# CSC 433/533
# Computer Graphics

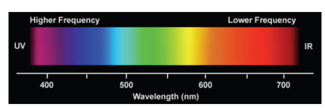
# Lecture 05
# Color and Perception

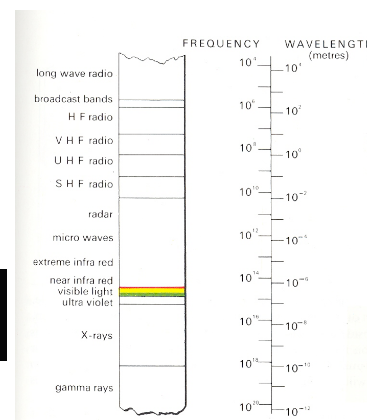
# Today's Agenda

- Reminders:
  - A01: any questions?
- Goals for today:
  - Discuss color and perceptual phenomena.

# Recall: Light is Electromagnetic Radiation

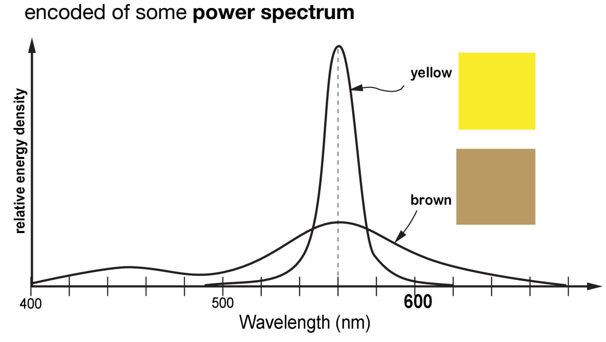
- Visible spectrum is "tiny"
- Wavelength range: 380-740 nm



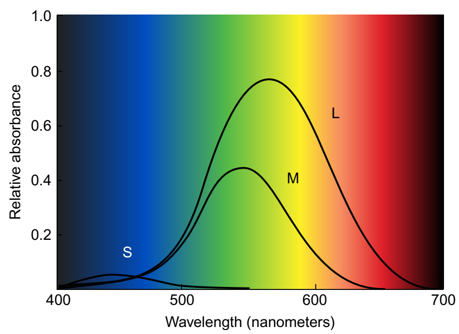

# Recall: Color != Wavelength

- But rather, an integral over the wavelengths of the energy encoded of some **power spectrum**




# Color and Perception

## Recall: We have three types of cones (Short, Medium, and Long)




**Colin Ware, Information Visualization: Perception for Design**

## Hunters

## Gatherers

## Trichromacy

- Our 3 cones cover the visible spectrum (theoretically, all we might are 2 though)
- Most birds, some fish, reptiles, and insects have 4, some as many as 12 (e.g. the mantis shrimp)
- This is a "reason" why many of our acquisition devices and displays use 3 channels, and why many of our color spaces are three dimensional


## Key Idea: Perception of color

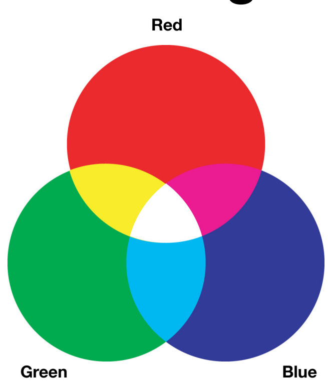
**Ultimately, color is a perceptual phenomenon, we all perceive it differently**

# Color Models

# Color Terminology

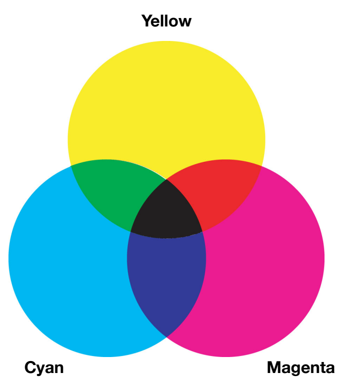
- **Color Model**
  - Is an abstract mathematical system for representing color.
  - Is often 3-dimensional, but not necessarily.
  - Is typically limited in the range of colors they can represent and hence often can't represent all colors in the visible spectrum
- **Gamut** or **Color Space**
  - The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

# Light Mixing



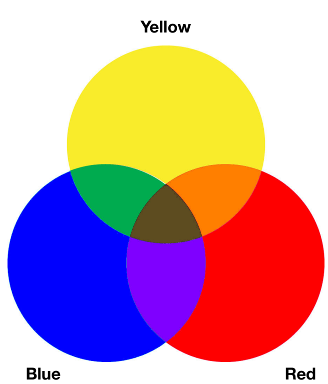

- **Additive** mix of colored lights
  - Add up wavelengths of light to make new colors
- Primary: RGB
- Secondary:
  CMY (cyan, magenta yellow)
- Neutral = R + G + B
- Commonly used by monitors, projectors, etc.

# Ink Mixing




- **Subtractive** mix of transparent inks
  - Start with white and other wavelengths are selectively filtered.
- Primary: CMY
- Secondary: RGB
- ~Black: C + M + Y
- In practice, we use CMYK, with some amount K of black ink, to get true black

# Paint Mixing

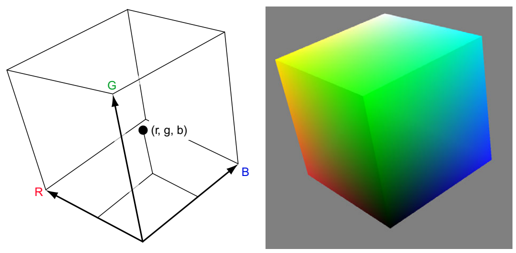



- Physical mix of opaque paints that reflect light
- Primary: RYB
- Secondary: OGV
- Neutral: R + Y + B
- Additive or Subtractive?

# Color Spaces

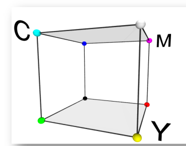
# RGB Color Space

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

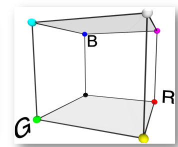



# Converting from RGB to CMY

- 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

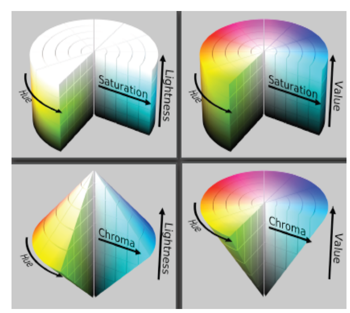
- Assuming CMY values are normalized (all channels between [0,1]), the exact same color in CMYK is

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

- 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

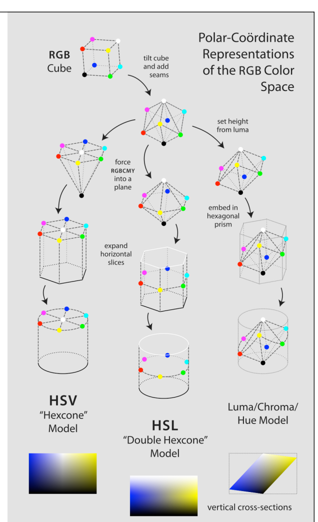
- **H**ue - what people think of as color
- **S**aturation - purity, distance from grey
  - Also called **C**hroma
- **L**ightness - from dark to light
  - Also **B**rightness or **V**alue




# 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

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

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

$$B = \max.$$

**Note: this method returns H as a value betweeen 0° and 360°**

# Encoding Color Images

- Could encode 256 colors with a single unsigned byte. But what convention to use?
- One of the most common is to use 3 **channels** or bands
- Red-Green-Blue or RGB color is the most common -- based on how color is represented by lights.
- Coincidentally, this just happens to be related to how our eyes work too.

**NOTE : There are many schemes to represent color, most use 3 channels, but the same idea extends to >3 channels**

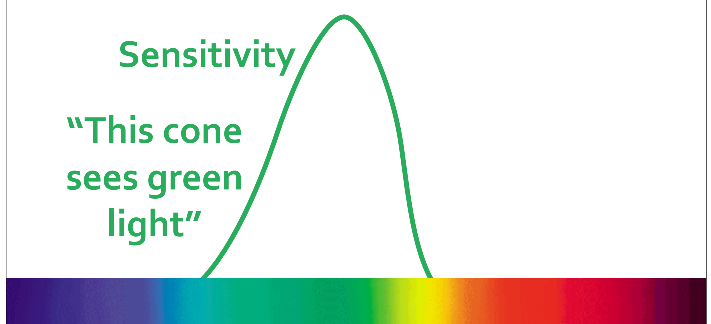
```
//separate channel encoding
let red_pixmap = new Uint8Array(ROWS*COLS);
let green_pixmap = new Uint8Array(ROWS*COLS);
let blue_pixmap = new Uint8Array(ROWS*COLS);

//all together, could use an 32-bit uint,
//by standard convention we have 4 channels
let rgb_pixmap = new Uint8Array(4*ROWS*COLS);

//access colors
let index = COLS*r + c;
rgb_pixmap[4*index + 0];  //red
rgb_pixmap[4*index + 1];  //green
rgb_pixmap[4*index + 2];  //blue

//can we do better???  What about OOP?
```

Recall: RGB Pixmap Encoding Options

# Approximating Human Vision With Color Spaces

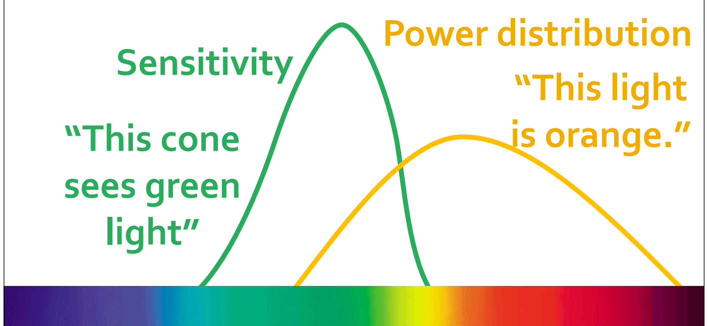
## From Sensitivity To Response

**Slides from Justin Solomon**



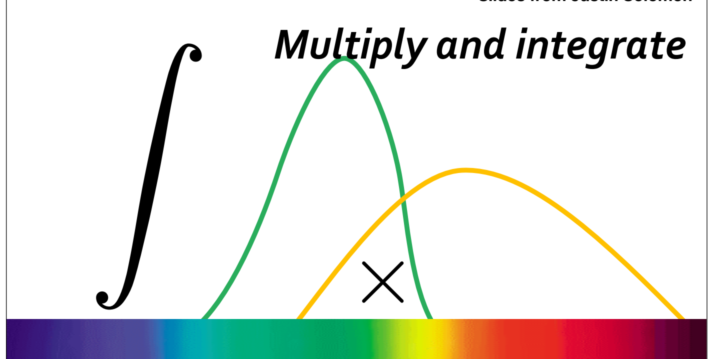

## From Sensitivity To Response

**Slides from Justin Solomon**



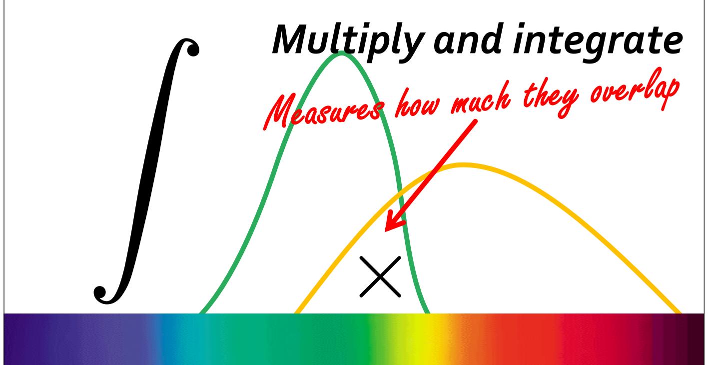

## From Sensitivity To Response

**Slides from Justin Solomon**



## From Sensitivity To Response

Slides from Justin Solomon




## From Sensitivity To Response

Slides from Justin Solomon

$$L = \int_\lambda \Phi(\lambda) \boxed{L(\lambda)}\, d\lambda$$

$$M = \int_\lambda \Phi(\lambda) \boxed{M(\lambda)}\, d\lambda$$

$$S = \int_\lambda \Phi(\lambda) \boxed{S(\lambda)}\, d\lambda$$

Sensitivity

**Tristimulus Values**

## From Sensitivity To Response

Slides from Justin Solomon

Power distribution

$$L = \int_\lambda \boxed{\Phi(\lambda)} L(\lambda)\, d\lambda$$

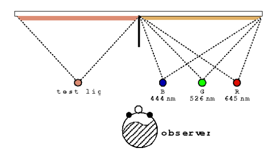
$$M = \int_\lambda \boxed{\Phi(\lambda)} M(\lambda)\, d\lambda$$

$$S = \int_\lambda \boxed{\Phi(\lambda)} S(\lambda)\, d\lambda$$

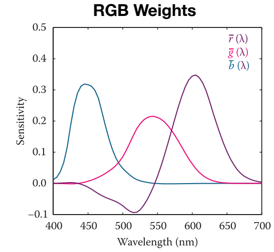
**Tristimulus Values**

## Tristimulus Experiment

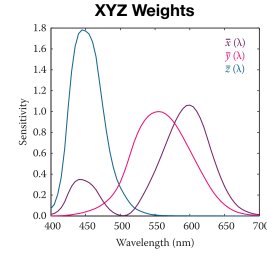
- Color Matching Experiment in 1931
- CIE = International Commission on Illumination (Commission internationale de l'éclairage)
- Since some weighting factors for R,G,B lights are negative, they computed a new set of weights for a new of components X,Y,Z




**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:

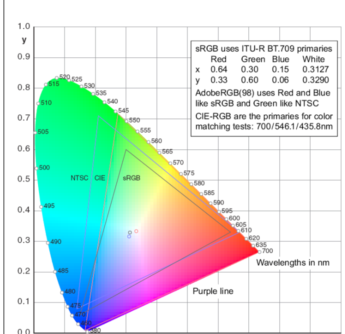
x = X / (X + Y + Z)

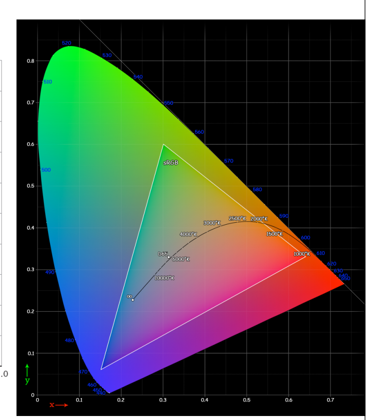
y = Y / (X + Y + Z)

Y = luminance

## CIE Space

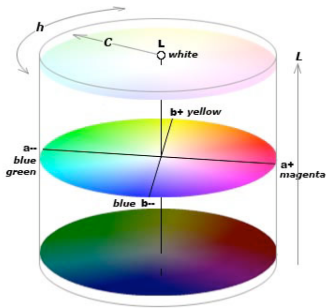
**Note: Colors outside the triangle cannot be accurately displayed!**



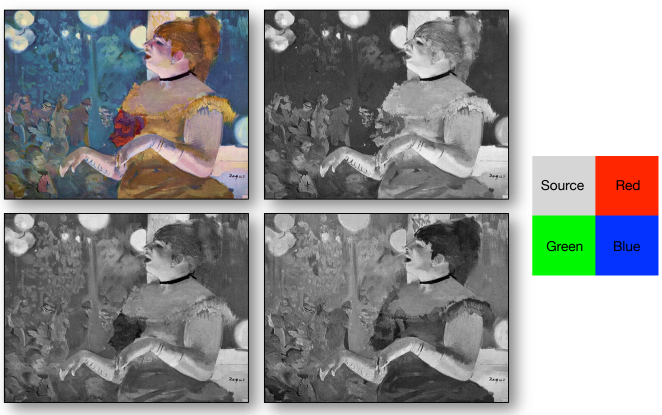
# CIELab/Luv

- 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)

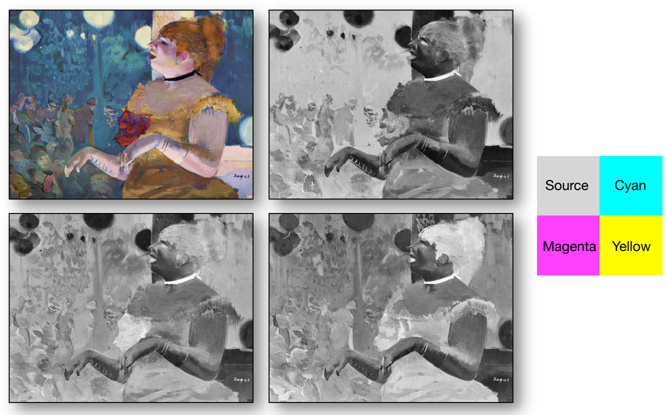



# A Comparison of Color Spaces

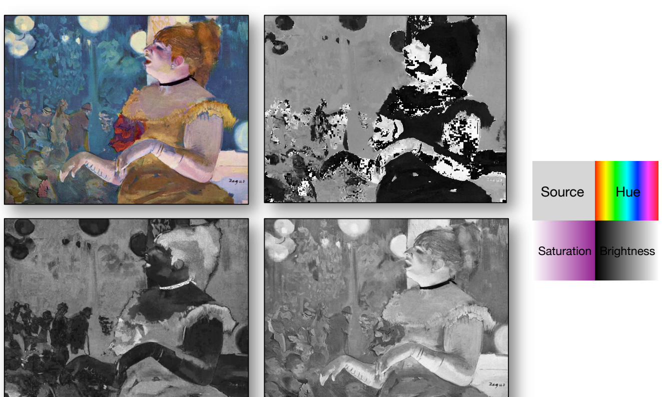
# Example RGB Color Space



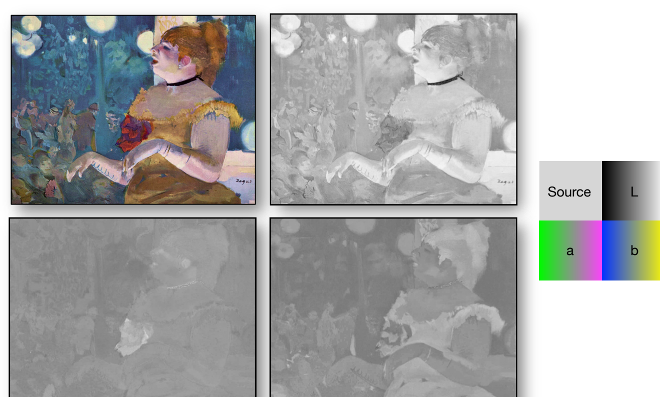

# Example CMY Color Space




# Example HSV Color Space

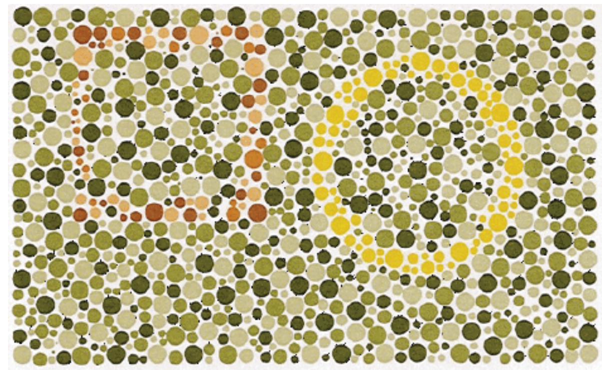



# Example CIELab Color Space

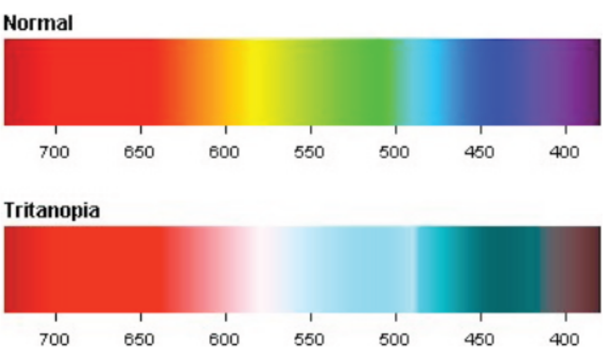


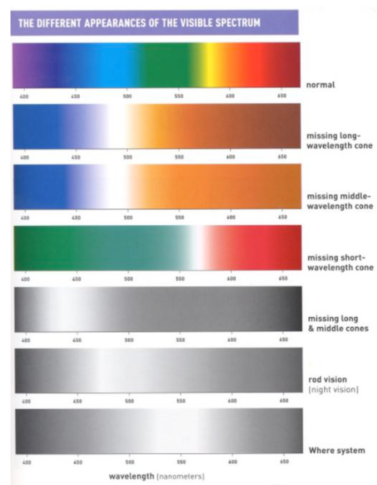
# Understanding Color Perception

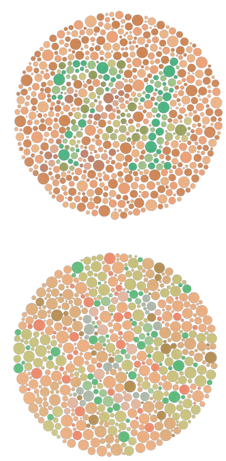
# RG Color Blindness



# BY Color Blindness

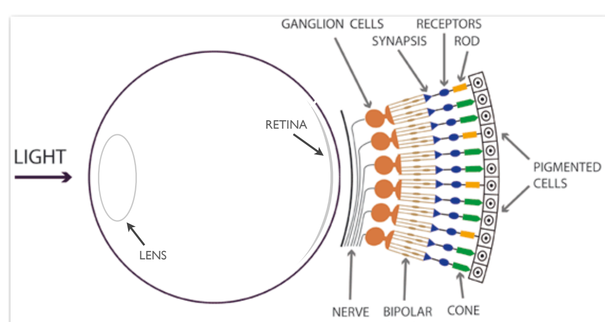


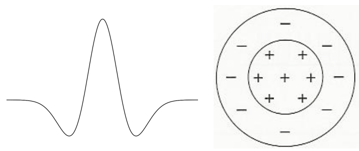



# Color Illusions

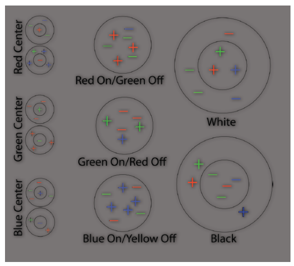
# Recall: Physiology of the Eye

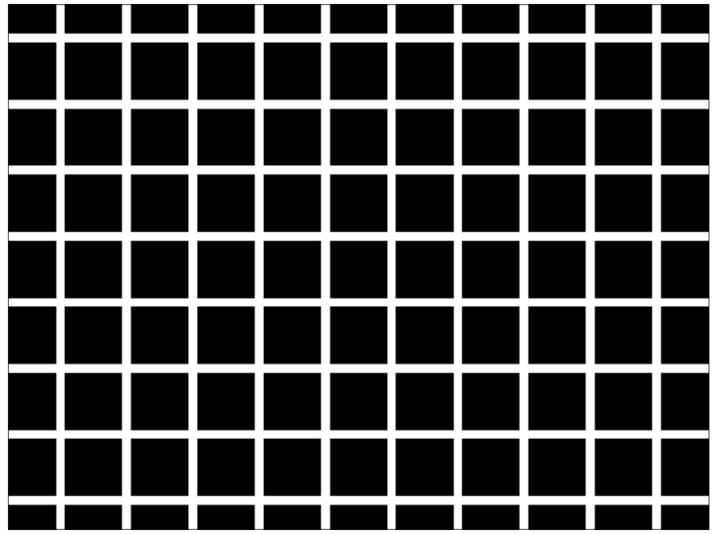


# Color Illusions

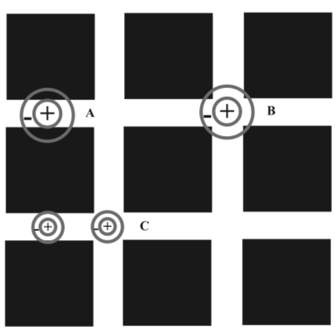


- Primary cause: the Retinal Ganglion Response
- Triggered by light in the center, suppressed by light in the surround
- Causes selective sensitivities to discontinuities in color as well.



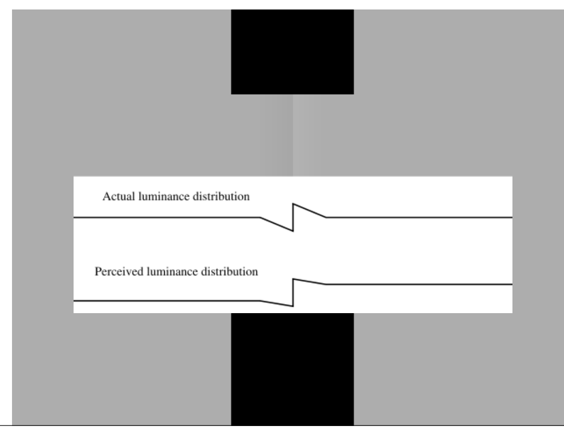



# Hermann grid effect (Brightness Adaptation)

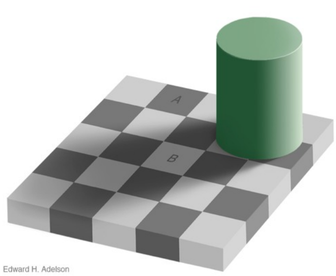



Annie Prud'homme-Généreux

# Cornsweet Illusion



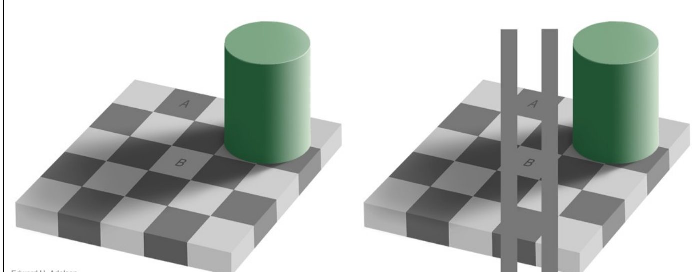

# Simultaneous Contrast




- 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

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## Simultaneous Contrast

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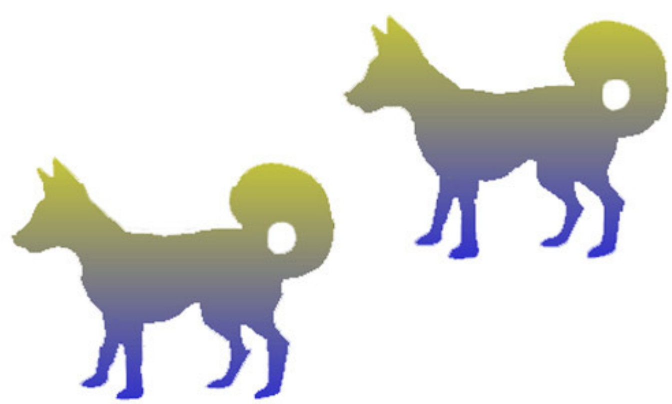
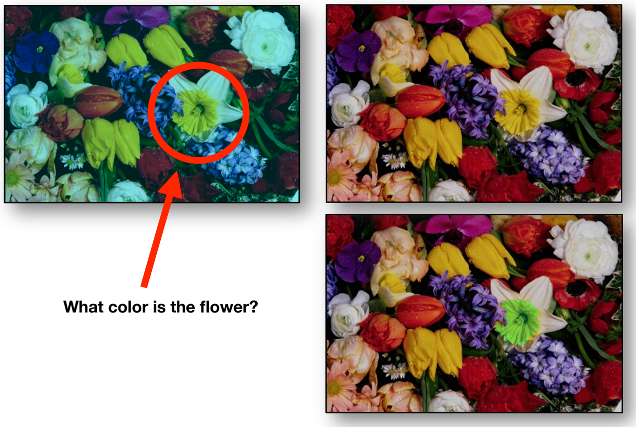
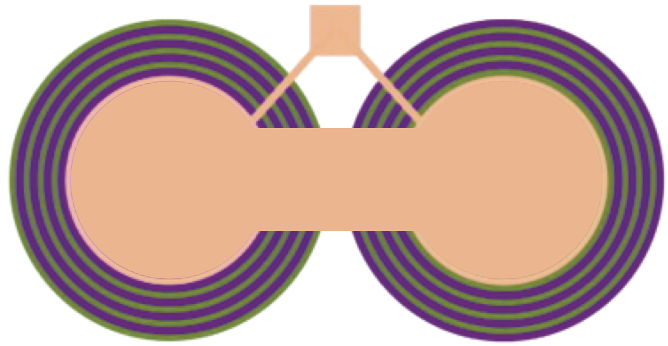


# Chromatic Adaptation

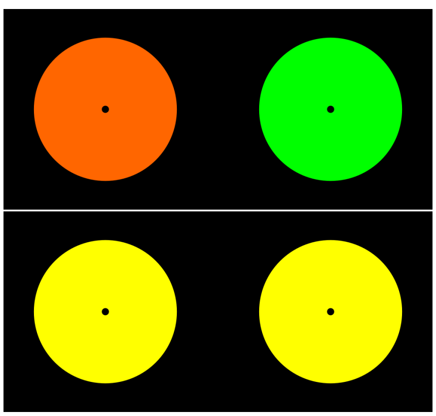



# Chromatic Induction



P. Monnier

# Successive Contrast



# Next Lecture - Required Reading

- FOCG, Ch. 9 (Particularly 9.1-9.2)
- See also optional readings!