Color and Perception

CS334 Spring 2025

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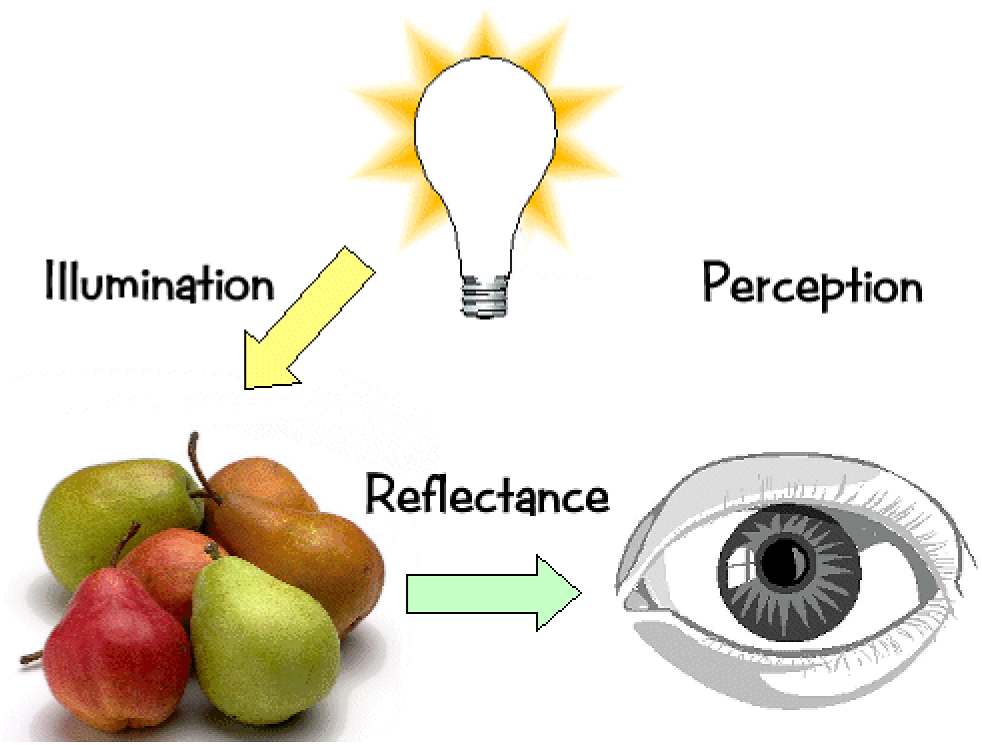
Elements of Color Perception

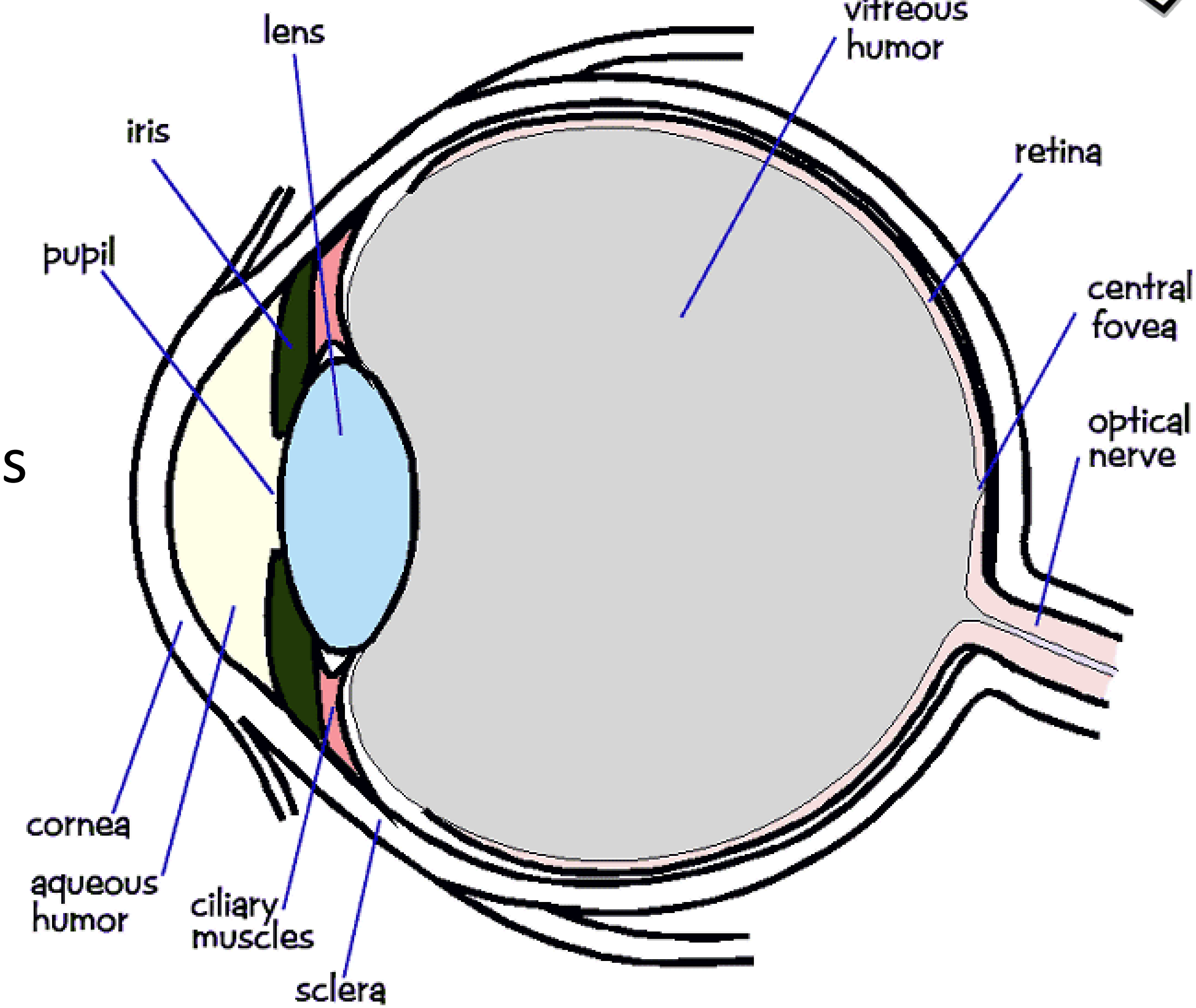


Elements of Color

- 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

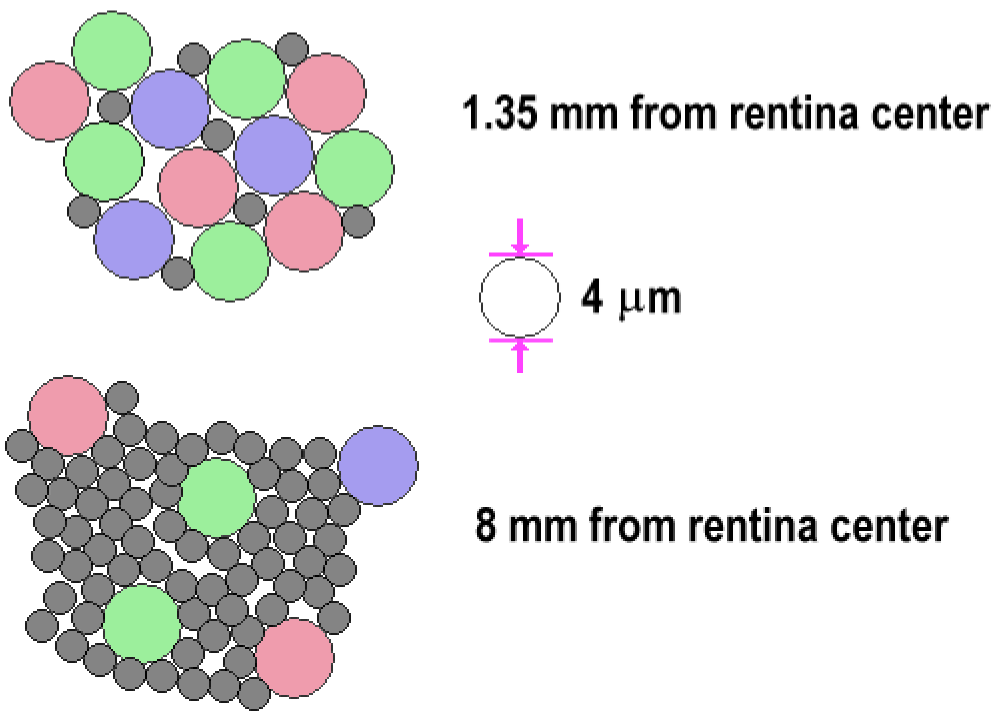
Physiology of the Eye

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



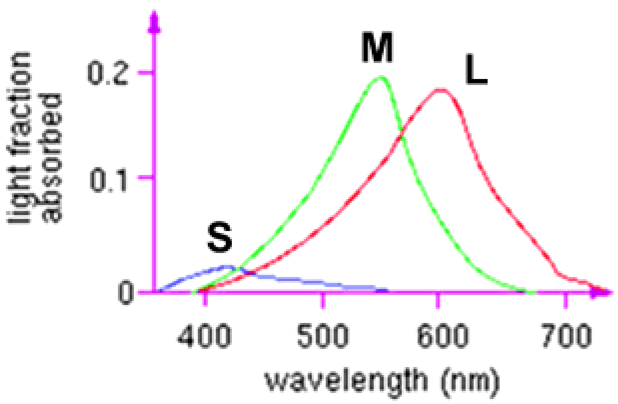
Physiology of the Retina

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



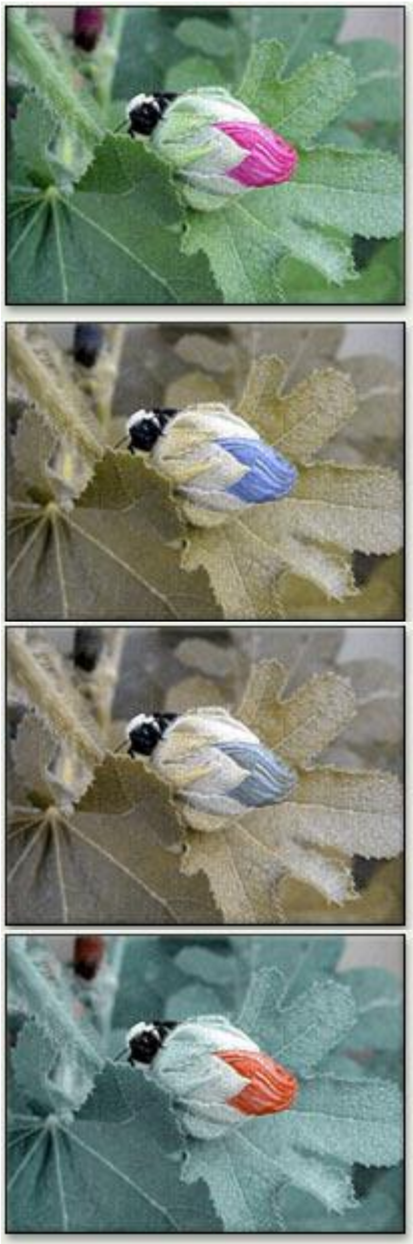
Types of Cones

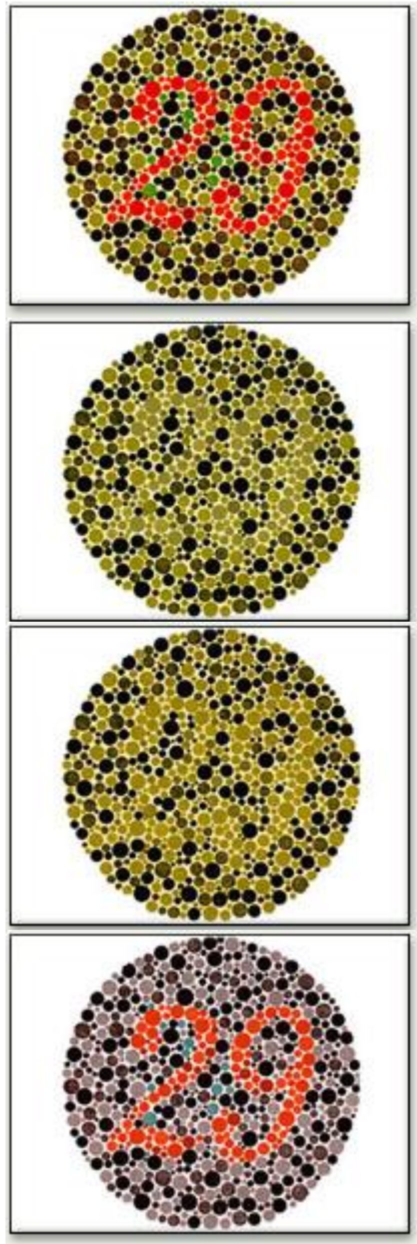
- Three types of cones:
  - **L** or **R**, most sensitive to red light (610 nm)
  - **M** or **G**, most sensitive to green light (560 nm)
  - **S** or **B**, most sensitive to blue light (430 nm)



  - Color blindness results from missing cone type(s)

Color Blindness





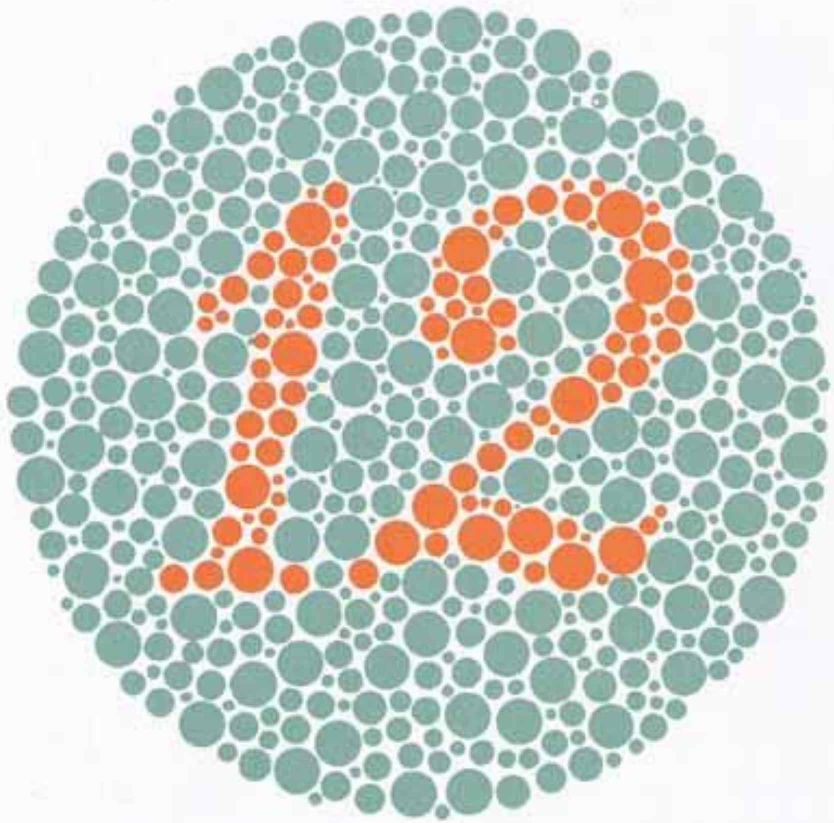
Normal

Protan (L-cone) “red insensitivity”

Deutan (M-cone) “green insensitivity”

Tritan (S-cone) “B=G and Y=violet”

Mini Color Blindness Test



What do <u>YOU</u> see?

Image 1

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

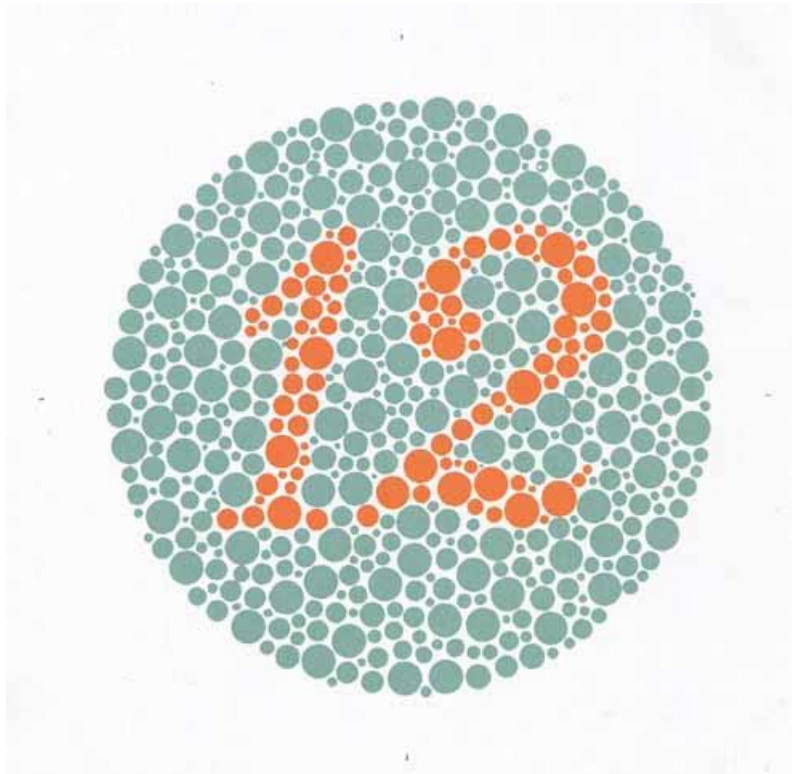
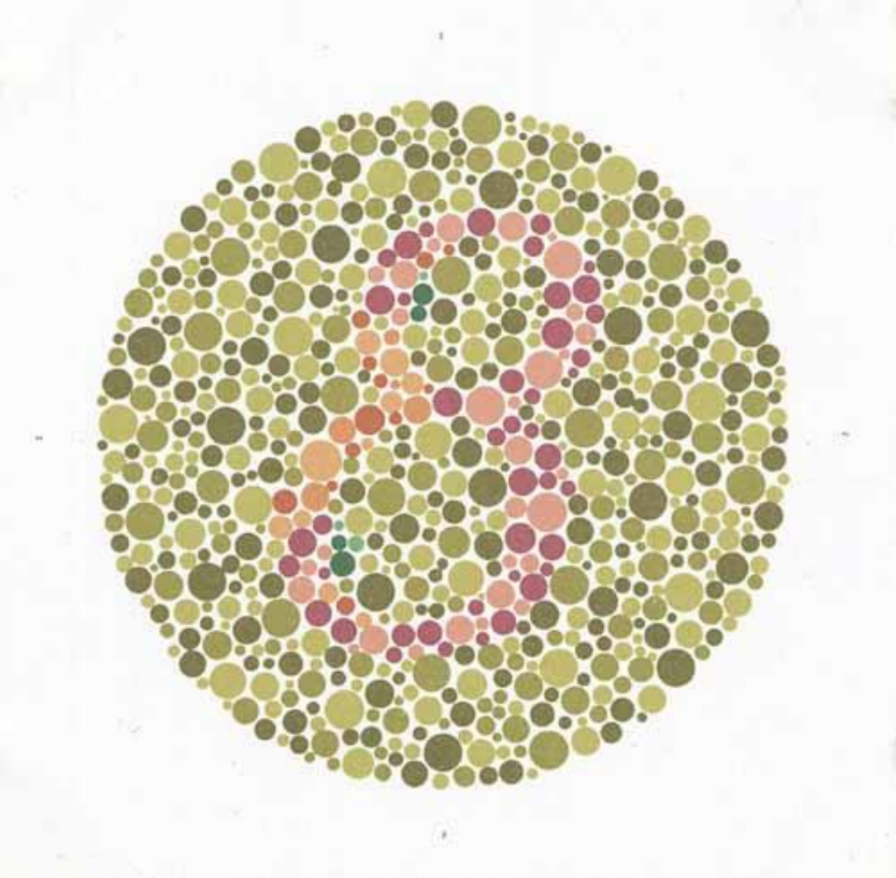


Image 2

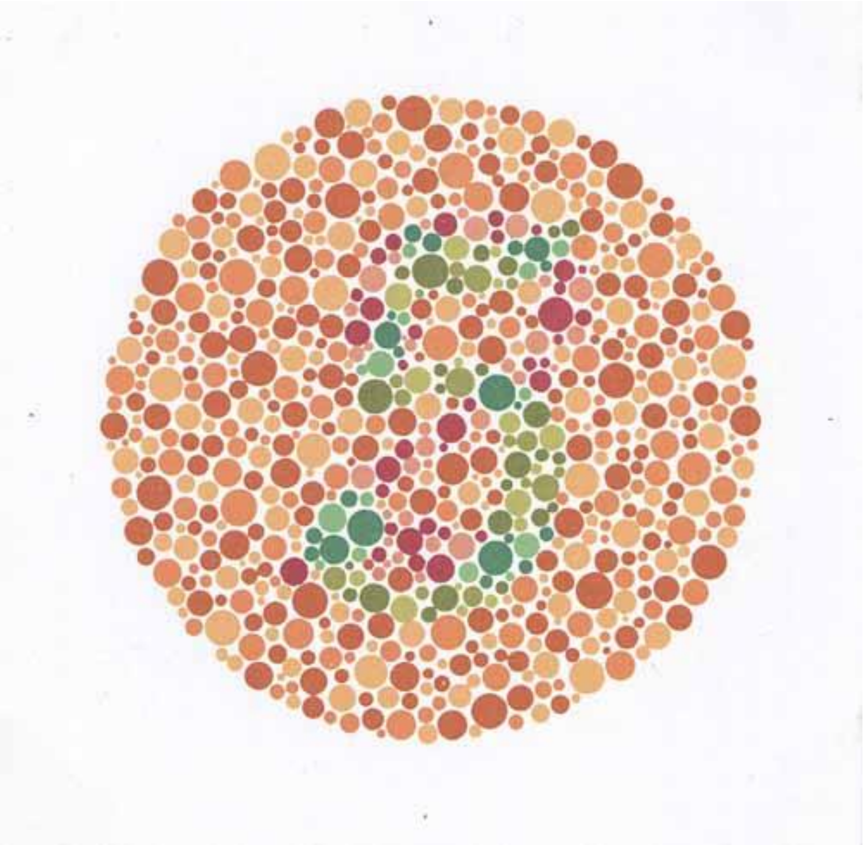


The normal read this as 8.

Those with red-green deficiencies read this as 3.

Those with total color blindness cannot read any numeral.

Image 4

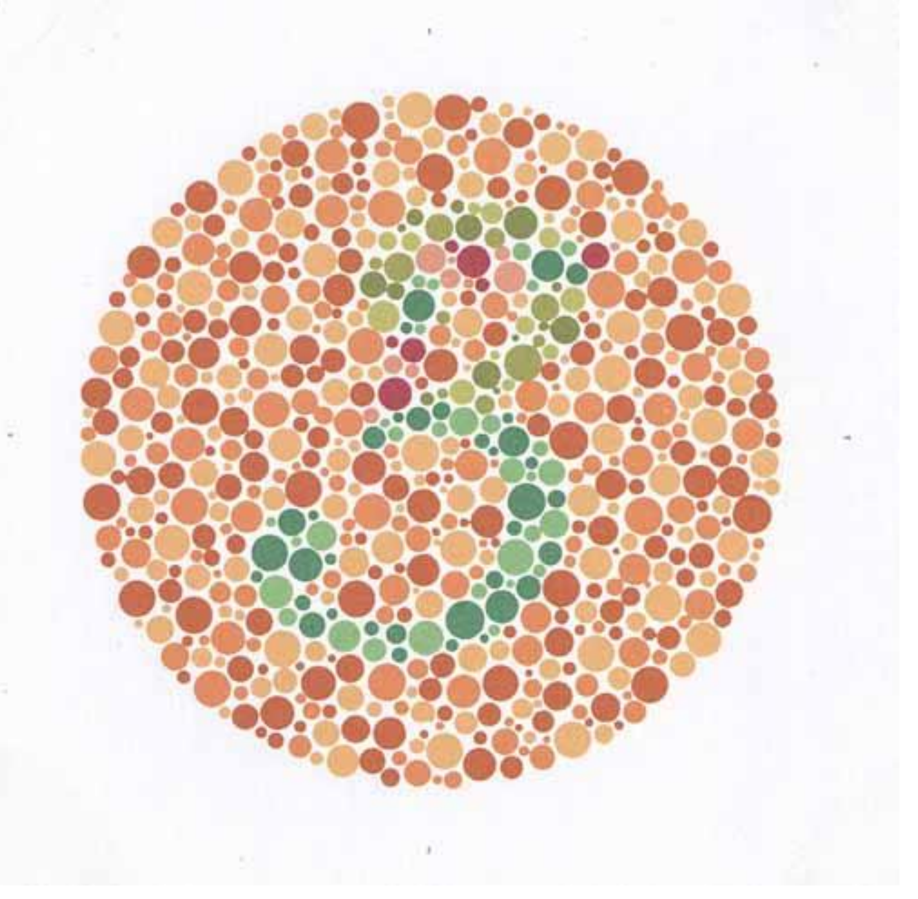


The normal read this as 5.

Those with red-green deficiencies read this as 3.

Those with total color blindness cannot read any numeral.

Image 5

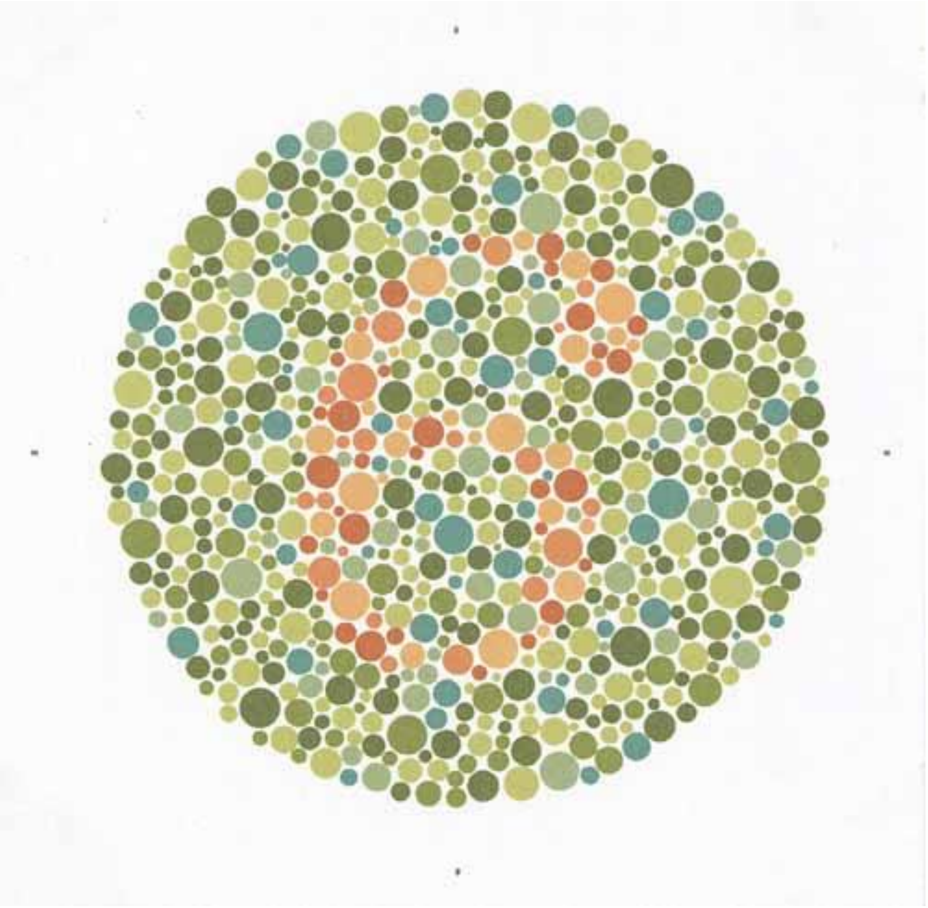


The normal read this as 3.

Those with red-green deficiencies read this as 5.

Those with total color blindness cannot read any numeral.

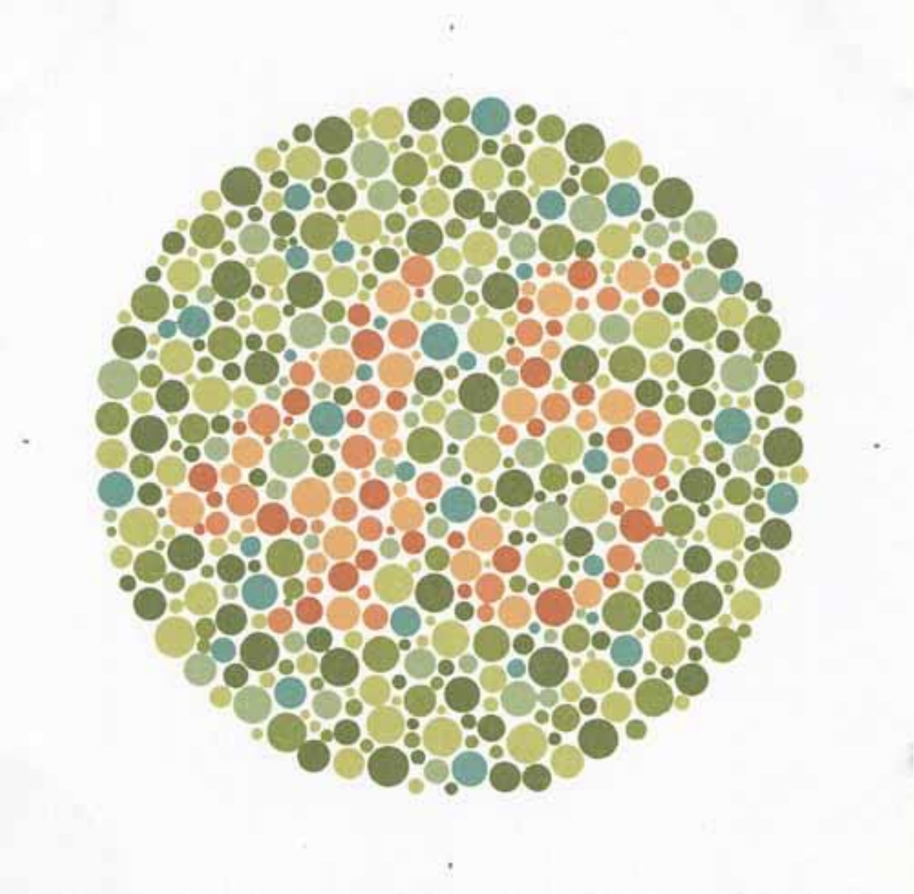
Image 8



The normal read this as 6.

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

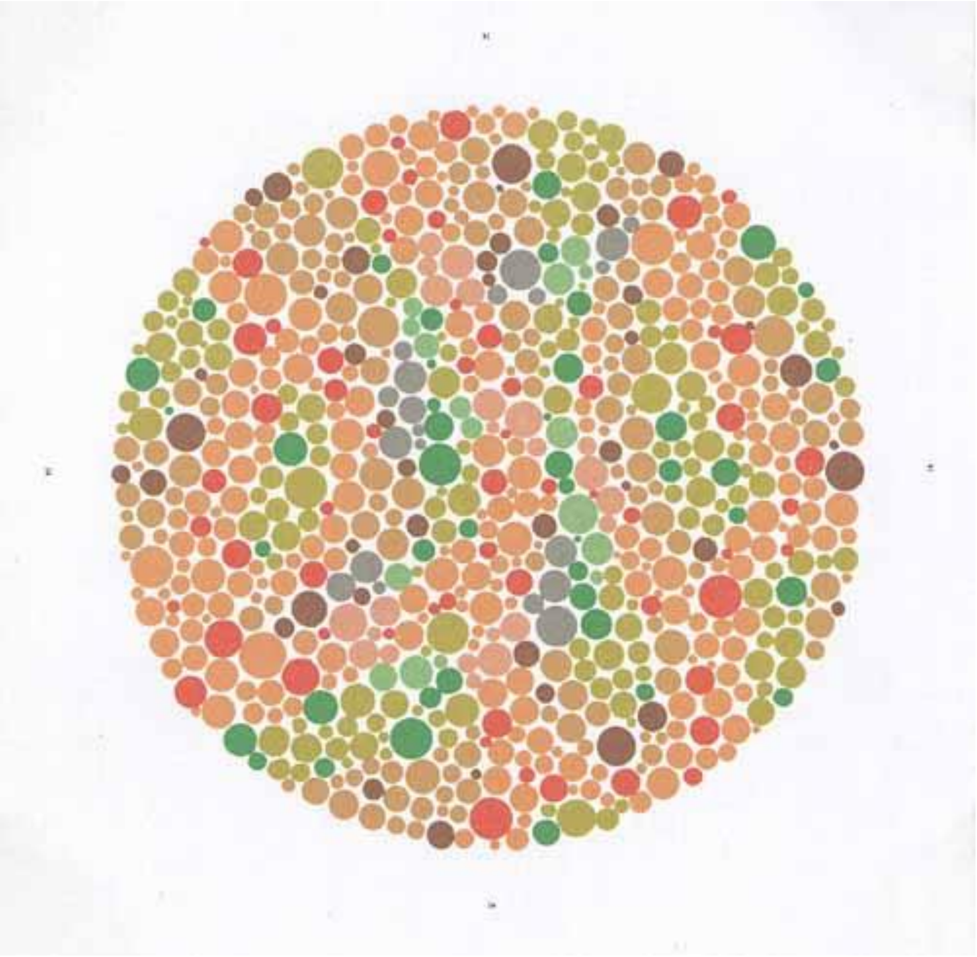
Image 9



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

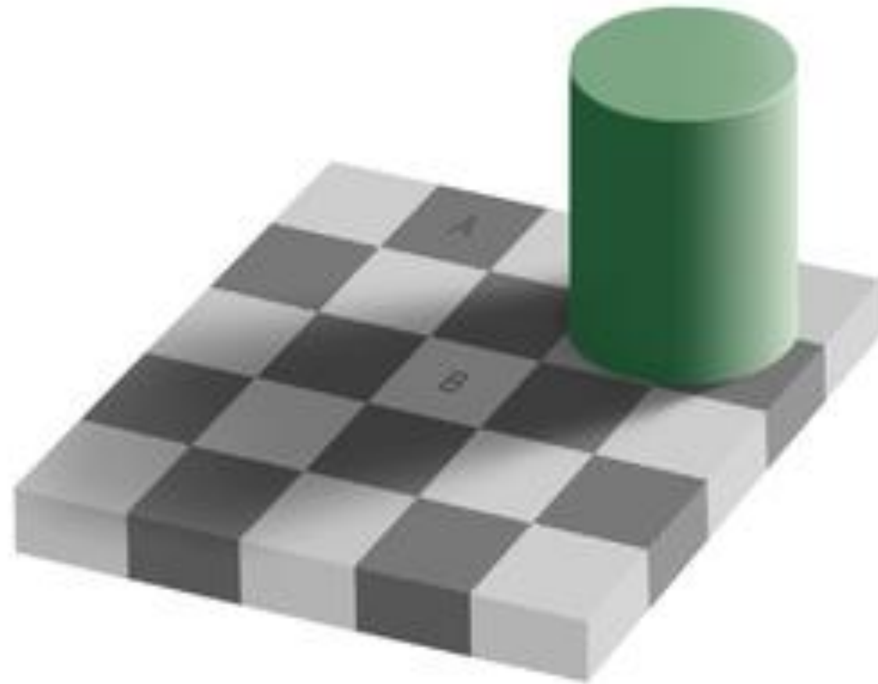
- Subjectively, the human eye seems to perceive color by three conceptual dimensions:
  - hue,
  - brightness, and
  - saturation.
- This suggests a 3D color space.
- Hardware reproduction of color cannot match human perception perfectly.

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

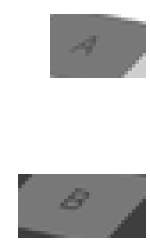
Simultaneous Contrast

- Is “A” looks darker than “B”?



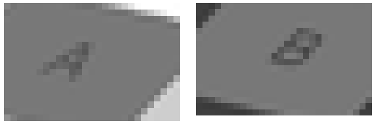
Simultaneous Contrast

- Is “A” looks darker than “B”?



Simultaneous Contrast

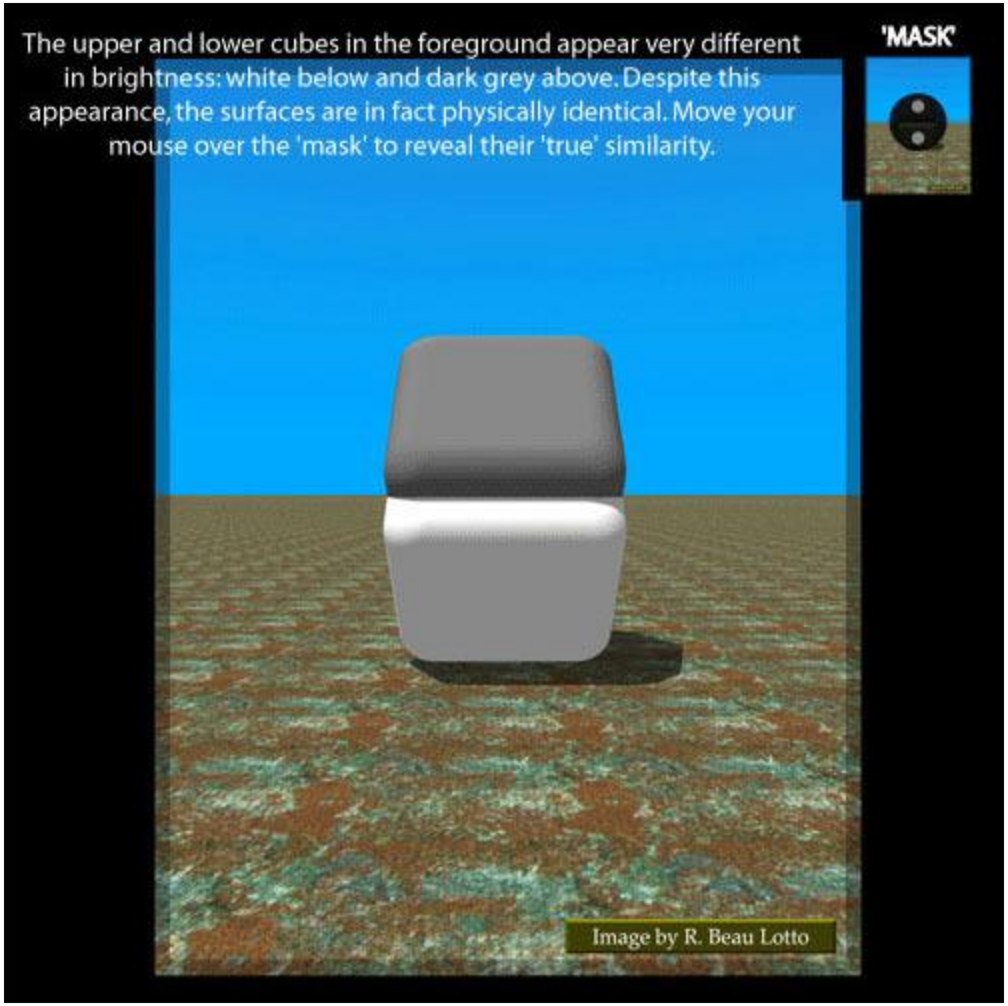
- Is "A" looks darker than "B"?
- Nope! Why?



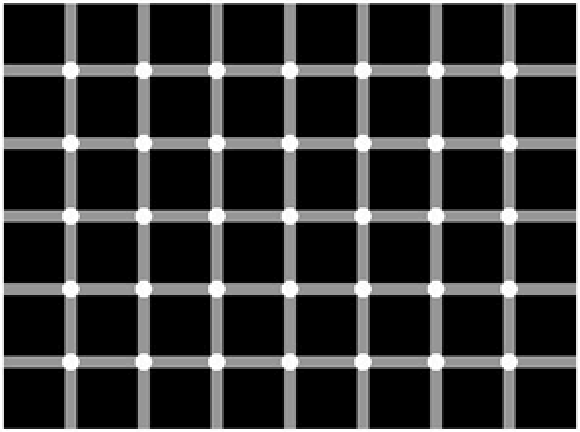
- What about in color?

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

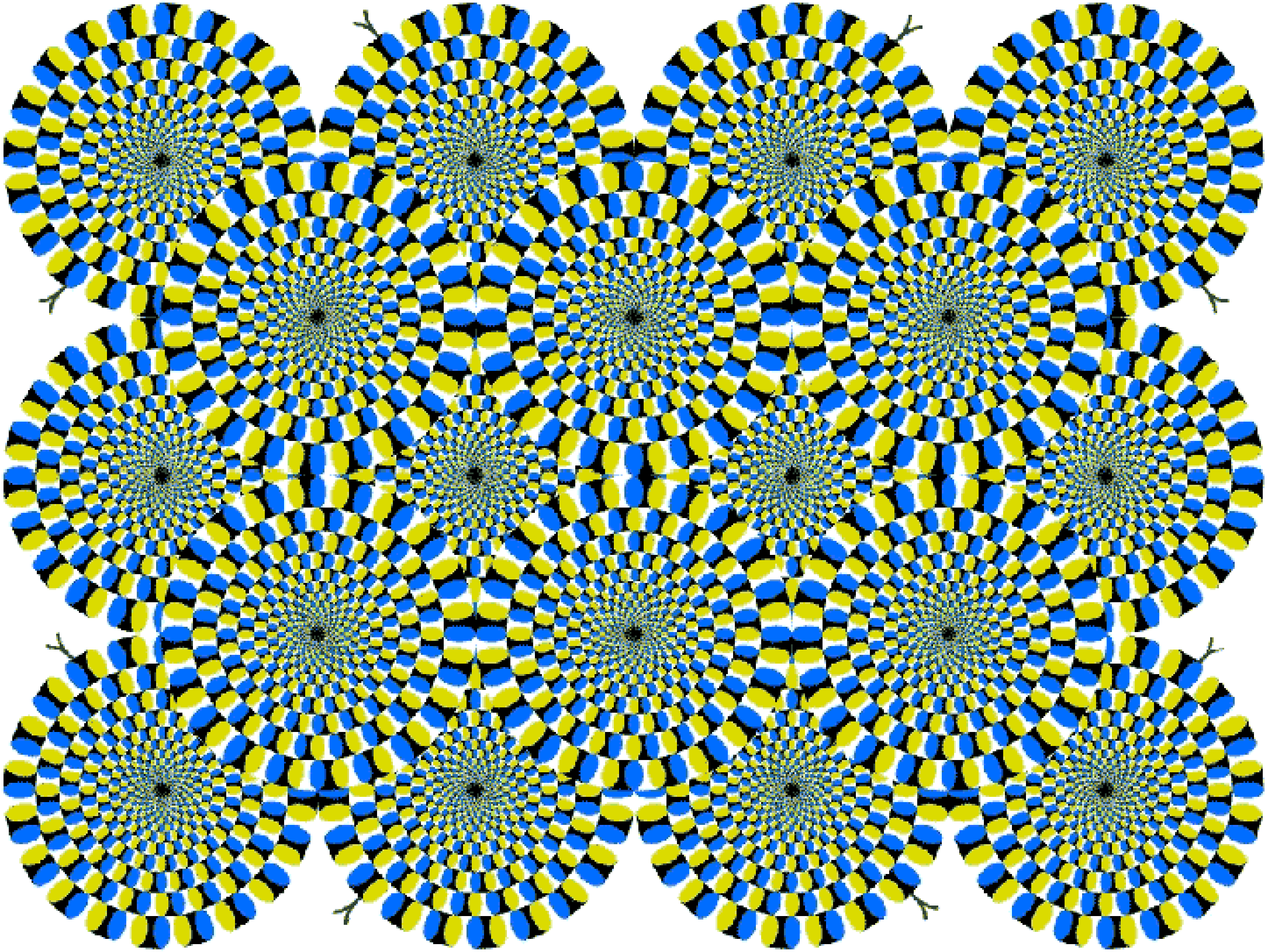
Cornsweet Illusion



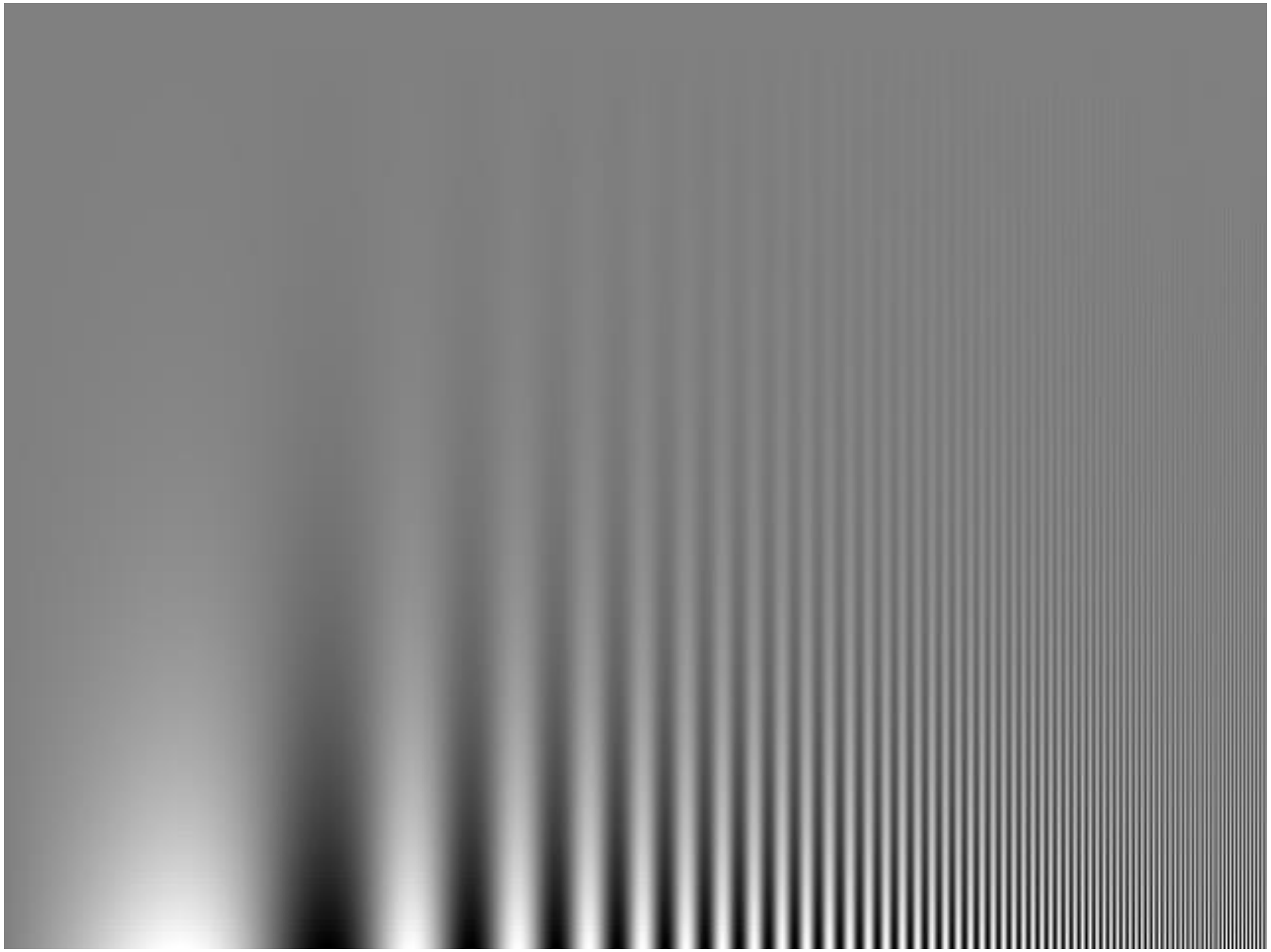
Changing Contrast



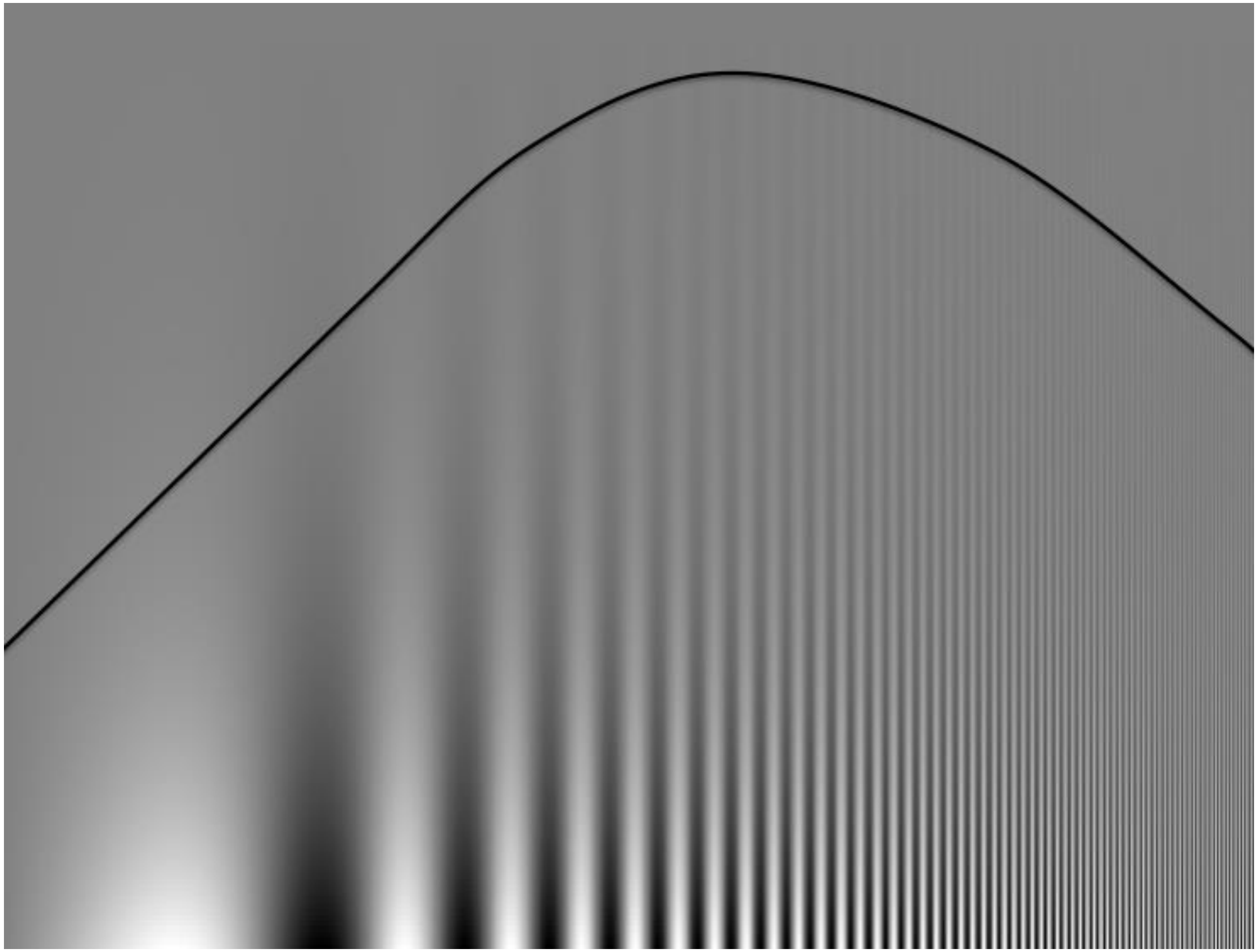
Changing Contrast



Contrast Sensitivity Function



Contrast Sensitivity Function



Learned Expectation

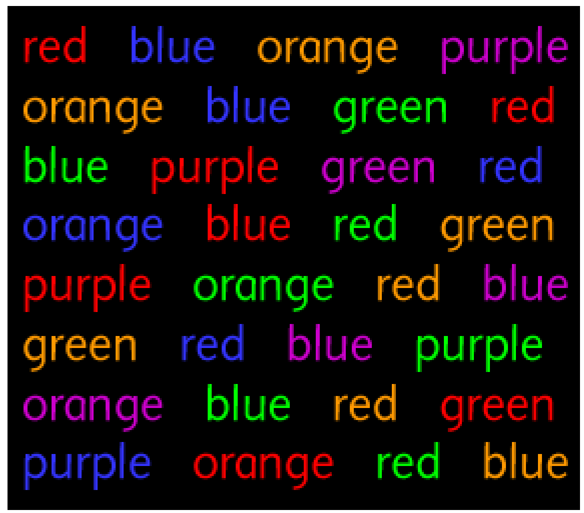
Learned Expectation

Learned Expectation

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.

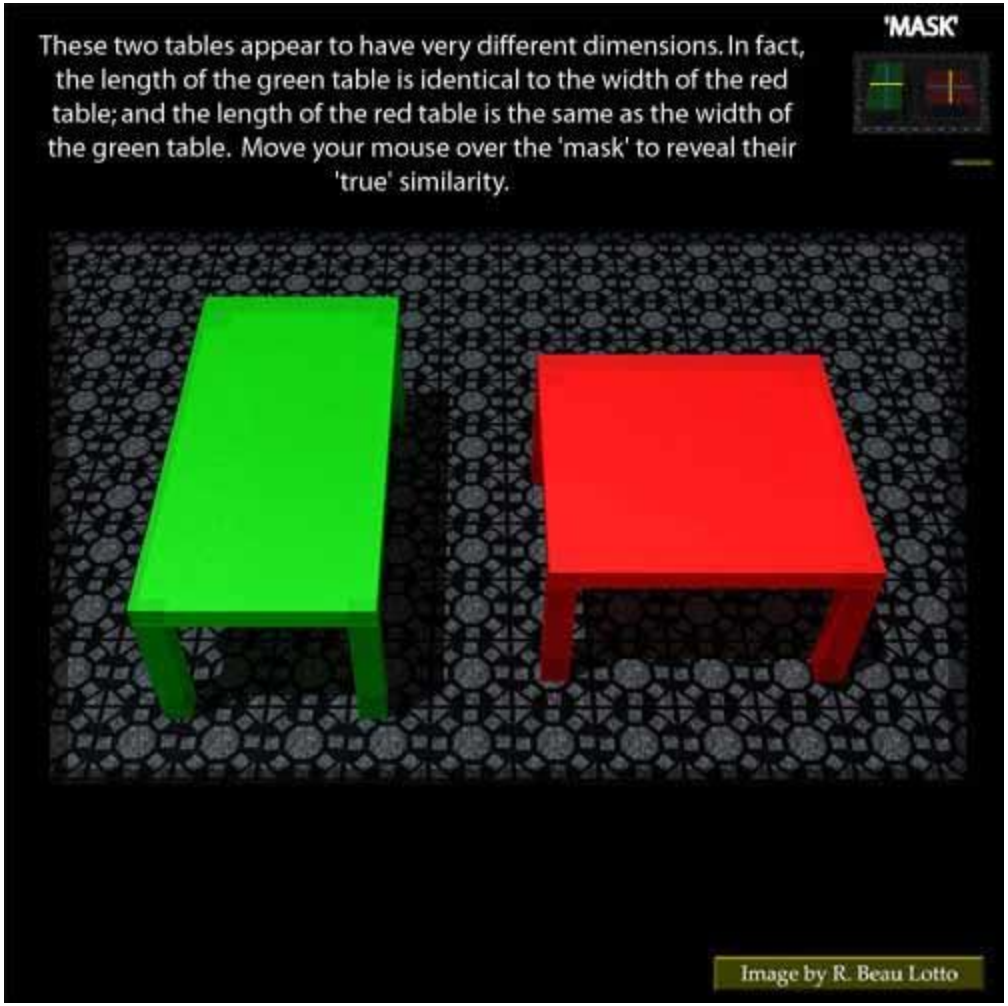
Learned Expectation

- Starting the below left to right, top to bottom



- Stroop Effect [1935]

Learned Expectation



Ambiguity = Visual Confusion

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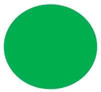
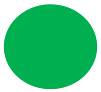
Stereo Depth Perception



Stereo Depth Perception

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

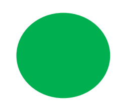


[http://www.mediacollege.com/3d/depth-perception/test.html]

Stereo Depth Perception

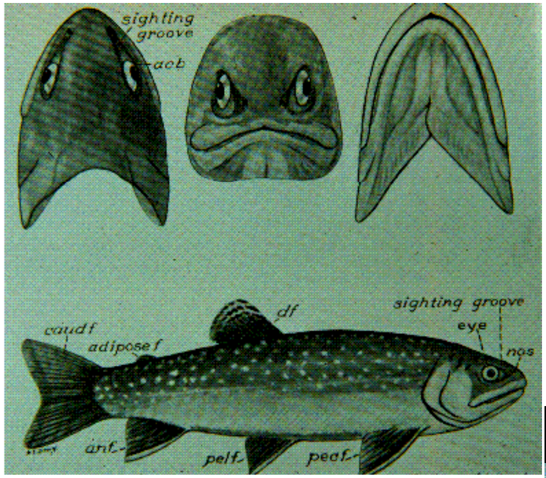
- 1. Place finger in between circle and eyes
- 2. Focus on finger

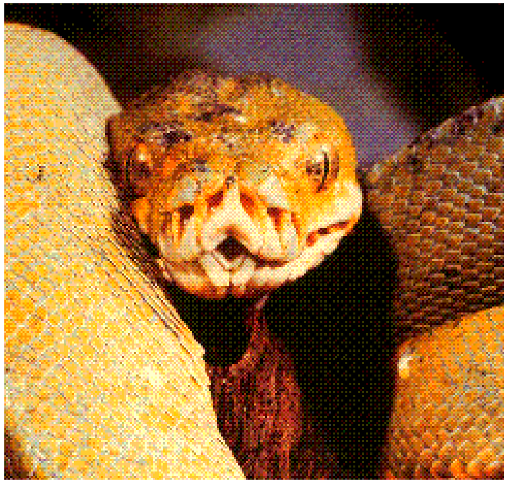
- 3. Focus on circle

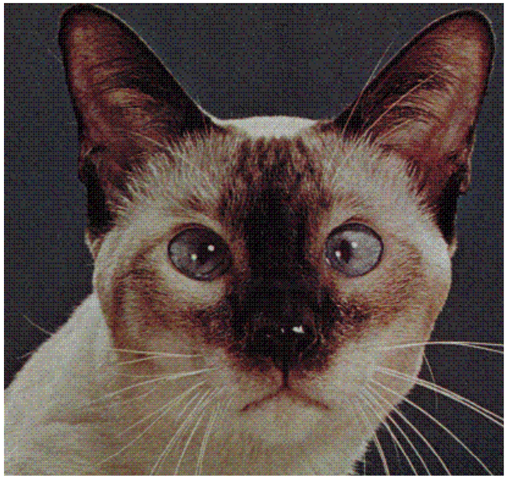


[http://www.mediacollege.com/3d/depth-perception/test.html]

Perception and Stereopsis

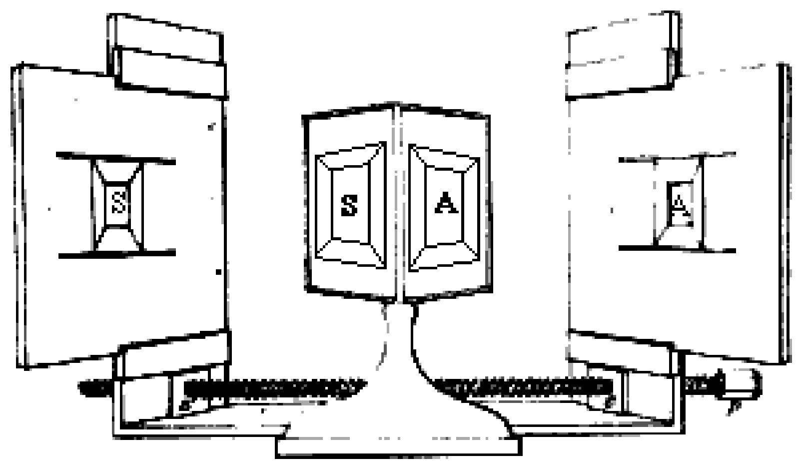




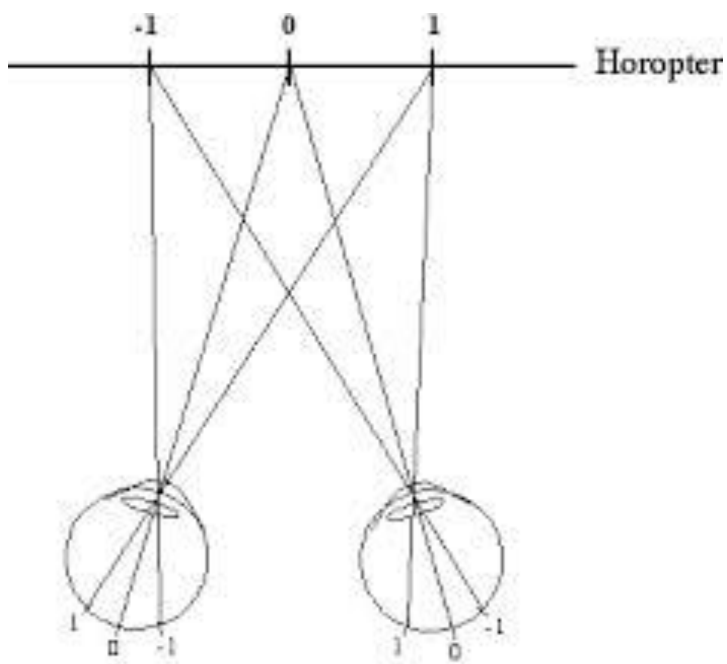


Sir Charles Wheatstone

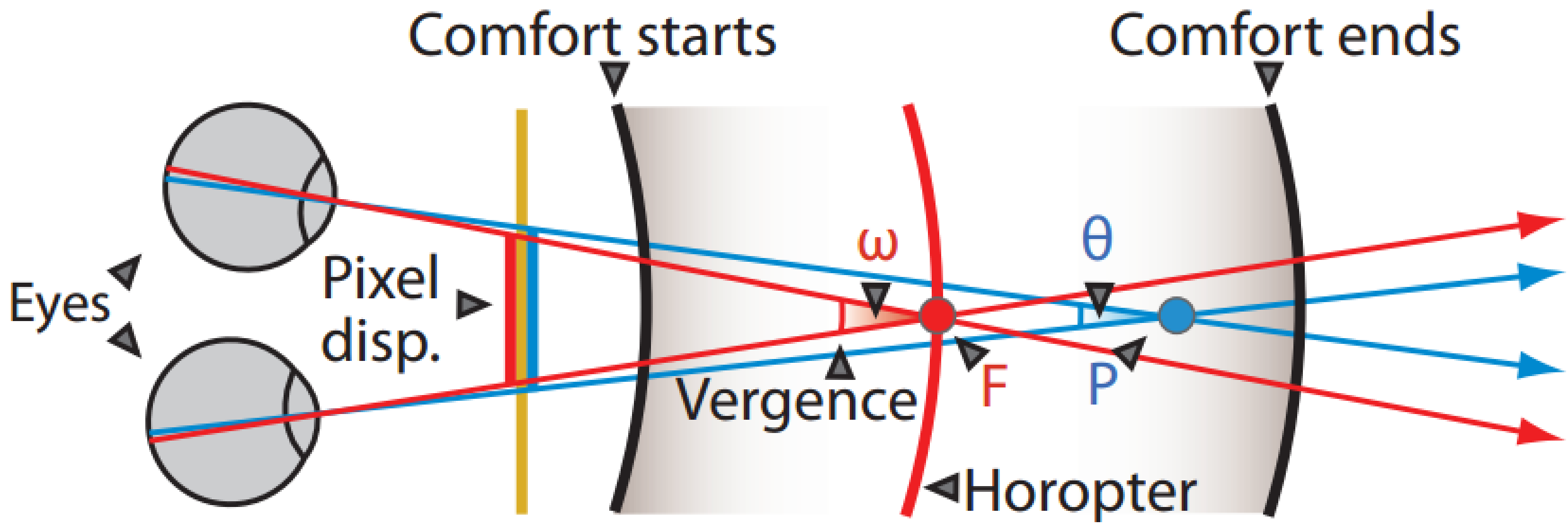
- Circa 1840



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

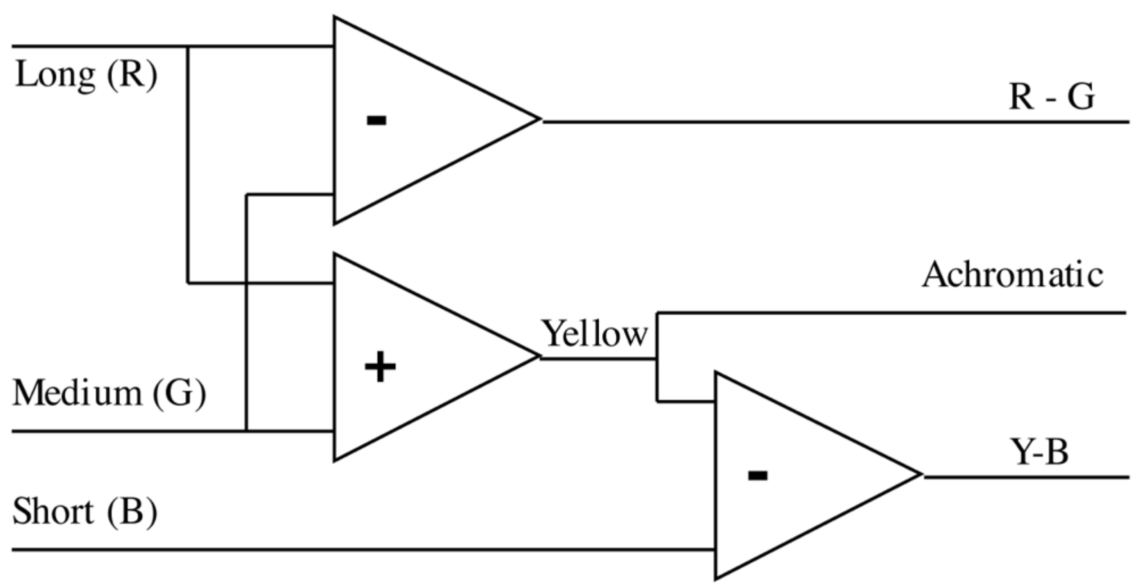
  http://resources.mpi-inf.mpg.de/HighlightMicrodisparity/paper.pdf

- To account for luminance as well

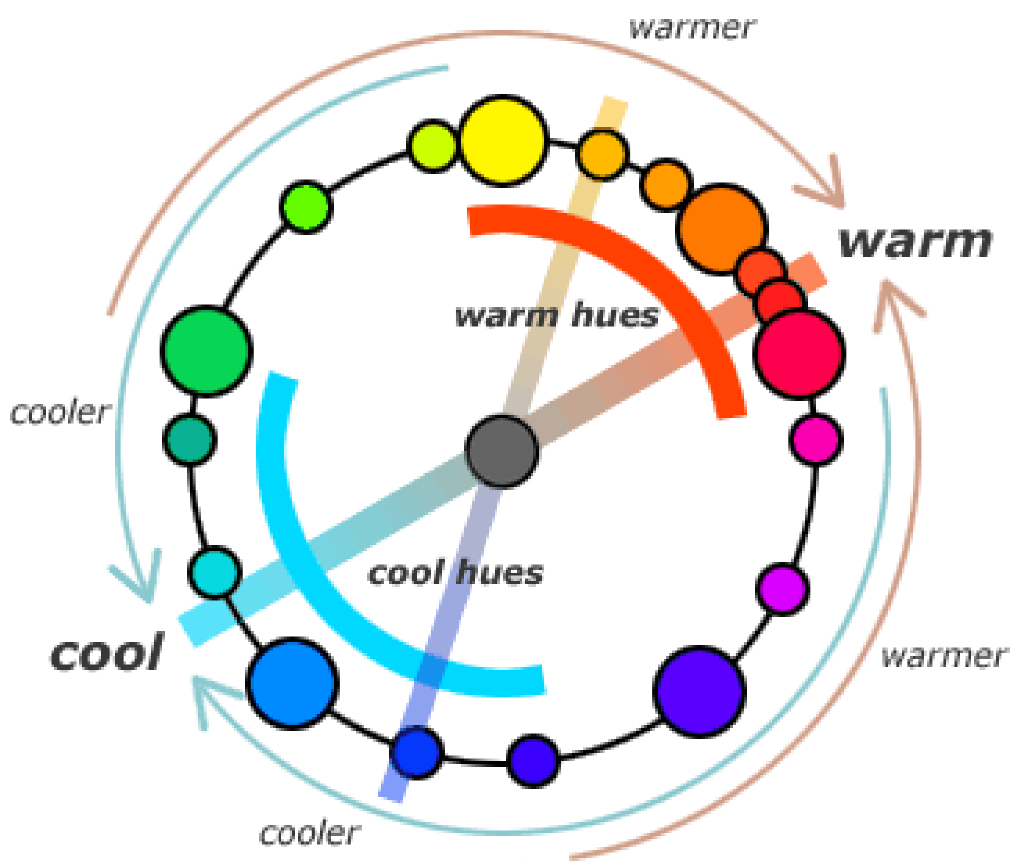
  http://people.csail.mit.edu/pdidyk/projects/LuminanceDisparityModel/LuminanceDisparityModel.pdf

Opponent Color Theory

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

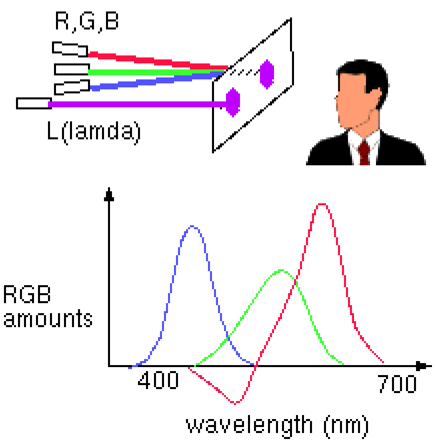


Artistic Color Space



Color Spaces

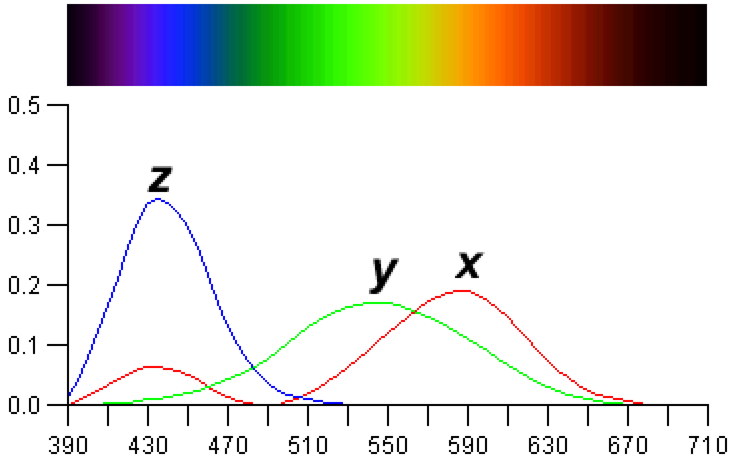
- Three types of cones suggests color is a 3D quantity. How to define 3D color space?
- Idea: shine given wavelength (λ) on a screen, and mix three other wavelengths (R,G,B) on same screen. Have user adjust intensity of RGB until colors are identical:



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

CIE Color Space

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



- Approximately:

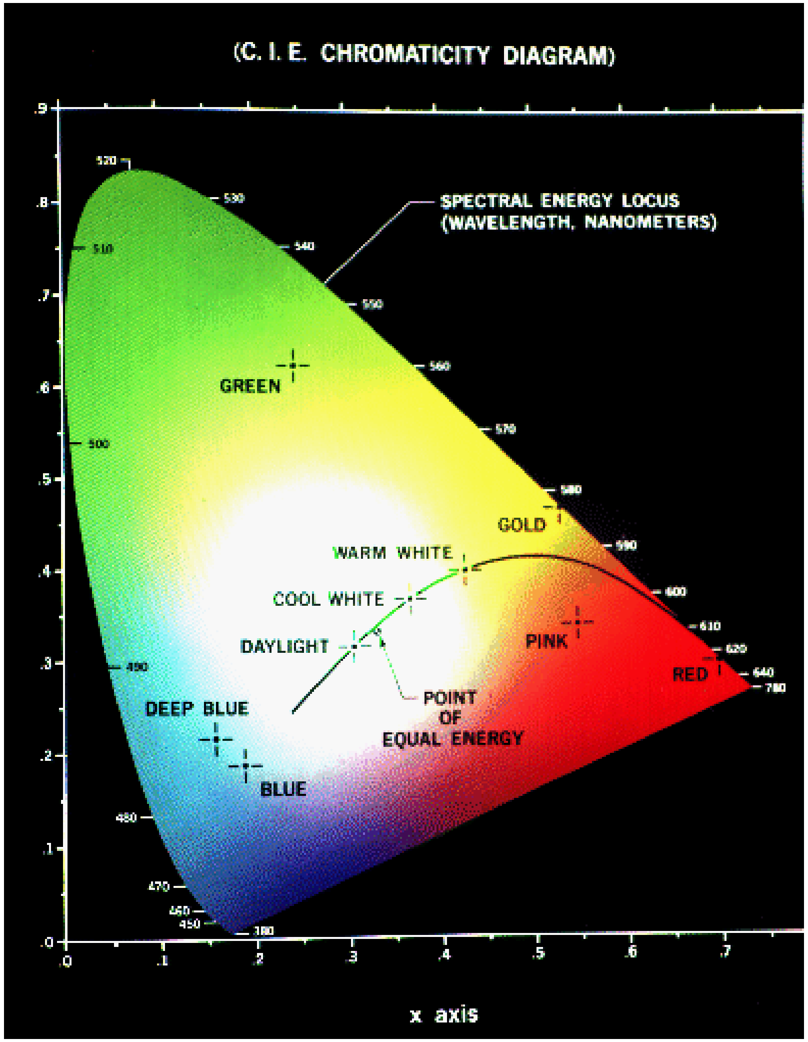
  X ~ R

  Y ~ G

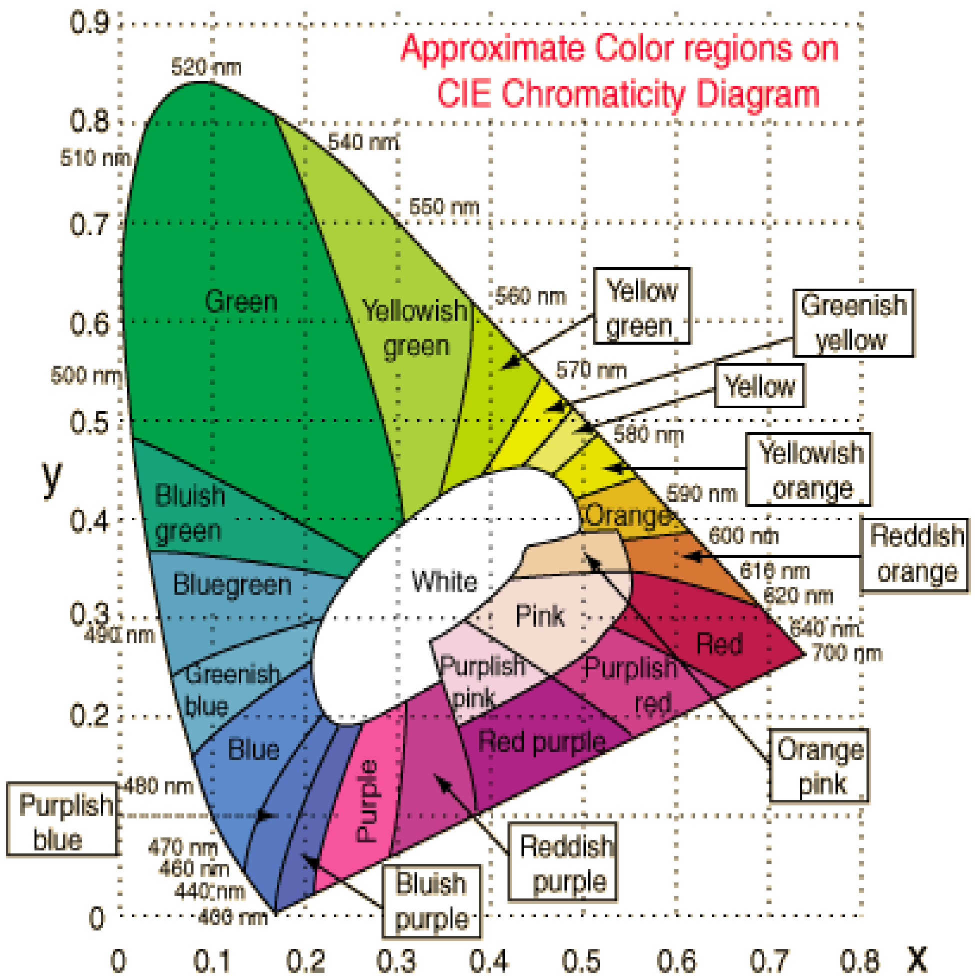
  Z ~ B

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

CIE Color Space

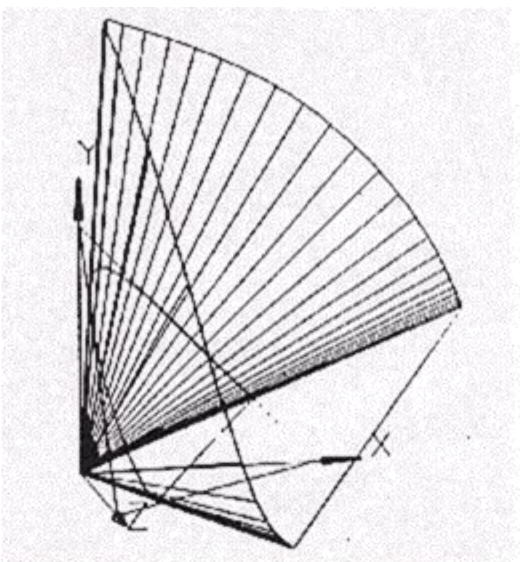


CIE Color Space



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.:

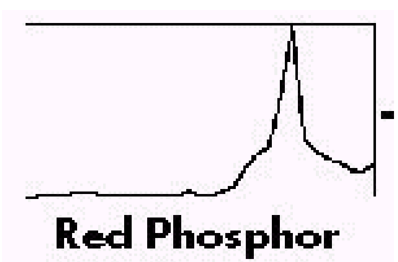
$$X = X / (X+Y+Z)$$

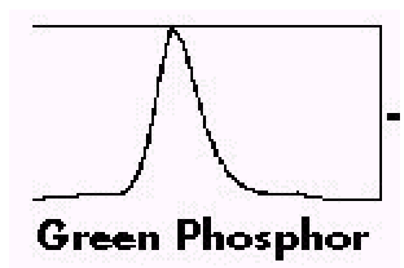
$$Y = Y / (X+Y+Z)$$

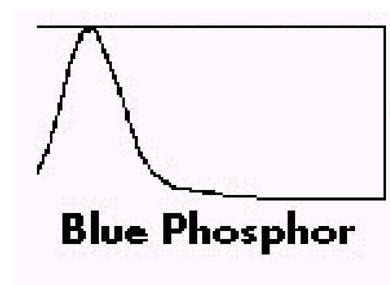
$$Z = 1 - X - Y$$

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

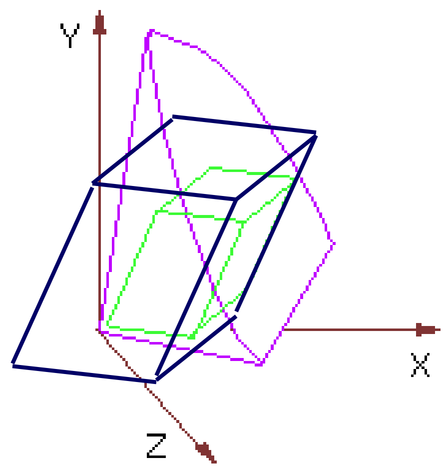






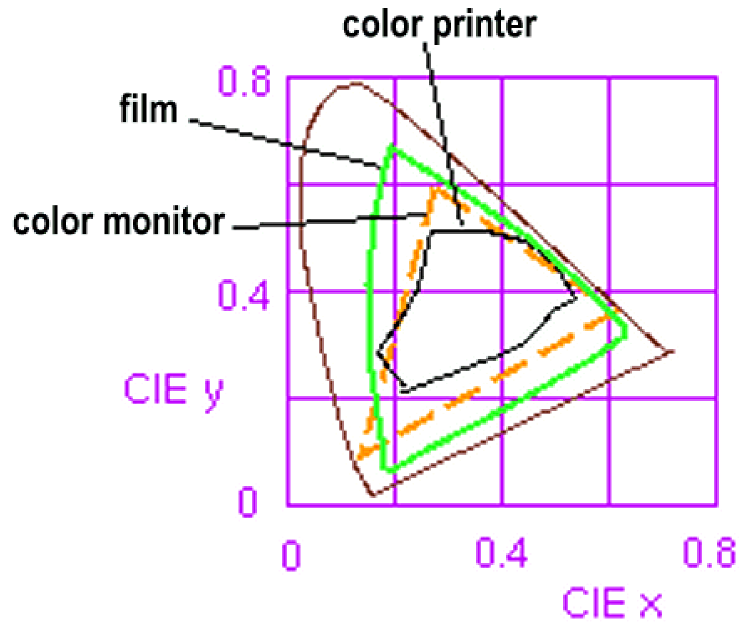
Device Color Gamuts

- 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.

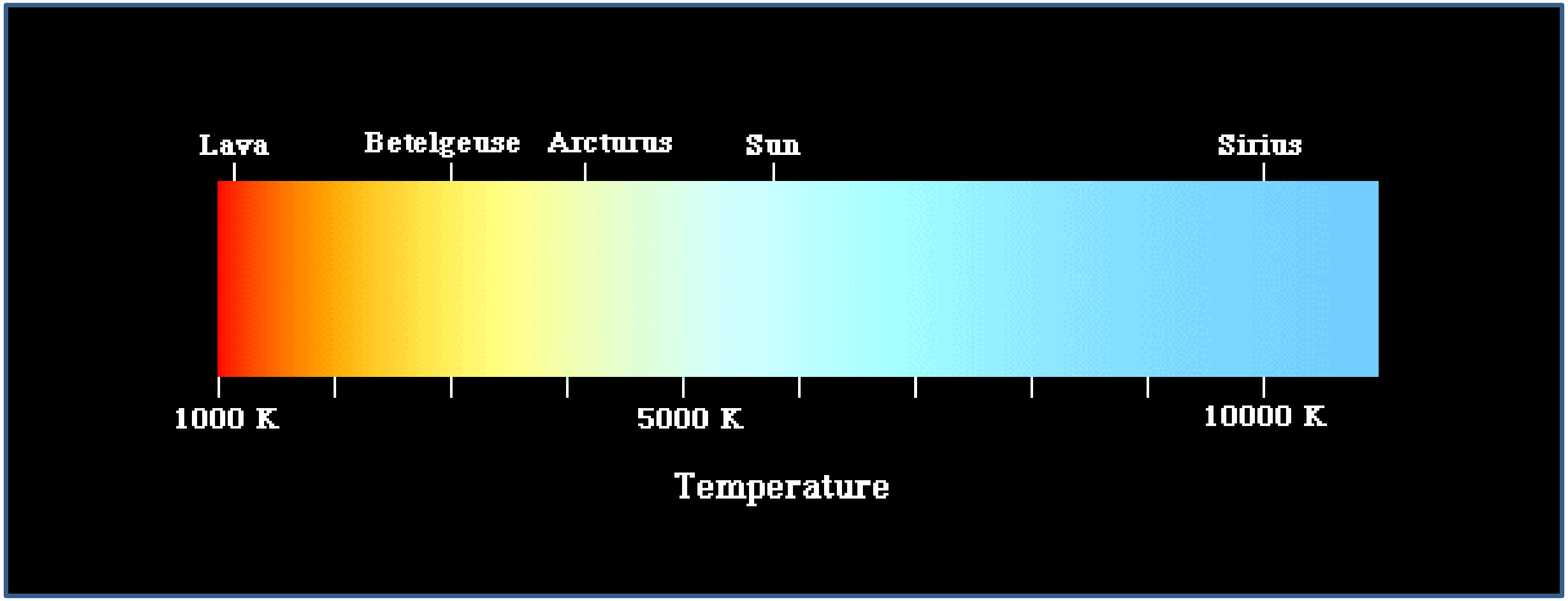
$$
\begin{aligned}
L^\star &= 116 f(Y/Y_n) - 16 \\
a^\star &= 500 \left[f(X/X_n) - f(Y/Y_n) \right] \\
b^\star &= 200 \left[f(Y/Y_n) - f(Z/Z_n) \right]
\end{aligned}
\qquad
f(t) = \begin{cases} t^{1/3} & \text{if } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29}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

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

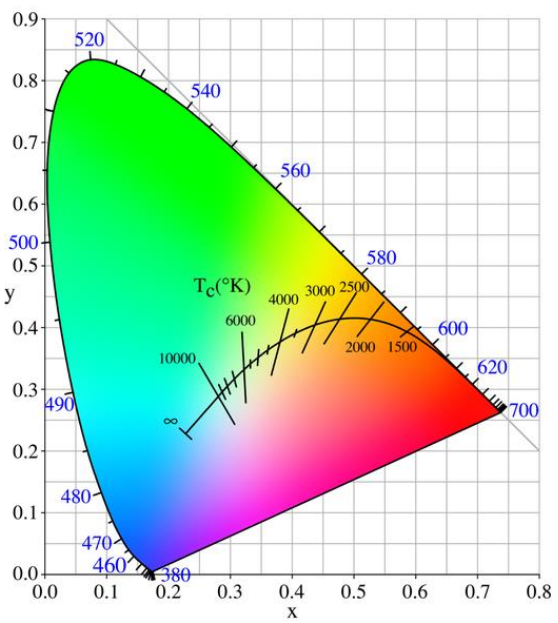
LAB Space Perceptually Fun Facts: a^* axis

- 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

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

LAB Space Perceptually Fun Facts: Examples

- 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

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

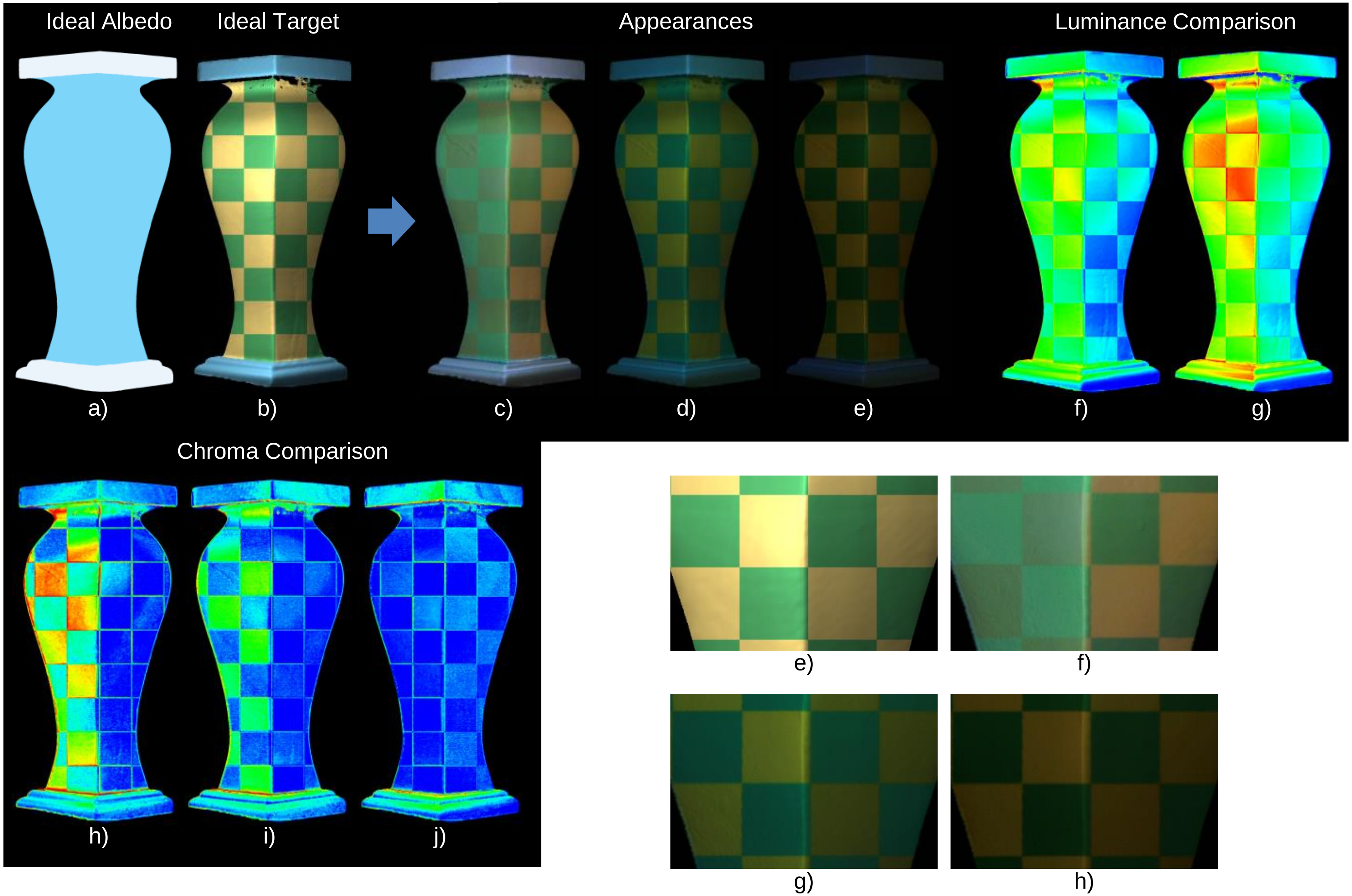
- The colors will seem relatively the same (or "constant")

Perceptually Significant Color Differences

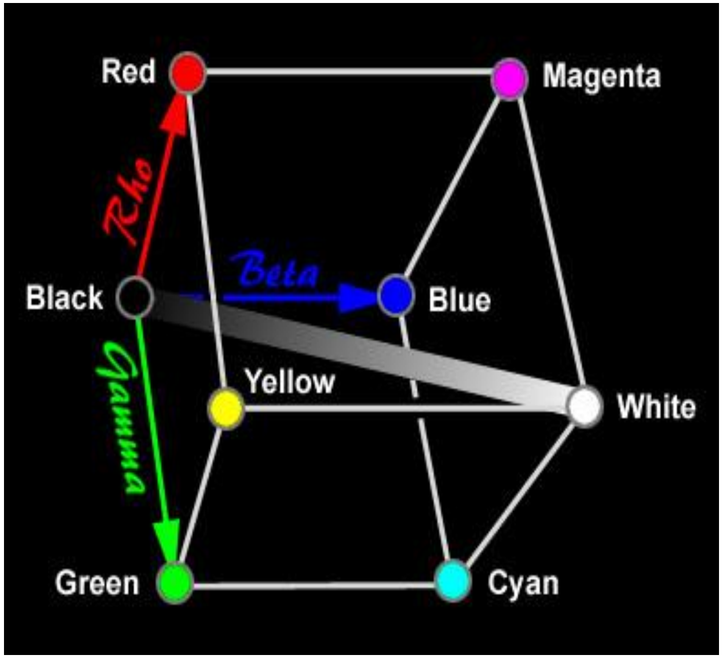
- In LAB, one unit means a perceptually significant color/luminosity difference
- This is not the case in, for example, RGB
- Check out:

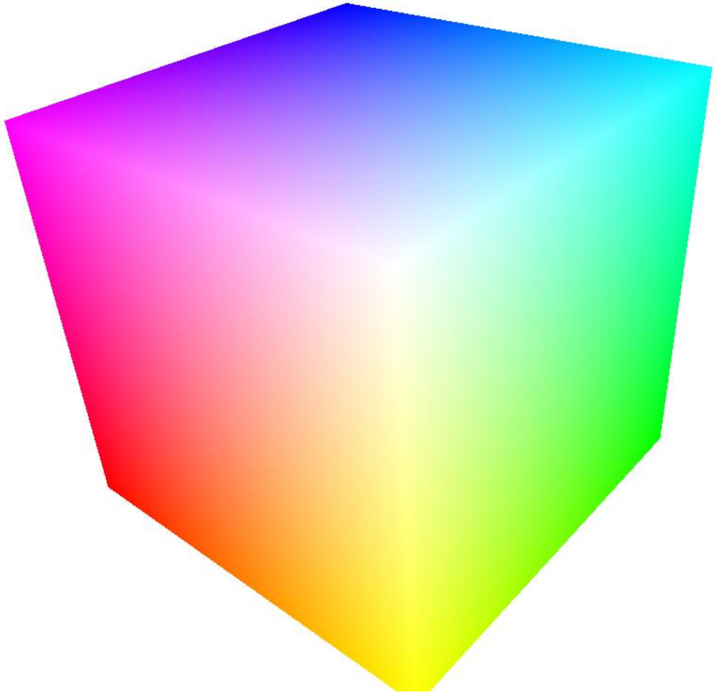
  http://colormine.org/delta-e-calculator/

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

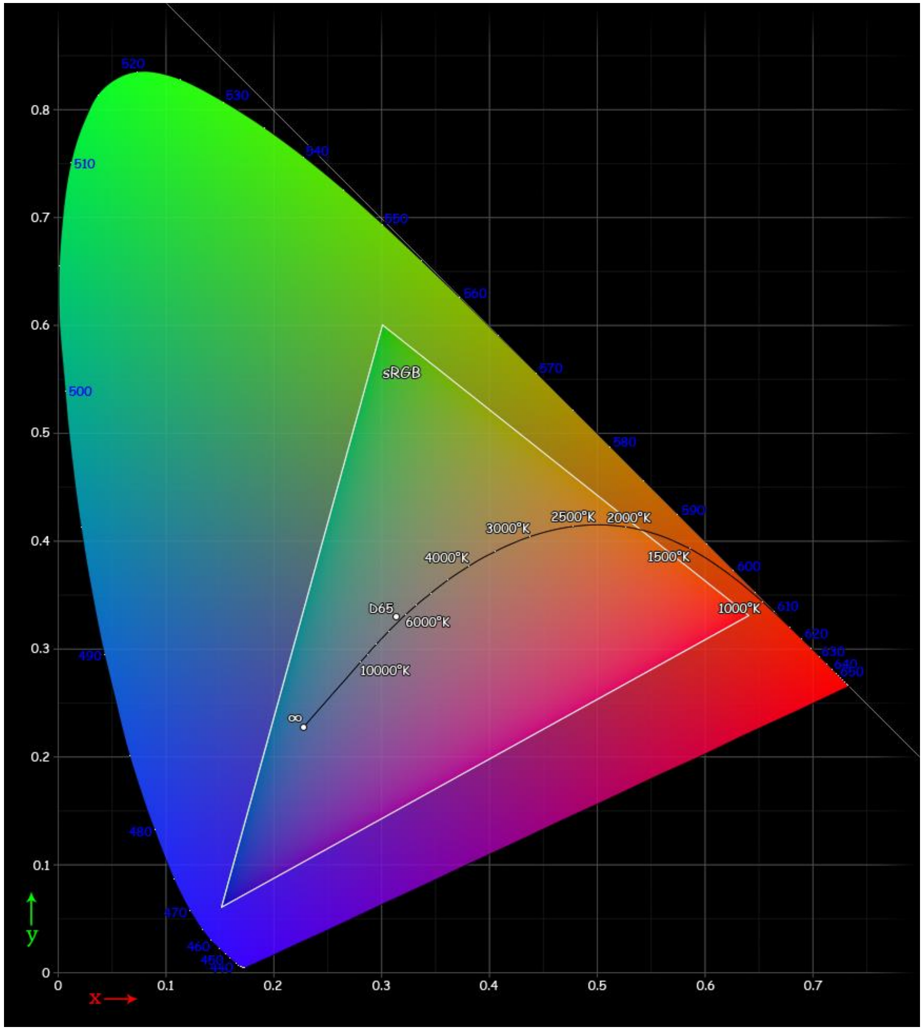
- Standard RGB space of a “RGB device” assuming a gamma correction of 2.2
  - (gamma correction to be explained in a few slides)

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

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

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

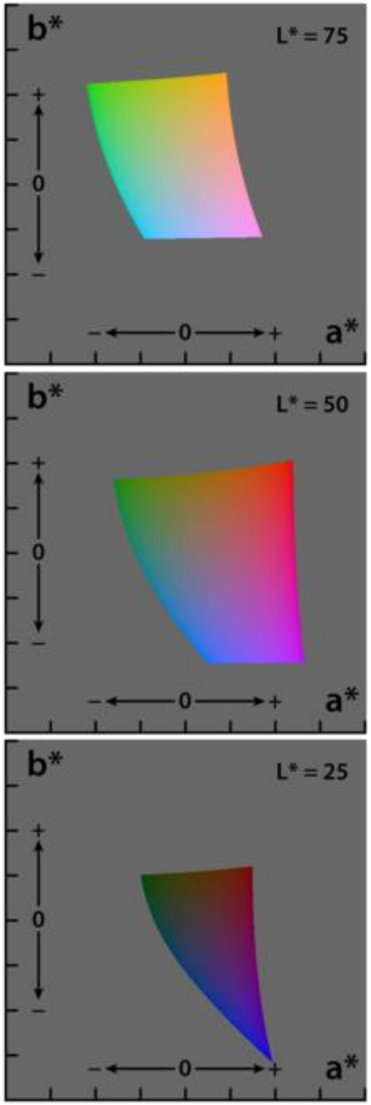
sRGB



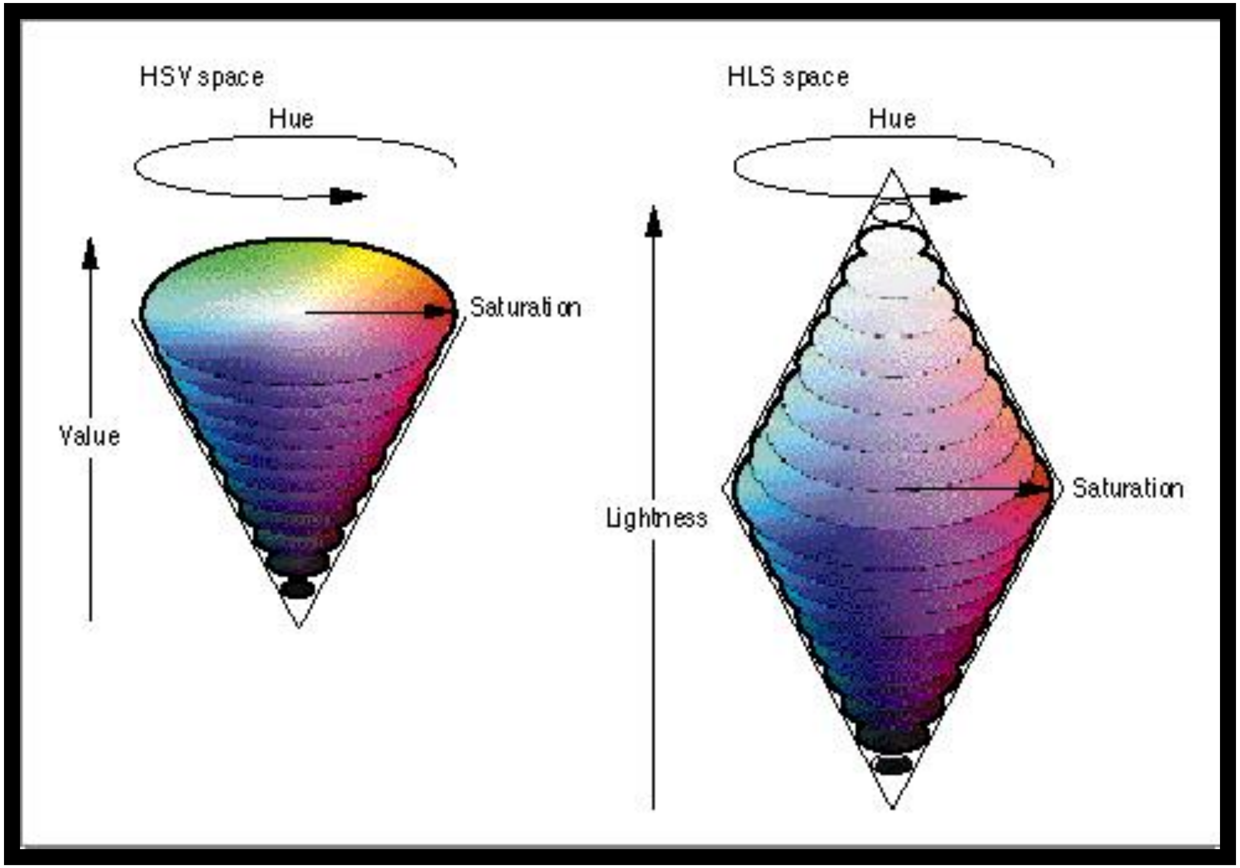
sRGB
D65
∞
10000°K
6000°K
4000°K
3000°K
2500°K
2000°K
1500°K
1000°K
520
530
540
510
550
560
570
500
580
590
600
610
620
490
480
470
460
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x
y

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



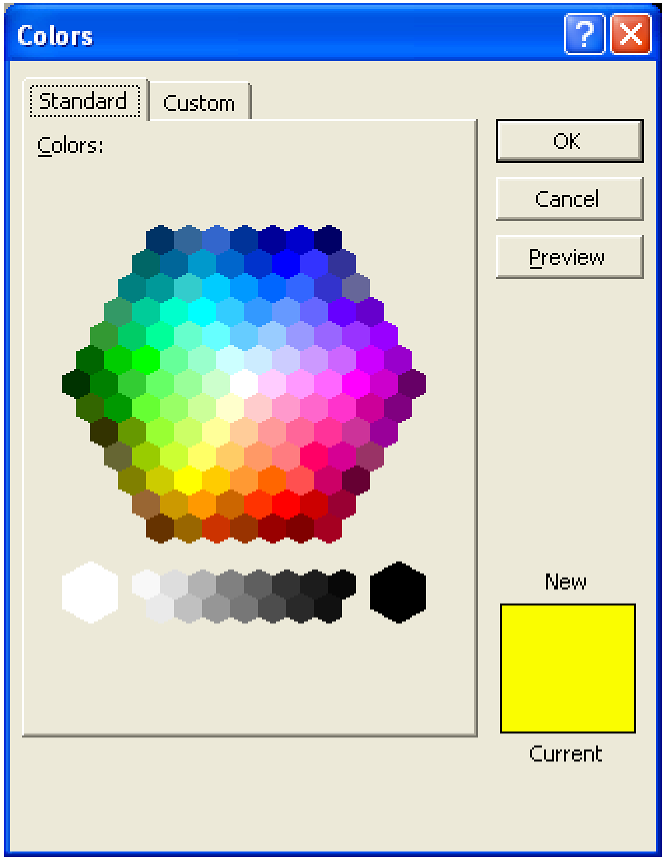
HSV/HSL Color Space

- 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

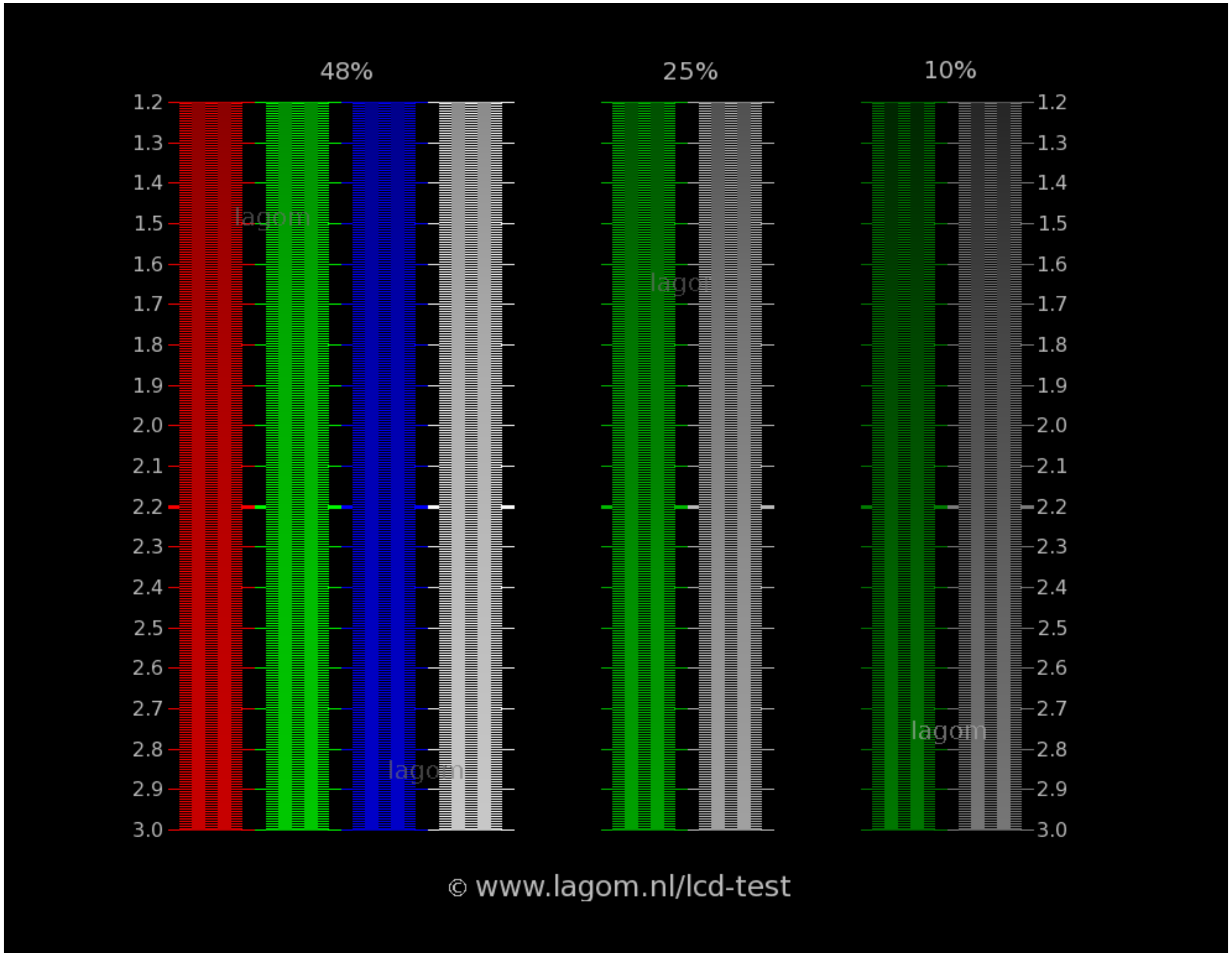
- We generally assume color brightness is linear
- But most display devices are inherently nonlinear
  - brightness(voltage) ≠ 2×brightness(voltage/2): $I = {V_s}^{\gamma}$
- Common solution: *gamma correction*
  - Post-transformation on RGB values to map them to linear range on display device: $V_c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

Gamma Correction

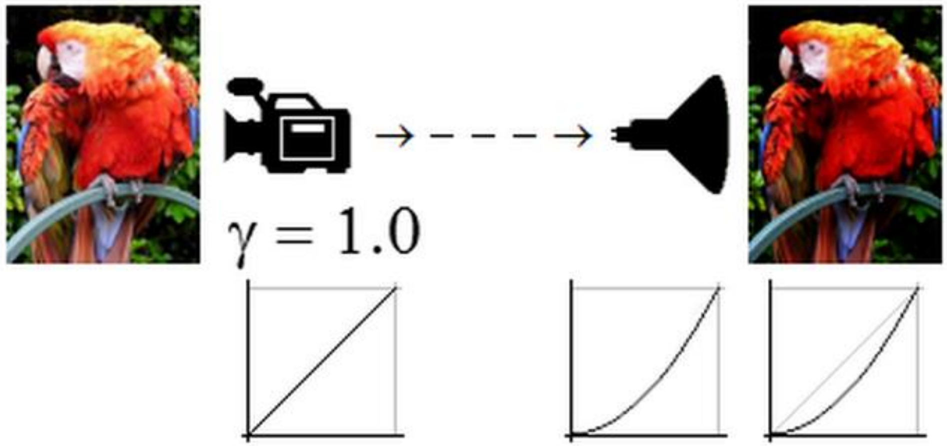
Linear encoding V_S =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Linear intensity I =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

Gamma Correction Test

The fg+bg should blend at near 2.2

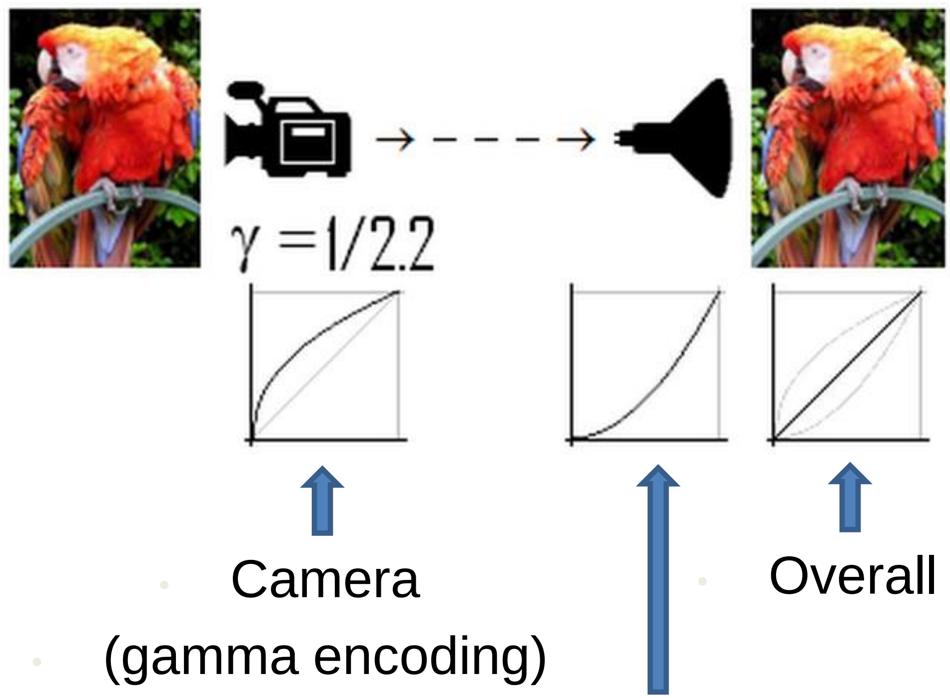


Gamma Correction



- Camera
- (gamma encoding)
- Overall
- Display
- (gamma expansion)

Gamma Correction



- Camera
- (gamma encoding)
- Overall
- Display
- (gamma expansion)

Examples

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

Supercool!

- [Video]