DSCI 554 LECTURE

COLOR, D3 COMPLEX CHARTS AND USING COLORS

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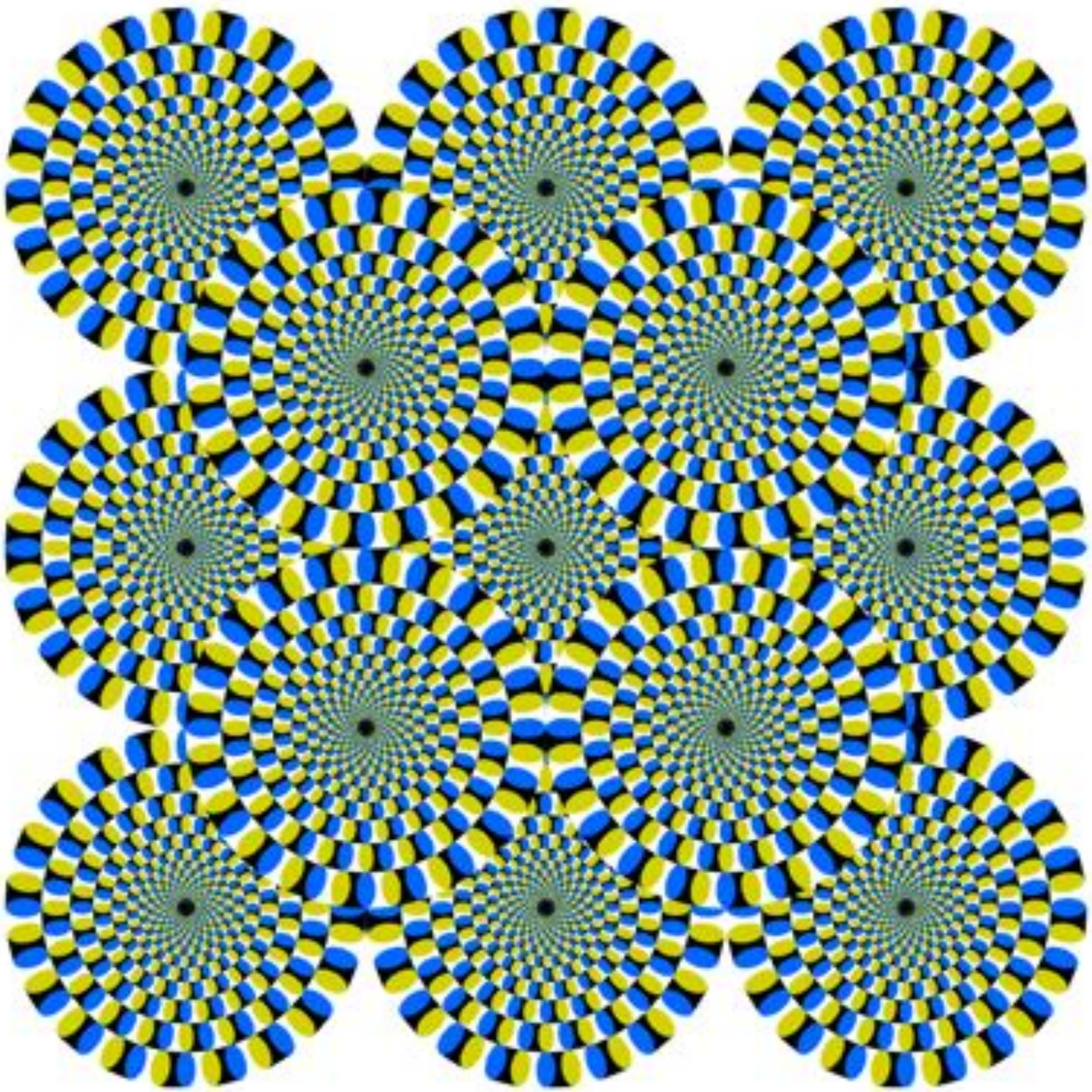


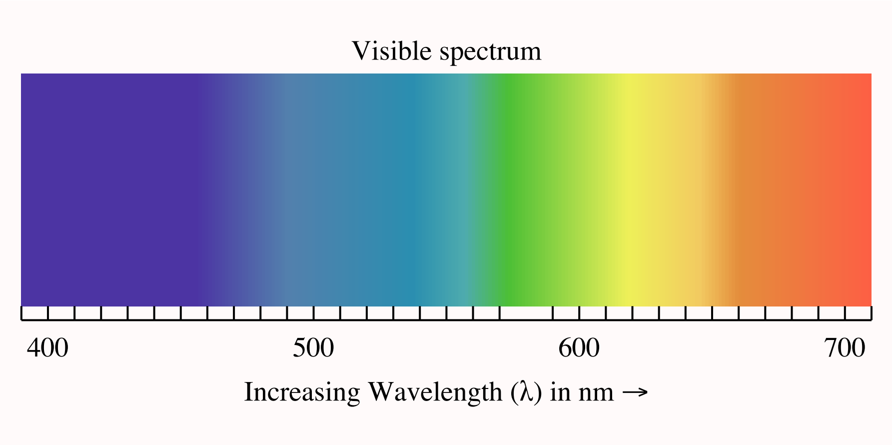
B.Backus, I Oruç, Illusory motion from change over time in the response to contrast and luminance, Journal of Vision December 2005.

OUTLINE

- Color perception
- Color theory
- Color design
- Colors in D3
- Complex D3 charts

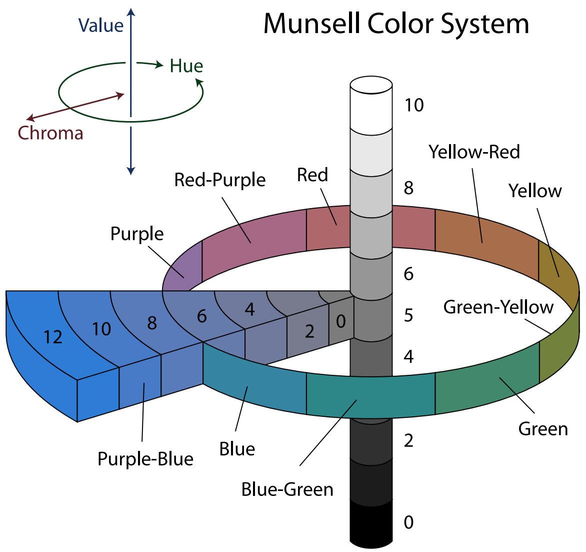
WHAT IS COLOR?

Color is the perception of a kind of light



COLOR PROPERTIES WE CAN DISTINGUISH

Hue	Degree to which a stimulus can be described as similar to or different from stimuli that are described as red, orange, yellow, green, blue, and purple.
Saturation	Also called **colorfulness**, **chroma**, intensity, purity. It is the perceived intensity (chromatic strength) of a hue.
Brightness	Also called **value** or **lightness**. It is the attribute of a visual sensation according to which an area appears to emit more or less light.



Munsell color space showing the three properties of color: hue (basic color), chroma (color intensity), and value (lightness). CC BY-SA 3.0, Link

WHAT IS COLOR VISION?

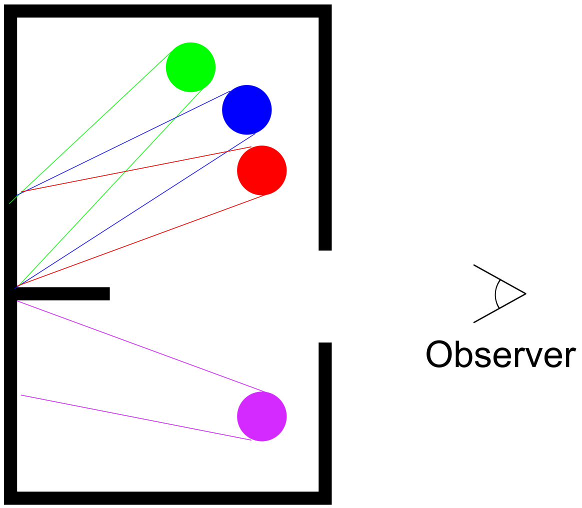
Color vision is the ability to discriminate light composed of different wavelengths

COLOR VISION THEORIES

- Trichromatic theory [Young and Helmholtz 1802]
- Opponent process theory [Hering 1878]

TRICHROMATIC THEORY

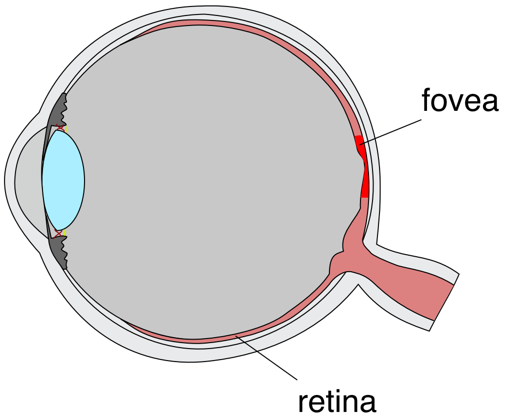
The eye has 3 kinds of color receptors roughly corresponding to blue, green and red



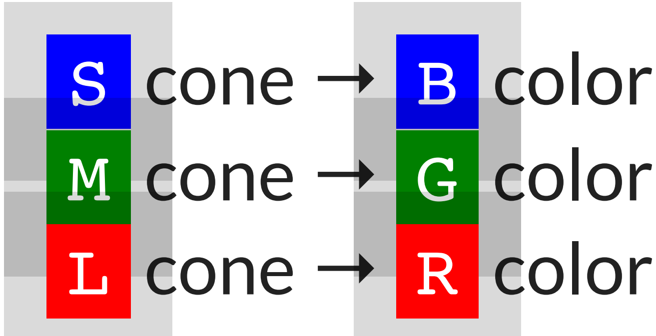
Color matching experiment (Helmholtz & Maxwell 1850): subjects adjust wavelengths of primaries to match a sample Most people will match, same light, same primary colors with the same weights

TRICHROMATIC VISION

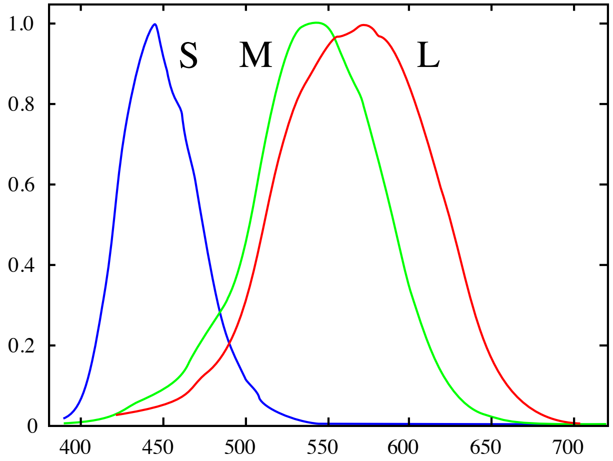
- Humans are routinely trichromatic*
- Trichromacy through three types of cone cells: S, M, L
- We can distinguish ~10 million different colors



Cones cells are predominantly situated in the fovea



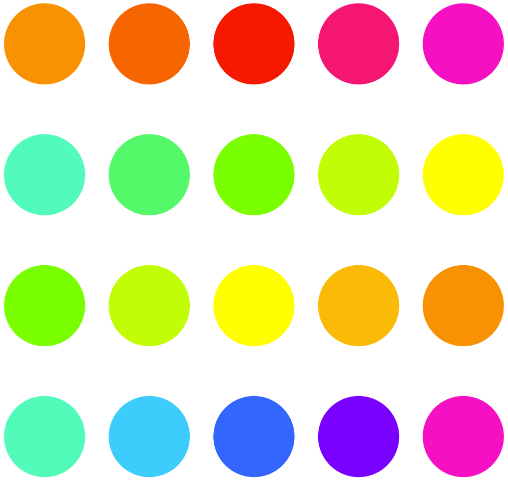
Cones cell types associated with color



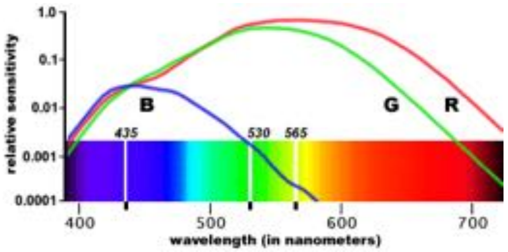
Normalized cones response

* believed to be a folivory and frugivory adaptation

TRICHROMATIC THEORY PROBLEMS



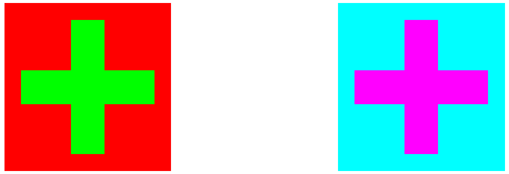
reddish-green and yellowish-blue are not seen or named



Photoreceptor distribution is not related to perceived colors:

- S, M and L overlap
- S is a fraction of M + L
- M, L have similar responses
- $\frac{M}{L}$ varies greatly*

*$\frac{M}{L}$ in two male subjects $\frac{20.0\%}{75.8\%}$ vs. $\frac{44.2\%}{50.6\%}$ [Roorda 1999]



Afterimages cannot be explained:

- Same dominant waveband in the light reflected from the central area and surround
- Afterimages are opponent to perceived colors rather than wavelengths

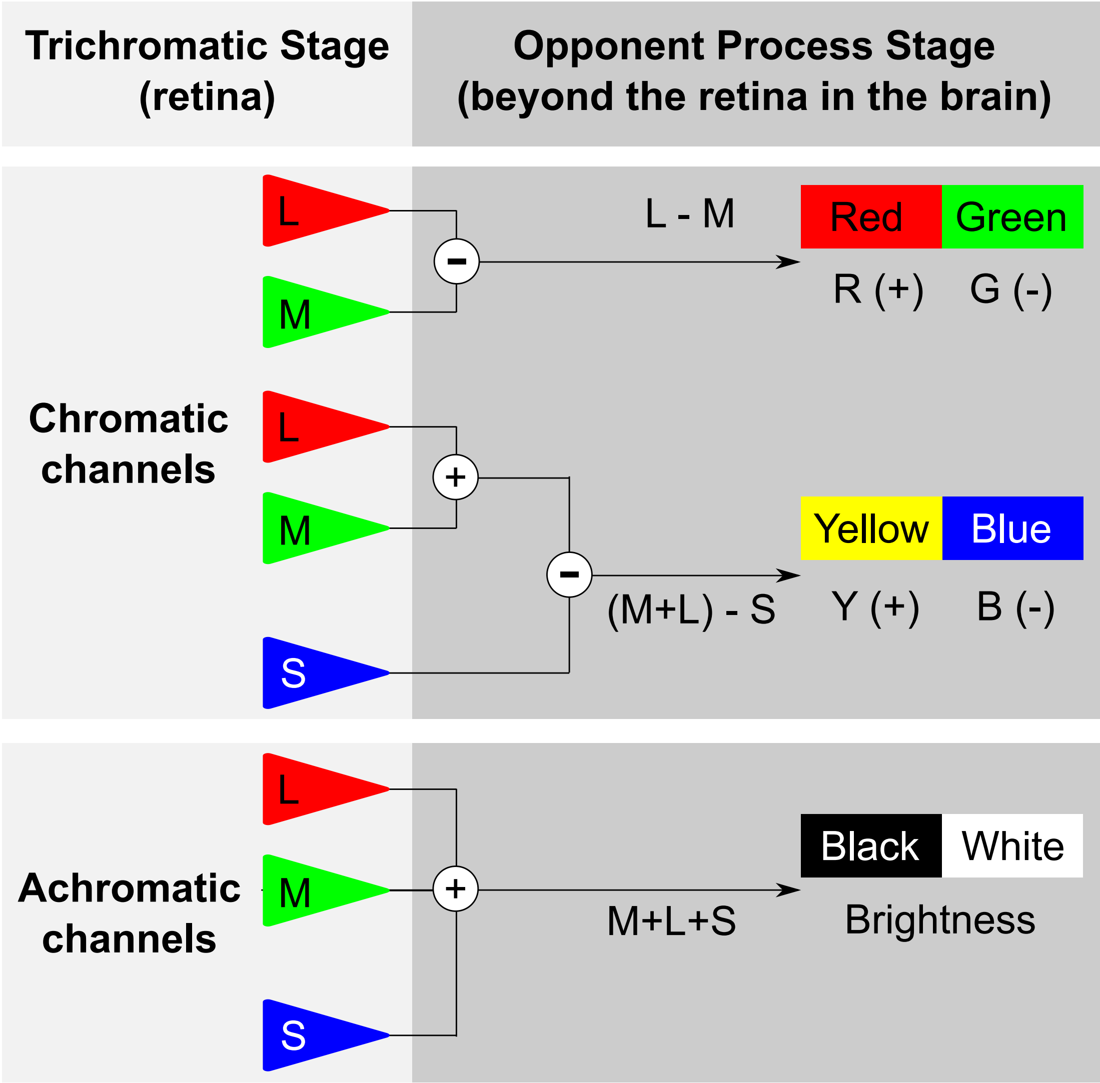
OPPONENT PROCESS THEORY

The visual system responds to opponent channels

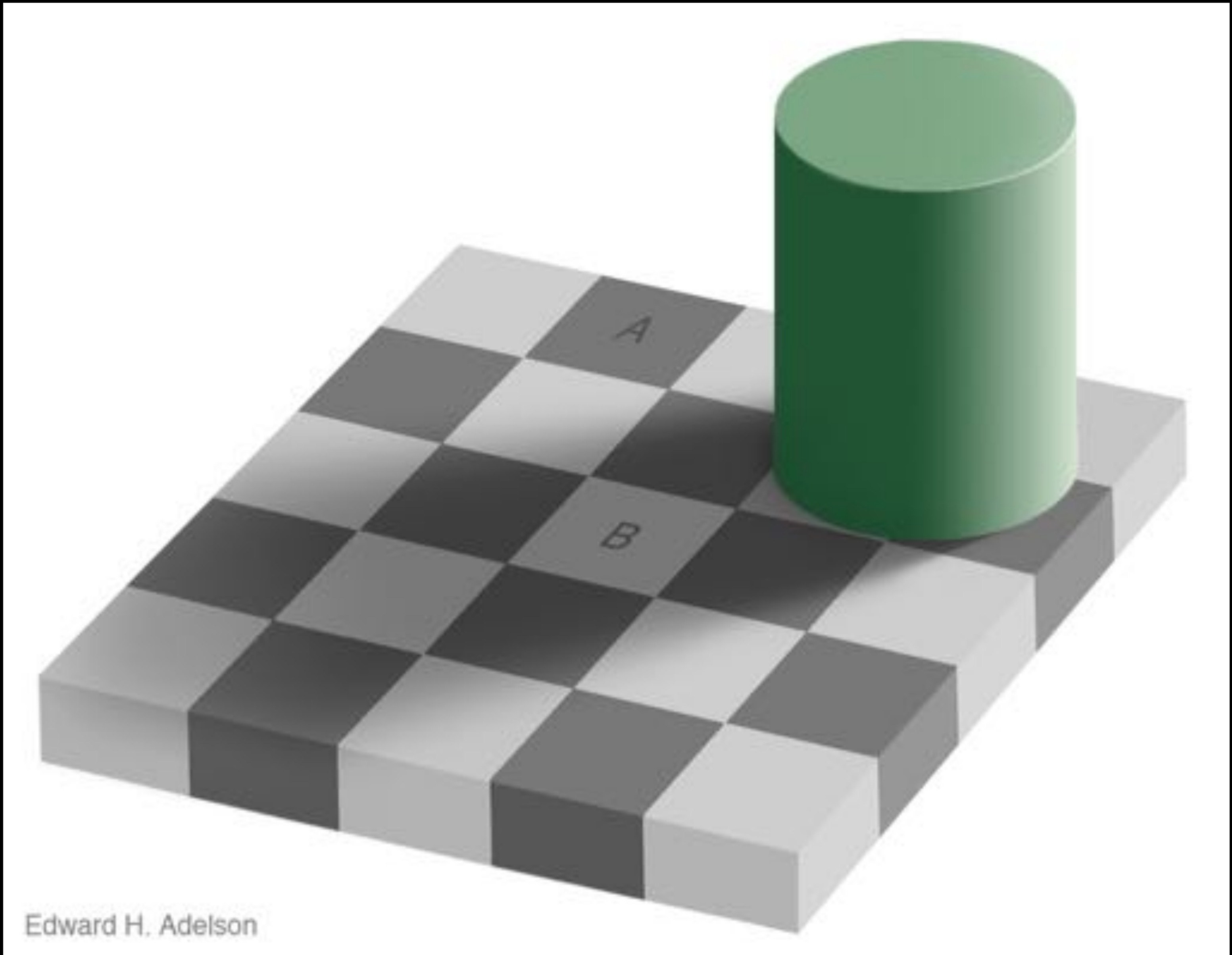
The visual system records differences between the responses of cones, rather than each type of cone's individual response

Chromatic channel	red	vs.	green
Chromatic channel	blue	vs.	yellow
Achromatic channel	black	vs.	white

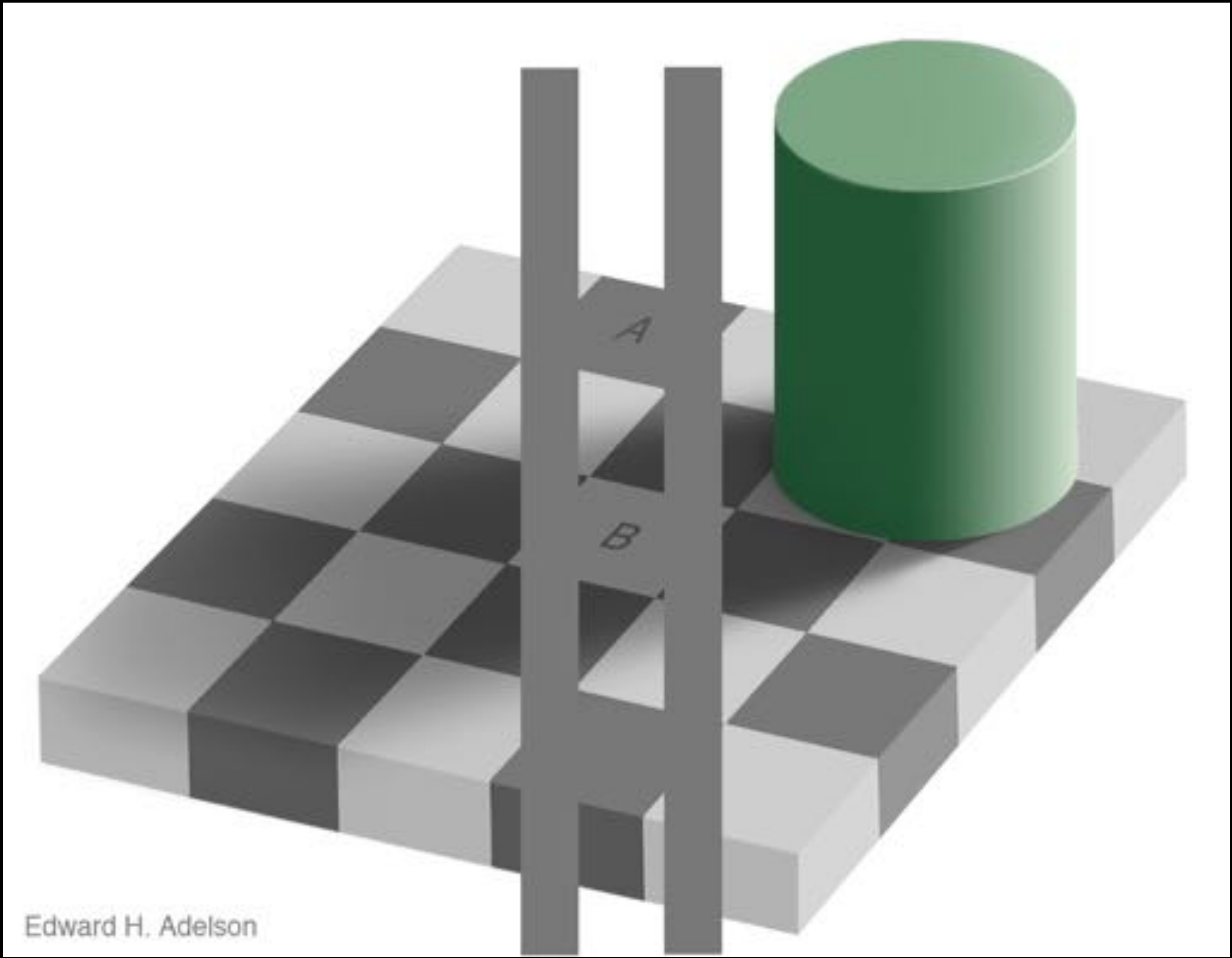
COLOR PROCESSING STAGES



COLOR PERCEPTION

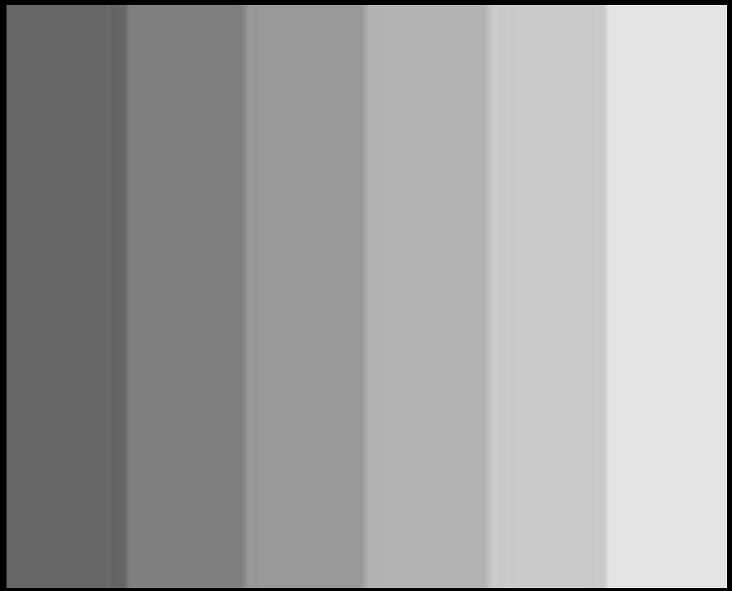


Edward H. Adelson, 1995



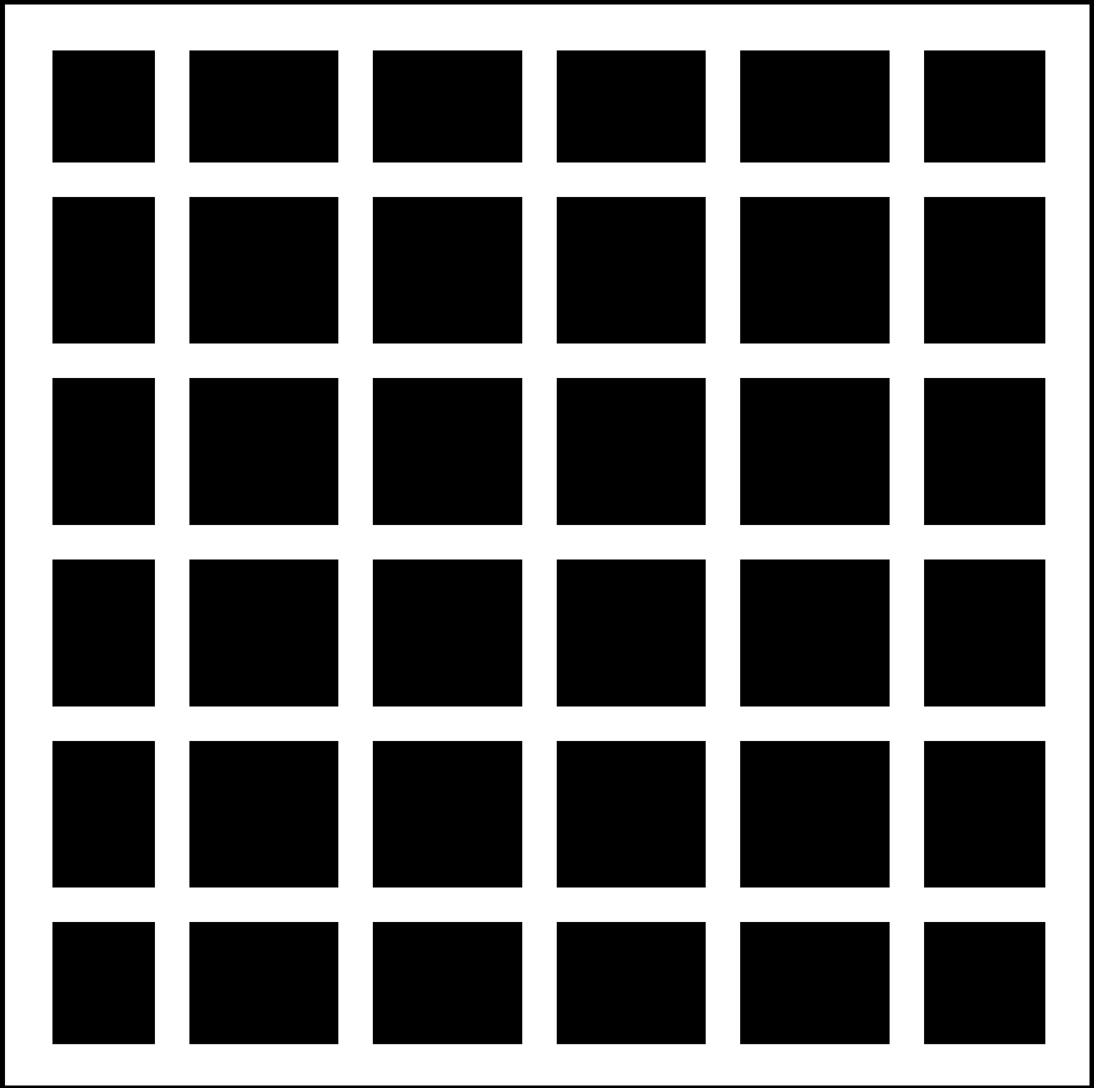
Edward H. Adelson, 1995

MACH BANDS ILLUSION (1865)



The illusion appears as soon as the bands touch. Mach conjectured that filtering is performed in the retina itself by lateral inhibition.

HERMAN GRID ILLUSION



SIMULTANEOUS CONTRAST (UNIVERSAL)

Colors of different objects affect each other

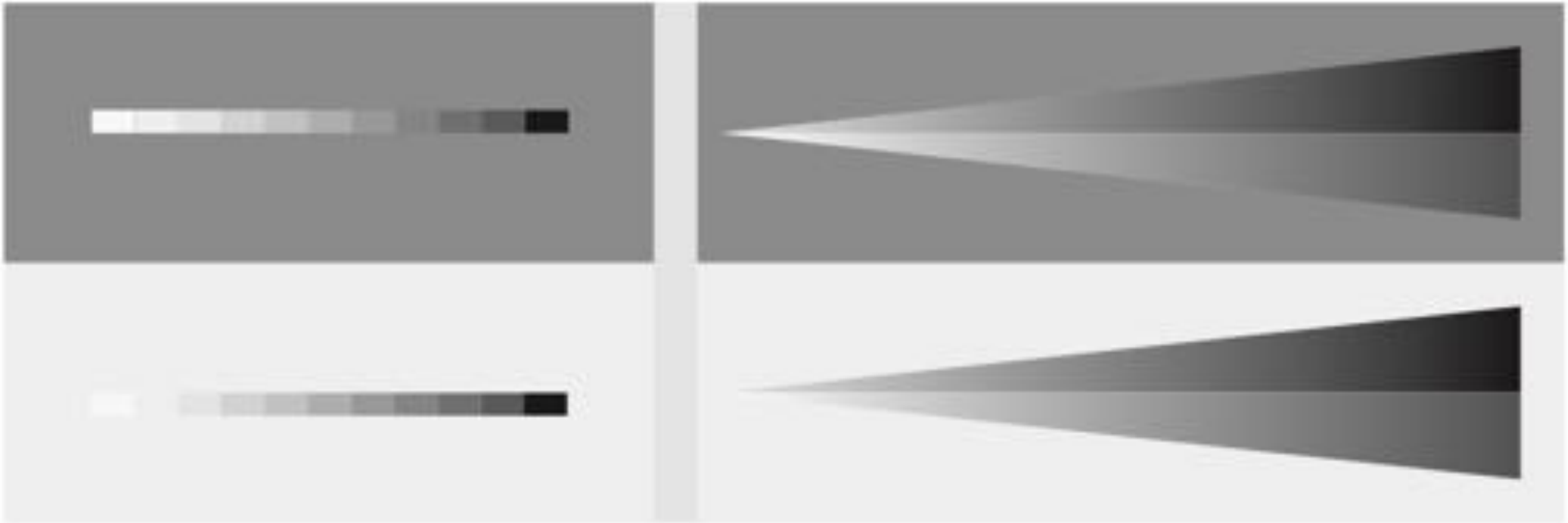
Simultaneous chromatic contrast on the chromatic channels

Simultaneous luminance contrast on the achromatic channel

SHARPENING (UNIVERSAL)

We are more sensitive to dark than light differences

Dark background accentuates midrange



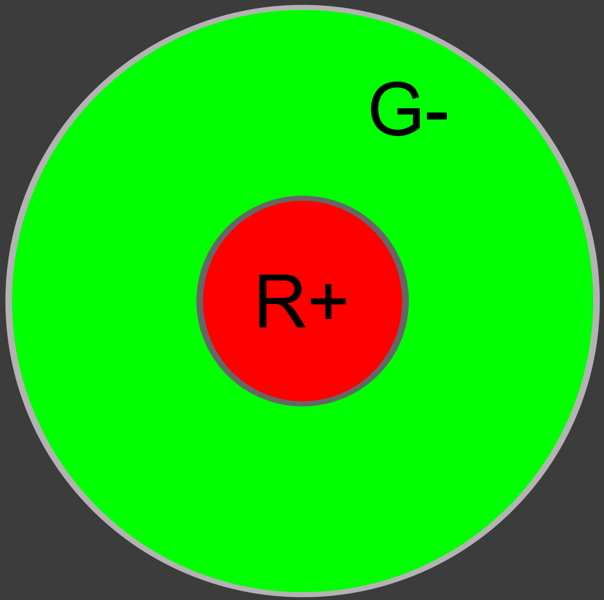
Light background accentuates near white

COLOR CONSTANCY (UNIVERSAL)

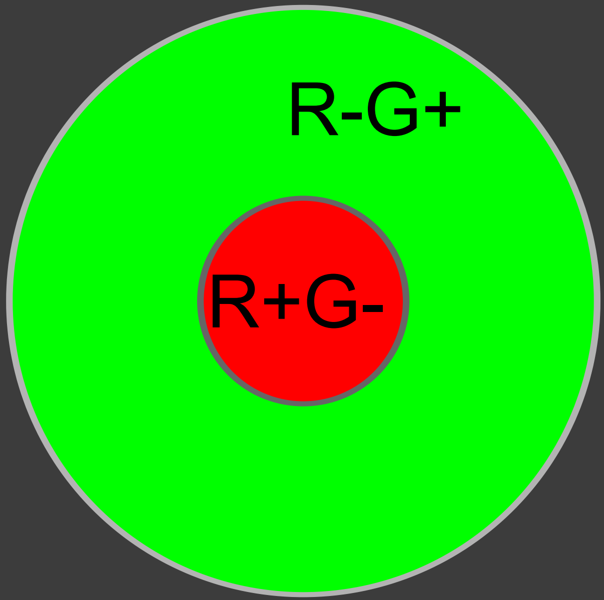
- Color perception to ensure colors remain constant under varying illumination
- Helps identify objects at different times of the day and lighting

OPPONENT CELLS

SINGLE OPPONENT



DOUBLE OPPONENT

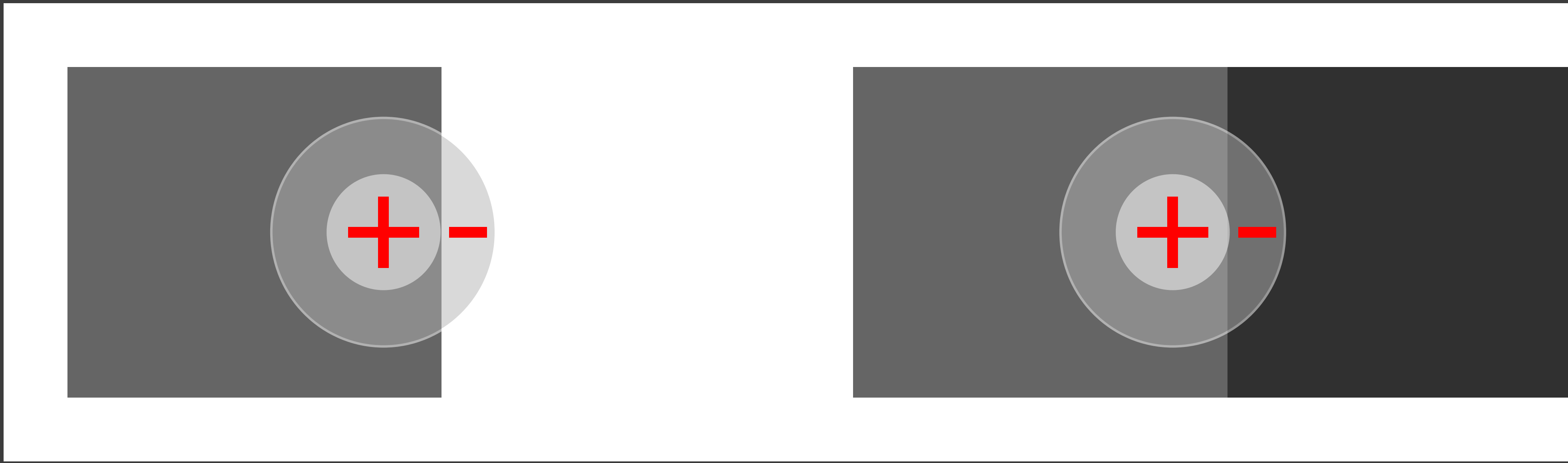


- [Wiesel, Hubel 1966] discovers single opponent cells
- [De Valois 1965] existence of color opponent neurons in the primate visual system

- [Daw 1967] evidence that color constancy is supported by double-opponent cells in V1
- Double opponent cells have a large receptive field than single-opponent cells

LATERAL INHIBITION

Lateral inhibition explains simultaneous contrast



Left: light background causes greater inhibition at the center making the gray surface appear darker. Right: dark background causes smaller inhibition at the center making the gray surface appear lighter

VISION DEFICIENCIES (INDIVIDUAL)

Blurred vision

Color vision deficiency (color blindness)

"As someone with protanomaly, I can see all colors, including red, it's just that red is noticeably weak and so it looks very dark to me. I often can't read black writing on a red background (or vice versa) and sometimes mistake purple with blue."

Colors seen by non-colorblind person

"As someone with protanomaly, I can see all colors, including red, it's just that red is noticeably weak and so it looks very dark to me. I often can't read black writing on a red background (or vice versa) and sometimes mistake purple with blue."

Colors seen by person with protanomaly

TYPES OF COLOR BLINDNESS

Color blindness affects ∼9% of males

Normal vision
All colors in visible spectrum
M: 91.2% F: 99.57%

Deuteranopia
Deuteranomaly
Cone affected: M (green)
M: 6.2% F: 0.36%

Protanopia
Protanomaly
Cone affected: L (red)
M: 2.6% F: 0.04%

Tritanopia
Tritanomaly
Cone affected: S (blue)
M: 0.01% F: 0.03%

Prefixes: nopia is missing, nomaly is reduced response

OUTLINE

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- Colors in D3
- Complex D3 charts

COLOR THEORY

- Color theory is a practical guidance to color mixing and the visual effects of color combinations
- We use a **Color Model** to describe the way colors can be represented as tuples and understand how colors can be mixed

HTML COLOR MODEL

- Colors encoded as tuples: (red, green, blue, opacity)
- 8 bits per channel, i.e., 256x256x256 (~16.7M) colors
- Decimal encoding:
  - Color: integer number $\in [0, 255]$
  - Opacity: real number $\in [0, 1]$, $0 \equiv$ transparent, $1 \equiv$ opaque
- Hexadecimal: color and opacity as hex* number $\in$ [00-FF], 00 $\equiv$ transparent, FF $\equiv$ opaque

name

```html
<div style="background-color: red">name</div> <!-- named colors: red ≡ (255, 0, 0) -->
```

rgba

```html
<div style="background-color: rgba(255, 0, 0, 0.3);">rgba</div> <!-- rgb(,,) or rgba(,,,) -->
```

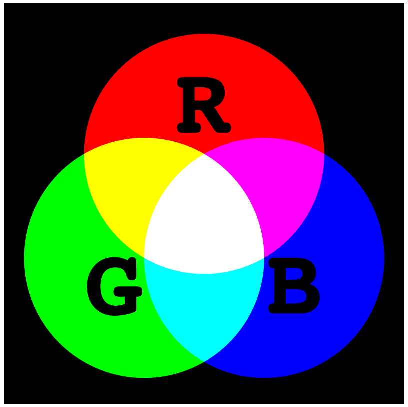
hex

```html
<!-- opacity = 55 → 85, 85/255 = 0.333 -->
<div style="background-color: #ff000055;">hex</div> <!-- #rgb or #rgba -->
```

* Example conversion from hexadecimal to decimal: A = (10×16^1), F = (15×16^0), AF = $(10 \times 16^1) + (15 \times 16^0) = 175$

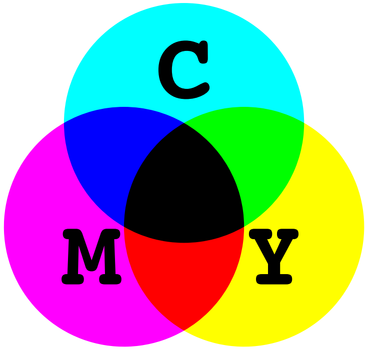
ADDITIVE AND SUBTRACTIVE MODELS

Additive Color Model

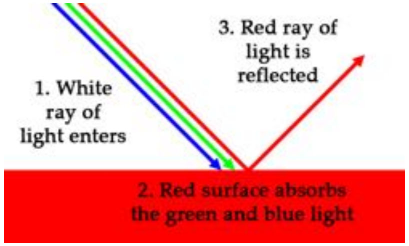


- Primary colors: RGB
- Secondary colors: CMY
- Good for: LCD displays, and projectors

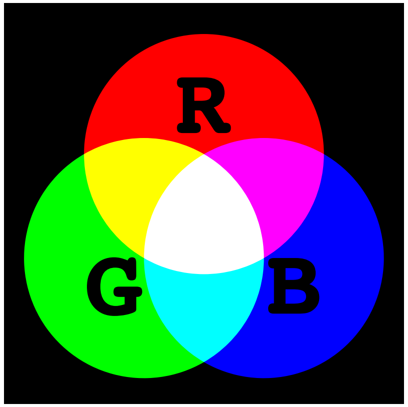
Subtractive Color Model



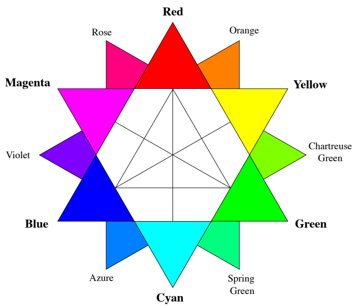
- Primary colors: CMY
- Secondary colors: RGB
- Good for: printed material and painting



PRIMARY, SECONDARY AND COMPLEMENTARY COLORS



Additive color model cube



Additive color model star (wheel)
Charles Blanc (1867)

Primaries

Mixed create all other colors
Cannot be mixed from other colors

red | green | blue — 3 primary colors

red + green + blue = white

Secondary

Colors mixed from 2 primaries

cyan | magenta | yellow — 3 secondary colors

cyan + magenta + yellow = white

red + blue = magenta — mixed from 2 primaries

blue + green = cyan

green + red = yellow

Complementary

Pairs that combined cancel out.

red + cyan = white

blue + yellow = white

green + magenta = white

orange + azure = white

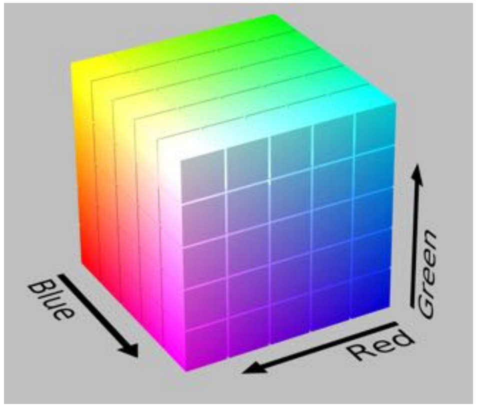
ADDITIVE COLOR MODEL TECHNIQUES

Addition of illumination	Projected colors overlap, e.g., stage projectors
Partitive mixing	Closely spaced colored dots, e.g., LCD screens
Time mixing	OLED micro displays, rotating color wheels, sequential illumination
Binocular mixing	Different colors on each eye, mixed by the brain

RGB COLOR MODEL

Characteristics

- Additive color model
- Named after the three primary colors, red, green, and blue.
- Based on the Young–Helmholtz theory of trichromatic color vision
- Representation: RGB color cube



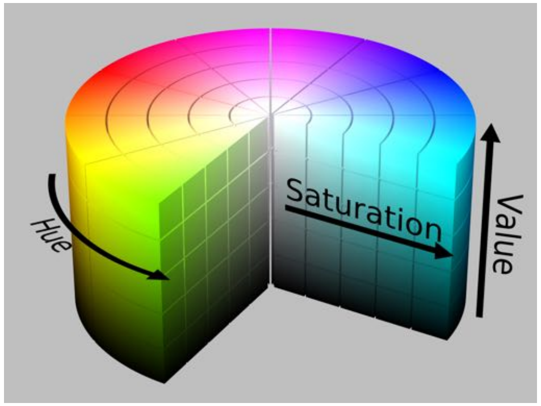
RGB color model mapped to a cube

Color picker in RGB color model mode

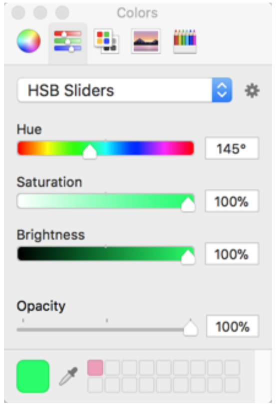
HSV COLOR MODEL

Characteristics

- HSV for hue, saturation, value
- Also know as HSB, for hue, saturation, brightness
- Additive color model
- HSL for hue, saturation, lightness is the corresponding subtractive model
- Designed in the 1970s by computer graphics researchers to more closely align with the way human vision perceives color-making attributes
- Representation: HSV color cylinder



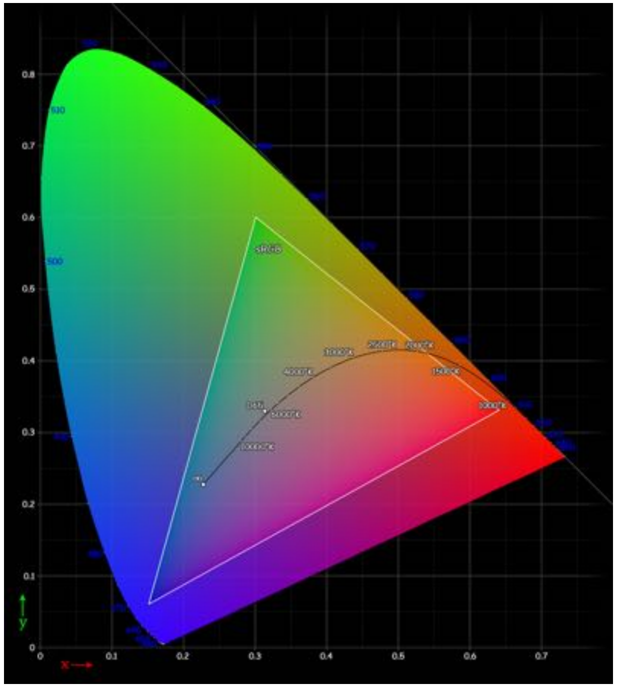
HSV color cylinder



Color picker in HSB color model mode

COLOR SPACES

- A color space is a specific organization of colors
- Used to represent the gamut (subset of colors) that is accurately represented by a device or digital file
- Color in color spaces are represented as:
  - Chromaticity (2d): hue and saturation
  - Luminance (1d)
- The CIE 1931 color spaces were created by the International Commission on Illumination (CIE) in 1931 as a quantitative link between distributions of wavelengths in the electromagnetic visible spectrum and physiologically perceived colors
- Default in browsers: sRGB color space HP and Microsoft, 1996



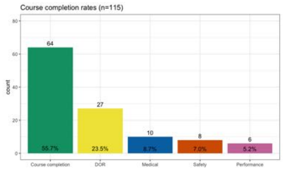
sRGB gamut shown on CIE xy chromaticity diagram. Larger triangle is the entire range of possible chromaticities for CIE 1931. Smaller triangle is the gamut available to the sRGB color space typically used in computer monitors. Curved edge represents the monochromatic (single-wavelength) or spectral colors. Color temperature curve shown in black in degrees Kelvin.

OUTLINE

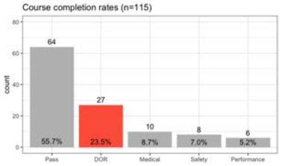
- Color perception
- Color theory
- Color design
- Colors in D3
- Complex D3 charts

USES OF COLOR [TUFTE]

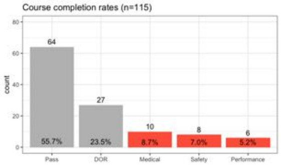
Color used to label to identify, highlight or group



Identify

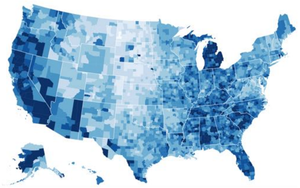


Highlight

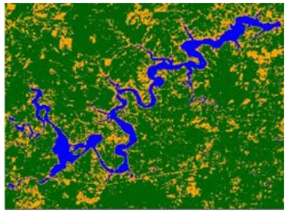


Group

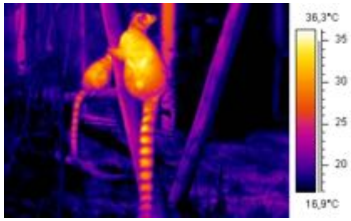
Measure, represent or imitate reality



Choropleth

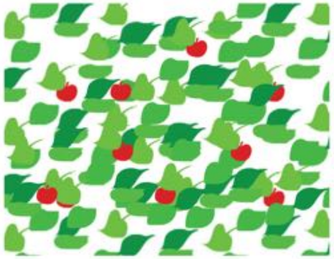


Density slicing



False colors

Enliven (make more attractive) or decorate

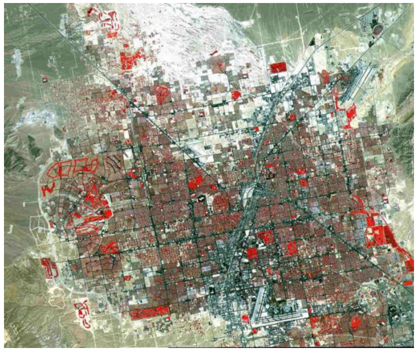


TRUE, FALSE AND PSEUDO COLORS

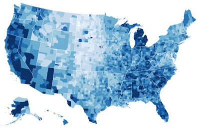
True-color

Colors appear similar to a viewer of the image and to an observer of the scene

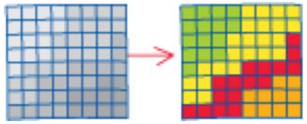
False-color



Aerial imagery where N (near-infrared band) is mapped to red, i.e., NRG → RGB

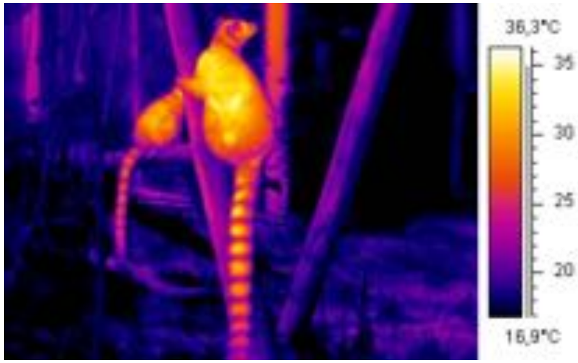


Choropleth map



Density slicing

Pseudocolor



Derived from a grayscale image by mapping each intensity value to a color according to a table or function, e.g., G → RGB

OPTIMAL COLOR CONTRAST

Blue text is harder to read (relatively smaller number of S cones)

Red text is easier to read (relatively larger number of L cones)

Green text is easier to read (relatively larger number of M cones)

Achromatic white on black is easier to read than chromatic channels (3 x better than color because we use all 3 receptors)

Achromatic black on white as clear than black on white with less strain (e.g., *"dark mode"*)

If using colors for text and background opponent channels provide the best contrast

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When placed next to each other, complementary colors create the strongest contrast for those two colors.

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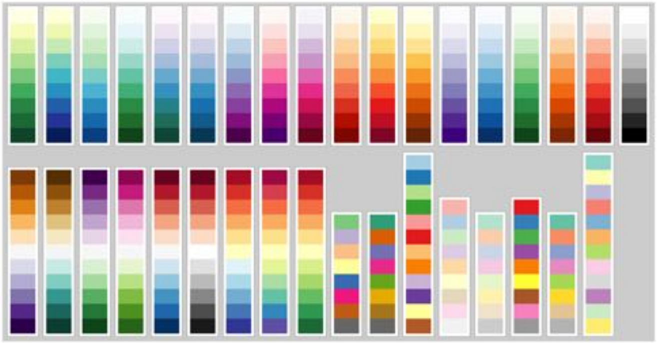
COLOR SCALES

- Use established color sequences, e.g., ColorBrewer
- Use appropriate color scale type (continuous, discrete) and/or sequence type (sequential, diverging, qualitative)
- Use colorblind safe colors (e.g., test with Dev Tools)
- With discrete scales, limit colors used as keys to 5-7

Every ColorBrewer Scale



TYPES OF COLOR SEQUENCES

Sequential

Ordered data, light colors for lower values to dark colors for higher values

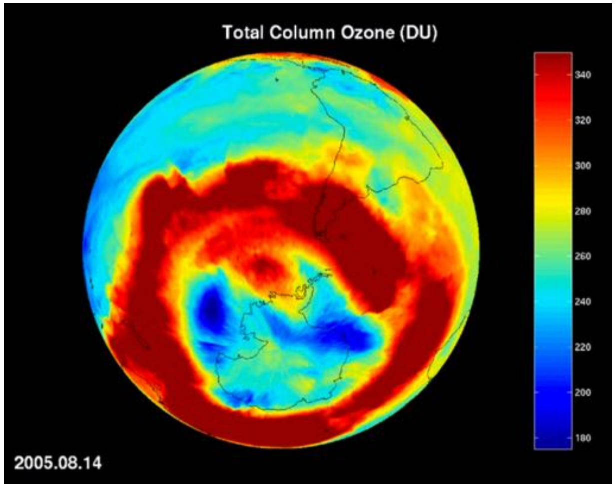
Diverging

Critical class or break in the middle, sequential sequences of contrasting hues on both ends.

Qualitative

For nominal or categorical data.

MISC RECOMMENDATIONS (1)

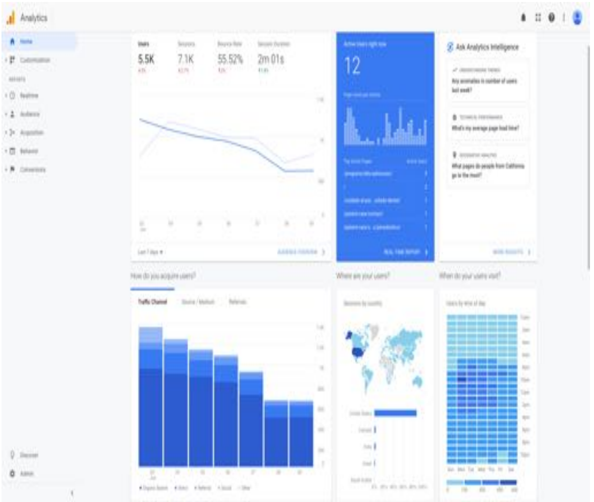


Respect well-established color sequences

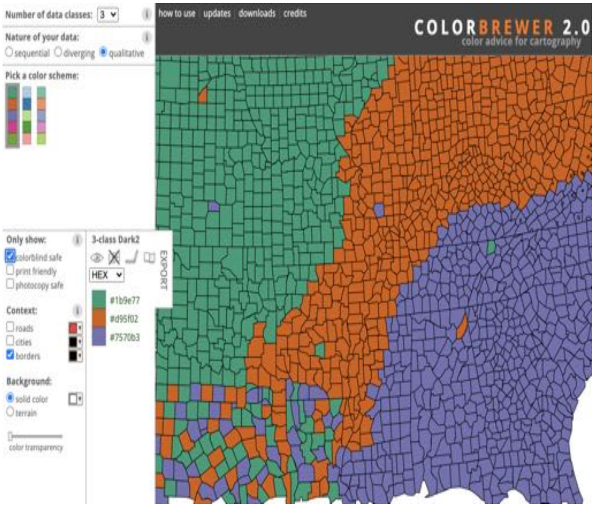
Observe cultural conventions

Use color palettes for more attractive and effective displays

MISC RECOMMENDATIONS (2)



Use consistent color encodings across graphics



Use colorblind safe colors

A 3:1 contrast ratio

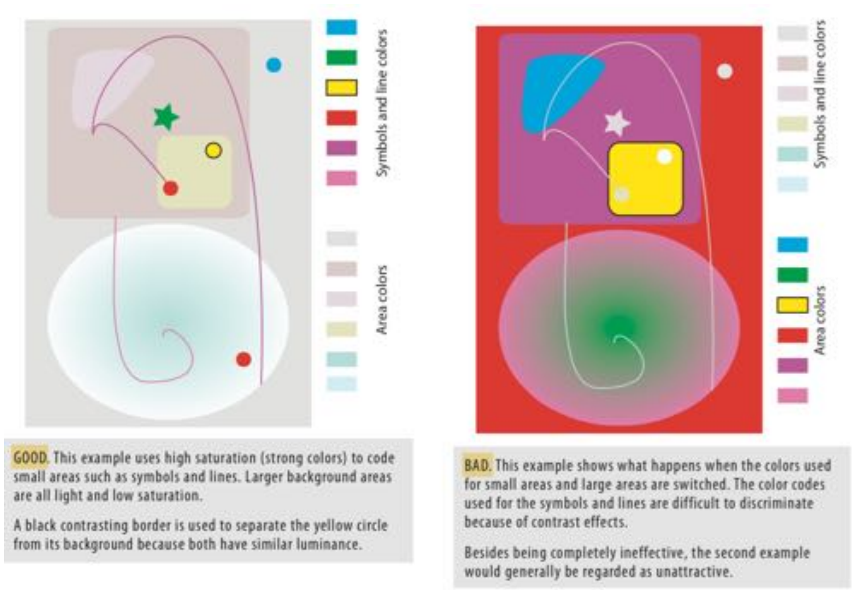
AA 4.5:1 contrast ratio

AAA 7:1 contrast ratio

Apply color accessibility standards

MISC RECOMMENDATIONS (3)

- Use accent colors for the most important visual queries
- Use lighter colors for background, saturated colors for small areas, and ensure good color contrast



Colin Ware. Visual thinking: For design. Morgan Kaufmann, 2010.

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D3 COLOR UTILITIES

```
//d3-color and d3-scale-chromatic are included in d3

//d3-color provides color manipulation and color space conversion.
var c = d3.hsl("steelblue");
console.log(c);  //{h: 207.272, s: 0.44, l: 0.343, ...}

c = c.darker();
console.log(c);  //{h: 207.272, s: 0.44, l: 0.490, ...}

c = c.brighter();
console.log(c);  //{h: 207.272, s: 0.44, l: 0.490, ...}

//d3-scale-chromatic provides ColorBrewer and other colors schemes
var accent = d3.schemeAccent;  //["#7fc97f", "#beaed4", "#fdc086", ...]

//d3-hsv needs to be loaded separately (npm install d3-hsv)
var yellow = d3.hsv("yellow"); // {h: 60, s: 1, v: 1, opacity: 1}
```

d3/d3-color
d3/d3-hsv
d3/d3-scale-chromatic

D3 COLOR SCALES

Input Domain Data	$\longmapsto$ scale	Ouput Range Colors

	Continuous	Discrete
Continuous	Linear Sequential Diverging	Quantize Quantile
Discrete		Ordinal Threshold

OUTLINE

- Color perception
- Color theory
- Color design
- Colors in D3
- Complex D3 charts

D3 LIBRARIES FOR COMPLEX CHARTS

Library	Type	Description	Charts
d3-shape	Generator	Graphical primitives for visualization, such as lines and areas.	Line, area, pie charts, symbols...
d3-chord	Layout	Relationships or network flow in circular layout.	Chord diagram
d3-force	Layout	Force-directed graph layout using velocity Verlet integration.	Physical simulations in networks and hierarchies, bubbles charts...
d3-hierarchy	Layout	2D layout algorithms for visualizing hierarchical data.	Treemaps, dendrograms, circle-packing...
d3-sankey	Layout	Directed flow between nodes in an acyclic network.	Sankey diagrams
d3-hexbin	Generator	Group two-dimensional points into hexagonal bins.	Hexbins plots
d3.histogram	Generator	Computes the histogram for the given array.	Histograms