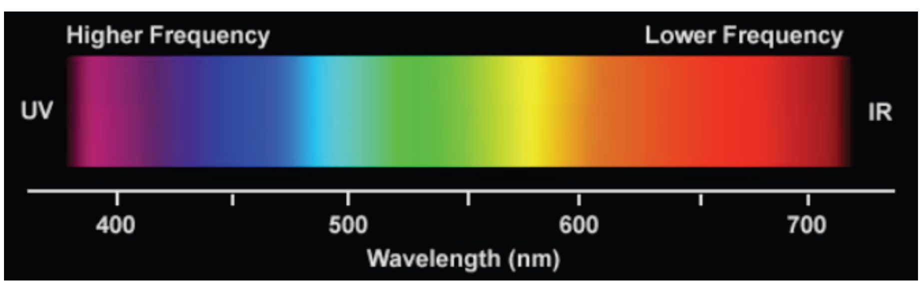
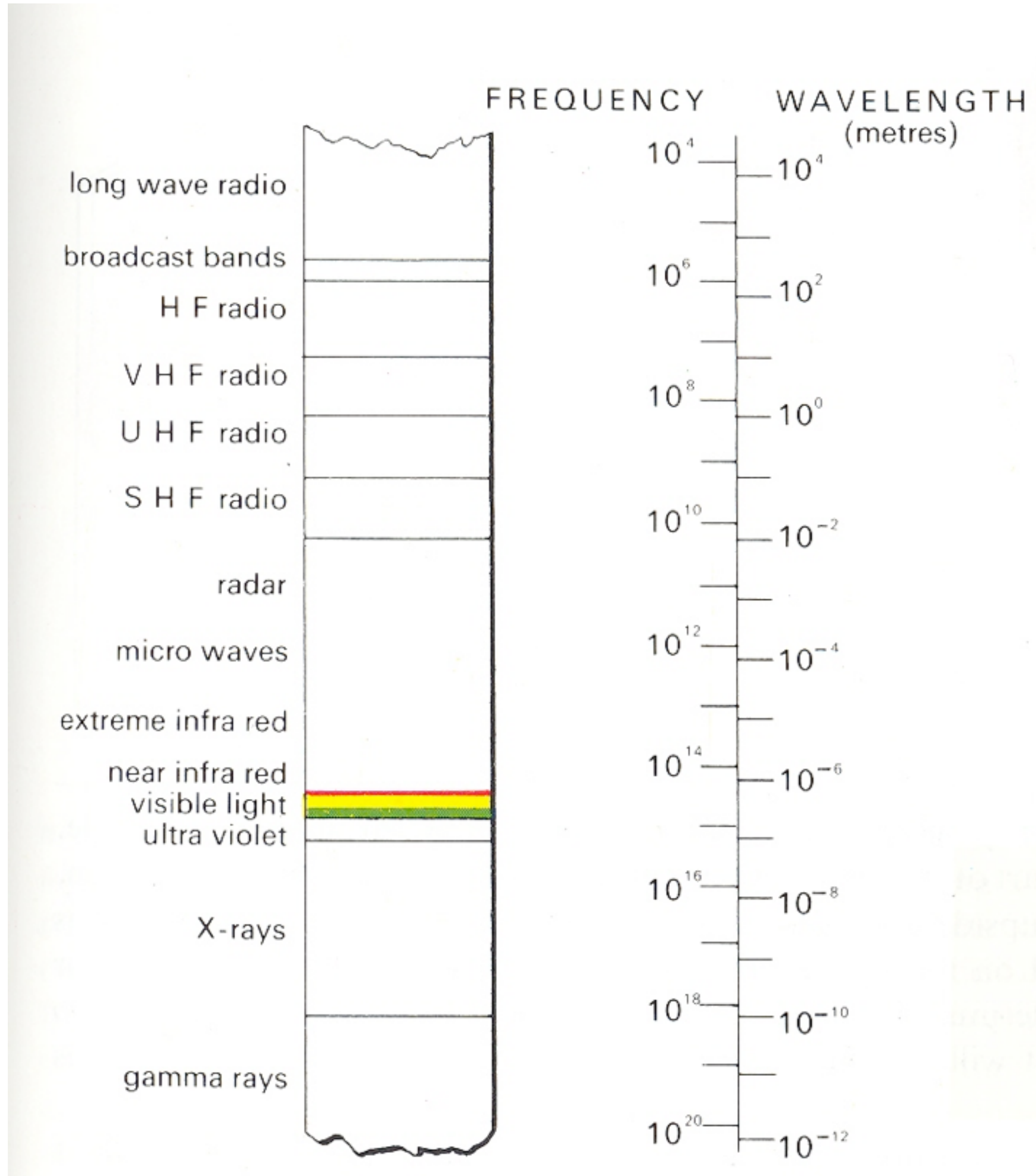
Light is Electromagnetic Radiation

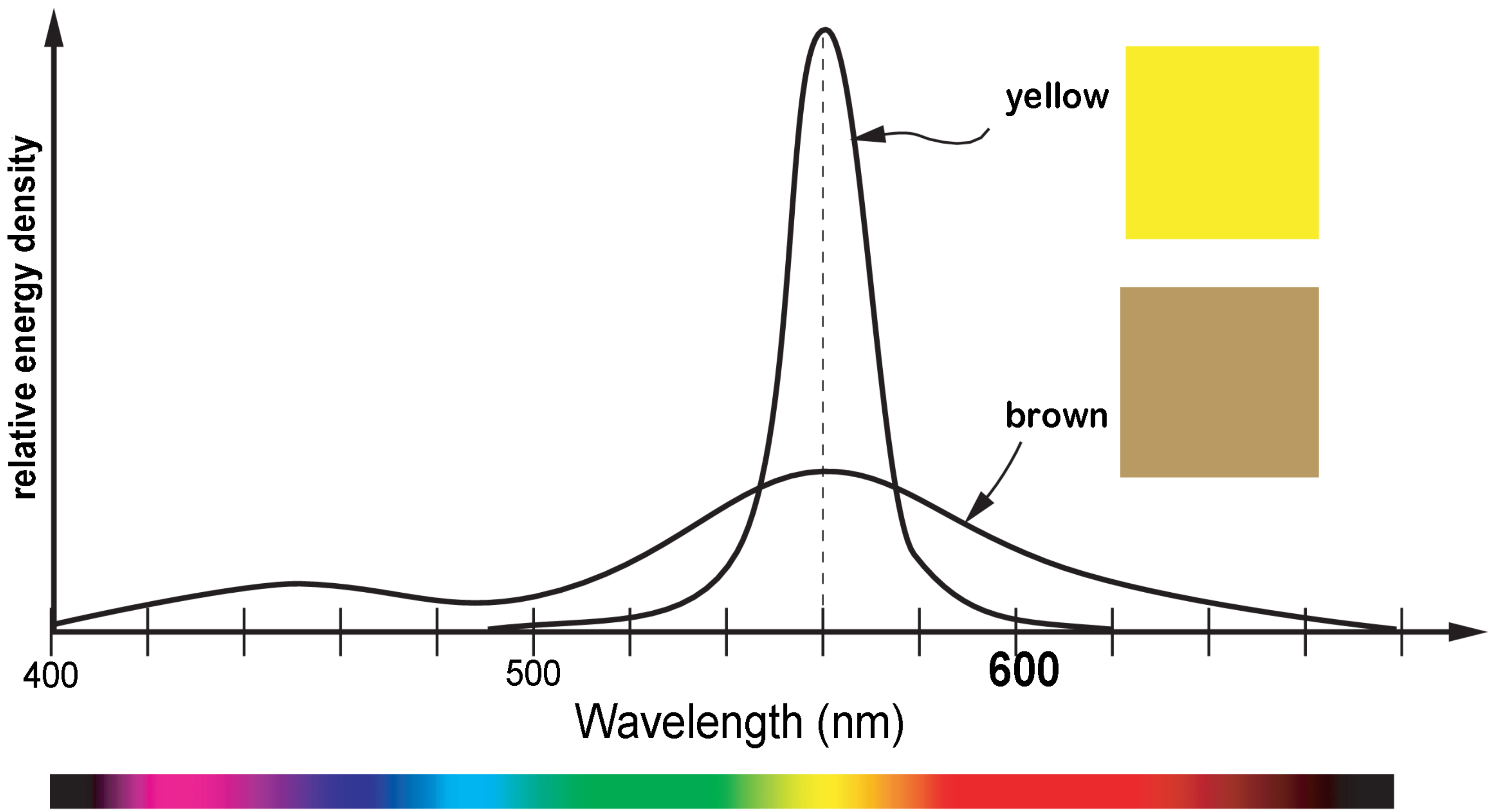
- Visible spectrum is "tiny"
- Wavelength range: 380-740 nm





Color != Wavelength

But rather, a combination of wavelengths and energy



Photoreceptors

Rods

- Approximately 100-150 million rods.
- Non-uniform distribution across the retina
- Sensitive to low-light levels (scotopic vision)

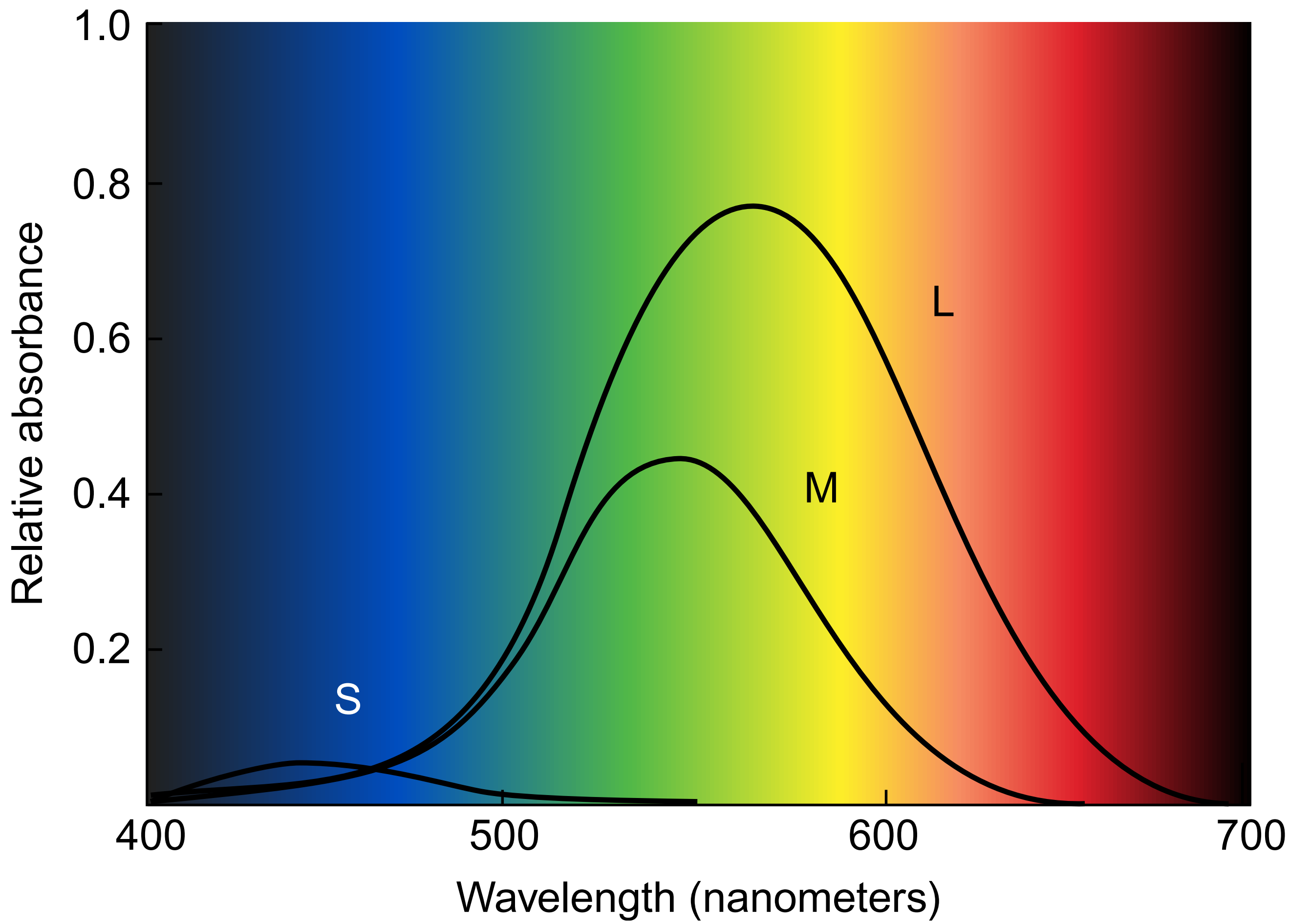
Cones

- Approximately 6-7 million cones.
- Sensitive to daytime-light levels (photopic vision)
- Detect color by the use of 3 different kinds:
    - Red (L cone) : 564-580nm wavelengths (65% of all cones)
    - Green (M cone) : 534-545nm (30% of all cones)
    - Blue (S cone) : 420-440nm (5% of all cones)

Color and Perception

Cones (SML)

(short, medium, long)



Colin Ware, Information Visualization: Perception for Design

Hunters

Gatherers

Trichromacy

- Our 3 cones cover the visible spectrum
  - Theoretically, all we need are 2 though
- Most birds, some fish, reptiles, and insects have 4, some as many as 12 (Mantis Shrimp)
- This is a “reason” why many of our color spaces are 3D


Mantis Shrimp
16 Photoreceptors, 12 for color sensitivity!

Idea: Perception of Color

Ultimately, color is a perceptual phenomenon, we all see it differently

Color Models

Terminology

- **Color Model**
  - Is an abstract mathematical system for representing color.
  - Is often 3-dimensional, but not necessarily.
  - Is typically limited in the range of colors they can represent and hence often can’t represent all colors in the visible spectrum
- **Gamut** or **Color Space**
  - The range of colors that are covered by a color model.


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.
10-29 WATTERSON

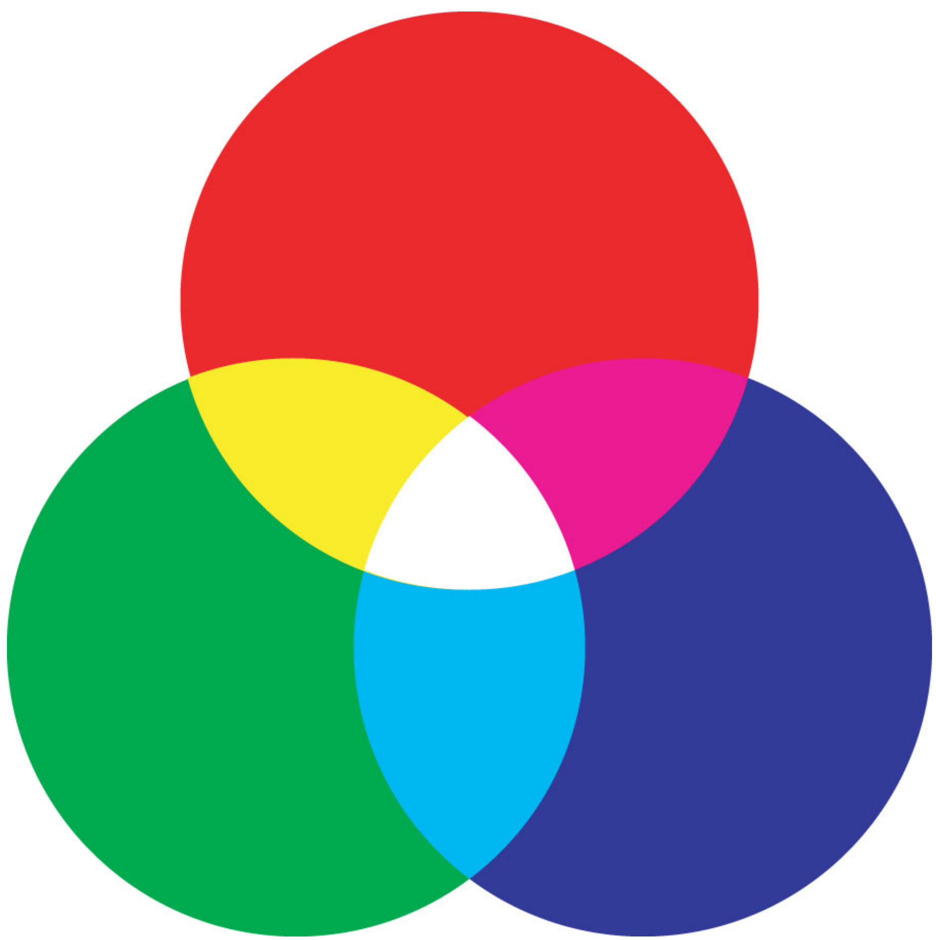
What are the primary colors?

1. Red, Green, Blue
2. Red, Yellow, Blue
3. Orange, Green, Violet
4. Cyan, Magenta, Yellow

What are the primary colors?

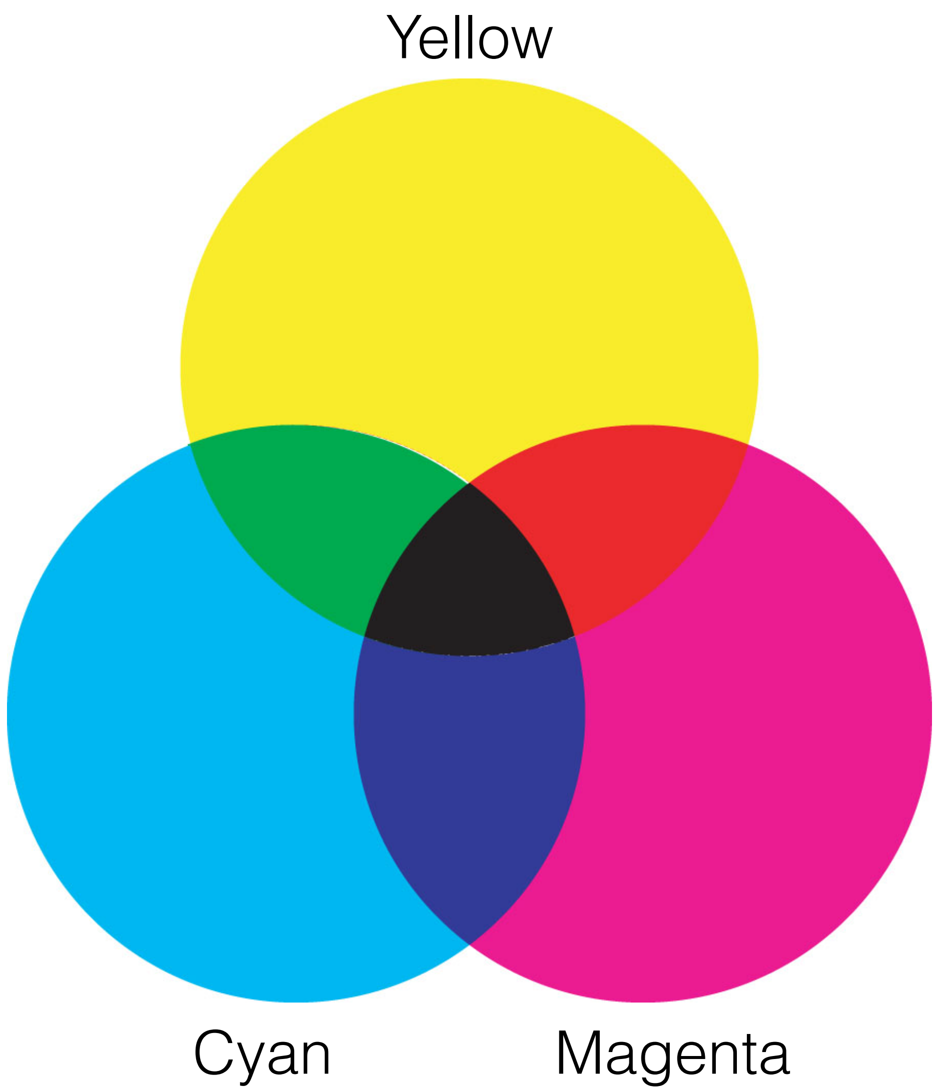
1. Red, Green, Blue
2. Red, Yellow, Blue
3. Orange, Green, Violet
4. Cyan, Magenta, Yellow
5. All of the above

Light Mixing



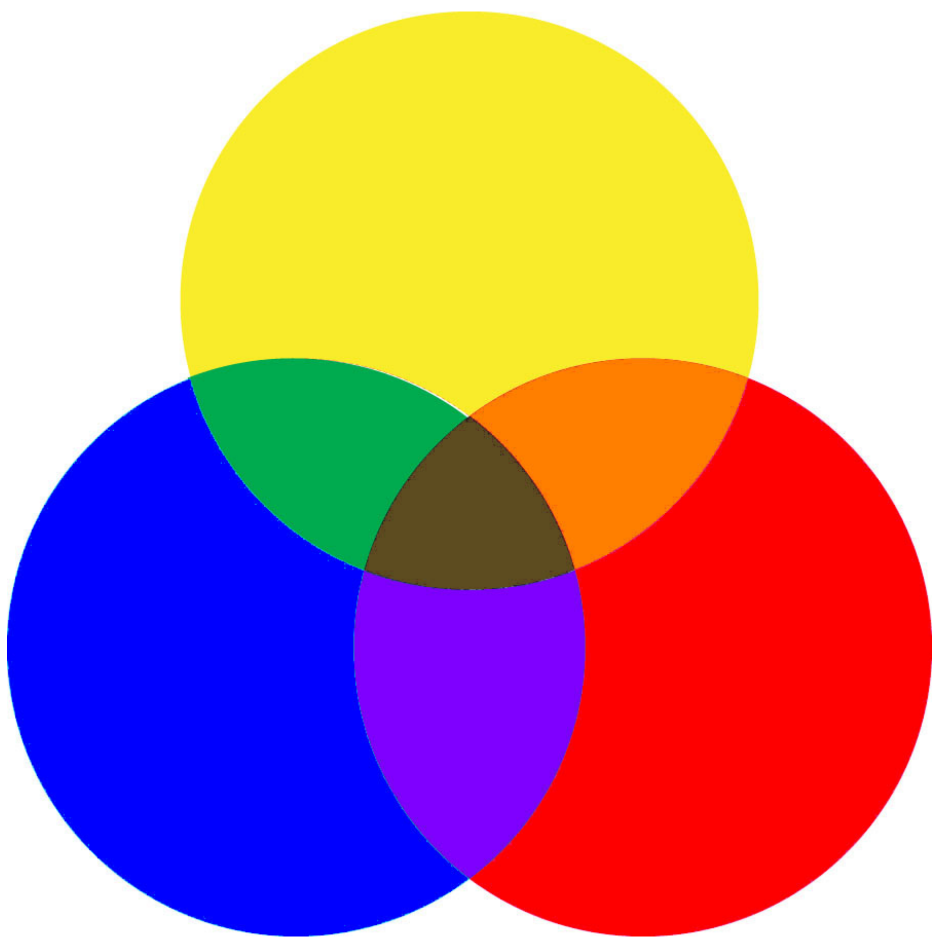
- **Additive** mix of colored lights
  - Add up wavelengths of light to make new colors
- Primary: RGB
- Secondary: CMY
- Neutral = R + G + B
- Commonly used by monitors, projectors, etc.

Ink Mixing



- **Subtractive** mix of transparent inks
  - Start with white and other wavelengths are selectively filtered.
- Primary: CMY
- Secondary: RGB
- ~Black: C + M + Y
- Actually use CMYK to get true black

Paint Mixing

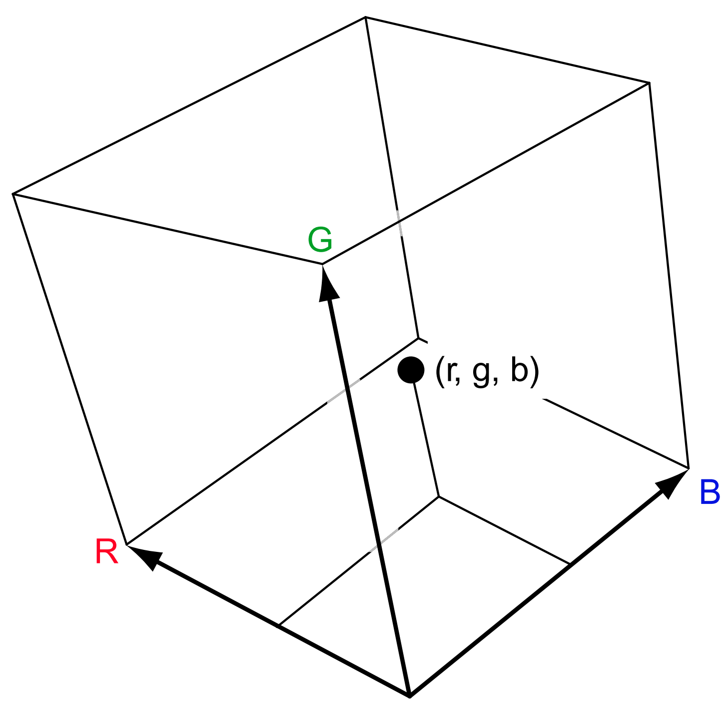


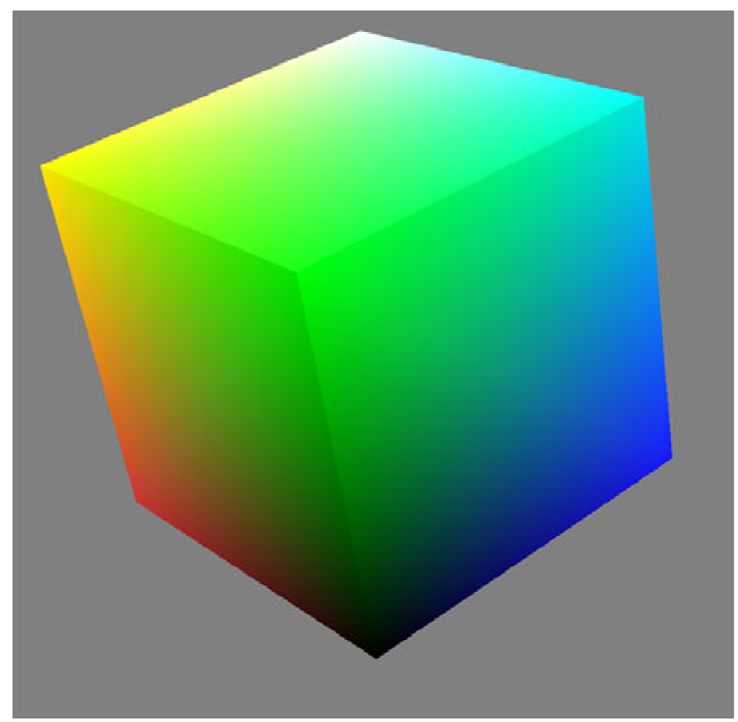
- Physical mix of opaque paints
- Primary: RYB
- Secondary: OGV
- Neutral: R + Y + B
- Additive or Subtractive?

Color Spaces

RGB Color Space

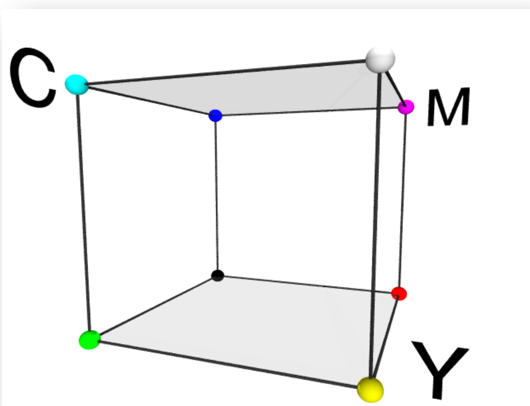
- Additive, useful for computer monitors
- Not perceptually uniform
  - For example, more “greens” than “yellows”



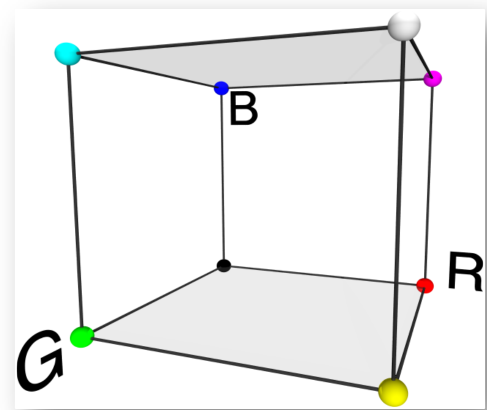


Converting from RGB to CMY

- Assuming RGB values are normalized (all channels between [0,1]), the exact same color in CMY space can be found by inverting:



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



Converting from CMY to CMYK

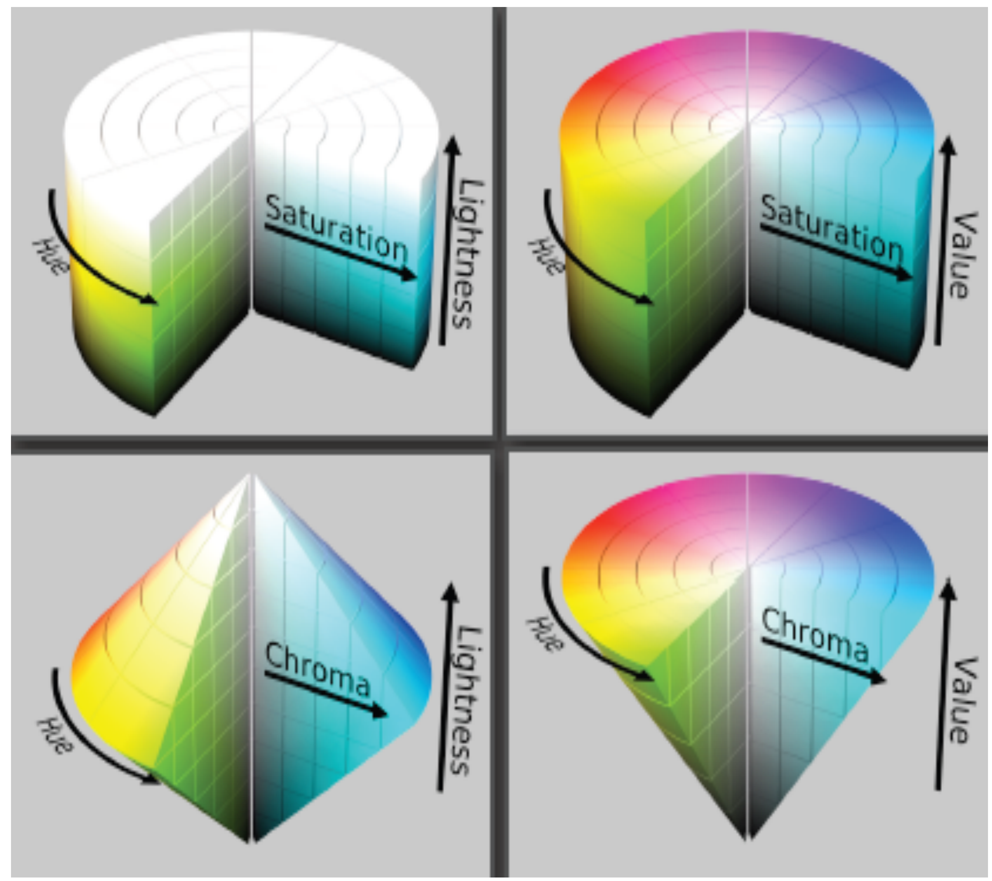
- Assuming CMY values are normalized (all channels between [0,1]), the exact same color in CMYK is

$$\langle C, M, Y, K \rangle = \begin{cases} \langle 0, 0, 0, 1 \rangle & \text{if } \min(C', M', Y') = 1, \\ \langle \frac{C'-K}{1-K}, \frac{M'-K}{1-K}, \frac{Y'-K}{1-K}, K \rangle & \text{otherwise where } K = \min(C', M', Y') \end{cases} \quad (3.2)$$

- K is a measure of the ‘blackness’ of the color and essentially serves as an offset after which the remaining amounts of cyan, magenta and yellow are ‘added’

(H,C/S,L/B/V) Color Space

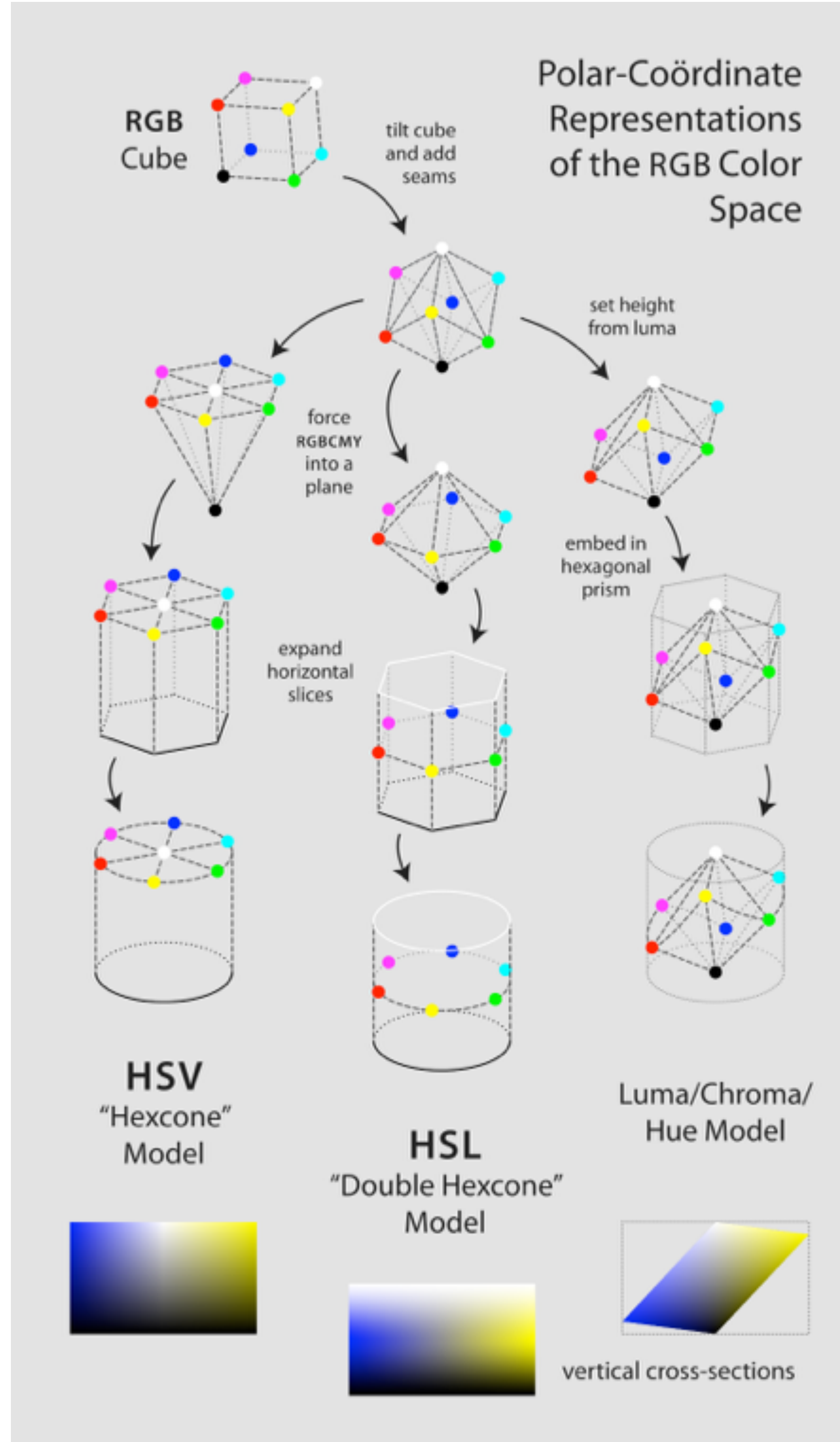
- Hue - what people think of as color
- Saturation - purity, distance from grey
  - Also called Chroma
- Lightness - from dark to light
  - Also Brightness or Value



HSV by Projection of RGB

- This decomposition is more natural for how we sense color, decomposes brightness component from color.
- More natural for artists, regardless of which variant
- Note that H is cyclical
    - H=0 is the same as H=1.

http://en.wikipedia.org/wiki/HSV_color_space



Conversion from RGB to HSB

- Assuming RGB values are normalized (all channels between [0,1]), the exact same color in HSB space can be found by first figuring out which channel (R,G, or B) has the max intensity

$$H = \begin{cases} \text{undefined} & \text{if } \max = \min, \\ 60 \times \frac{G-B}{\max - \min} & \text{if } \max = R \text{ and } G \geq B, \\ 60 \times \frac{G-B}{\max - \min} + 360 & \text{if } \max = R \text{ and } G < B, \\ 60 \times \frac{B-R}{\max - \min} + 120 & \text{if } \max = G, \\ 60 \times \frac{R-G}{\max - \min} + 240 & \text{if } \max = B. \end{cases} \tag{3.3}$$

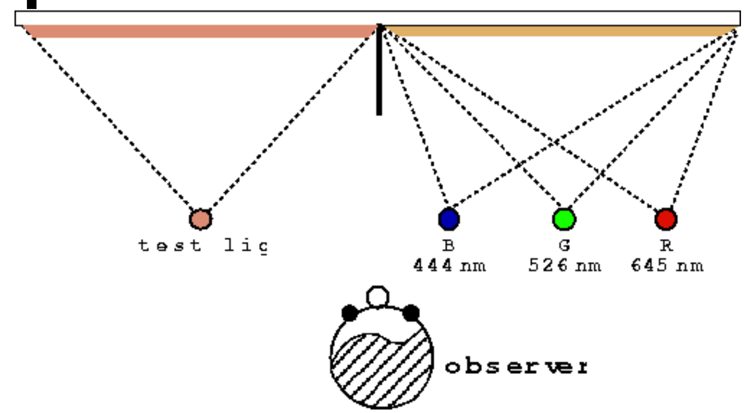
$$S = \begin{cases} 0 & \text{if } \max = 0, \\ 1 - \frac{\min}{\max} & \text{otherwise} \end{cases}$$

$$B = \max .$$

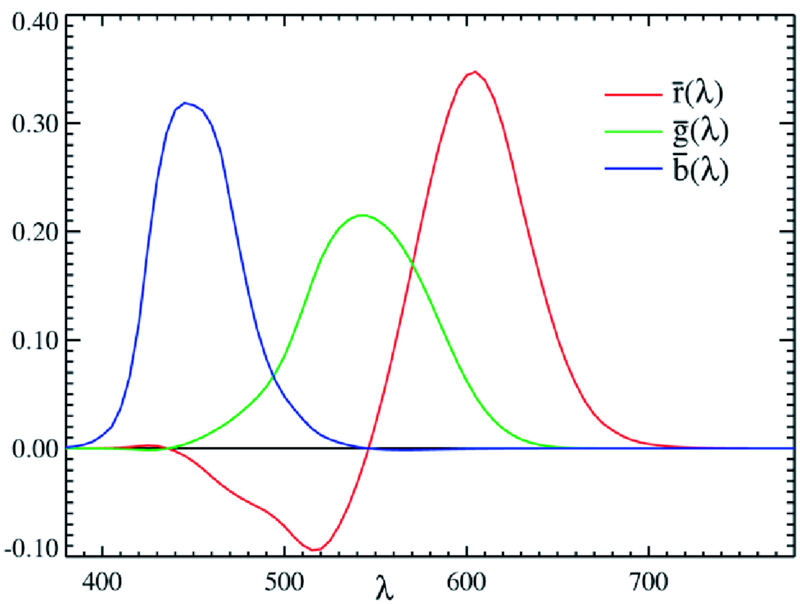
Note: returns H as a value between 0° and 360°

Tristimulus Experiment

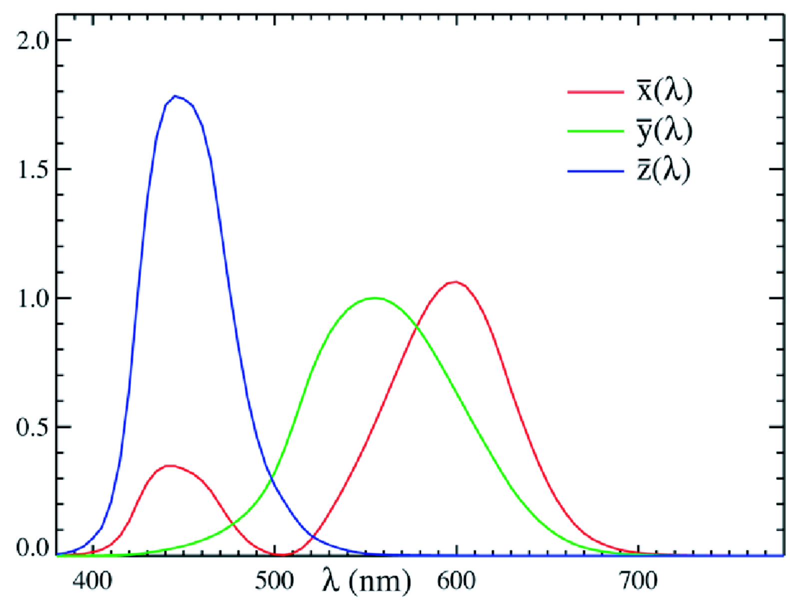
- Color Matching Experiment in 1931
- CIE = International Commission on Illumination (Commission internationale de l'éclairage)
- Since some weighting factors for R,G,B lights are negative, they computed a new set of weights for a new of components X,Y,Z



RGB Weights



XYZ Weights



Converting from CIE XYZ to xyY

- To build a system which separates luminance (Y) from chromaticity (xy) we can do an operation similar to converting CMY to CMYK:

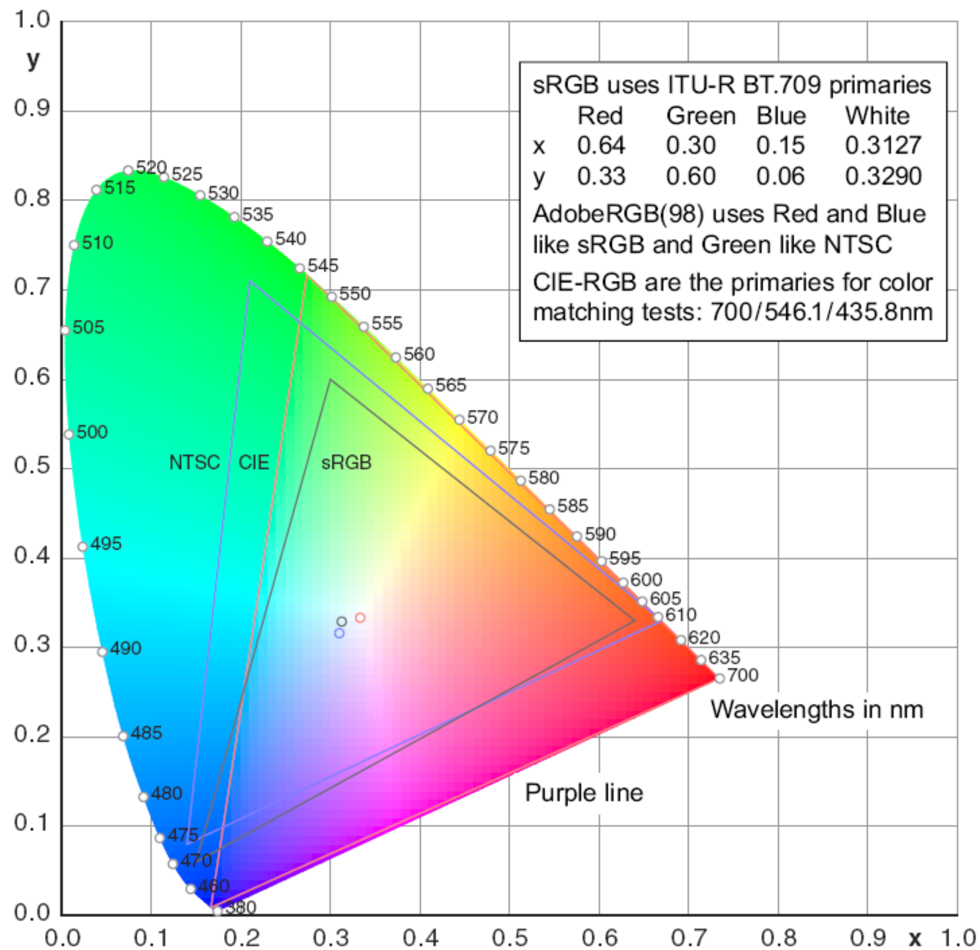
$$x = X / (X + Y + Z)$$

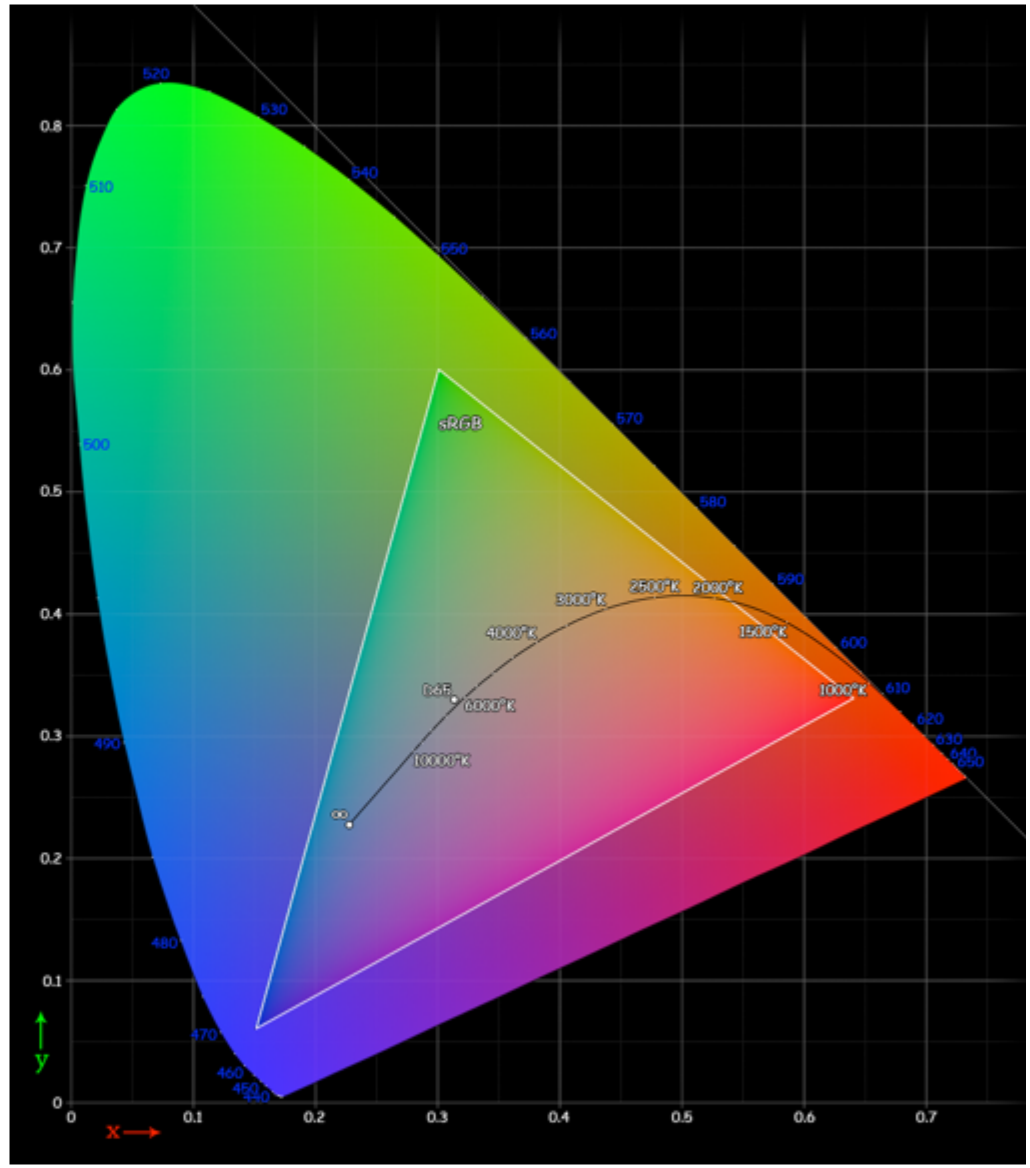
$$y = Y / (X + Y + Z)$$

$$Y = \text{luminance}$$

CIE Space

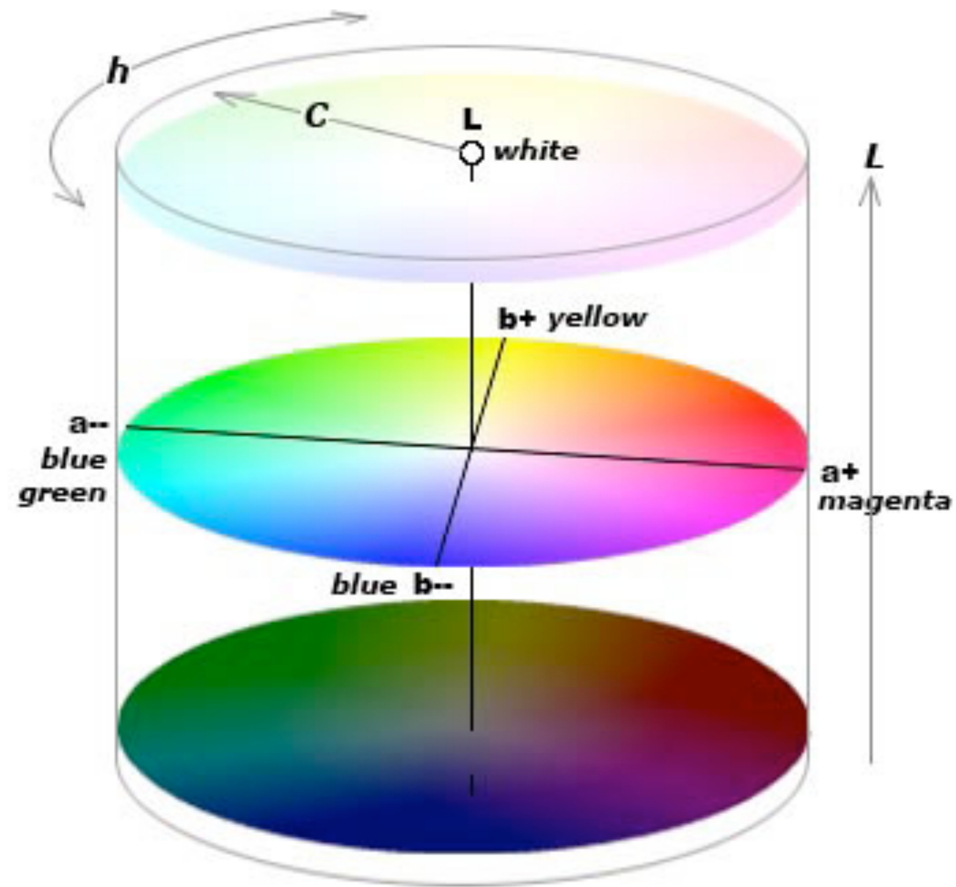
Note: Colors outside the triangle cannot be accurately displayed





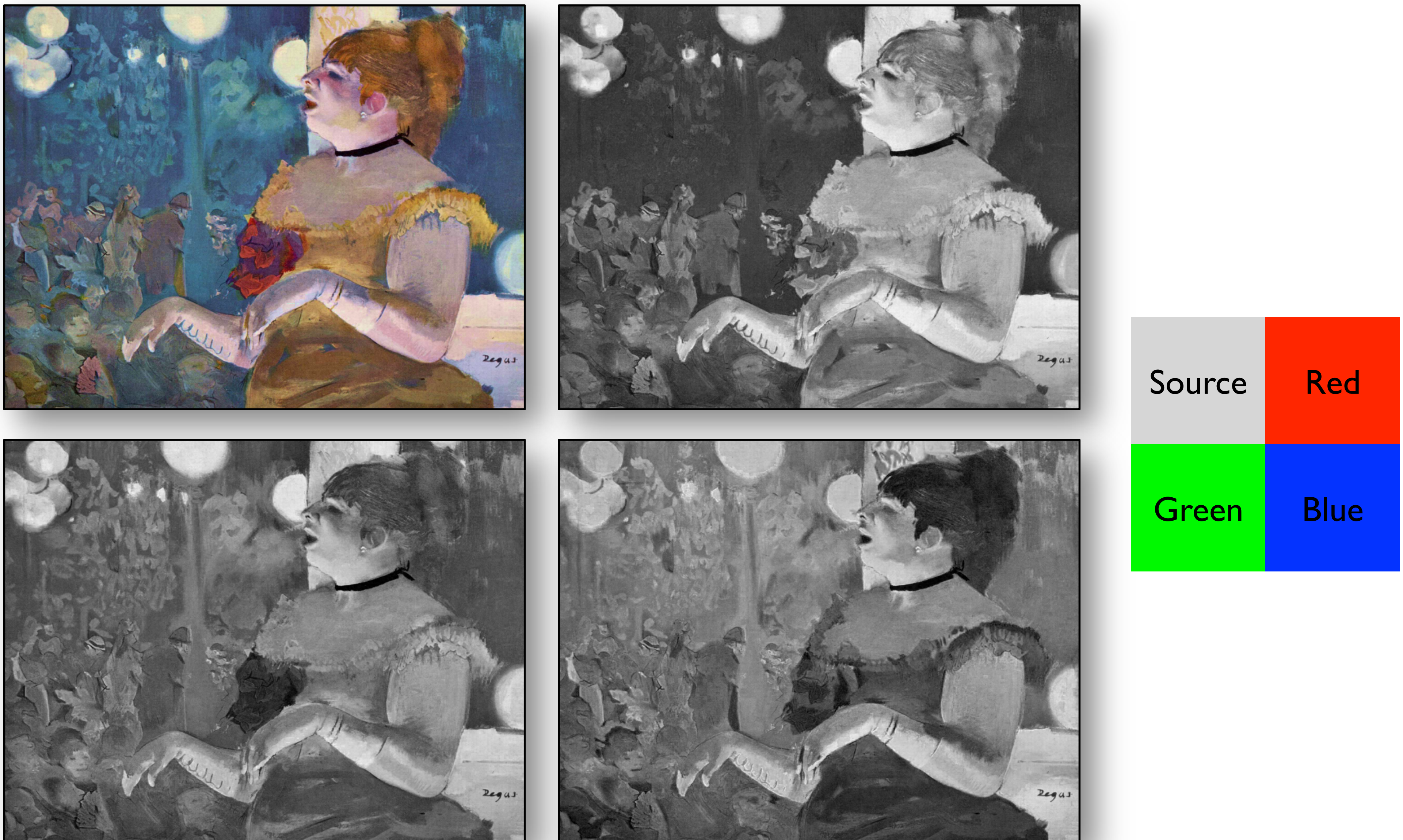
CIELab/Luv

- Perceptual uniform transformation of XYZ
- L approximates luminance or Y in XYZ
- (a,b) & (u,v) approximate chromaticity or M-to-G and Y-to-B channels (the XZ in XYZ)

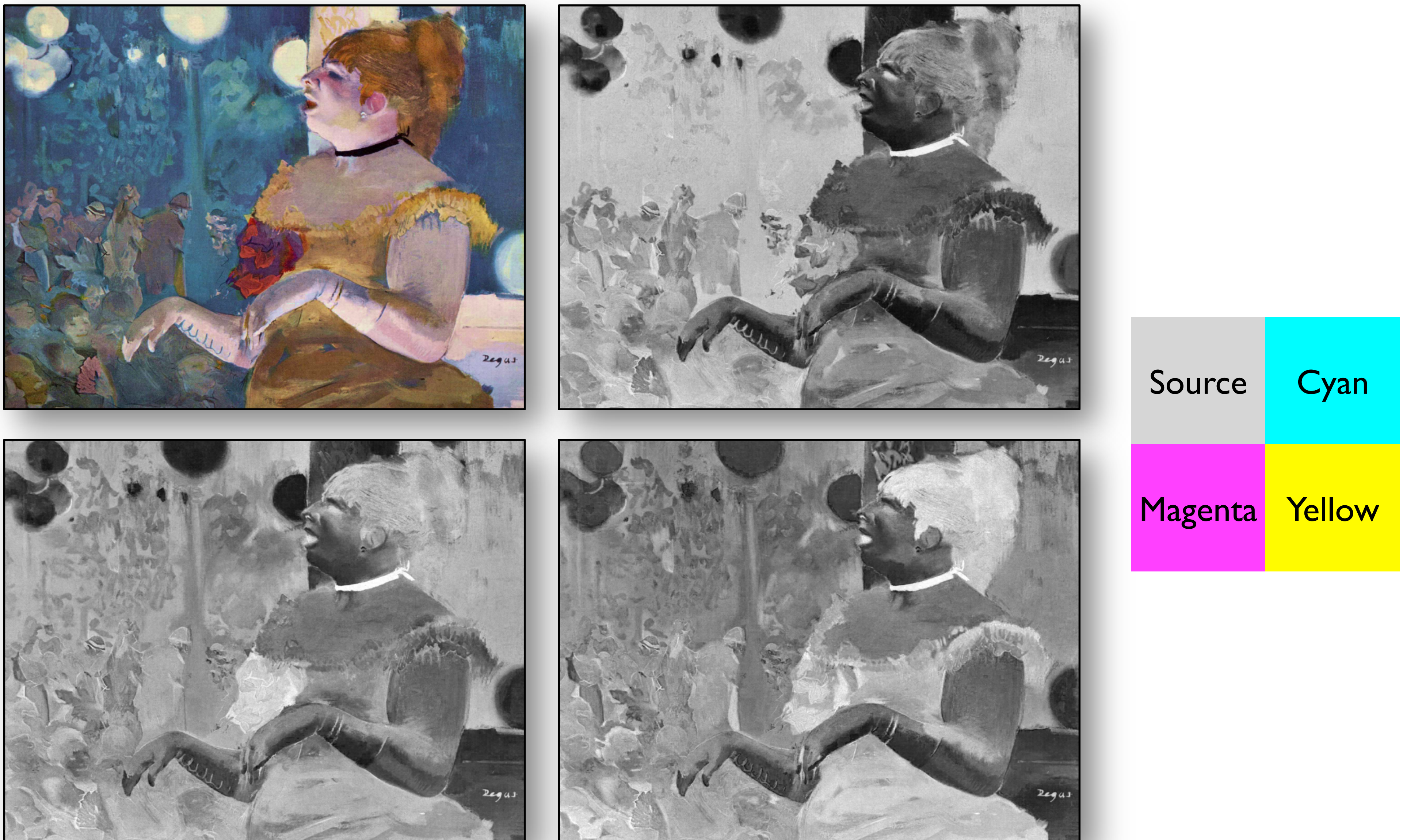


A Comparison of Color Spaces

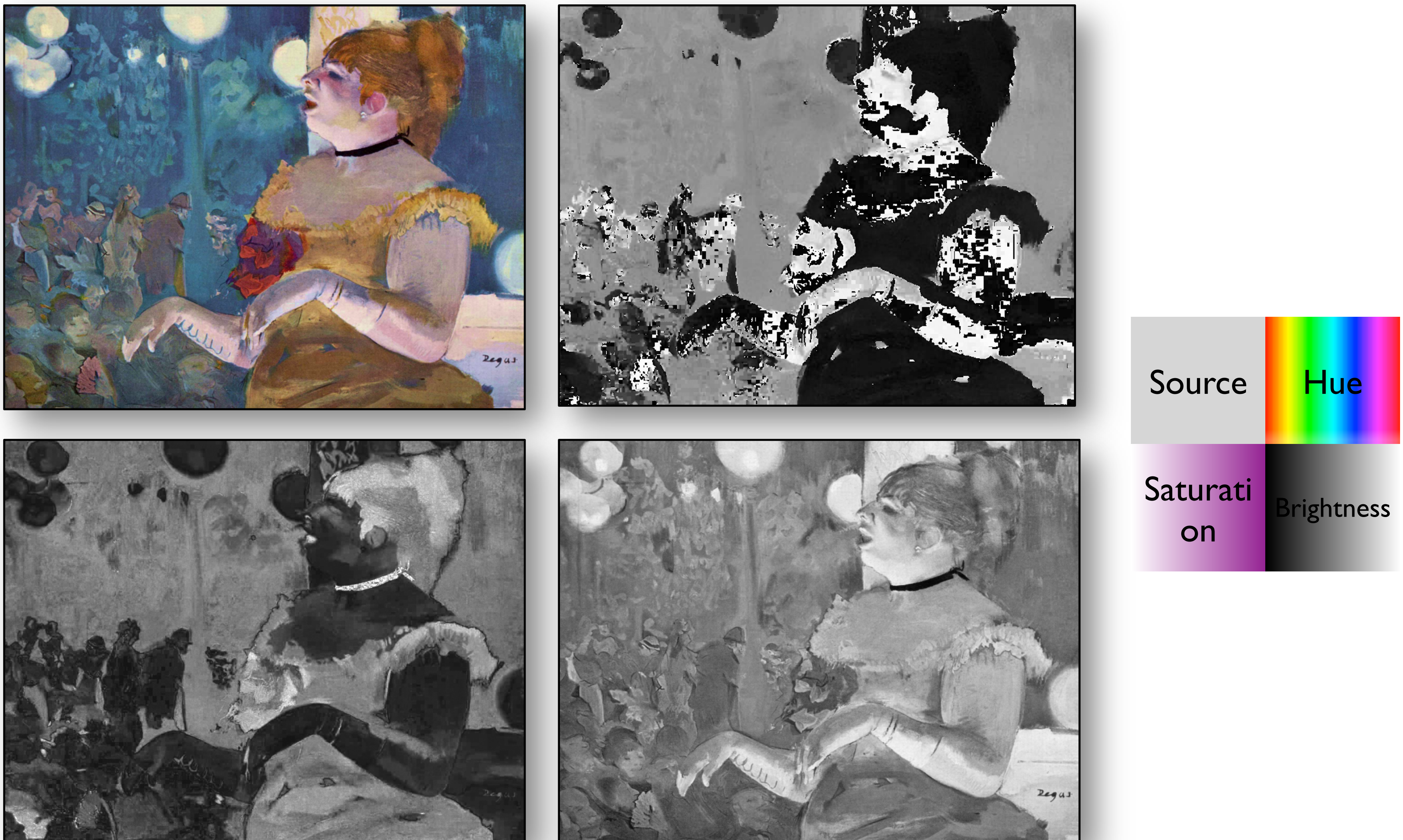
Example RGB Color Space



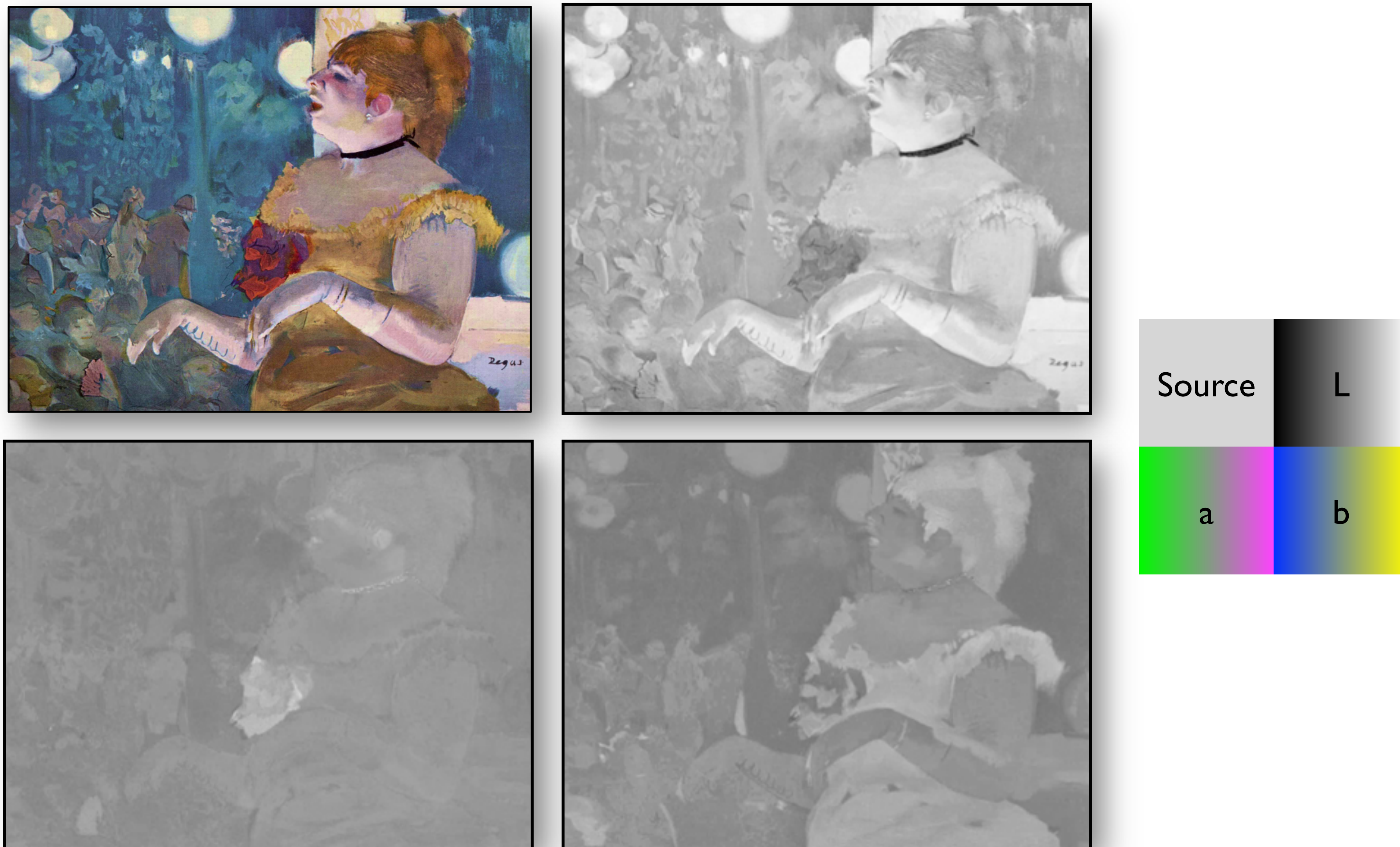
Example CMY Color Space



Example HSV Color Space

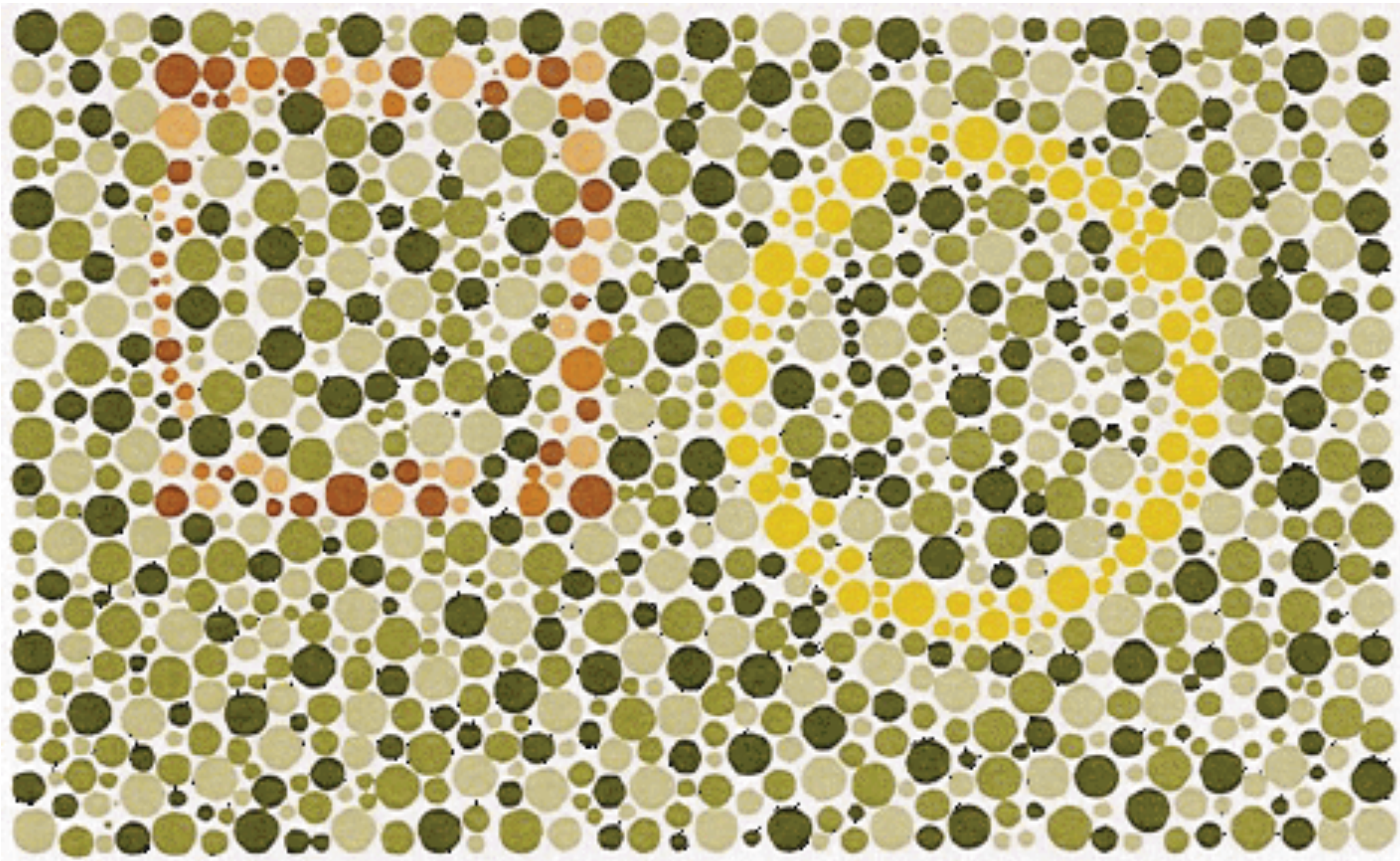


Example CIELab Color Space

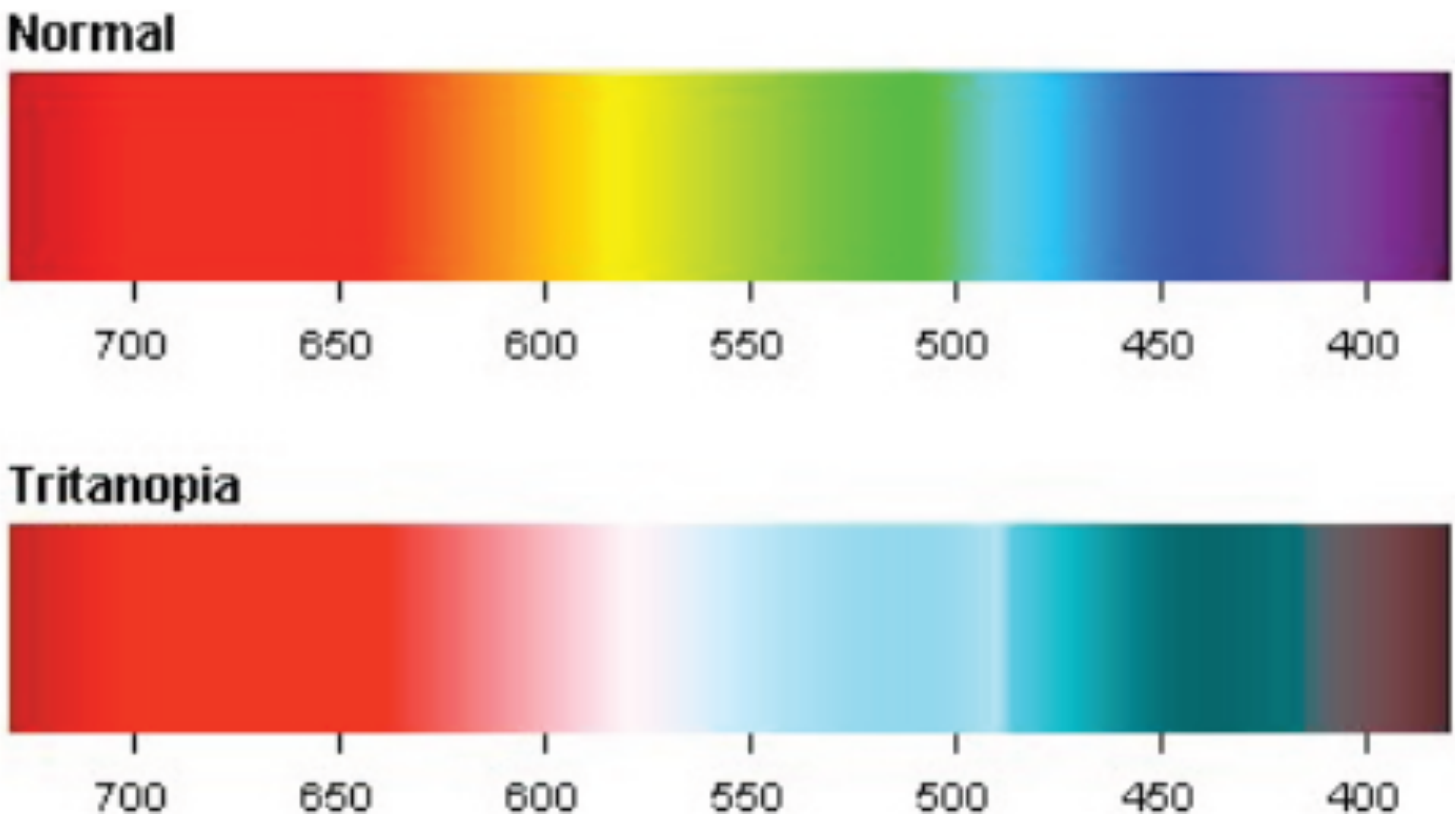


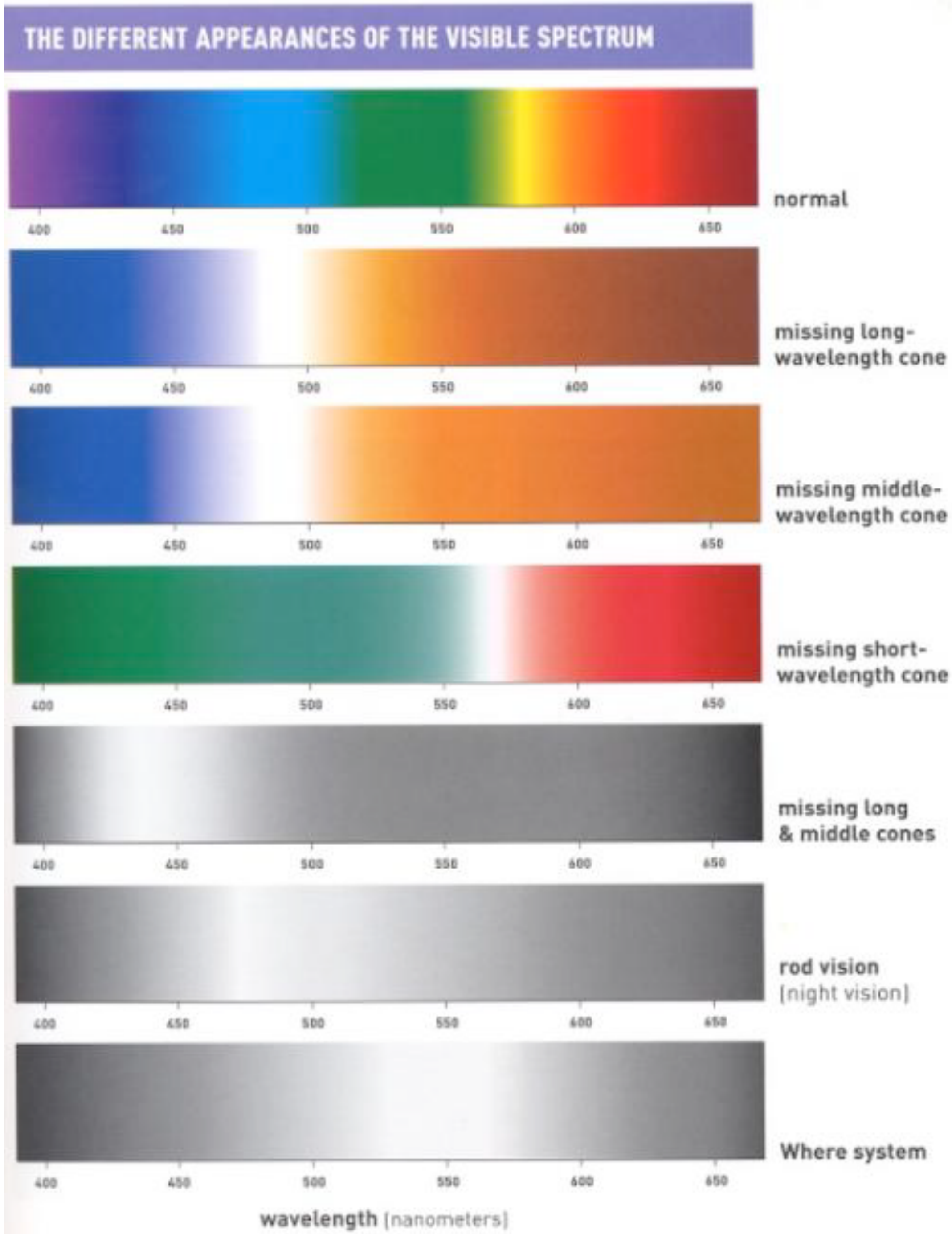
Understanding Color Perception

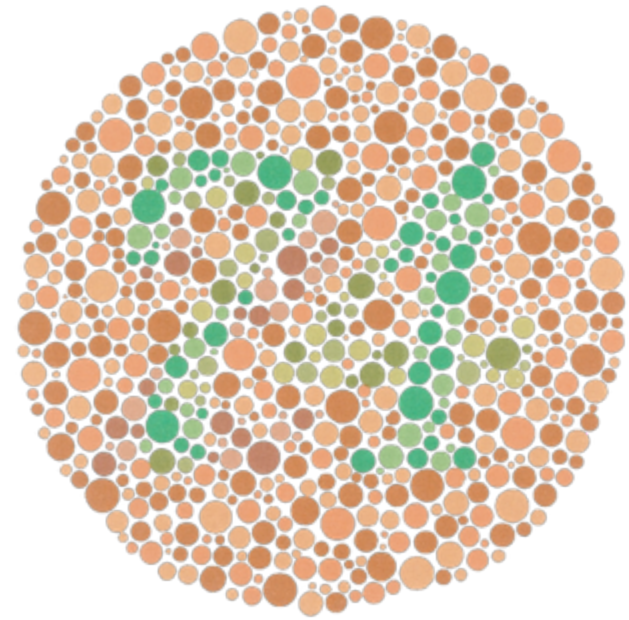
RG Color Blindness

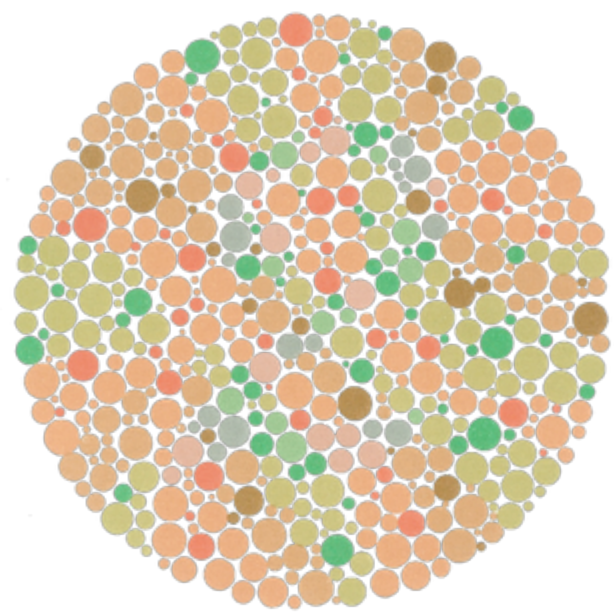


BY Color Blindness



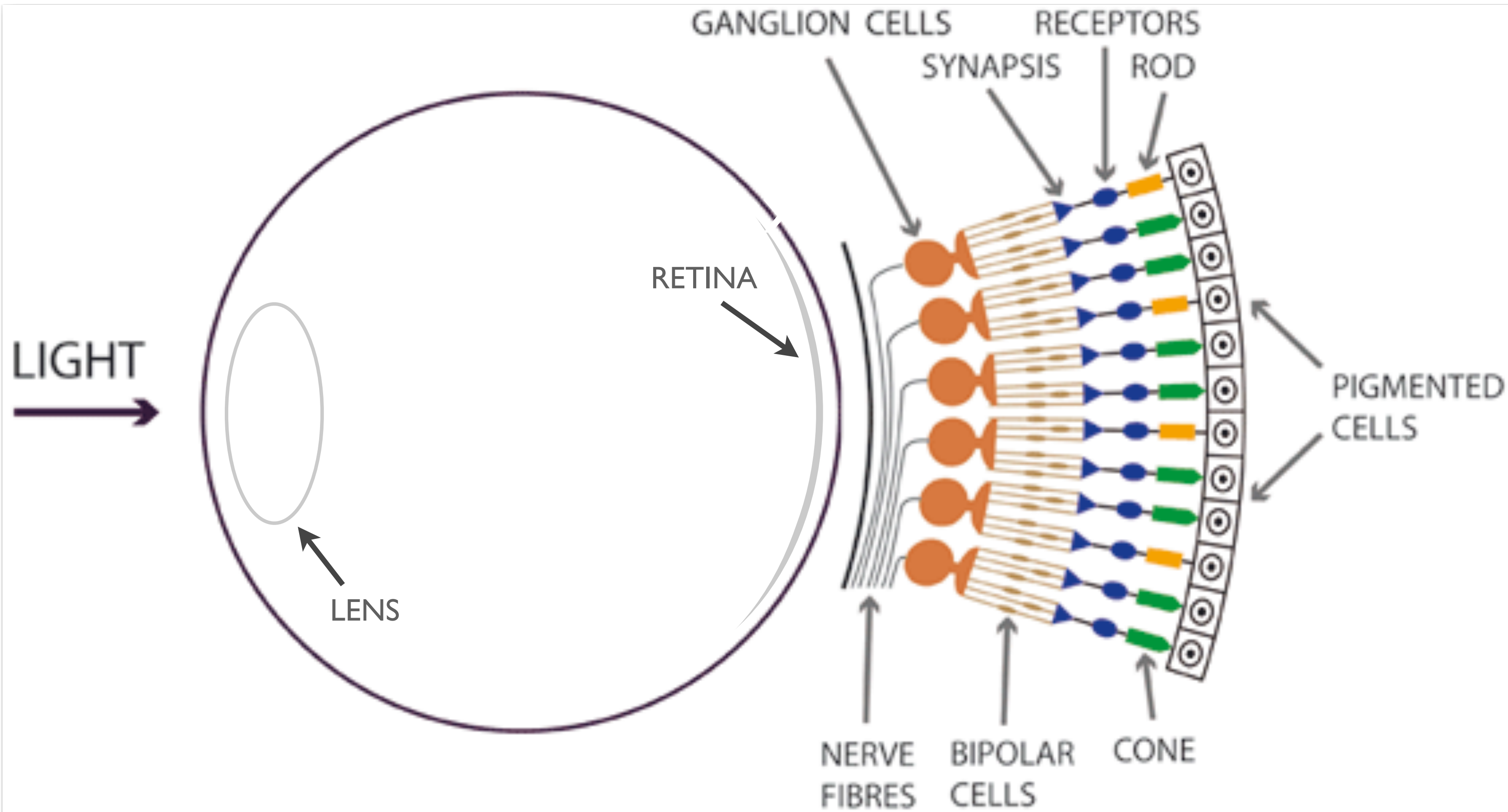

THE DIFFERENT APPEARANCES OF THE VISIBLE SPECTRUM
normal
missing long-wavelength cone
missing middle-wavelength cone
missing short-wavelength cone
missing long & middle cones
rod vision [night vision]
Where system
400
450
500
550
600
650
wavelength [nanometers]





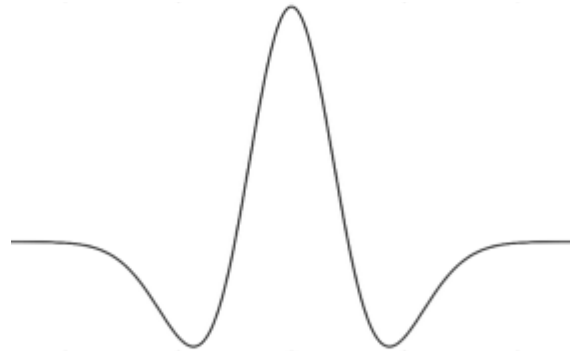
Color Illusions

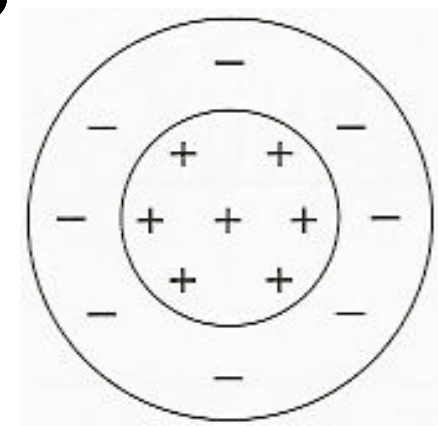
Physiology of the Eye

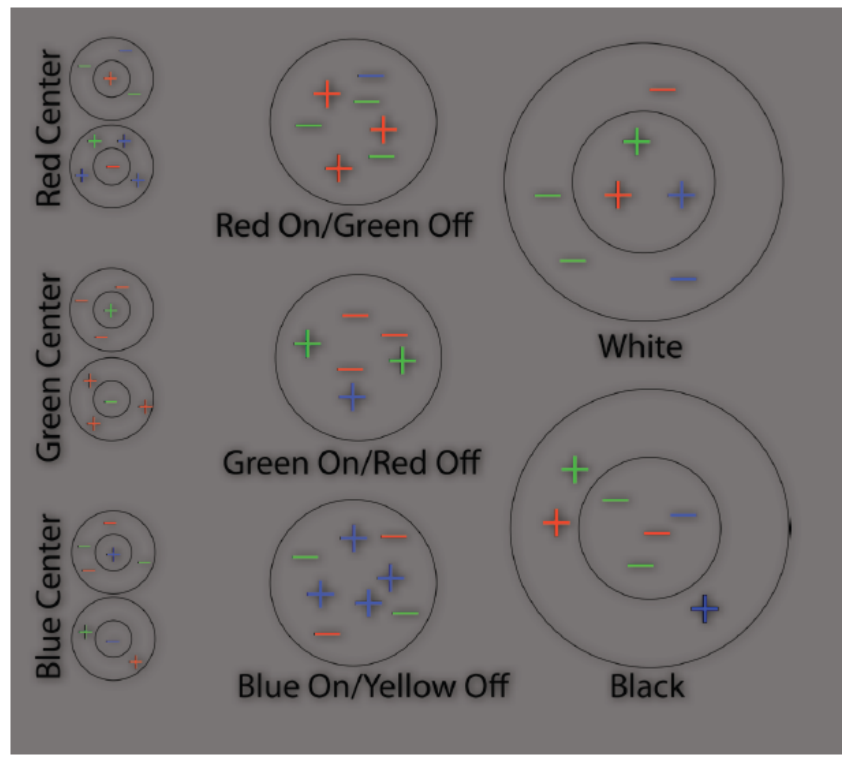


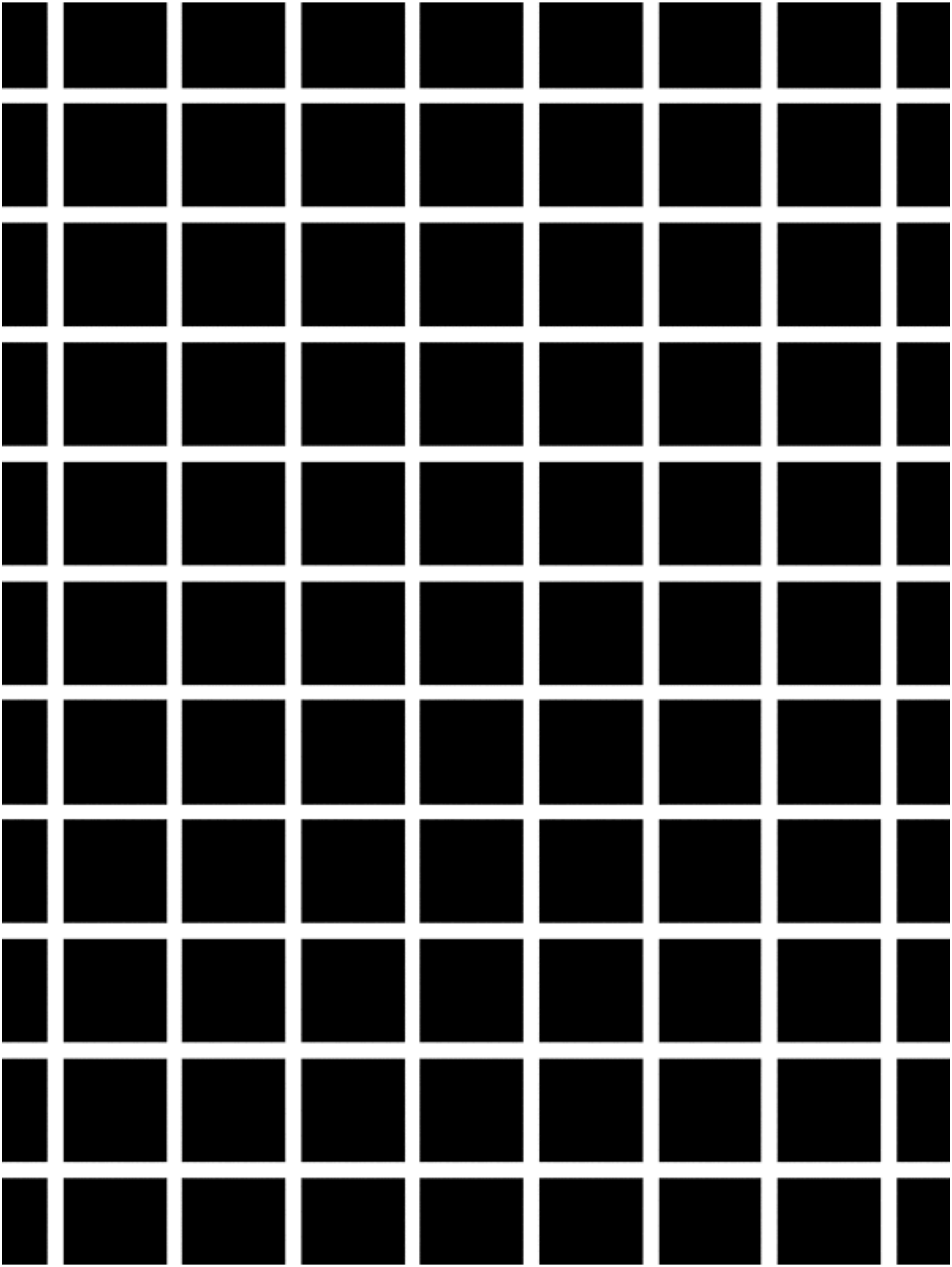
Color Illusions

- Primary cause: the Retinal Ganglion Response
- Triggered by light in the center, suppressed by light in the surround
- Causes selective sensitivities to discontinuities in color as well.

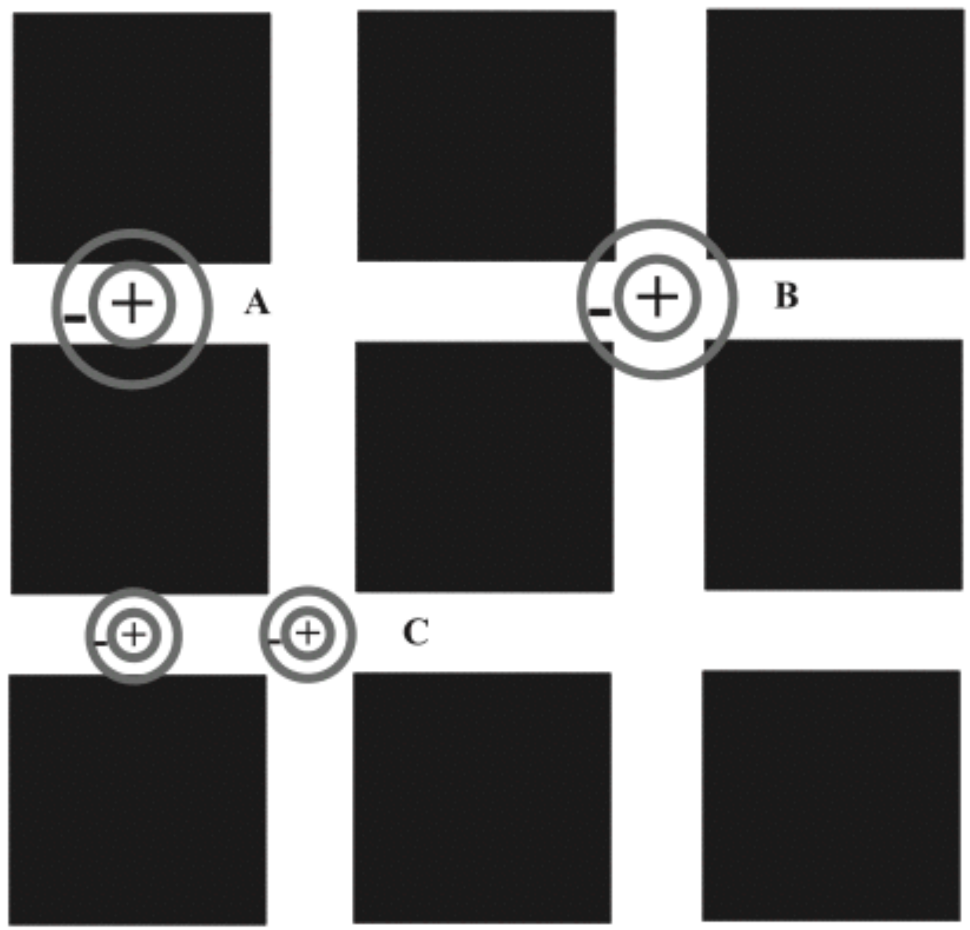






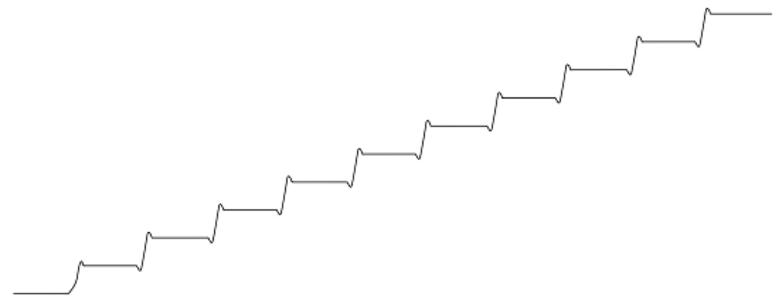


Hermann grid effect (Brightness Adaptation)



Mach Banding

(a) Mach banding.

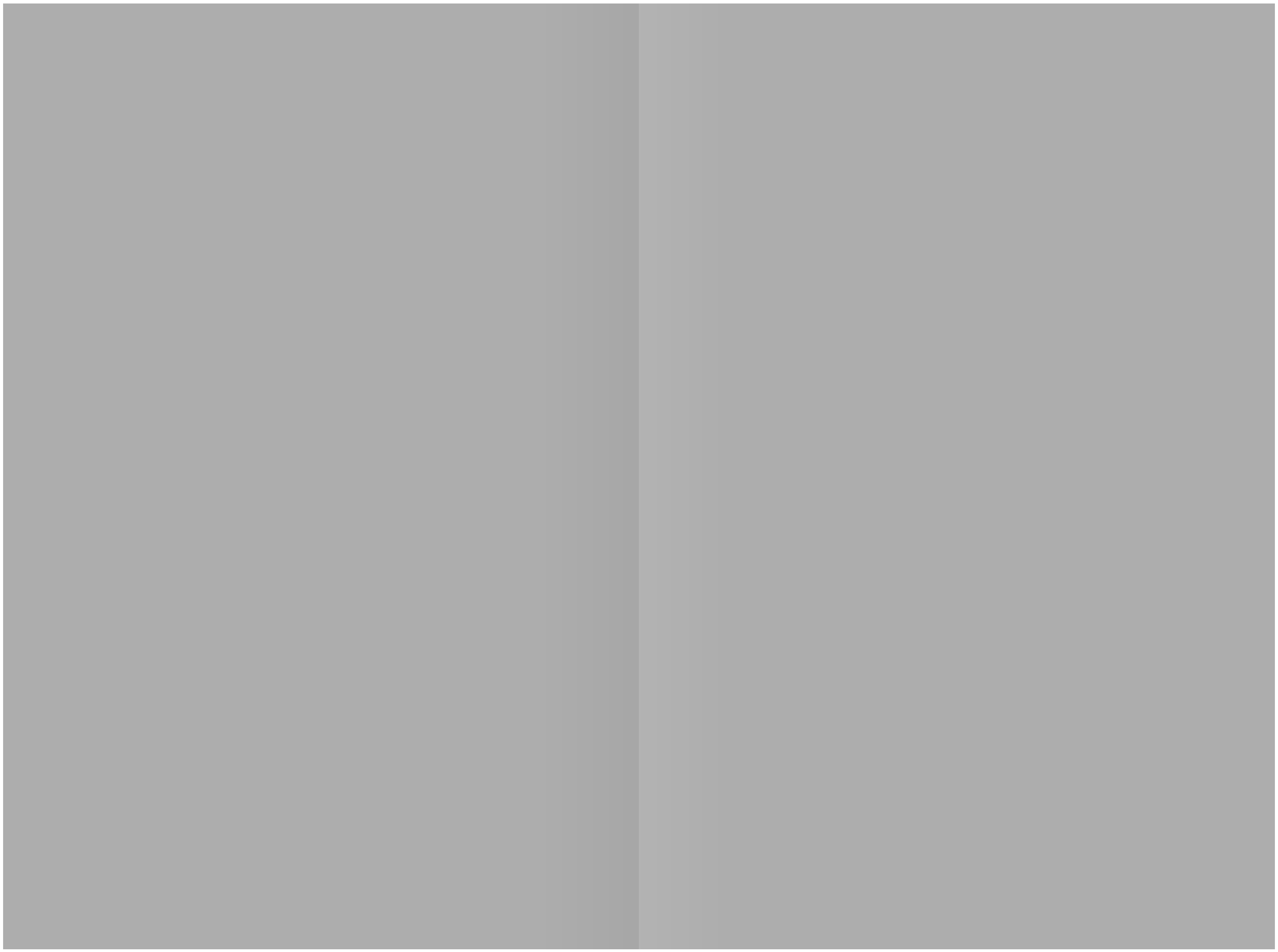


(b) Row profile of perceived brightness.

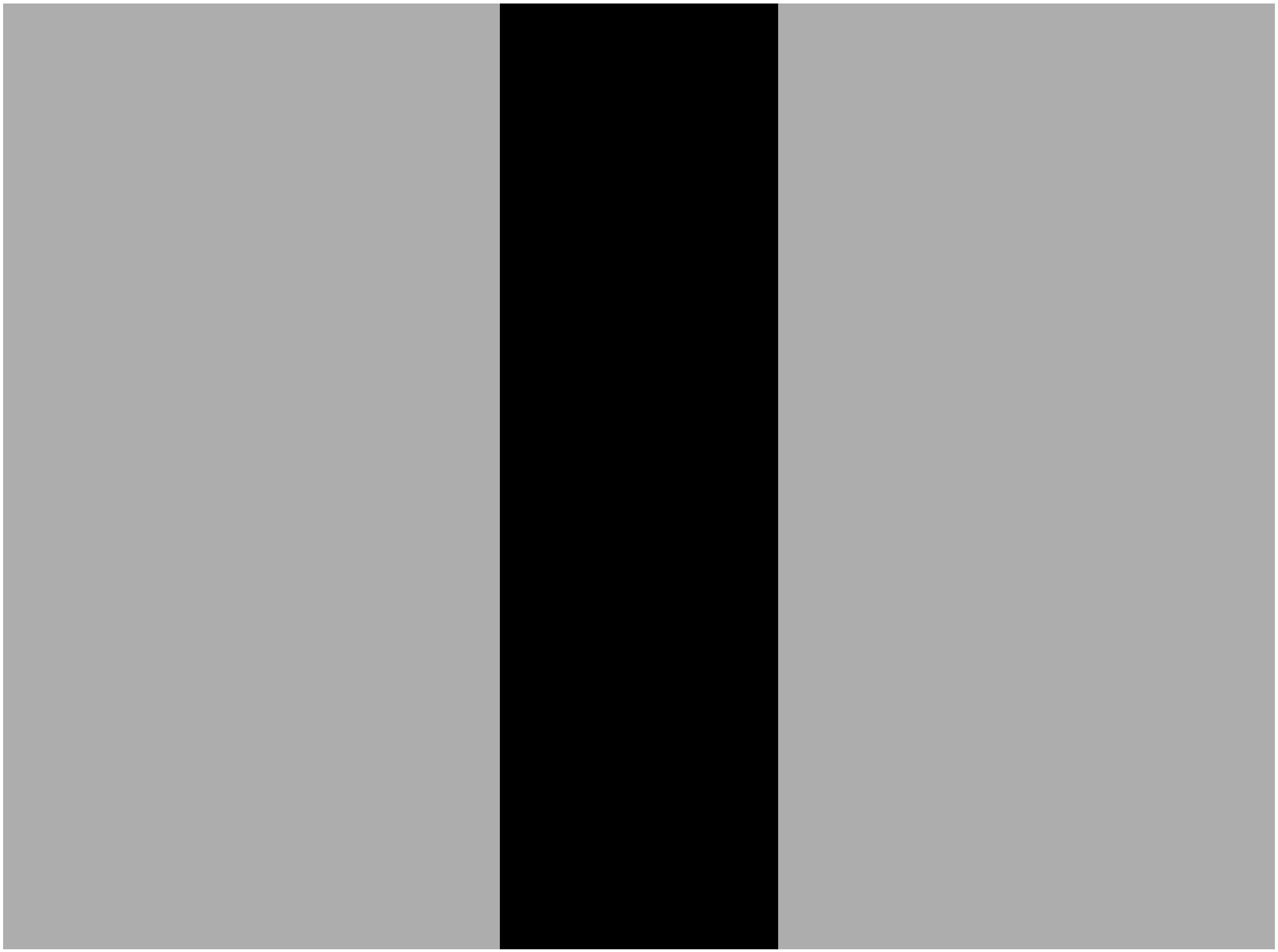
Figure 2.8. Mach banding effect.

- The eye rapidly scans across the field of view while coming to momentary rest at each point of particular interest.
- At each of these points the eye adapts to the average brightness of the local region surrounding the point of interest.
- This phenomena is another type of (local) brightness adaptation.
- The eye over-shoots/under-shoots at edges where the brightness changes rapidly. This causes 'false perception' of the intensities

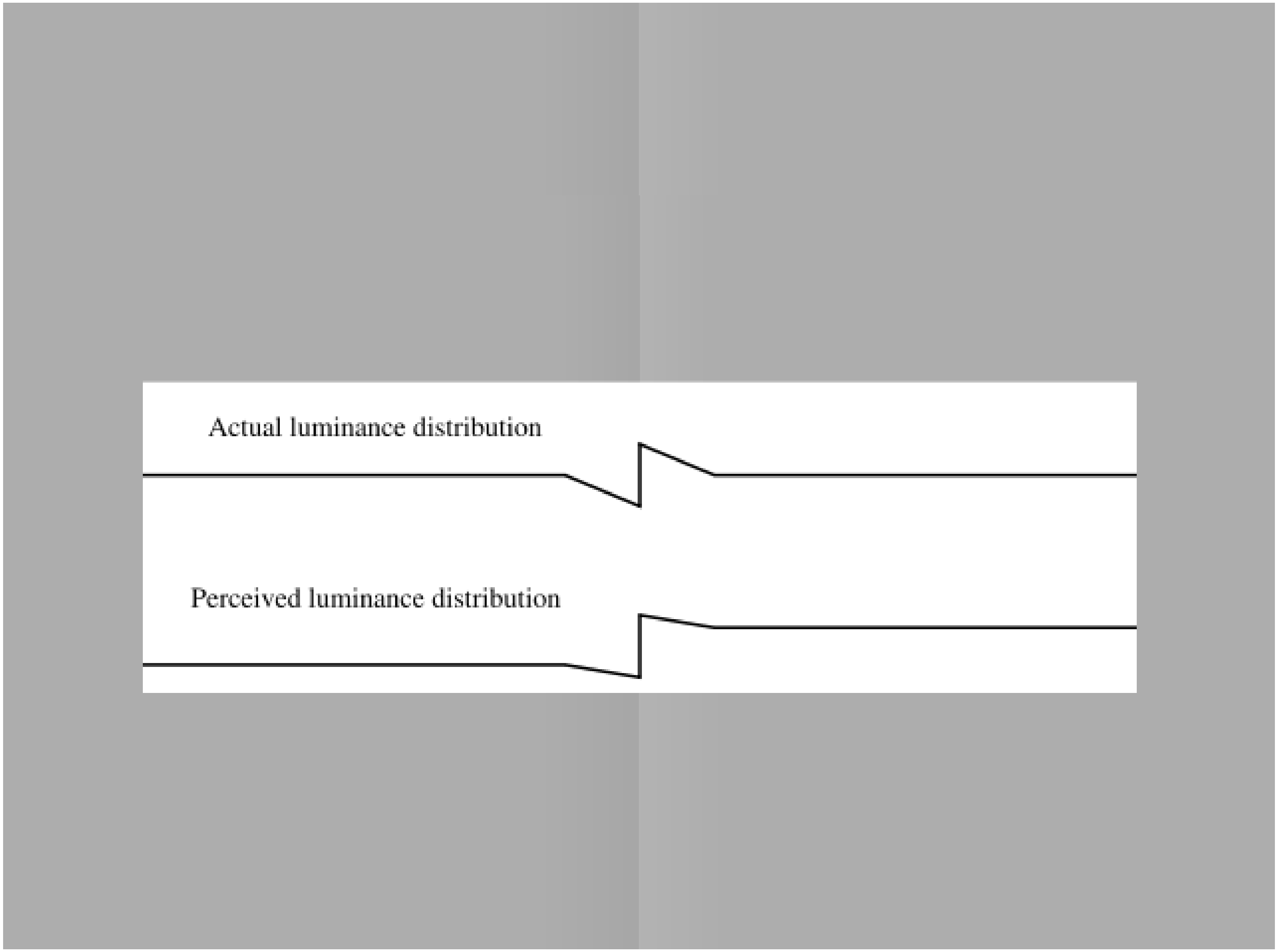
Cornsweet Illusion



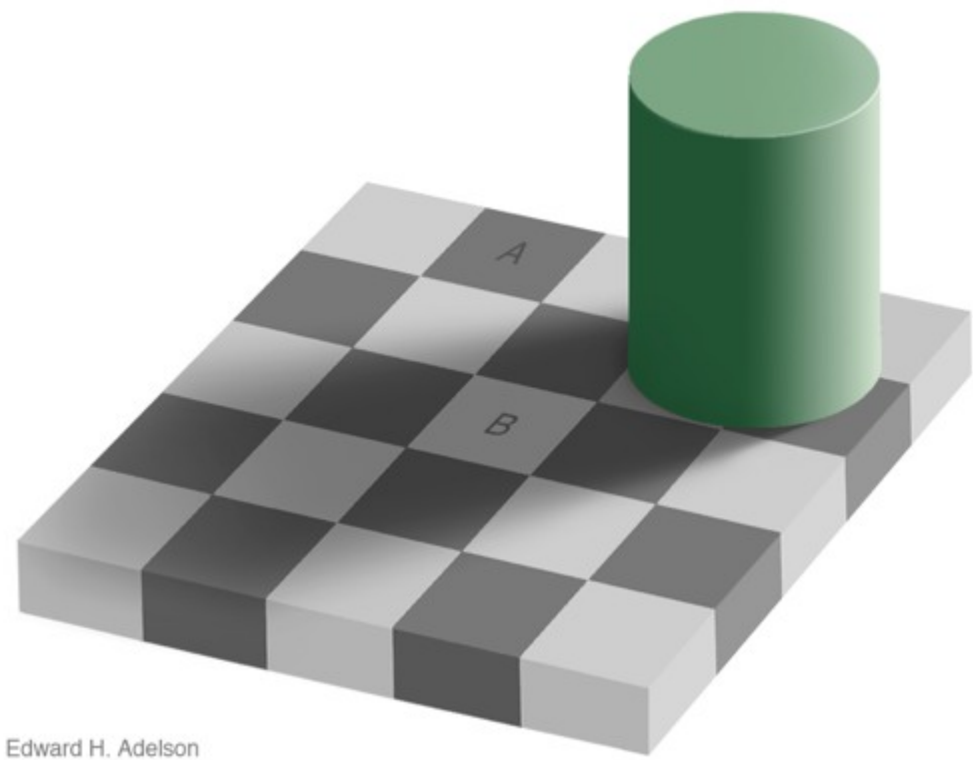
Cornsweet Illusion



Cornsweet Illusion



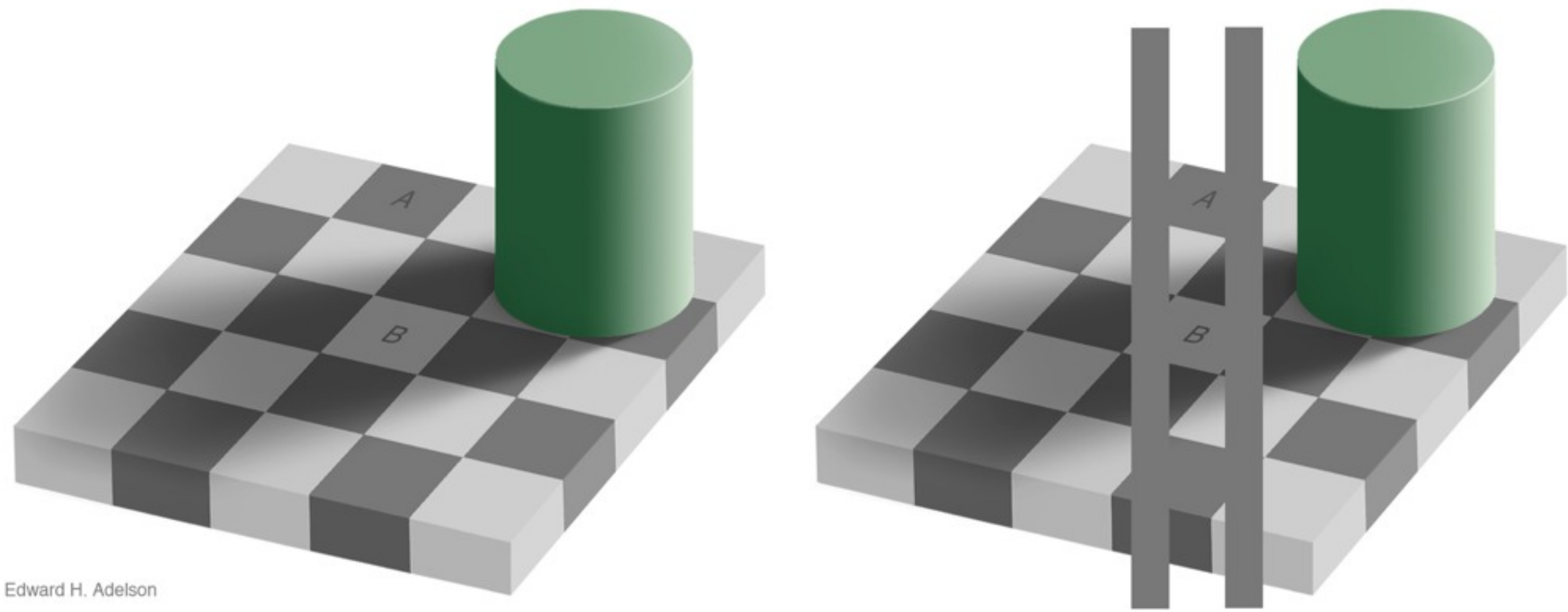
Simultaneous Contrast



- Perceived color is highly context dependent
- Variable lighting and background conditions affect what we see.

http://persci.mit.edu/_media/gallery/checkershadow_double_full.jpg

Simultaneous Contrast

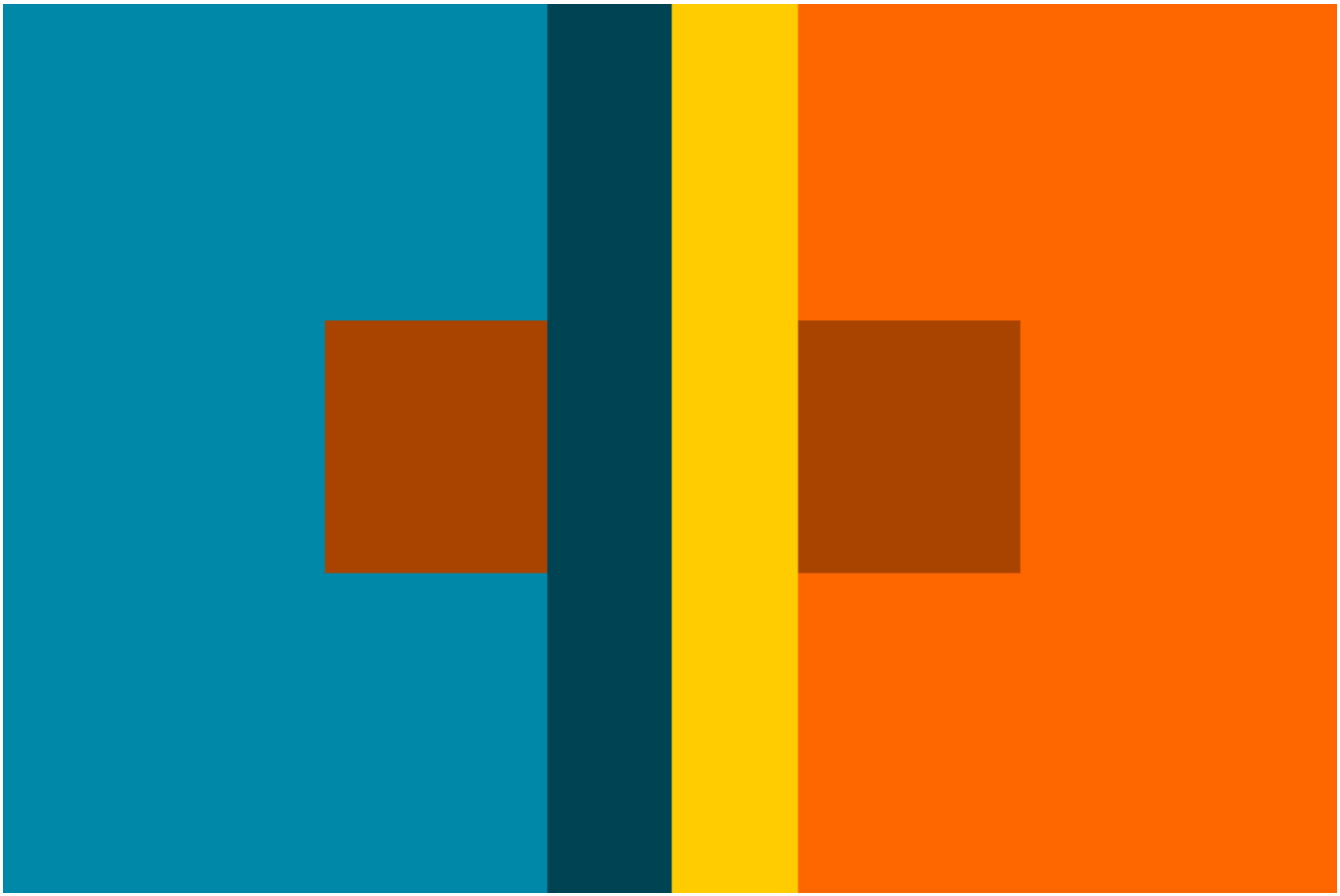


http://persci.mit.edu/_media/gallery/checkershadow_double_full.jpg

Simultaneous Contrast

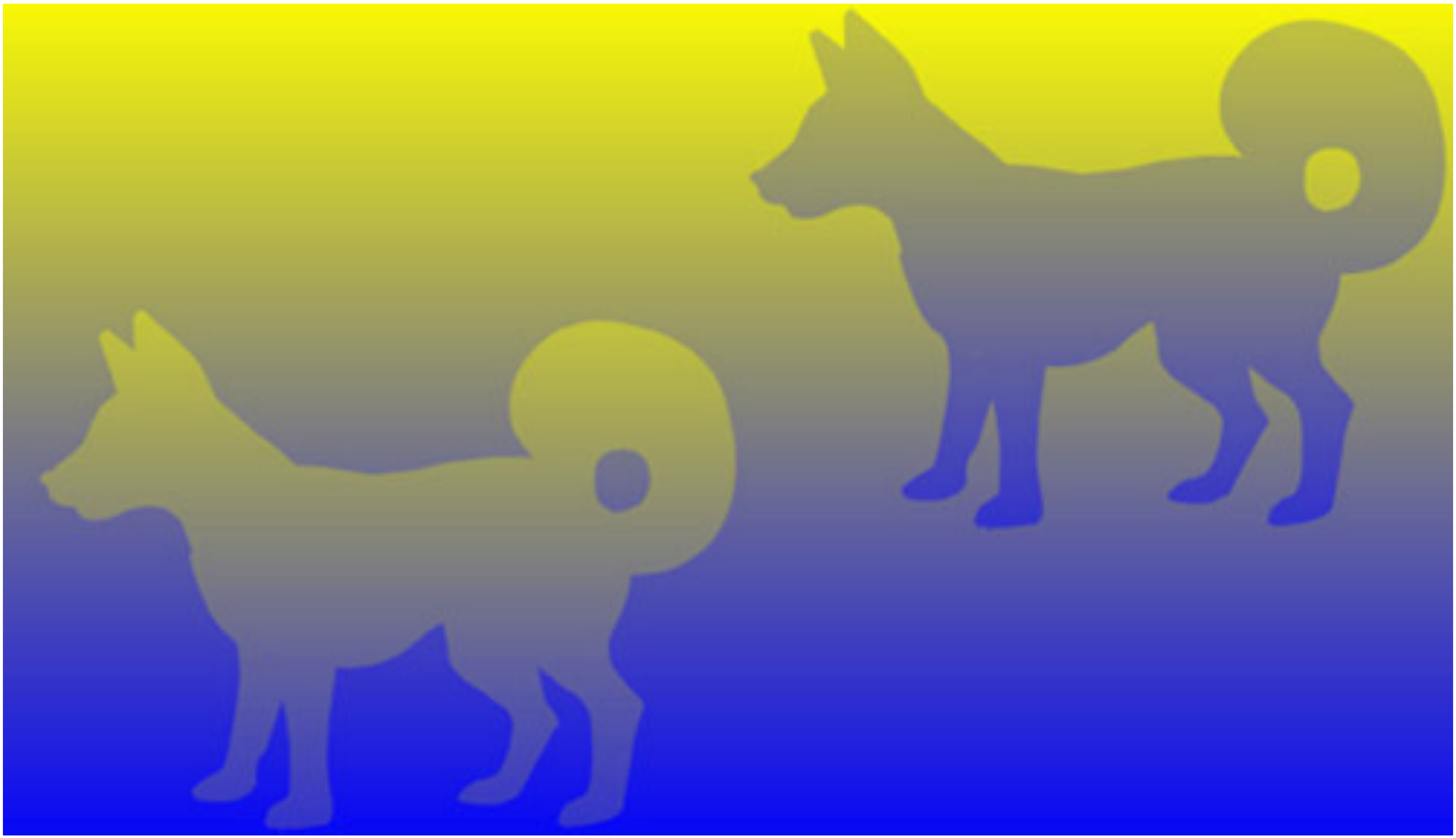
Simultaneous Contrast

Simultaneous Contrast

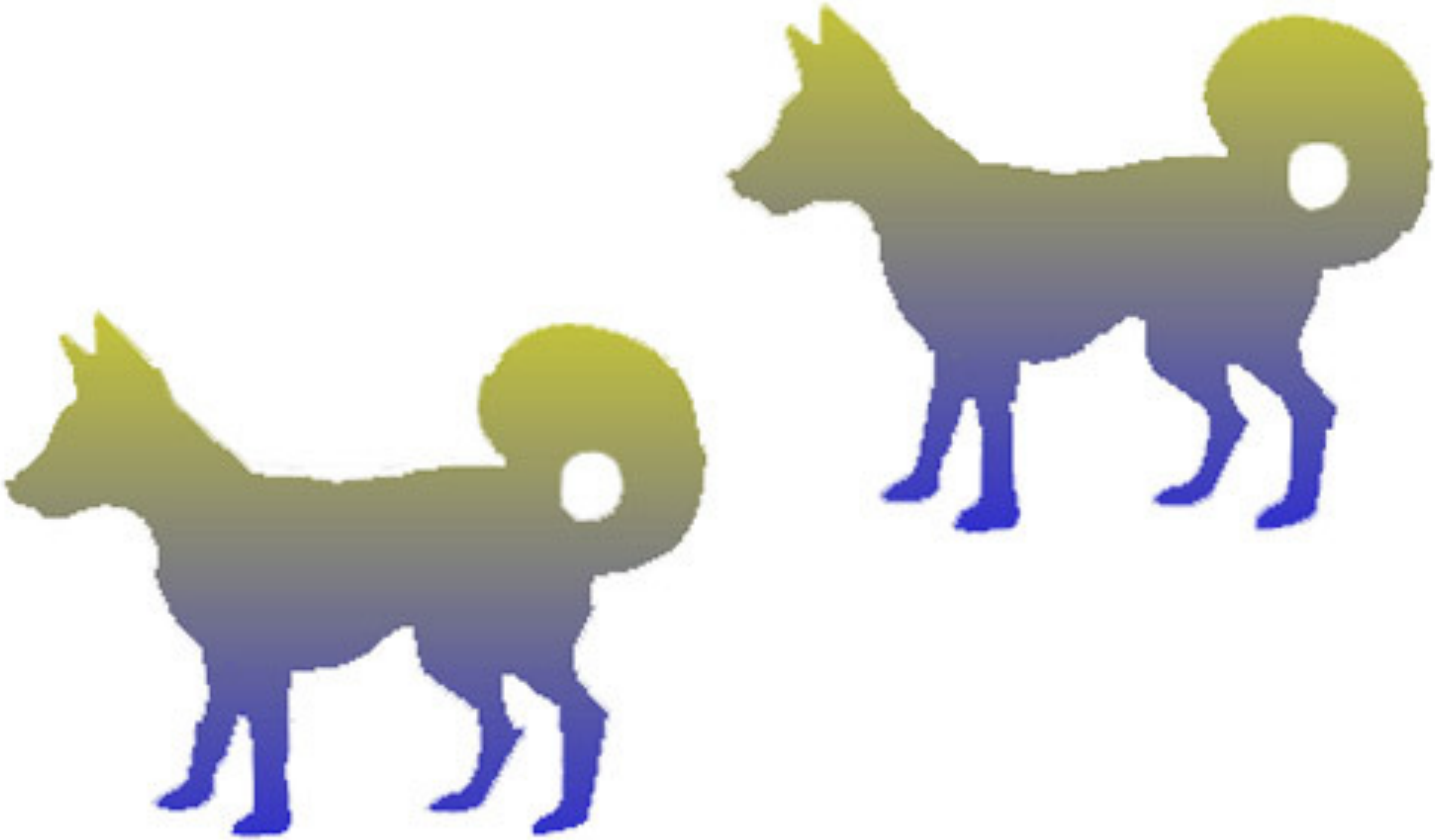


Simultaneous Contrast

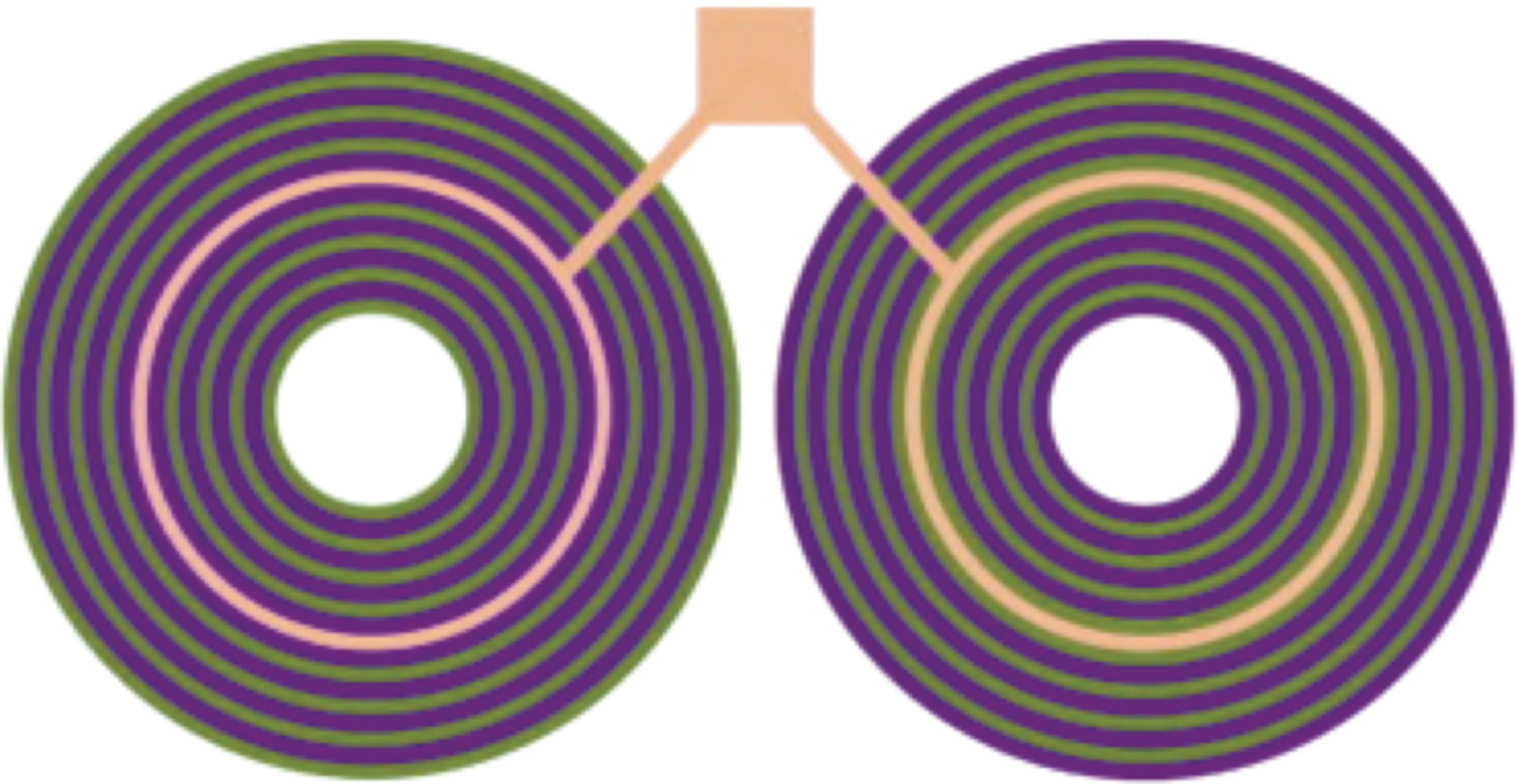
Simultaneous Contrast



Simultaneous Contrast

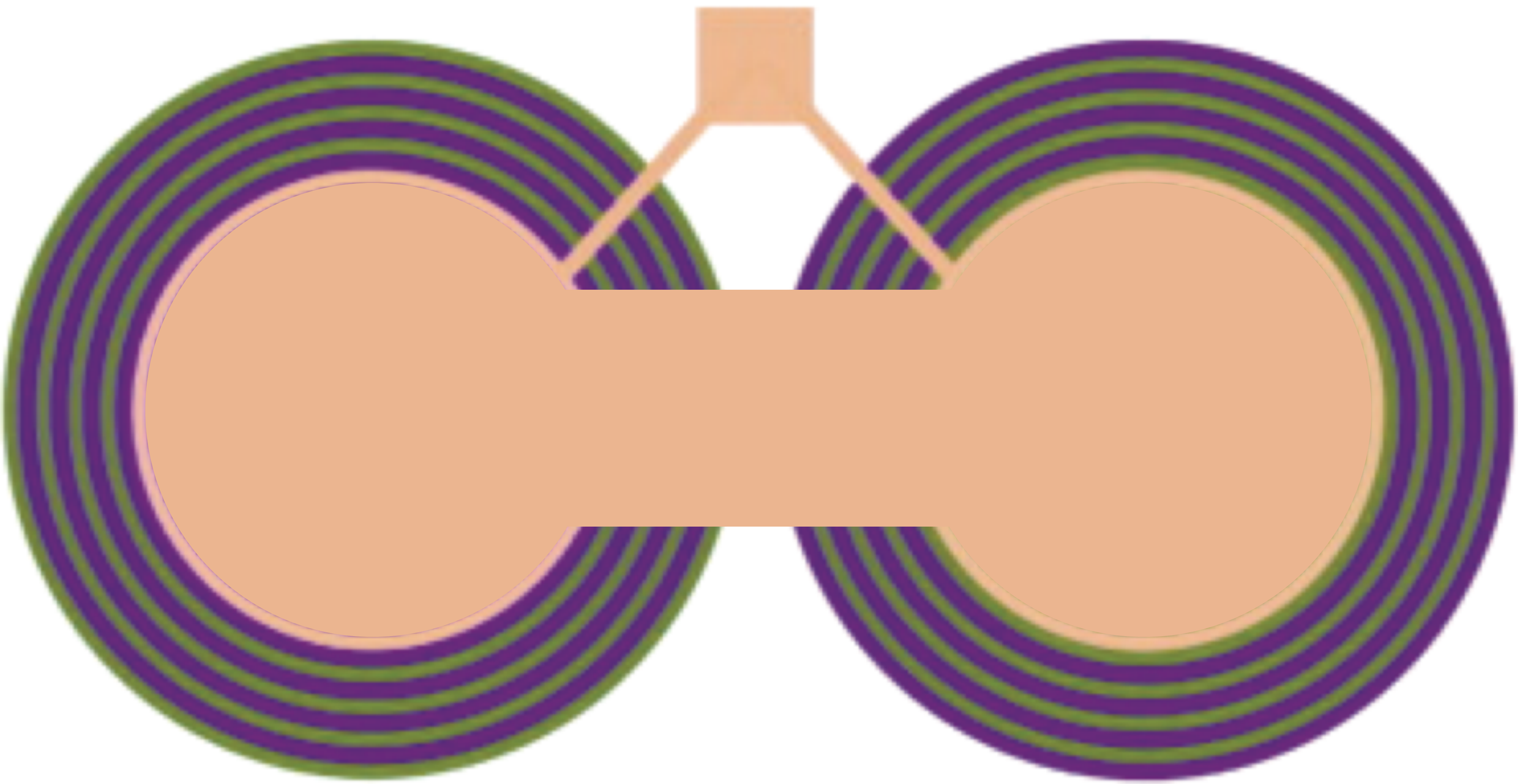


Chromatic Induction



P. Monnier

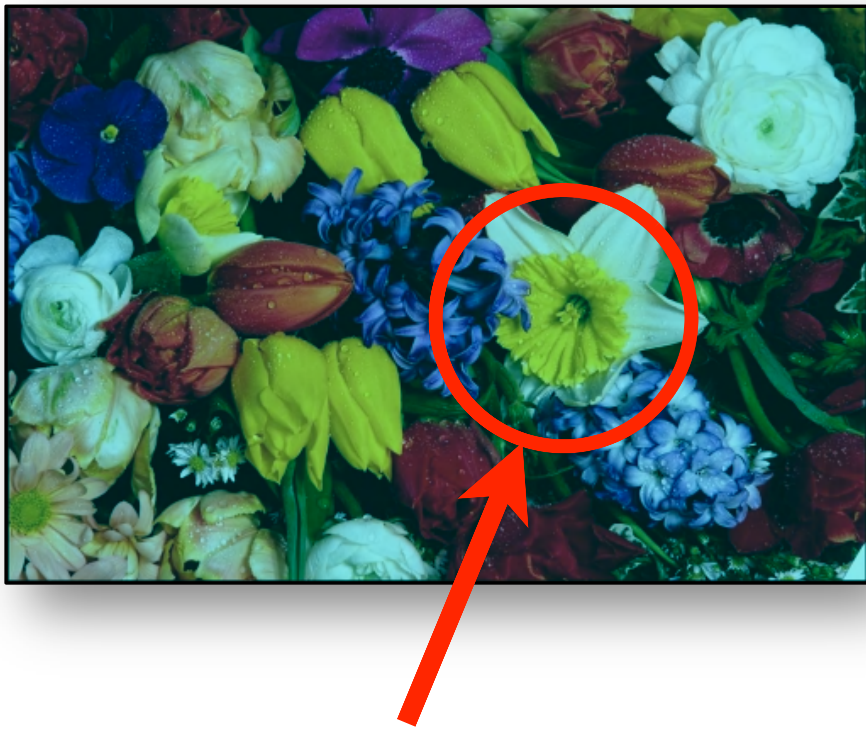
Chromatic Induction



P. Monnier

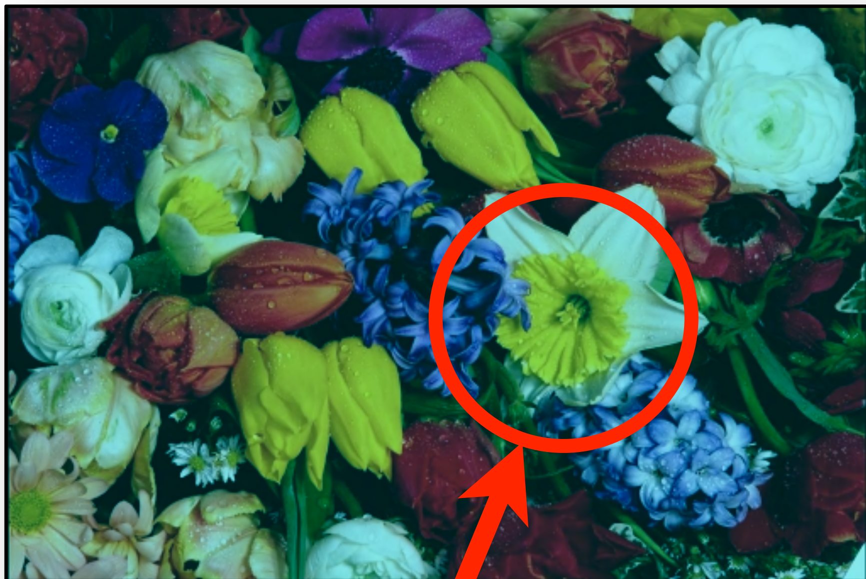
Chromatic Adaptation

Chromatic Adaptation



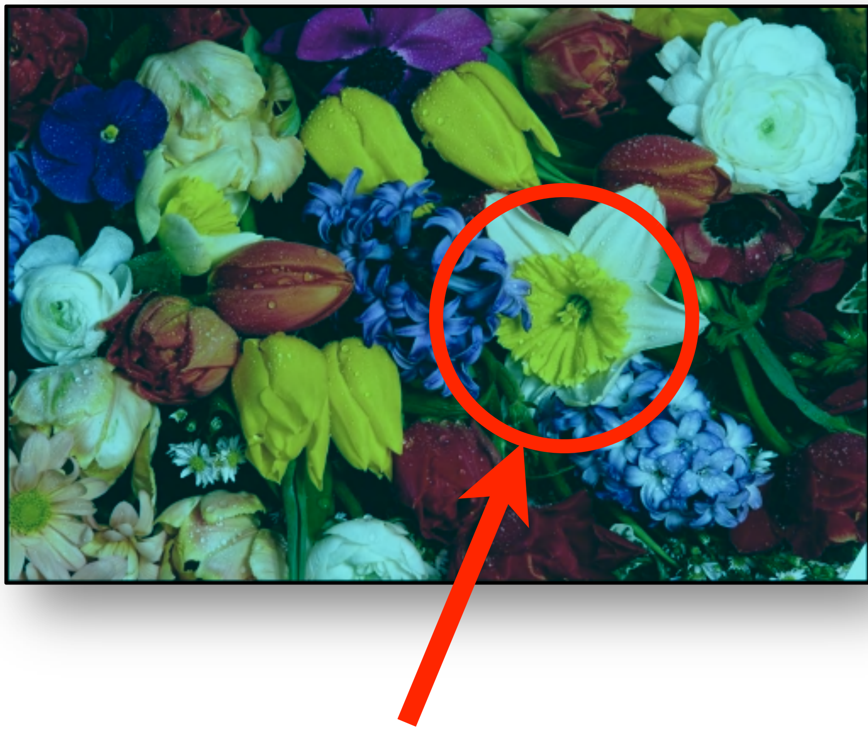
What is the color
of the flower?

Chromatic Adaptation



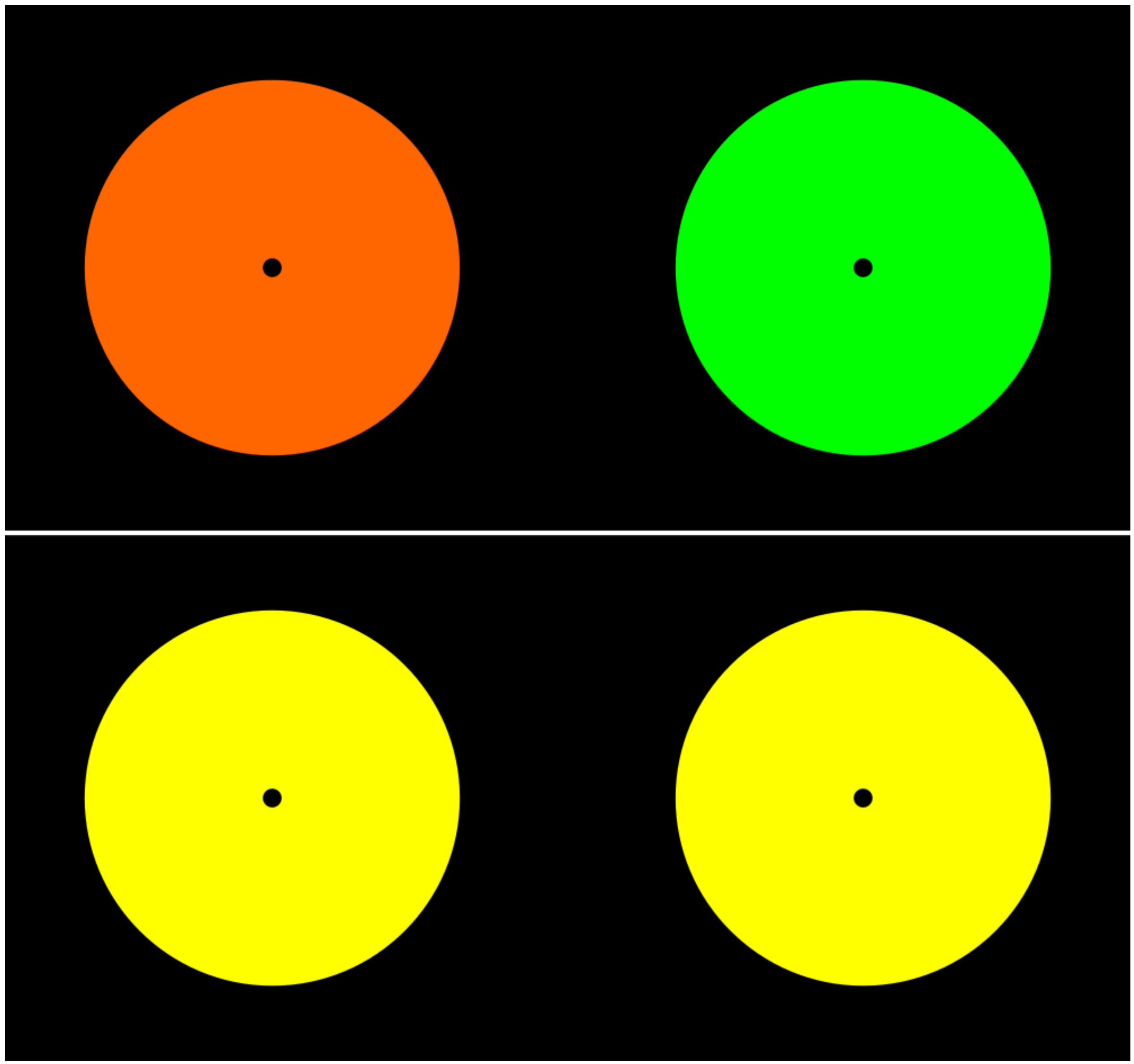
What is the color
of the flower?

Chromatic Adaptation



What is the color of the flower?

Successive Contrast



Lec06 Required Reading

- House Ch. 7
- Recommended: Brinkmann, The Art and Science of Digital Compositing