CS49000-VIZ - Fall 2020

Introduction to Data Visualization

Vision and Color Perception

Lecture 3

September 1, 2020

Slides acknowledgment: P. Rheingans (UMBC) and A. Lex (Utah)

Outline

- Preamble: human vision
- Physiological basis of color perception
- Color vision models
- Color spaces

Functions of Human Vision

- Shape/size
- Depth
- Motion
- Recognition

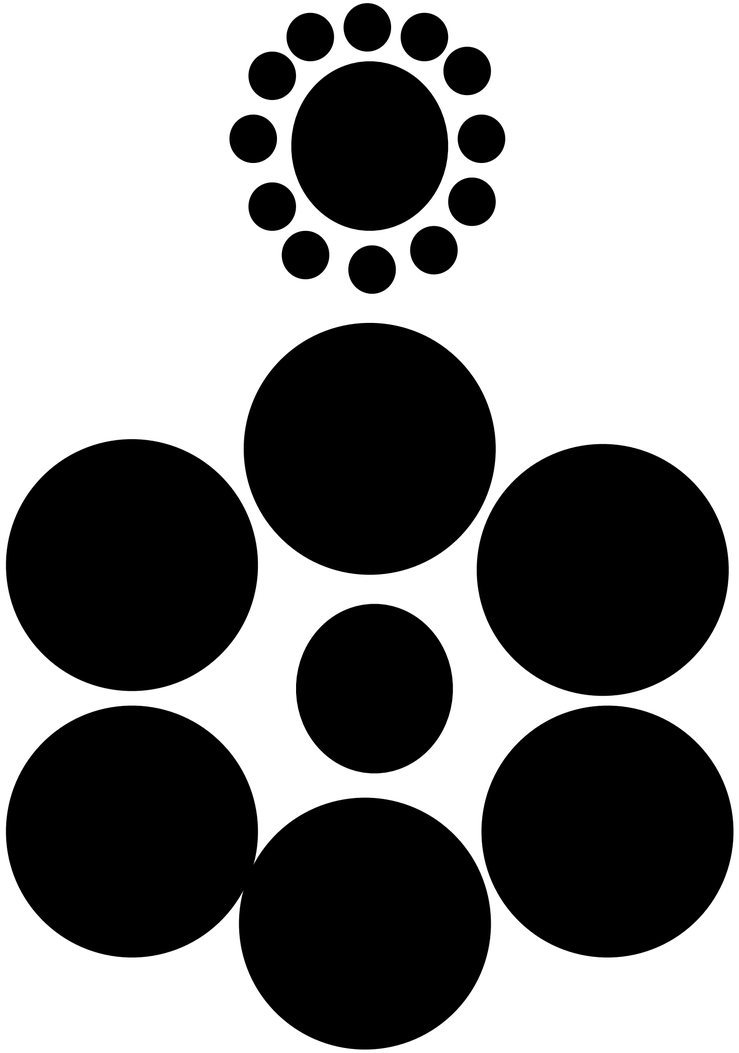
Properties of Vision

More accurate than other senses

- Location, size, and identification at a distance

But…

Perceived Sizes Are Relative



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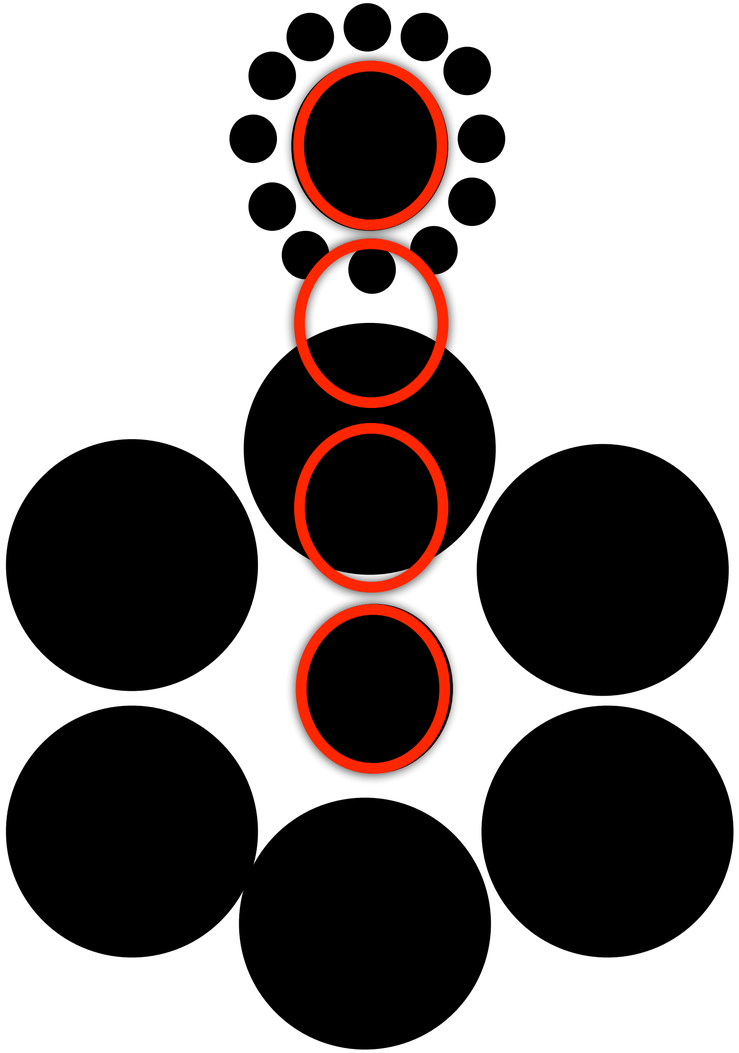
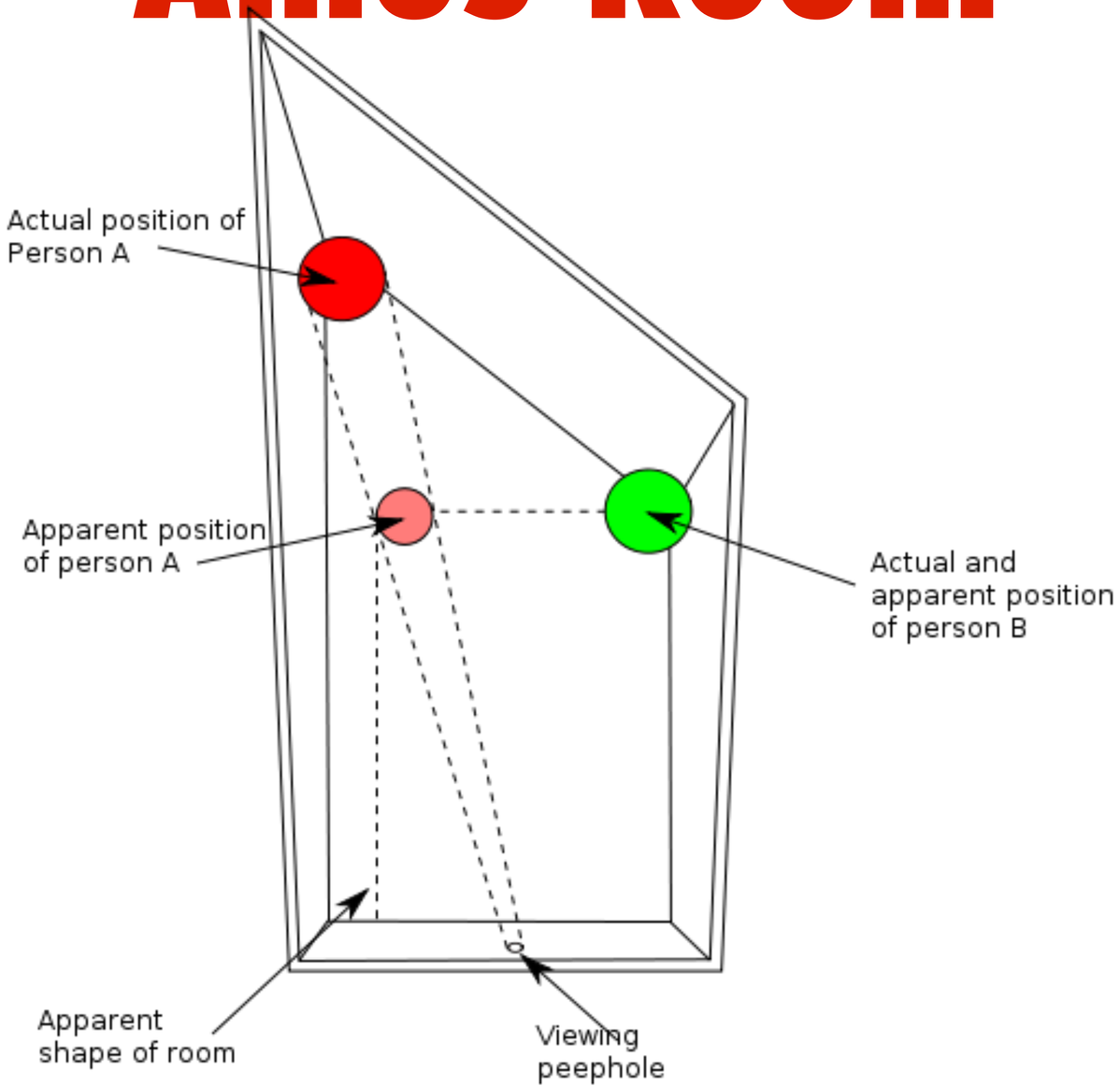
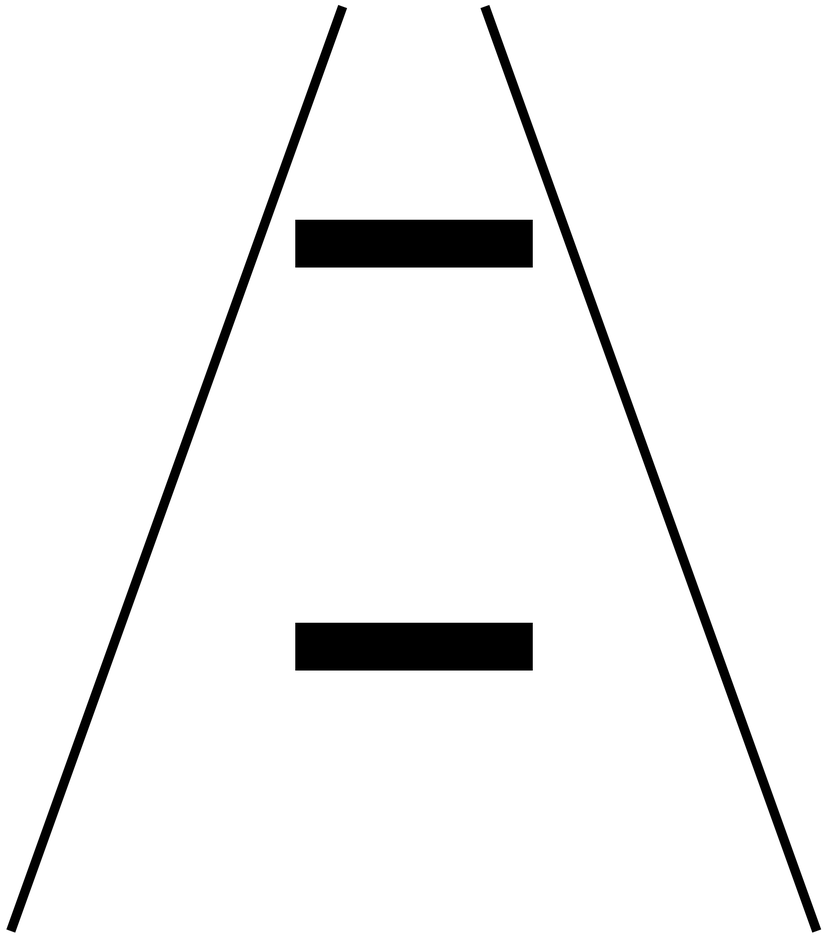


Ames Room


Actual position of
Person A
Apparent position
of person A
Actual and
apparent position
of person B
Apparent
shape of room
Viewing
peephole

Ponzo Illusion



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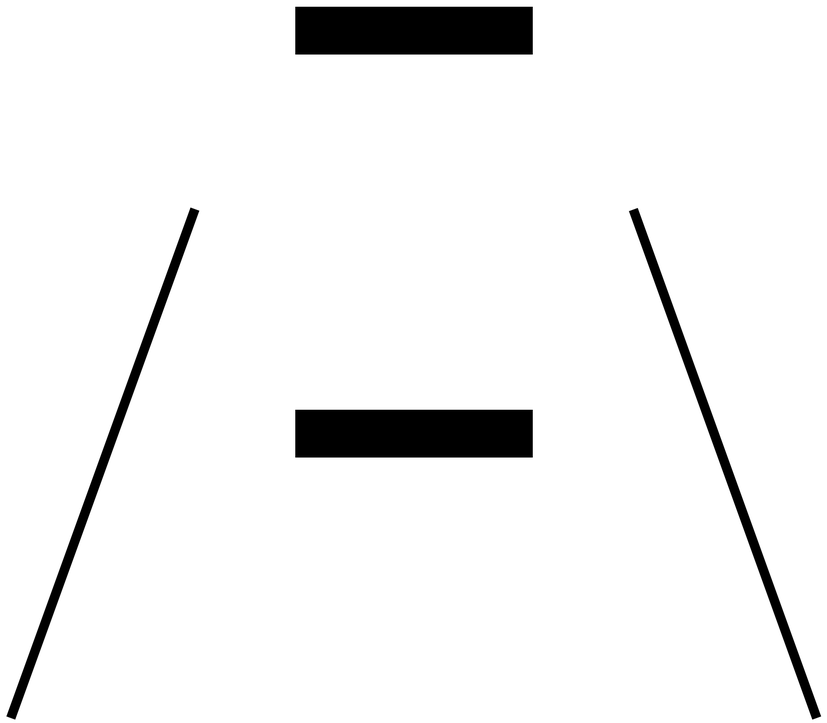
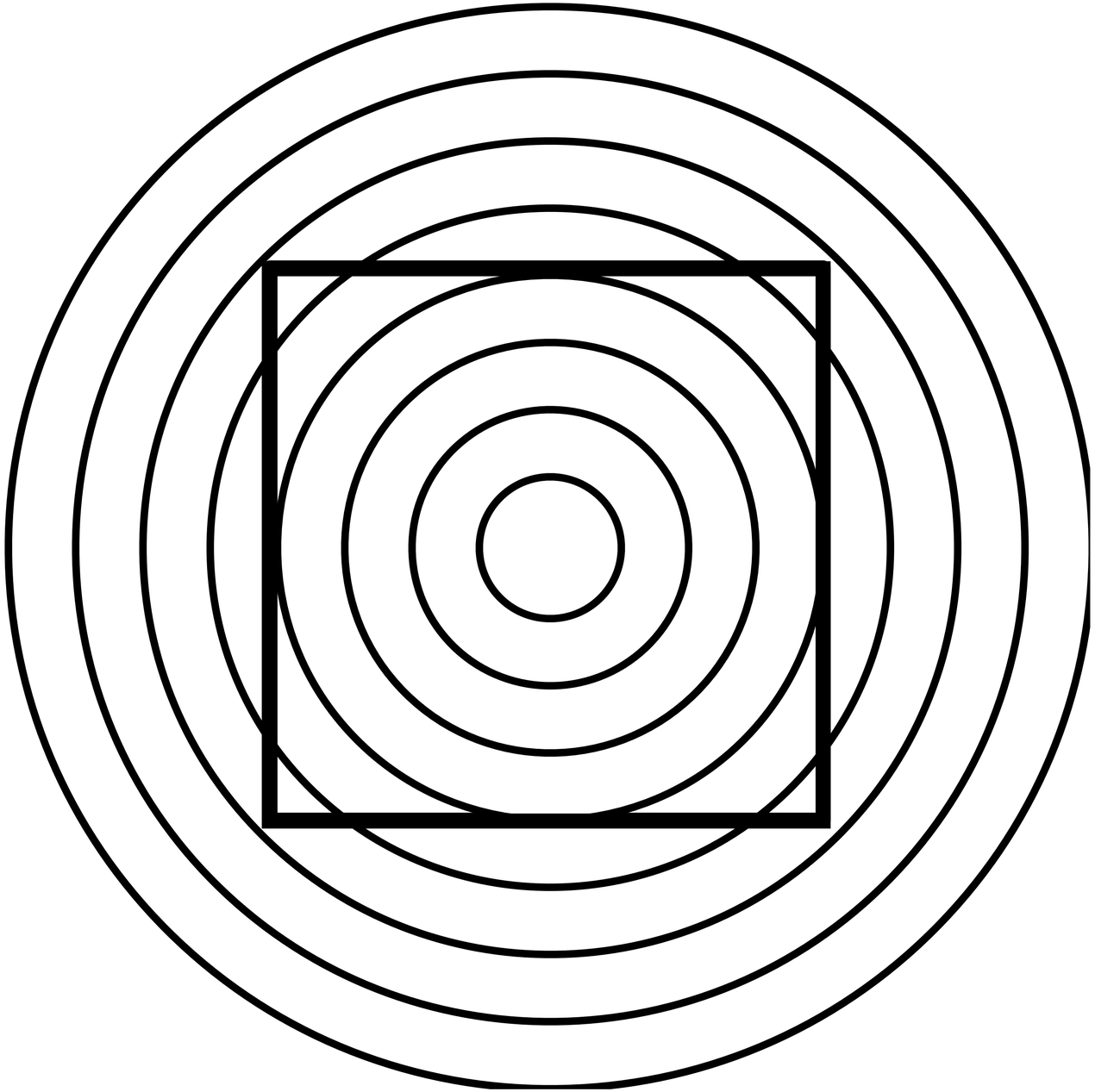
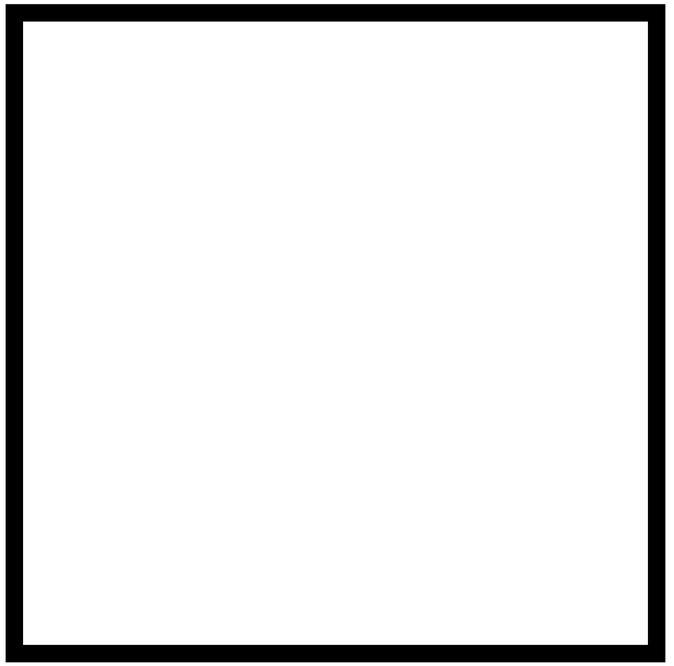






Properties of Vision

Limitations

truthful

- V*eridical* perception is limited
- Absolute judgments are often poor
- Lack of quantification

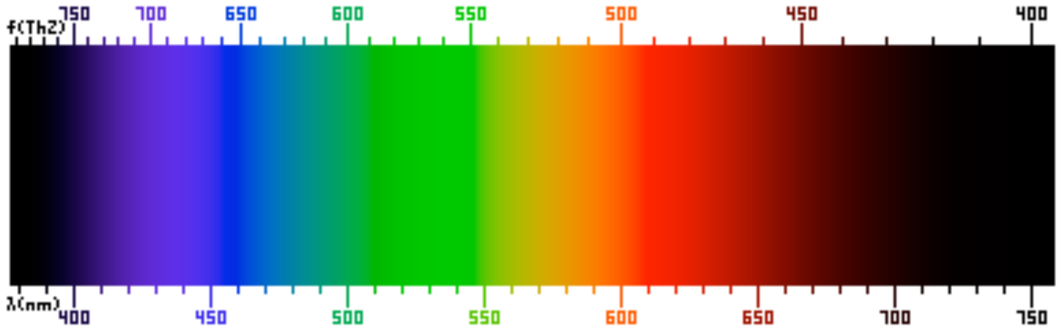
Properties of Vision

Good at

- Relative judgments
- Time and space
- Identification

Light

- Visible range: 390-700nm
- Luminance has a large dynamic range
- Colors result from spectral curves
  - dominant wavelength, hue
  - brightness, lightness
  - purity, saturation



Light

light energy per m^2

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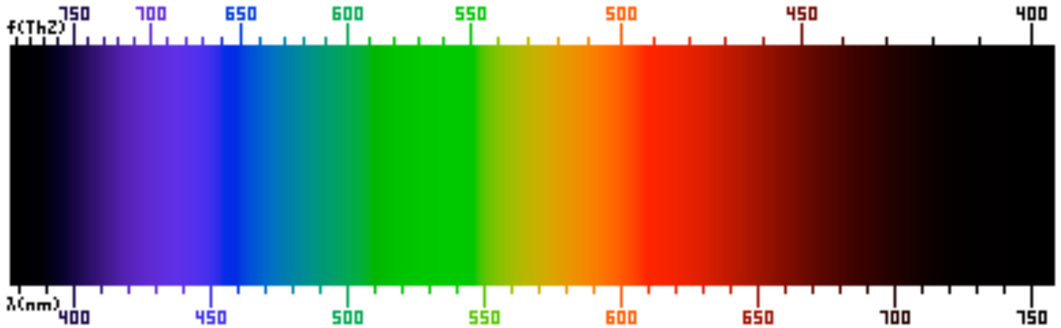
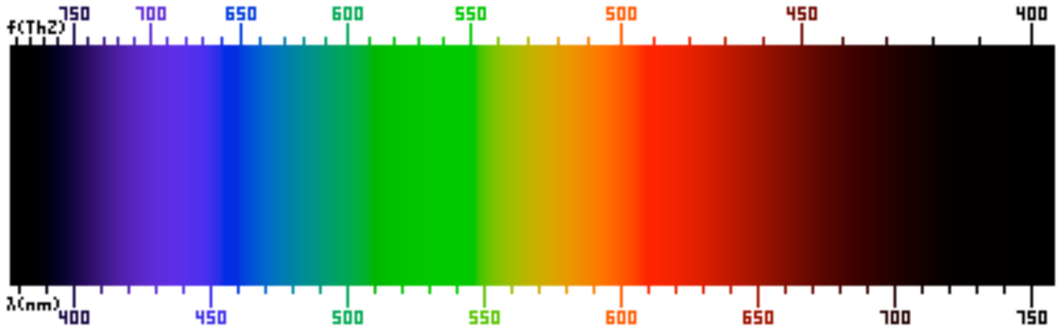


Light

- Visible range: 390-700nm
- Luminance has
- Colors result fro
  - dominant wavelength, hue
  - brightness, lightness
  - purity, saturation

- 0.00003 -- Moonless overcast night sky
- 30 -- Sky on overcast day
- 3000 -- Sky on clear day
- 16,000 -- Snowy ground in full sunlight



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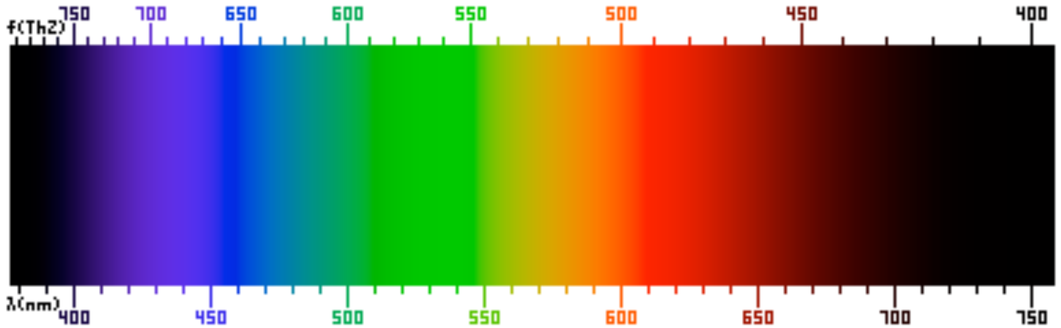
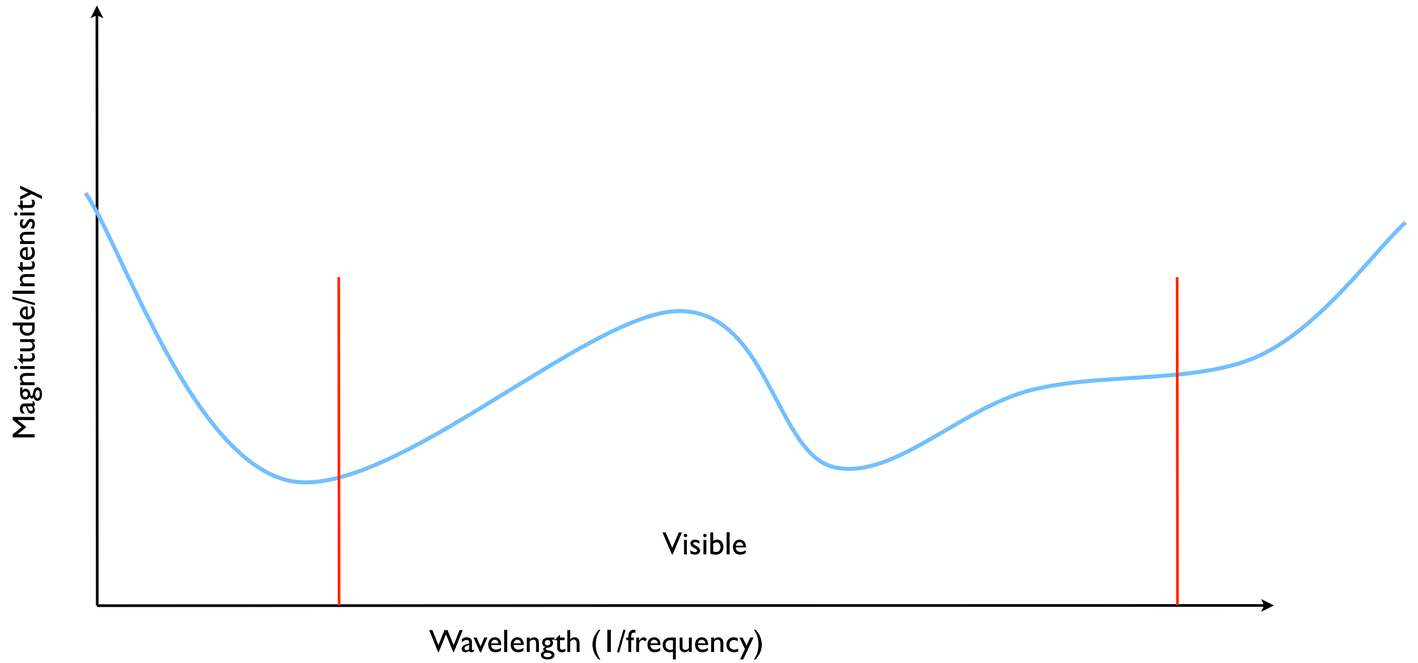
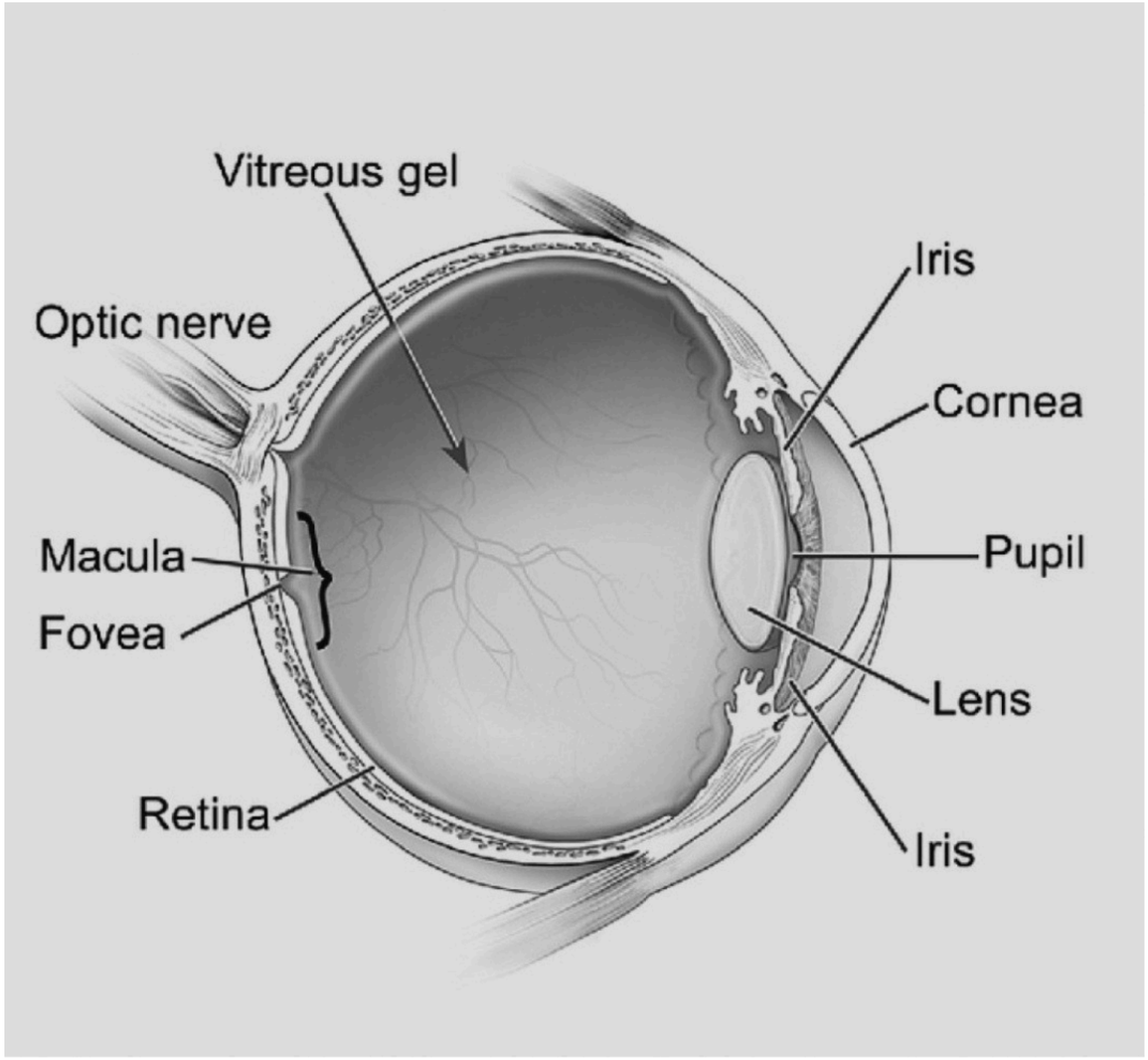


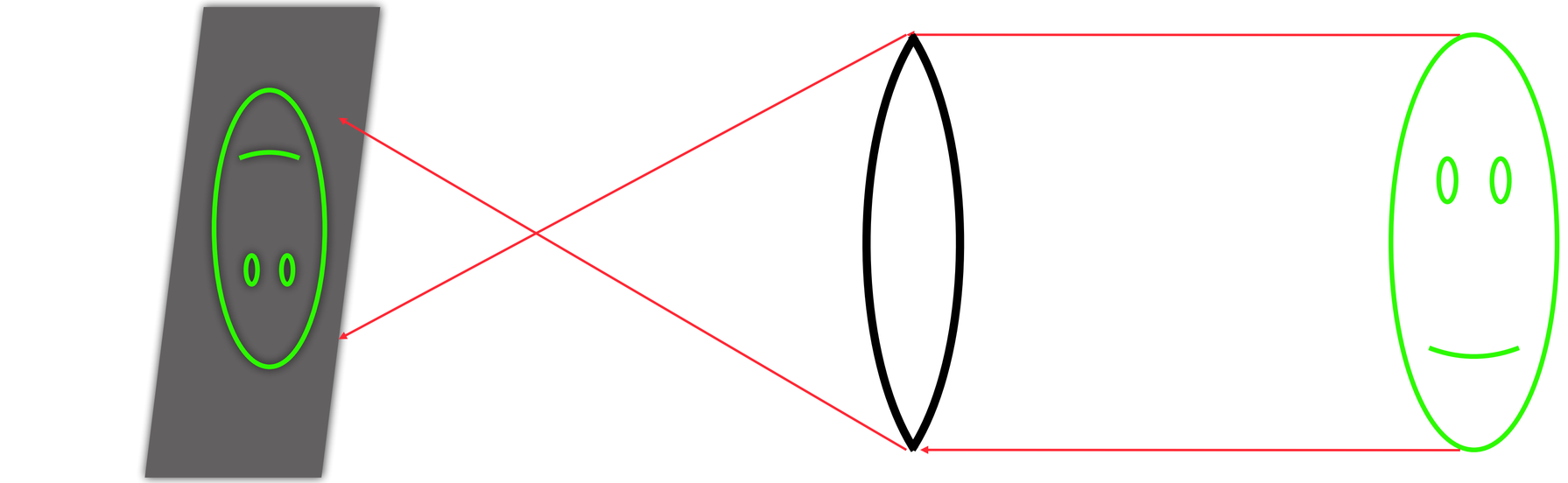
Spectral Curve (of incoming radiation)



Physiology: Eye

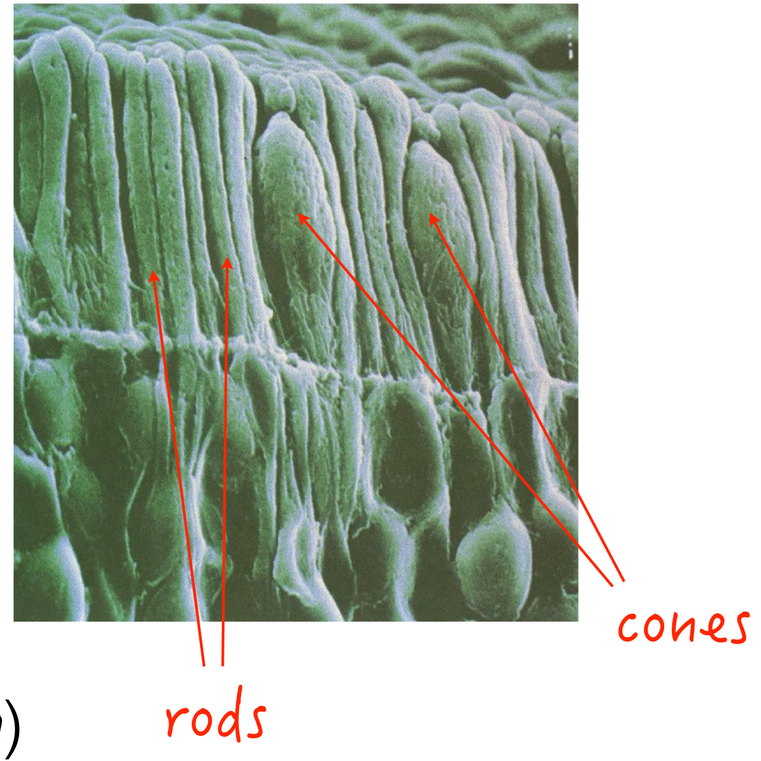


Perspective Projection and Image Formation



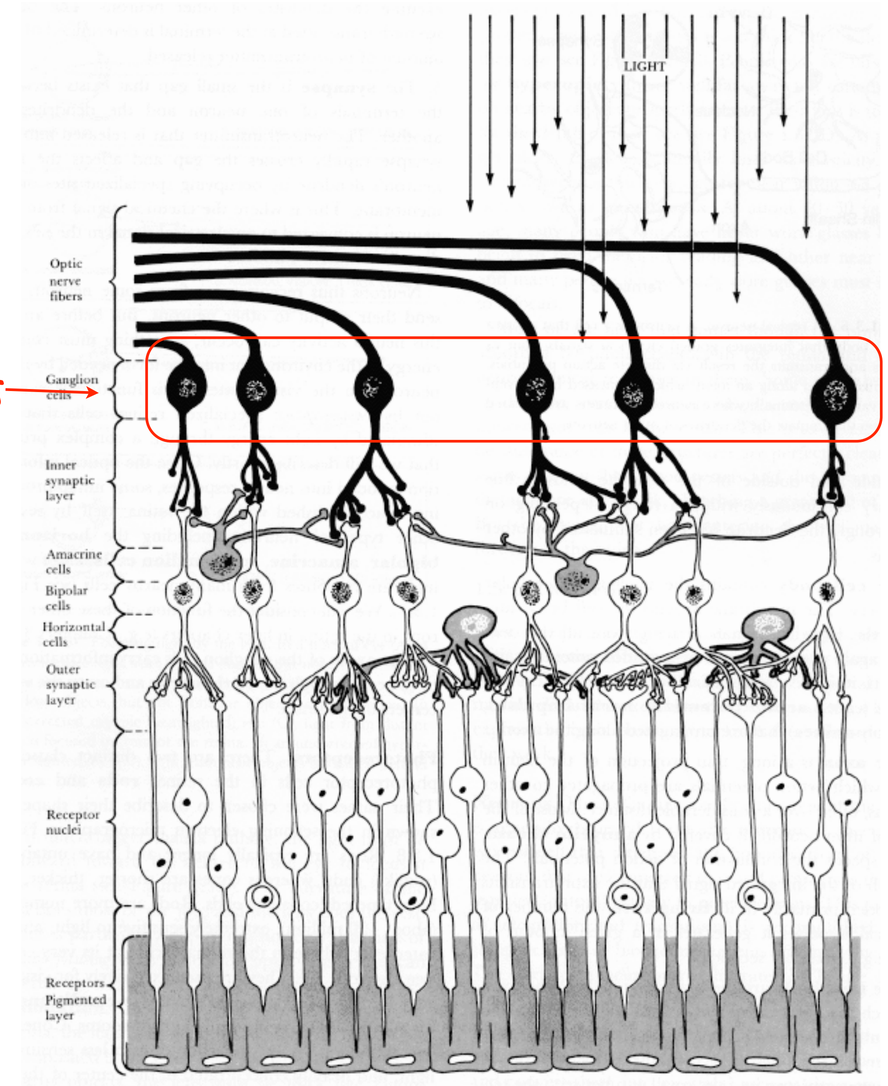
Physiology: Photoreceptors

- Discrete sensors that measure energy
  - Adaptation
- Rods ~ 120 million
  - Active at low light levels (*scotopic* vision)
  - Only one wavelength-sensitivity function
- Cones ~ 6-7 million
  - Active at normal light levels (*photoptic vision*)
  - Three types: sensitivity functions with different peaks

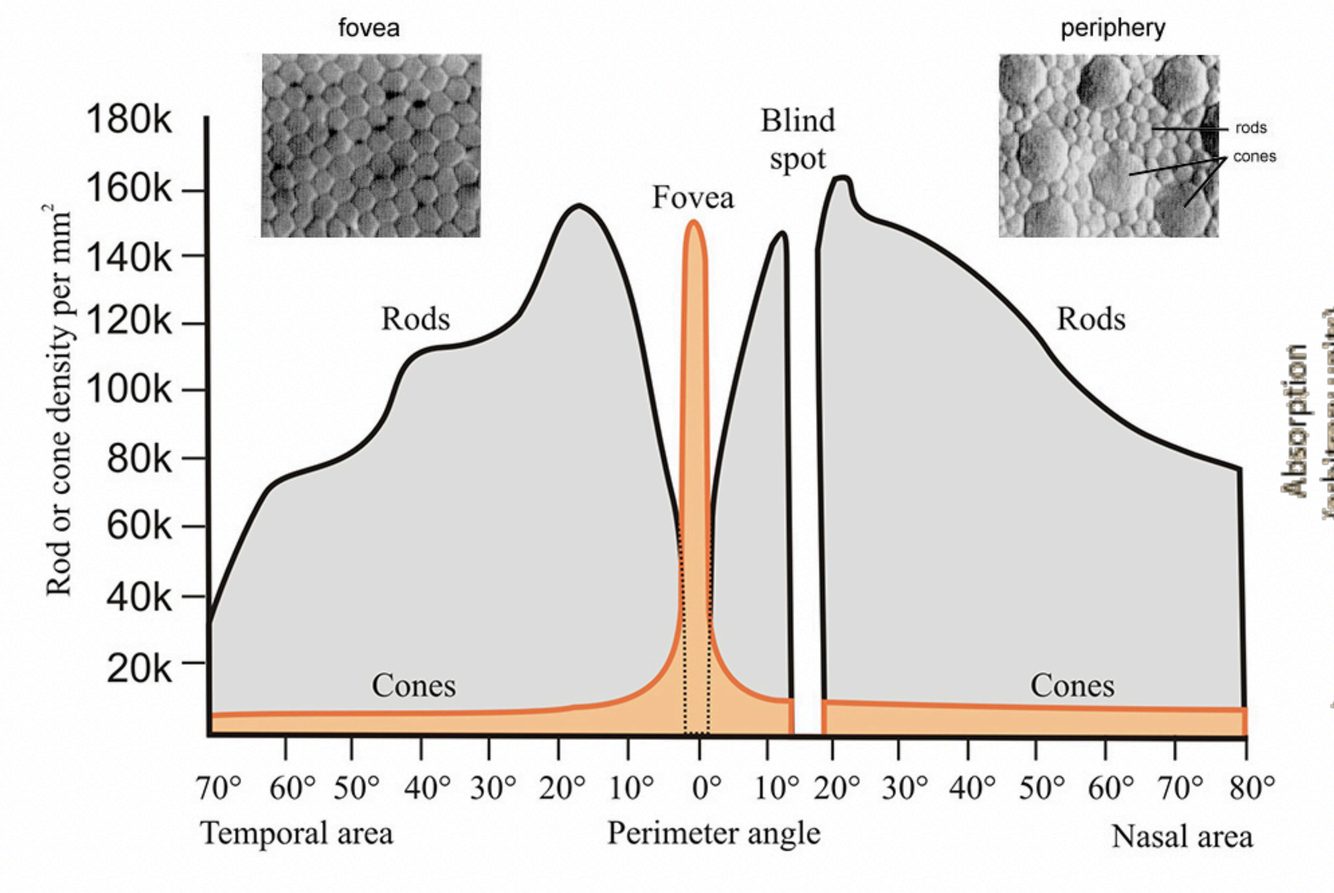


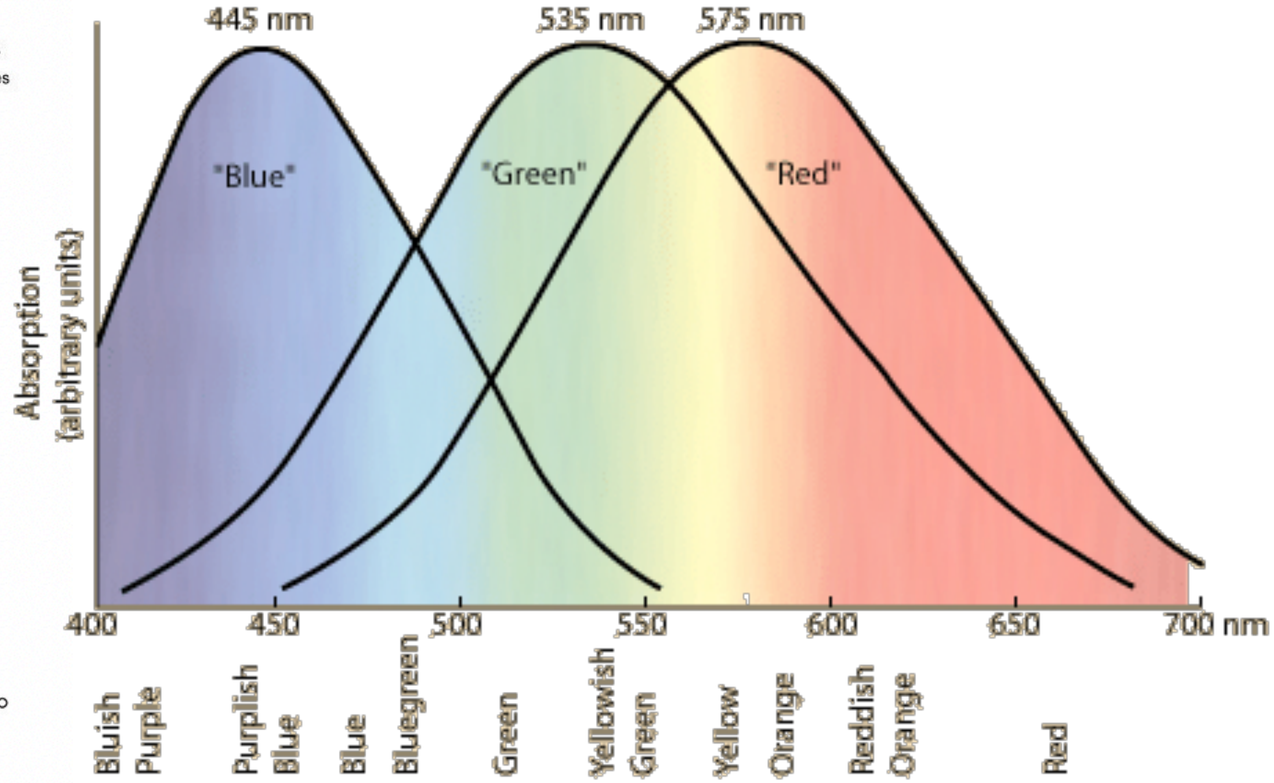
Retina

ganglion cells



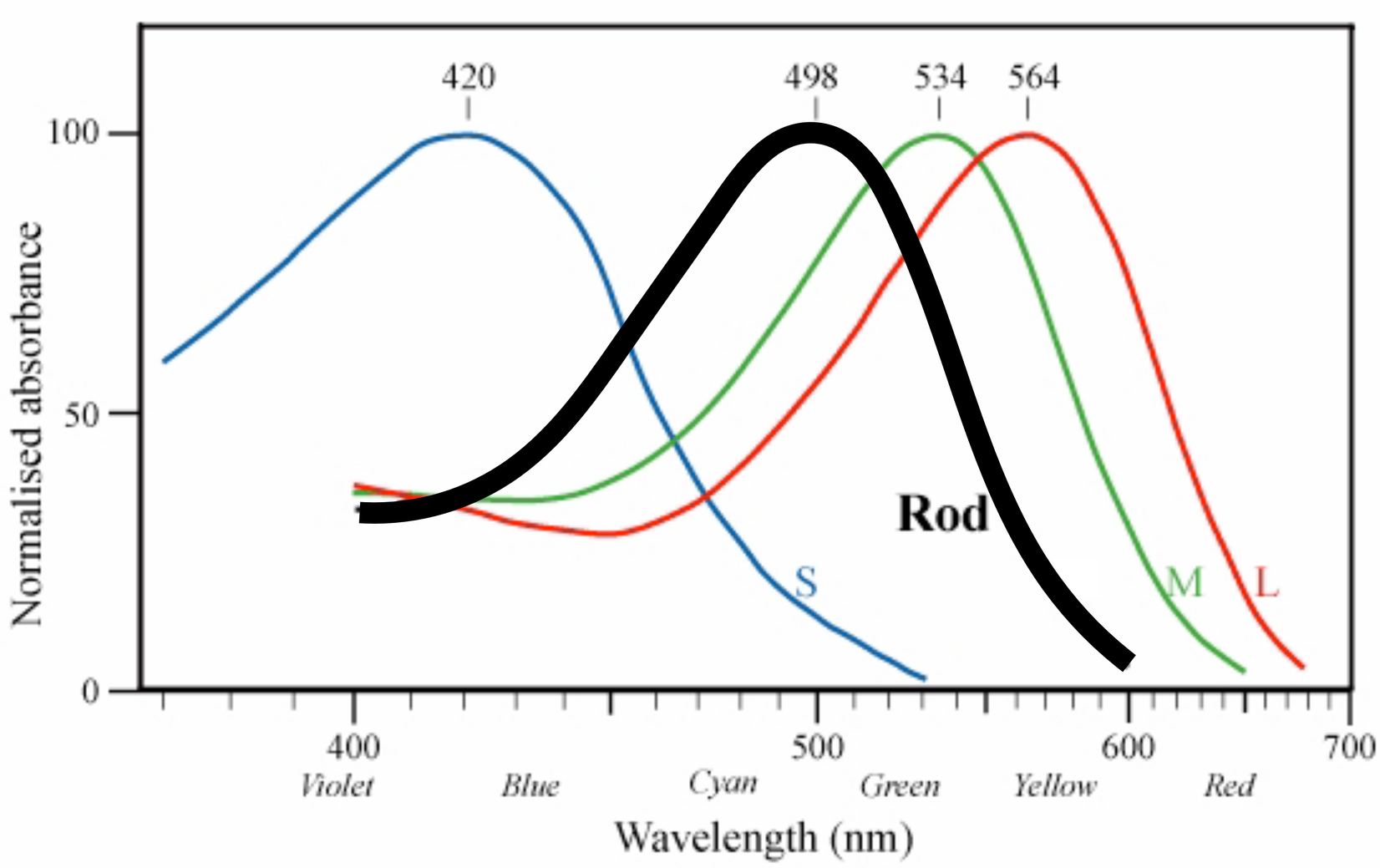
Cone Sensitivity

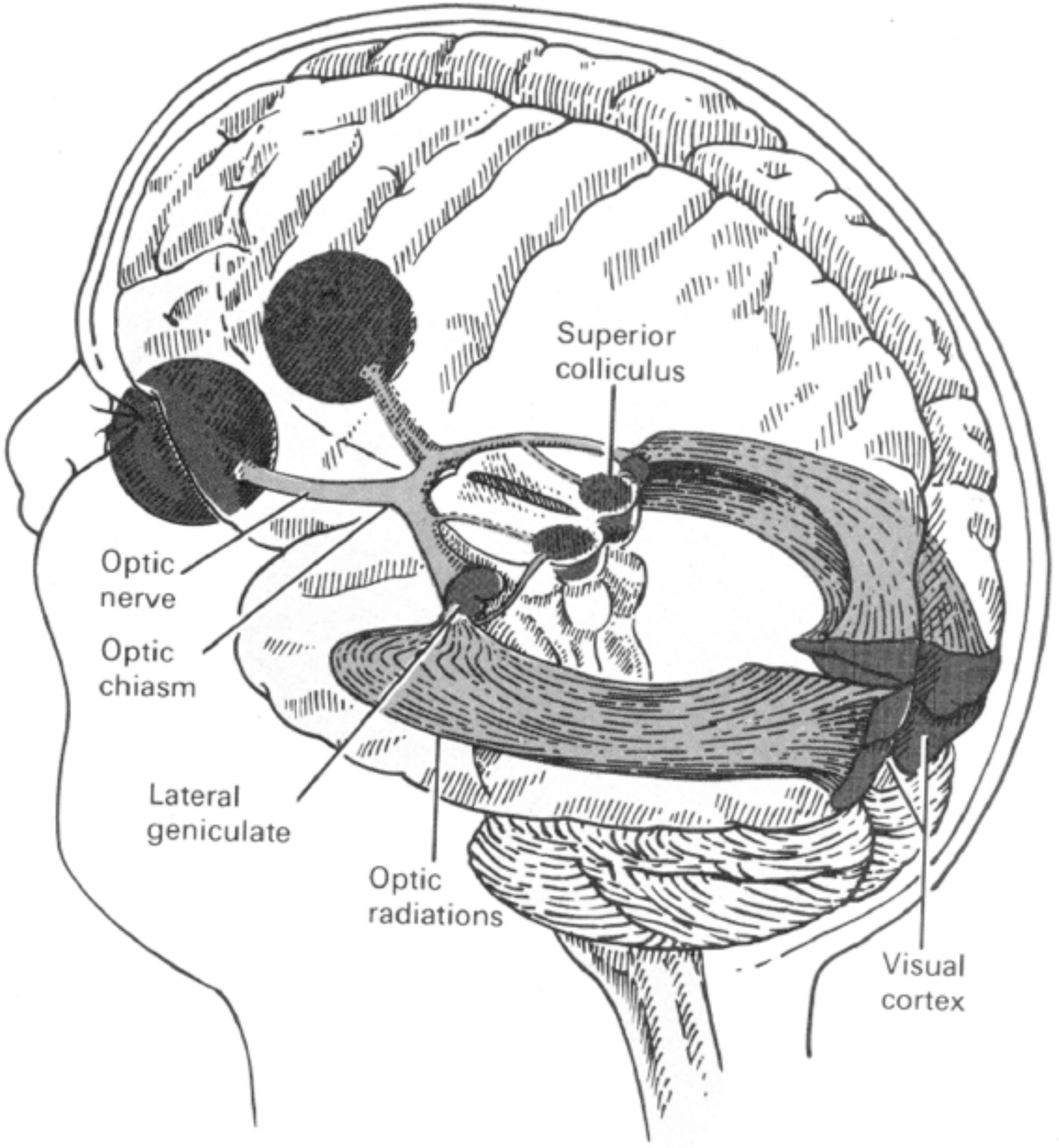




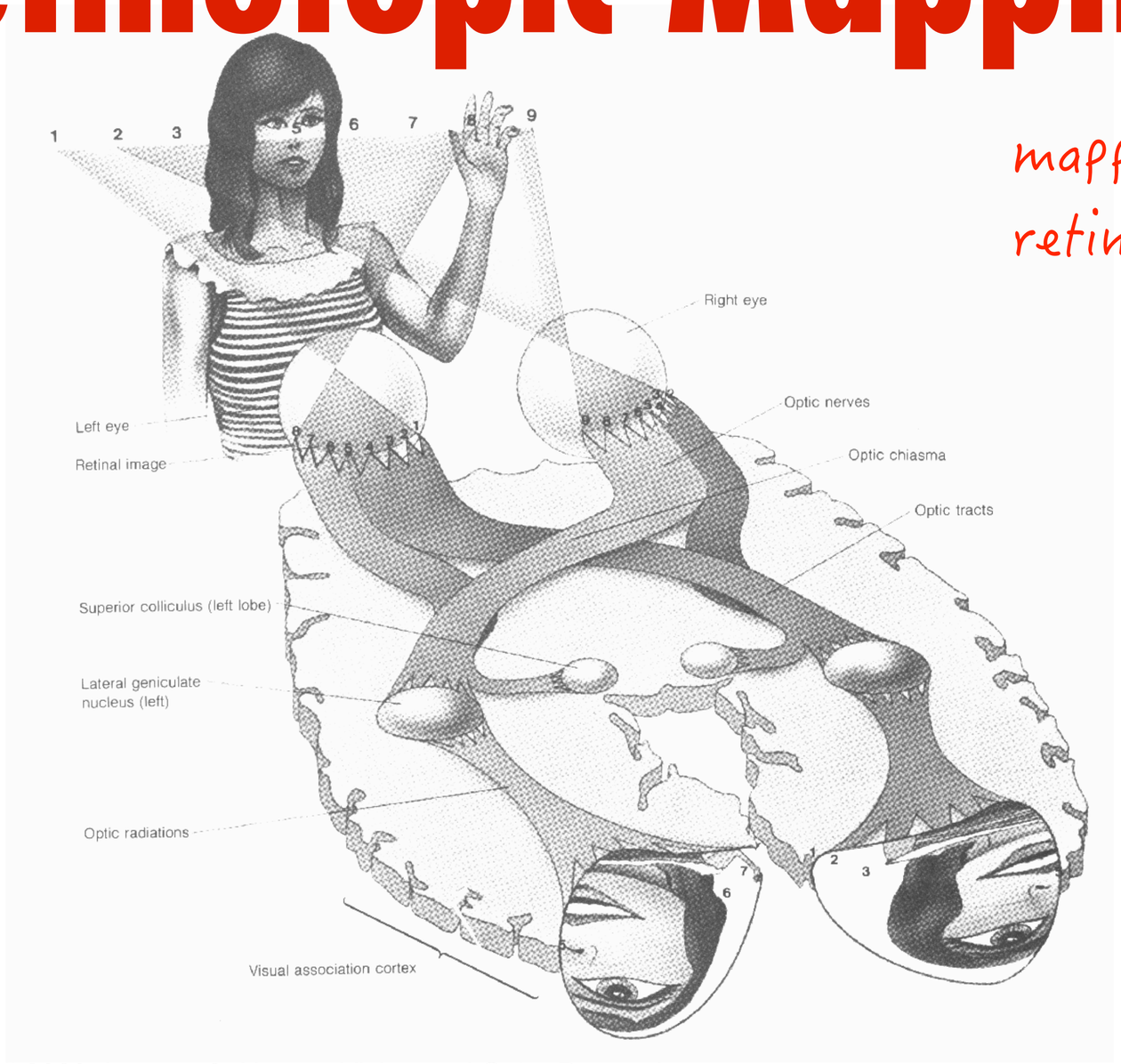
HyperPhysics, Georgia State University

Rod Sensitivity Function




Superior
colliculus
Optic
nerve
Optic
chiasm
Lateral
geniculate
Optic
radiations
Visual
cortex

Retinotopic Mapping



mapping from
retina to visual cortex

Human Gaze

- Vision made up of fixations and saccades
- Fixation: 200-600 ms
- Motion: 20-100 ms

Models of Color Vision

- Tricolor theory
- Opponent process theory

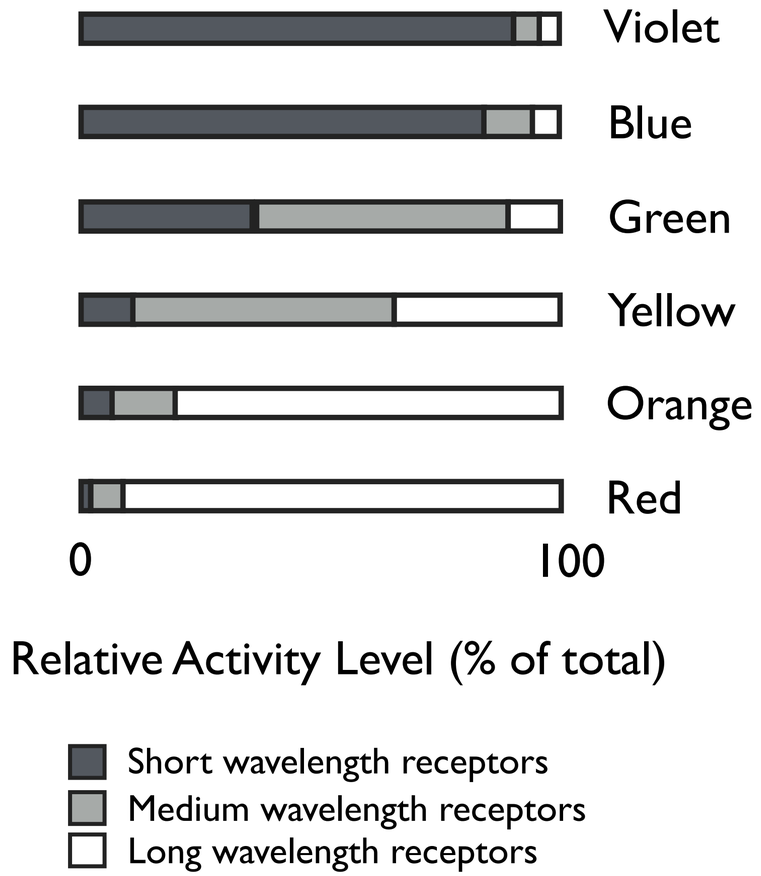
Trichromatic Theory

- Three types of cones – each with a characteristic wavelength
- Mixture of 3 responses defines color
- Explains some psychophysical data
- 3D color space (i.e. 3 colors match any perceived)

Trichromatic Theory

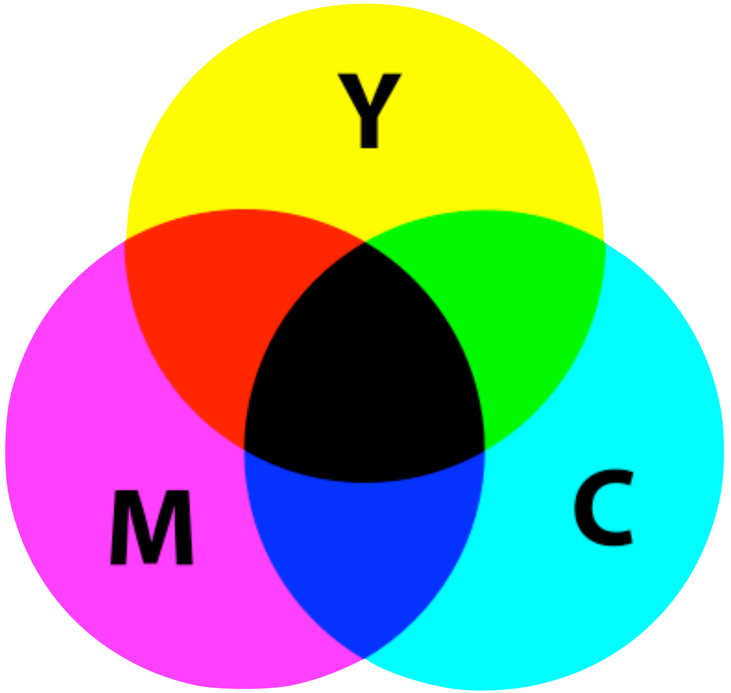
- Metamers: match of an apparent color with a different spectral distribution (3D basis)
- Color blindness (different types)

Trichromatic Theory

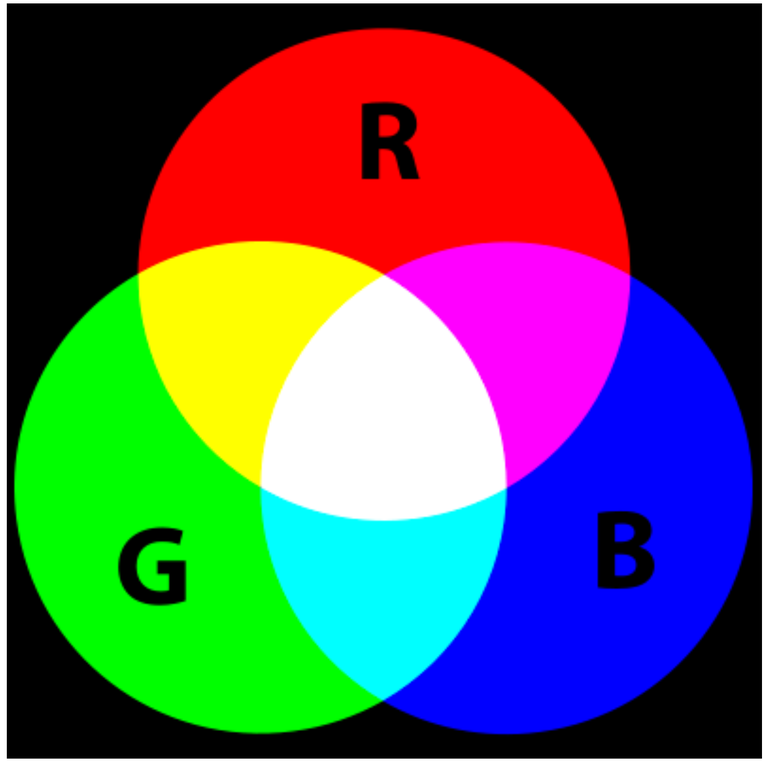


Trichromatic Theory Shortcomings

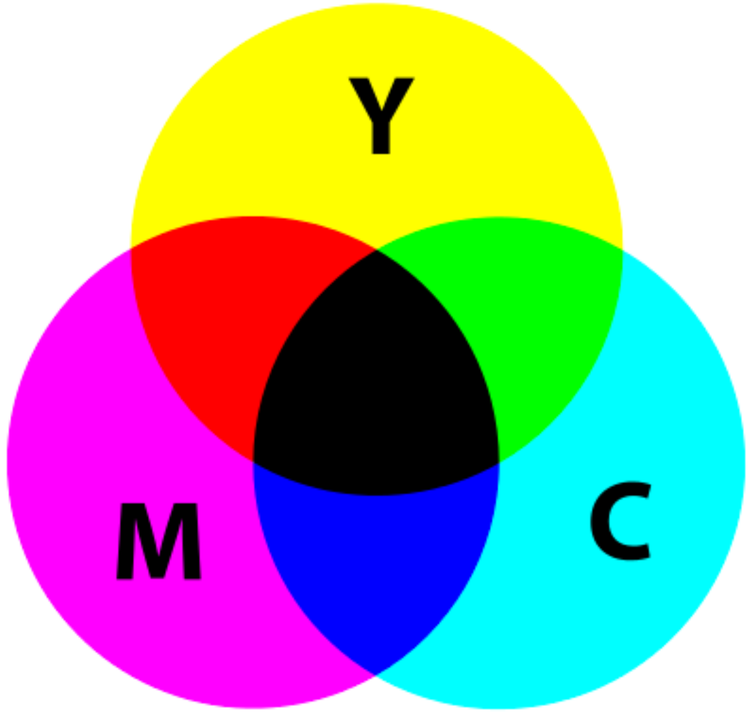
- Color blindness
  - R-G, B-Y, All
- Yellow seems primary
- Color constancy



Note: Additive vs. Subtractive Colors

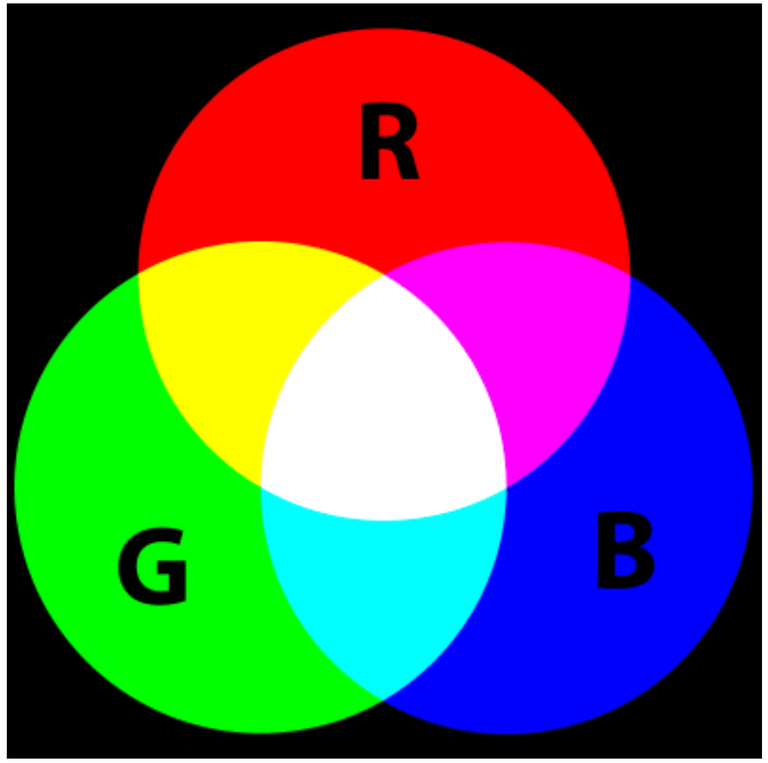


Additive



Subtractive

Note: Additive vs. Subtractive Colors

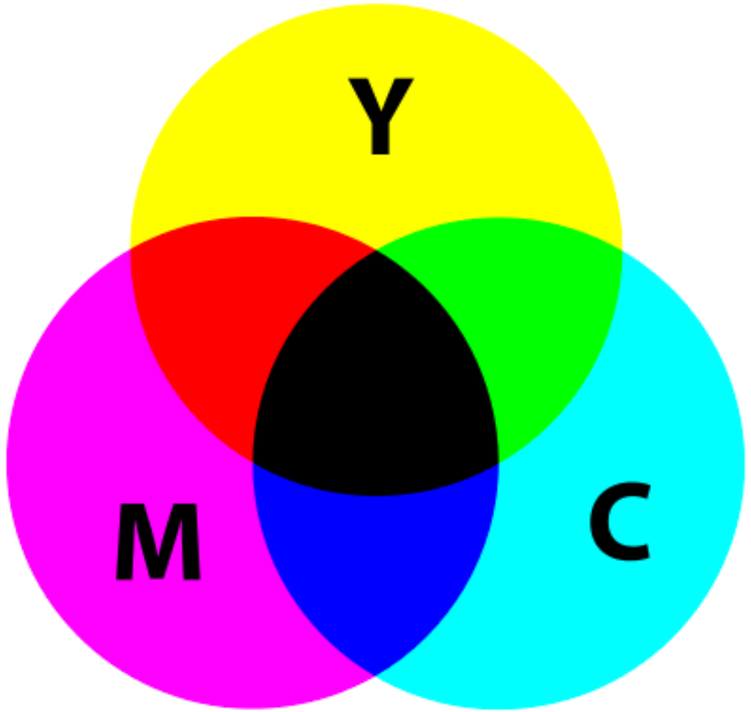


Additive coloring:
Colors are produced by combining (adding) electromagnetic radiations of different wavelength / frequency.

Example: computer screen

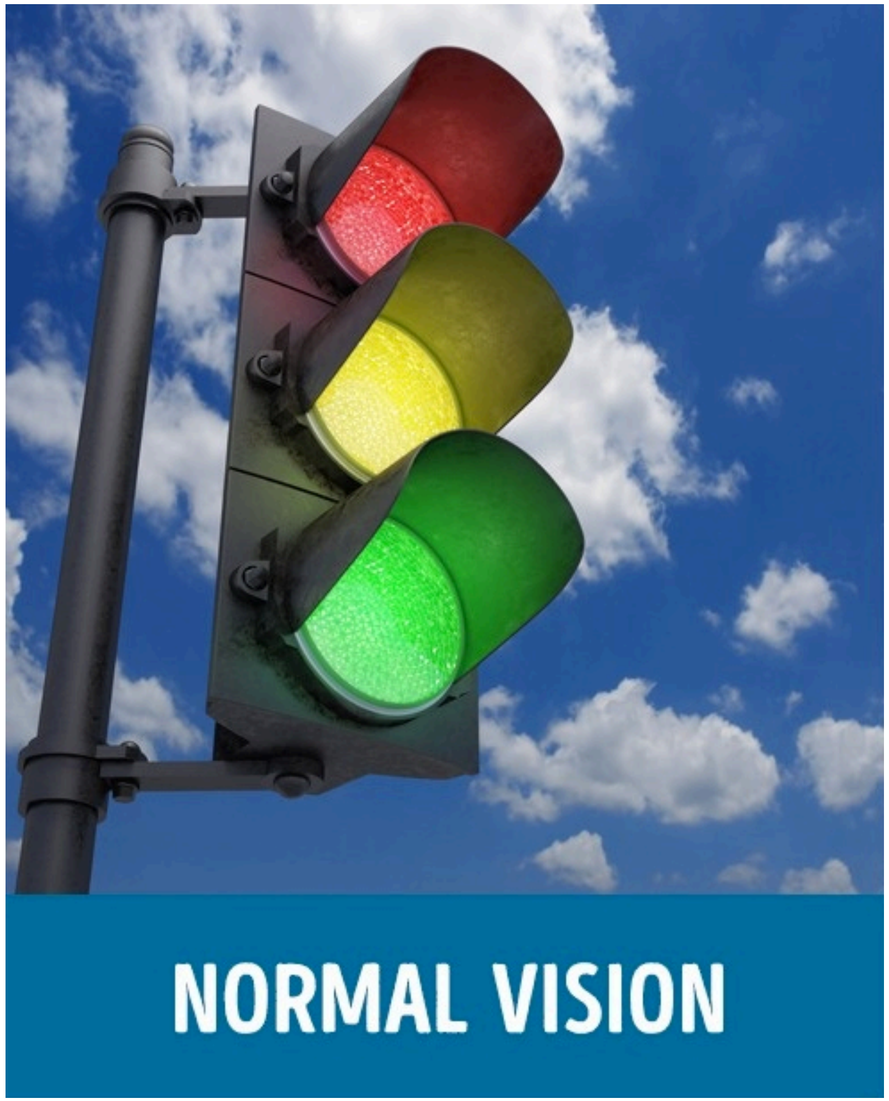
Note: Additive vs. Subtractive Colors

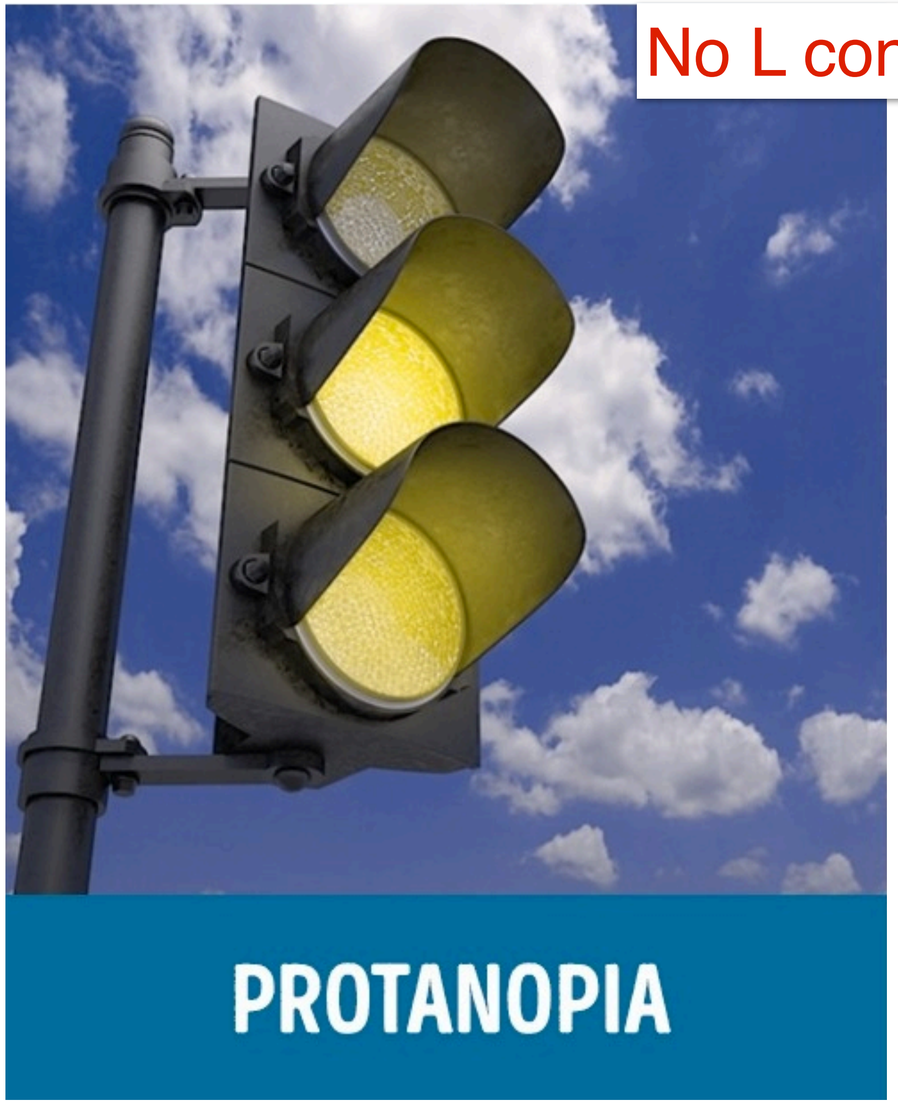
Subtractive coloring:
Colors are obtained by combining things that absorb different portions of the visual spectrum when they reflect/scatter the incoming light. Subtractive coloring defines the ***"color" of objects***.



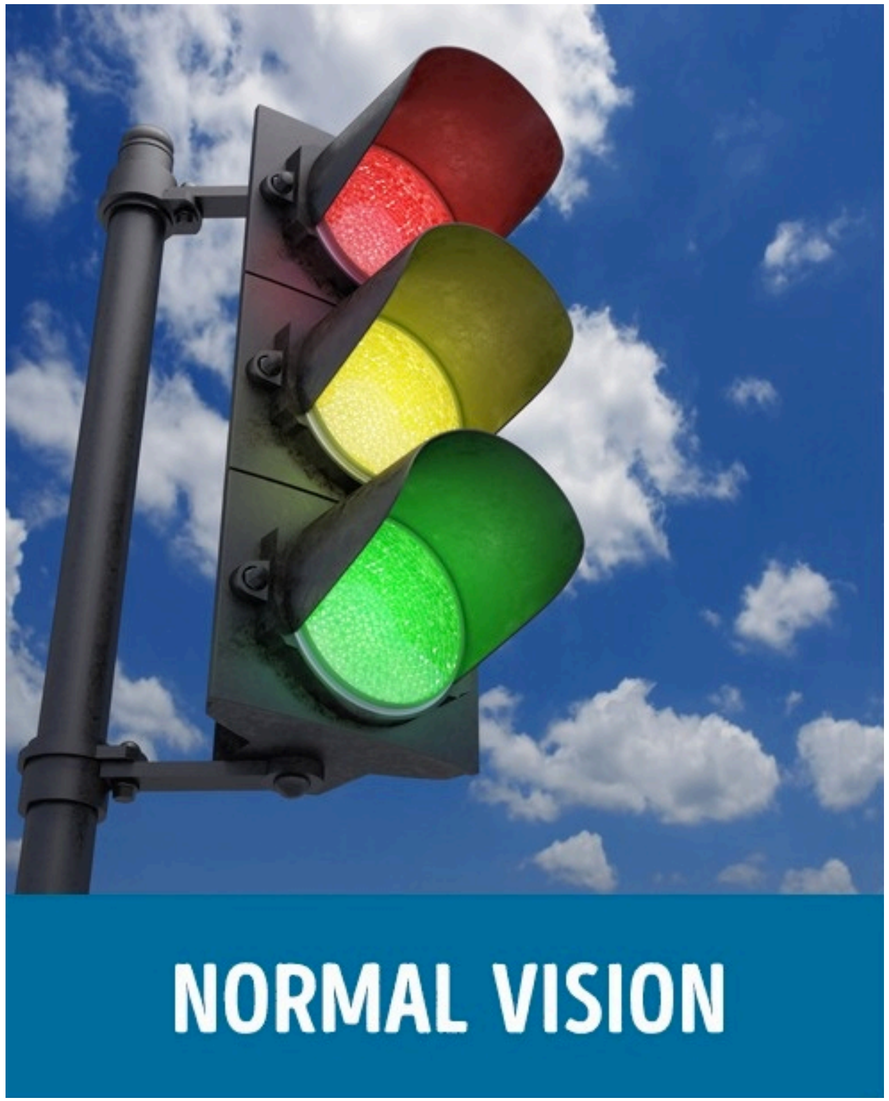
Example: pigments of paint, filters

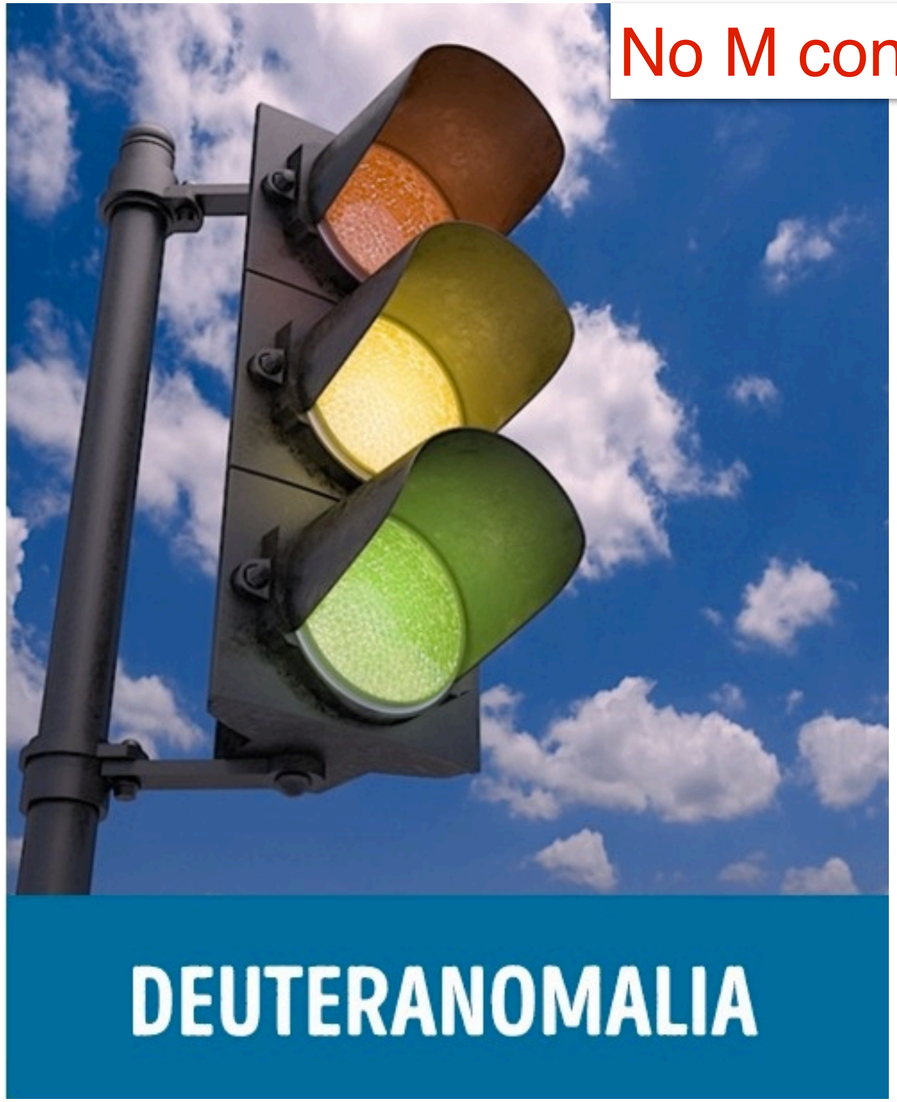
Color Blindness



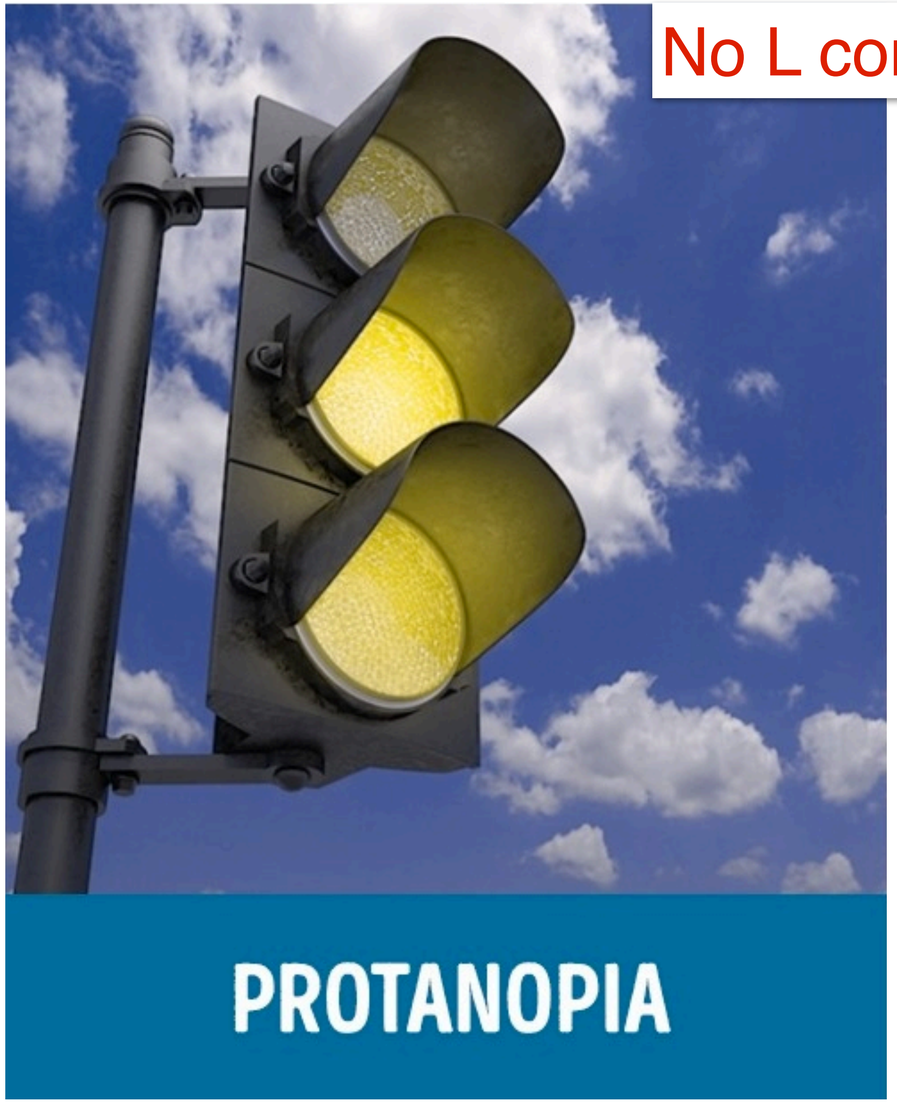


Color Blindness

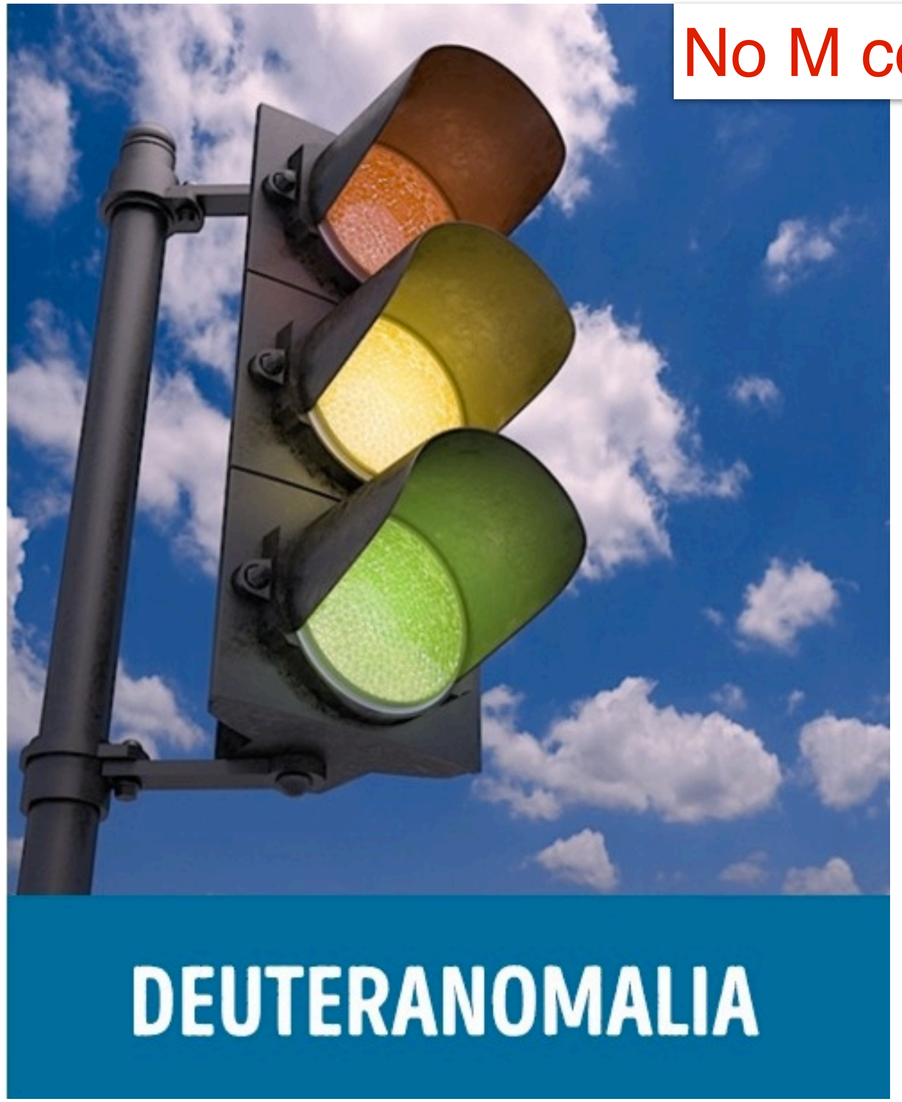




Color Blindness

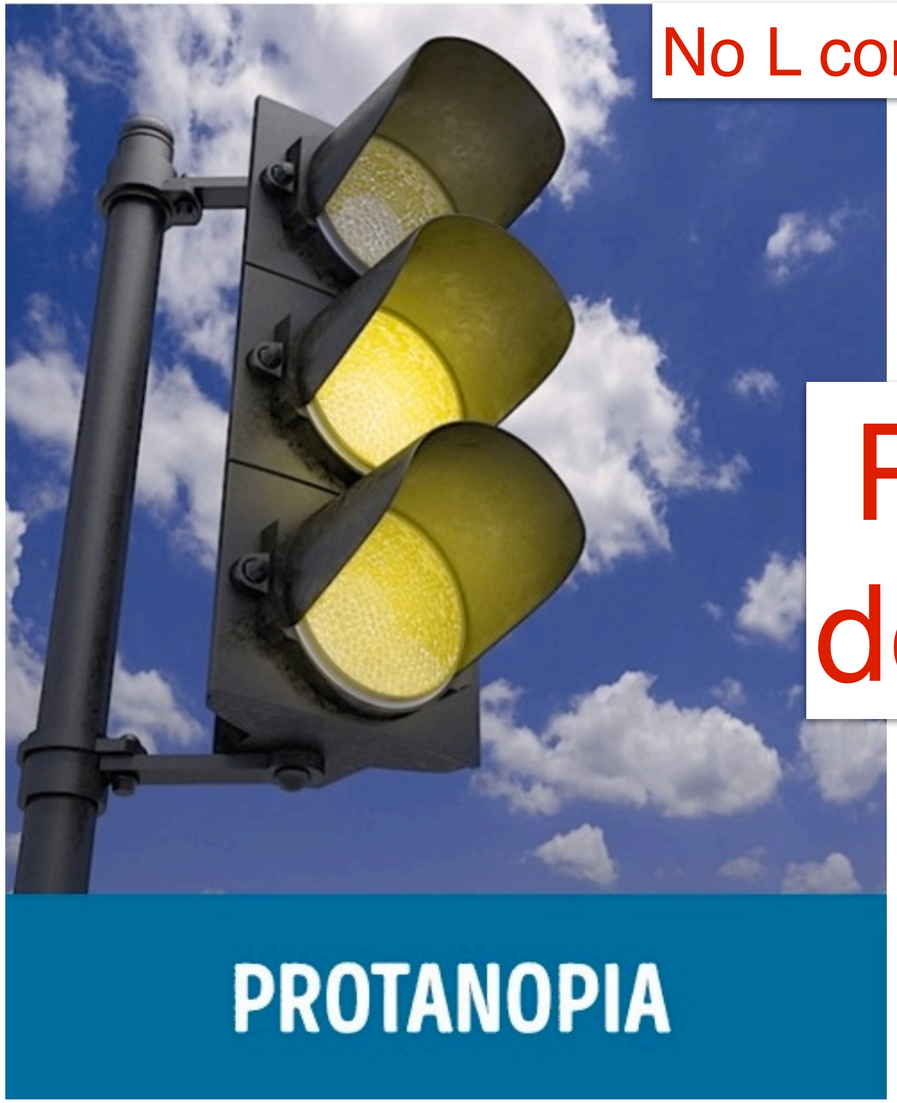


No L cones



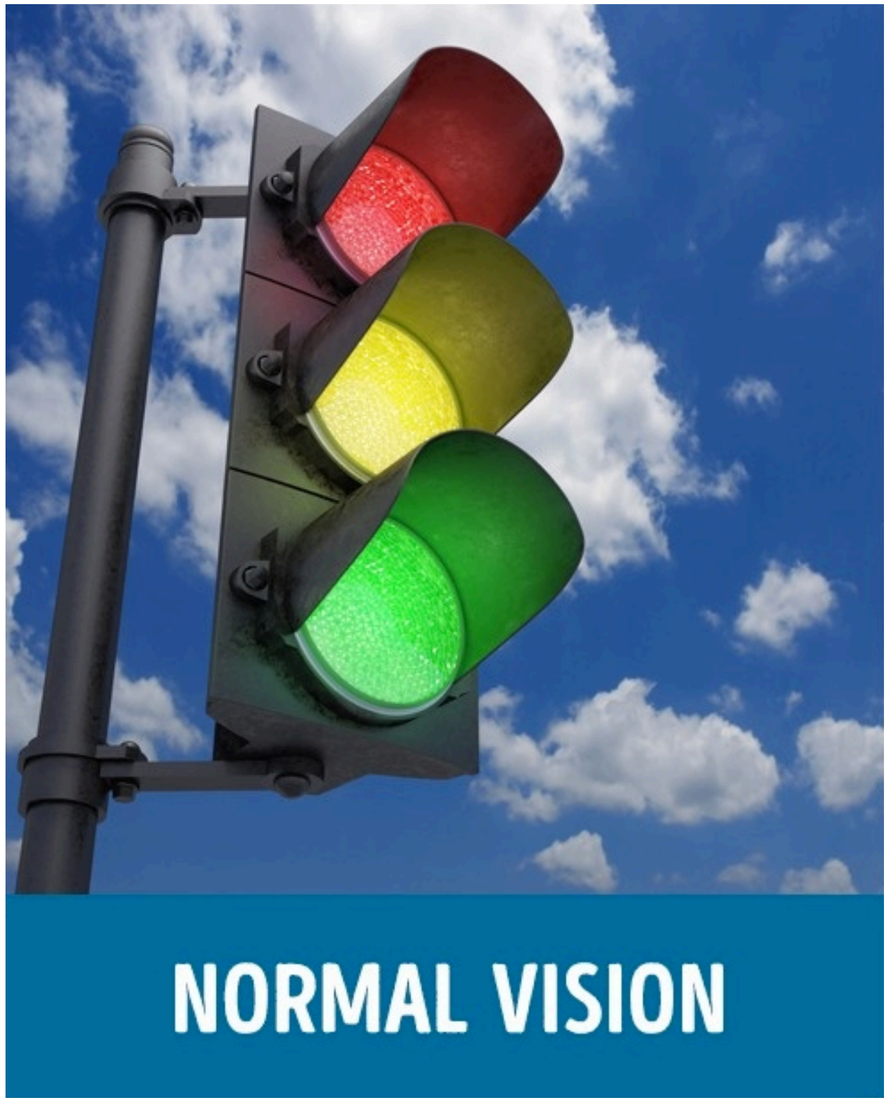
No M cones

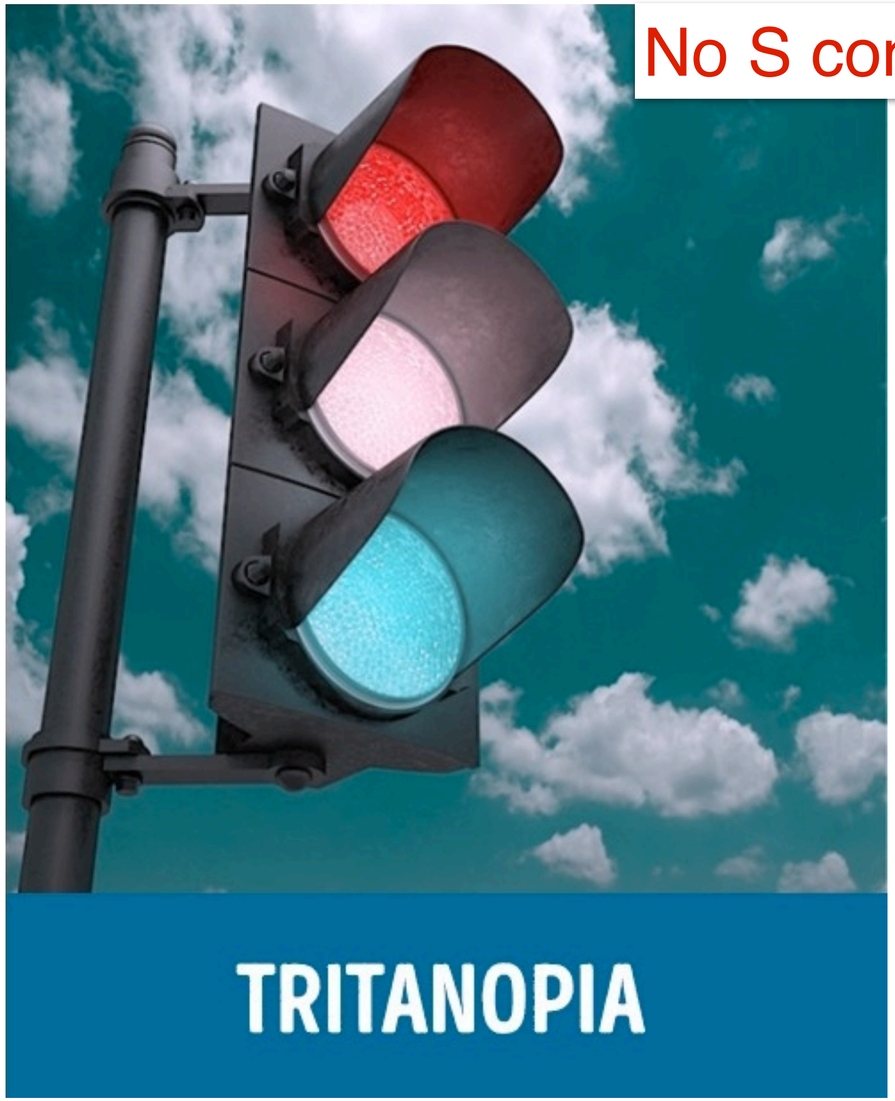
Color Blindness



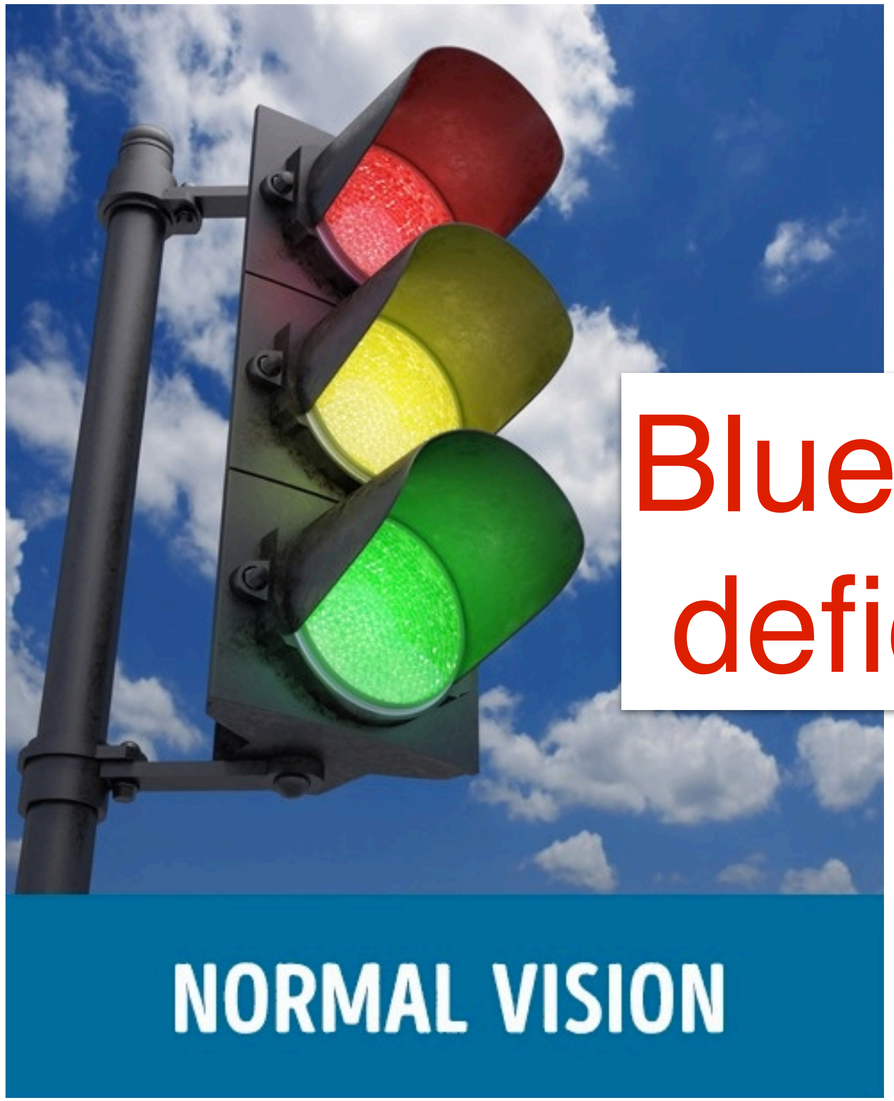
Red/green deficiencies

Color Blindness





Color Blindness



Blue/yellow deficiency

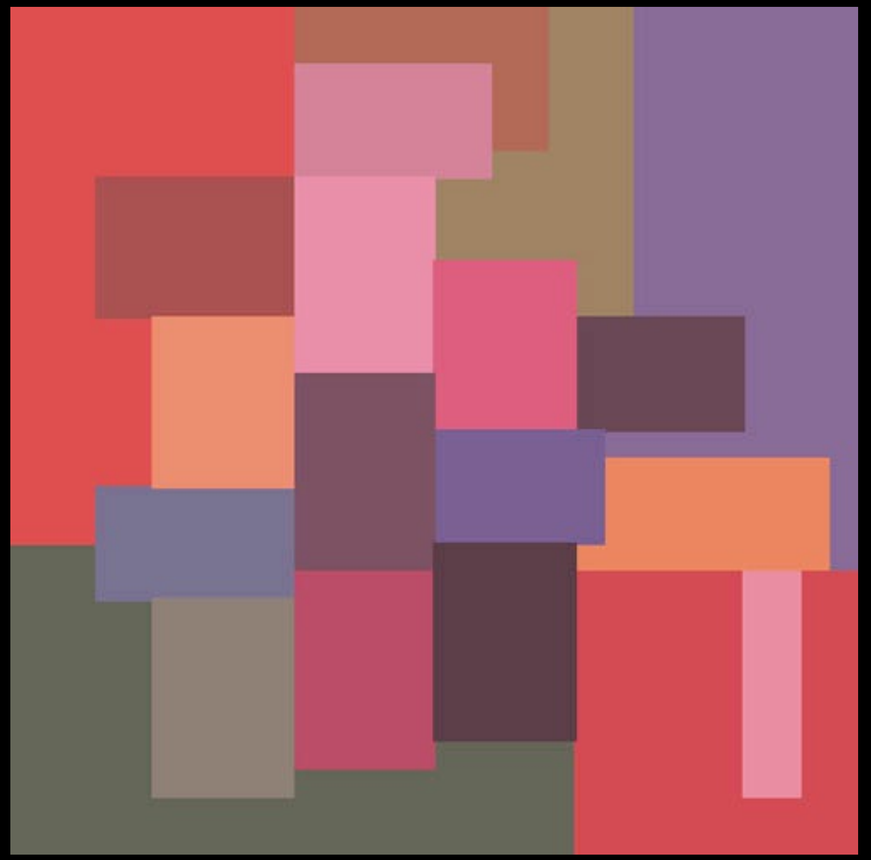
Luminance, Lightness, Brightness

Luminance: *measured* amount of light (luminous intensity per area)

Brightness: *perceived* amount of light

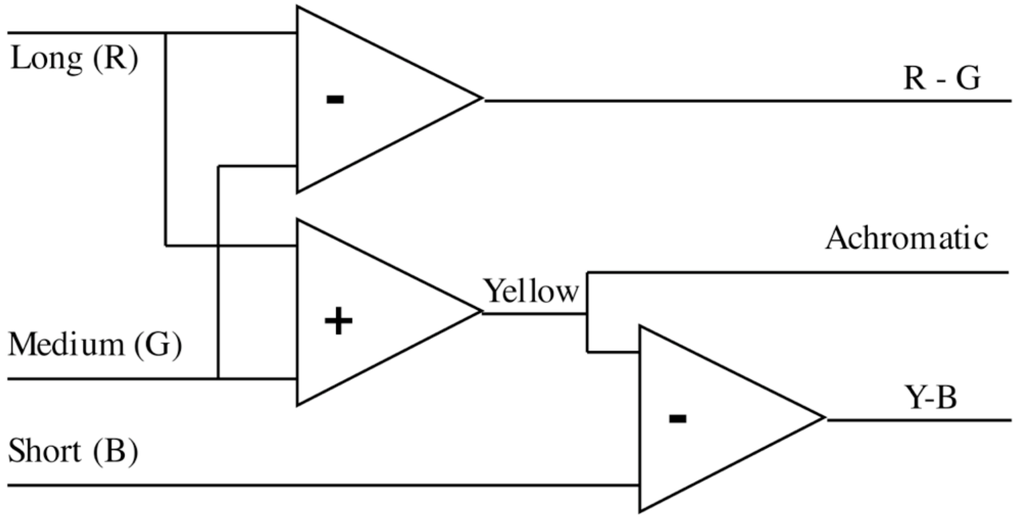
Lightness: perceived reflectance of a surface lightness of a color

Mondrian Color Patches



Opponent Process Theory

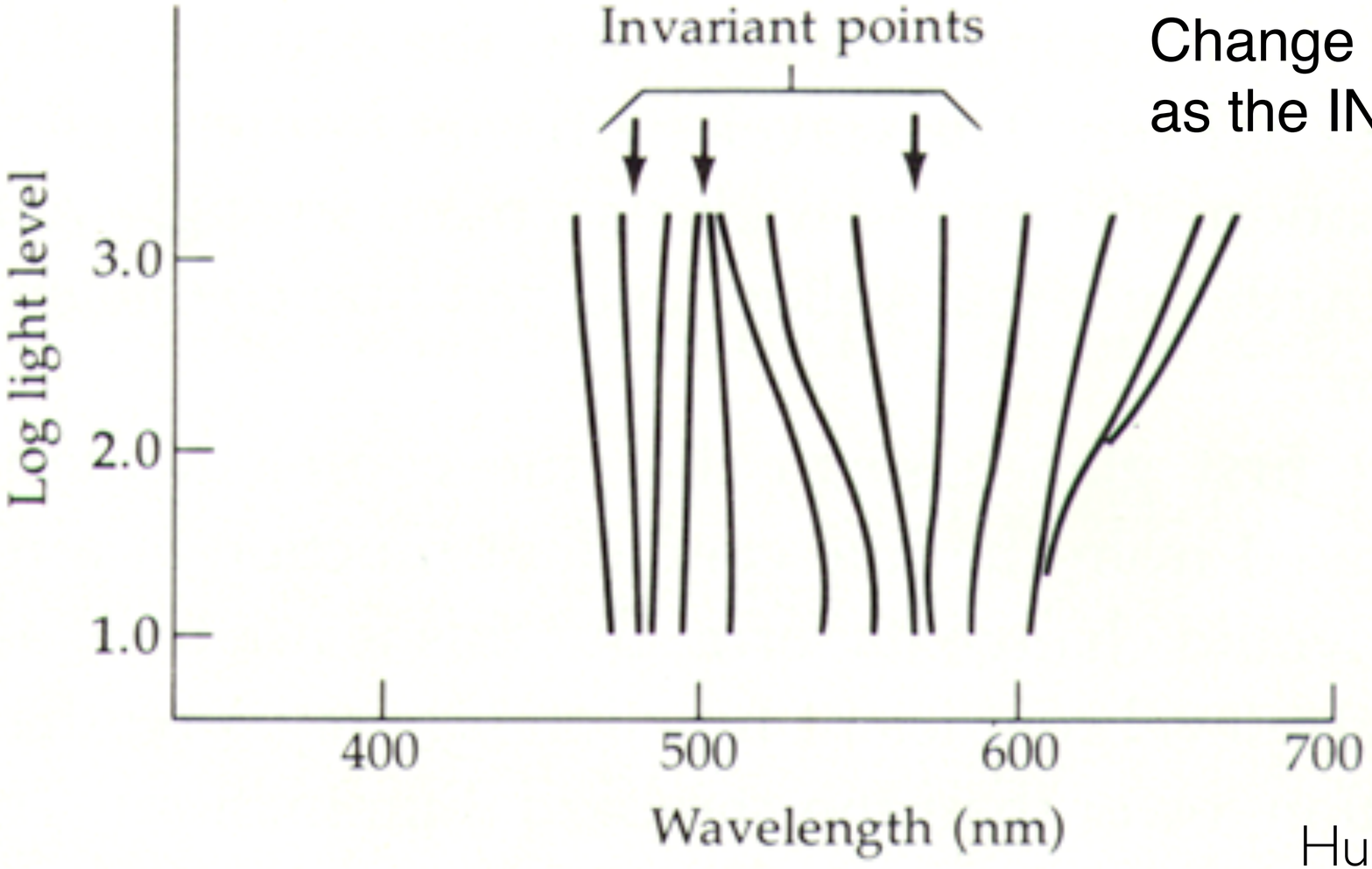
- Humans encode colors by differences
- E.g R-G, and B-Y Differences
- Color blindness



Perceptual Distortion

- Color-deficiency
- Interactions between color components
  - brightness/hue (Bezold-Brücke phenomenon)
  - saturation/brightness (Helmholtz-Kohlrausch effect)
- Simultaneous contrast
  - brightness
  - hue
- Small field achrominance
- Effects of color on perceived size

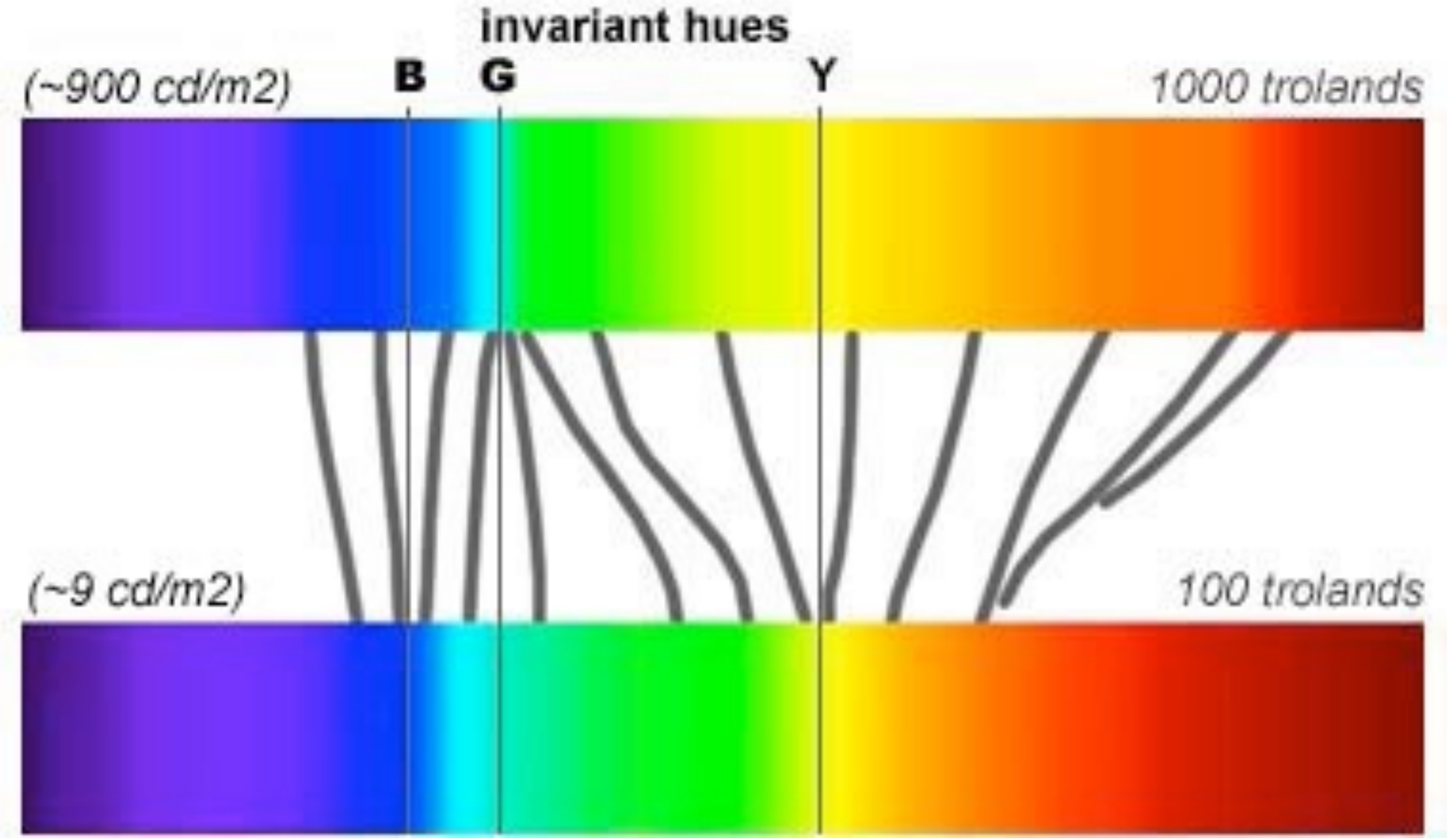
Bezold-Brucke Phenomenon



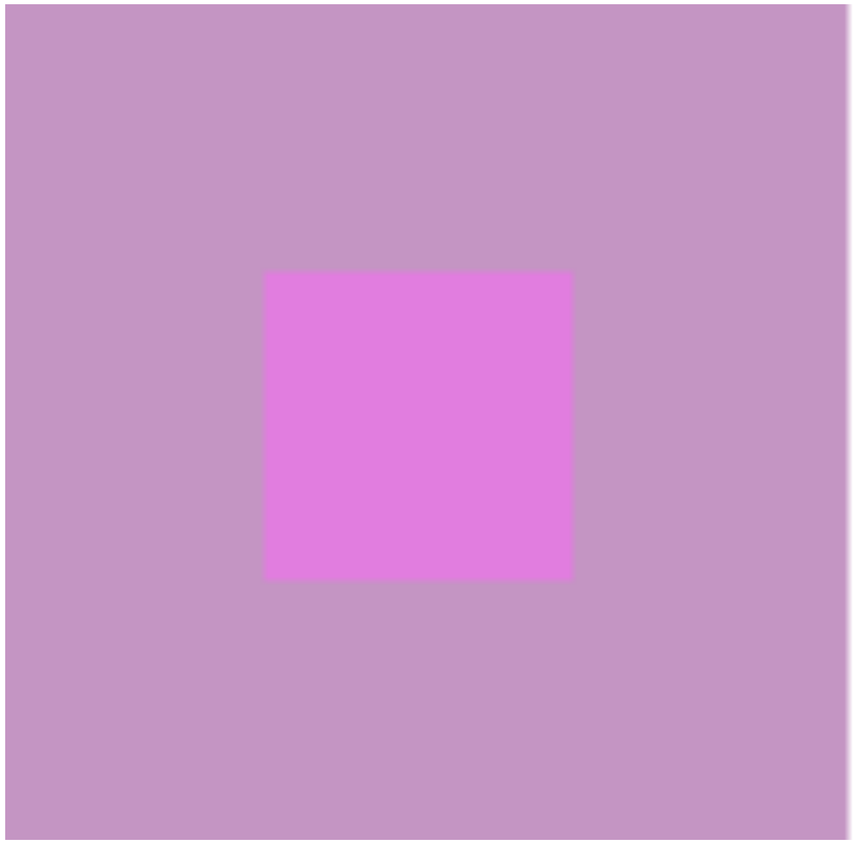
Change in HUE perception as the INTENSITY changes

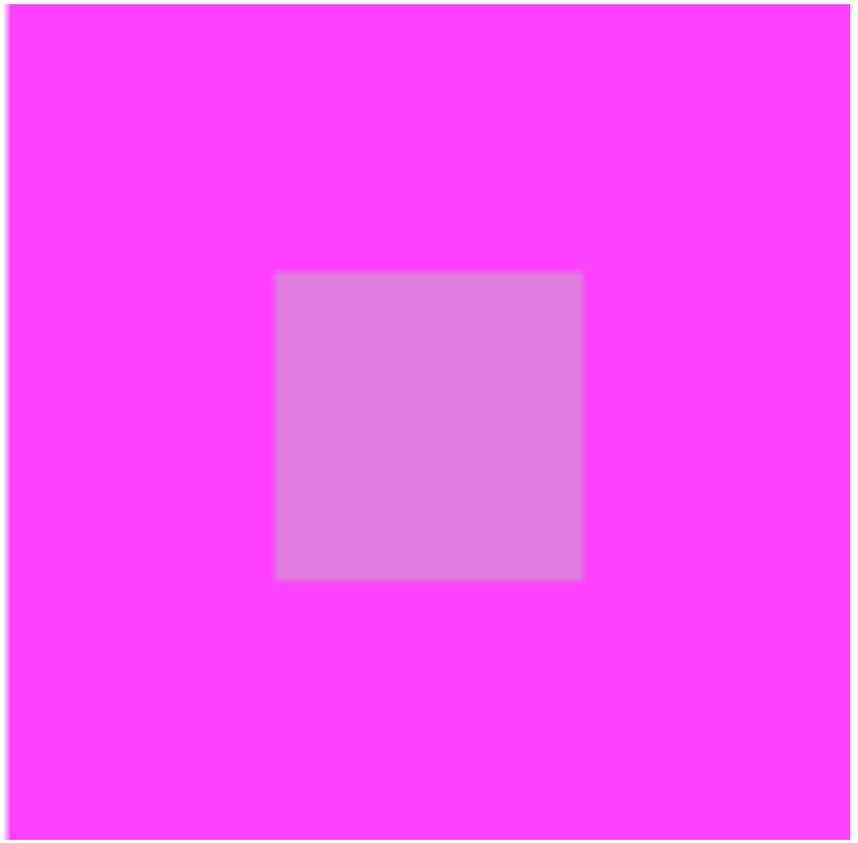
Hurvich '81, pg. 73.

Bezold-Brücke Phenomenon



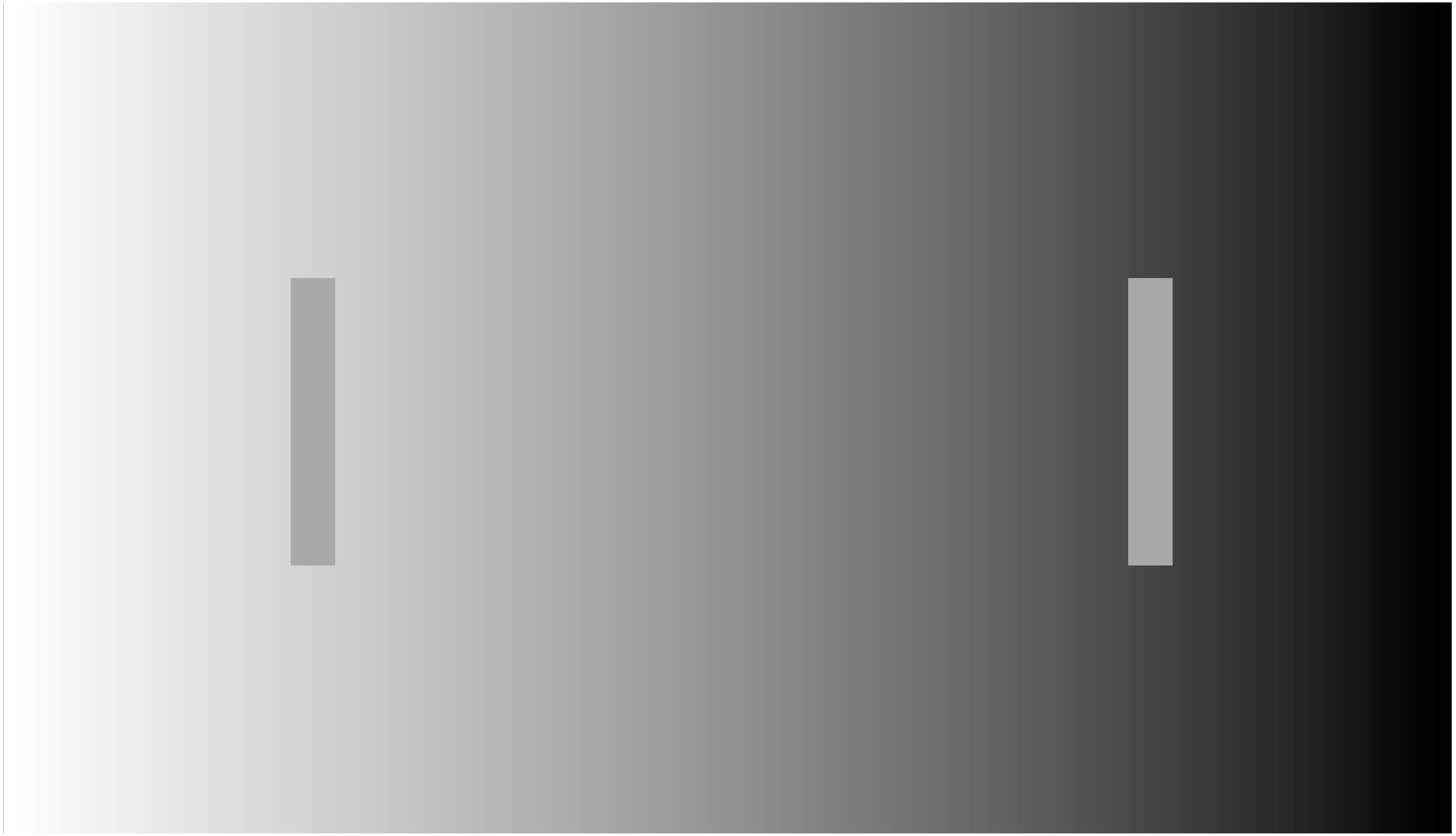
Helmholtz-Kohlraush effect





brightness increased by saturation

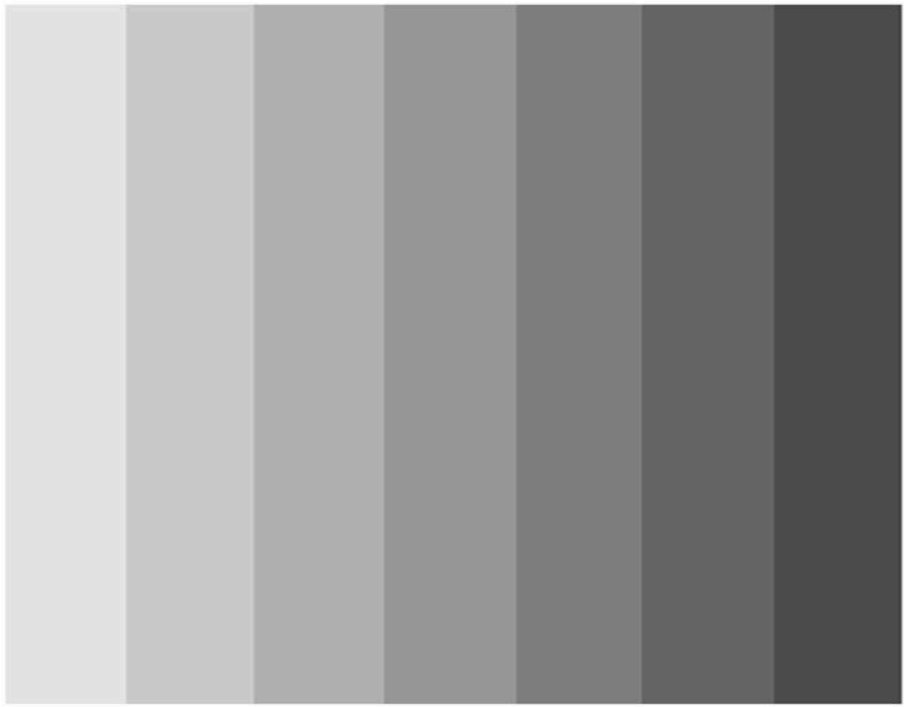
Simultaneous Brightness Contrast



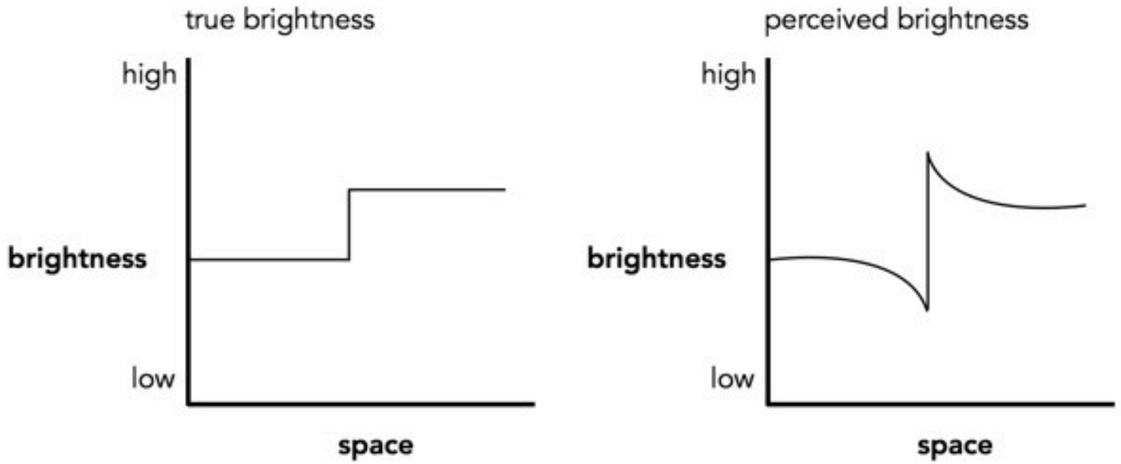
Simultaneous Brightness Contrast

Simultaneous Brightness Contrast

Mach Band effect



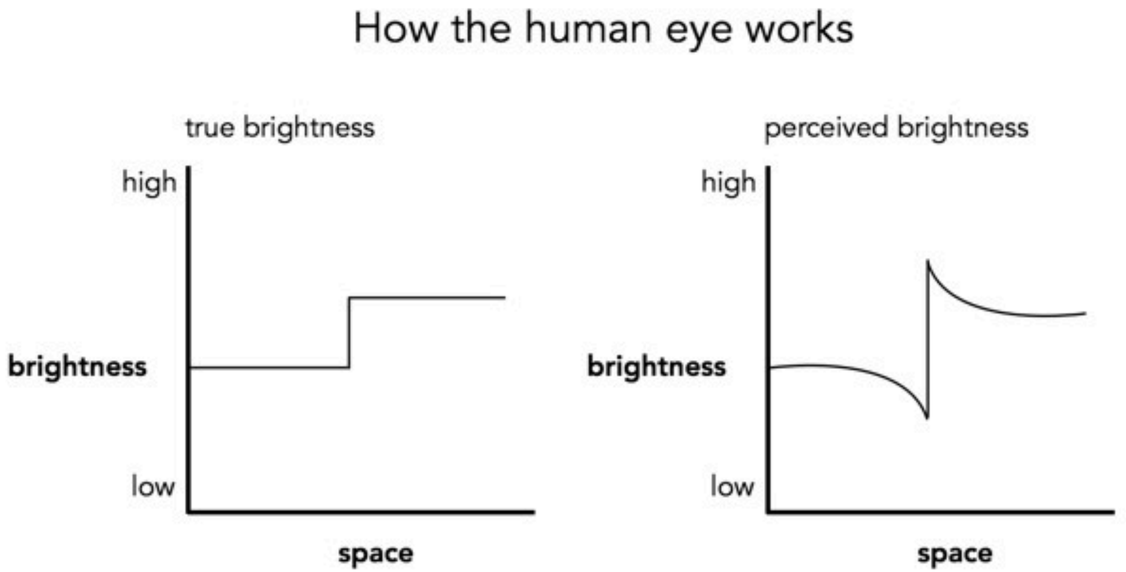
How the human eye works



Perceived brightness depends on background

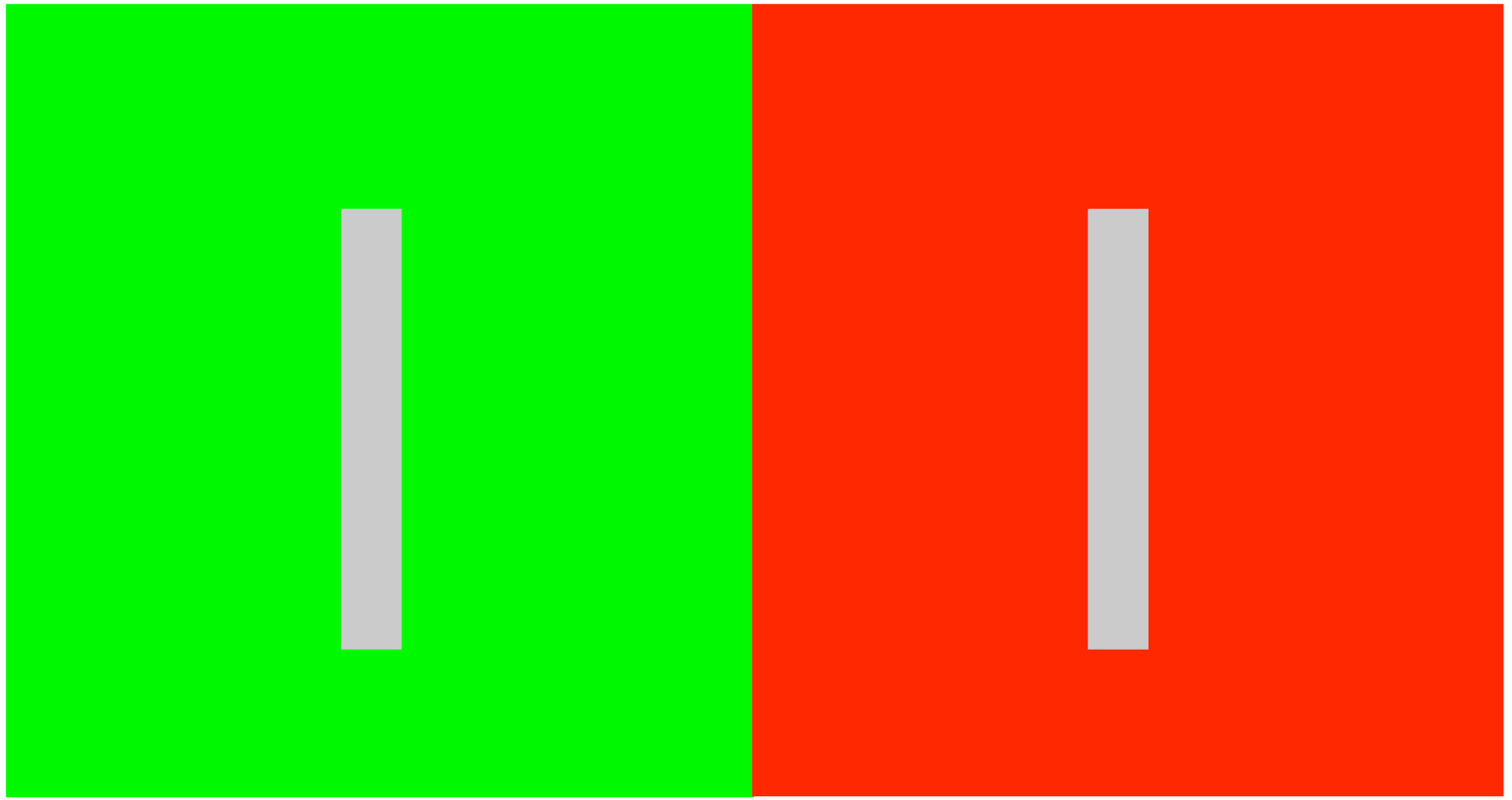
Simultaneous Brightness Contrast

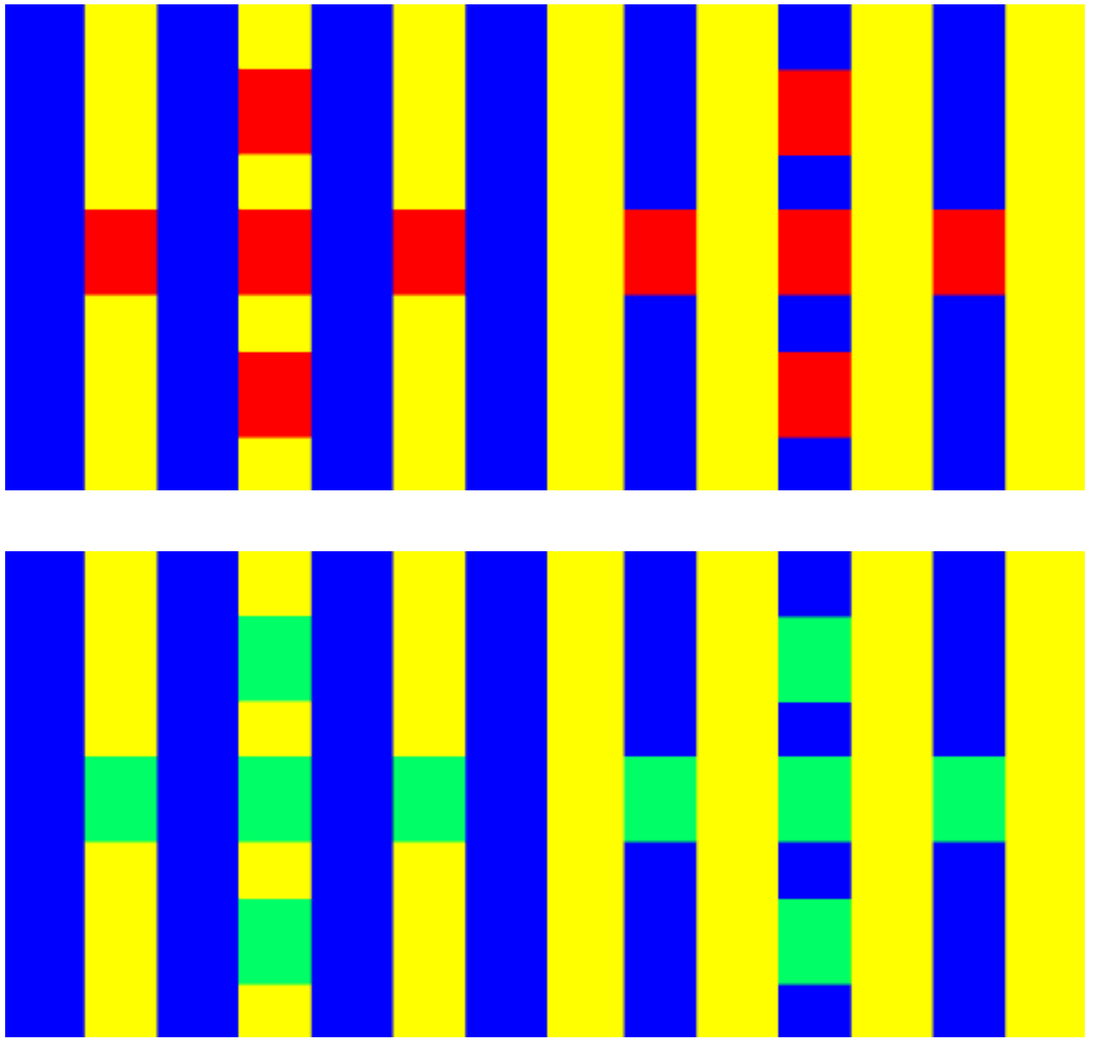
Mach Band effect



Perceived brightness depends on background

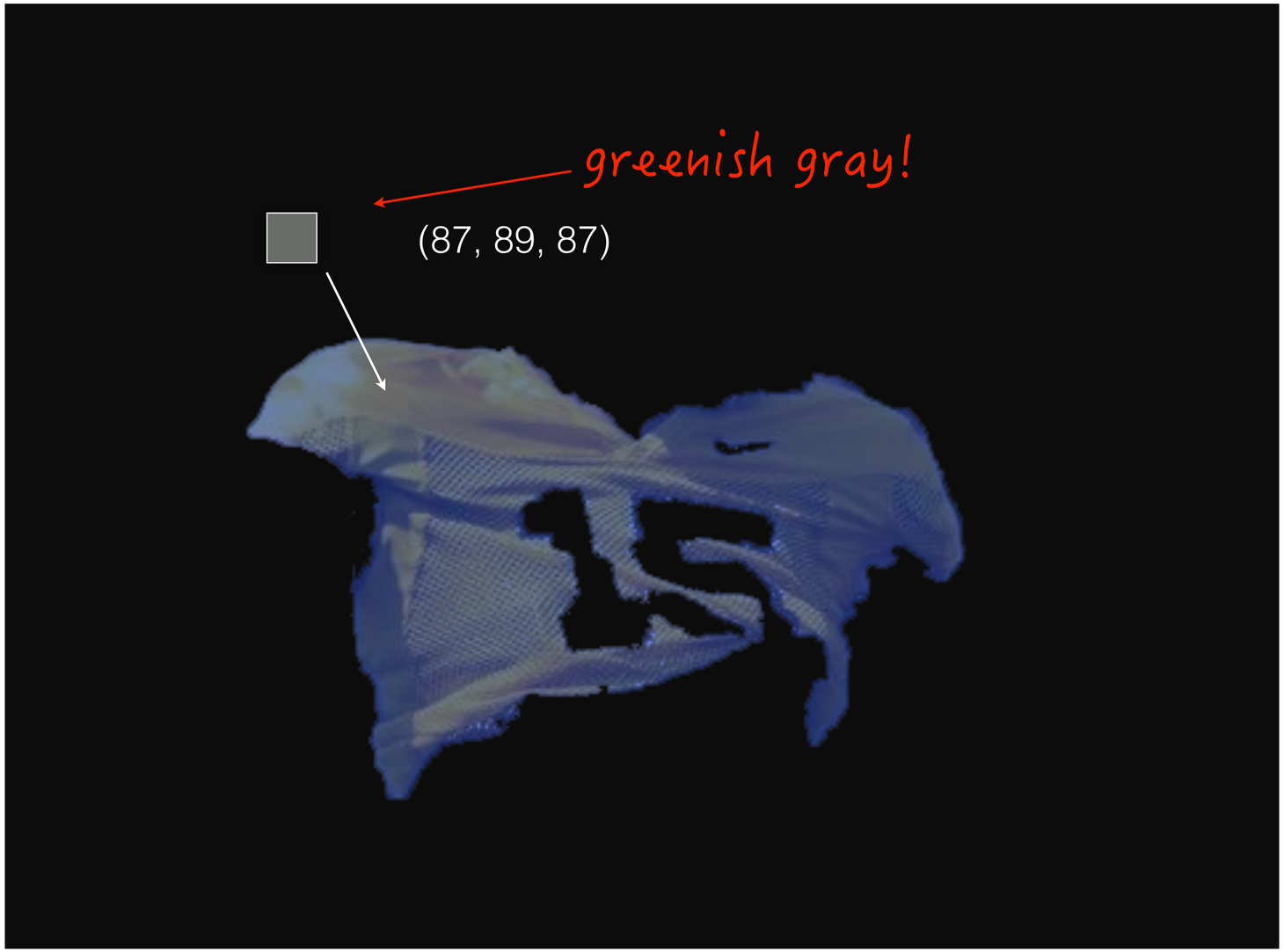
Simultaneous Brightness Contrast





Chromatic Adaptation

Chromatic Adaptation



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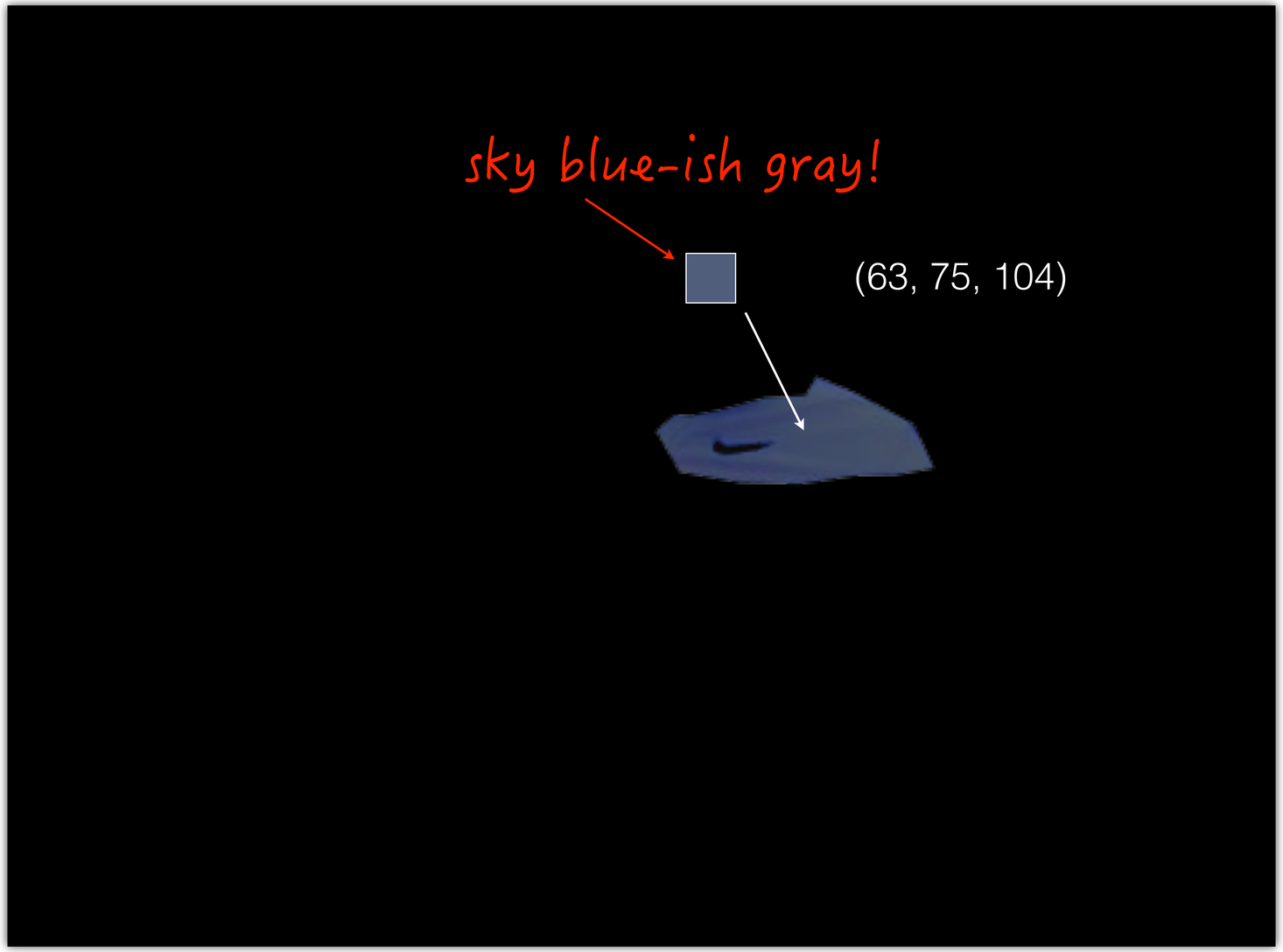
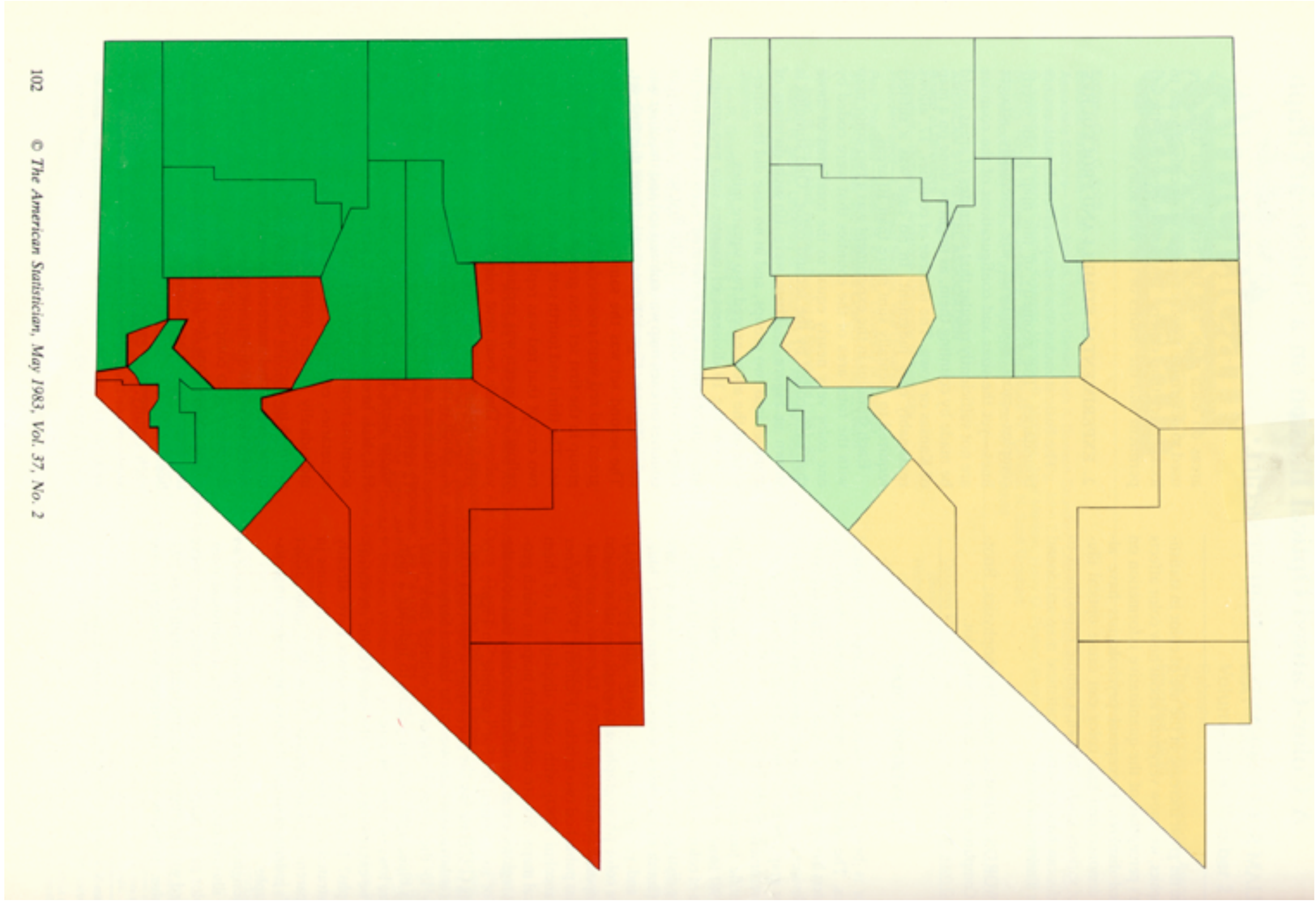


Chromatic Adaptation

Color-size Illusion



Color Spaces

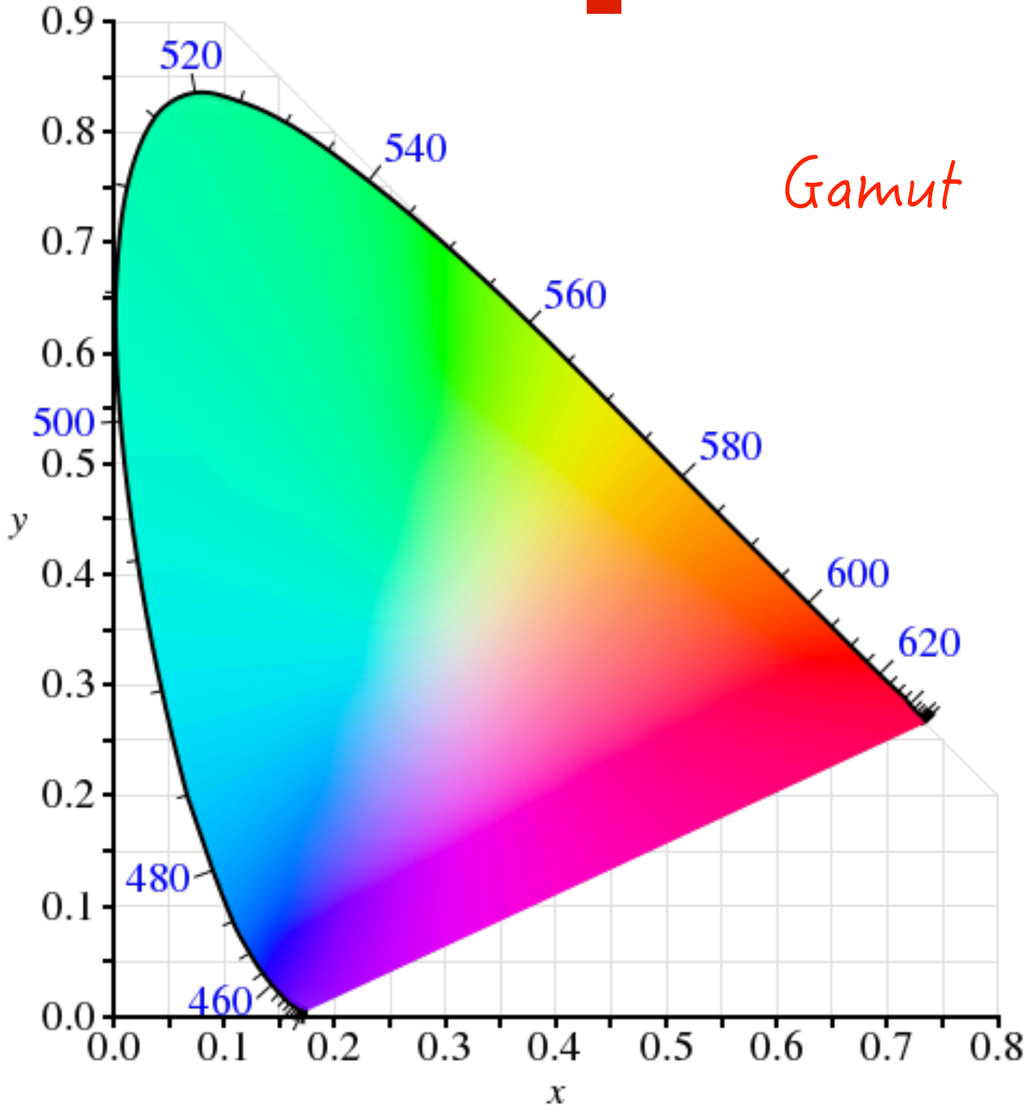
- Perceptually based
  - Device independent, perceptually uniform

    CIELUV, CIELAB, Munsell
- Device-derived
  - Convenient for describing display device levels

    RGB, CMY
- Intuitive (transformations)
  - Based on familiar color description terms

    HSV, HSB, HLS

The Space of Human Color



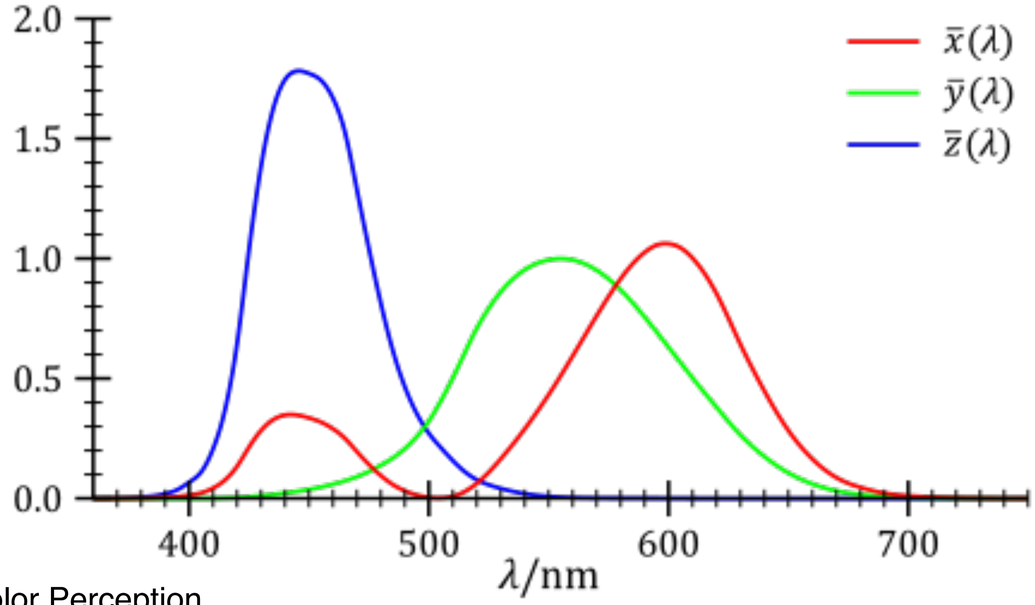
Gamut

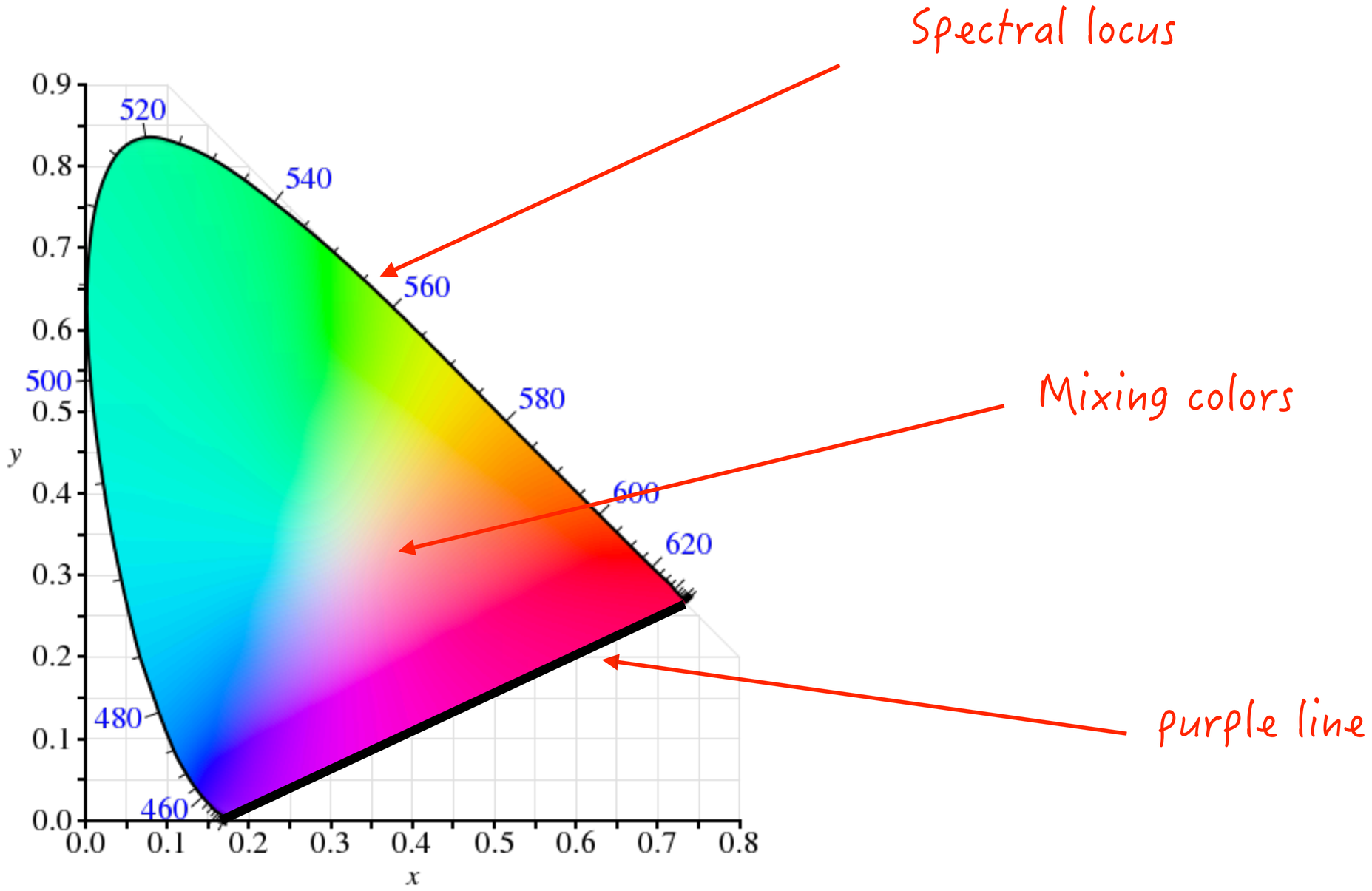
CIE 1931 XYZ

$$X = \int_0^\infty I(\lambda)\,\bar{x}(\lambda)\,d\lambda \qquad x = \frac{X}{X+Y+Z}$$

$$Y = \int_0^\infty I(\lambda)\,\bar{y}(\lambda)\,d\lambda \qquad y = \frac{Y}{X+Y+Z}$$

$$Z = \int_0^\infty I(\lambda)\,\bar{z}(\lambda)\,d\lambda \qquad z = \frac{Z}{X+Y+Z} = 1-x-y$$




Spectral locus
Mixing colors
purple line
0.9
0.8
0.7
0.6
500
0.5
0.4
0.3
0.2
0.1
0.0
y
520
540
560
580
600
620
480
460
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x

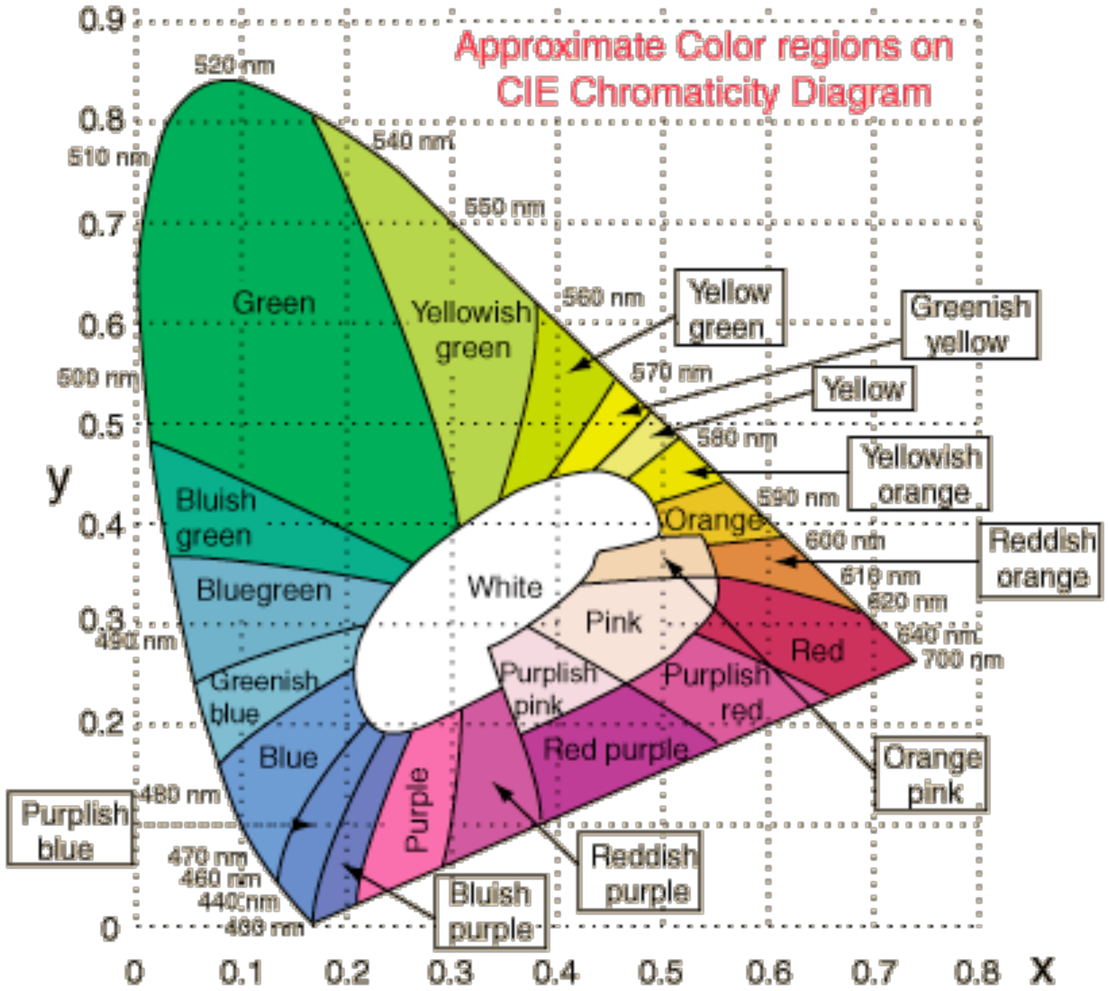
CIE Color Space

- Humans can mimic any pure light by addition (and subtraction) of 3 primaries
  - Color is a 3D space
- With R-G-B, addition and subtraction are both required to get all wavelengths

CIE Color Space

- In nature, light adds (but does not subtract)
- Conversion to another coordinate system X-Y-Z is a convenience — they are not primary colors
- Any 3 primaries (additive) can produce only a subset of all visible colors

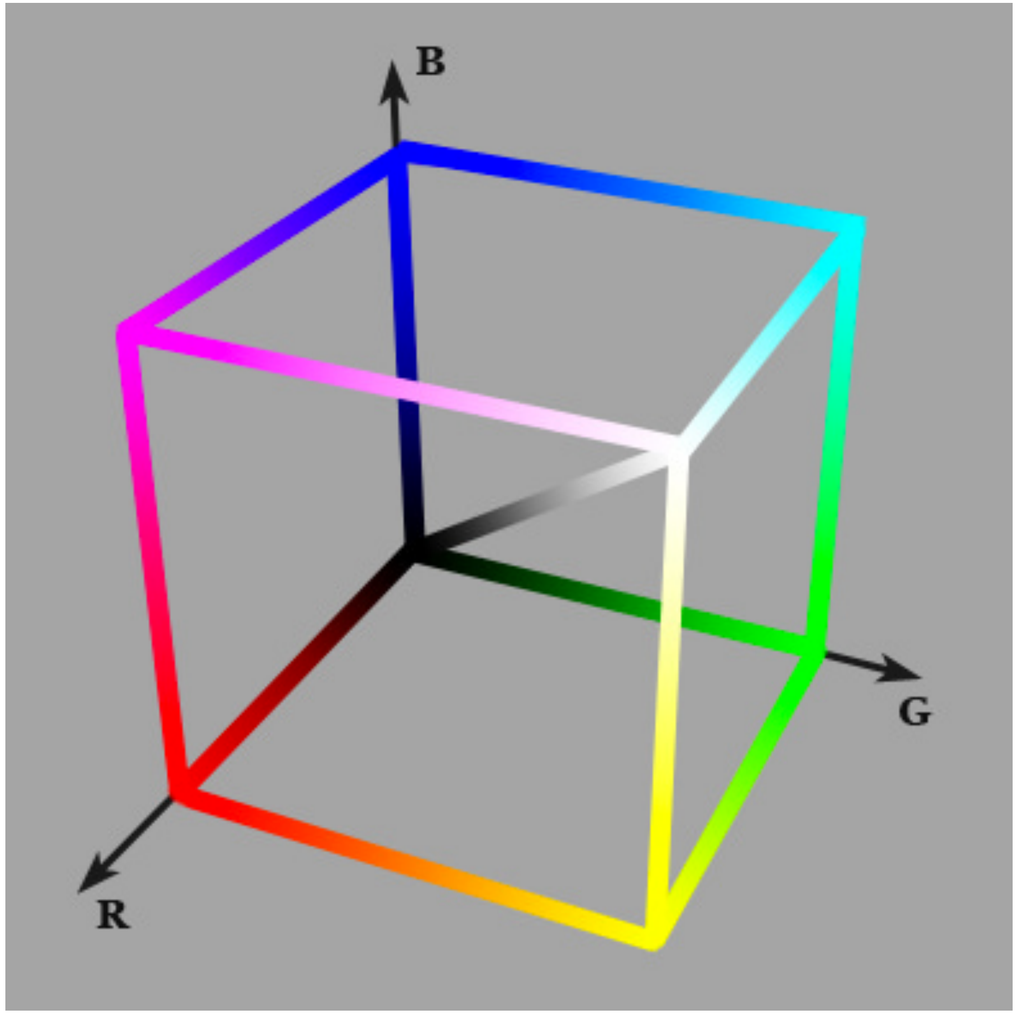
The Chromaticity Diagram



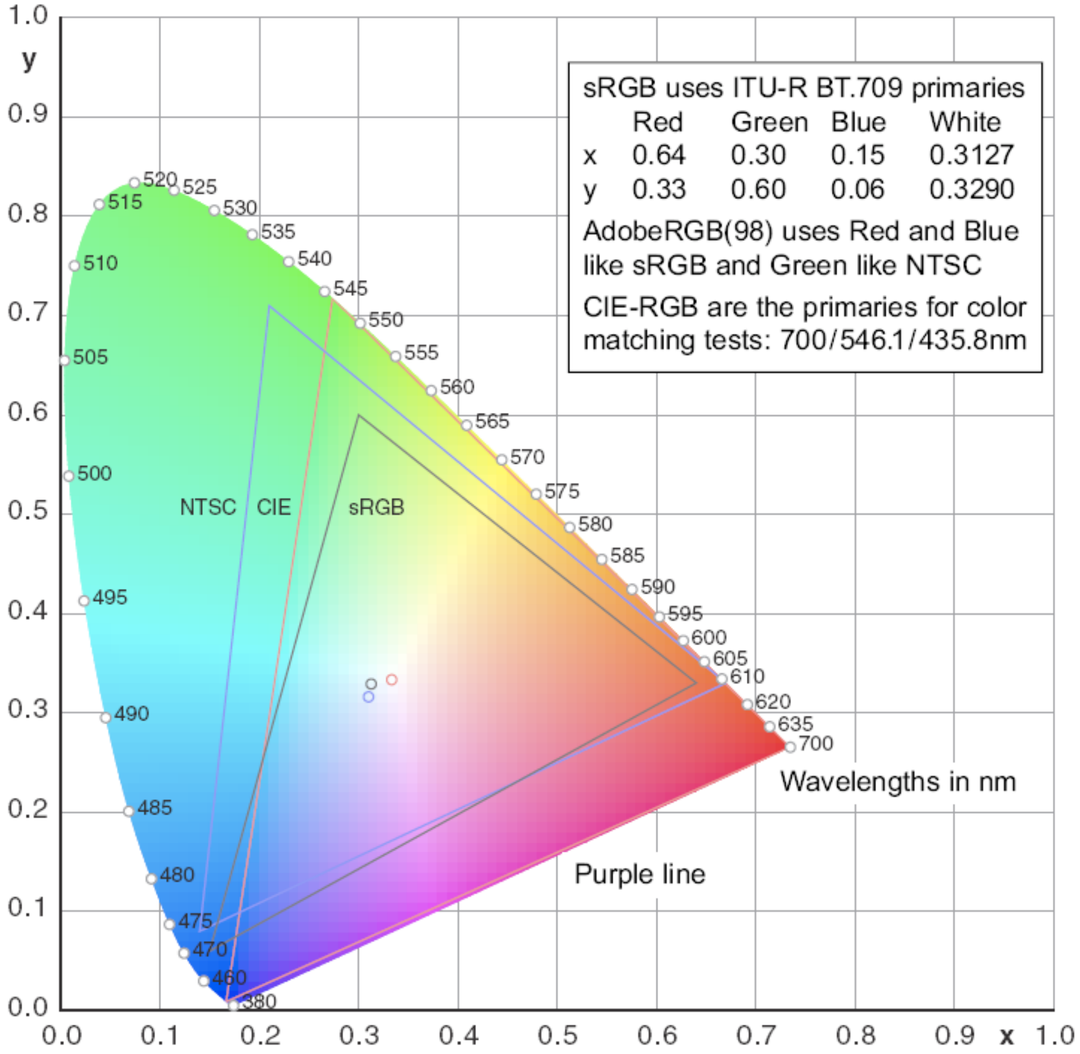
RGB Color Space

- Convenient colors (screen pixel LEDs)
- Decent coverage of the human color
- Not a particularly good basis for human interaction
  - Non-intuitive
  - Non-orthogonal (perceptually)

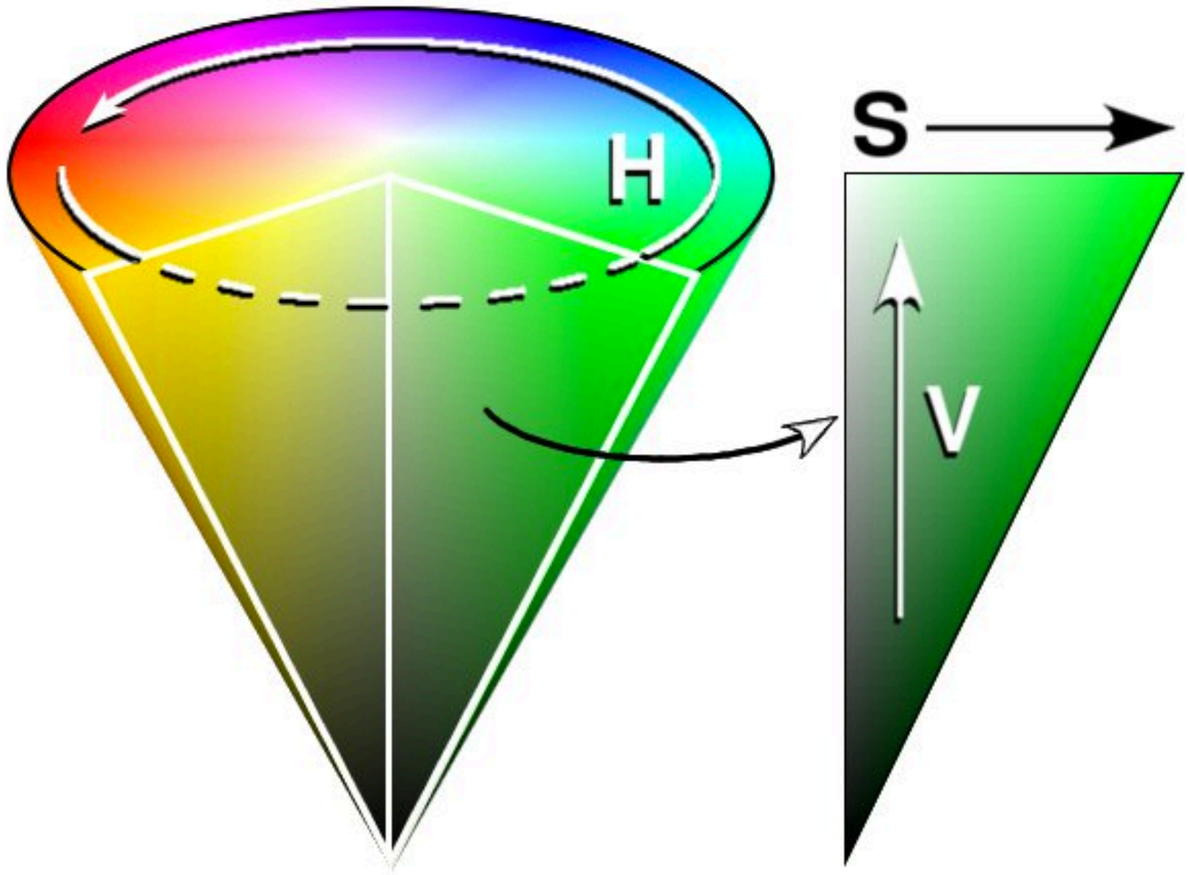
RGB Cube



The Chromaticity Diagram



HSV

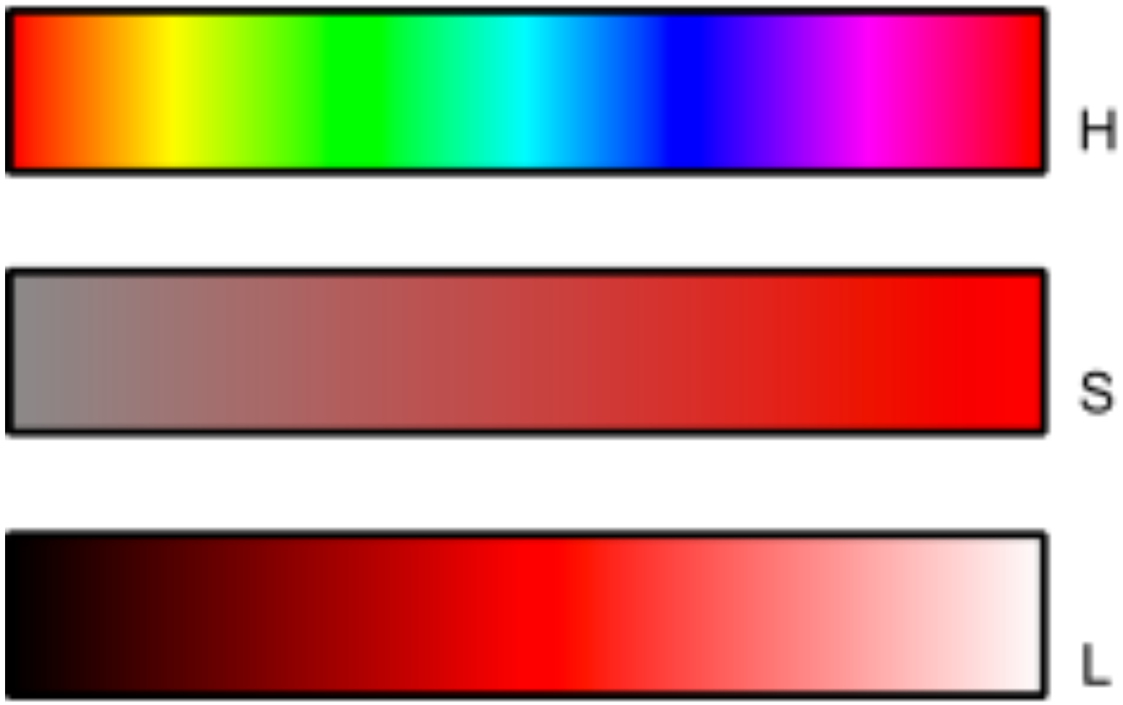


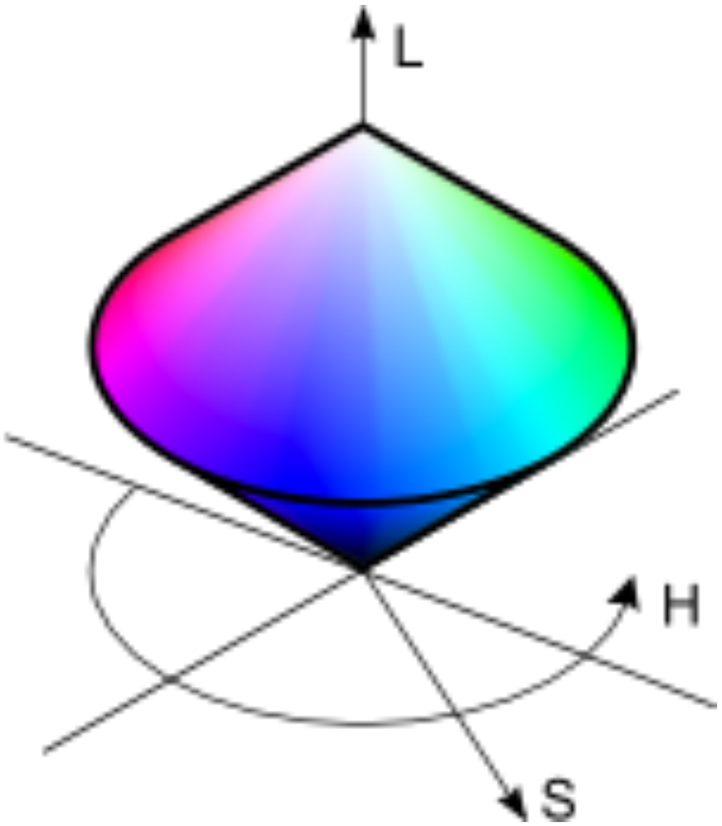
Hue:

Saturation:

Value:

HSL





L: lightness: from dark (black) to light (white)

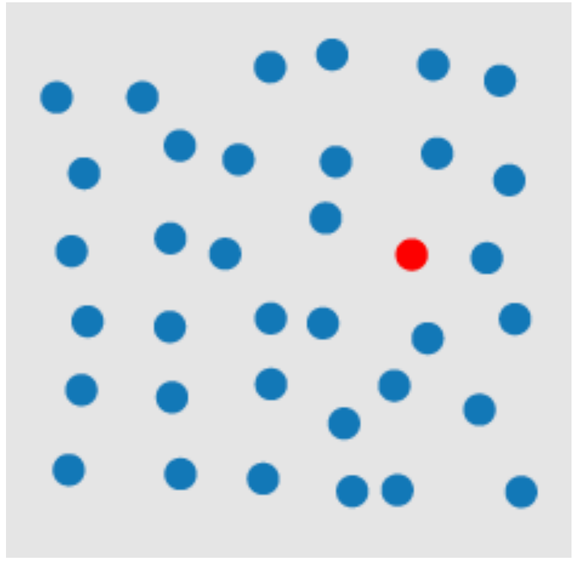
RGB to HSV

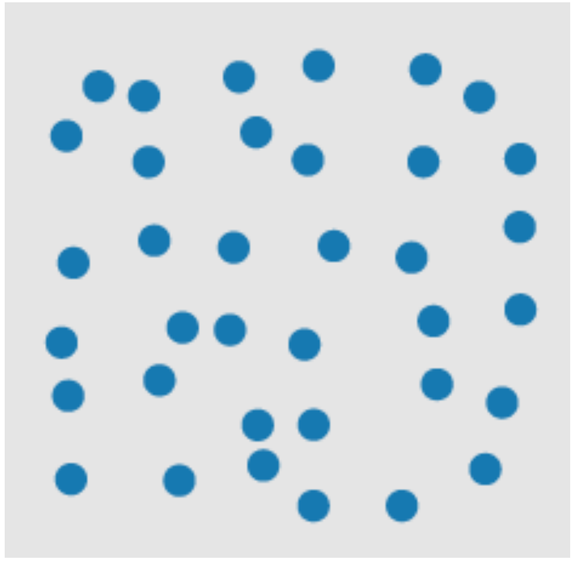
```
V = M = max(R, G, B);

m = min(R, G, B);

S = (M - m)/M;

if (R==M) h = (G-B)/(M-m);

if (G==M) h = 2 + (B-R)/(M-m);

if (B==M) h = 4 + (R-G)/(M-m);

if (h<0) H = h/6 + 1;

if (h>0) H = h/6;
```

Visual Popout

- Also known as "preattentive processing"

Images by C.H. Healy, NCSU



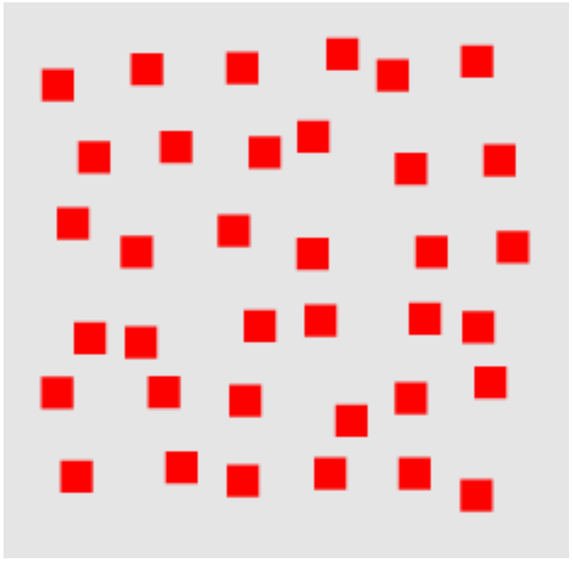


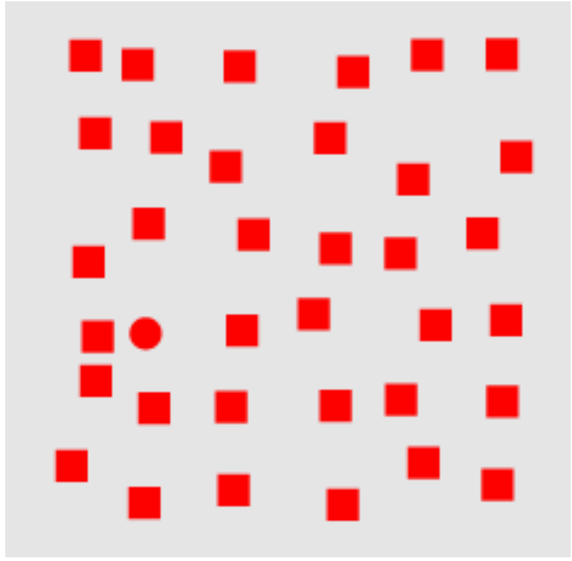
Difference in hue

Visual Popout

- Also known as "preattentive processing"

Images by C.H. Healy, NCSU





Difference in curvature

Change Blindness

Change Blindness