration
  - Deficiency can be caused by the central nervous system, by optical problems in the eye, injury, or by absent receptors

Color Deficiency



Today

- Color
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Recall

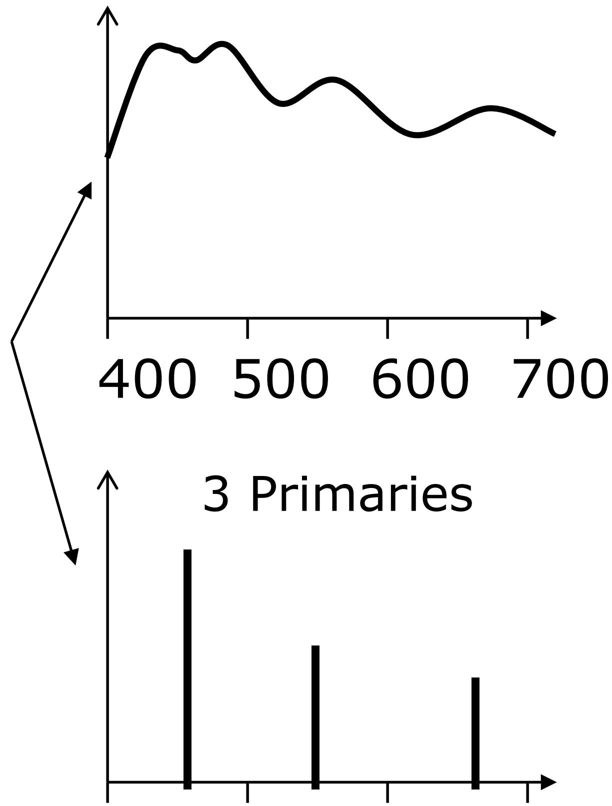
- We're working toward a representation for digital color
- We have seen that humans have three sensors for color vision
- Now, the implications …

Trichromacy

- Experiment:
  - Show a target color *spectrum* beside a user controlled color
  - User has knobs that adjust *primary sources* to set their color
    - Primary sources are just lights with a fixed spectrum and variable intensity
  - Ask the user to *match* the colors – make their light look the same as the target
- Experiments show that it is possible to match almost all colors using only three primary sources - *the principle of trichromacy*
- Sometimes, have to add light to the *target*
- In practical terms, this means that if you show someone the right amount of each primary, they will perceive the right color
- This was how experimentalists knew there were 3 types of cones

Trichromacy Means…

Color Matching:
People think these two spectra **look the same**
(*monomers*)



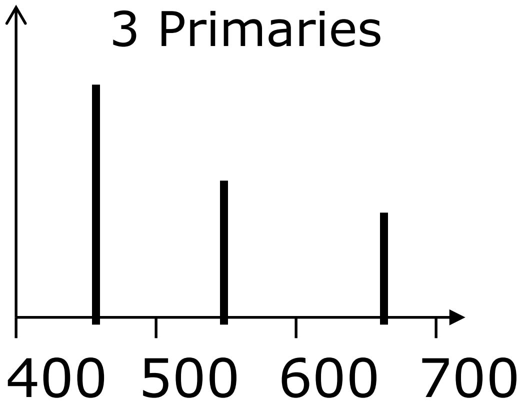
Representing color:
If you want people to "see" the continuous spectrum, you can just show the three primaries
(with varying intensities)

The Math of Trichromacy

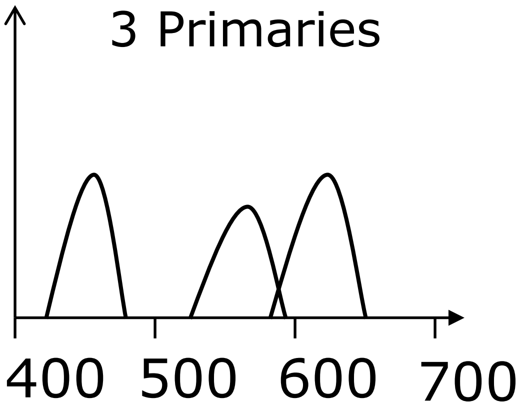
- Write primaries as R, G and B
  - We won't precisely define them yet
- Many colors can be represented as a mixture of R, G, B: $M = rR + gG + bB$ (Additive matching)
- Gives a color description system - two people who agree on R, G, B need only supply (r, g, b) to describe a color
- Some colors can't be matched like this, instead, write: $M + rR = gG + bB$ (Subtractive matching)
  - Interpret this as (-r, g, b)
  - Problem for reproducing colors – you can't subtract light using a monitor, or add it using ink

Primaries are Spectra Too

- A primary can be a spectrum
  - Single wavelengths are just a special case



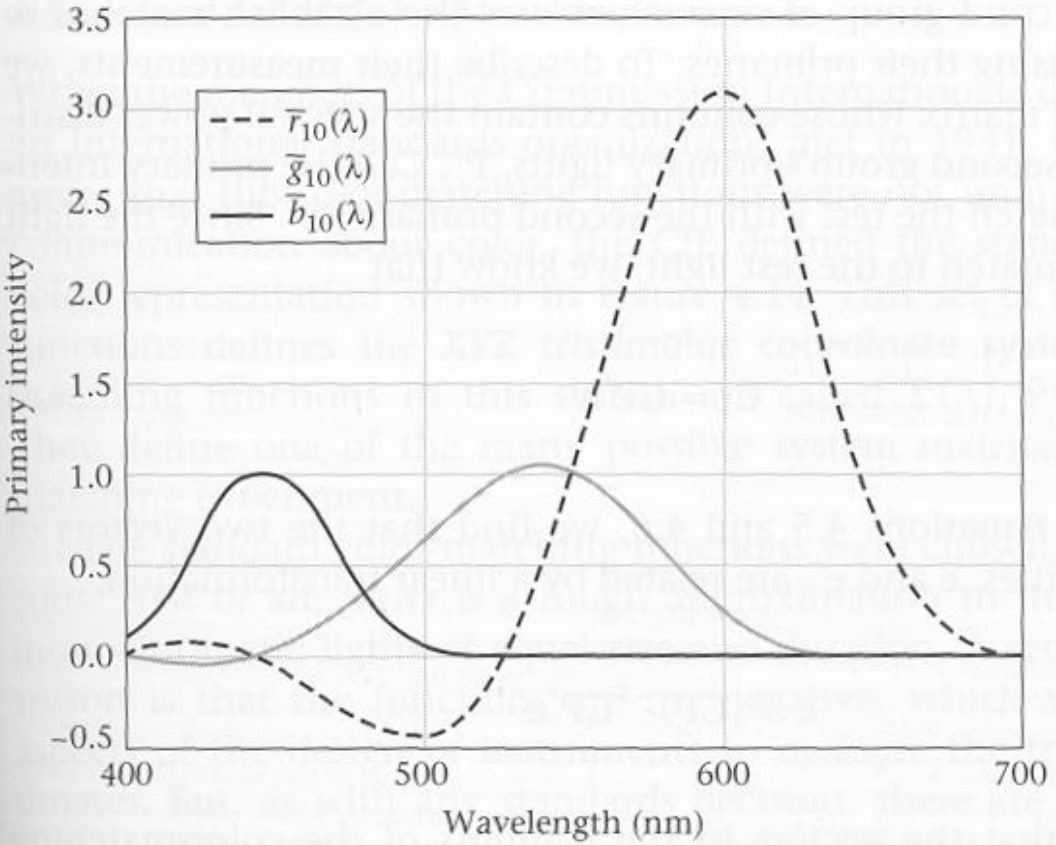
or



Color Matching

- Given a spectrum, how do we determine how much each of R, G and B to use to match it?
- First step:
  - For a light of unit intensity *at each wavelength*, ask people to match it using some combination of R, G and B primaries
  - Gives you, $r(\lambda)$, $g(\lambda)$ and $b(\lambda)$, the amount of each primary used for wavelength λ
  - Defined for all visible wavelengths, $r(\lambda)$, $g(\lambda)$ and $b(\lambda)$ are the RGB *color matching functions*

The RGB Color Matching Functions



4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, and $\bar{b}_{10}(\lambda)$.

Computing the Matching

- Given a spectrum, how do we determine how much each of R, G and B to use to match it?
- The spectrum function that we are trying to match, $E(\lambda)$, gives the amount of energy at each wavelength
- The RGB matching functions describe how much of each primary is needed to give one energy unit's worth of response at each wavelength

$$E = rR + gG + bB$$

$$r = \int r(\lambda)E(\lambda)d\lambda$$

$$g = \int g(\lambda)E(\lambda)d\lambda$$

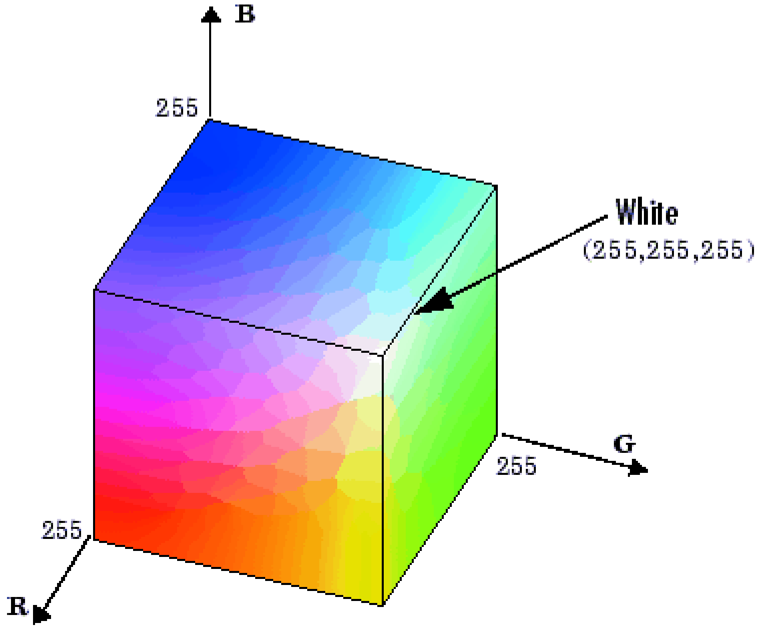
$$b = \int b(\lambda)E(\lambda)d\lambda$$

Color Spaces

- The principle of trichromacy means that the colors displayable are all the linear combination of primaries
- Taking linear combinations of R, G and B defines the *RGB color space*
  - the range of perceptible colors generated by adding some part of each of R, G and B
- If R, G and B correspond to a monitor’s phosphors (monitor RGB), then the space is the range of colors displayable on the monitor

RGB Color Space

- Demo



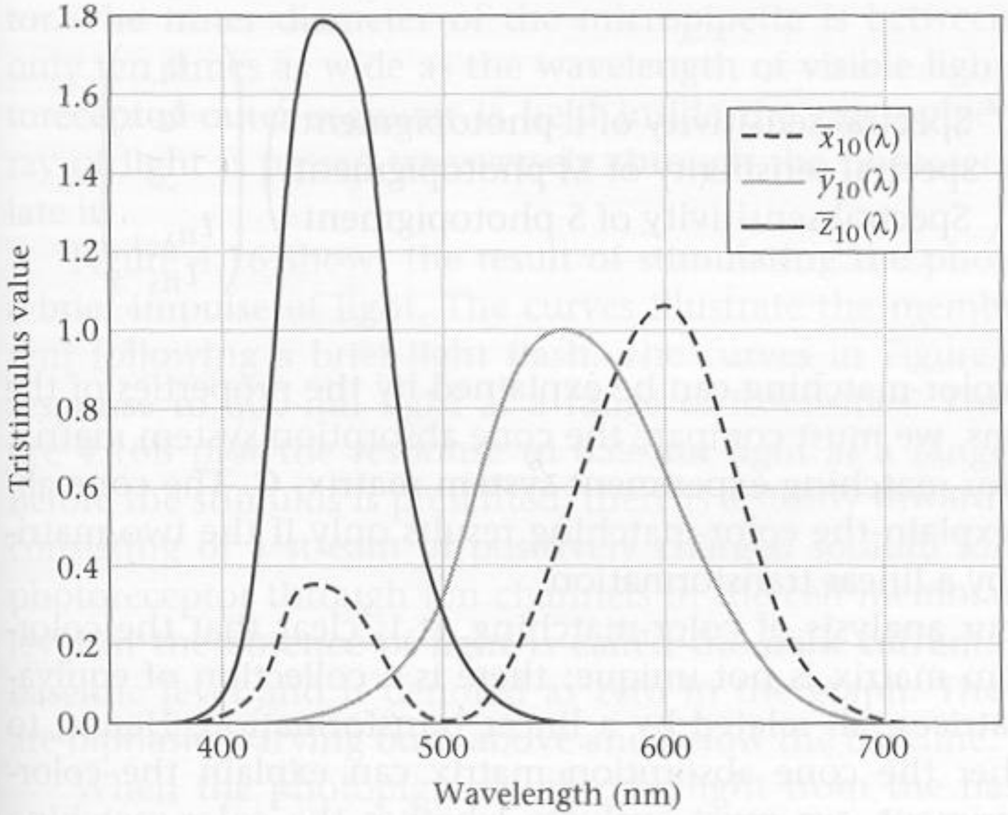
Problems with RGB

- Can only represent a small range of all the colors humans are capable of perceiving (particularly for monitor RGB)
- It isn't easy for humans to say how much of RGB to use to make a given color
  - How much R, G and B is there in "brown"? (Answer: .64,.16, .16)
- Perceptually non-linear

CIE XYZ Color Space

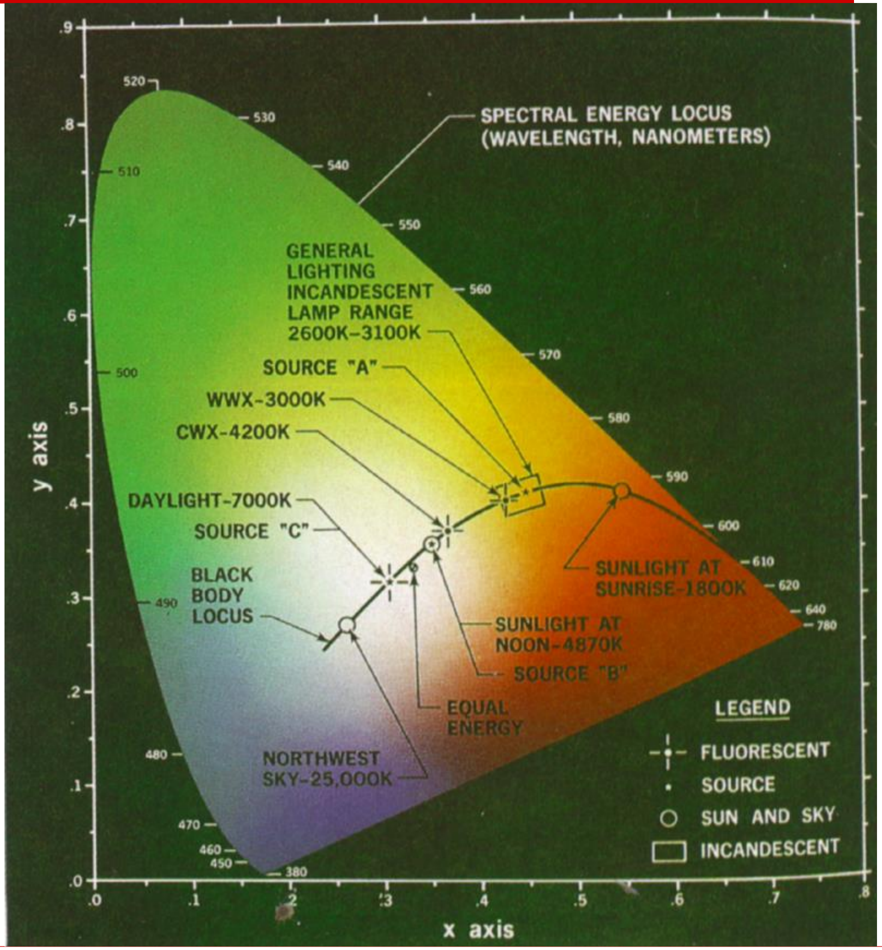
- Imaginary primaries
  - X, Y, Z
  - Y component intended to correspond to intensity
  - Cannot produce the primaries – need negative light!
- Defined in 1931 to describe the full space of perceptible colors
  - Revisions now used by color professionals
- Color matching functions are everywhere positive
- Most frequently set $x=X/(X+Y+Z)$ and $y=Y/(X+Y+Z)$
  - x,y are coordinates on a constant brightness slice

CIE Matching Functions



4.14 THE XYZ STANDARD COLOR-MATCHING FUNCTIONS. In 1931 the CIE standardized a set of color-matching functions for image interchange. These color-matching functions are called $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$. Industrial applications commonly describe the color properties of a light source using the three primary intensities needed to match the light source that can be computed from the XYZ color-matching functions.

CIE x, y



Note: This is a representation on a projector with limited range, so the correct colors are not being displayed

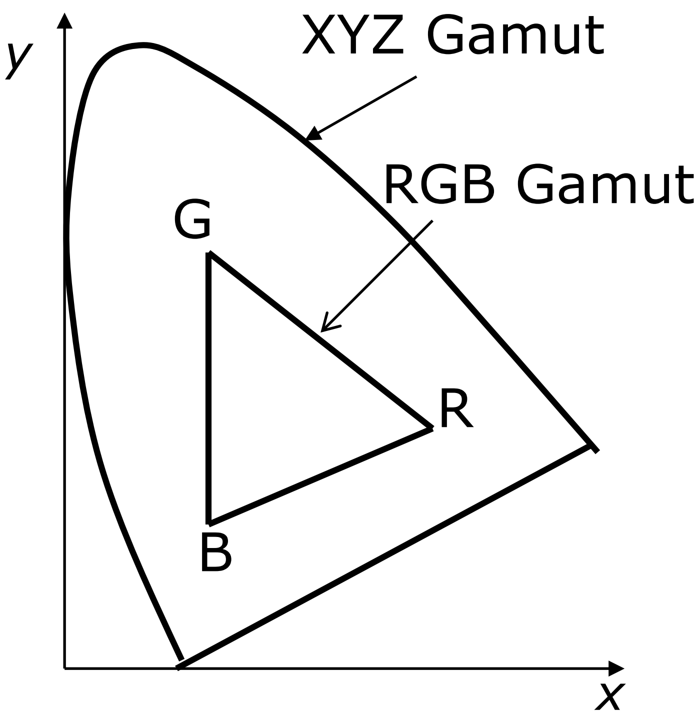
Standard RGB↔XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7151 & 0.0721 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- Note that each matrix is the inverse of the other
- Recall, Y encodes brightness, so the matrix tells us how to go from RGB to grey

Determining Gamuts



- Gamut: The range of colors that can be represented or reproduced
- Plot the matching coordinates for each primary. eg R, G, B
- Region contained in triangle (3 primaries) is gamut
- Really, it's a 3D thing, with the color cube distorted and embedded in the XYZ gamut

Accurate Color Reproduction

- Device dependent RGB space
- High quality graphic design applications, and even some monitor software, offers accurate color reproduction
- A color calibration phase is required:
  - Fix the lighting conditions under which you will use the monitor
  - Fix the brightness and contrast on the monitor
  - Determine the monitor's γ
  - Using a standard color card, match colors on your monitor to colors on the card: This gives you the matrix to convert your monitor's RGB to XYZ
  - Together, this information allows you to accurately reproduce a color specified in XYZ format

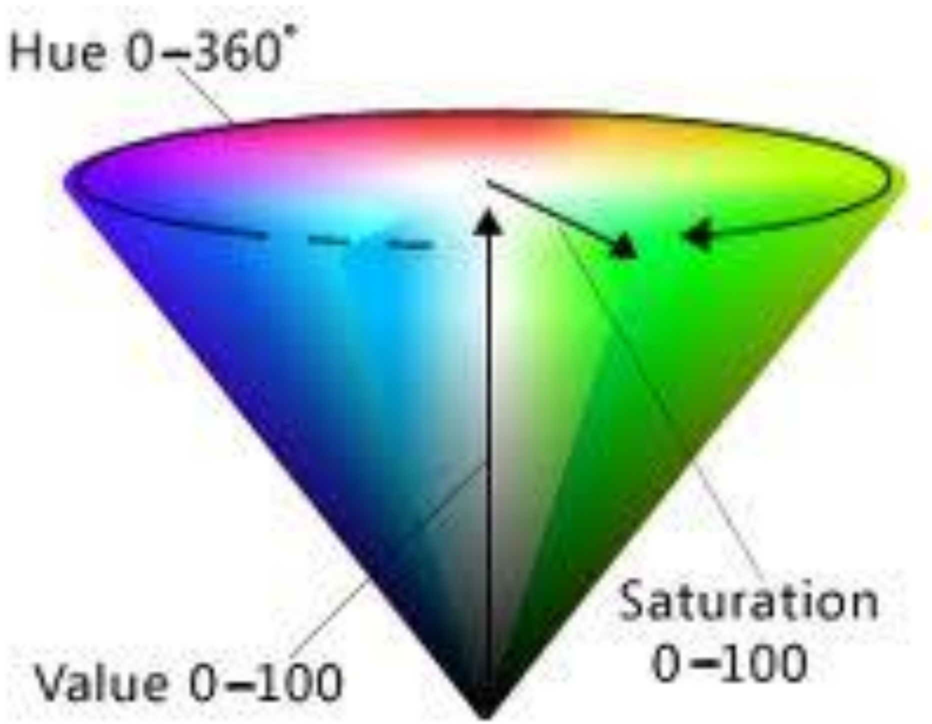
More Linear Color Spaces

- Monitor RGB: primaries are monitor phosphor colors, primaries and color matching functions vary from monitor to monitor
- sRGB: A new color space designed for web graphics
- YIQ: mainly used in television
  - Y is (approximately) intensity, I, Q are chromatic properties
  - Linear color space; hence there is a matrix that transforms XYZ coords to YIQ coords, and another to take RGB to YIQ

HSV Color Space (Alvy Ray Smith, 1978)

- Hue: the color family: red, yellow, blue…
- Saturation: The purity of a color: white is totally unsaturated
- Value: The intensity of a color: white is intense, black isn't
- Space looks like a cone
  - Parts of the cone can be mapped to RGB space
- Not a linear space, so no linear transform to take RGB to HSV
  - But there is an algorithmic transform

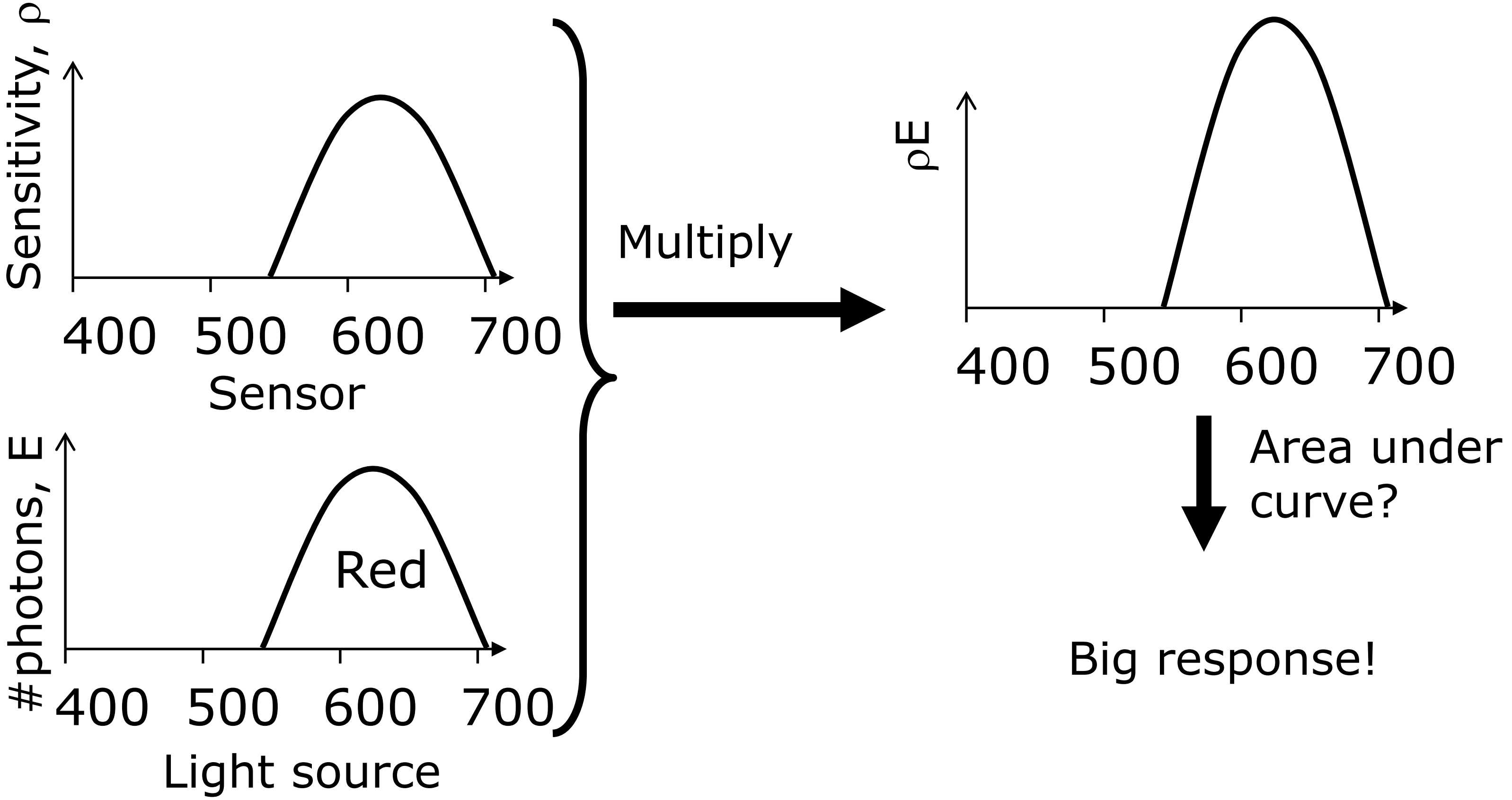
HSV Color Space



Next Time

- Color Quantization
- Dithering

Qualitative Response



Qualitative Response