# Color and Perception

CS334 Fall 2026

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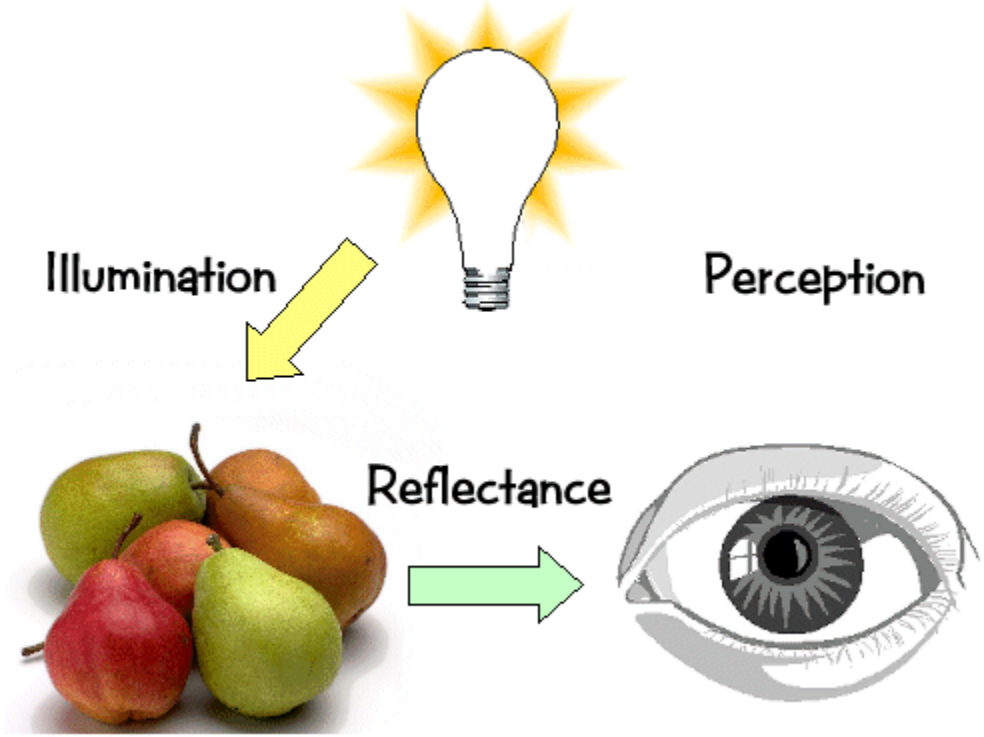
# Elements of Color Perception

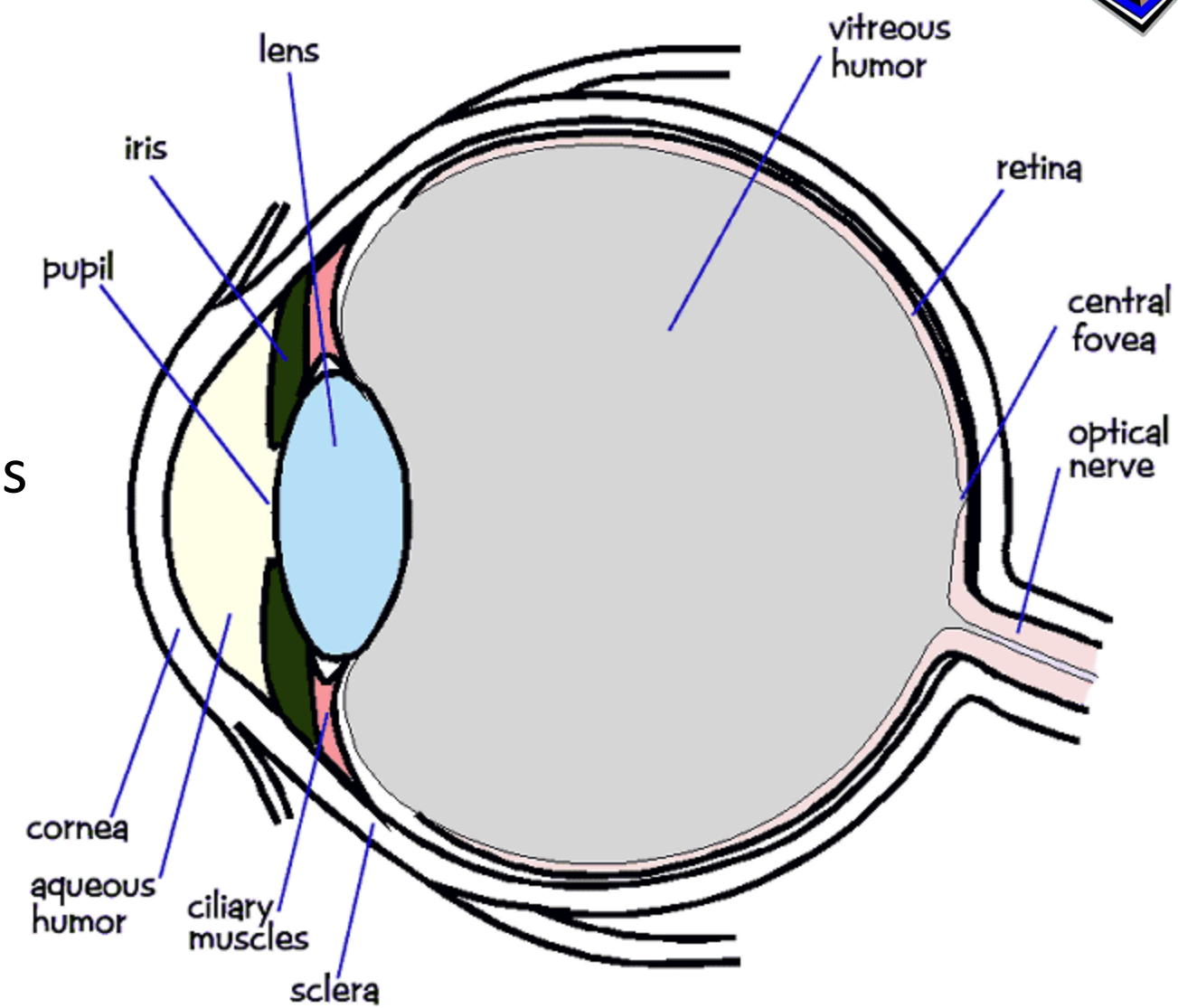


# Elements of Color

- Physics:
  - Illumination
    - Electromagnetic spectra; approx. 350 – 720 nm
  - Reflection
    - Material properties (i.e., reflectance, transparency)
    - Surface geometry and micro geometry (i.e., polished versus matte versus brushed)
- Perception
  - Physiology and neurophysiology
  - Perceptual psychology

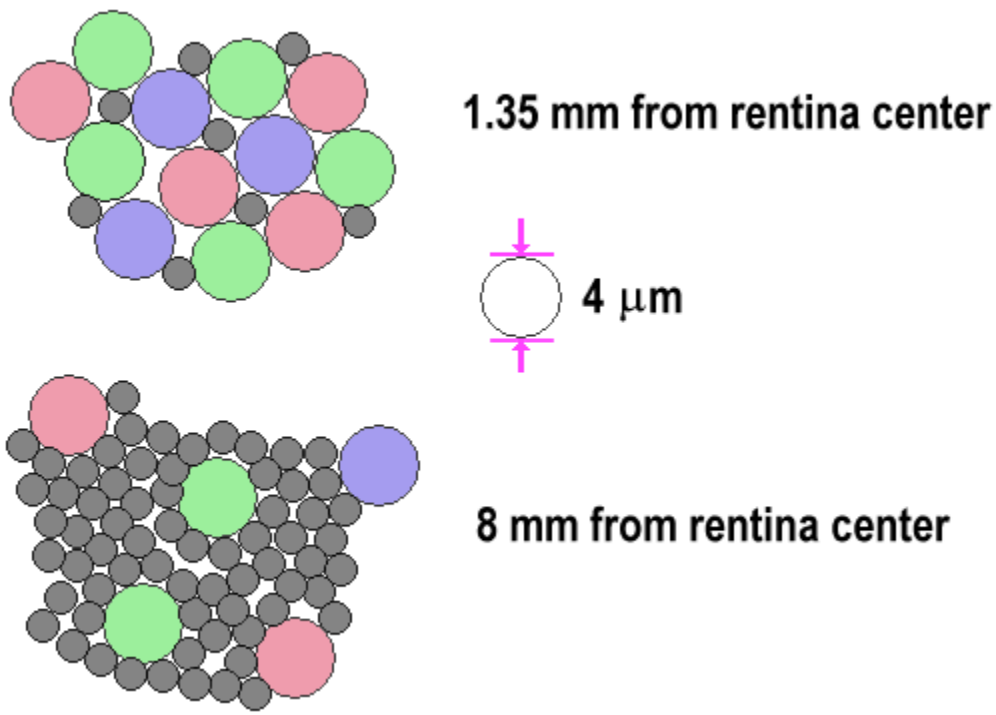
# Physiology of the Eye

- The eye:
- The retina
  - 100 M Rods
    - B&W
  - 5 M Cones
    - Color



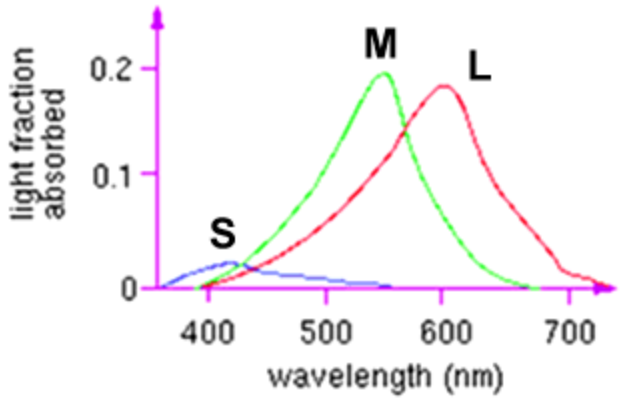
# Physiology of the Retina

- The center of the retina is a densely packed region called the *fovea*.
  - Cones much denser here than the *periphery*



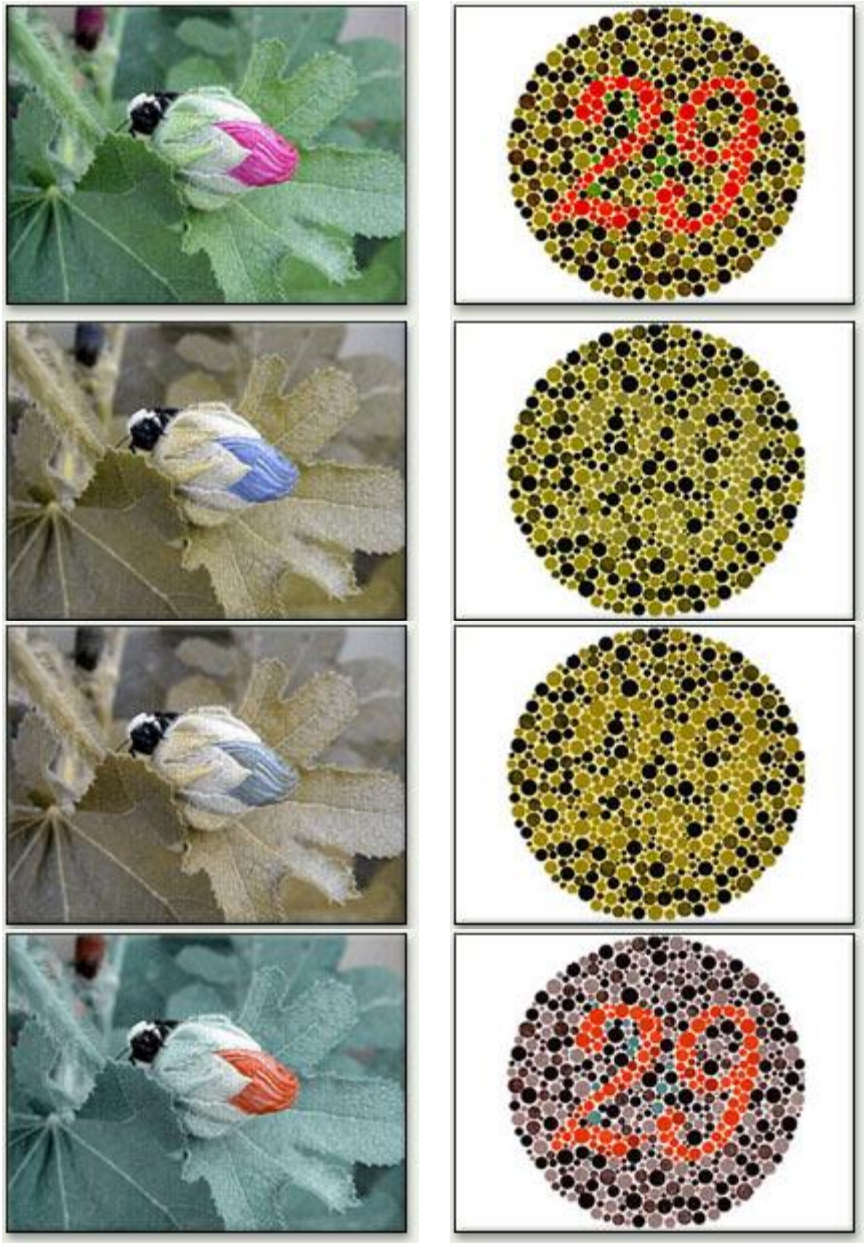
# Types of Cones

- Three types of cones:
  - **L** or **R**, most sensitive to red light (610 nm)
  - **M** or **G**, most sensitive to green light (560 nm)
  - **S** or **B**, most sensitive to blue light (430 nm)




  - Color blindness results from missing cone type(s)

# Color Blindness



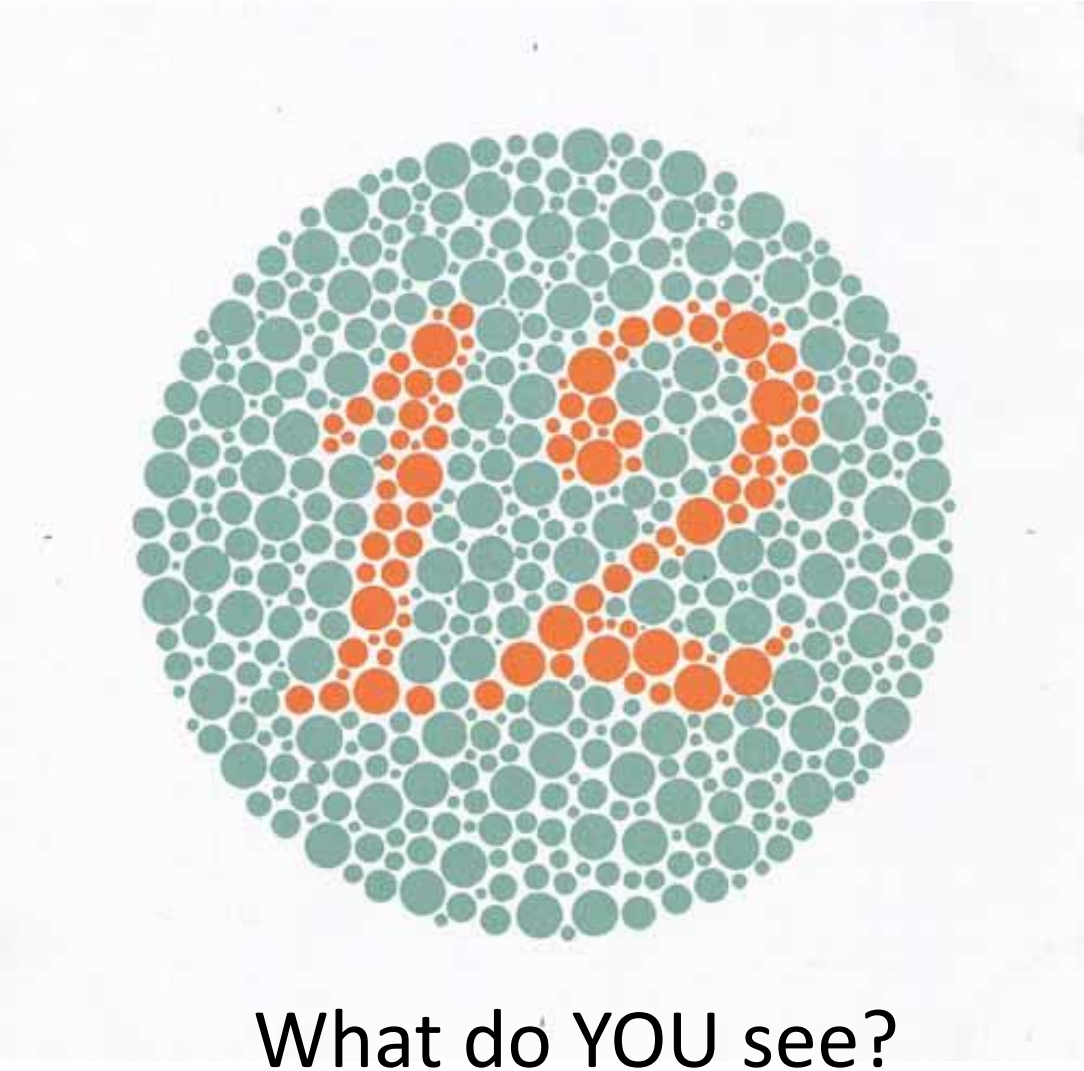
Normal

Protan (L-cone) “red insensitivity”

Deutan (M-cone) “green insensitivity”

Tritan (S-cone) “B=G and Y=violet”

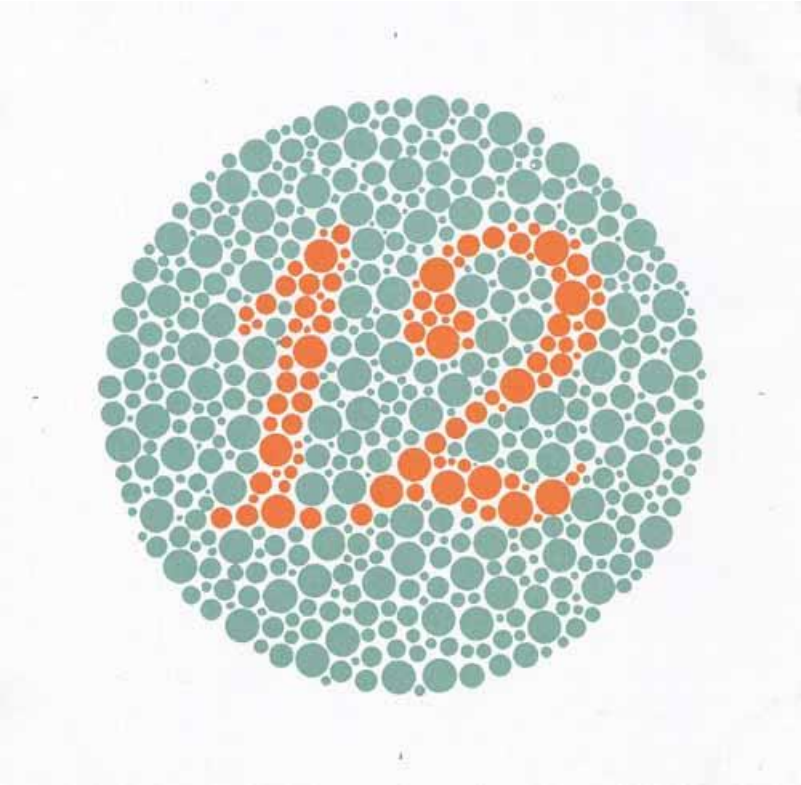
# Mini Color Blindness Test



What do YOU see?

Image 1

**Both the normal and those with all sort of color vision deficiencies read it as 12.**

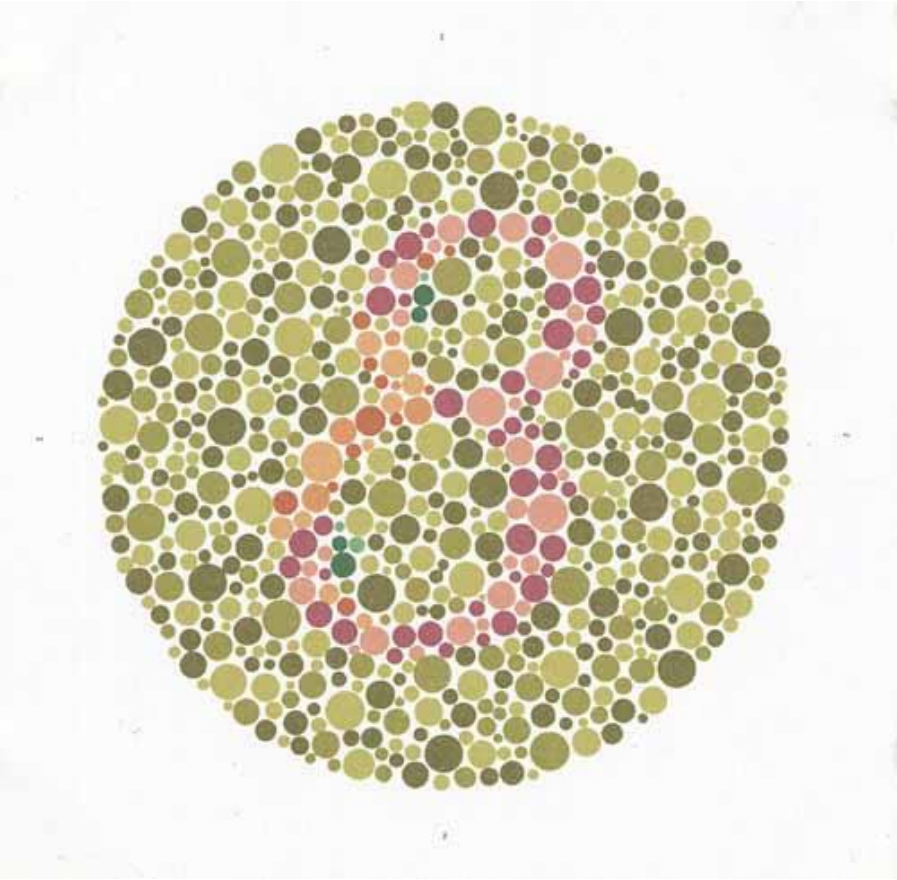


## Image 2

**The normal read this as 8.**

**Those with red-green deficiencies read this as 3.**

**Those with total color blindness cannot read any numeral.**

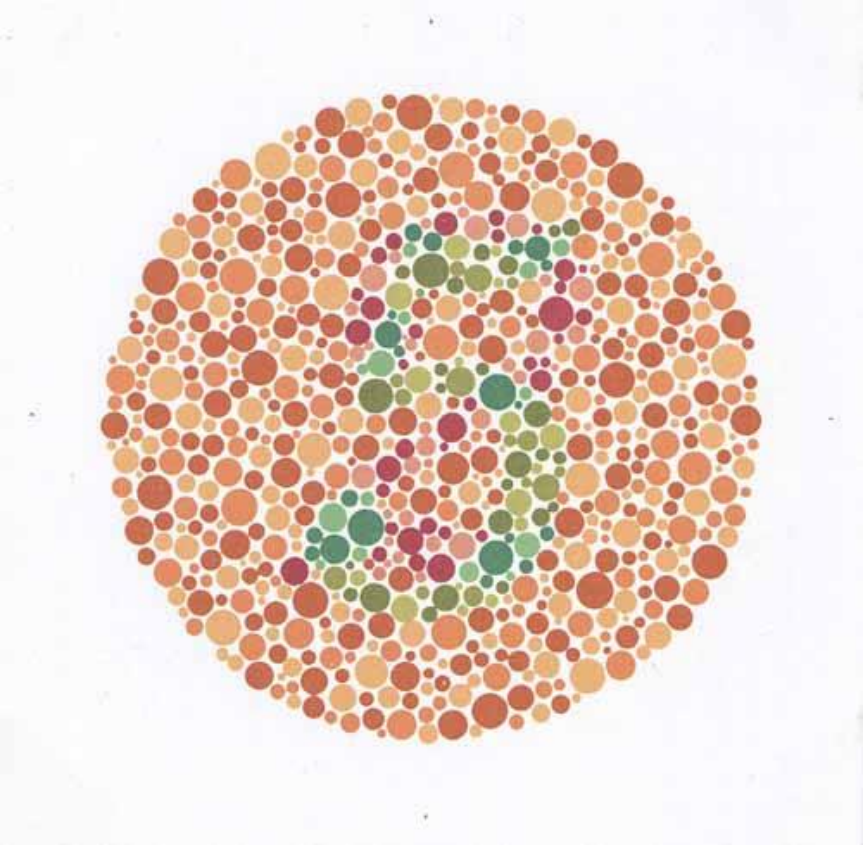


## Image 4

**The normal read this as 5.**

**Those with red-green deficiencies read this as 3.**

**Those with total color blindness cannot read any numeral.**

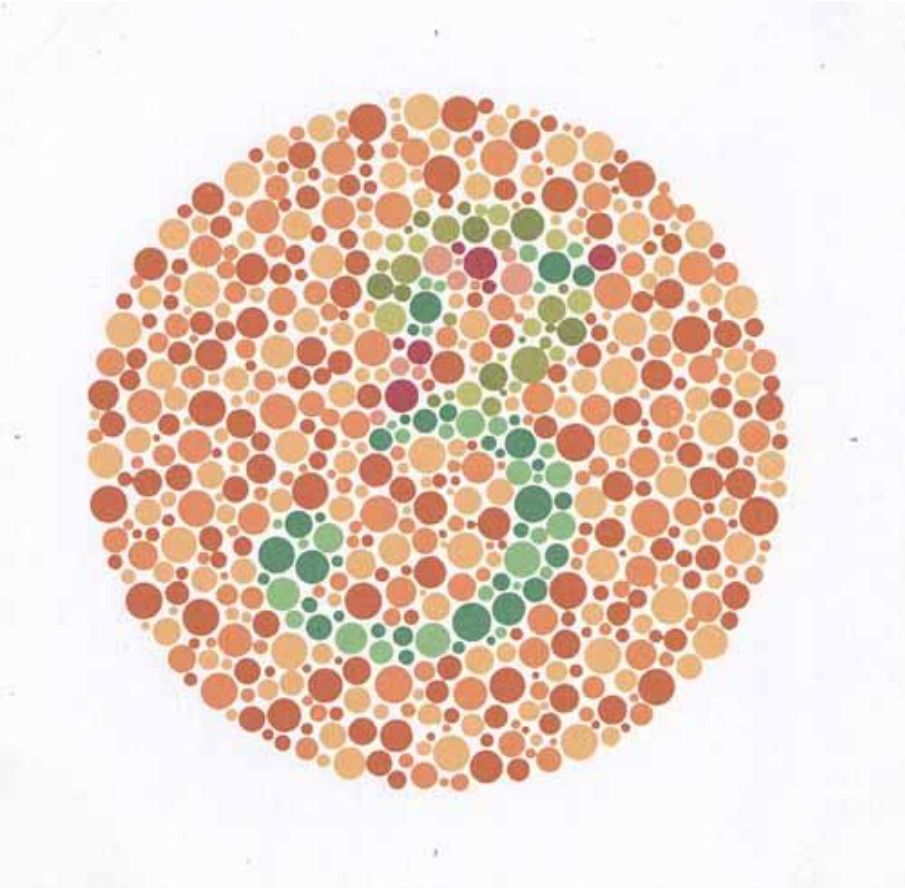


## Image 5

**The normal read this as 3.**

**Those with red-green deficiencies read this as 5.**

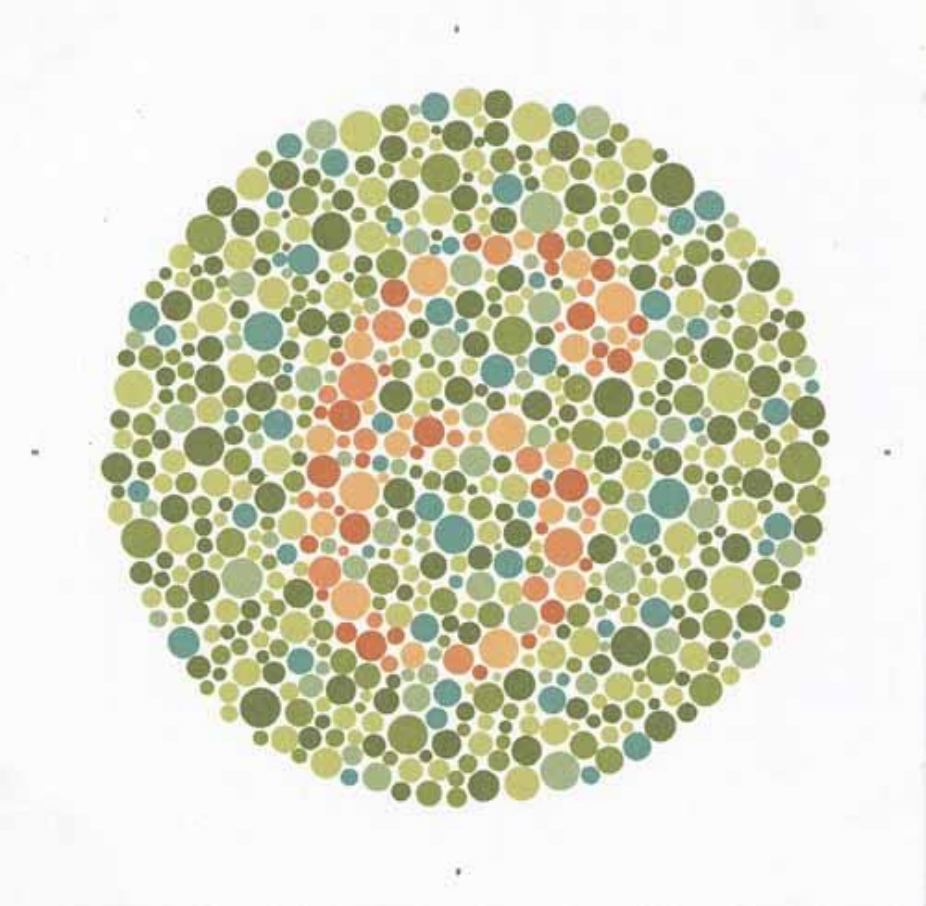
**Those with total color blindness cannot read any numeral.**



## Image 8

**The normal read this as 6.**

**The majority of those with color vision deficiencies can not read them or read them incorrectly.**



## Image 9

**The normal read this as 45.**

**The majority of those with color vision deficiencies can not read them or read them incorrectly.**

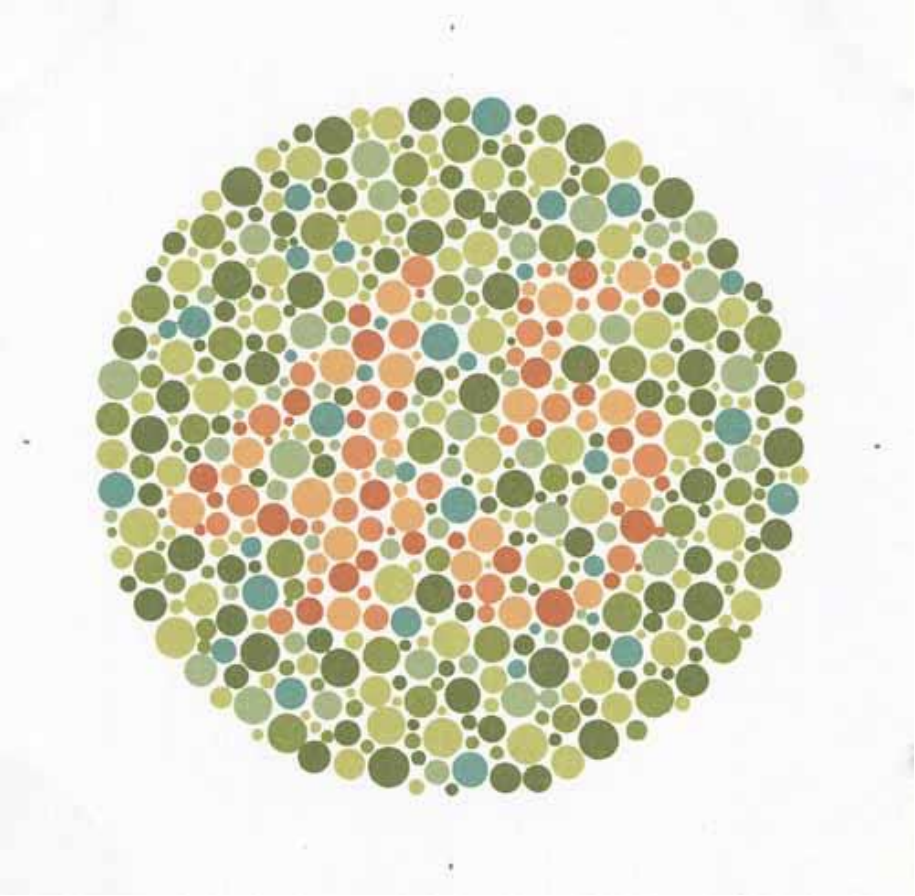
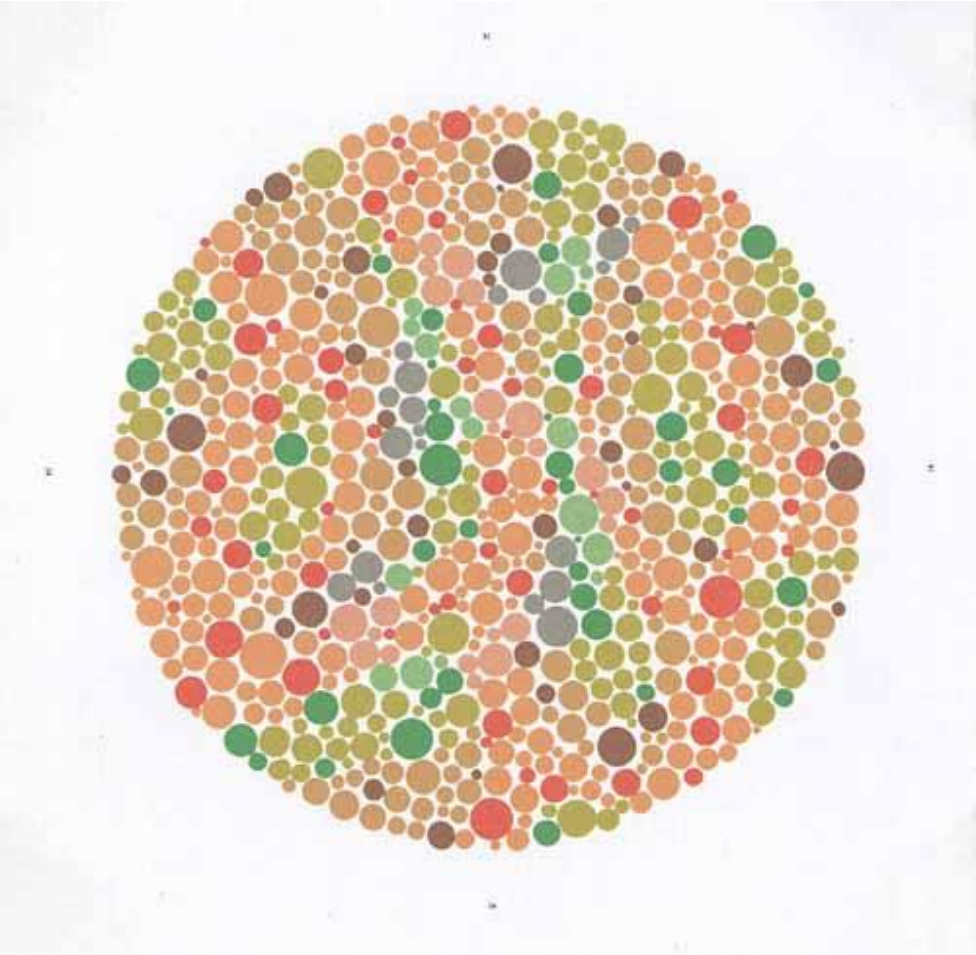


Image 14

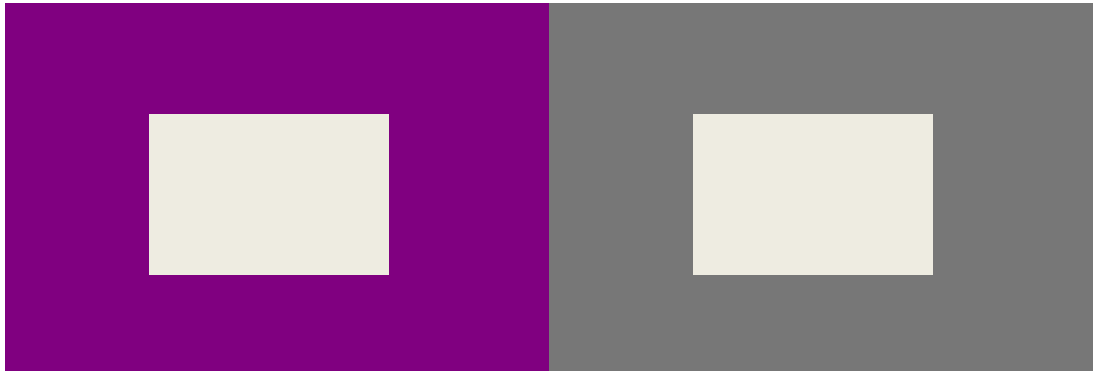
**The majority of the normal and those with total color blindness cannot read any numeral.**

**The majority of those with red-green deficiencies read this as 5.**



# Perception: Other Gotchas

- Color perception is also difficult because:
  - It varies from person to person (thus need "standard observers")
  - It is affected by adaptation
  - It is affected by surrounding color
  - There is Mach-banding

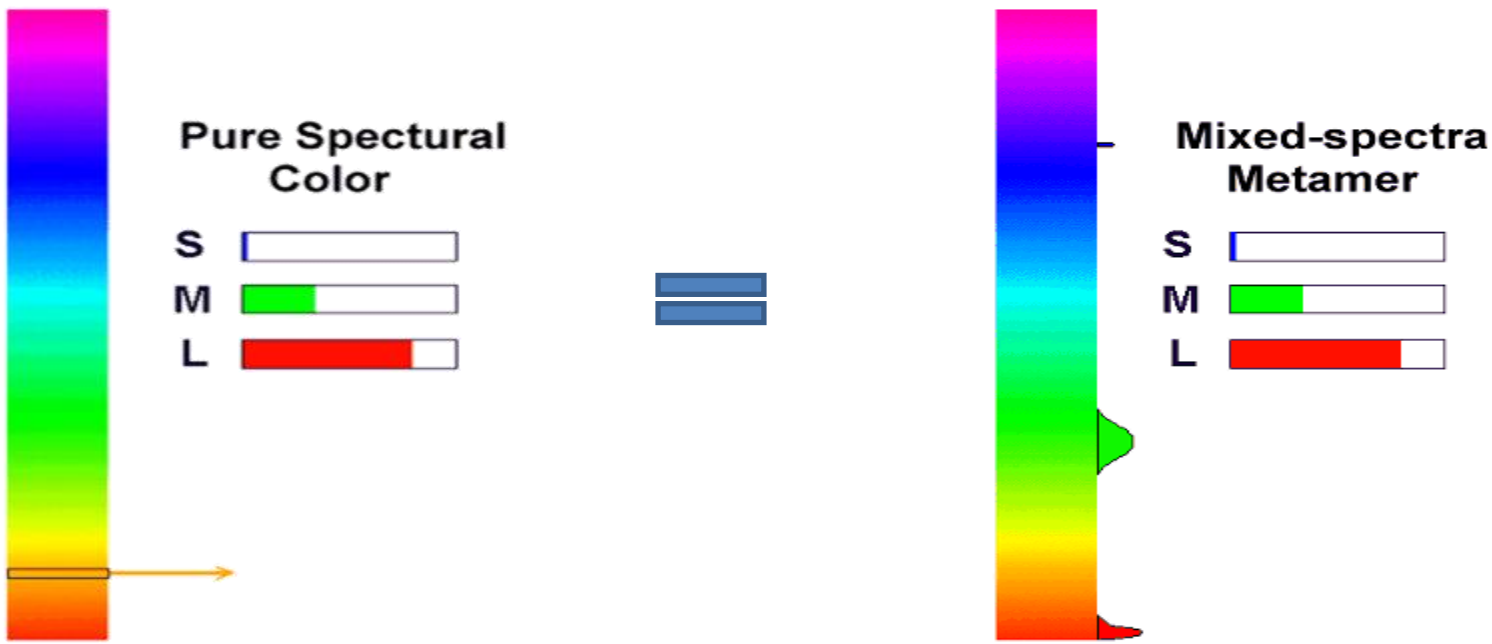


# Summary of Human Color Perception

- Subjectively, the human eye seems to perceive color by three conceptual dimensions:
  - hue,
  - brightness, and
  - saturation.
- This suggests a 3D color space.
- Hardware reproduction of color cannot match human perception perfectly.

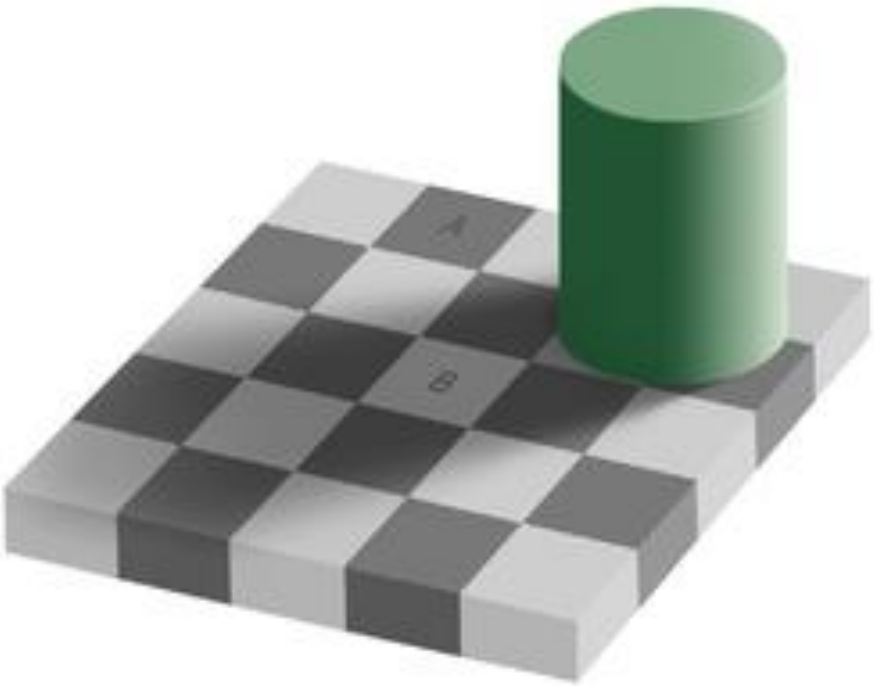
# Perception: Metamers

- A given perceptual sensation of color derives from the stimulus of all three cone types
- **Identical** perceptions of color can be caused by very **different** spectra



# Simultaneous Contrast

- Is “A” looks darker than “B”?

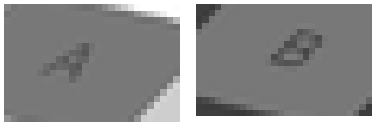


# Simultaneous Contrast

- Is “A” looks darker than “B”?

# Simultaneous Contrast

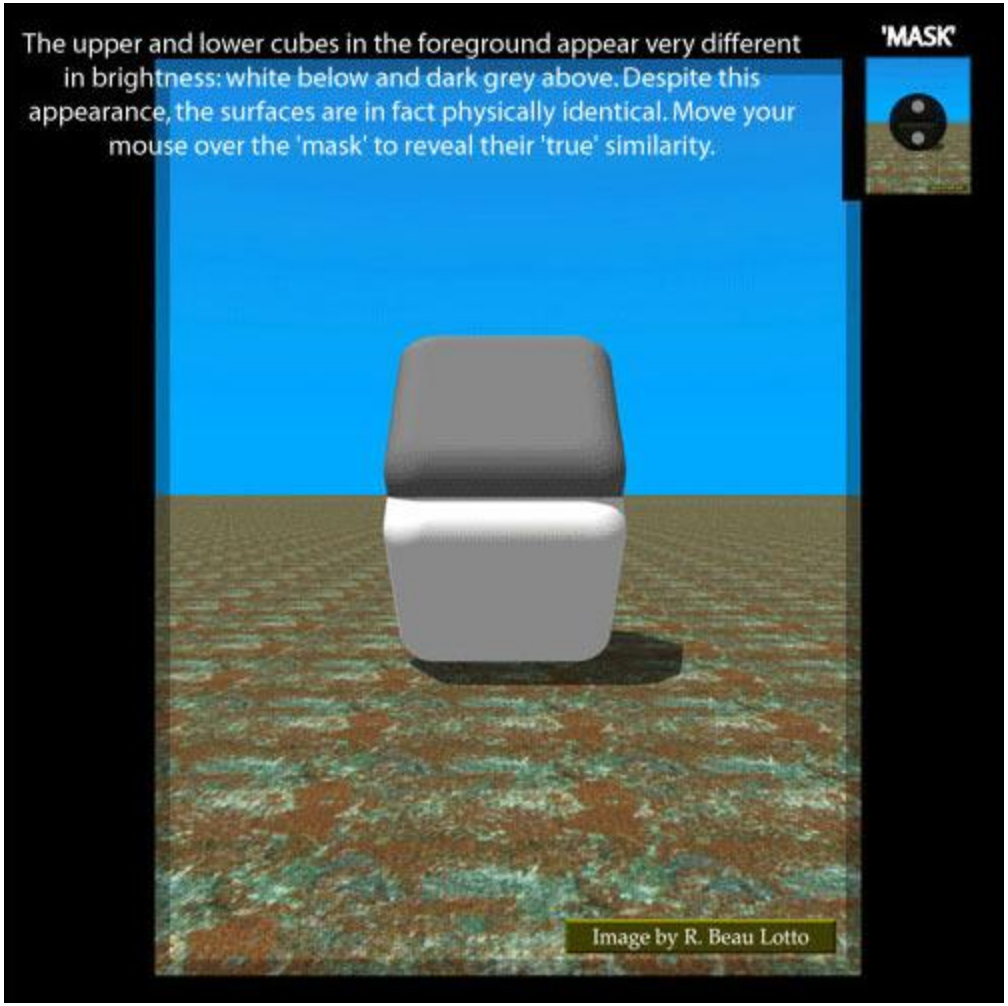
- Is “A” looks darker than “B”?
- Nope! Why?



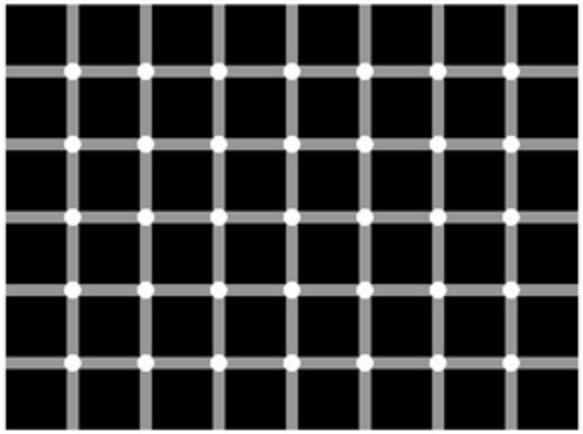

- What about in color?

  http://www.sandlotscience.com/Guided_Tours/Tour1/Tour_5.htm

# Cornsweet Illusion



# Changing Contrast



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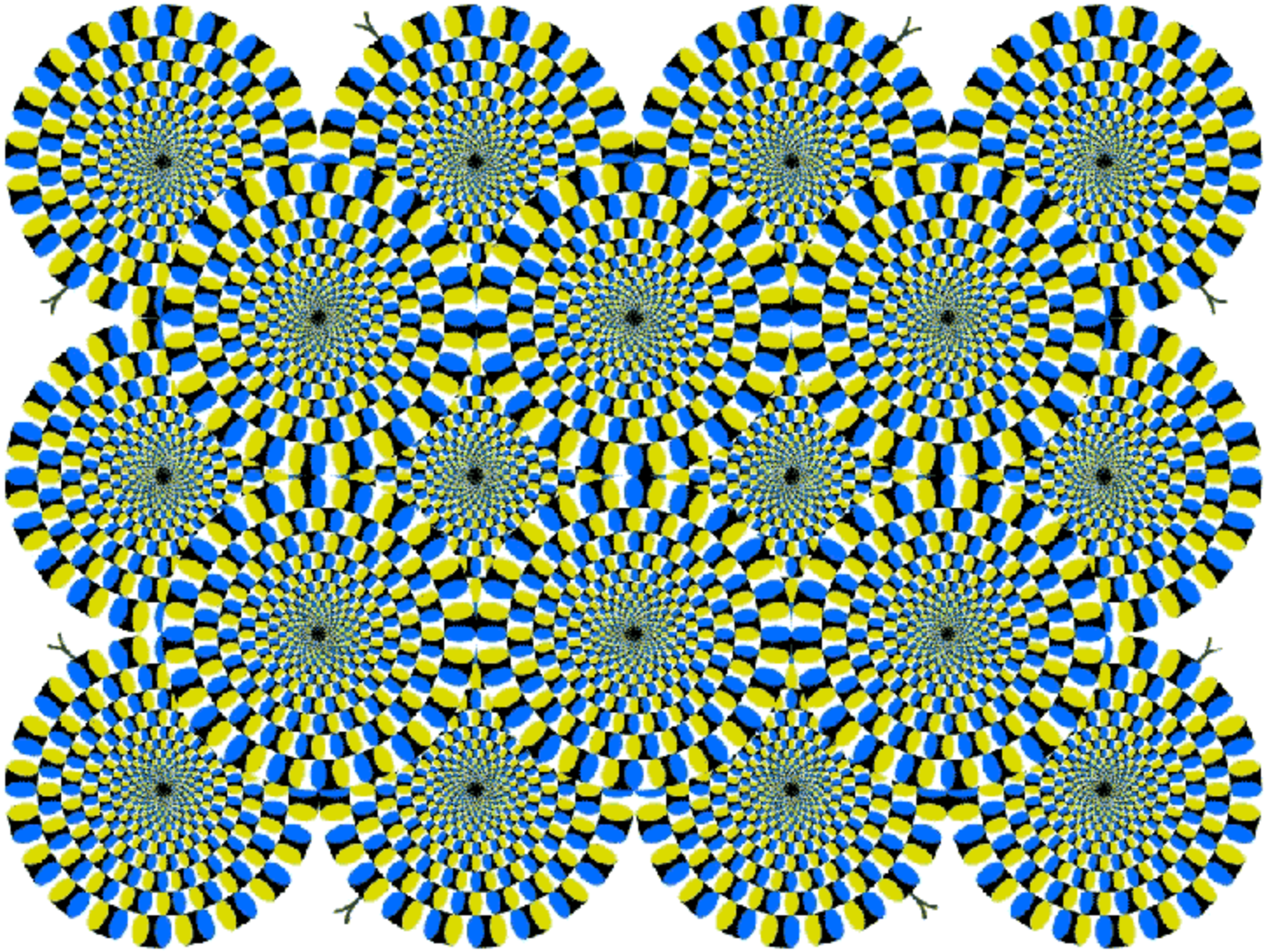
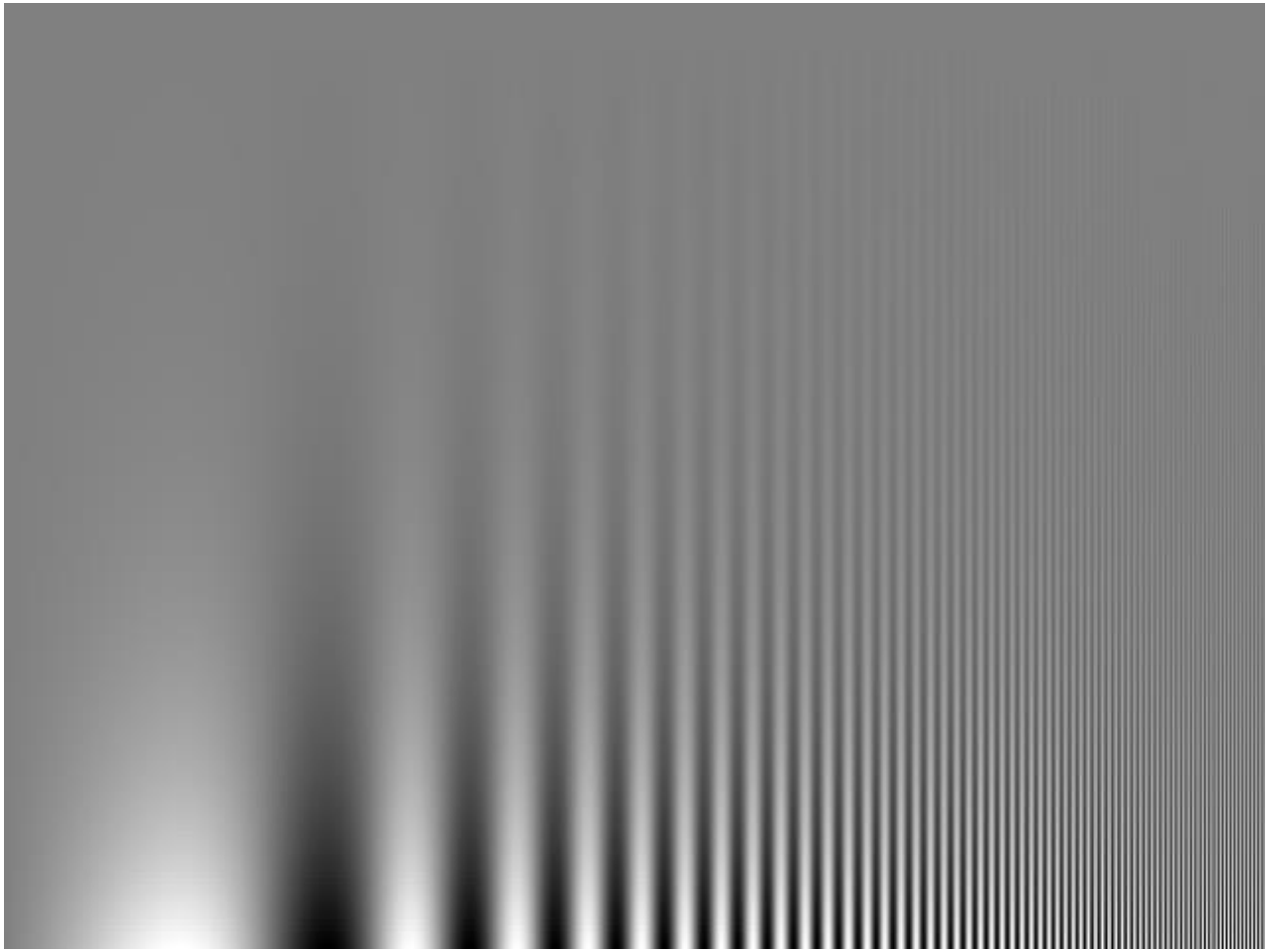


# Contrast Sensitivity Function



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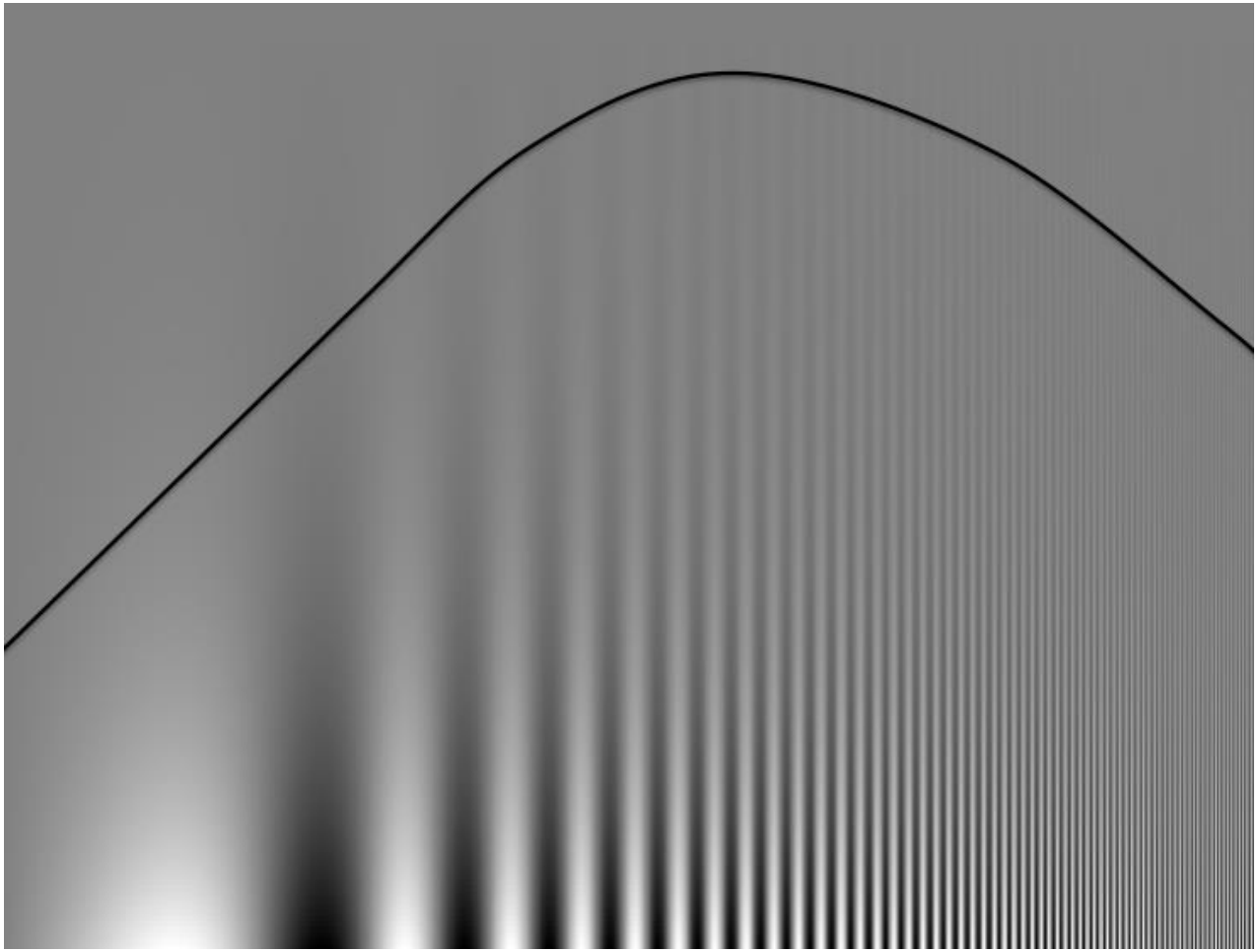

# Learned Expectation

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THE PAOMNNEHAL PWEOR OF THE HMUAN MNID. Aoccdrnig to a rscheearch at Cmabrigde Uinervtisy, it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoatnt tihng is taht the frist and lsat ltteer be in the rghit pclae. The rset can be a taotl mses and you can sitll raed it wouthit porbelm. Tihs is bcuseae the huamn mnid deos not raed ervey lteter by istlef, but the wrod as a wlohe.

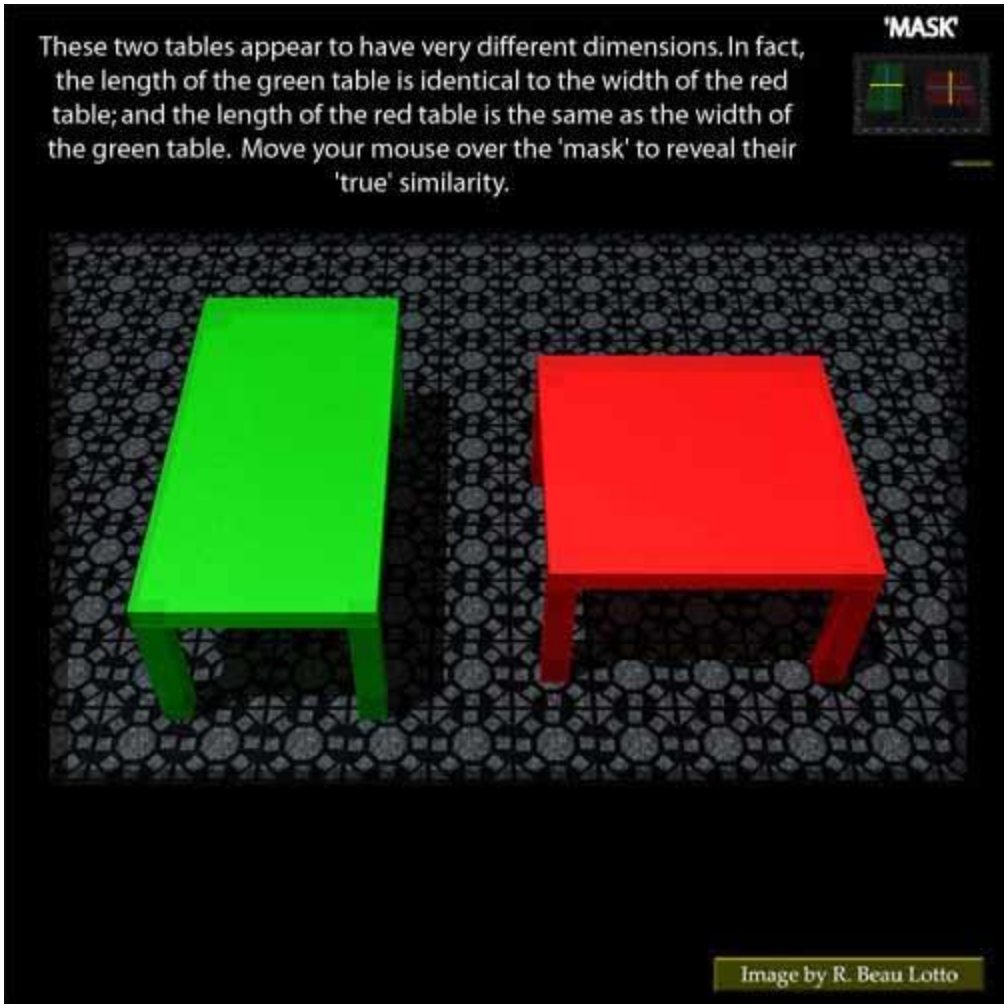
# Learned Expectation

- Starting the below left to right, top to bottom

| | | | |
|---|---|---|---|
| red | blue | orange | purple |
| orange | blue | green | red |
| blue | purple | green | red |
| orange | blue | red | green |
| purple | orange | red | blue |
| green | red | blue | purple |
| orange | blue | red | green |
| purple | orange | red | blue |

- Stroop Effect [1935]

# Learned Expectation



# Ambiguity = Visual Confusion

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# Stereo Depth Perception

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- 1. Place finger in between circle and eyes
- 2. Focus on finger
- 3. Focus on circle

[http://www.mediacollege.com/3d/depth-perception/test.html]

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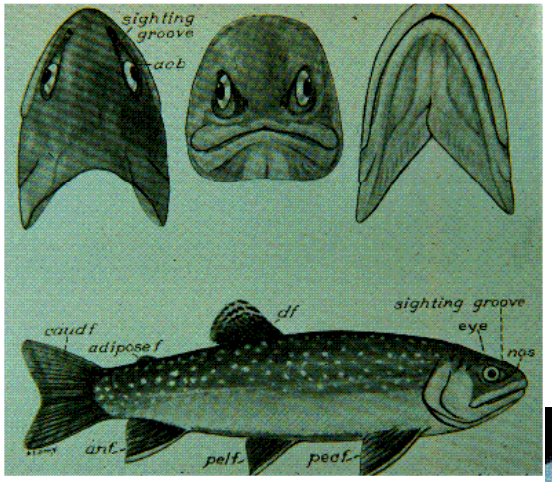
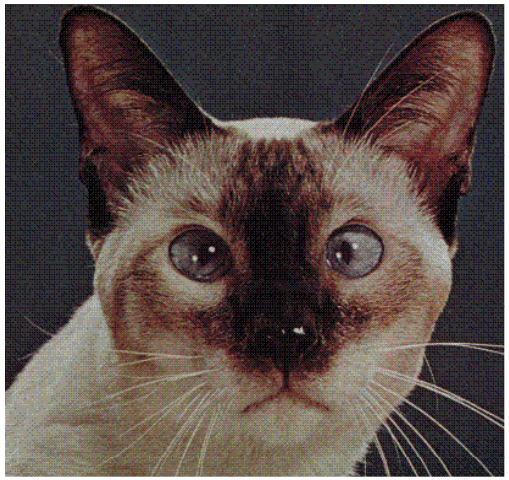
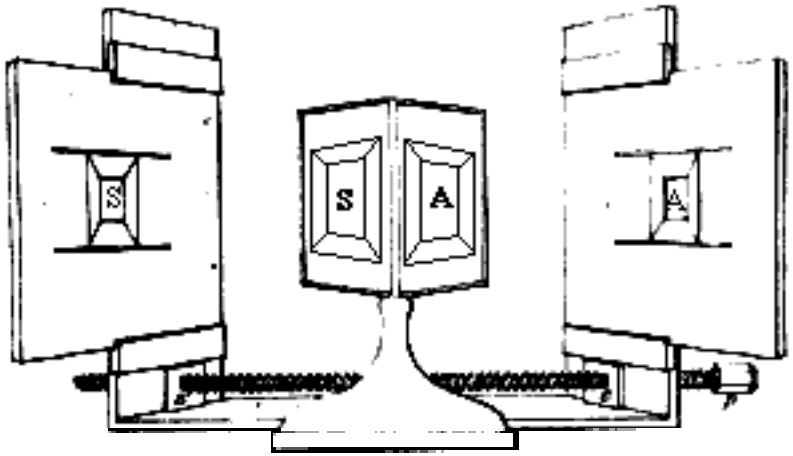
# Perception and Stereopsis



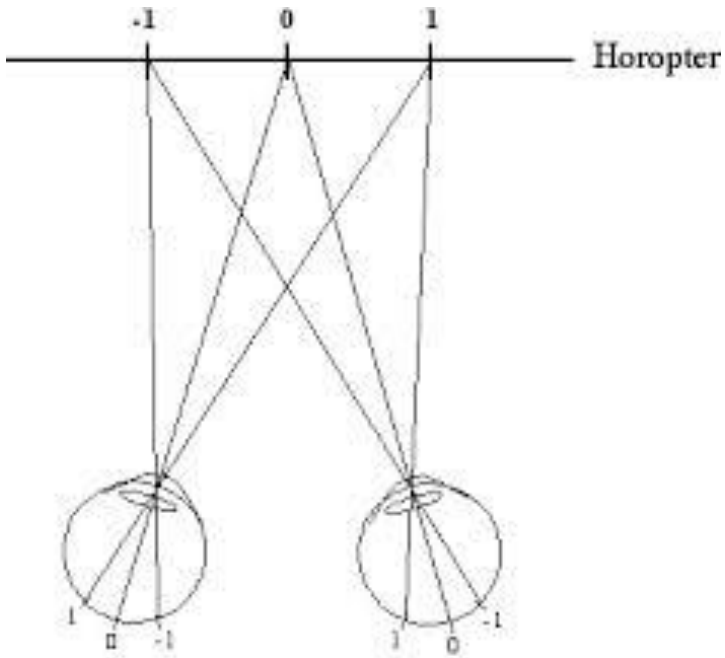


# Sir Charles Wheatstone

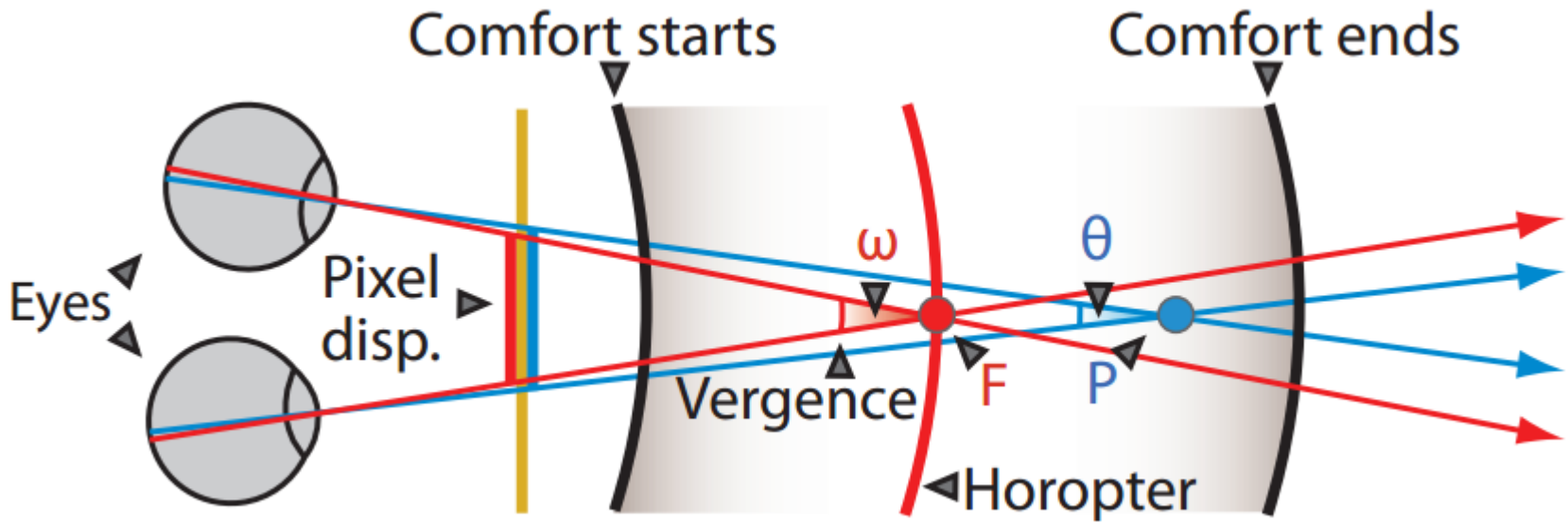
- Circa 1840



# Basic Stereopsis



# Perception and Stereopsis



# Examples

- Using Cornsweet Illusion to better stereopsis

  https://www.pdf.inf.usi.ch/papers/disparityCornsweet/disparityCornsweet.pdf

  To improve gloss depiction

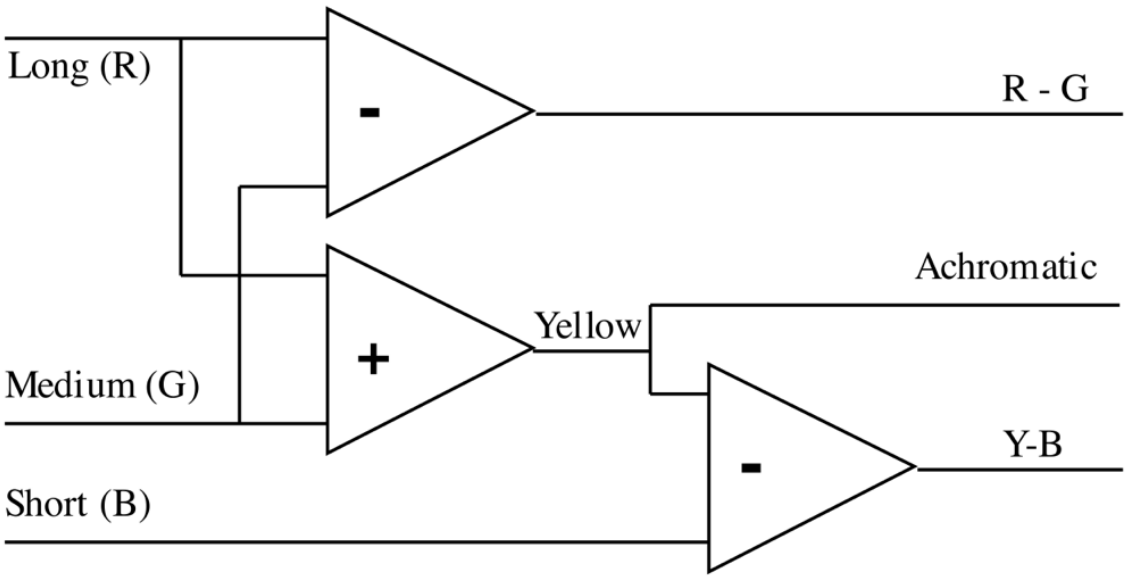
  http://resources.mpi-inf.mpg.de/HighlightMicrodisparity/paper.pdf

- To account for luminance as well

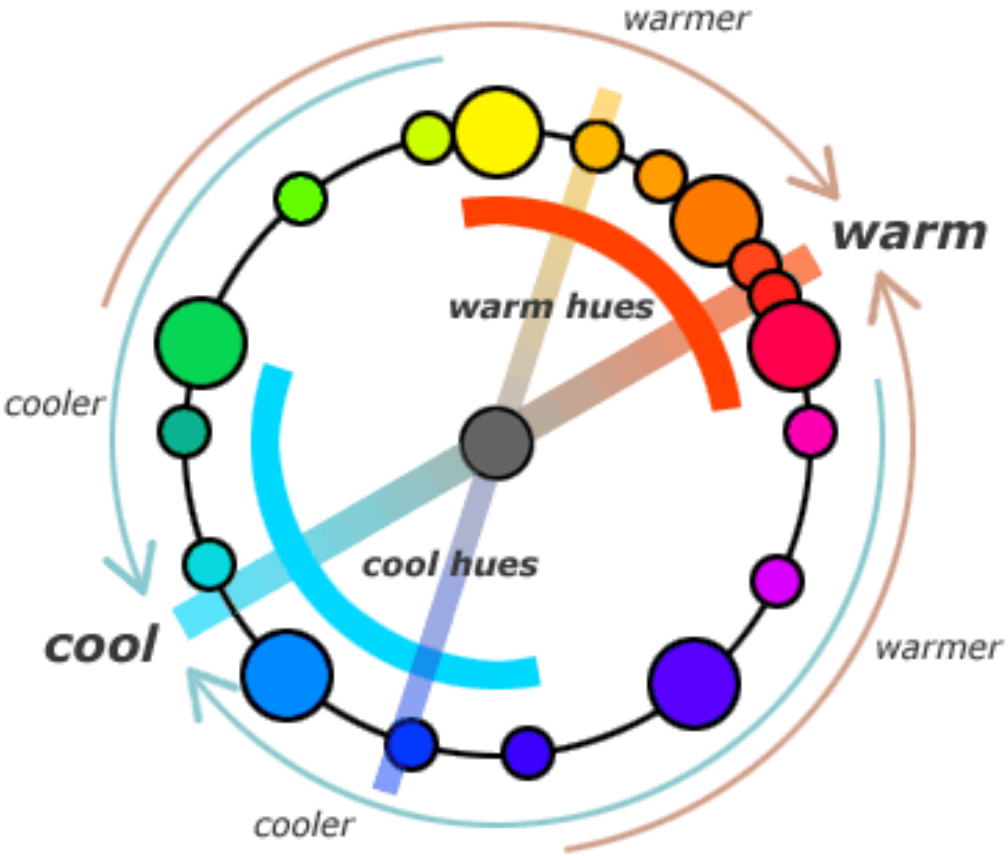
  http://people.csail.mit.edu/pdidyk/projects/LuminanceDisparityModel/LuminanceDisparityModel.pdf

# Opponent Color Theory

- Humans encode colors by differences
- E.g R-G, and B-Y Differences

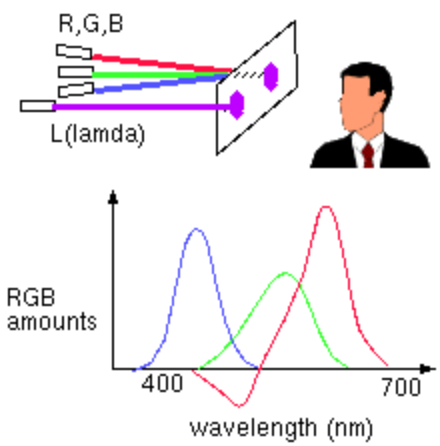


# Artistic Color Space



# Color Spaces

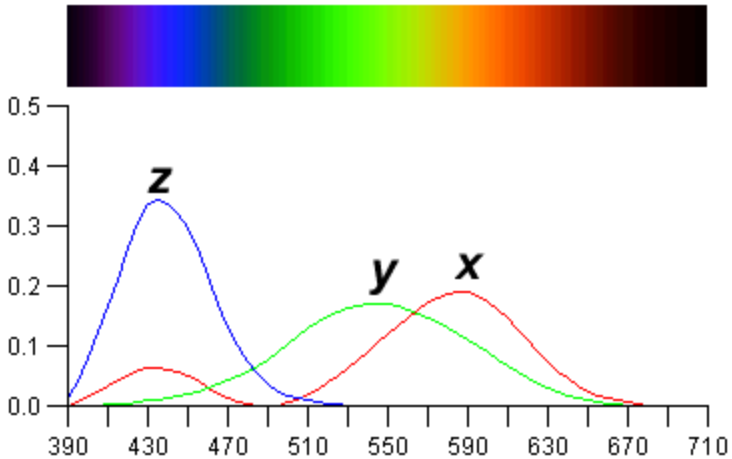
- Three types of cones suggests color is a 3D quantity. How to define 3D color space?
- Idea: shine given wavelength ($\lambda$) on a screen, and mix three other wavelengths (R,G,B) on same screen. Have user adjust intensity of RGB until colors are identical:




- *How closely does this correspond to a color CRT?*
- Problem:
- sometimes need to "subtract" R to match $\lambda$

# CIE Color Space

- The *CIE* (Commission Internationale d'Eclairage) came up with three hypothetical lights X, Y, and Z with these spectra:




- Approximately:

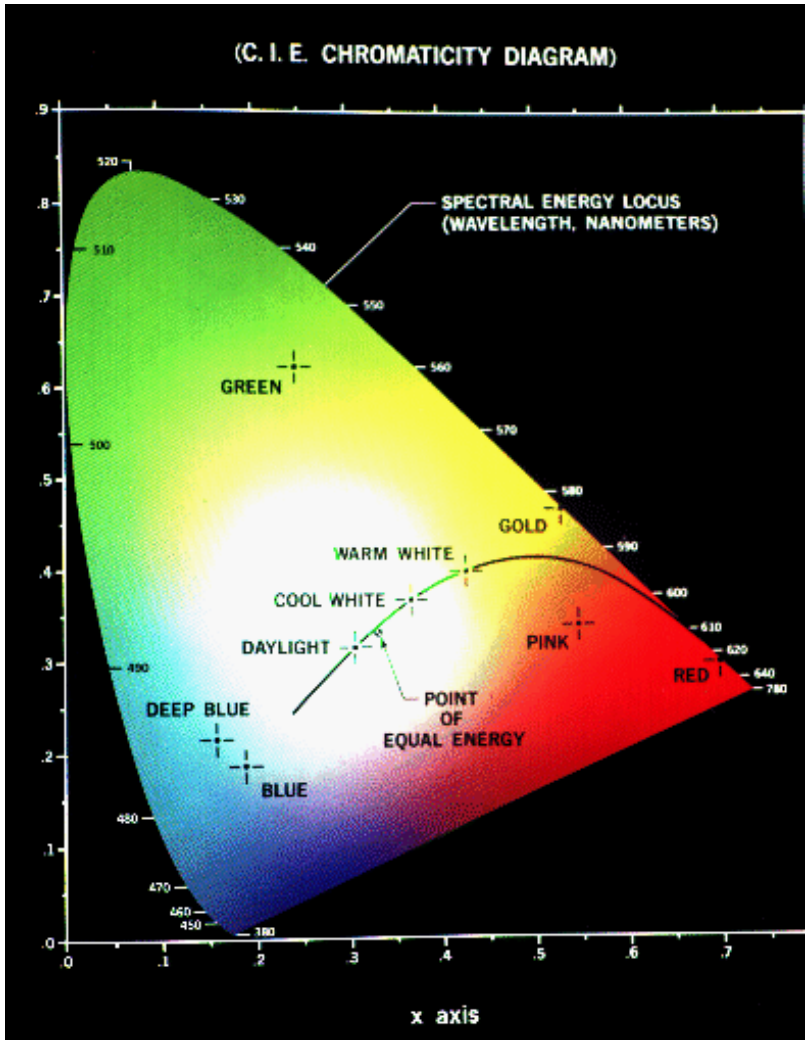
  X ~ R

  Y ~ G

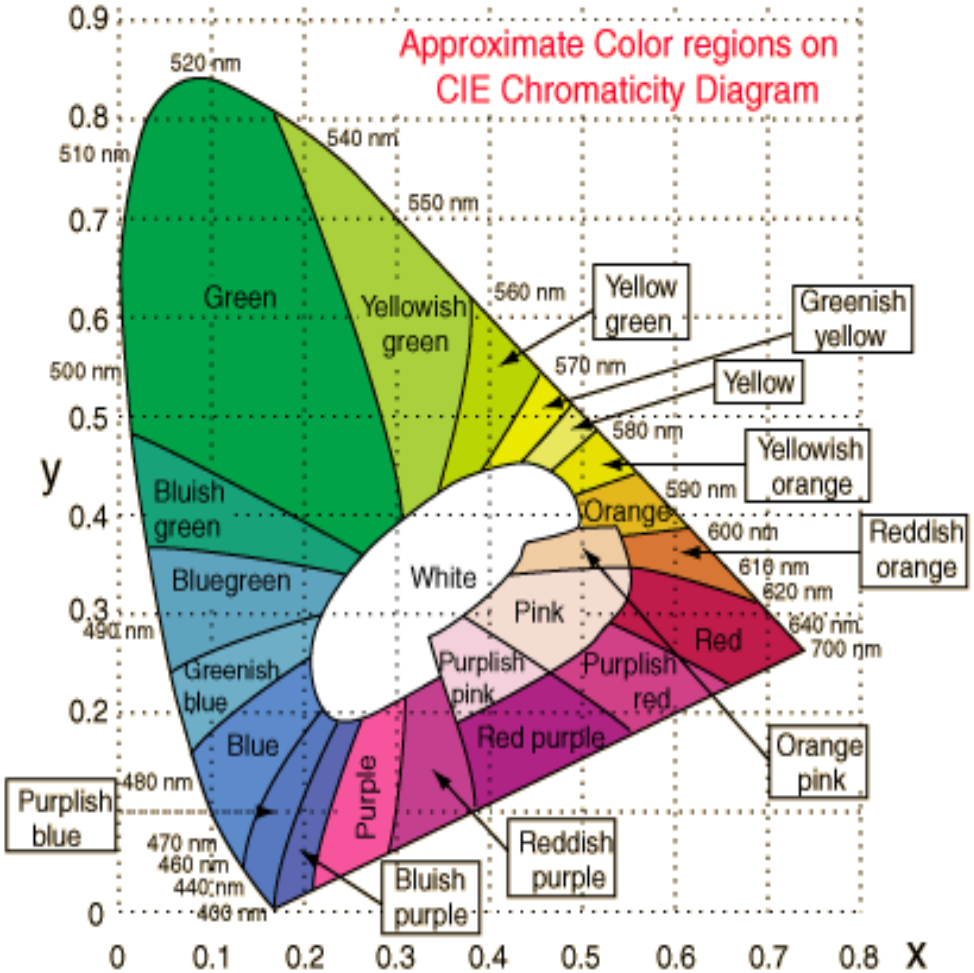
  Z ~ B

- Idea: any wavelength $\lambda$ can be matched perceptually by *positive* combinations of X,Y,Z

# CIE Color Space

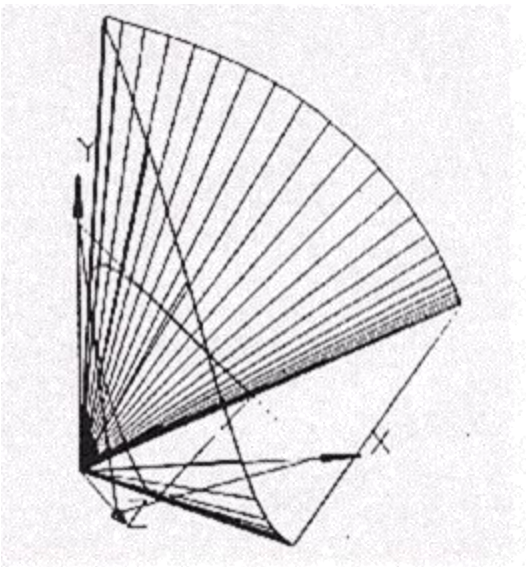


# CIE Color Space



# CIE Color Space

- The *gamut* of all colors perceivable is thus a three-dimensional shape in X,Y,Z:




**Human Perceptual Gamut**

For simplicity, we often project to the 2D plane X+Y+Z=1, e.g.:

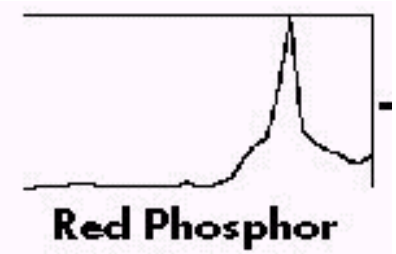
$$X = X / (X+Y+Z)$$

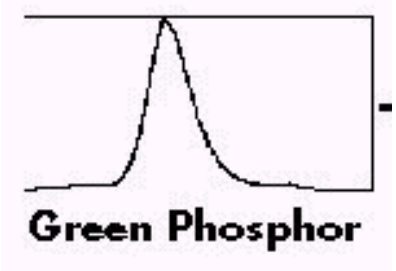
$$Y = Y / (X+Y+Z)$$

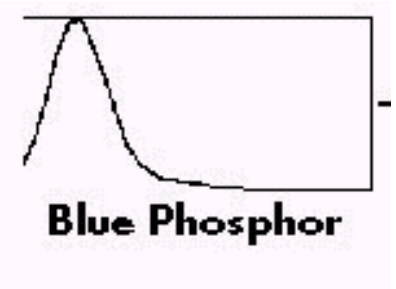
$$Z = 1 - X - Y$$

# Device Color Gamuts

- X, Y, and Z are hypothetical light sources; no real device can produce the entire gamut of perceivable color
- Example: CRT monitor

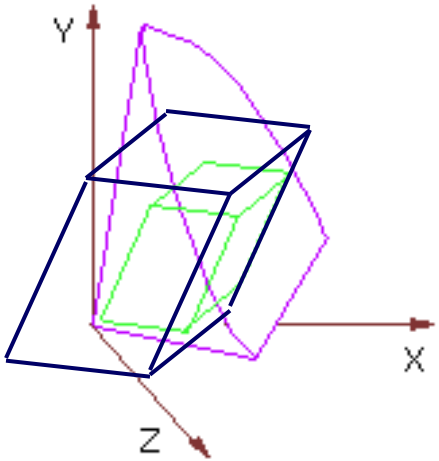


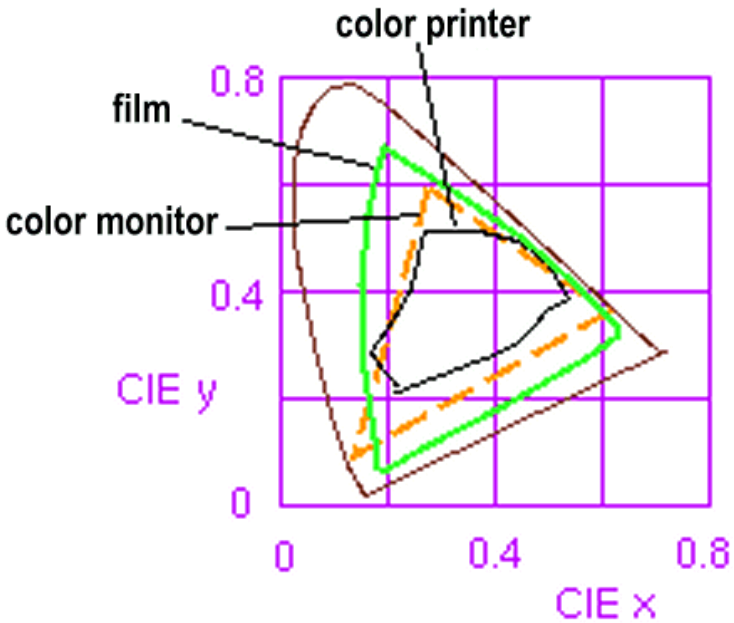
# Device Color Gamuts

- The RGB color cube sits within CIE color space something like:



# Device Color Gamuts

- We can use the CIE chromaticity diagram to compare the gamuts of various devices:
- Note, for example, that a color printer cannot reproduce all shades available on a color monitor



# LAB Space

- A $L^*a^*b^*$ color space is a color-opponent space with dimension $L^*$ for lightness and $a^*$ and $b^*$ for the color-opponent dimensions, based on nonlinearly compressed CIE XYZ color space coordinates.

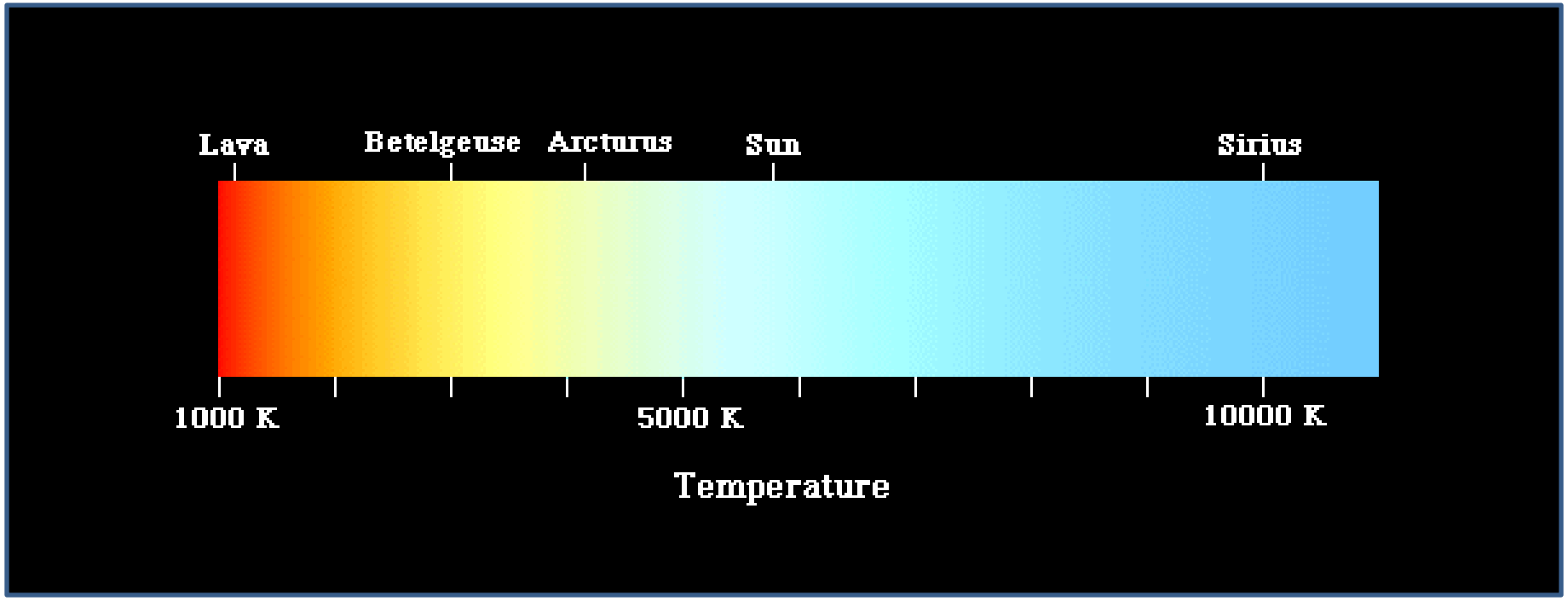
$$
\begin{aligned}
L^\star &= 116 f(Y/Y_n) - 16 \\
a^\star &= 500\left[f(X/X_n) - f(Y/Y_n)\right] \\
b^\star &= 200\left[f(Y/Y_n) - f(Z/Z_n)\right]
\end{aligned}
\qquad
f(t) = \begin{cases} t^{1/3} & \text{if } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{otherwise} \end{cases}
$$

# LAB Space

- $L^*a^*b^*$ color is designed to approximate human vision. It aspires to perceptual uniformity, and its $L^*$ component closely matches human perception of “lightness”, and $a^*$ and $b^*$ alters “color”.
  - In contrast, RGB, CMYK, and other spaces model the output of physical devices rather than human visual perception

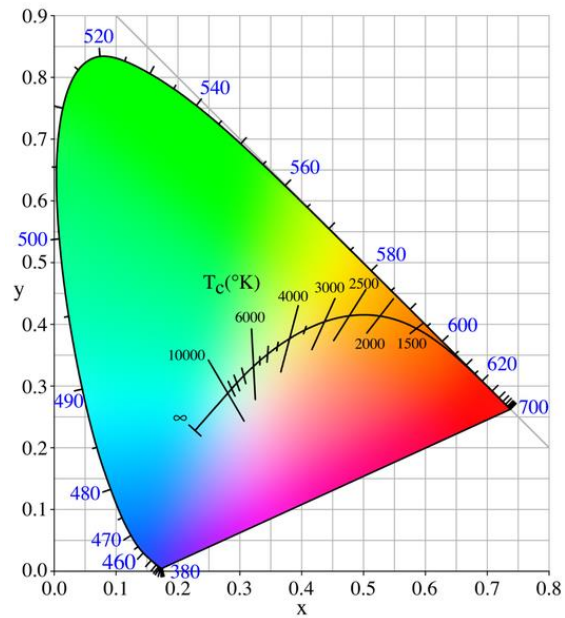
# LAB Space Perceptually Fun Facts: $a^*$ axis

- $a^*$ axis corresponds to “blue yellow” range which approximates black body radiation



# LAB Space Perceptually Fun Facts: $a^*$ axis

- $a^*$ axis corresponds to “blue yellow” range which approximates black body radiation
- We *seem* to be less sensitive to changes along that axis – maybe because “its everywhere”



# Color Constancy

- Lets look at this:
  - https://www.youtube.com/watch?v=XYnqH_HHZDo

# Color Constancy

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- What is happening?

# Color Constancy

- What color is the fruit on top of the pie?

# Color Constancy

# LAB Space Perceptually Fun Facts: Color Constancy

- Color constancy is an example of subjective constancy
- It states that the perceived color of objects remains relatively constant under varying illumination conditions.
  - e.g., A green apple looks green to us at noon (white sunlight) or at sunset (red sunlight)

# LAB Space Perceptually Fun Facts: Examples

- In both pictures, we can recognize the same colors, why?

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- In both pictures, we can recognize the same colors, why?

# Color Constancy

- Can we write this down as an equation?

# Color Constancy

- Given two colors, we compute

$$C_1/C_2 = R_{12}$$

- Now change the colors but keep the ratio, so

$$C'_1/C'_2 = R_{12}$$

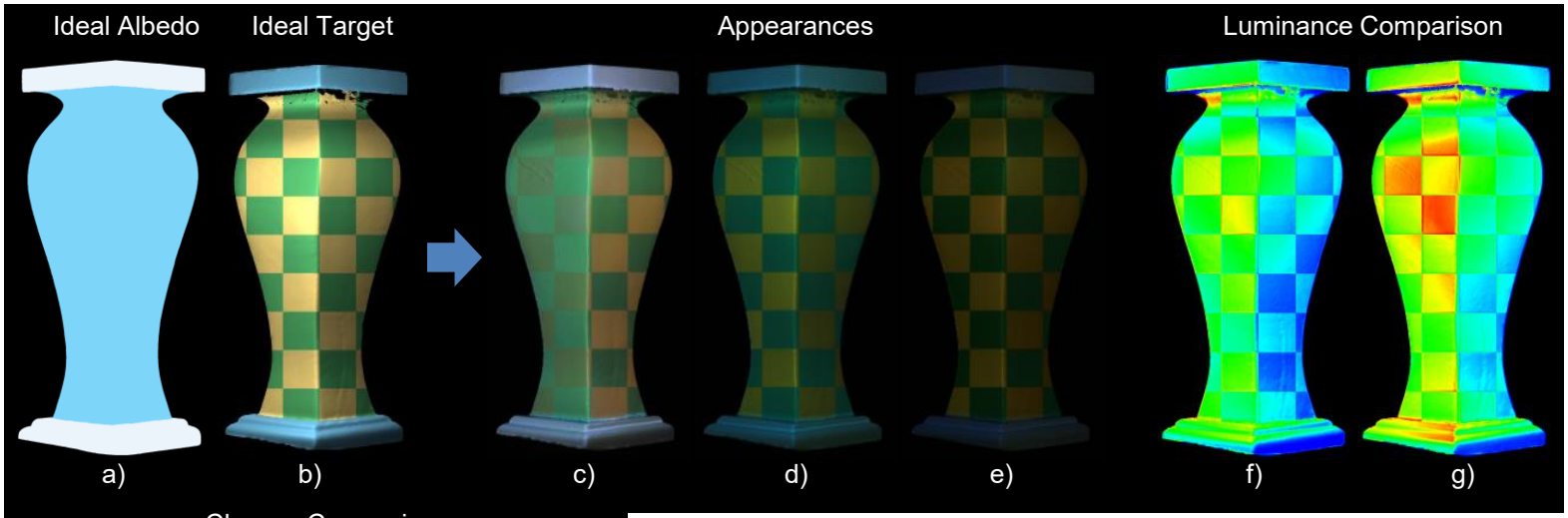
- The colors will seem relatively the same (or "constant")

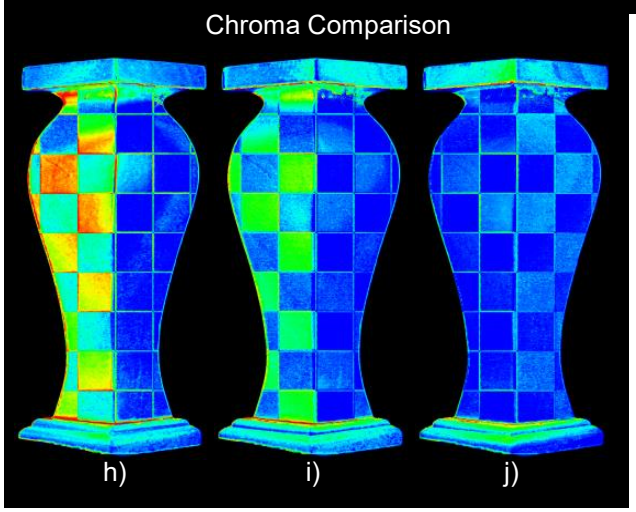
# Perceptually Significant Color Differences

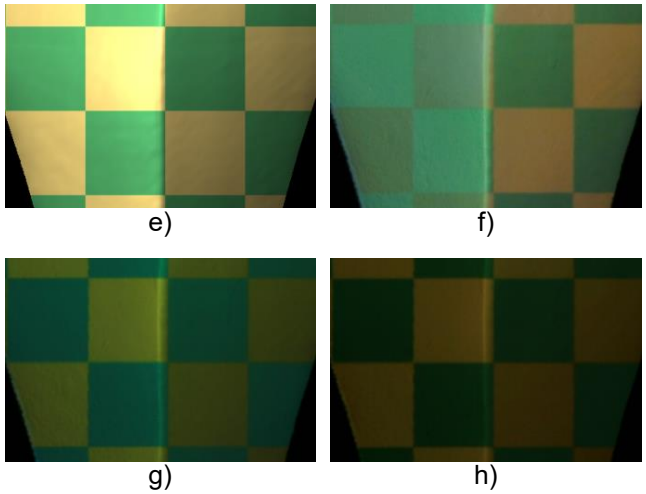
- In LAB, one unit means a perceptually significant color/luminosity difference
- This is not the case in, for example, RGB
- Check out:

  http://colormine.org/delta-e-calculator/

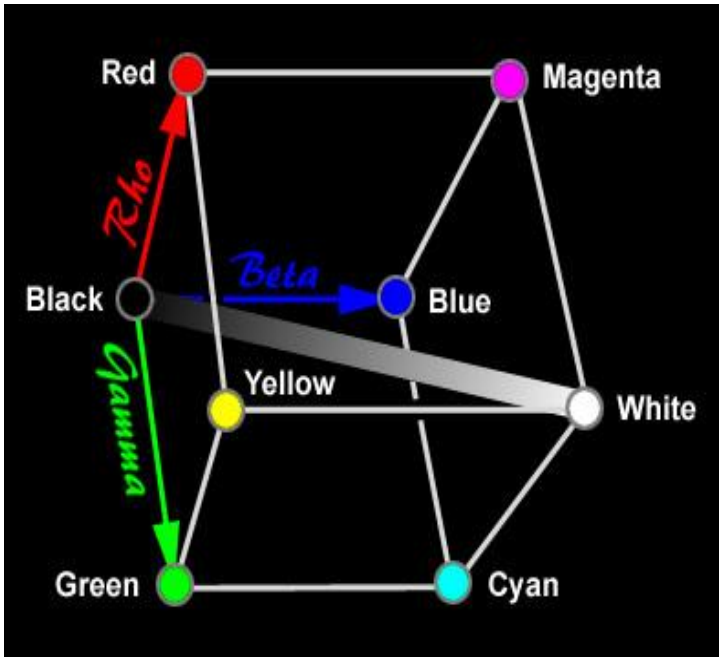
# Example use in current research…

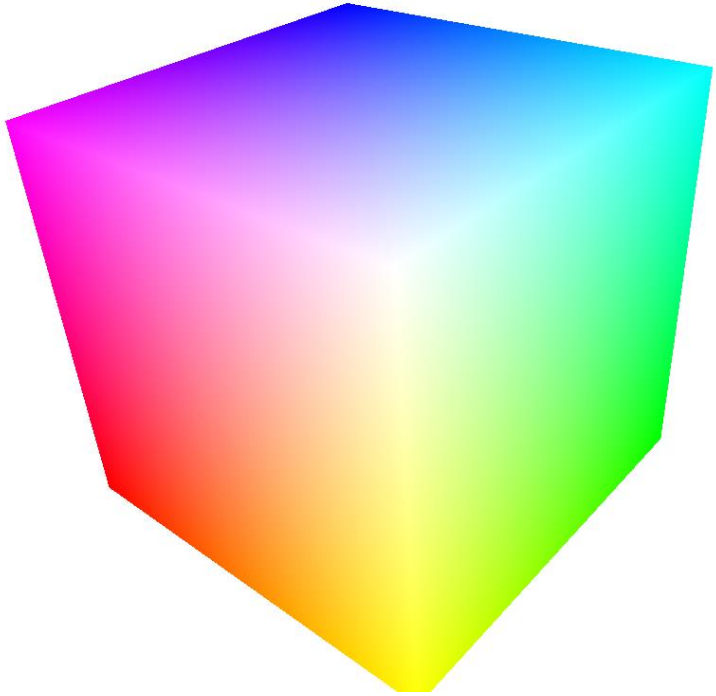


# RGB Color Space



# RGB Color Space

- Convenient colors (screen phosphors)
- Decent coverage of the human color
- Customarily quantized in the range 0…255
- Full color = 3 bytes/pixel
- Not a particularly good basis for human interaction
  - Non-intuitive
  - Non-orthogonal (perceptually)

# RGB Color Space

- The RBG colors can be arranged in a cube, in a space with the dimensions R, G, and B. The colors at the vertices of the RGB cube are then:

| Color | R | G | B |
|---|---|---|---|
| black | 0 | 0 | 0 |
| white | 255 | 255 | 255 |
| red | 255 | 0 | 0 |
| green | 0 | 255 | 0 |
| blue | 0 | 0 | 255 |
| cyan | 0 | 255 | 255 |
| magenta | 255 | 0 | 255 |
| yellow | 255 | 255 | 0 |

# RGB Cube Properties

- The main diagonal from black to white contains the gray scale.
- If a specific color is given as (R,G,B) and k is a number smaller than 1, then (kR, kG, kB) has *approximately* the same hue and is dimmer. So, we can model color intensity by
  - (kR, kG, kB), $k < 1$
  - Note that the brightness of (R,G,B) is not exceeded

# Converting Within Some RGB Color Spaces

- Sometimes only a simple matrix operation is needed:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- The transformation $\mathbf{C_2 = M^{-1}_2\, M_1\, C_1}$ yields RGB on monitor 2 that is equivalent to a given RGB on monitor 1
- Analogous to change of coordinate system.

# sRGB

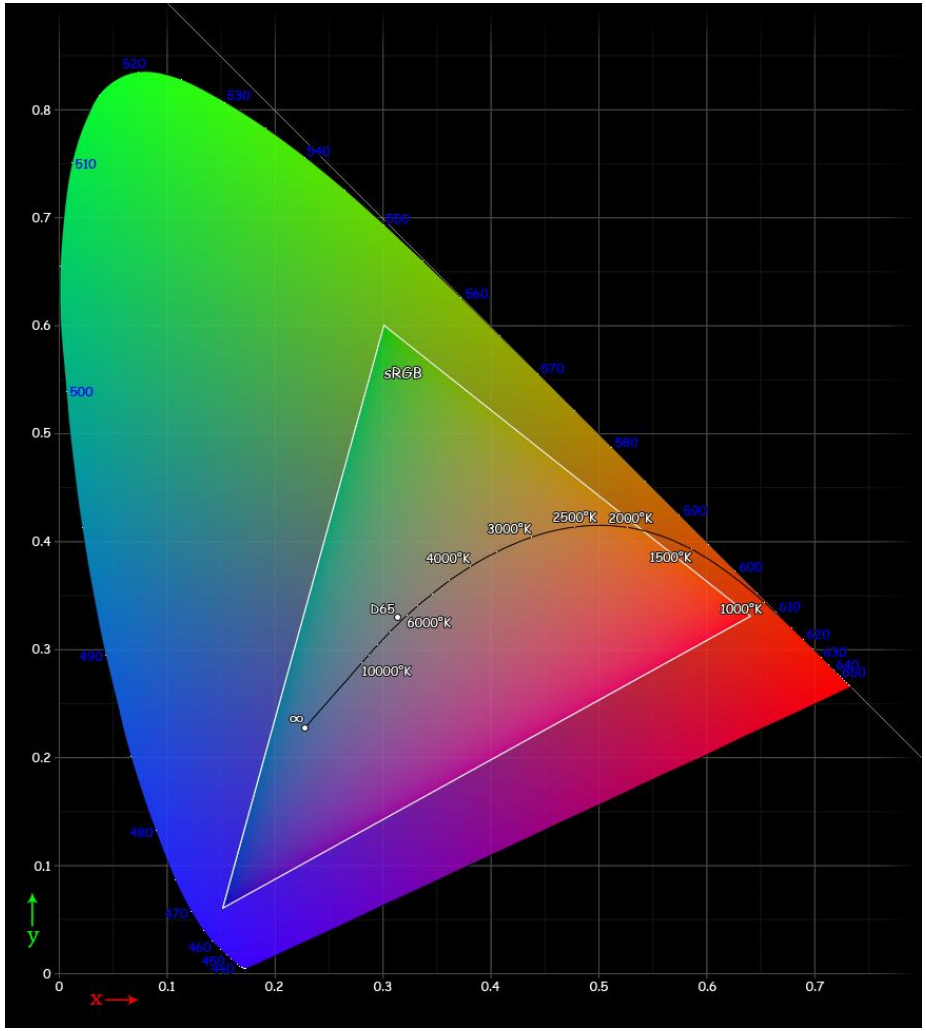
- Standard RGB space of a "RGB device" assuming a gamma correction of 2.2
  - (gamma correction to be explained in a few slides)

$$\begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$C_{\text{srgb}} = \begin{cases} 12.92 C_{\text{linear}}, & C_{\text{linear}} \leq 0.0031308 \\ (1+a) C_{\text{linear}}^{1/2.4} - a, & C_{\text{linear}} > 0.0031308 \end{cases}$$

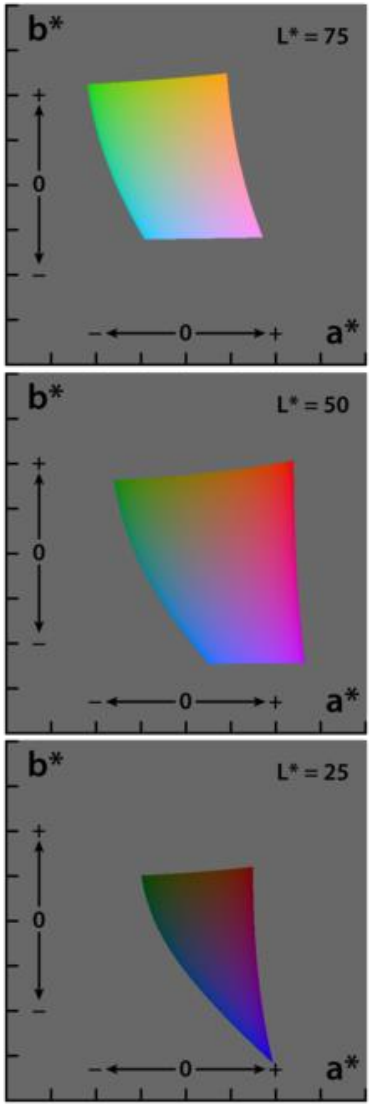
where C corresponds to any of R, G or B; and a = 0.055

# sRGB

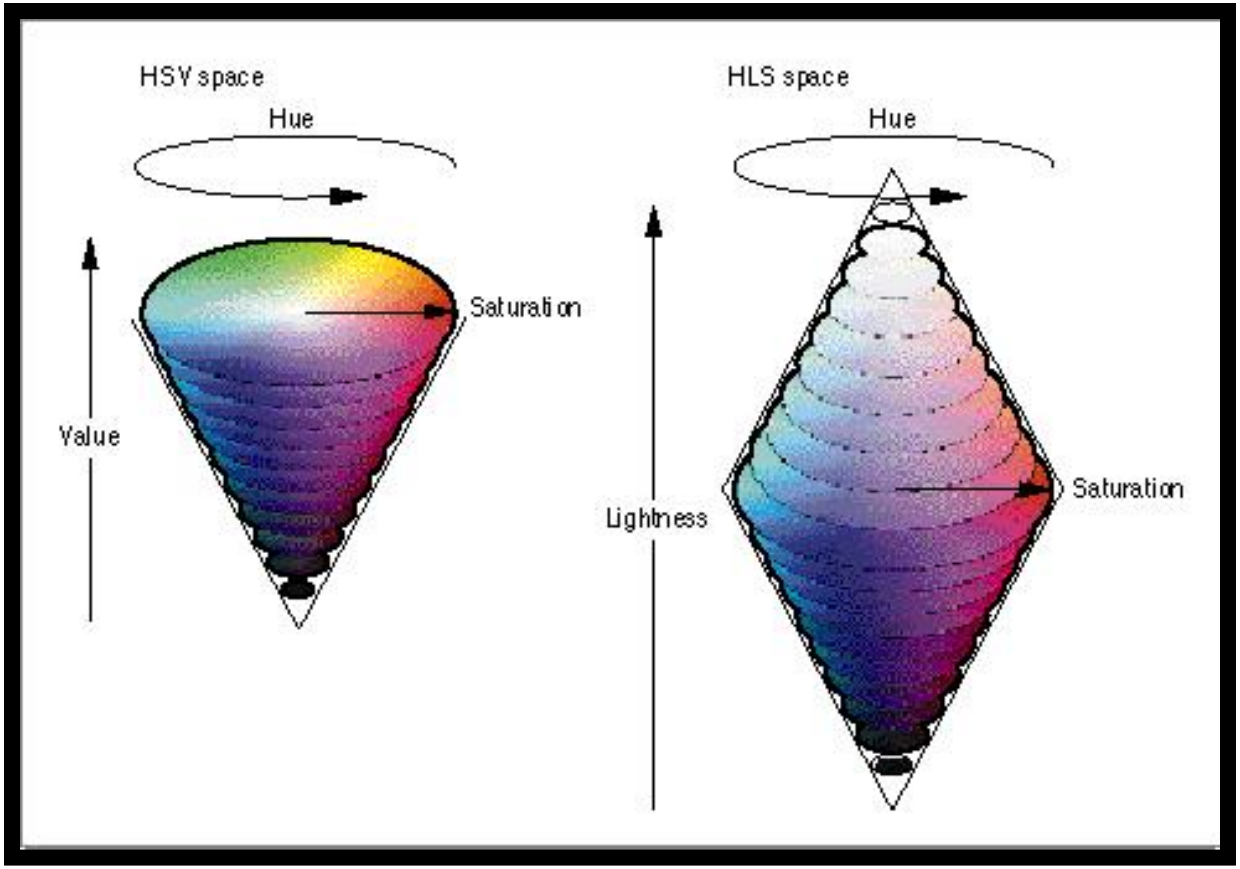

sRGB
D65
3000°K
2500°K
2000°K
1500°K
1000°K
4000°K
6000°K
10000°K
∞
520
530
540
550
560
570
580
590
600
610
620
630
510
500
490
480
470
460
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
y
x

# LAB and sRGB

- “ab” slices of LAB space that fall within the sRGB gamut of a typical display
  - sRGB = “standard RGB gamut”



# HSV/HSL Color Space



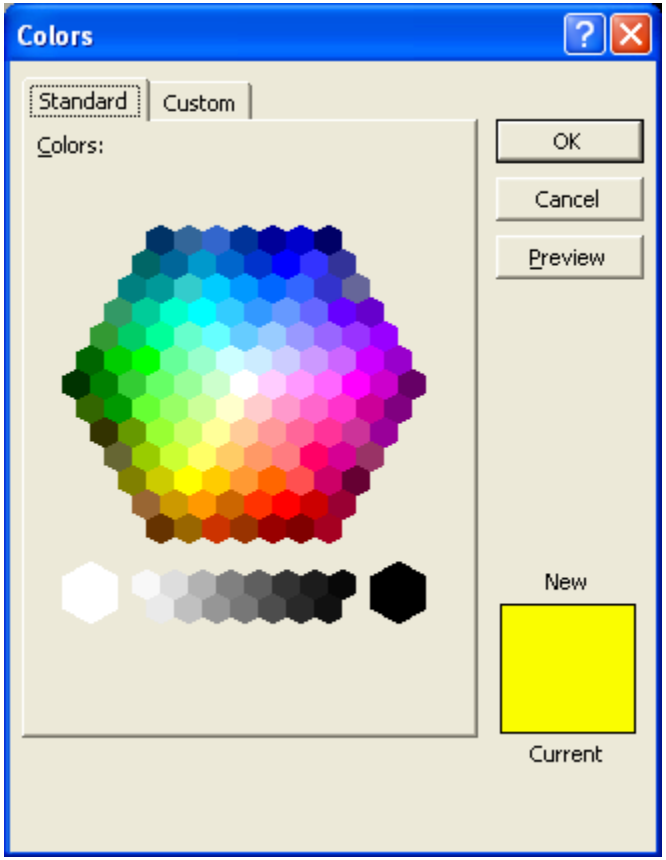
# HSV/HSL Color Space

- Intensity/Value
  - total amount of energy
- Saturation
  - degree to which color is one wavelength
- Hue
  - dominant wavelength

# HSV

- Max = max(R, G, B)
- Min = min(R, G, B)
- S = (max – min)/max
- If R==Max → h = (G-B)/(max-min)
- If G==Max → h = 2+(B-R)/(max-min)
- If B==Max → h = 4 + (R-G)/(max-min)
- If h<0 → H = h/6 + 1
- If h>0 → H = h/6

# HSV User Interaction



# HSL

$$S = \sqrt{\frac{(R-G)^2 + (R-B)^2 + (G-B)^2}{2}}$$

$$I = \frac{R+G+B}{3}$$

$$H = \frac{a - \arctan \frac{(R-1)b}{G-B}}{2\pi}$$

$$a = \frac{\pi}{2} \text{ if G>B, } \frac{3\pi}{2} \text{ if G<B}$$

$$H = 1 \text{ if G=B}$$

$$a = \sqrt{3}$$

# YIQ/YUV Color Space

- *YIQ* is the color model used for color TV in the US
  - *Y* is luminance; *I* & *Q* are color
  - Note: *Y* is the same as CIE's *Y*
  - Result: backwards compatibility with B/W TV!

# Converting Between RGB and YIQ

- Converting between color models can also be expressed as such a matrix transform, e.g.:

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

# Gamma Correction

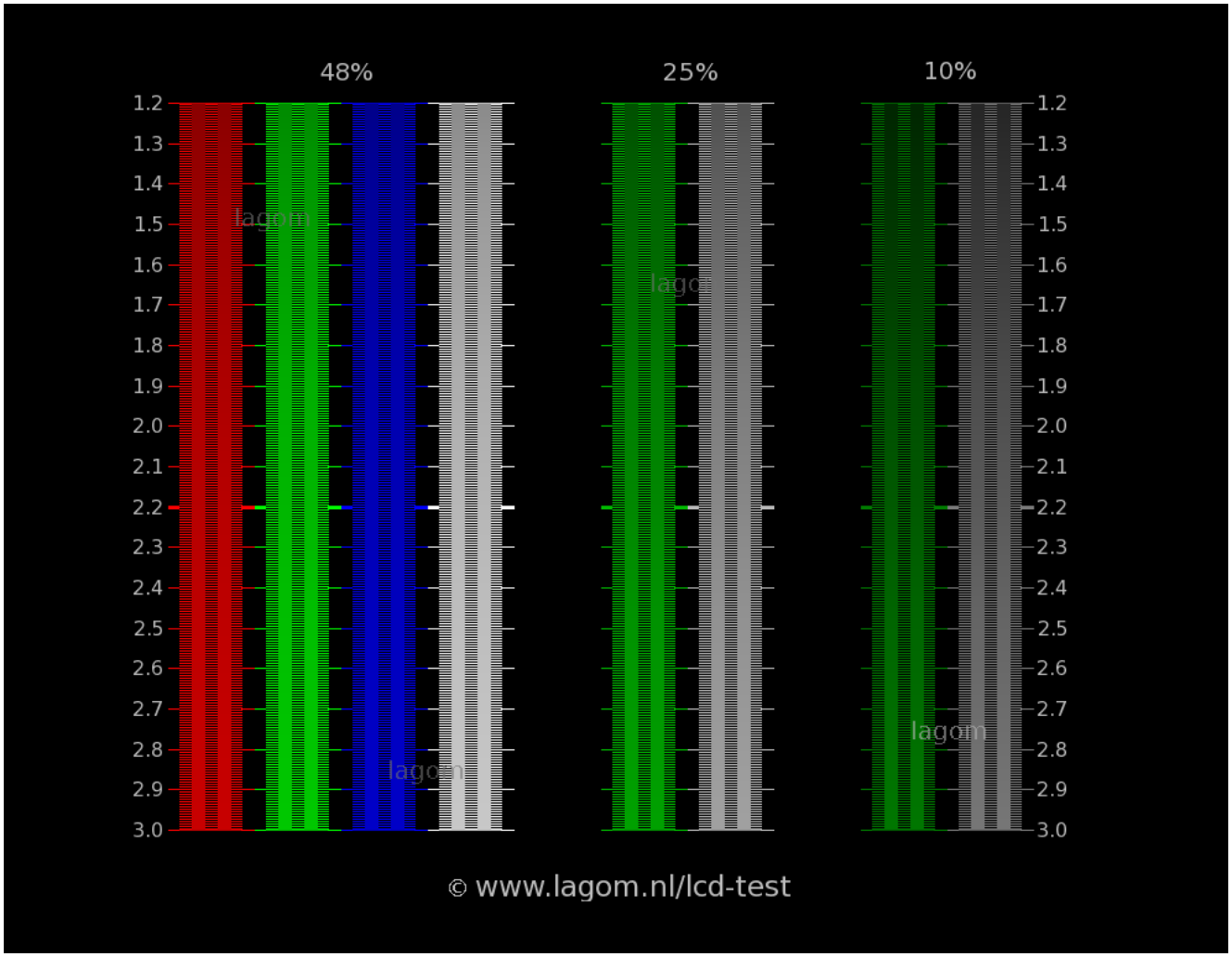
- We generally assume color brightness is linear
- But most display devices are inherently nonlinear
  - brightness(voltage) ≠ 2×brightness(voltage/2): $I = V_s^{\gamma}$
- Common solution: *gamma correction*
  - Post-transformation on RGB values to map them to linear range on display device: $V_c = V_s^{\frac{1}{\gamma}}$
  - Can have separate $\gamma$ for R, G, B
  - $\gamma$ is usually in range 1.8 to 2.2

# Gamma Correction

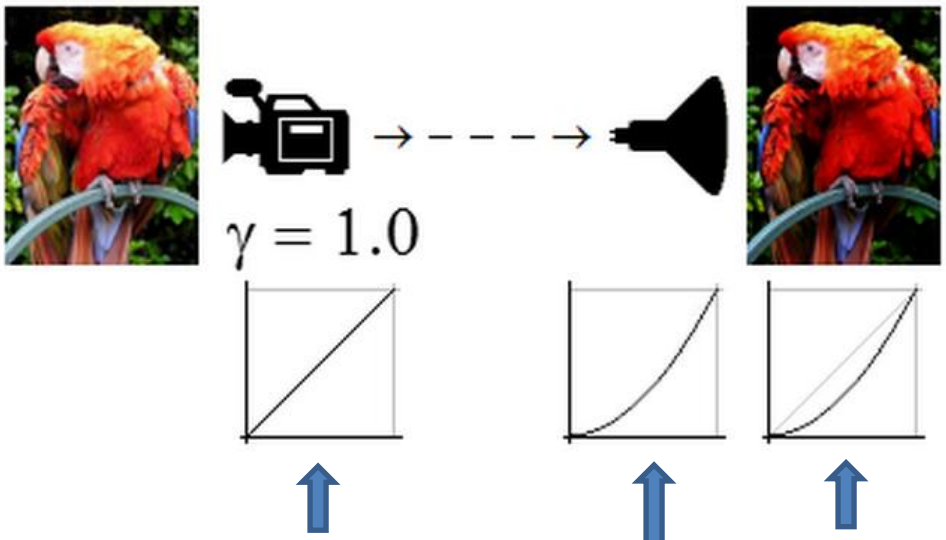
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Linear encoding $V_S$ = | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| Linear intensity $I$ = | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |

# Gamma Correction Test

The fg+bg should blend at near 2.2



# Gamma Correction

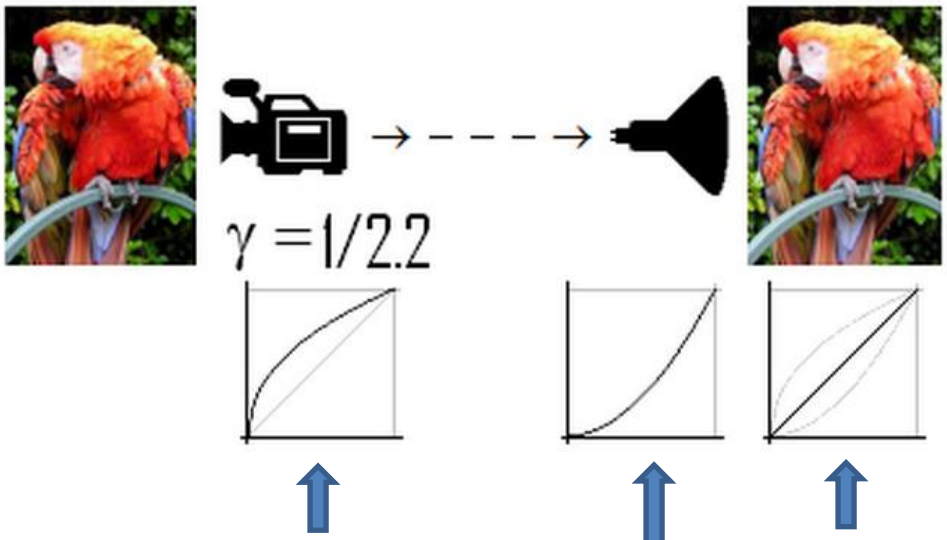



Camera
(gamma encoding)

Display
(gamma expansion)

Overall

# Gamma Correction




Camera
(gamma encoding)

Display
(gamma expansion)

Overall

# Examples

- Demo apps
- Website:
  - http://www.webexhibits.org/colorart/contrast.html

# Supercool!

- [Video]