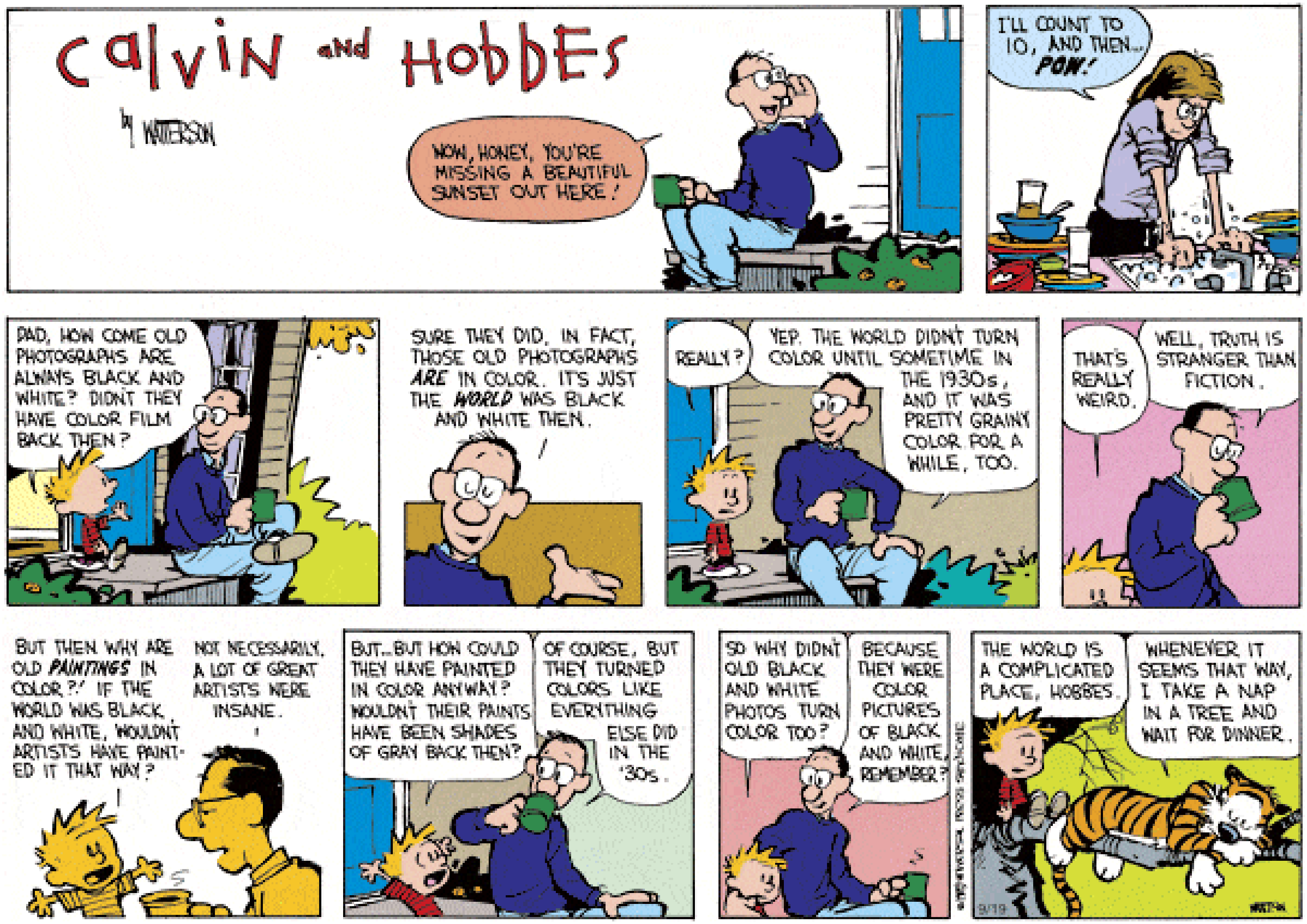
Color

CS 498VR: Virtual Reality

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

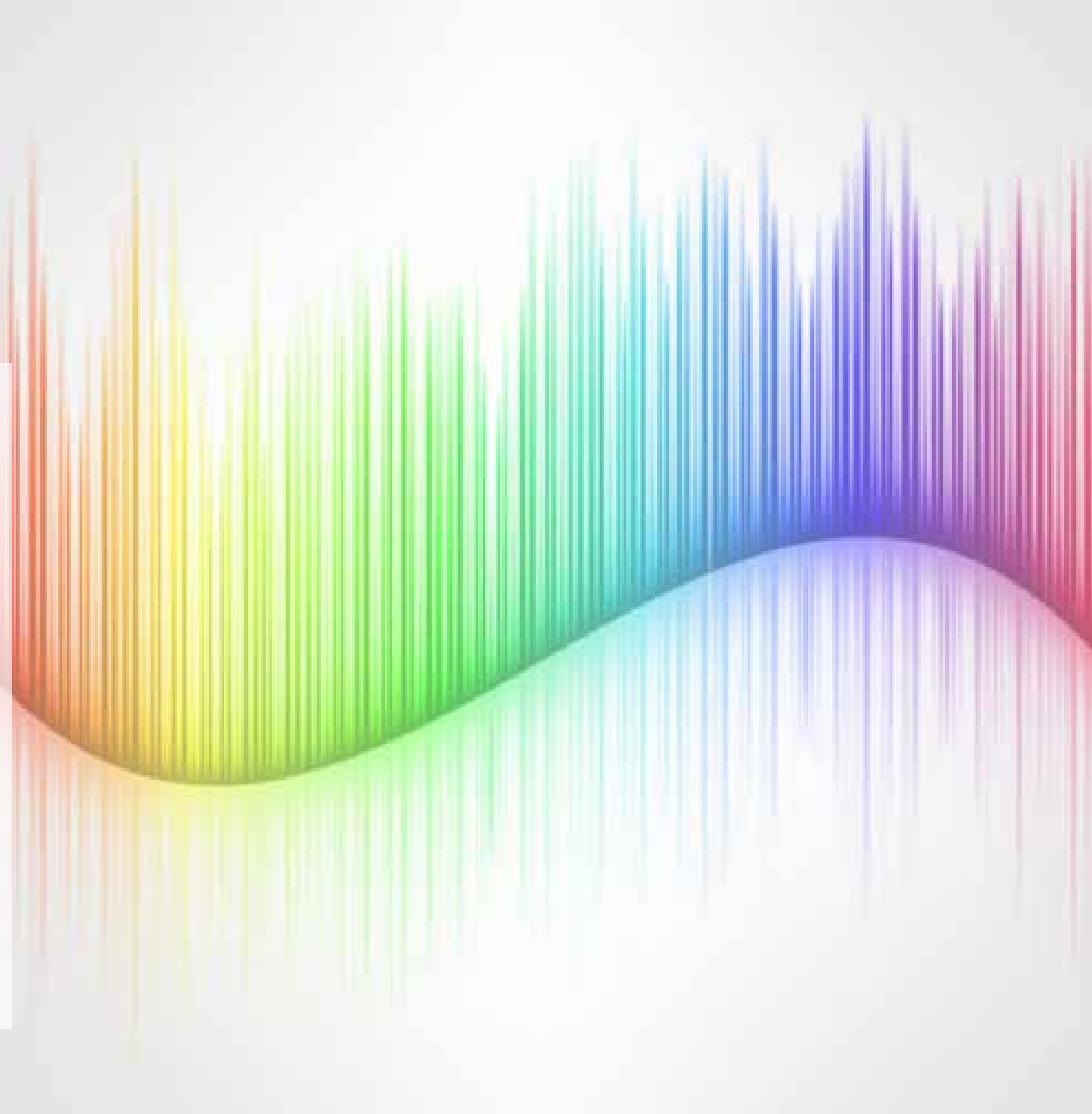
Eric Shaffer

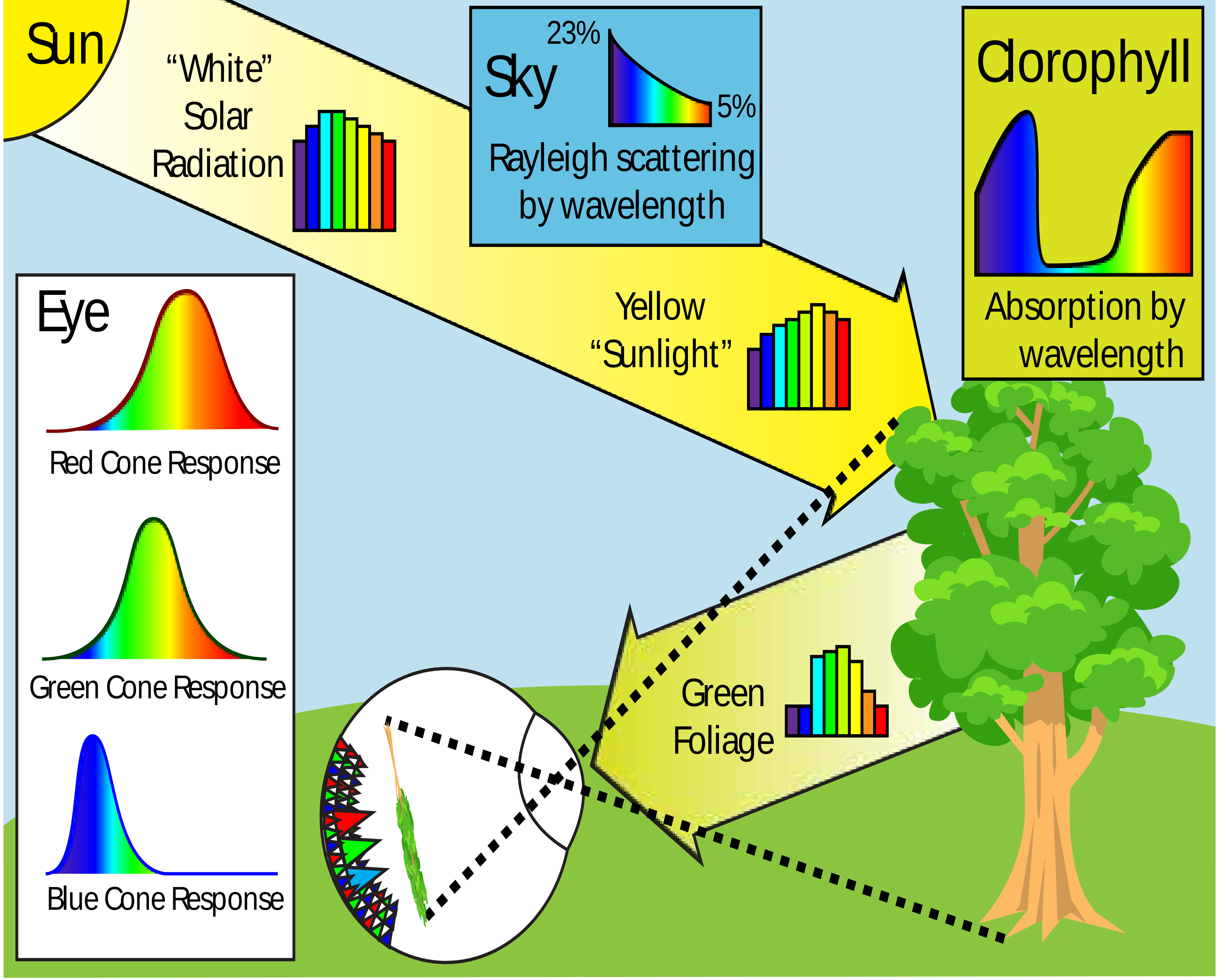
Color is Weird


calvin and HOBBES
by WATTERSON
WOW, HONEY, YOU'RE MISSING A BEAUTIFUL SUNSET OUT HERE!
I'LL COUNT TO 10, AND THEN... POW!
DAD, HOW COME OLD PHOTOGRAPHS ARE ALWAYS BLACK AND WHITE? DIDN'T THEY HAVE COLOR FILM BACK THEN?
SURE THEY DID. IN FACT, THOSE OLD PHOTOGRAPHS ARE IN COLOR. IT'S JUST THE WORLD WAS BLACK AND WHITE THEN.
REALLY?
YEP. THE WORLD DIDN'T TURN COLOR UNTIL SOMETIME IN THE 1930s, AND IT WAS PRETTY GRAINY COLOR FOR A WHILE, TOO.
THAT'S REALLY WEIRD.
WELL, TRUTH IS STRANGER THAN FICTION.
BUT THEN WHY ARE OLD PAINTINGS IN COLOR?! IF THE WORLD WAS BLACK AND WHITE, WOULDN'T ARTISTS HAVE PAINTED IT THAT WAY?
NOT NECESSARILY. A LOT OF GREAT ARTISTS WERE INSANE.
BUT... BUT HOW COULD THEY HAVE PAINTED IN COLOR ANYWAY? WOULDN'T THEIR PAINTS HAVE BEEN SHADES OF GRAY BACK THEN?
OF COURSE, BUT THEY TURNED COLORS LIKE EVERYTHING ELSE DID IN THE '30s.
SO WHY DIDN'T OLD BLACK AND WHITE PHOTOS TURN COLOR TOO?
BECAUSE THEY WERE COLOR PICTURES OF BLACK AND WHITE, REMEMBER?
THE WORLD IS A COMPLICATED PLACE, HOBBES.
WHENEVER IT SEEMS THAT WAY, I TAKE A NAP IN A TREE AND WAIT FOR DINNER.
9/19

Color

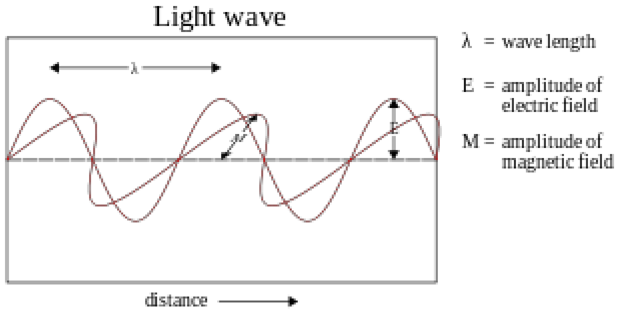
- Color is a perceptual phenomenon
- A frequency spectrum of light is a physical phenomenon
- In computer graphics, we need to specify colors
    - We define “color spaces”
        - In a color space, points correspond to colors
    - We can then work with colors mathematically
- Ideally, a color space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

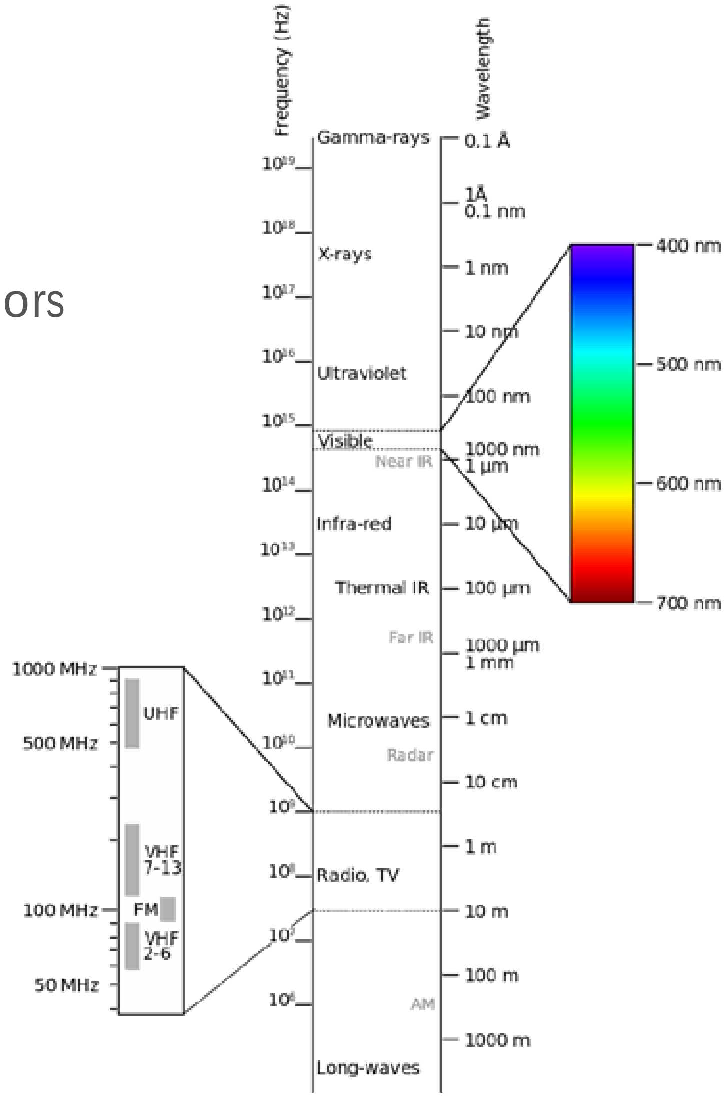



Sun
“White”
Solar
Radiation
Sky
23%
5%
Rayleigh scattering
by wavelength
Clorophyll
Absorption by
wavelength
Yellow
“Sunlight”
Eye
Red Cone Response
Green Cone Response
Blue Cone Response
Green
Foliage

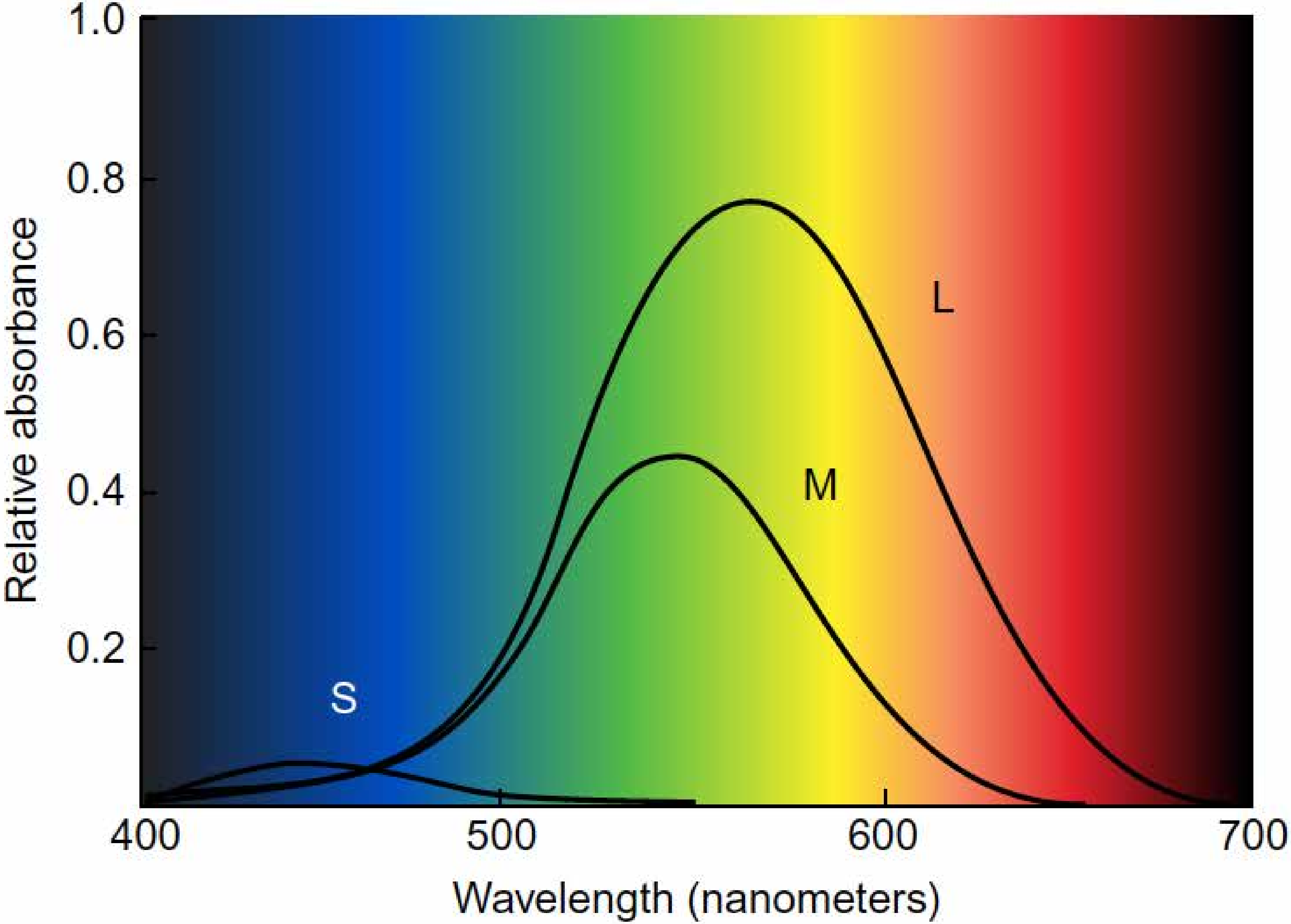
Light and Color

- 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


Light wave
λ
distance
λ = wave length
E = amplitude of electric field
M = amplitude of magnetic field

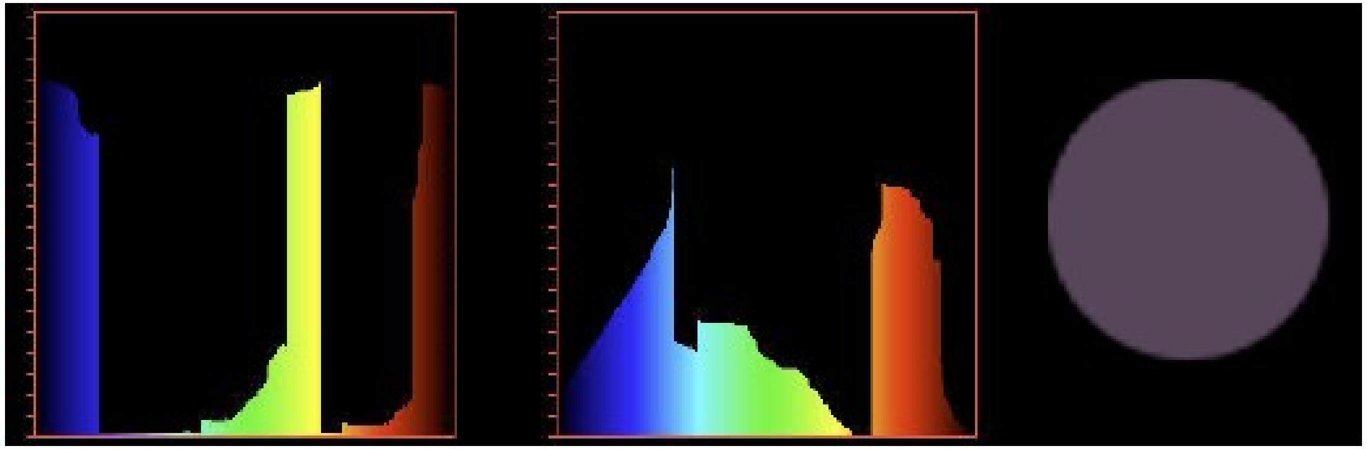


Cone Response



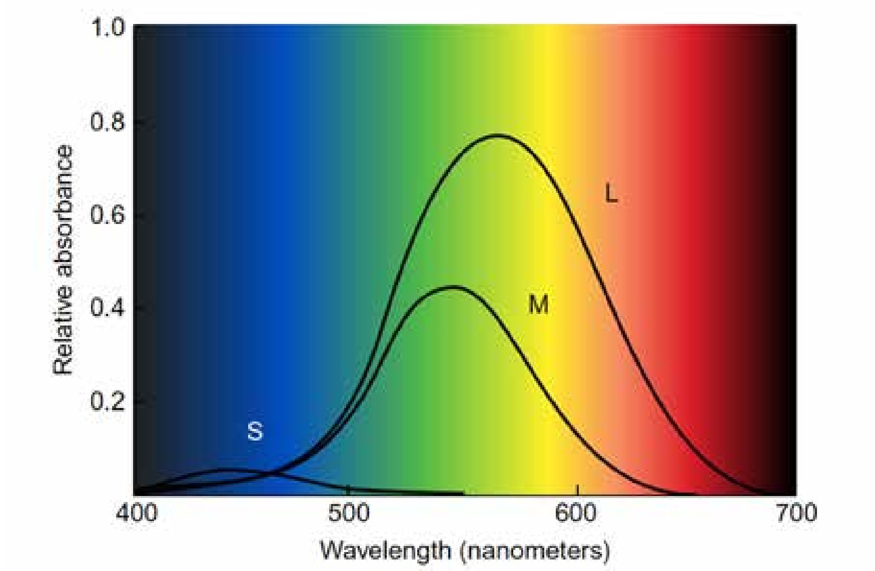
Tristimulus Theory

- 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)

More on Metamers



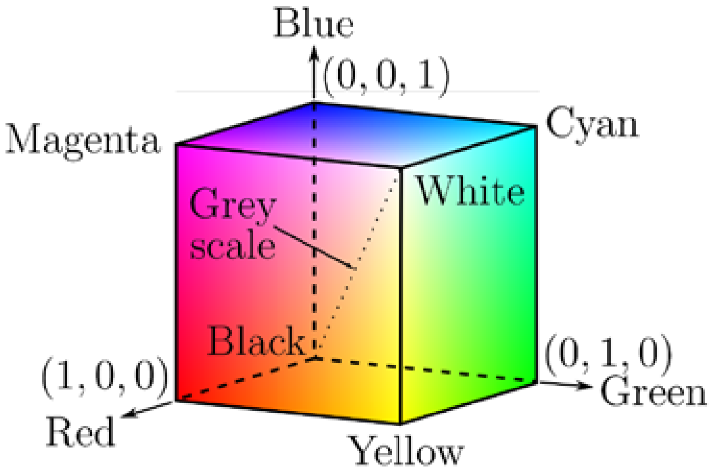
- Imagine you see a yellow laser (580nm)
  - You do not have cone that senses just yellow
  - Your perception is based on an activation of green(M) and red(L) cones
  - Both have sensitivity ranges including 580nm

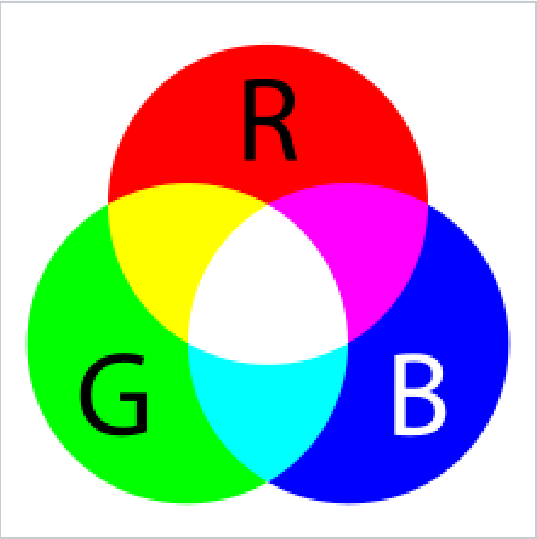
- You would have the same response to a mix of 2 non-yellow lights
  - Maybe some green at 533nm and some red at 564nm
  - ...and you would see yellow

- This blending is the principle behind RGB displays

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





Additive color mixing: adding red to green yields yellow; adding red to blue yields magenta; adding green to blue yields cyan; adding all three primary colors together yields white.

CMY Color Space: Subtractive Color

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

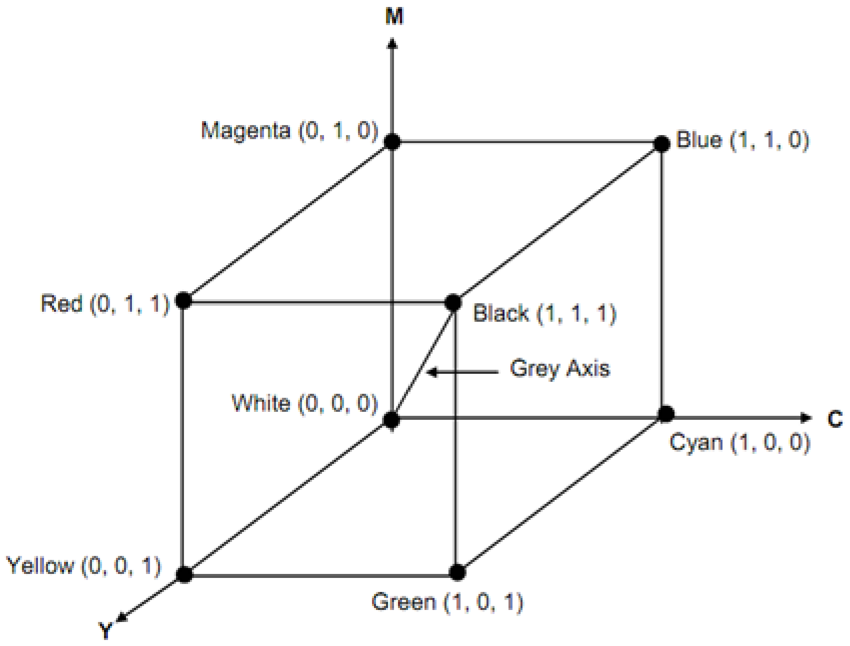
  Blue + Yellow = Green?

  Cyan + Yellow = Green
- Also CMYK (blacK)

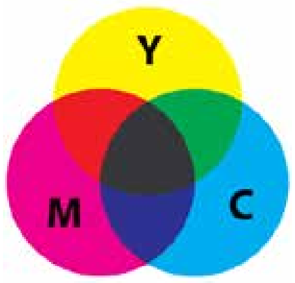
  C + M + Y = Brown?

  C + M + Y = Black (in theory)

  C + M + Y = Gray (in practice)



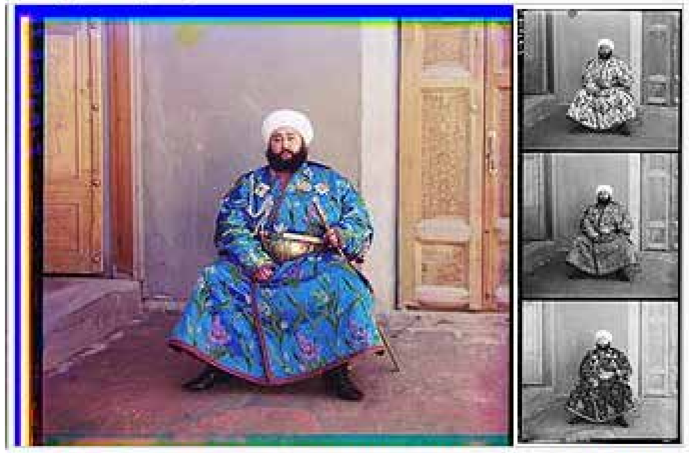
$$\begin{bmatrix} C \\ M \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} -1 & & & 1 \\ & -1 & & 1 \\ & & -1 & 1 \\ & & & 1 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix}$$



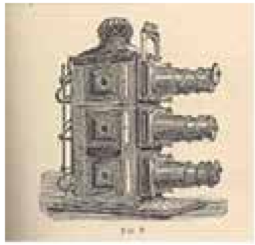
Early Color Photography

The Sergei Mikhailovich Prokudin-Gorskii Collection features color photographic surveys of the vast Russian Empire made between ca. 1905 and 1915.

Prokudin-Gorskii created his negatives by using a camera that exposed one oblong glass plate three times in rapid succession through three different color filters: blue, green, and red. For formal presentations, he printed positive glass slides of these negatives and projected them through a triple lens magic lantern. Prokudin-Gorskii would project the slide through the three lenses, and, with the use of color filters, superimpose the three exposures to form a full color image on a screen.



A photograph of Mohammed Alim Khan (1880–1944), Emir of Bukhara, taken in 1911 by Sergey Prokudin-Gorsky using three exposures with blue, green, and red filters.



HSV Color Space

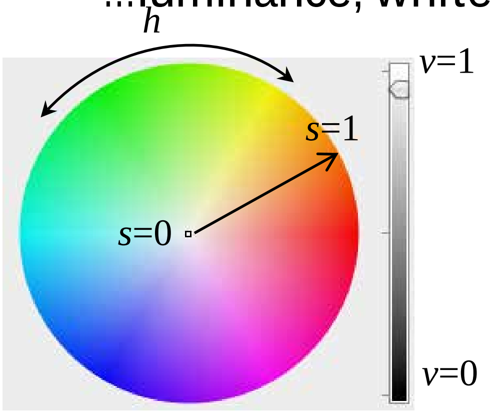
HSV = Hue, Saturation, Value
1978, Alvy Ray Smith

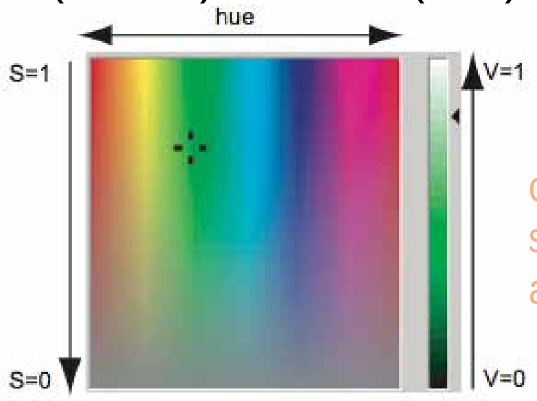
$$c=(h,s,v)\in[0,1]^3$$

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

- 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



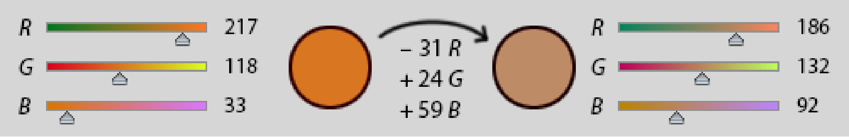


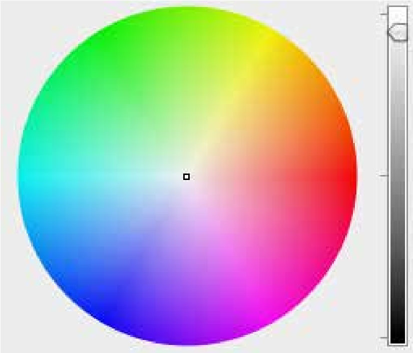
color wheel stretched onto a square

- 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

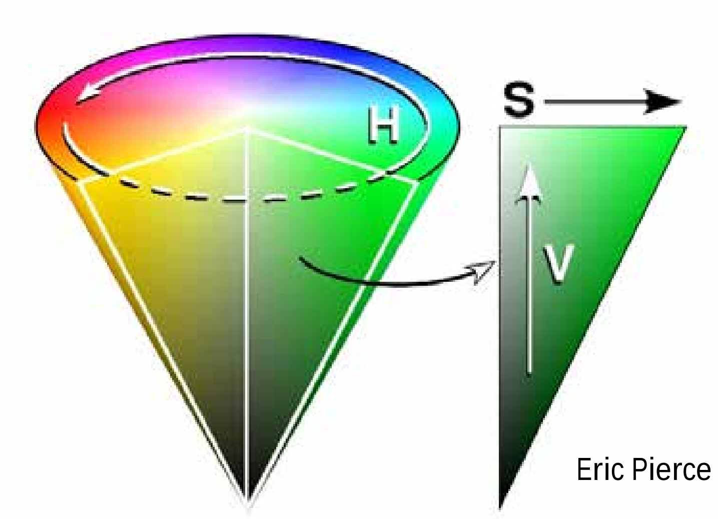
- More intuitive than RGB





- On the other hand it’s still not perceptually defined

RGB to HSV conversion



Eric Pierce

- 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

D = maxRGB – minRGB

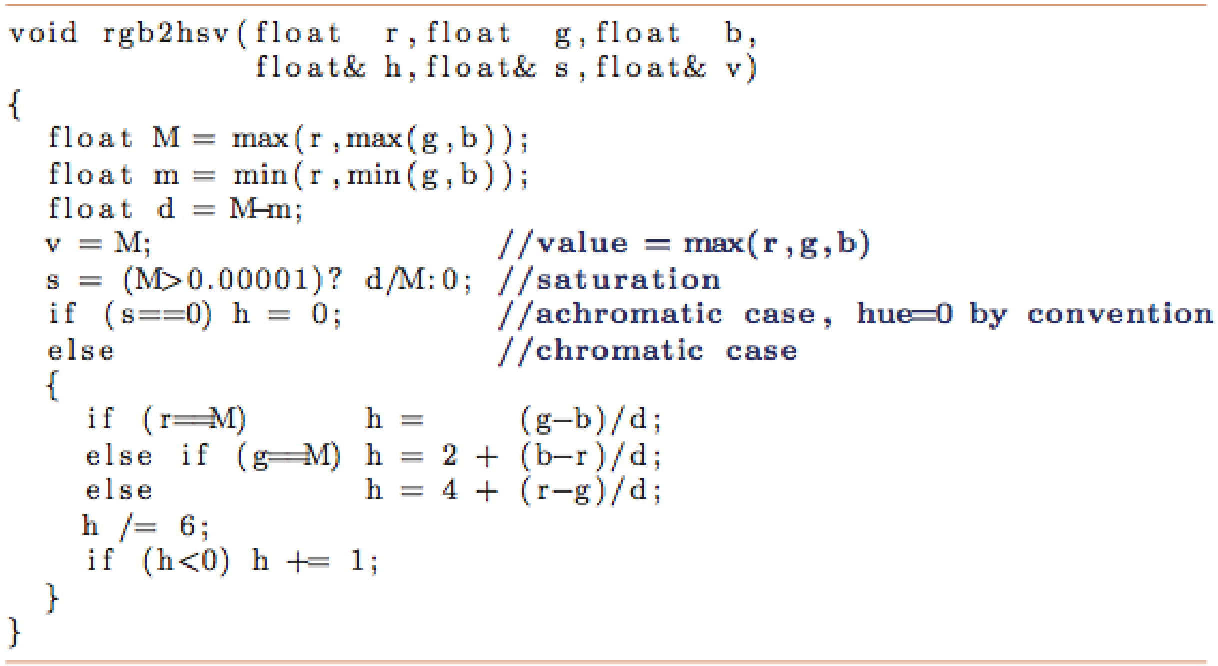
if maxRGB == R à H = (G – B)/D

if maxRGB == G à H = 2+(B – R)/D

If maxRGB == B à H =4+ (R – G)/D

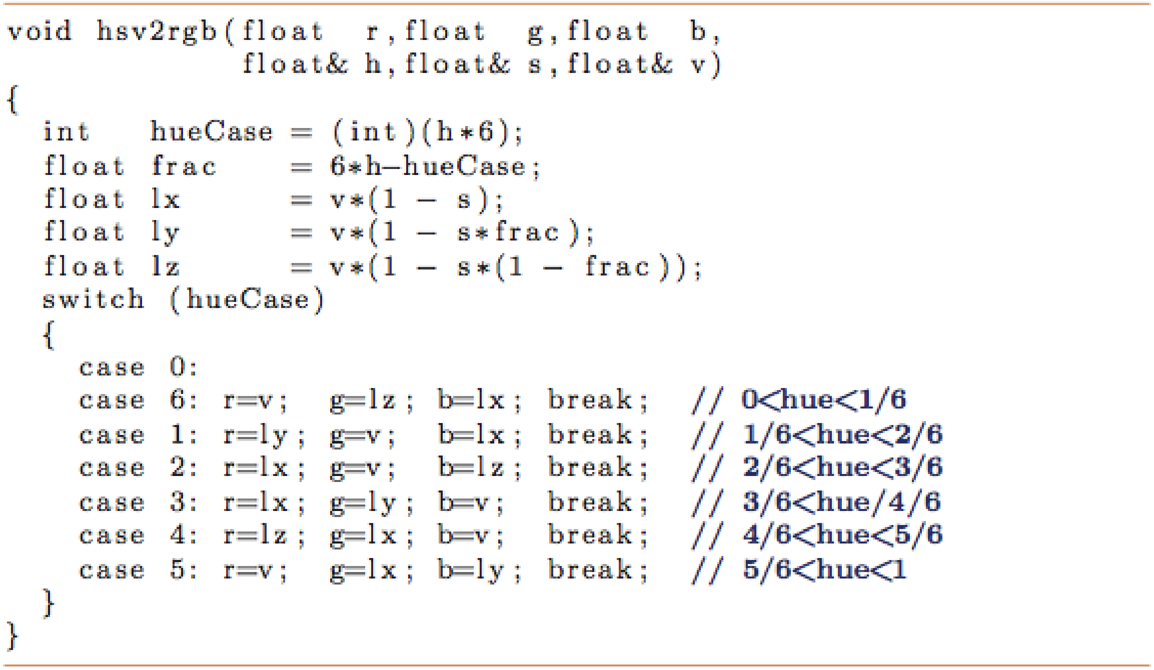
H = (60*H) mod 360

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;
  }
}
```

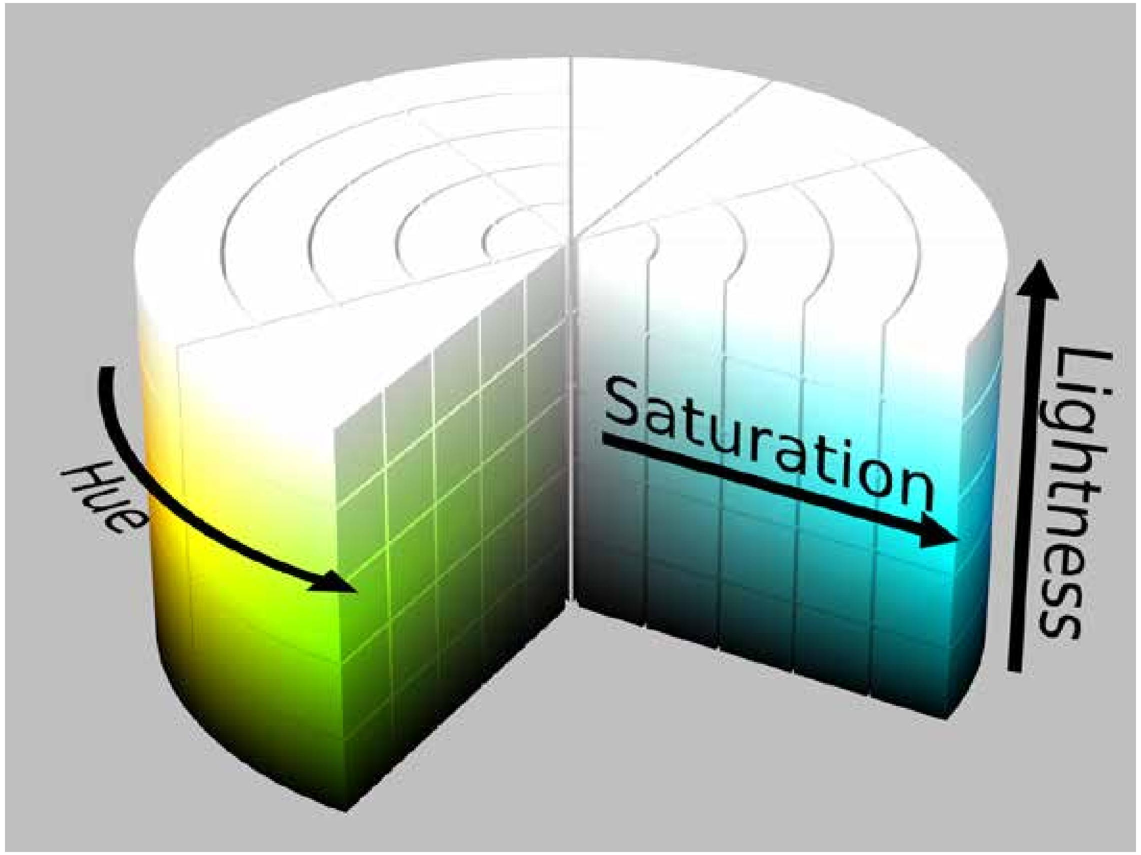
Listing 3.2. Mapping colors from RGB to the HSV space.



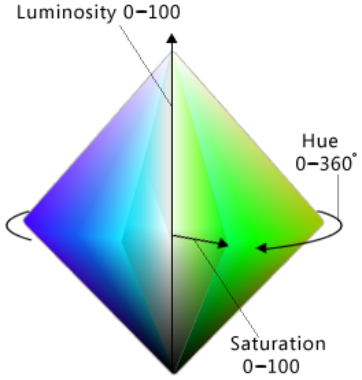
```
void hsv2rgb(float r,float g,float b,
             float& h,float& s,float& v)
{
  int   hueCase = (int)(h*6);
  float frac    = 6*h-hueCase;
  float lx      = v*(1 - s);
  float ly      = v*(1 - s*frac);
  float lz      = v*(1 - s*(1 - frac));
  switch (hueCase)
  {
    case 0:
    case 6: r=v;  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.

HSL Color Space

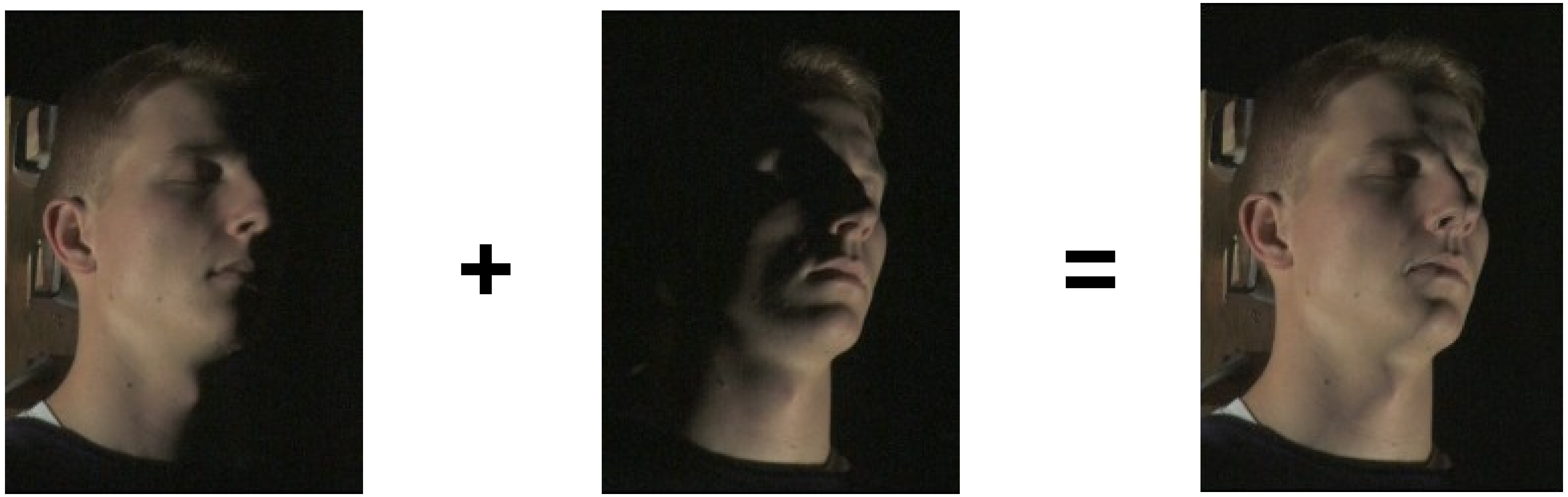


- Hue, Saturation, and Lightness
- Similar to HSV….but….
- Saturated colors (S=1) occur at L = ½
- Often uses with S and L in [0,100]
  - Saturation at L =50
- Visualized as a double cone



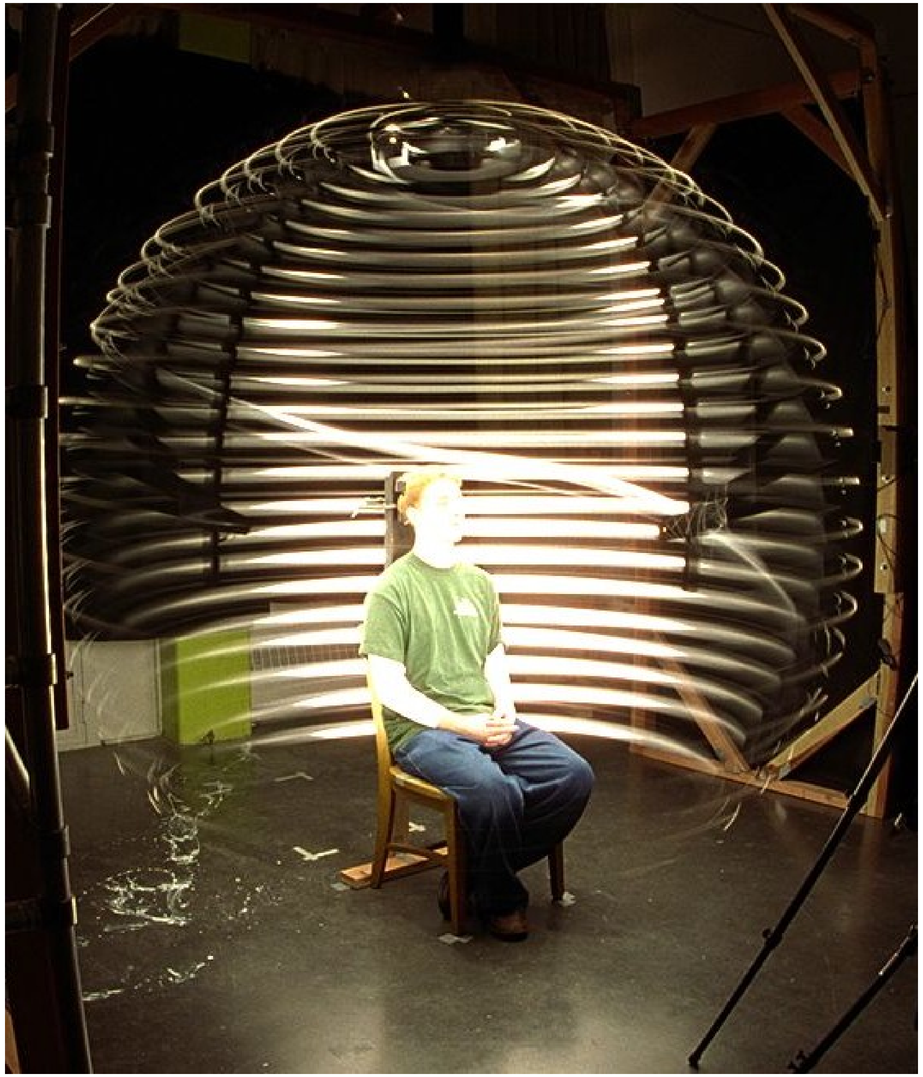
Fun with the Additive Property of Light

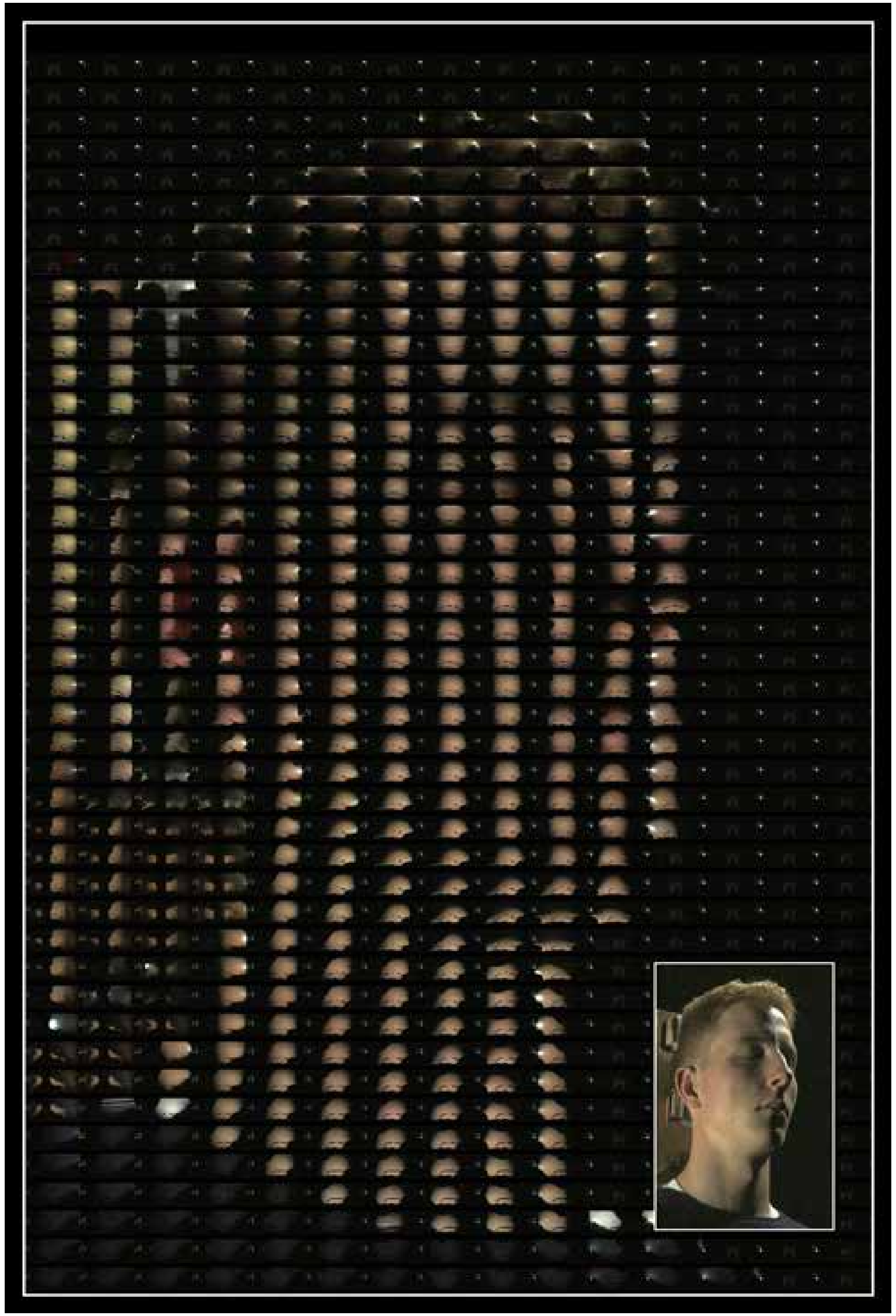
$$R(L_1) + R(L_2) = R(L_1 + L_2)$$



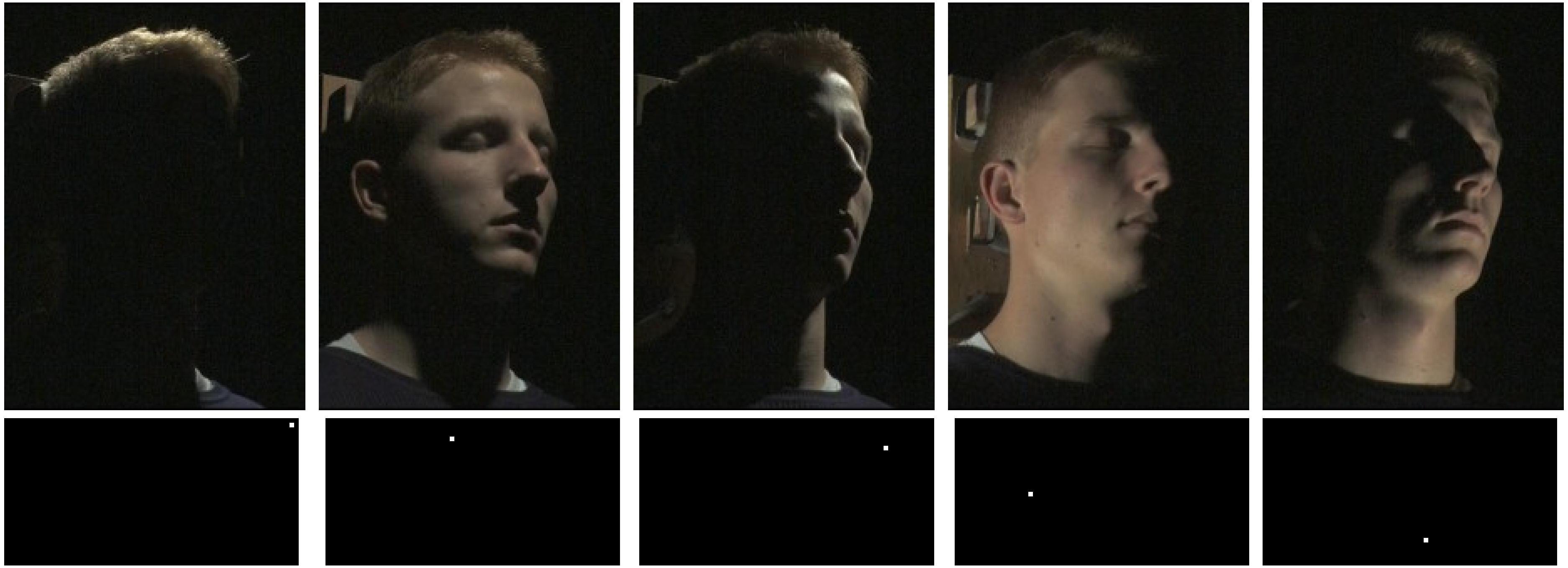
Debevec et al., Acquiring the Reflectance Field of a Human Face,
Proc. SIGGRAPH 2000

Light Stage



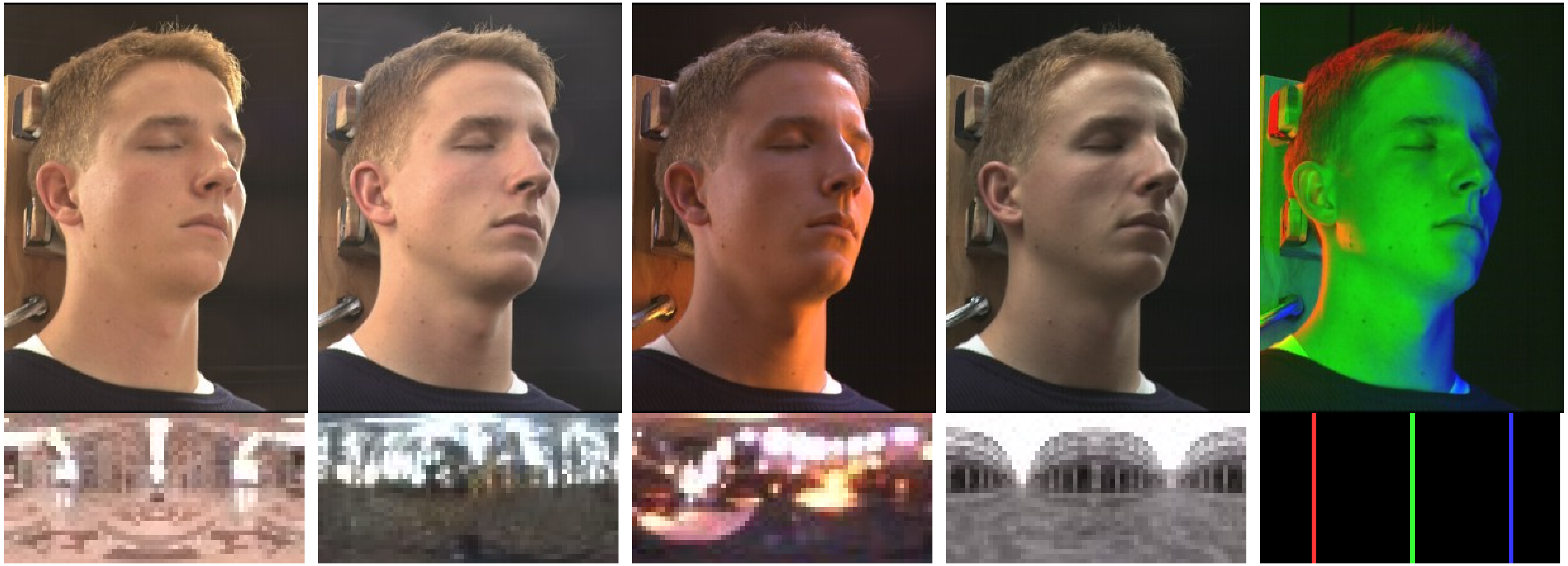


Point Light Sources



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

Environment Lighting



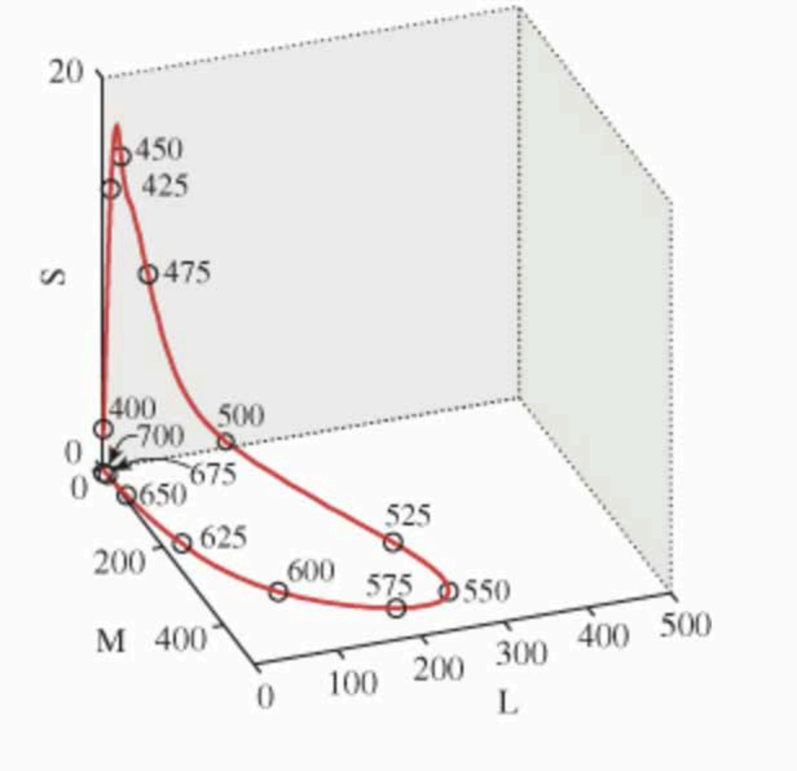
Debevec et al., Acquiring the Reflectance Field of a Human Face, Proc. SIGGRAPH 2000

Color Matching Experiments

Can three single-wavelength colors generate all the colors humans can see? How can we find out?

- 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 luminance
- CIE standard primaries
  - Red (R): 700nm
  - Green (G): 546.1 nm
  - Blue(B): 435.8 nm

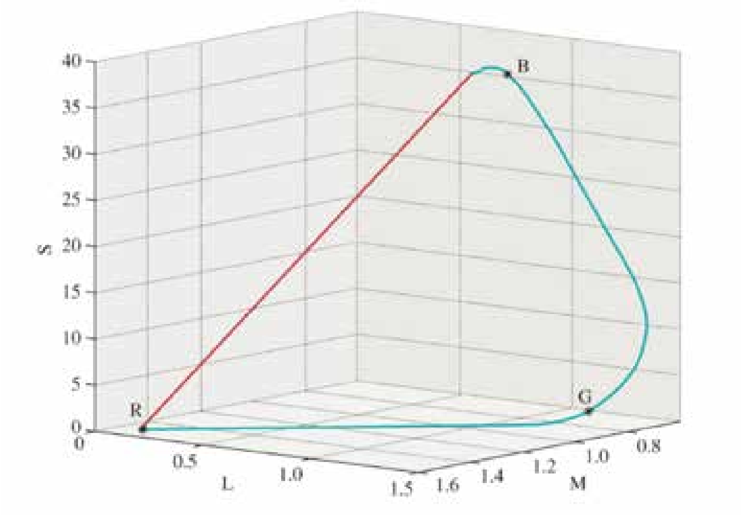
Human Response to Monospectral Light



Points on red curve are wavelengths

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

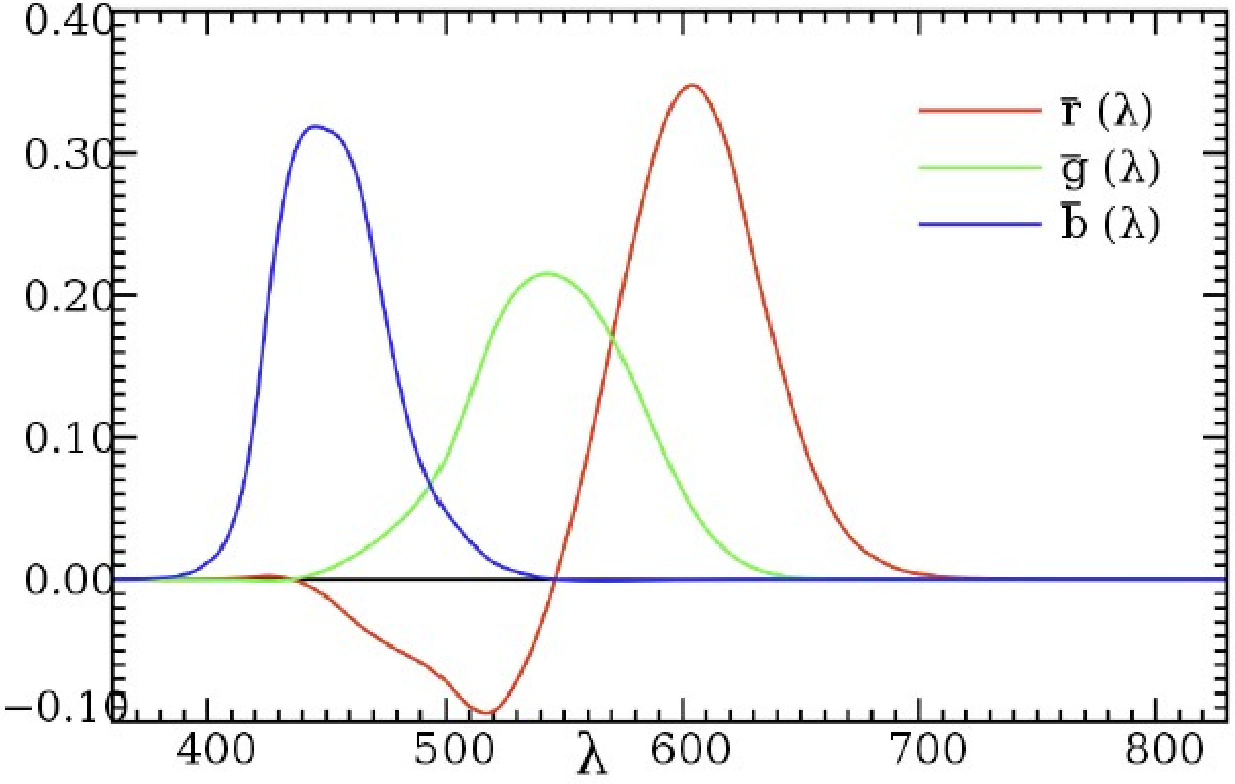
Human Response to Monospectral Light



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.

Color Matching Function for CIE RGB



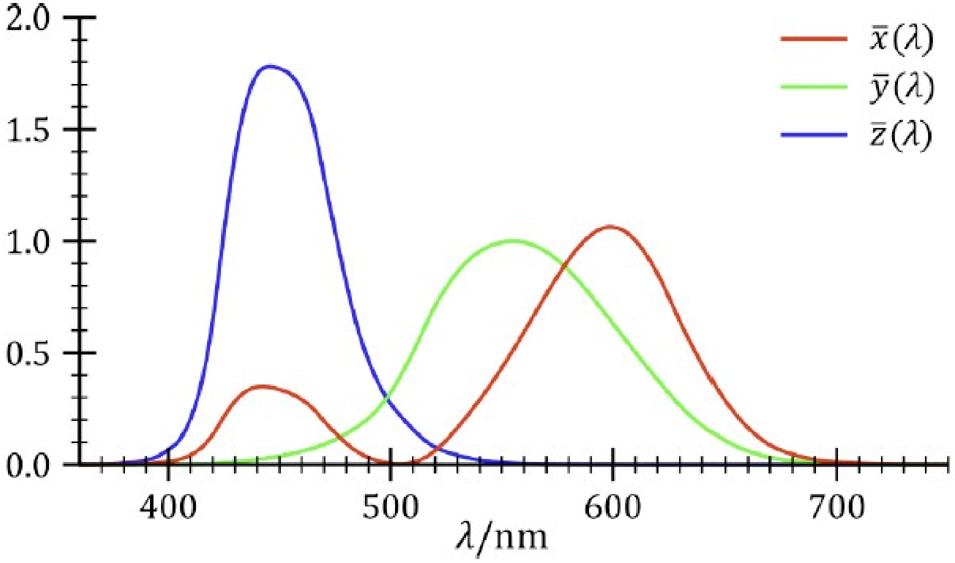
Amounts of the red, green and blue primaries needed to match any color [1]

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

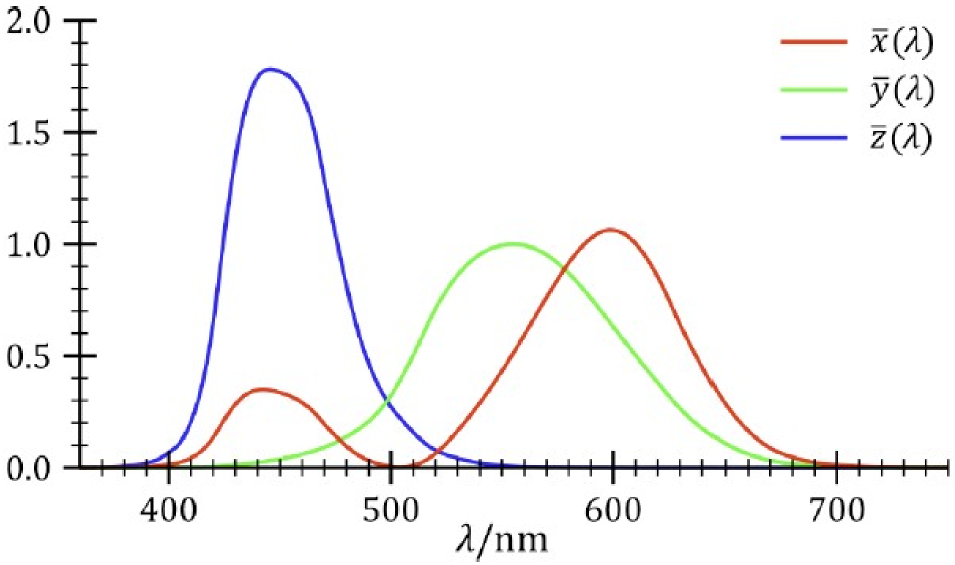


Amounts of the XYZ primaries needed to match any color
($\bar{y}$ function is precisely CIE-standardized photopic luminous efficiency, 1931)

- 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



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 $p_x X + p_y Y + p_z Z$

where

$$p_x = k \int P(\lambda)$$

CIE Color Space

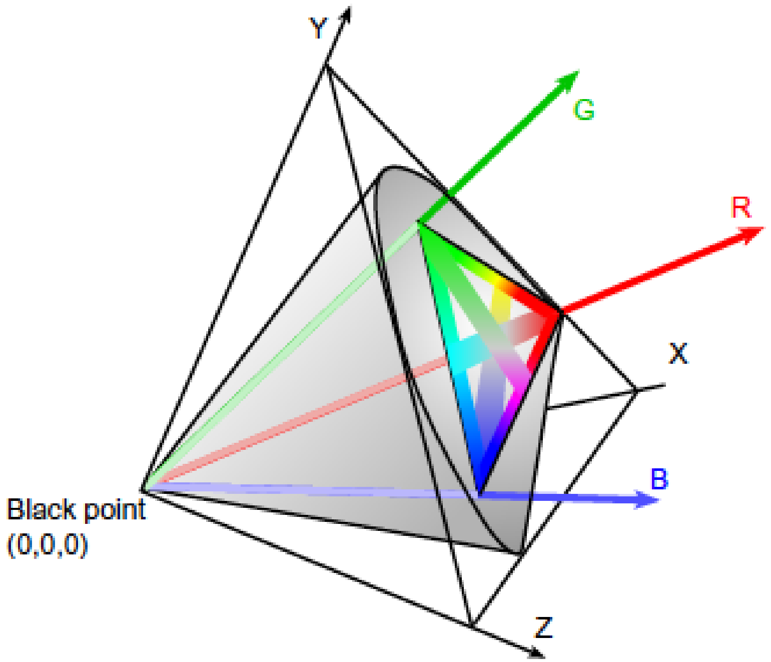


Figure 4.6 The *X*, *Y*, and *Z* axes represent the CIE standard virtual primaries. Within the positive space defined by the axes, the gamut of perceivable colors is represented as a gray solid. The colors that can be created by means of the red, green, and blue monitor primaries are defined by the pyramid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

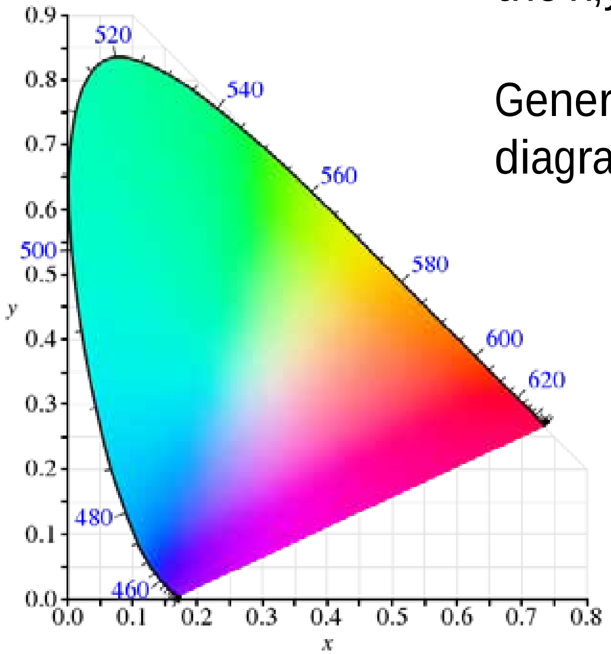
$$x = \frac{X}{X + Y + Z}$$

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

Note: $Y = Y$

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

Generates the CIE Chromaticity diagram



CIE Chromaticity Diagram

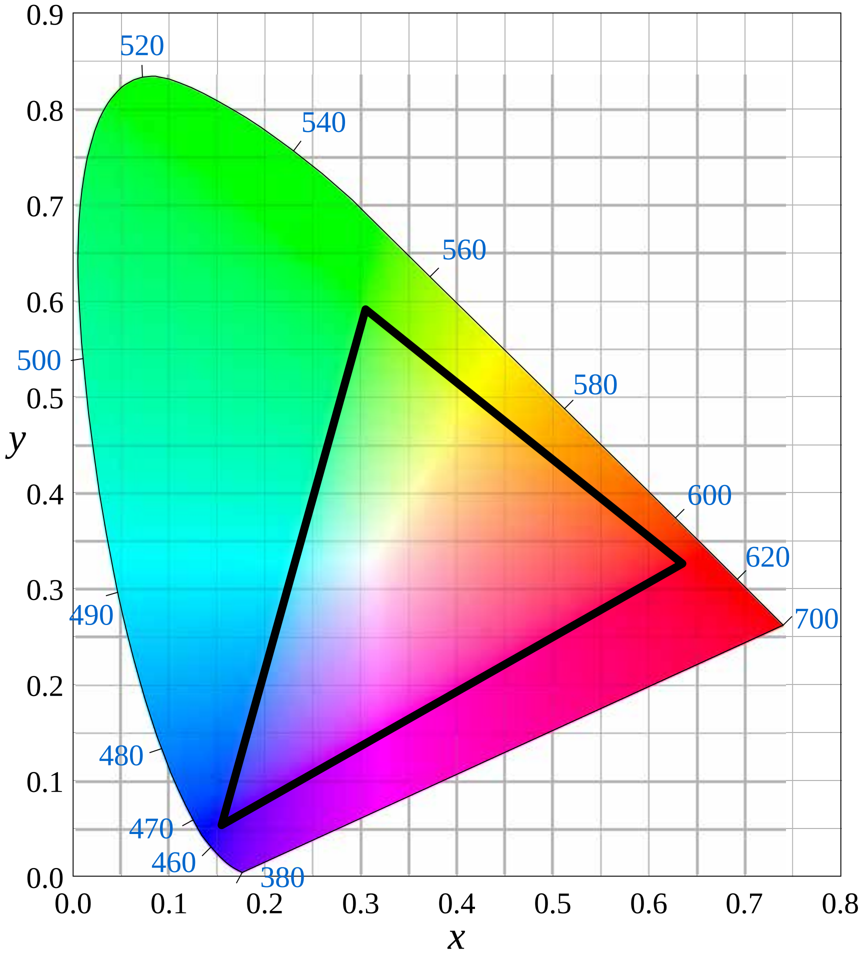
- What runs around the edge of the horseshoe?
- What is inside the horseshoe?

- **Gamut**: Portion of the spectrum reproduced by a given color space

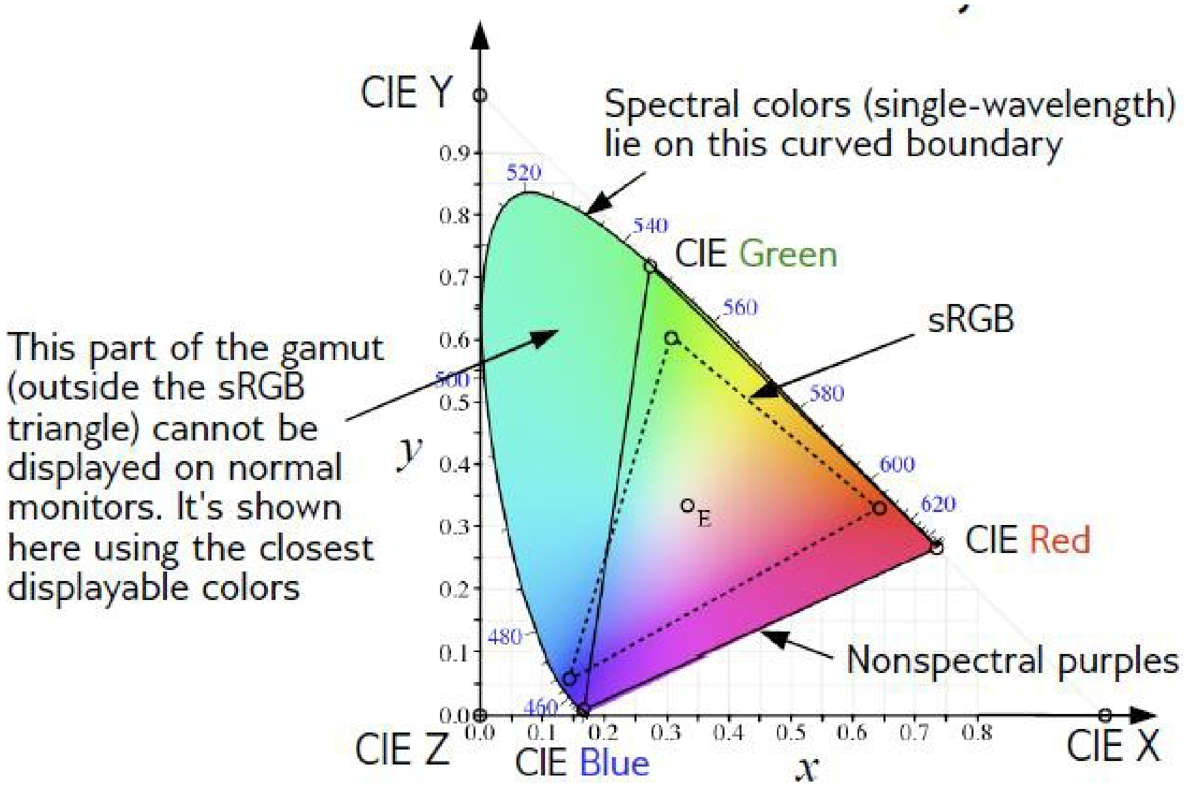
  Any guess as to what the triangle represents?

- **Quick Quiz:** Are the colors shown inside the diagram correct?

  Why or why not?



CIE XYZ Gamut



Spectral colors (single-wavelength) lie on this curved boundary

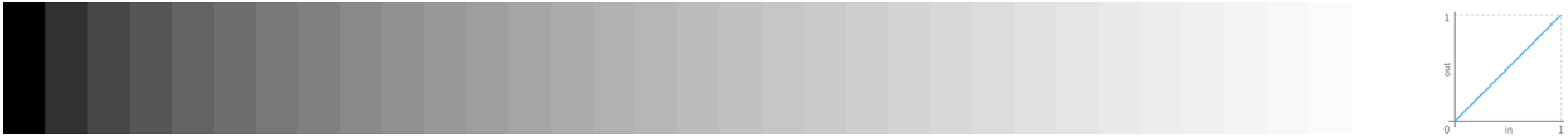
This part of the gamut (outside the sRGB triangle) cannot be displayed on normal monitors. It's shown here using the closest displayable colors

All visible chromaticities mapped to xy plane

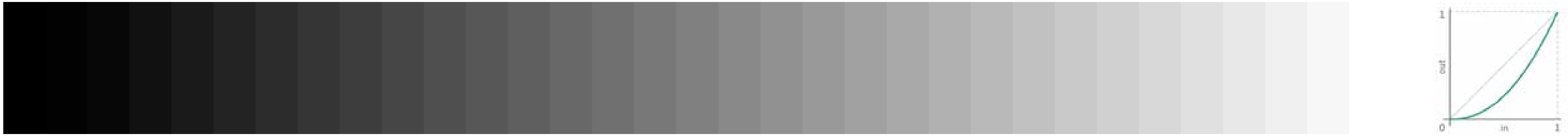
Gamma Correction

Human visual response better at distinguishing darker shades

Greyscale bars that increase by a constant amount of luminosity:



Greyscale bars with luminosity increasing according to a power law:

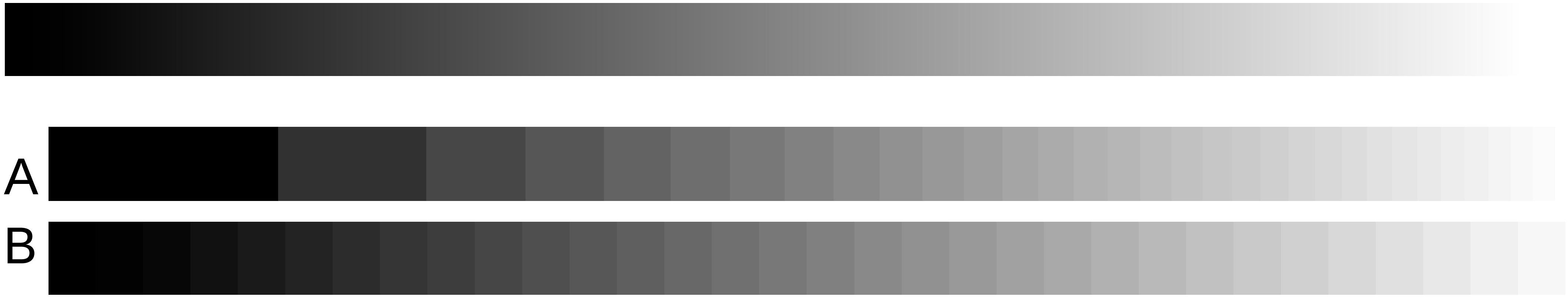


The smoother visual appearance of the second means it is more perceptually uniform

Gamma Correction

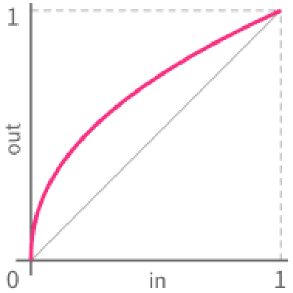
- Imagine we can only store 5-bit greyscale colors
    - 32 distinct colors
- We could select 32 shades generated on the straight line (A)
- We could select 32 shades generated on the power curve (B)

Suppose we use our 32 shades to render a smooth gradient



Gamma Encoding

- So, to perceptually make the best use of 24-bit RGB color
- We can gamma encode each 8-bit channel using $I_{encoded} = I^{1/\gamma}$
  - Usually $\gamma = 2.2$

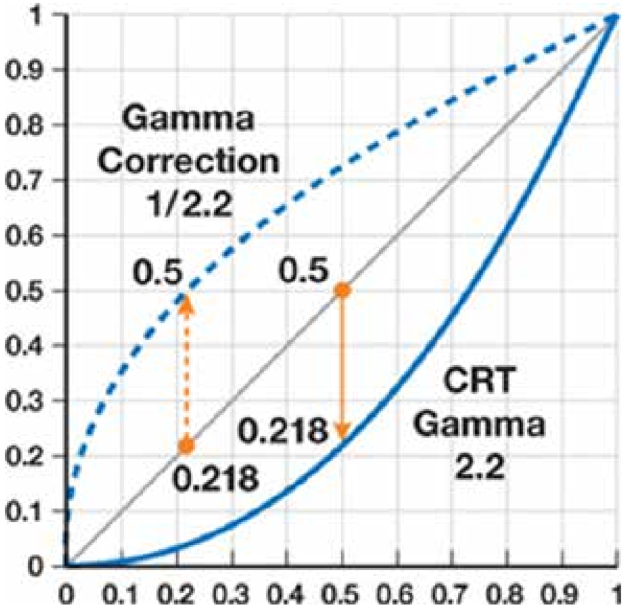


- Divide up the y-axis evenly into 256 integers…mapped onto the curve
- We sample the lower luminosities more densely

Gamma Decoding

Modern display devices decode color channels using $I_{decoded} = I_{encoded}^{\gamma}$

Example

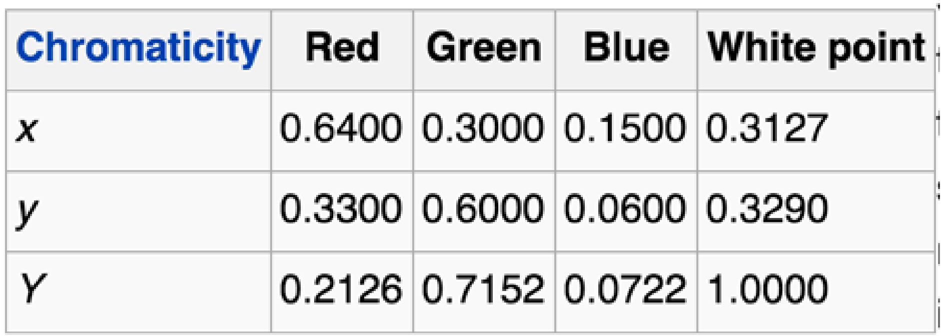


OK...a CRT

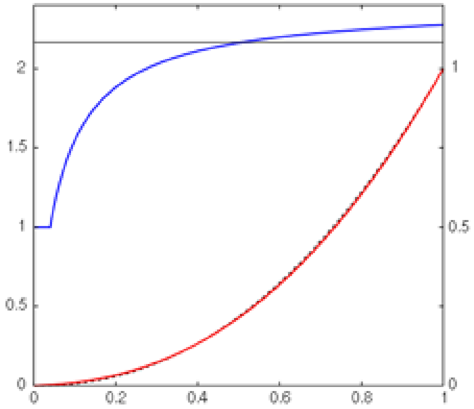
modern....

sRGB

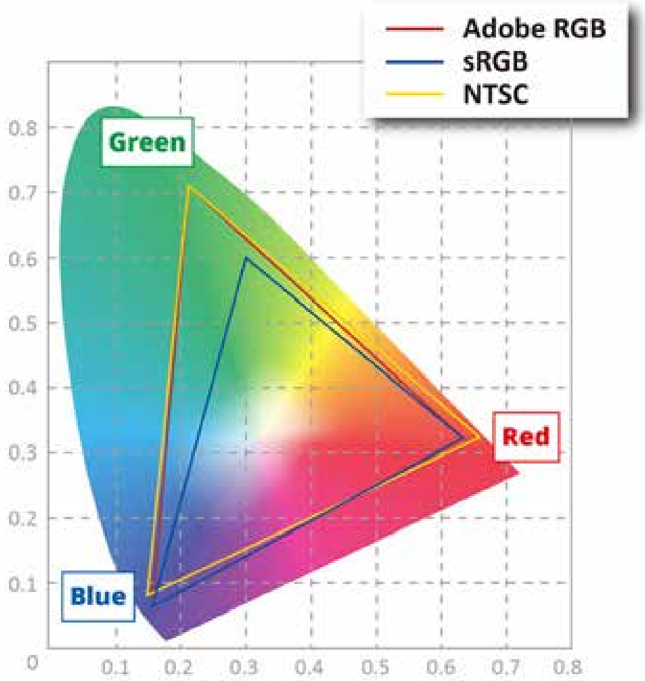
- sRGB is specified as a gamut inside the xyY colorspace
- And with a specific gamma curve to use for encoding/decoding



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



Blue curve is sRGB gamma value



- sRGB is the standard RGB color space used almost everywhere
  - When you use an image library (e.g. libpng) typically defaults to saving in sRGB
    - So…you do not need to gamma encode colors yourself
  - Supported directly on modern GPUs
- You can generate a matrix to convert from sRGB to XYZ and back using its inverse…