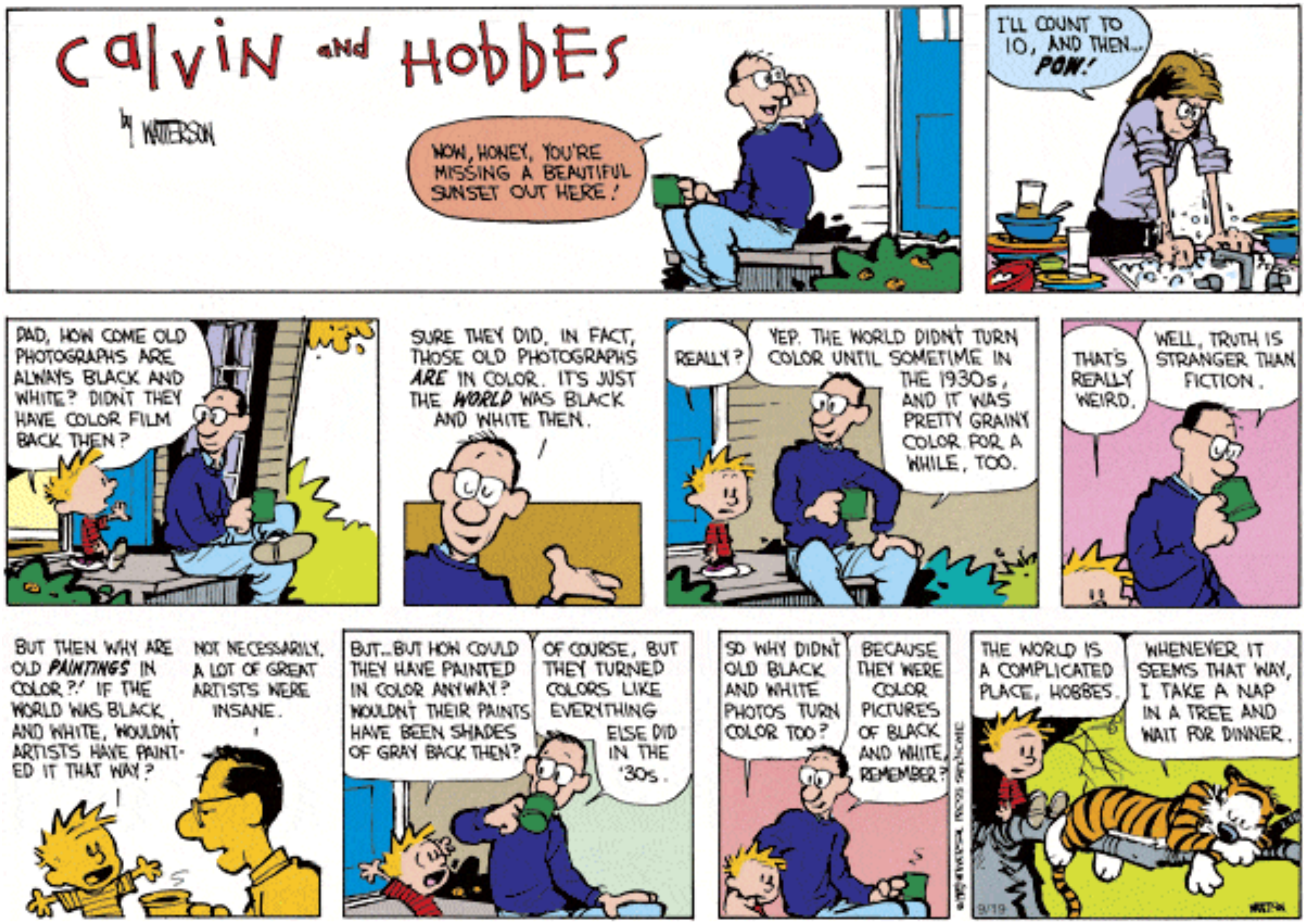
CS 418: Interactive Computer Graphics

Color

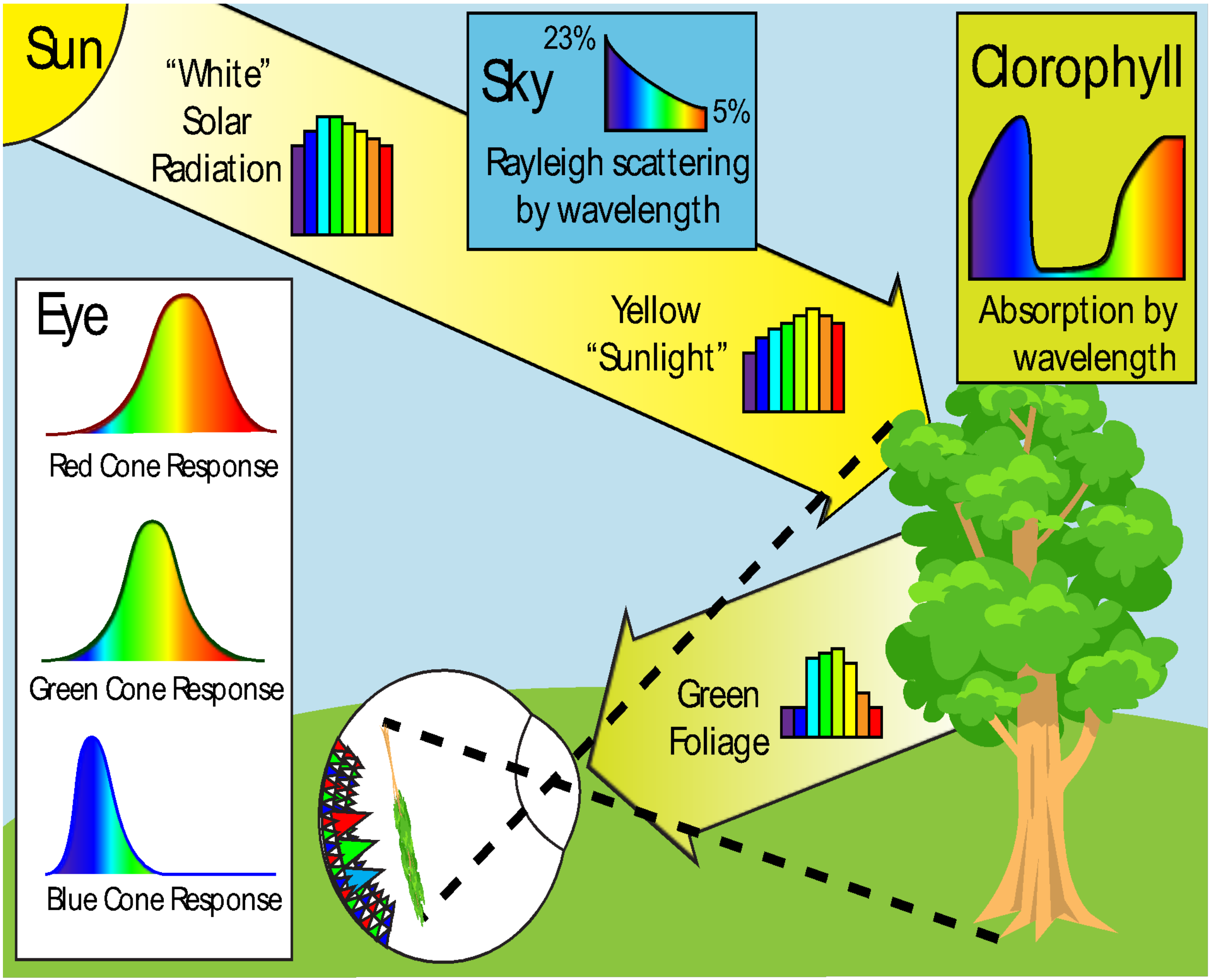
Eric Shaffer

Rainbow versus Black and White



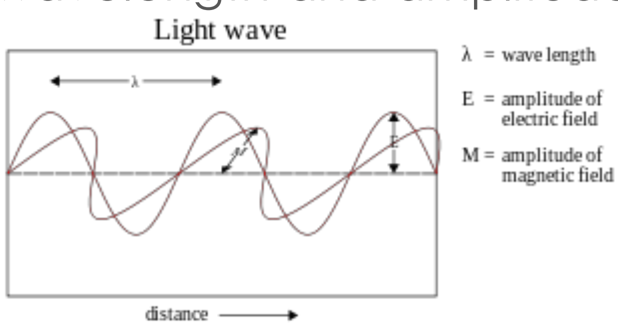
Color

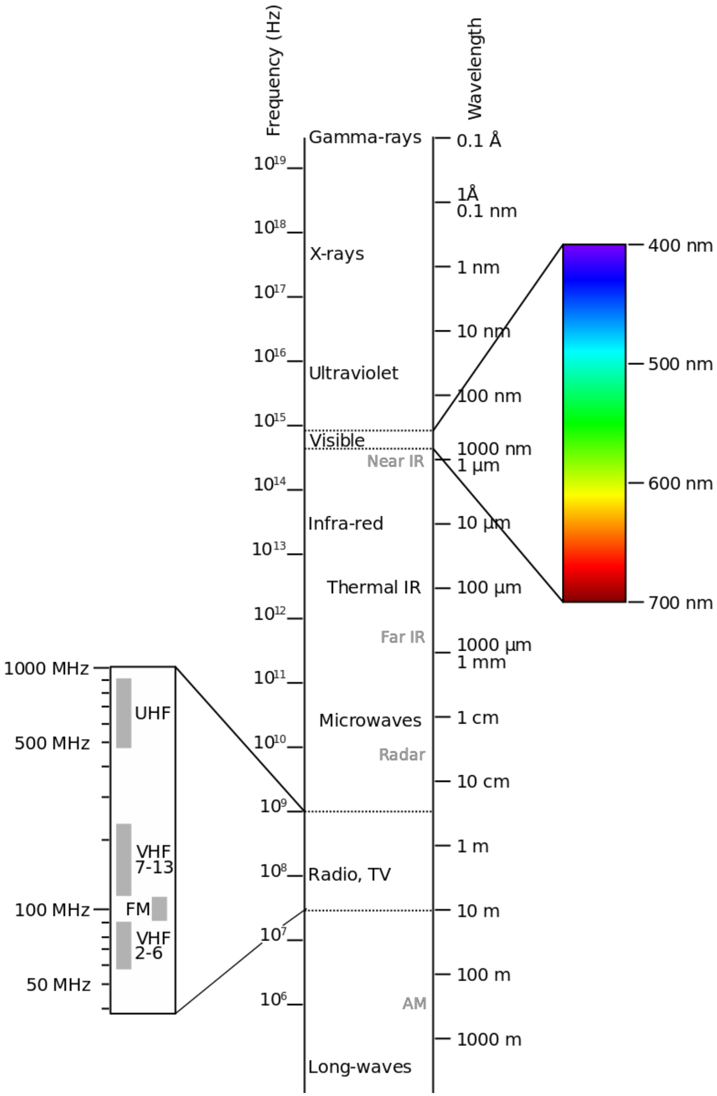
- Color is a perceptual phenomenon
- A frequency spectrum of light is a physical phenomenon
- In computer graphics, we need to specify colors
  - We define "color spaces" in which points correspond to colors
  - We can then work with colors mathematically
- Ideally, a color space would allow us to specify any color that humans can perceive…


Sun
"White" Solar Radiation
Sky
23%
5%
Rayleigh scattering by wavelength
Clorophyll
Absorption by wavelength
Yellow "Sunlight"
Eye
Red Cone Response
Green Cone Response
Blue Cone Response
Green Foliage

Light and Color

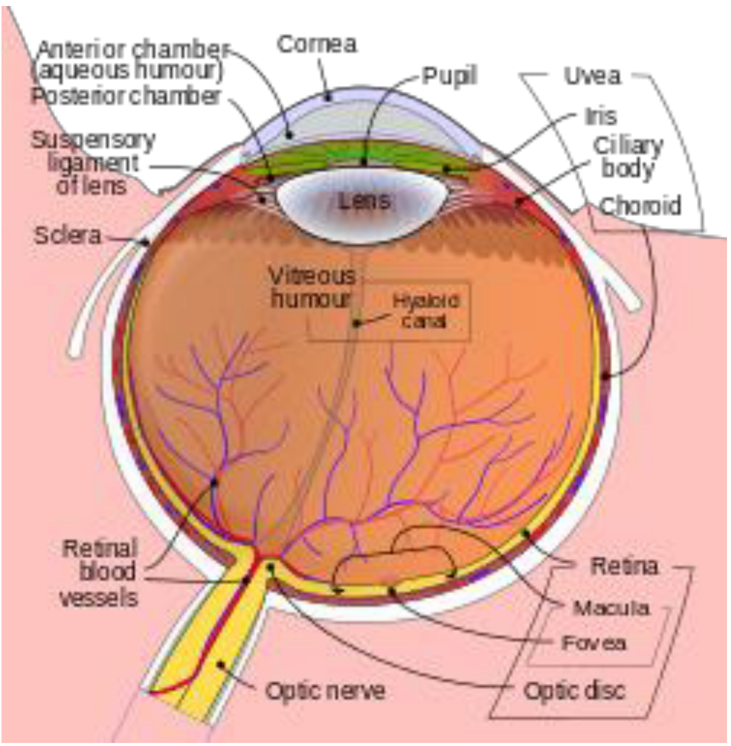
- Color is a perceptual phenomenon
  - Response of the human visual system to light…and other factors
- Light is a physical phenomenon
  - Electromagnetic radiation visible to the human eye
  - Emitted in quanta called photons
  - Has wavelength and amplitude

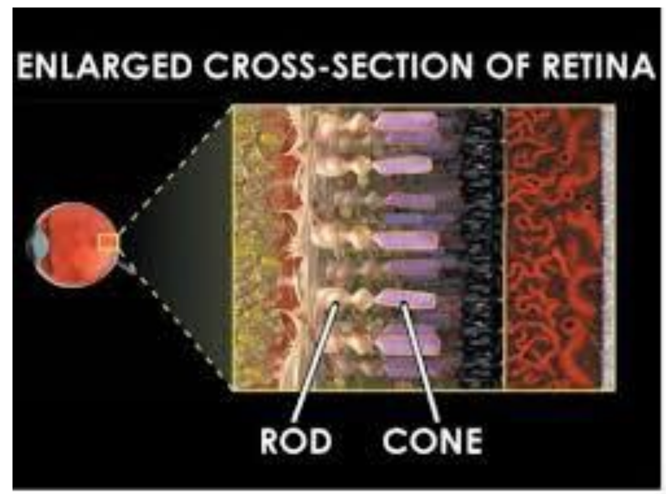




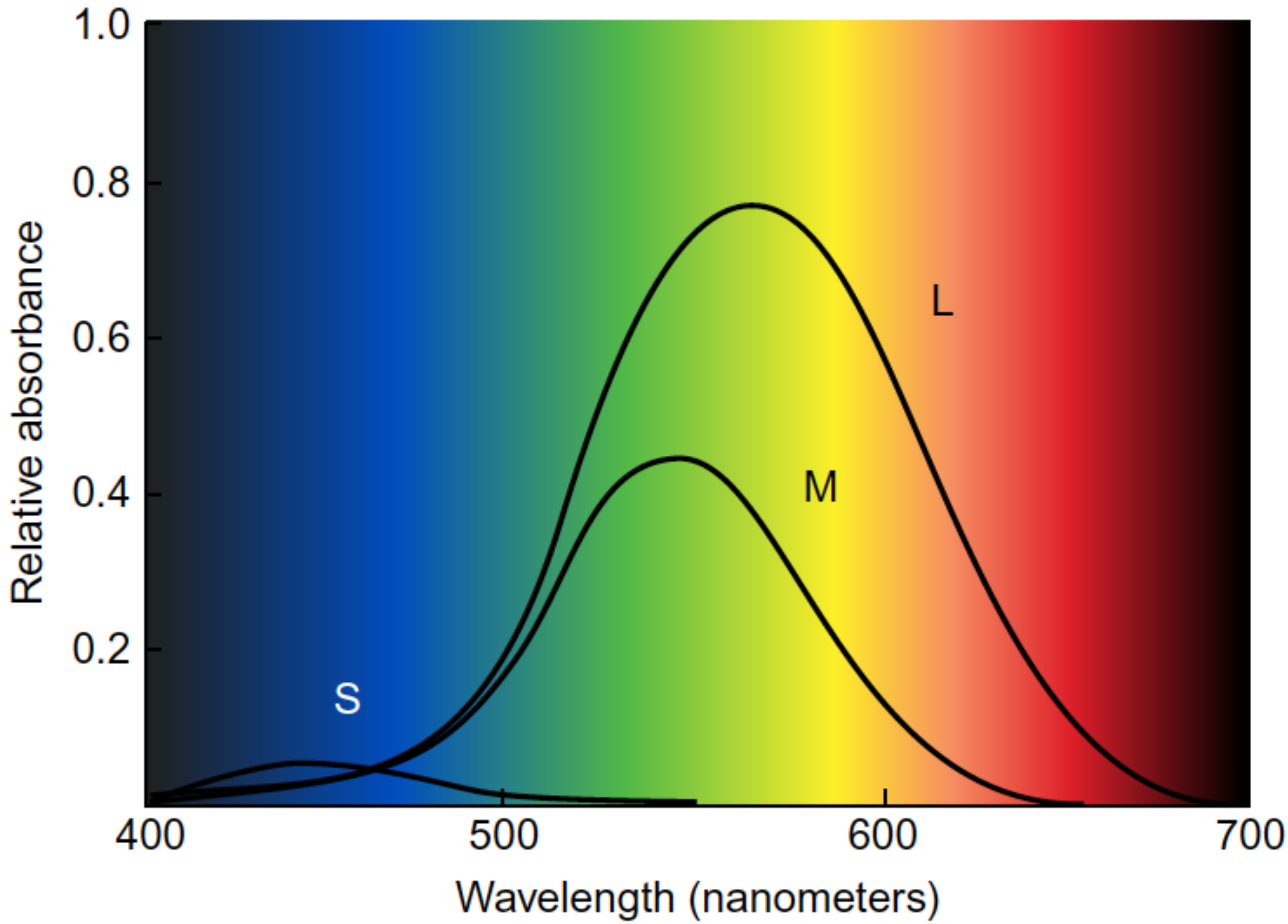
Photometry

- Perceptual study of light
- Color depends on interaction of light and the human eye



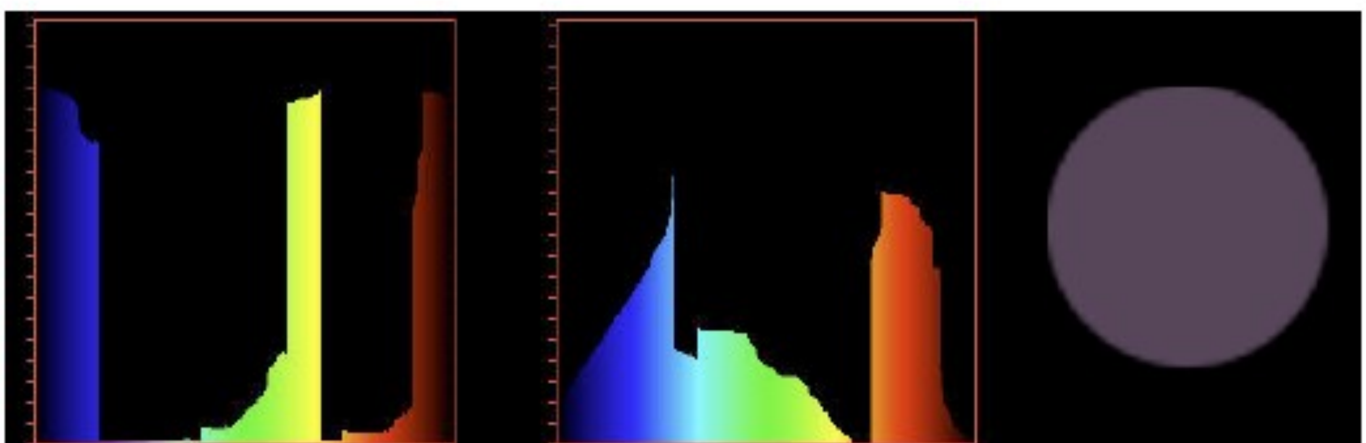


Cone Response



Tristimulus Theory

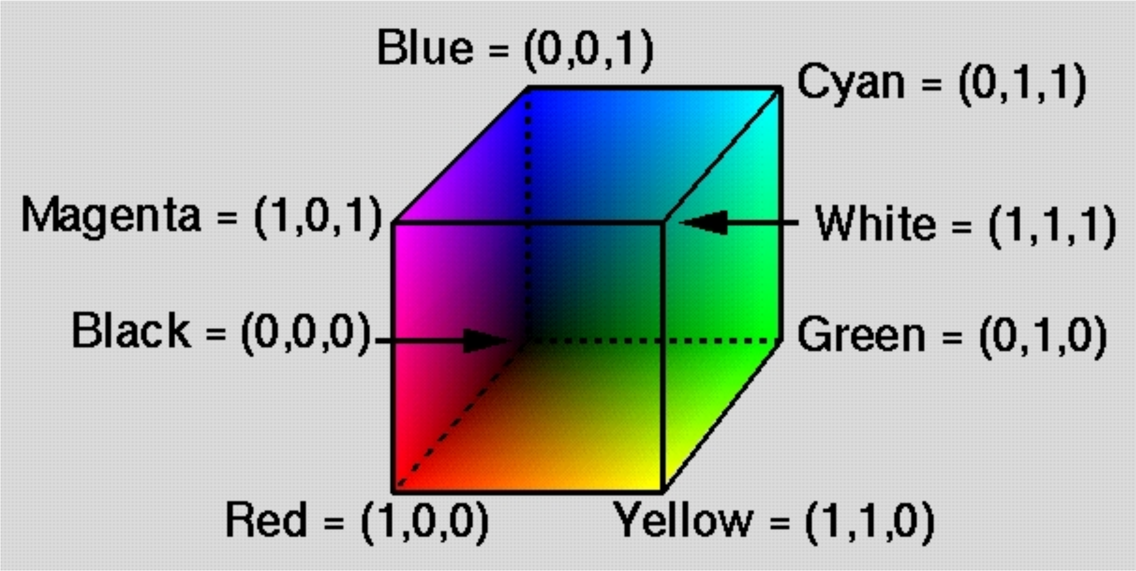
- 3 cone types suggest 3 parameters describe all colors
- Two different spectral distributions can appear the same
  - metamers

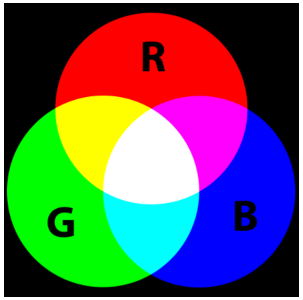


Different spectra can appear the same color (Hughes, Bell and Doppelt)

RGB Additive Color

- Red, Green, Blue
- Color model used in luminous displays (CRT, plasma, LCD)
- Physically linear
- Perceptually logarithmic
- Additive
- Designed to stimulate each kind of cone





CMY Color Space: Subtractive Color

- Cyan, Magenta, Yellow
- Color model used in pigments and reflective materials (ink,paint)
- Grade school color rules

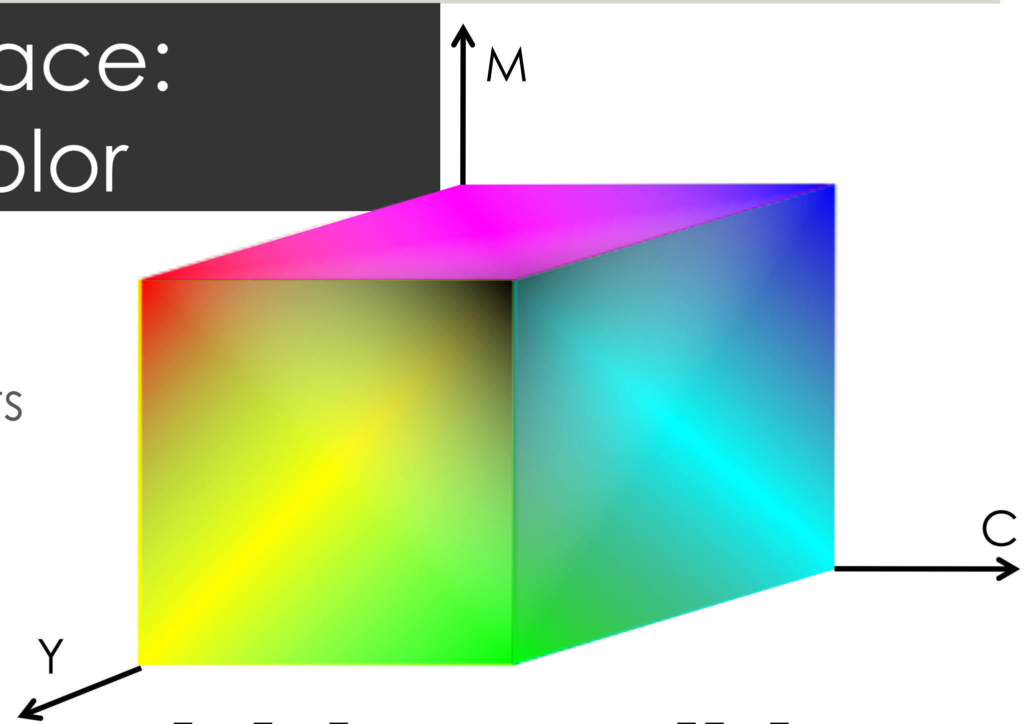
  Blue + Yellow = Green?

  Cyan + Yellow = Green
- Also CMYK (blacK)

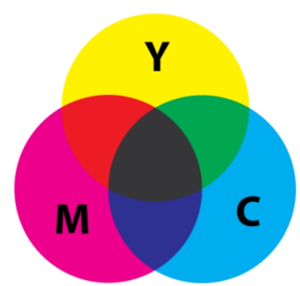
  C + M + Y = Brown?

  C + M + Y = Black (in theory)

  C + M + Y = Gray (in practice)



$$\begin{bmatrix} C \\ M \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} -1 & & & 1 \\ & -1 & & 1 \\ & & -1 & 1 \\ & & & 1 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix}$$



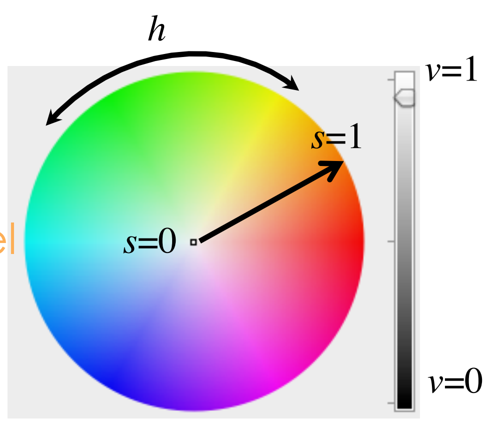
HSV Color Space

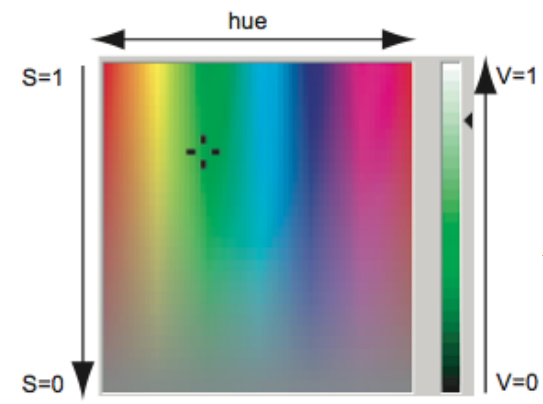
- three floating-point components in $[0,1]$

$$c = (h, s, v) \in [0,1]^3$$

- hue: tint of the color (red, green, blue, yellow, cyan, magenta, yellow, …
- saturation: strong color (s=1), grayish color (0<s<1) or gray (s=0)
- value: luminance; white (v=1), dark (0<v<1), or black (v=0)

color wheel



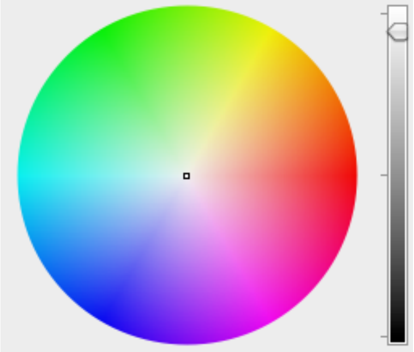


color wheel stretched onto a square

- HSV widgets: typically specify h and s in a 2D canvas and v separately (slider)
- show a ‘surface slice’ in the RGB cube

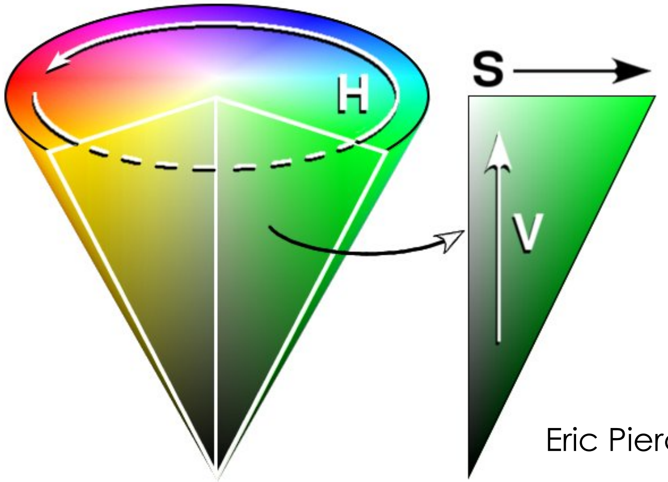
Advantages and Disadvantages

- More intuitive than RGB



- On the other hand it's not perceptually defined
  - Defined in relationship to some RGB space
  - e.g. HSV Saturation poorly models perceived lightness

HSV Color Space



Eric Pierce

HSV = Hue, Saturation, Value

- 1978, Alvy Ray Smith
- Hue [0,360] is angle about color wheel

  0° = red, 60° = yellow, 120° = green,

  180° = cyan, 240° = blue, 300° = magenta
- Saturation [0,1] is distance from gray

  S = (maxRGB – minRGB)/maxRGB
- Value [0,1] is distance from black

  V = maxRGB

Δ = maxRGB – minRGB

maxRGB = R → H = (G – B)/Δ

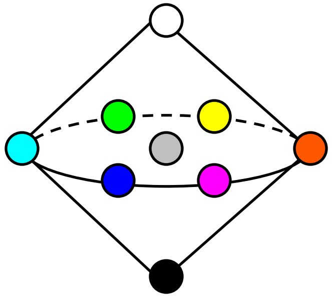
maxRGB = G → H = 2+(B – R)/Δ

maxRGB = B → H =4+ (R – G)/Δ

H = (60*H) mod 360

HLS = Hue, Saturation, Lightness

- Double cone, saturation in middle



HSV to RGB and back….

```
void rgb2hsv(float  r, float  g, float  b,
             float& h, float& s, float& v)
{
  float M = max(r,max(g,b));
  float m = min(r,min(g,b));
  float d = M-m;
  v = M;                      //value = max(r,g,b)
  s = (M>0.00001)? d/M:0;     //saturation
  if (s==0) h = 0;            //achromatic case, hue=0 by convention
  else                        //chromatic case
  {
    if (r==M)      h =     (g-b)/d;
    else if (g==M) h = 2 + (b-r)/d;
    else           h = 4 + (r-g)/d;
    h /= 6;
    if (h<0) h += 1;
  }
}
```

Listing 3.2. Mapping colors from RGB to the HSV space.

```
void hsv2rgb(float  r, float  g, float  b,
             float& h, float& s, float& v)
{
  int   hueCase = (int)(h*6);
  float frac    = 6*h-hueCase;
  float lx      = v*(1 - s);
  float ly      = v*(1 - s*frac);
  float lz      = v*(1 - s*(1 - frac));
  switch (hueCase)
  {
    case 0:
    case 6: r=v;  g=lz; b=lx; break;  // 0<hue<1/6
    case 1: r=ly; g=v;  b=lx; break;  // 1/6<hue<2/6
    case 2: r=lx; g=v;  b=lz; break;  // 2/6<hue<3/6
    case 3: r=lx; g=ly; b=v;  break;  // 3/6<hue/4/6
    case 4: r=lz; g=lx; b=v;  break;  // 4/6<hue<5/6
    case 5: r=v;  g=lx; b=ly; break;  // 5/6<hue<1
  }
}
```

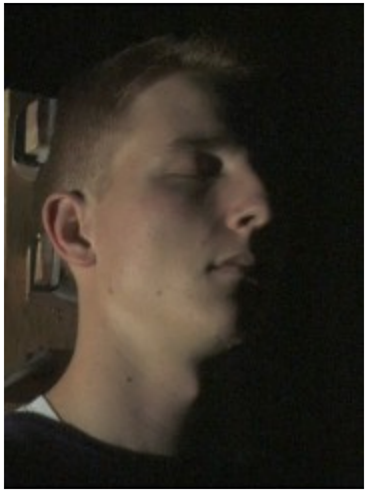
Listing 3.3. Mapping colors from HSV to the RGB space.

Grassmann's Law

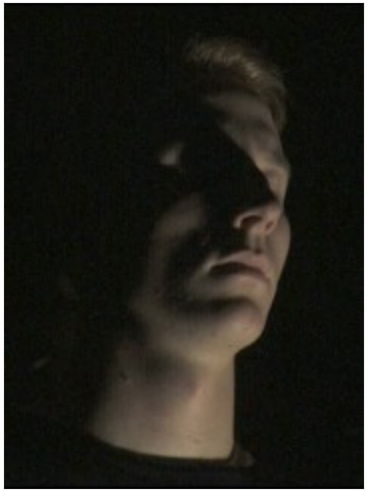
- Chromatic sensation is linear
  - Light 1 is (R1,G1,B1)
  - Light 2 is (R2, G2, B2)
  - Then:
    a(Light 1) + b(Light 2) matches
    (aR1+bR2, aG1+bG2, aB1 + bB2)

$$R(L_1) + R(L_2) = R(L_1 + L_2)$$

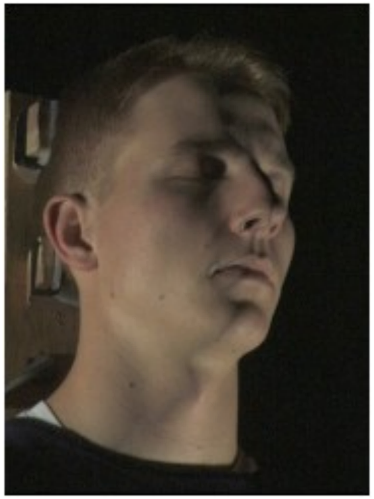
Light Adds



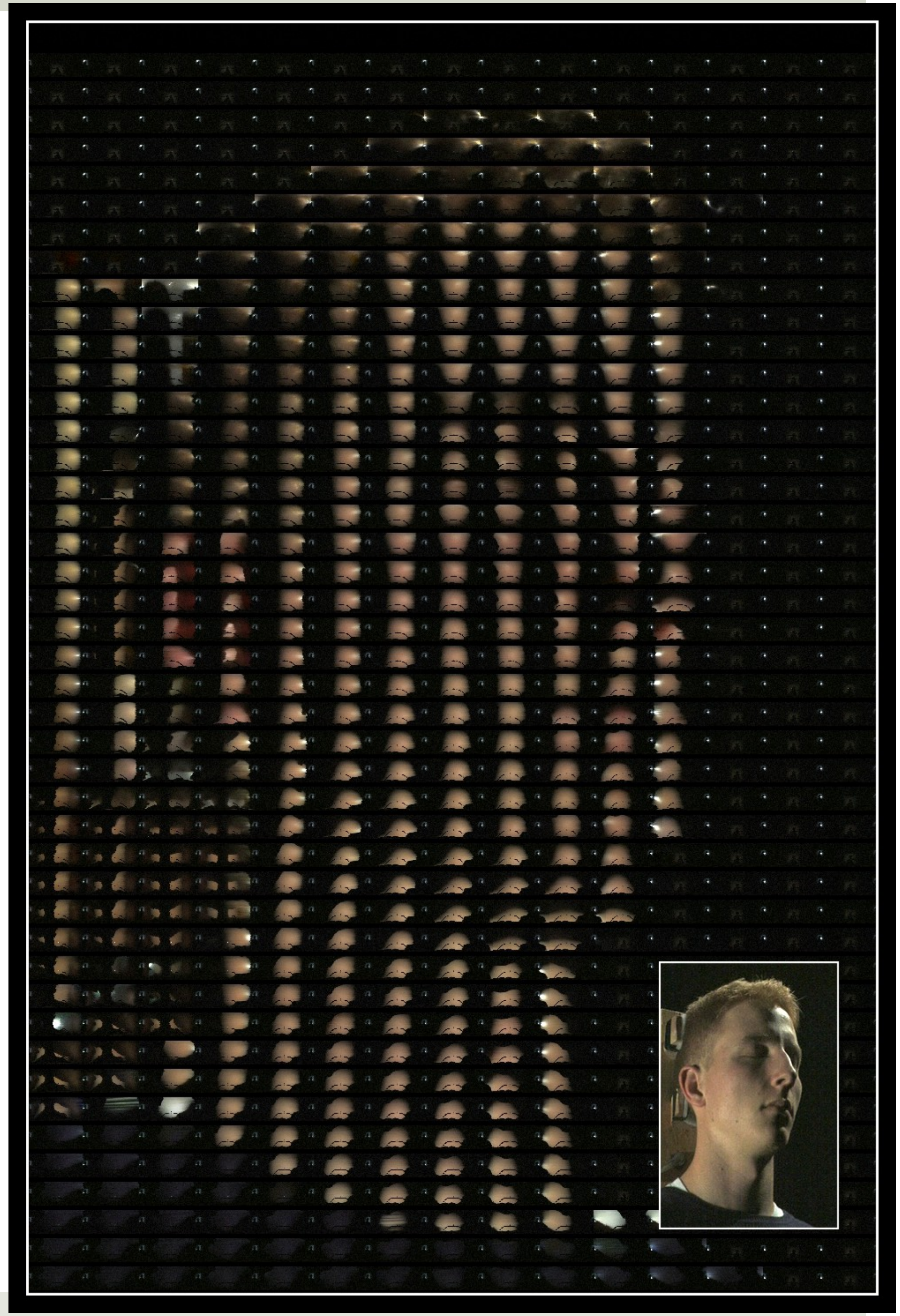
+



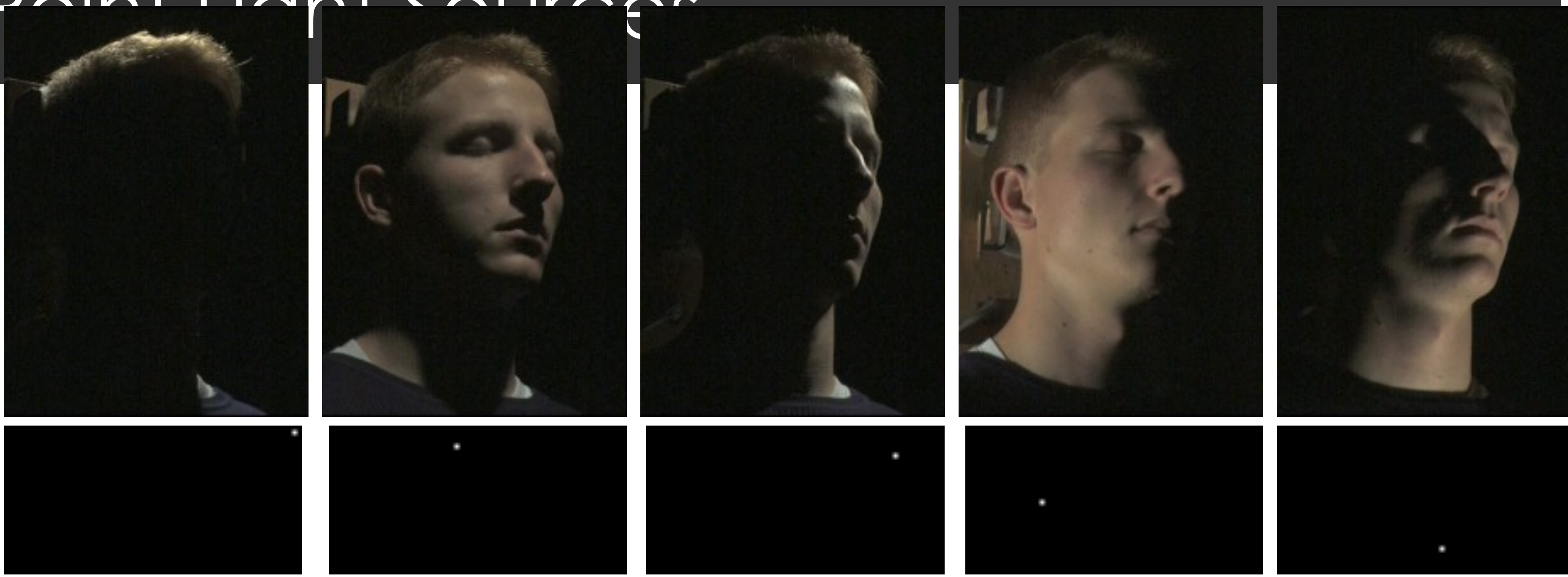
=



Light Stage



Point Light Sources



Debevec et al., Acquiring the Reflectance Field of a Human Face,
Proc. SIGGRAPH 2000

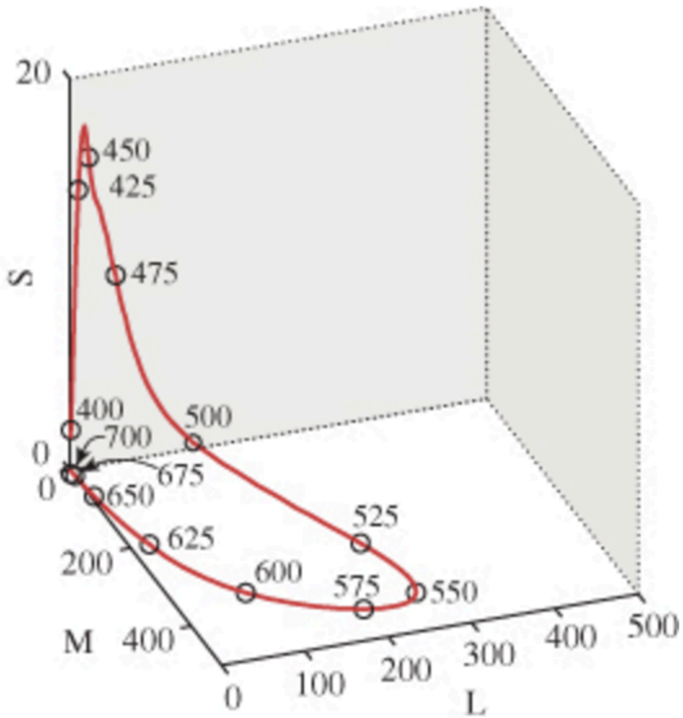
Environment Lighting

Debevec et al., Acquiring the Reflectance Field of a Human Face, Proc. SIGGRAPH 2000

Color Matching Experiments

- Wright and Guild (1920s)
  - Choose lights of 3 different primary colors
  - Show human subject a single-wavelength test light
  - Have subject match test light
    - Use a weighted combination of primaries
    - Weight is luminence
- CIE standard primaries
  - Red (R): 700nm
  - Green (G): 546.1 nm
  - Blue(B): 435.8 nm

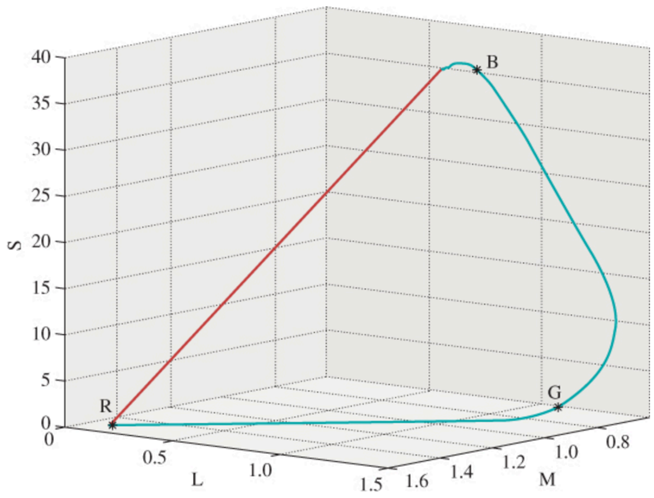
Human Response to Monospectral Light



Points on red curve are wavelengths

Curve position in space shows the response of the the L, M, and S cones

Human Response to Monospectral Light

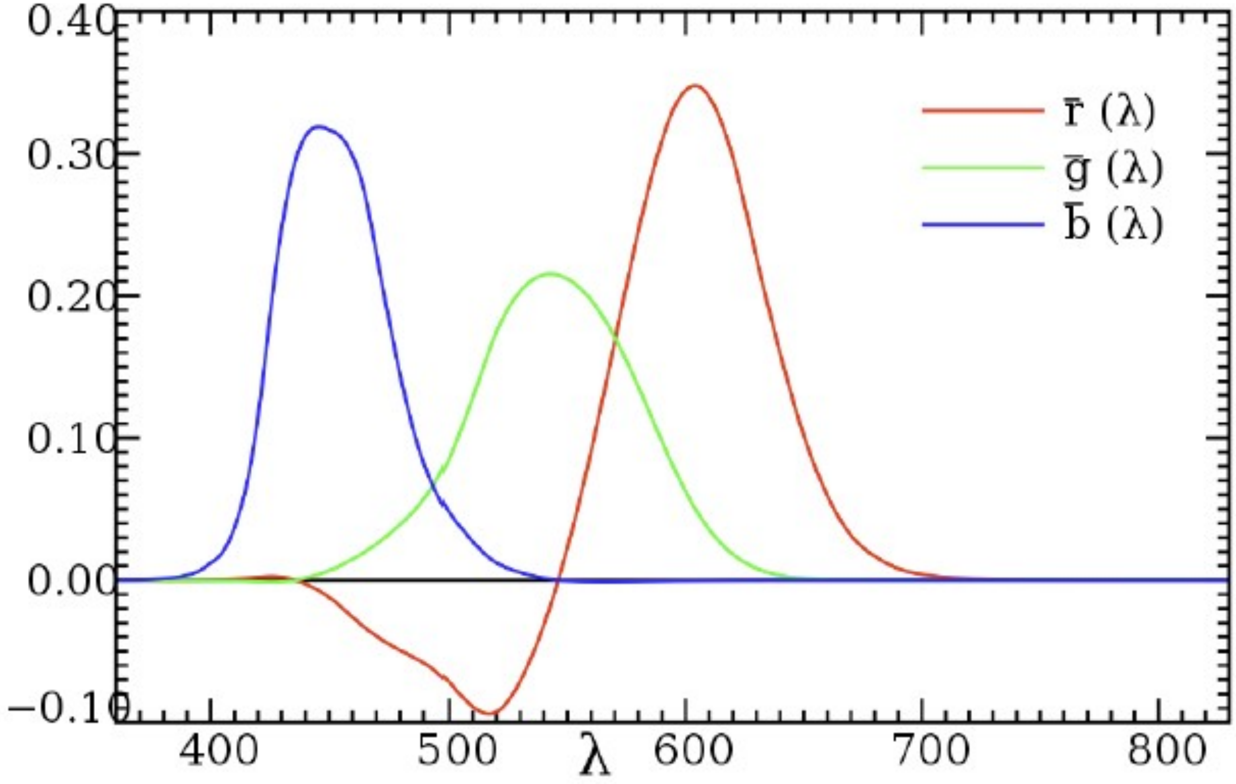


The set of responses to all combinations of monospectral light forms a cone…shaped a little like a horseshoe.

A slice through the cone is shown here.

Can a linear combination of 3 different wavelengths generate all possible color responses?

Color Matching Function for CIE RGB



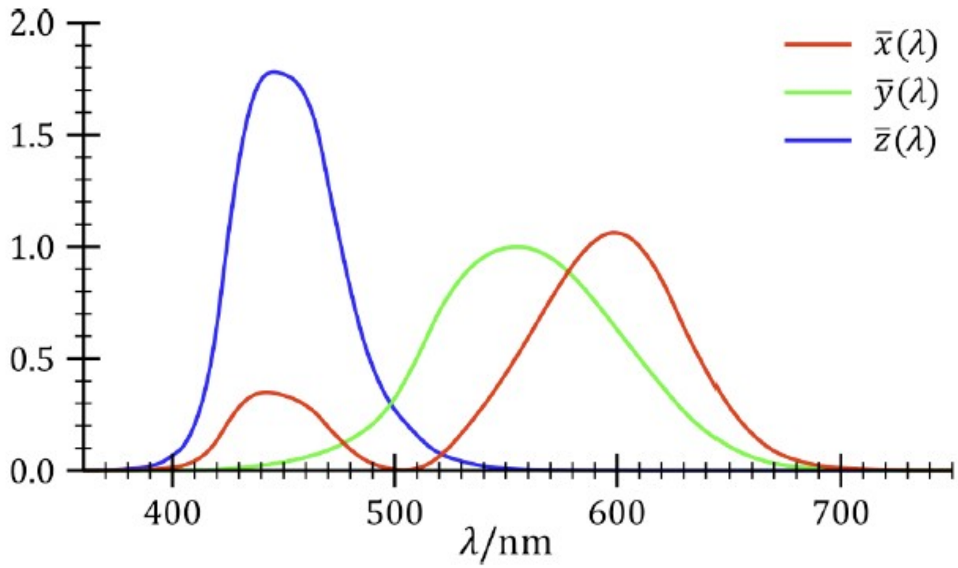
Amounts of the red, green and blue primaries needed to match any color [1]

CIE RGB Color Space

- Experiments by the International Commission on Illumination
  - Commission internationale de l'éclairage
- Defined CIE RGB…you'll notice the negative on the red curve
  - What does this mean happened physically in the experiment?
  - Example: orange = 0.45 R + 0.45 G – 0.1B
  - We can empirically discover that by allowing test subject to add a primary to the test color:

    orange+ 0.1B = 0.45 R + 0.45 G

Color Matching Functions for CIE XYZ

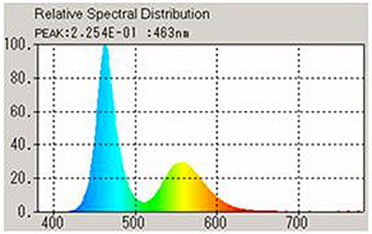


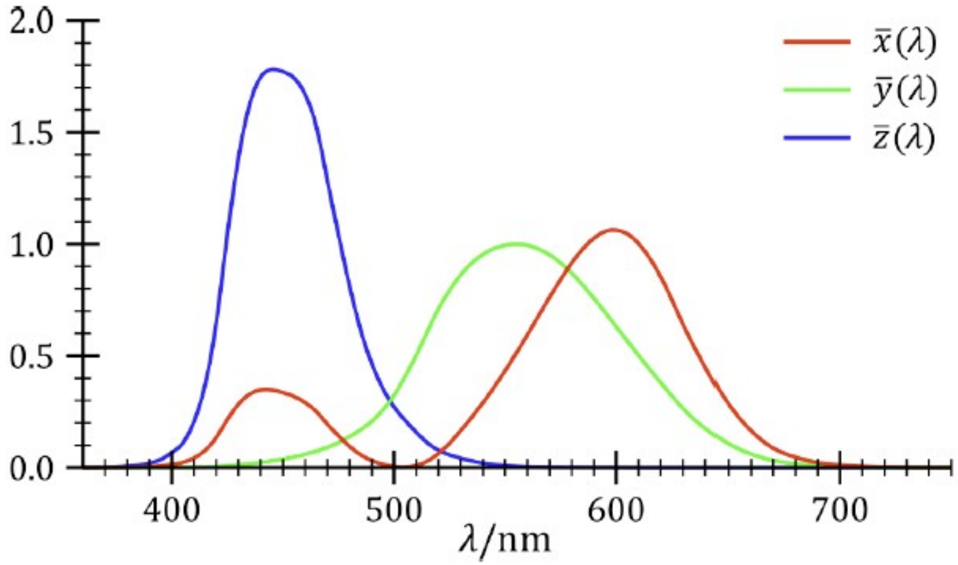
Amounts of the XYZ primaries needed to match any color
($\bar{y}$ function is precisely CIE-standardized photopic luminous efficiency, 1931)

- CIE XYZ is another color space based on the experiments…
  - But adjusted to have non-negative functions
- Think of X, Y, and Z being primary colors…but not physically realizable

CIE XYZ Color Space

White LED





Amounts of the XYZ primaries needed to match any color
($\bar{y}$ function is precisely CIE-standardized photopic luminous efficiency, 1931):

A light with spectral power distribution P can be expressed as $p_xX + p_yY + p_zZ$

where

$$p_x = k\int P(\lambda)\bar{x}(\lambda)d\lambda$$

$$p_y = k\int P(\lambda)\bar{y}(\lambda)d\lambda$$

$$p_z = k\int P(\lambda)\bar{z}(\lambda)d\lambda$$

k is 680lmW^{-1}

CIE Color Space

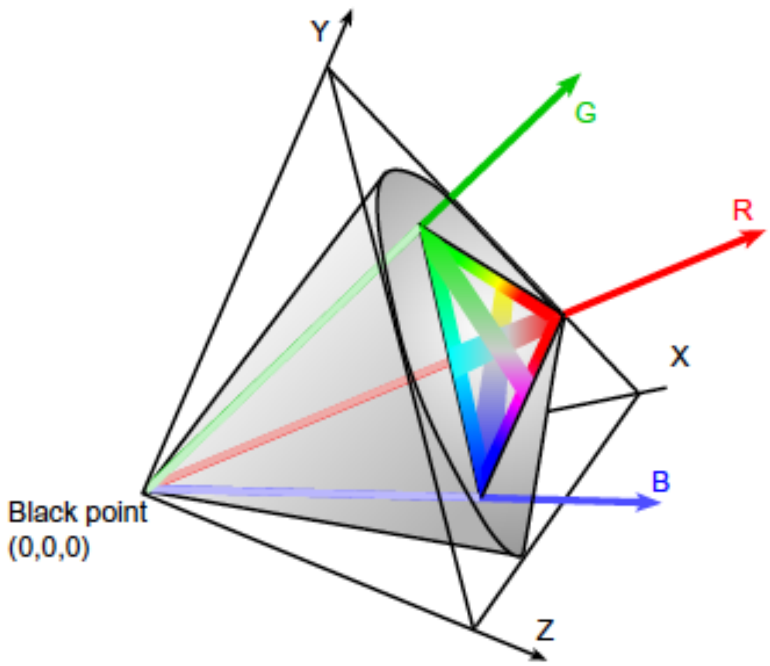


Figure 4.6 The *X*, *Y*, and *Z* axes represent the CIE standard virtual primaries. Within the positive space defined by the axes, the gamut of perceivable colors is represented as a gray solid. The colors that can be created by means of the red, green, and blue monitor primaries are defined by the pyramid enclosed by the *R*, *G*, and *B* lines.

From *Information Visualization* by Colin Ware

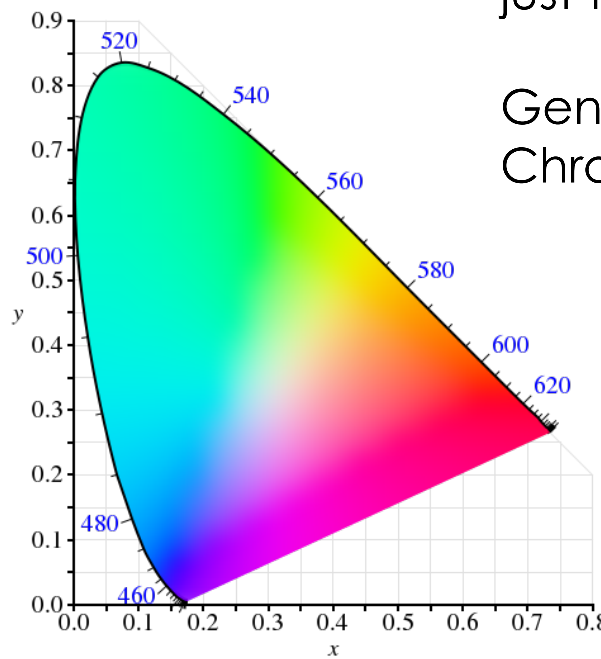
xyY: Separates Chromaticity and Luminence

Formed from X,Y,Z expression of a color

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

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

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



Note: $x + y + z = 1$

Used to specify intensity independent colors using just the x,y coordinates

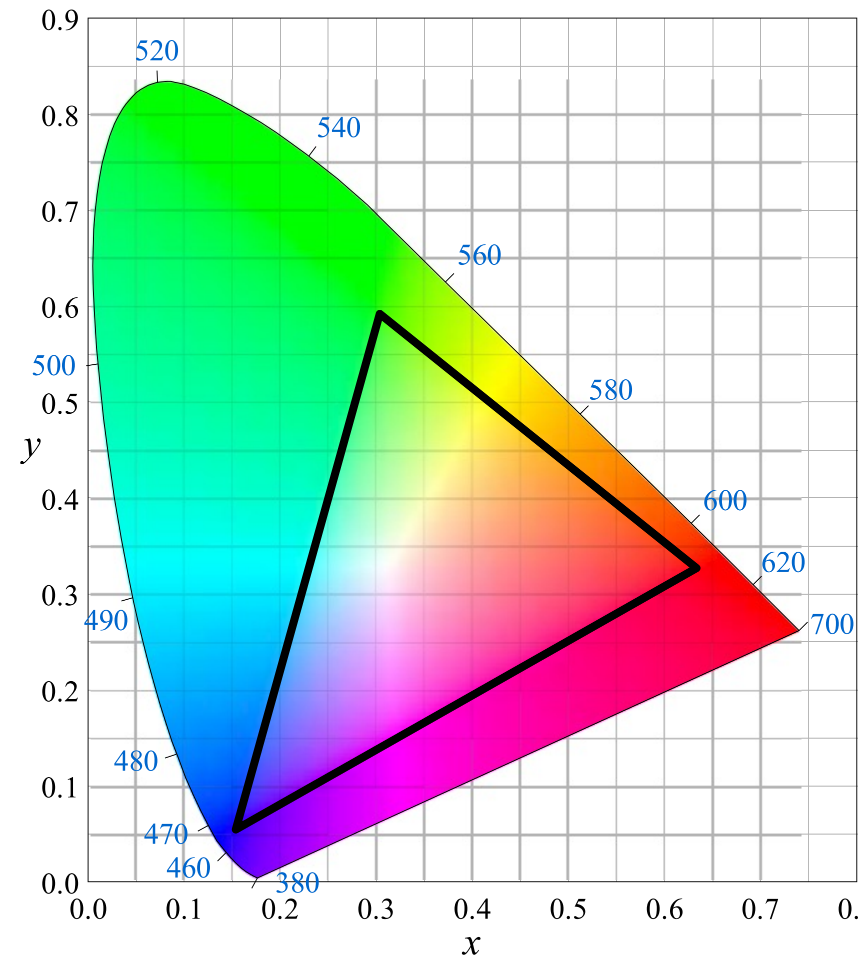
Generates the CIE Chromaticity diagram

CIE Chromaticity Diagram

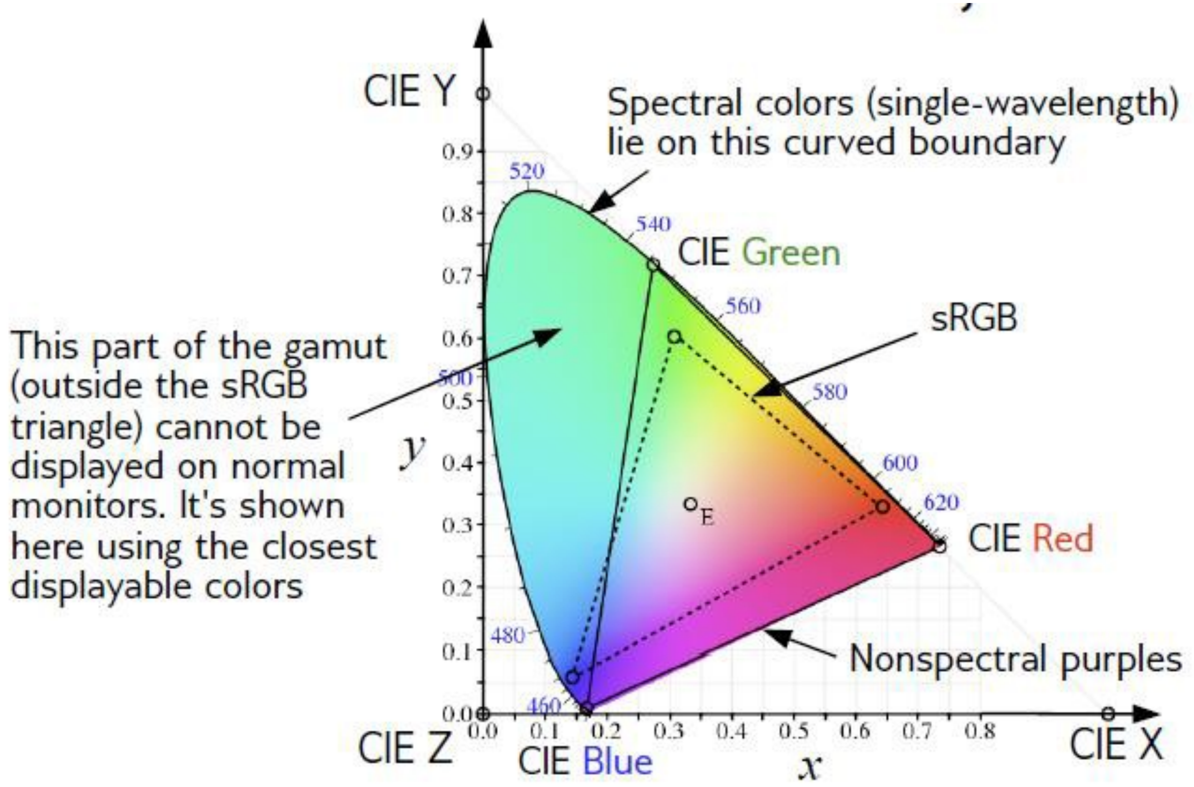
- What runs around the edge of the horseshoe?
- What is inside the horseshoe?
- **Gamut**: Portion of the spectrum reproduced by a given color space

  Any guess as to what the triangle represents?
- **Quick Quiz:**
  Are the colors shown inside the diagram correct?

  Why or why not?



CIE XYZ Gamut

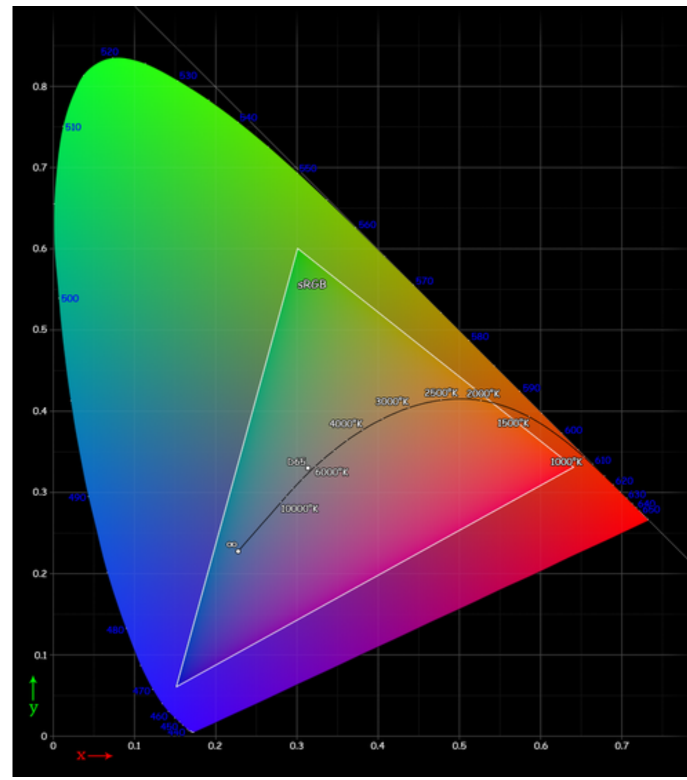


All visible chromaticities mapped to xy plane

sRGB

- sRGB is the standard RGB color space used almost everywhere

Chromaticity	Red	Green	Blue	White point
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
Y	0.2126	0.7152	0.0722	1.0000



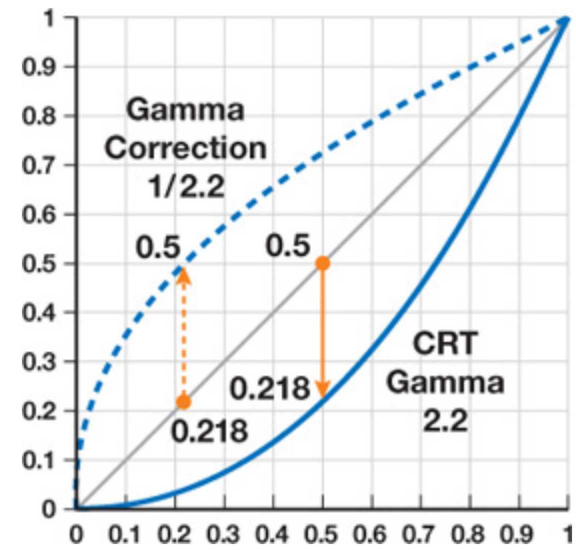
- Using the values above, you can generate a matrix to convert from sRGB to XYZ and back using its inverse…

Gamma Correction

- We perceive differences in intensity more carefully for darker shades
- Monitors accommodate this feature

$$I = V^{\gamma}$$

- Gamma usually between 2 and 2.5



(a) (b)

Figures from The Importance of Being Linear
Larry Gritz and Eugene d'Eon
NVIDIA Corporation

Gamma Correction Example

- A red value of 0.5 is between ¼ and 1/5 as bright as a red value of 1.0
- If we transform:

$$(0.5)^{\frac{1}{2.2}} = 0.729$$

we get a red value half as bright as 1.0 when displayed.