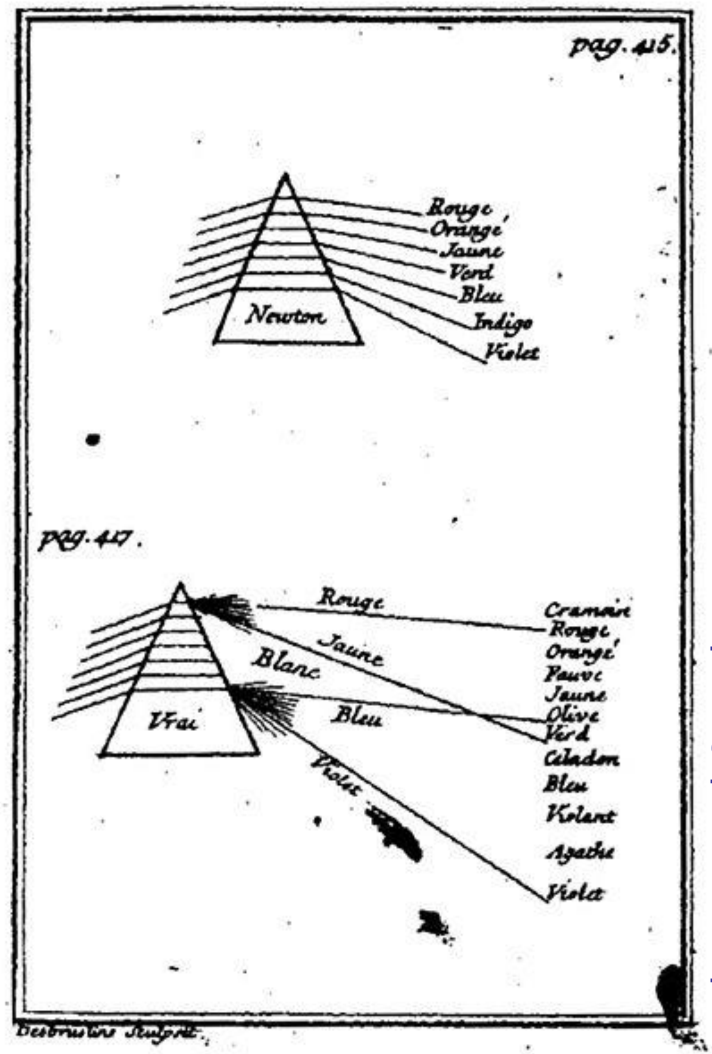
Computer Graphics

Color

Overview

- what is color?
- human color perception
- color models
  - CIE XYZ
  - RGB & CMY(K)
  - HSV/HSB & HSL/HLS
- color pitfalls
  - perception again
  - color deficiency



Louis-Bertrand Castel, 1714

Overview

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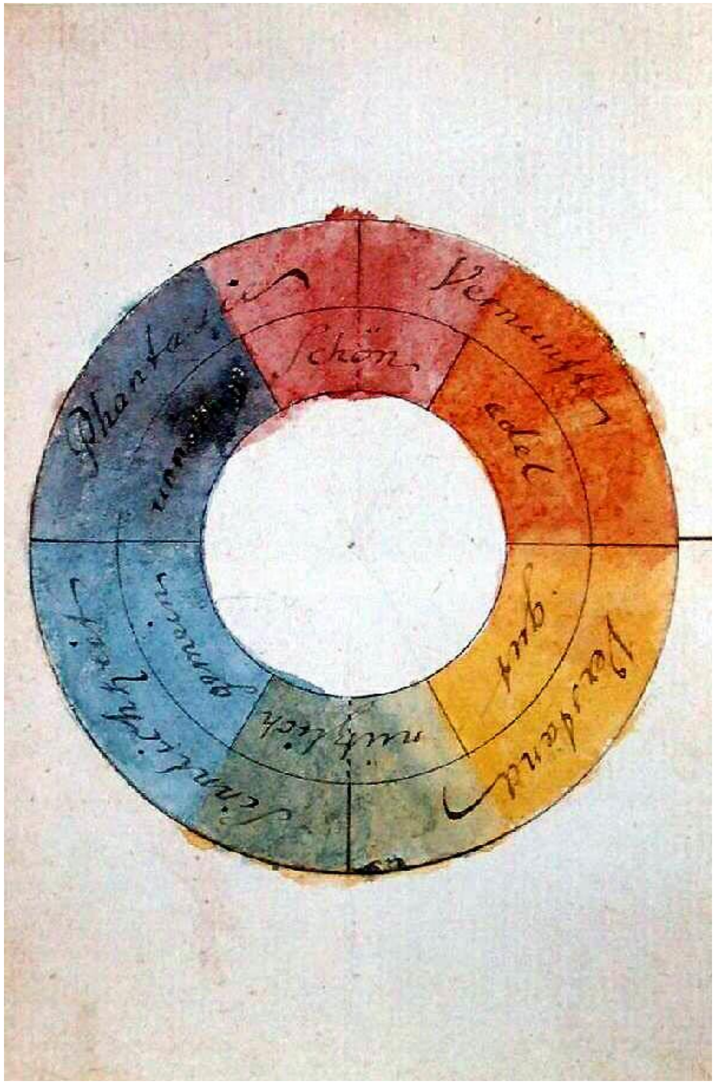
  - – perception again
  - – color deficiency



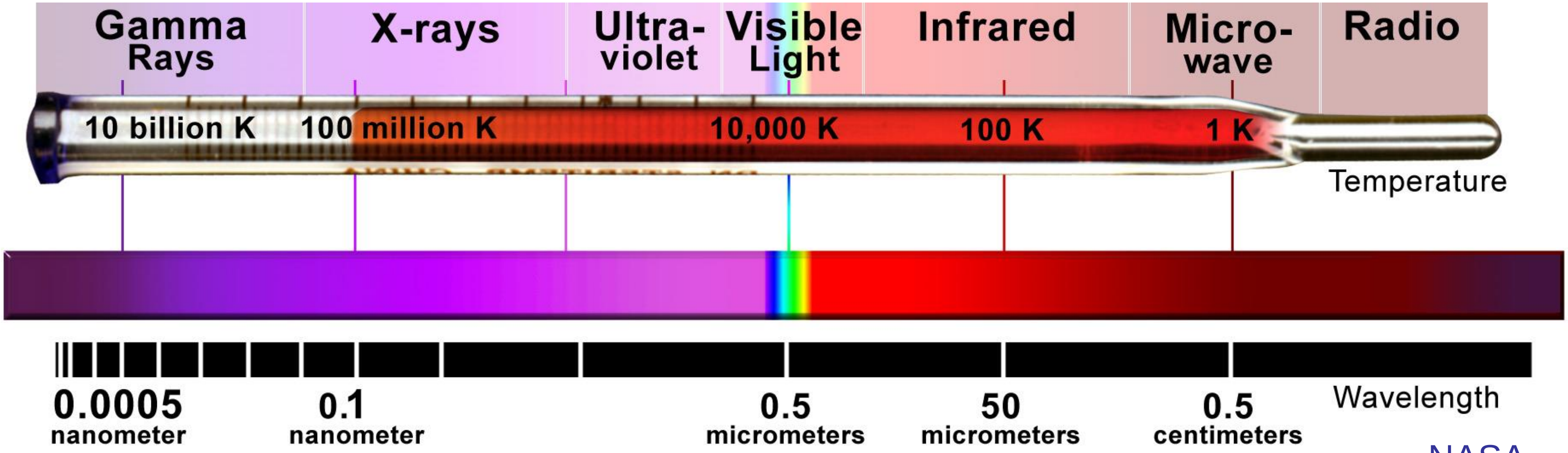
Johann Wolfgang von Goethe, 1809

What is Color?

What is Color?

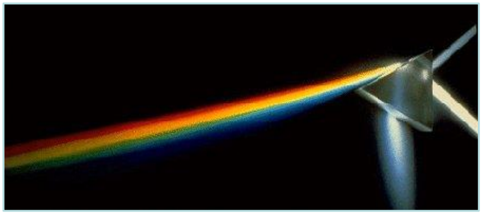
What is Color?

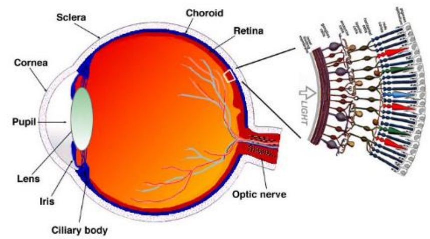
- color is a **human reaction** to light (change)
- what is light?
- light is the visible part (370–730nm) of the electromagnetic spectrum



NASA

What is Color?





“Yellow”

physical world → visual system → mental models

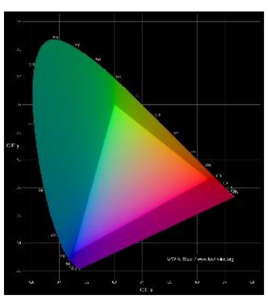
lights, surfaces, objects

eye, optic nerve, visual cortex

red, green, brown

bright, light, dark, vivid, colorful, dull

warm, cool, bold, blah, attractive, ugly, pleasant, jarring

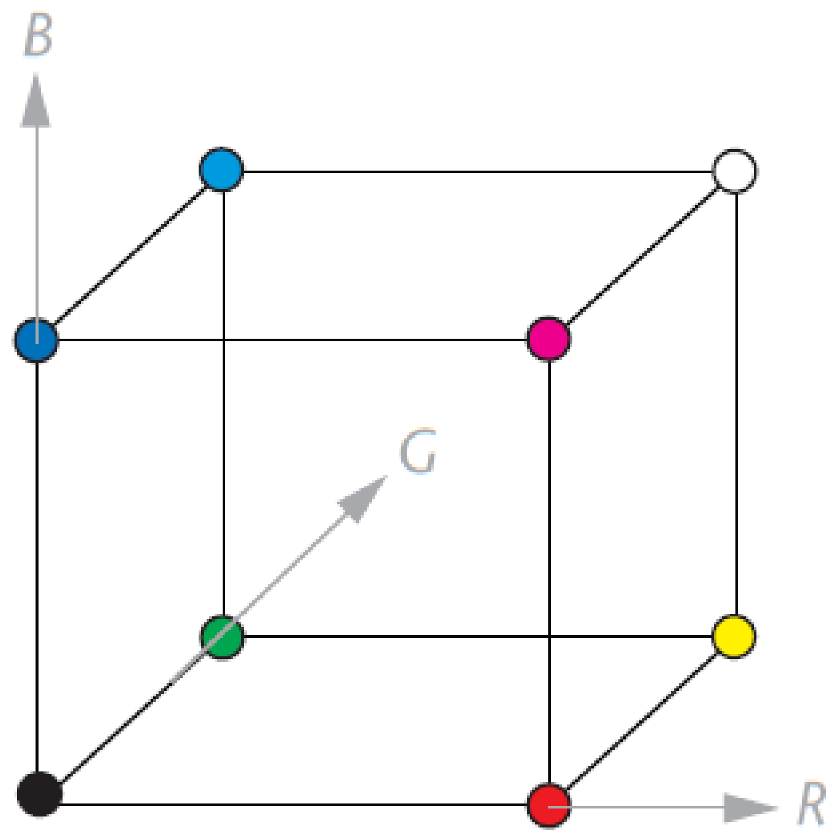


color models

RGB, CMYK, CIE XYZ, CIE Lab HSV/HSB, …

RGB color model

- so far: using 3 values (RGB) to represent the colors to use
- why three values?
- are three values enough?
- can all colors be represented by these three values?



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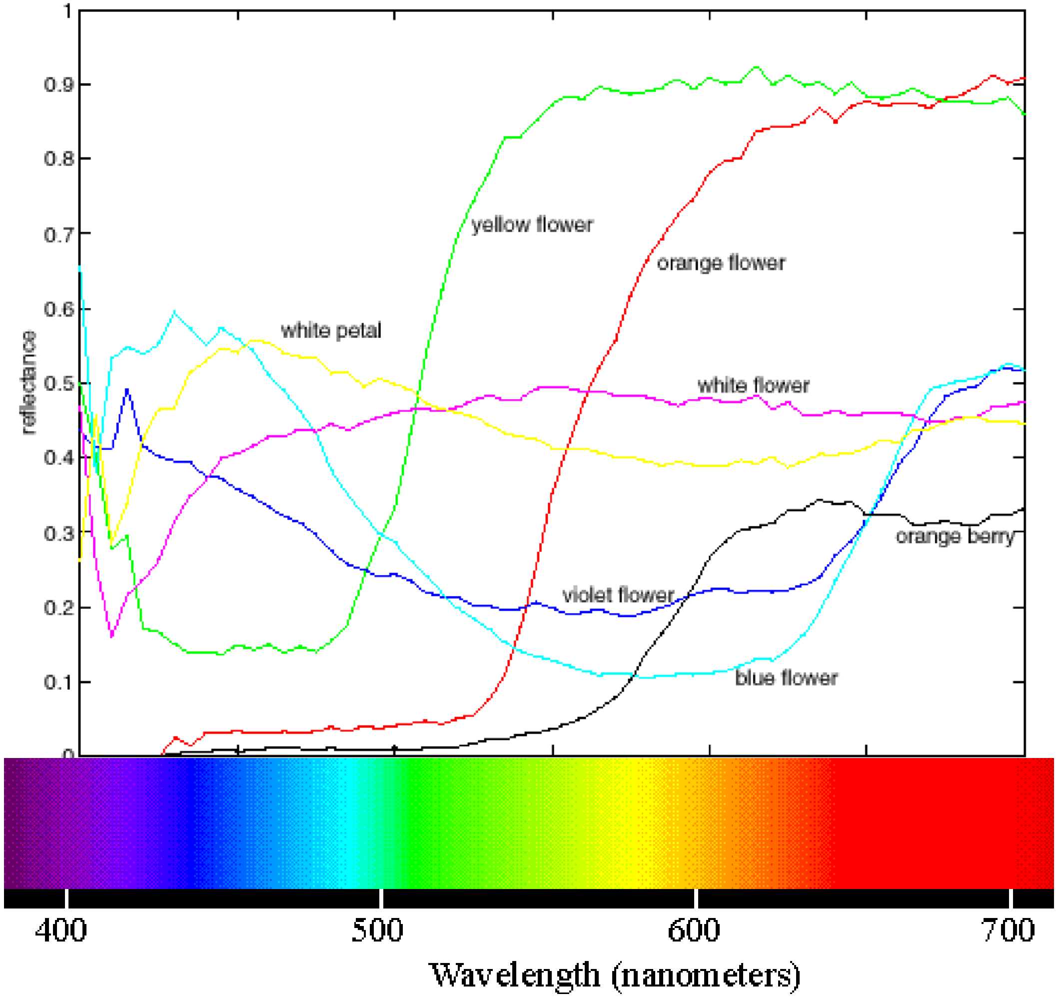
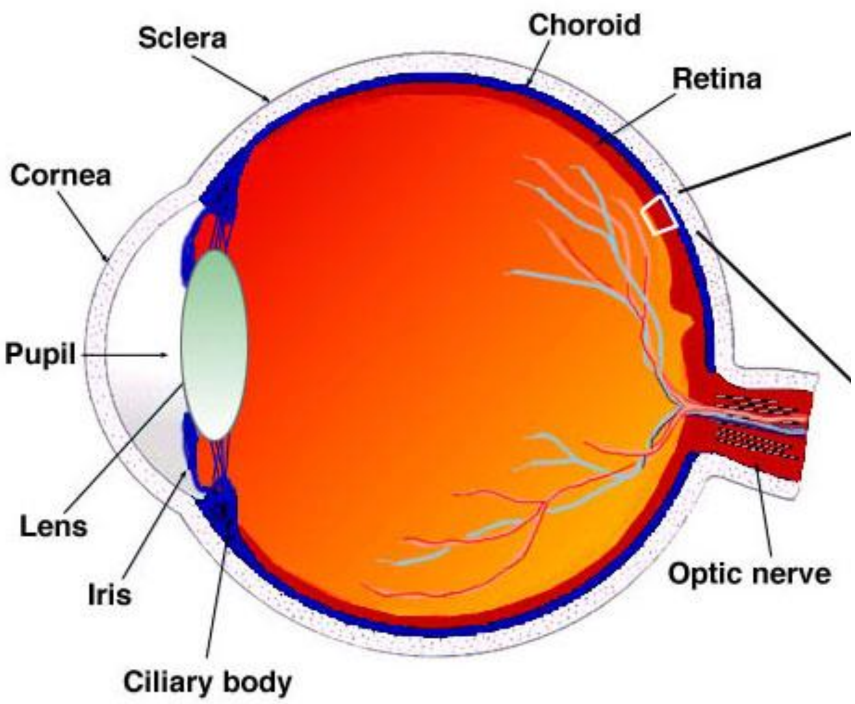
Most colors are not monochromatic



Physical World → Visual System

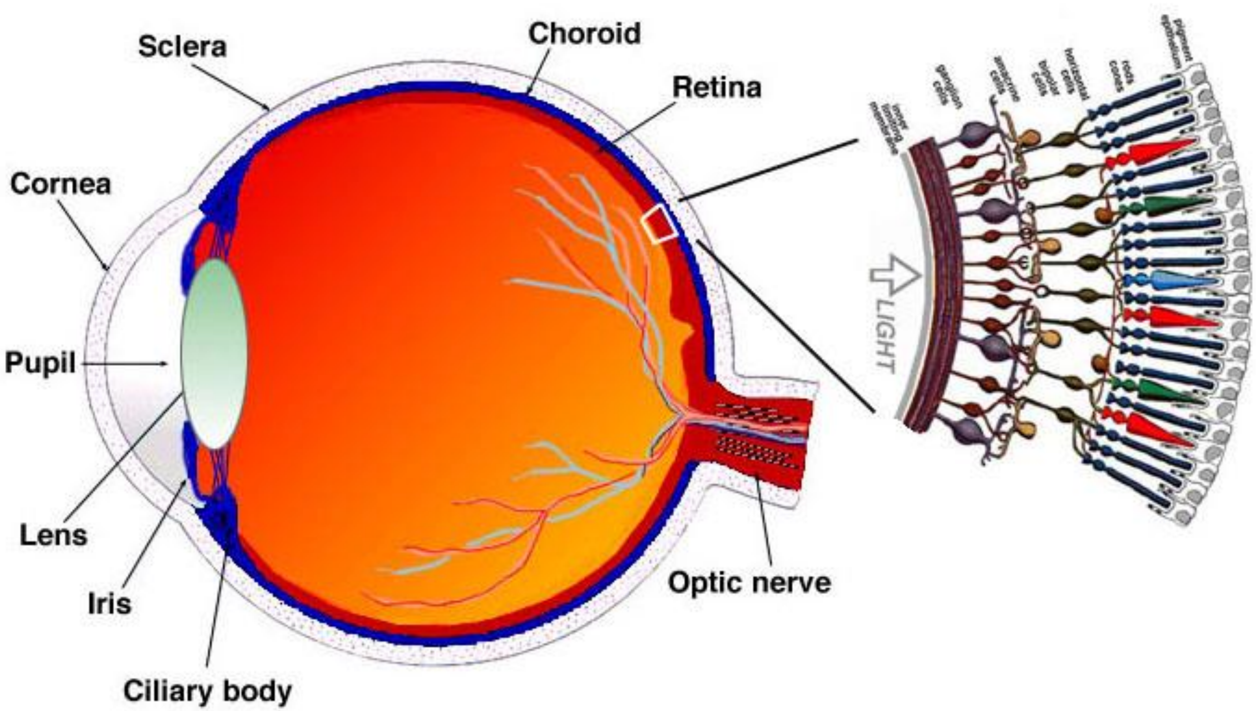


You **do not** see the spectrum of light

- Eyes make limited measurements
- Eyes physically adapt to circumstance
- You brain adapts in various ways
- Weird stuff happens

Simple Anatomy of the Retina, Helga Kolb

Physical World → Visual System



Rods

- No color (sort of)
- All over the retina
- More sensitive

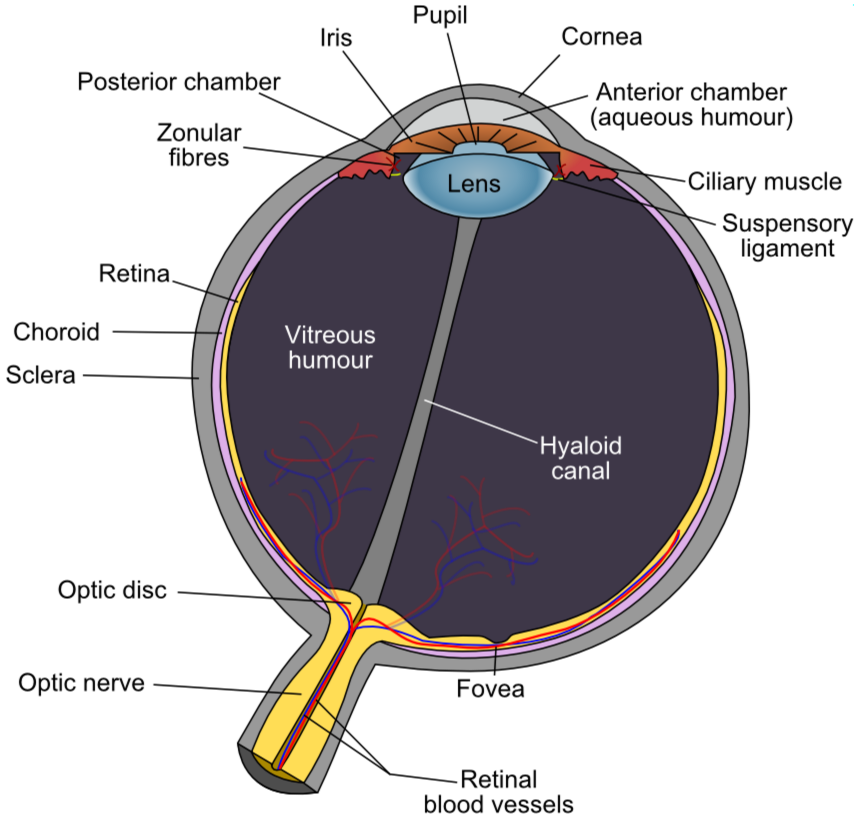
Cones

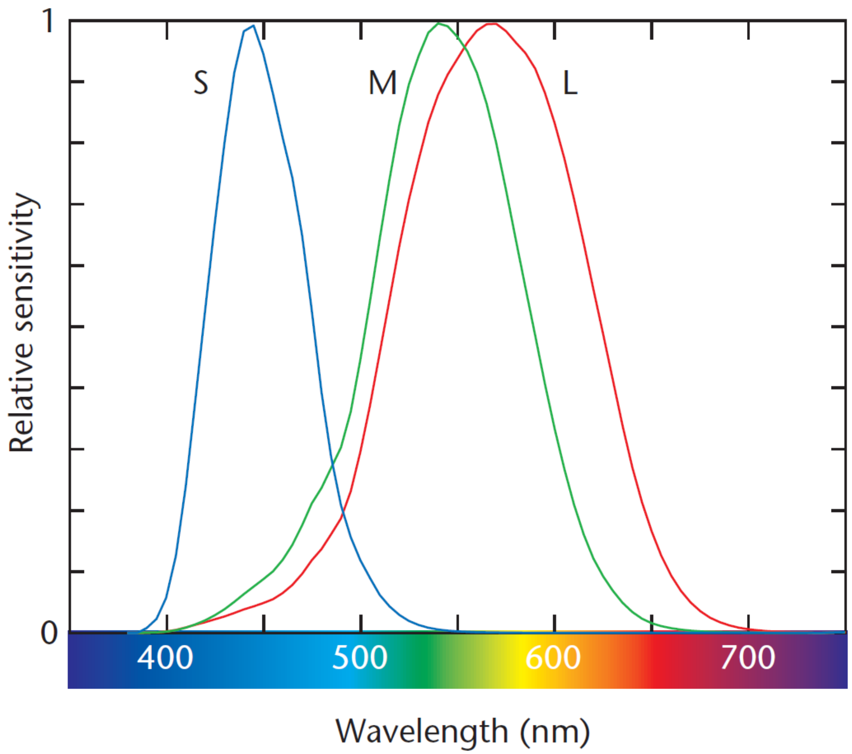
- Three different kinds of “color receptors”
- Mostly in the center
- Less Sensitive

Simple Anatomy of the Retina, Helga Kolb

Physical World → Visual System

- light is converted into signals by cone cells
- three cone types with different sensitivities





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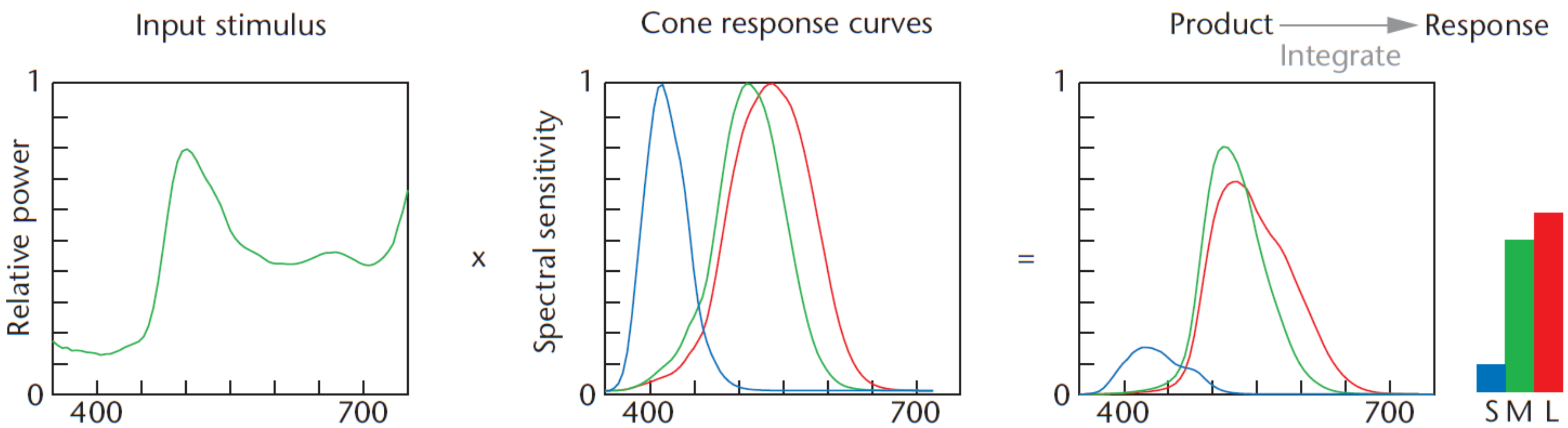
Physical World → Visual System

- colored light = spectral distribution function: light intensity as function of wavelength
- converted into 3 response values by cones (short, medium, and long wavelengths)



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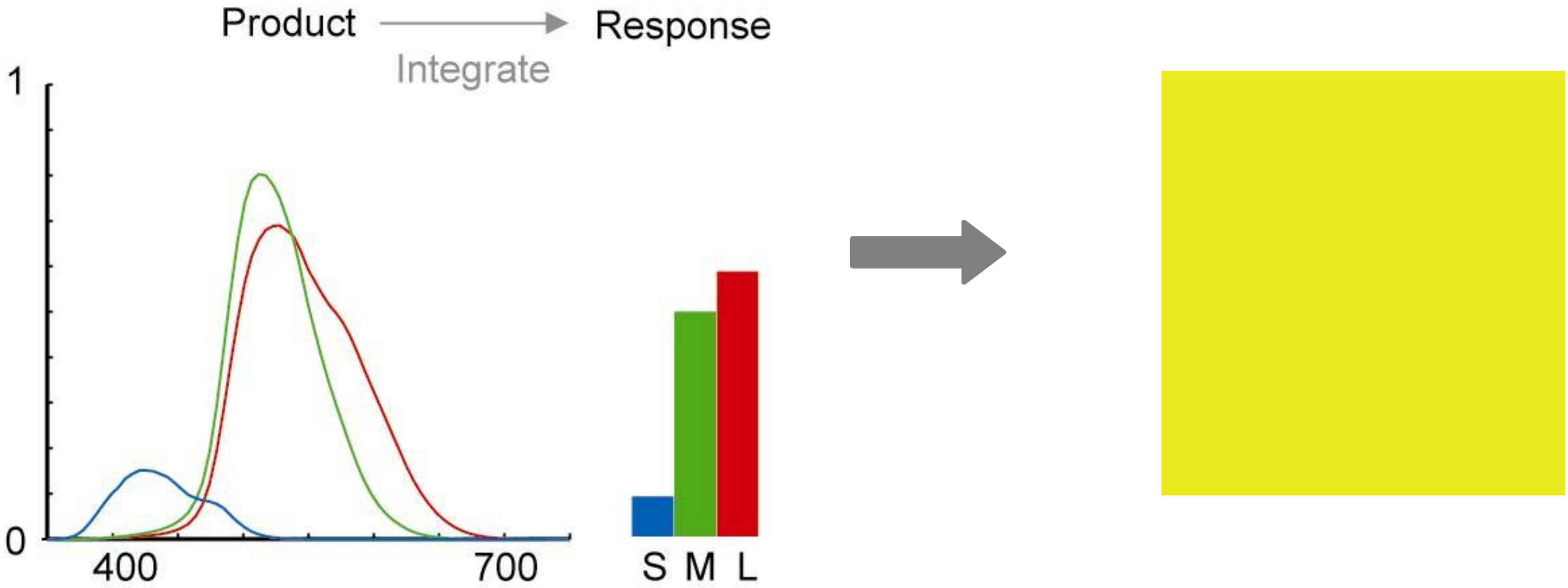
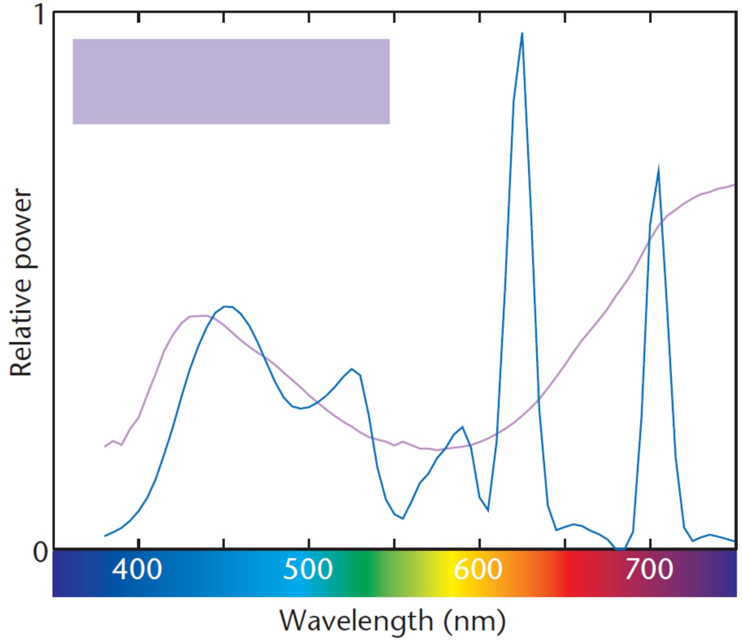
Visual System → Color Models



Two Principles of Color Perception

- **trichromacy**:
  representation of all spectral distributions possible with three values without information loss (w.r.t. the visual system)
  → essential for CG!
- **metamerism**:
  different spectra exist that produce the same trichromatic response



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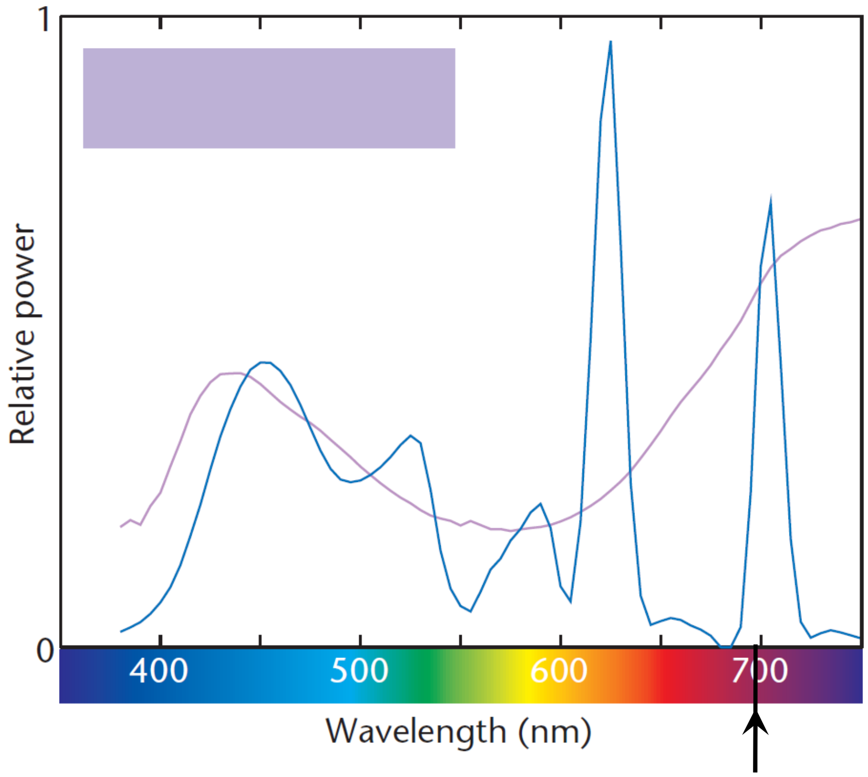
Dominant Wavelengths

- each spectrum can be represented by one wavelength (i.e., spectral color): **dominant wavelength**
- is a metamer for this spectrum
- usually **NOT** highest peak in the spectrum



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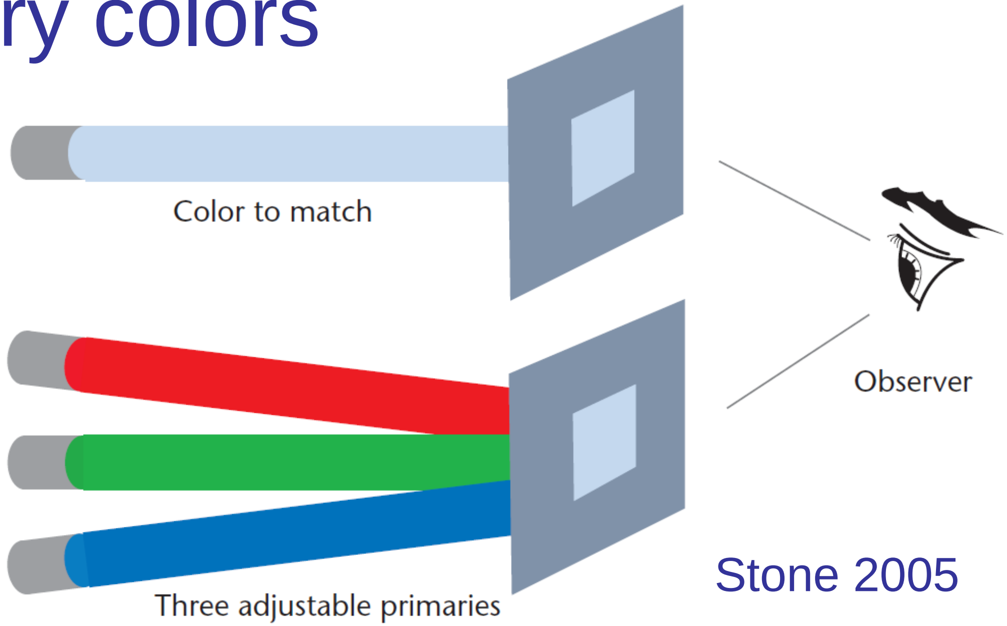
Color Matching Experiments

- given a reference light source with a specific color, three **primary colors** (e.g., red, green, blue), and an observer
- task: match the **reference color** by adjusting the primary colors
- result: **tristimulus values** for color
- specific to set of primaries and observer



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Color Matching Experiments

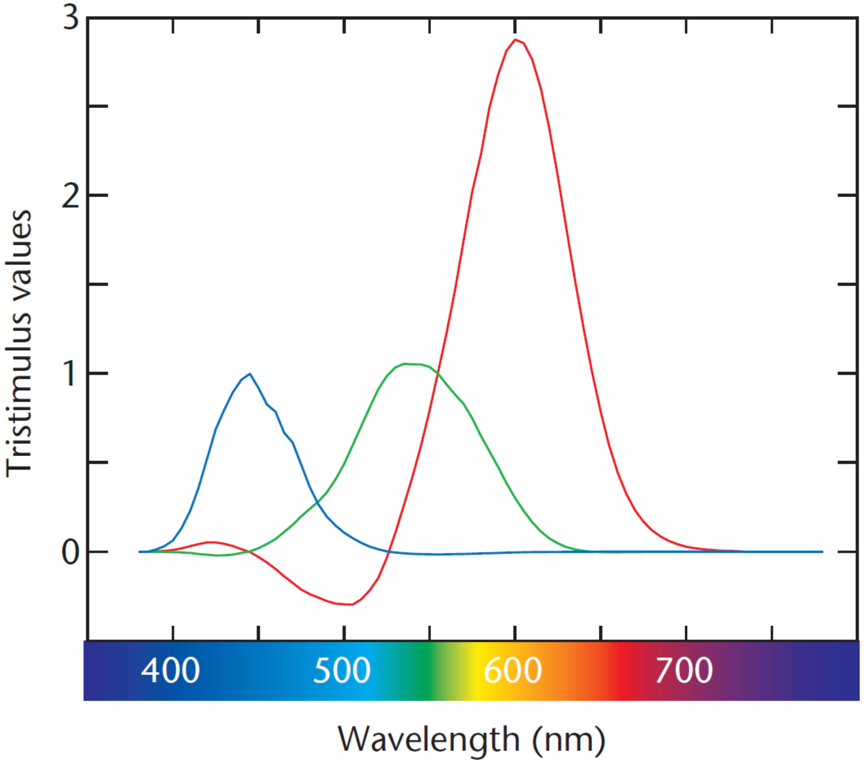
- **analogy to RGB** color representation: RGB values define mixture of primary colors to *uniquely define a color* (provided *identical display* is used with *identical phosphor mixtures*)
- problem: every human is different
  → so need one color model per person?
- experiments in the 1920s and 30s: most people have similar color perception
  → definition of standard observer

Color Matching Experiments

- observation: tristimulus values are additive:
  $RGB_1 \leftrightarrow S_1$ & $RGB_2 \leftrightarrow S_2 \Rightarrow$
  $RGB_1 + RGB_2 \leftrightarrow S_1 + S_2$
  (Grassmann's additivity law)
- i.e., using **a finite set of color matches** allows to **specify infinitely many colors**, or any spectral distribution can be modeled
- thus, any color can be modeled as a weighted sum of monochromatic (single wavelength) colors $\rightarrow$ new experiment

Color Matching Experiments

- color matching of **monochromatic colors**
- result: three color-matching functions
- primaries: red, green, and blue
- **negative color** necessary when monochromatic colors cannot be matched with primary colors



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Color Matching Experiments

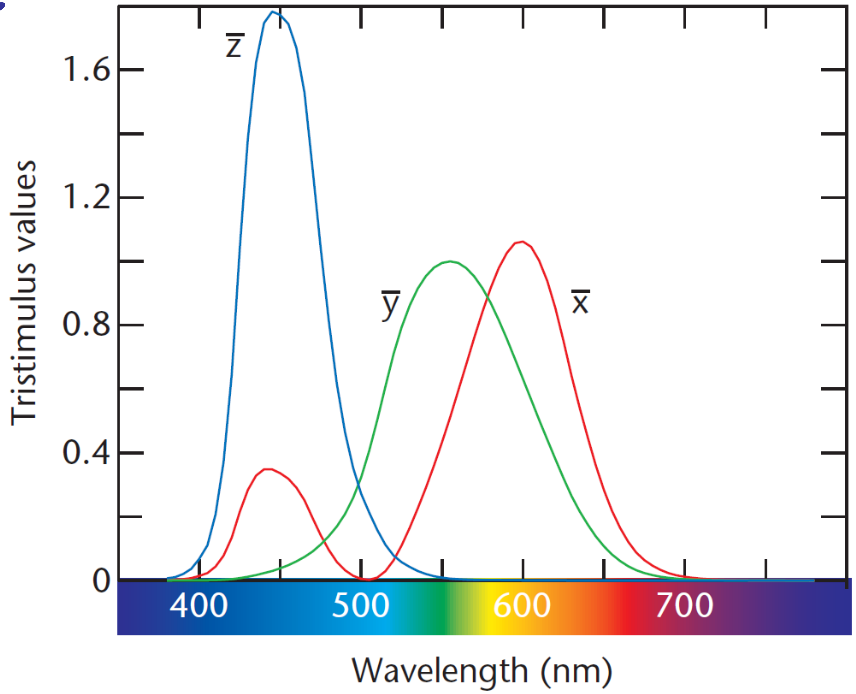
- to create tristimulus values for arbitrary spectrum:
  - multiply it separately with each of the (three) individual color-matching functions
  - integrate result for each of the (three) individual color-matching function
  - yields relative weight for primary light source
  - i.e., tristimulus values for the perceived color
- input spectrum and resulting weighted primary colors produce **metamers**

CIE Standard Observer

- Commission Internationale de l'Eclairage (International Commission on Illumination)
- averaged color matching experiments in 1931 (using small visual fields of 2°)
- second standard observer (10°) for larger visual fields (for 4° and above) in 1964
- most digital imaging applications use the 2° small visual field standard observer

XYZ Color Model

- definition of three primary colors: X, Y, Z
  - color-matching functions are non-negative
  - Y follows the standard human response to luminance, i.e., the Y value represents perceived brightness
  - can represent all perceivable colors
- mathematically derived from experimental curves



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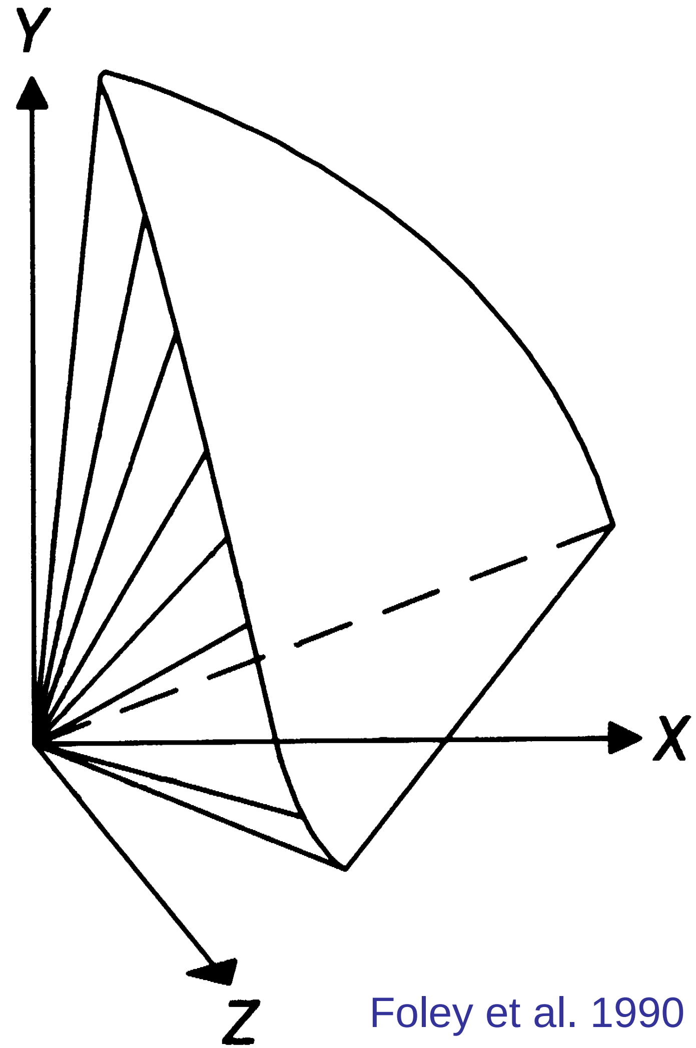
XYZ CIE Color Space

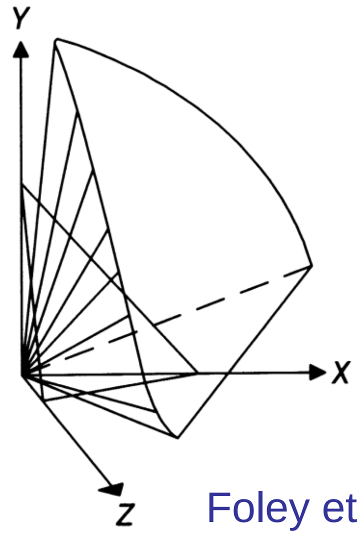
- plotting XYZ space in 3D
- all colors that are perceivable by humans form a deformed cone
- *X*, *Y*, and *Z*-axes are outside this cone

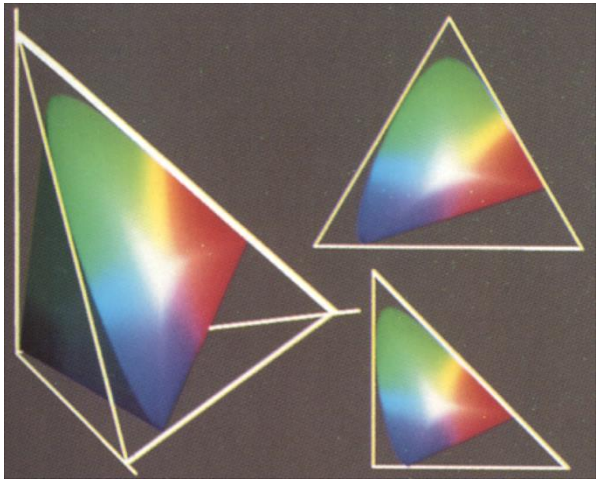


Foley et al. 1990

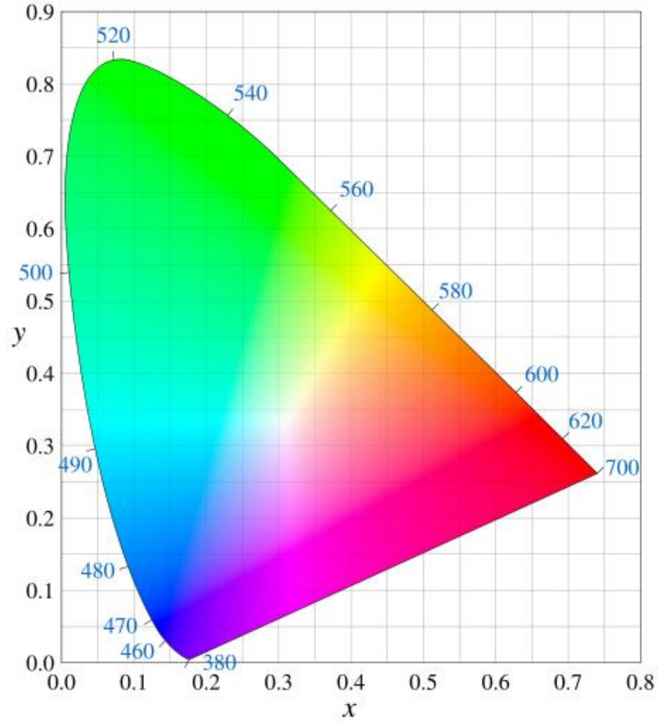
CIE Chromaticity Diagram

- projection of XYZ space onto X+Y+Z = 1 (to factor out a color's brightness):
  $x = X/(X+Y+Z)$ $\qquad$ $y = Y/(X+Y+Z)$
- monochromatic colors on upper edge



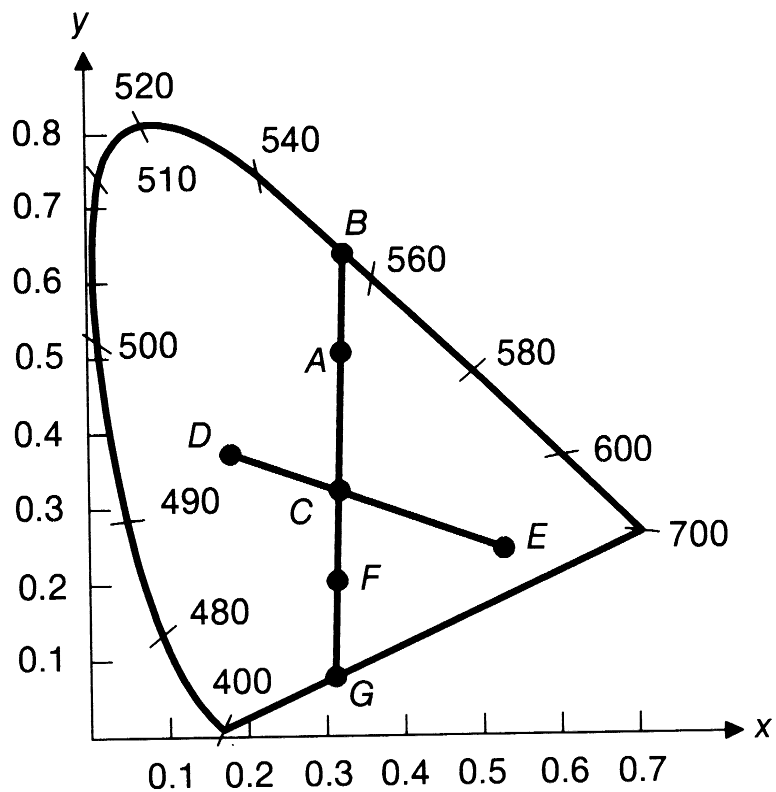


Foley et al. 1990



Chromaticity Diagram Properties

- colors on the same line outwards from white point have same dominant wavelengths (A–B)
- colors opposite of white point are *complementary* colors (D–E)

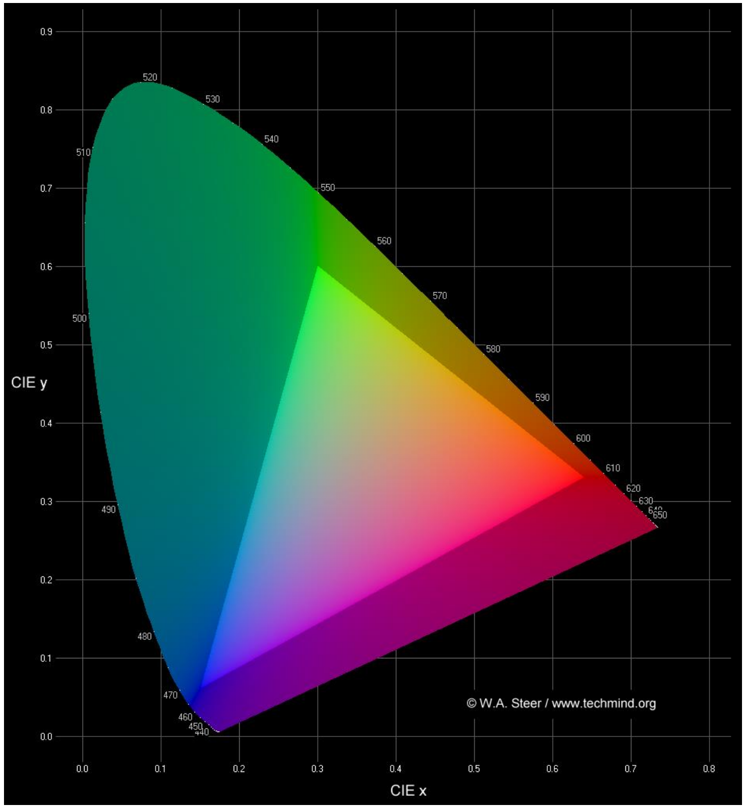


Foley et al. 1990

- dominant wavelength of F defined as complementary color of dominant wavelength of A

Color Gamut

- color gamut: the area of colors in the CIE chromaticity diagram that can be created by adding together colors from the base colors
- if two colors are added, resulting color lies on straight line between them
- RGB shape: triangle



http://www.techmind.org/

RGB to XYZ Conversion

- first: measure the XYZ values of R, G, & B
- linear transformation → 3×3 matrix:

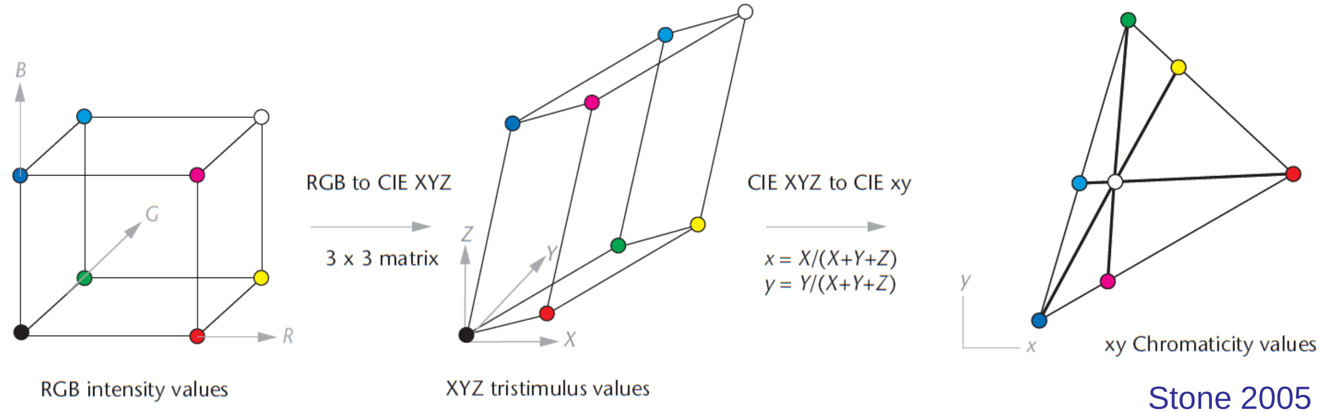
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

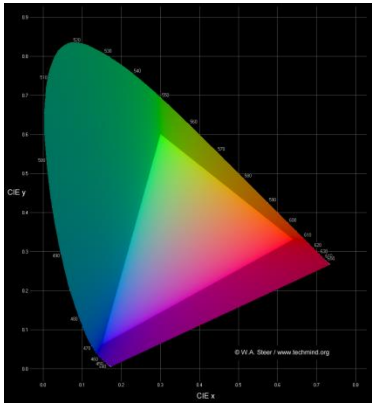
- matrix depends on specific monitor – why?

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

RGB to XYZ Conversion

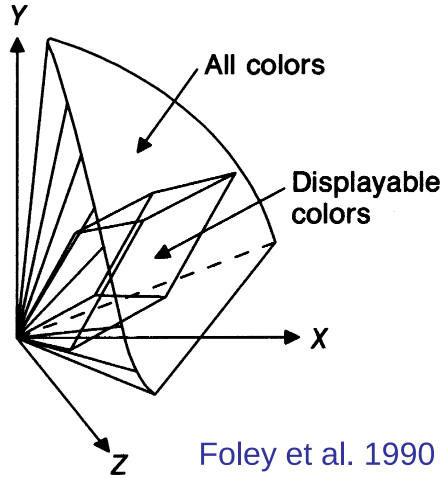
- RGB to XYZ conversion





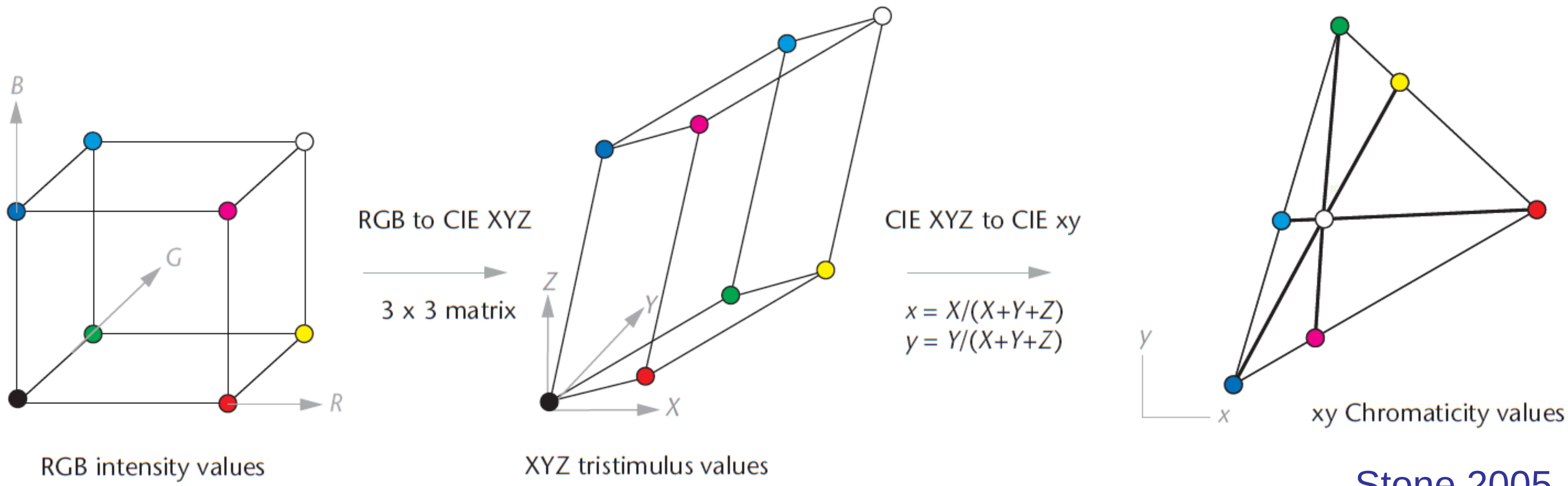
Stone 2005 http://www.techmind.org/

- RGB space: distorted cube
- black: origin of XYZ and projection center
- RGB projected to triangle



Foley et al. 1990

RGB to XYZ to xy Conversion



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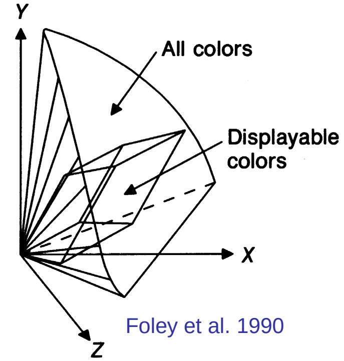
- triangle gamut of RGB:

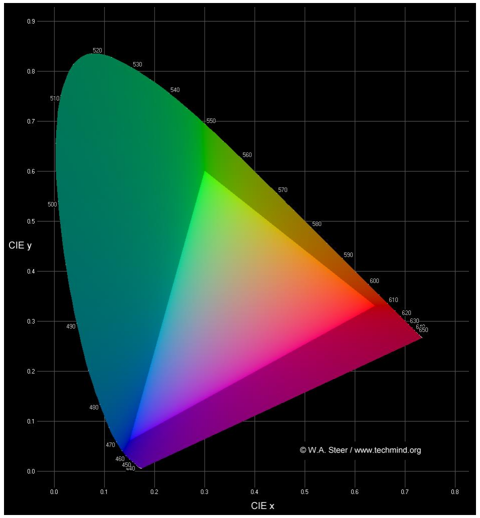
  central projection with origin of XYZ being the COP

Can RGB Represent Any Color?

- no, because all colors form horseshoe shape in CIE chromaticity diagram and RGB gamut is triangular

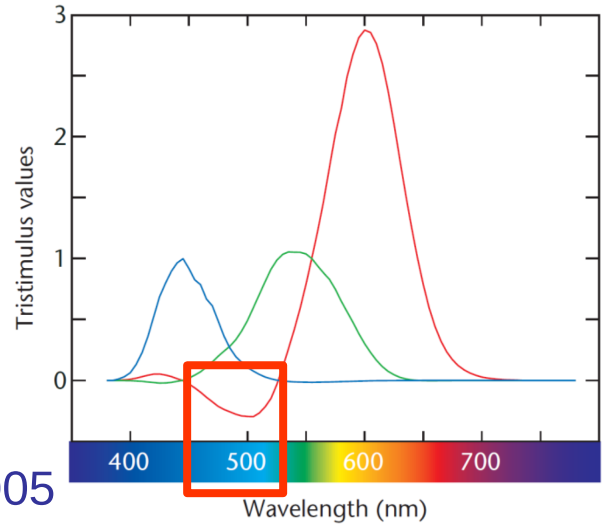


Foley et al. 1990



http://www.techmind.org/

- no, because with RGB primaries sometimes negative colors are necessary



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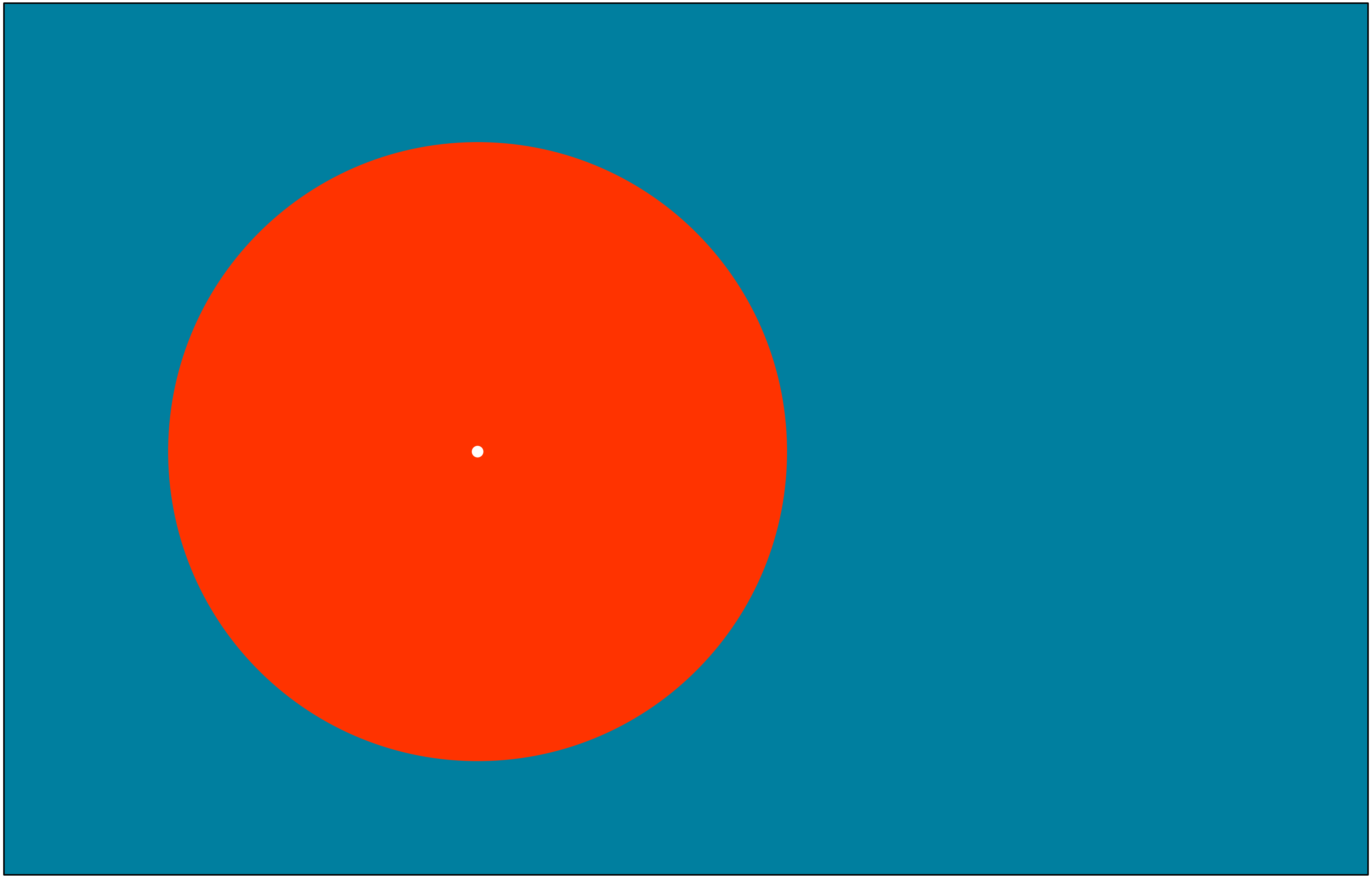
Can RGB Represent Any Color?

- “But my shiny new 85” Ultra-Mega-8K-HDR OLED TV is state-of-the-art, it can surely show all colors!”
- → Let’s see a color that it cannot show …
- another experiment, same proceedings as before
- look at the dot and continue staring at it

Let’s see REAL cyan …



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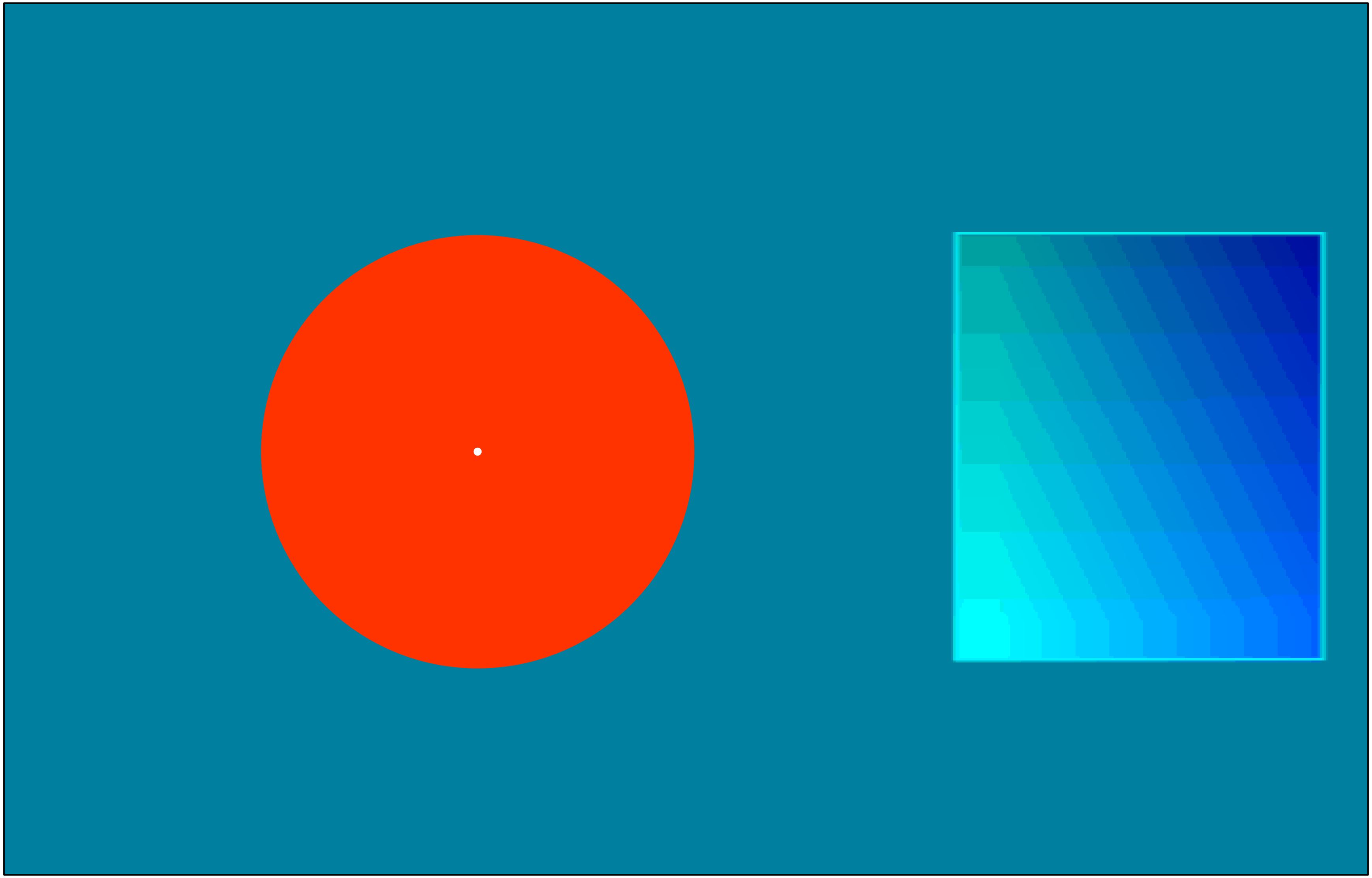
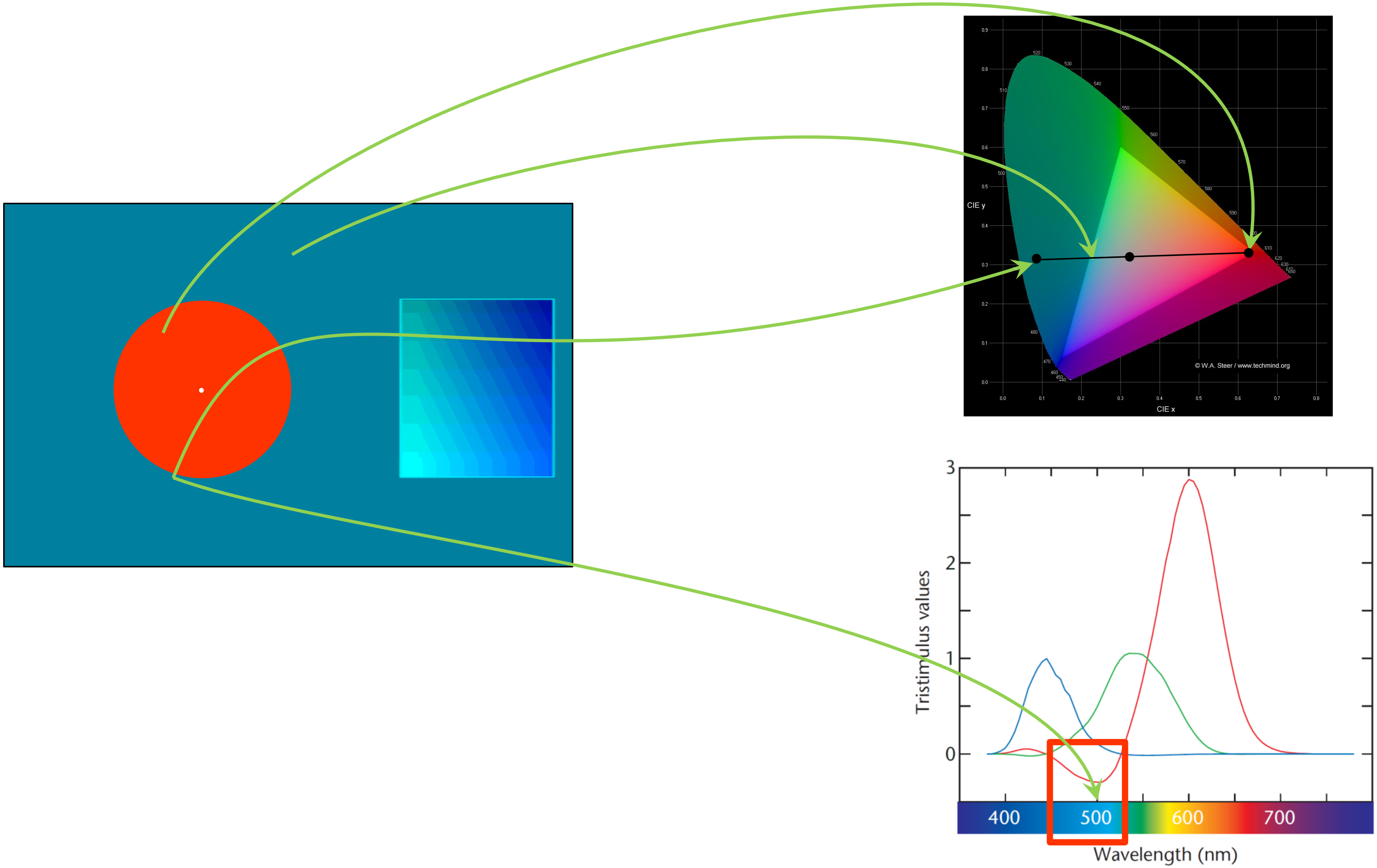
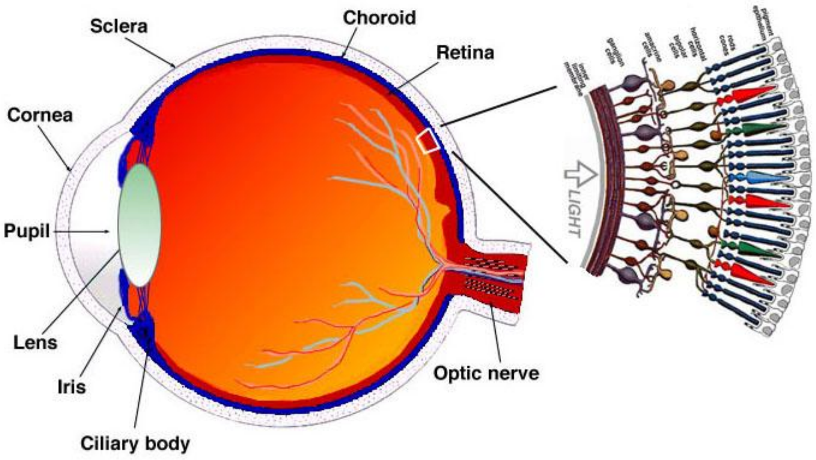


What we just saw …



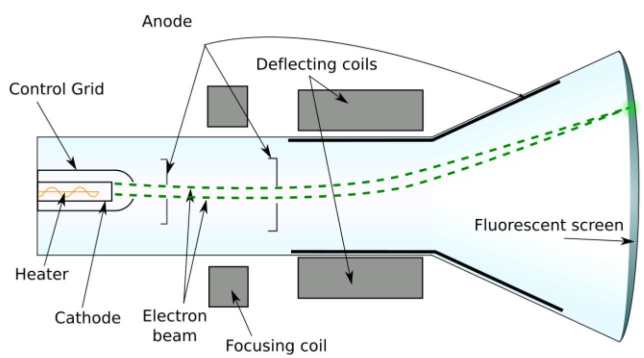
Non-Linear Colors: Gamma

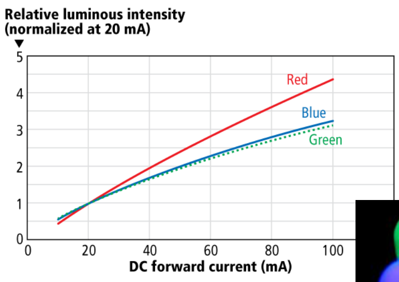
- RGB color values are assumed to be linear w.r.t. the color intensity
- but #1: human light perception not linear
  - eye is sensitive to relative changes
  - sensitive to small changes in low intensities
  - less sensitive to changes in high intensities



Non-Linear Colors: Gamma

- RGB color values are assumed to be linear w.r.t. the color intensity
- but #2: signal to physical light not linear

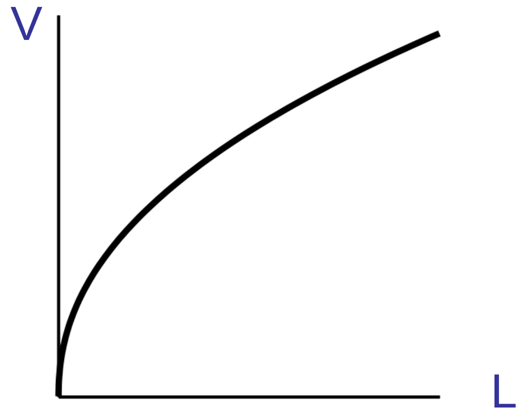


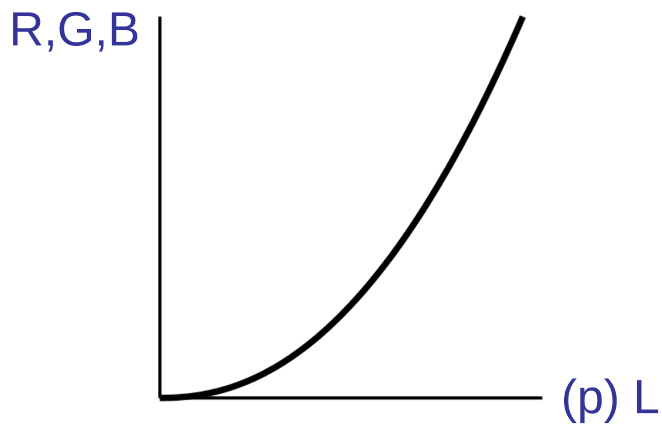


- gamma correction in recording & display technology and in color encoding (digital images & movies)

Gamma Correction

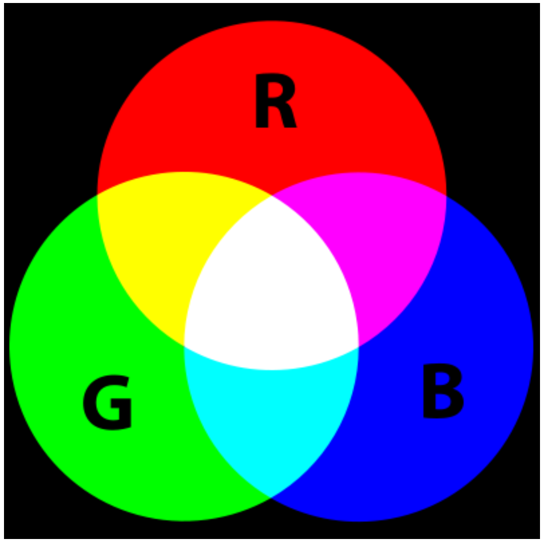
- correction to account for non-linearity
- hardware to make sure that linear values result in linear luminances
  - voltage to luminance: $L = V^{\gamma}$ (typically around 2.2)
  - corrected using 1/gamma
- images for perceptually similar luminance steps
  - opposite behavior
  - gamma of 0.45

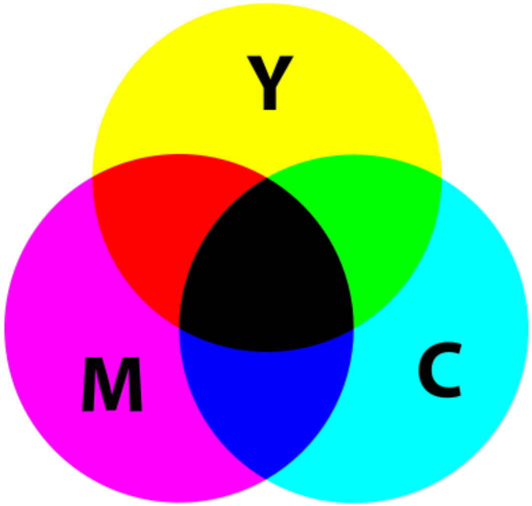




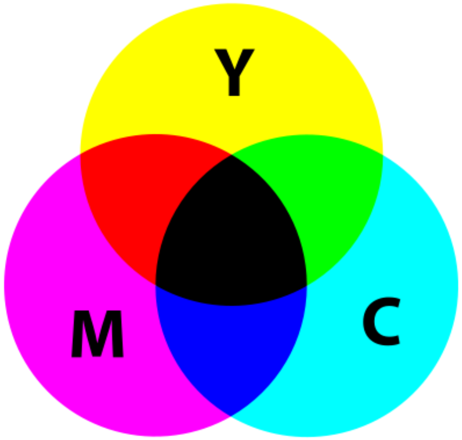
Additive vs. Subtractive Color

- (physical) color mixing depends on color production process
  - light emission: additive mixing (CRTs etc.): **RGB model**
  - light absorption: subtractive mixing (printing process): **CMY(K) model**





Subtractive Color Model: CMY(K)



- subtractive color mixing where light is filtered to produce color
- printing, transparent foils, etc.
- standard colors: cyan, magenta, & yellow
- describe subtraction from white light
- CMY(1, 1, 1) = black
- reproduction of black from CMY not perfect: add K as additional black channel

Converting CMY to RGB

- use subtractive character of CMY
- e.g., cyan subtracts red from white light

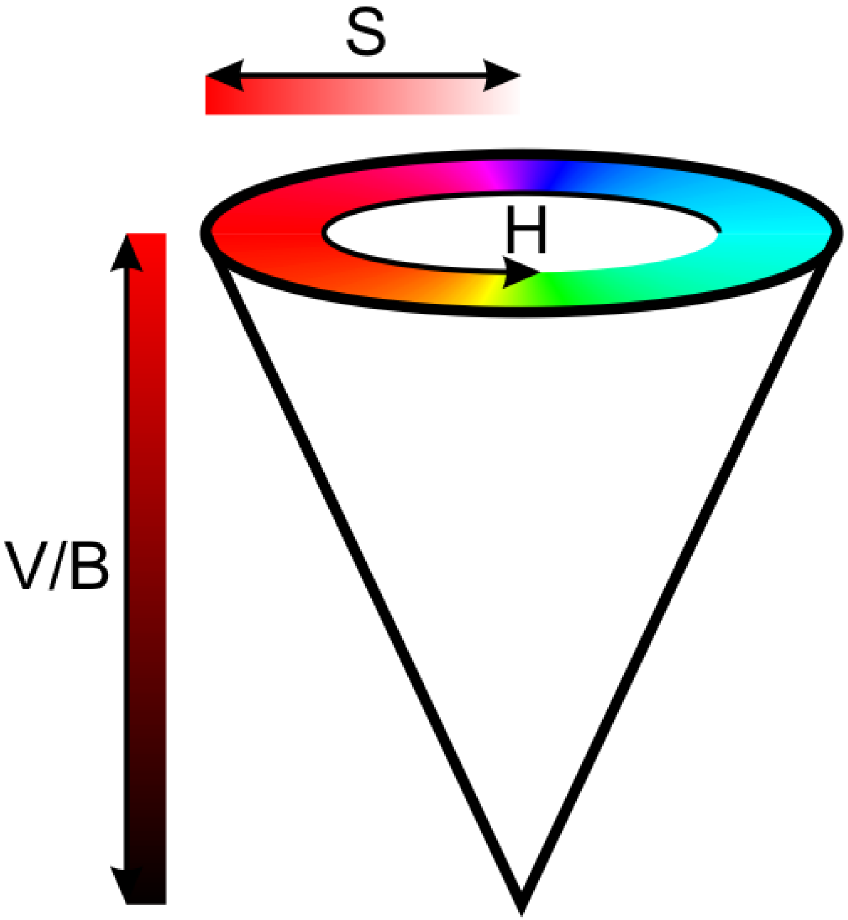
$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Perceptual Color Models

- another experiment: name that color:
- RGB {239, 230, 175}
- machine oriented color models (RGB, CMYK) not easy to use for humans
- perceptual models for human color specification
- 2 models
  - HSV/HSB
  - HSL/HLS

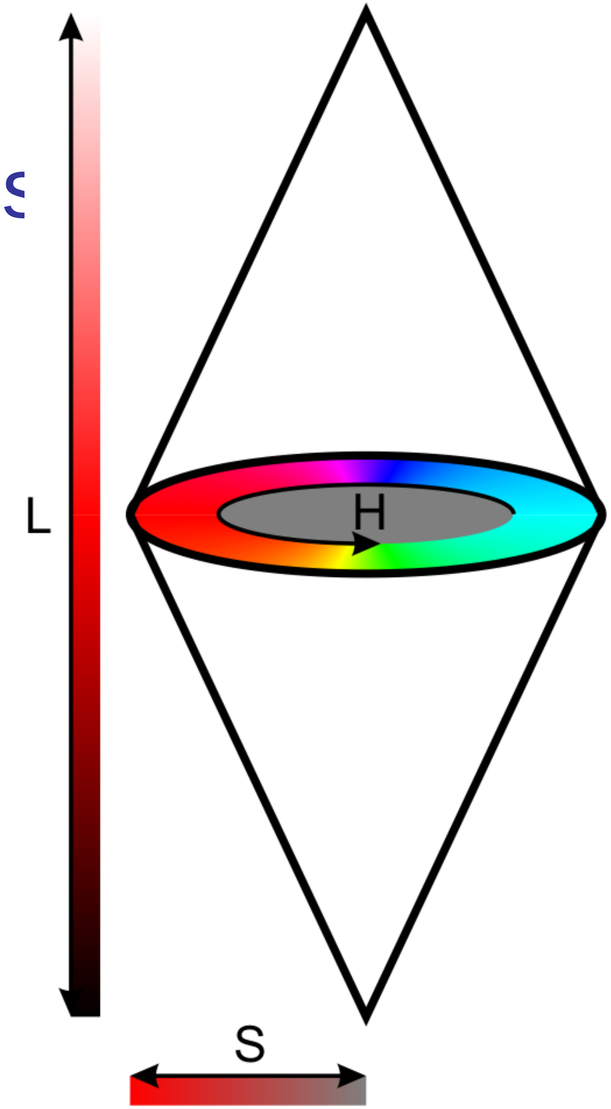
HSV/HSB Color Model

- hue, saturation, value/brightness
- arranged as cone
  - black at tip
  - white in ground plane center
- used for color selection tools

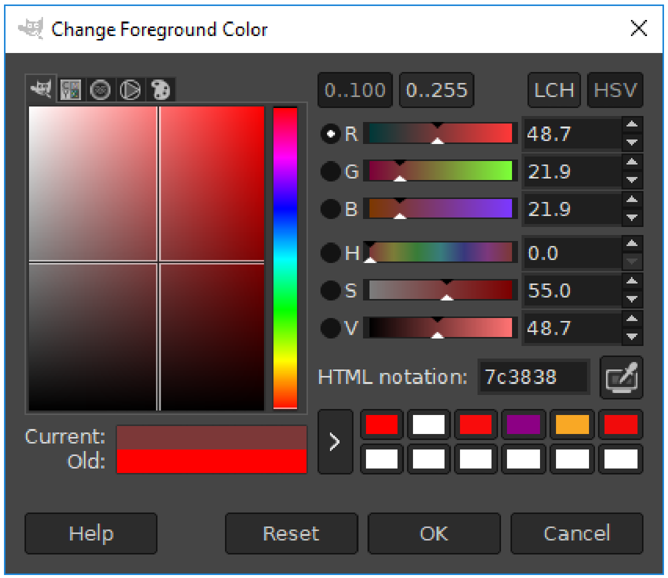


HSL/HLS Color Model

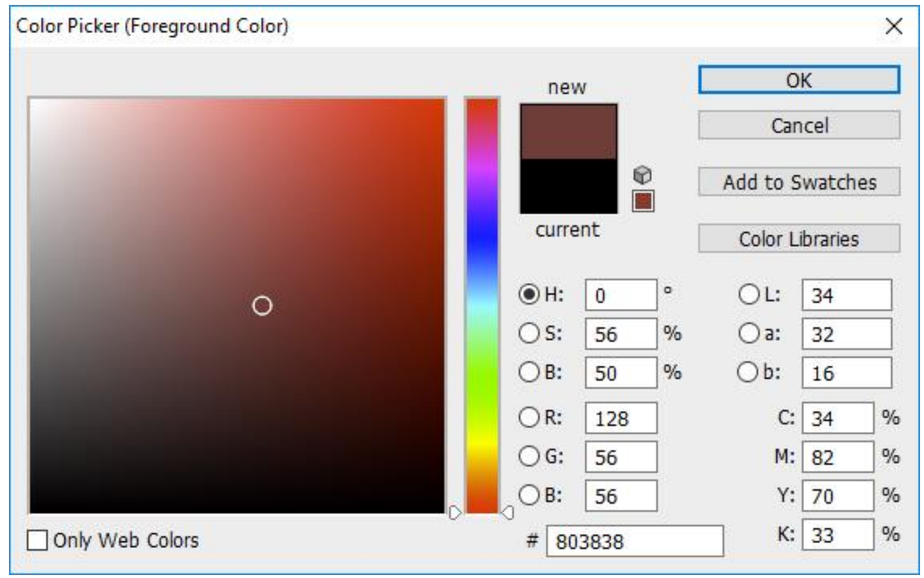
- double cone
- hue, saturation, and lightness
- better than HSV reflects the intuitive notions of “saturation” & “lightness” as independent parameters
- both can be used & are often offered as tools for color selection



Perceptual Color Model Examples



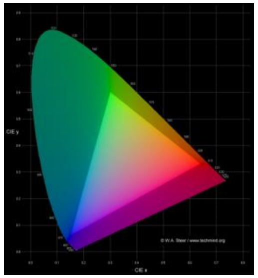
Gimp



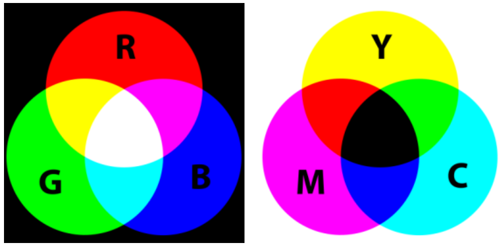
Photoshop

Color Models Summary

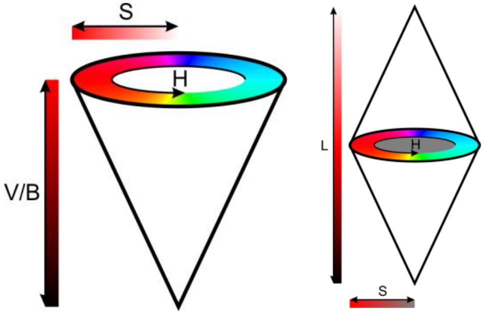
- human vision-oriented
  – CIE XYZ & LMS



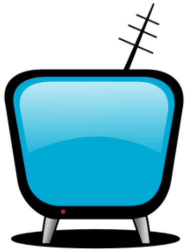
- hardware-oriented
  – RGB & CMY(K)



- perceptual models
  – HSV/HSB & HSL/HLS



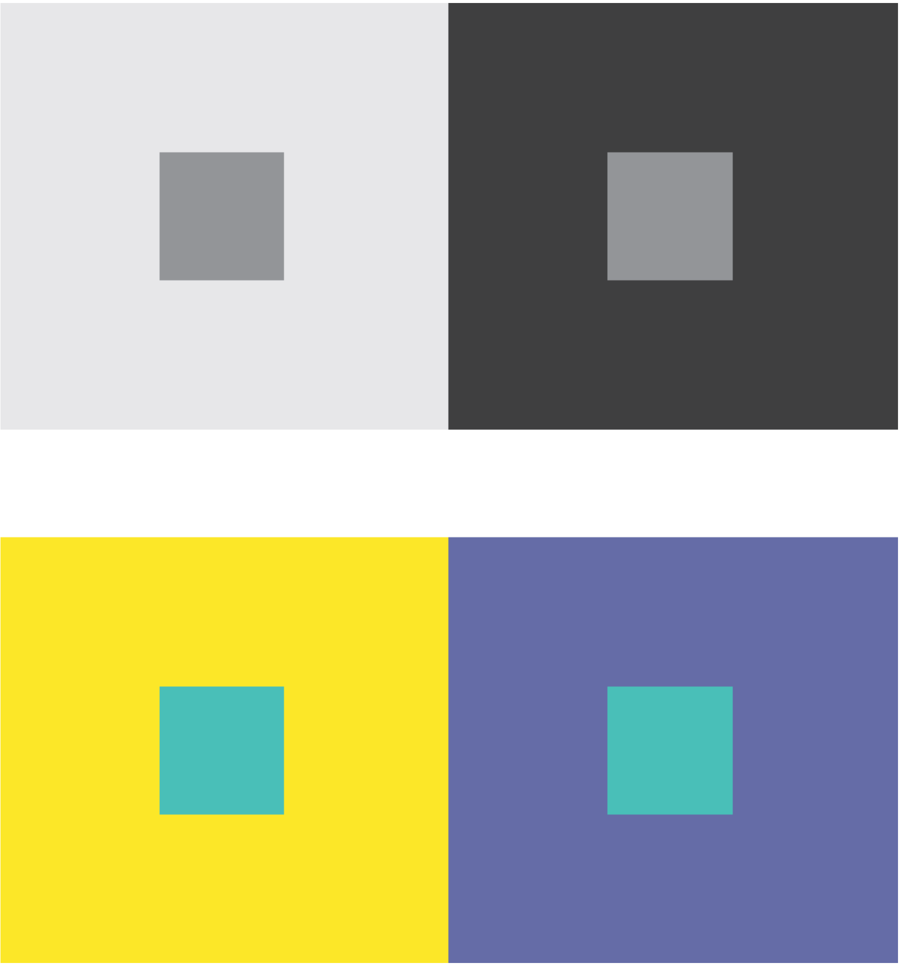
- other models (e.g., for TV)
  – YIQ (NTSC) & YUV (PAL)



Color Perception Effects

Color Perception in Context

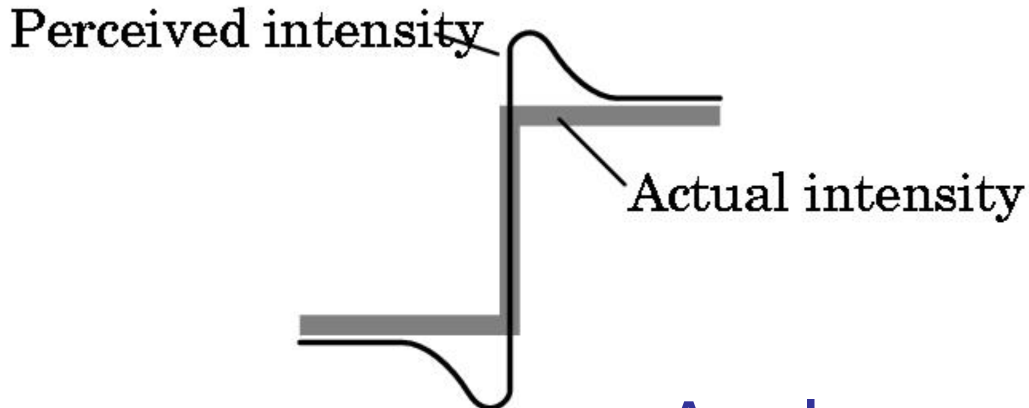
- so far: single color light sources only
- color perception is influenced by context
- tones can appear darker or lighter
- color hues may be changed
- examples:



Stone 2005

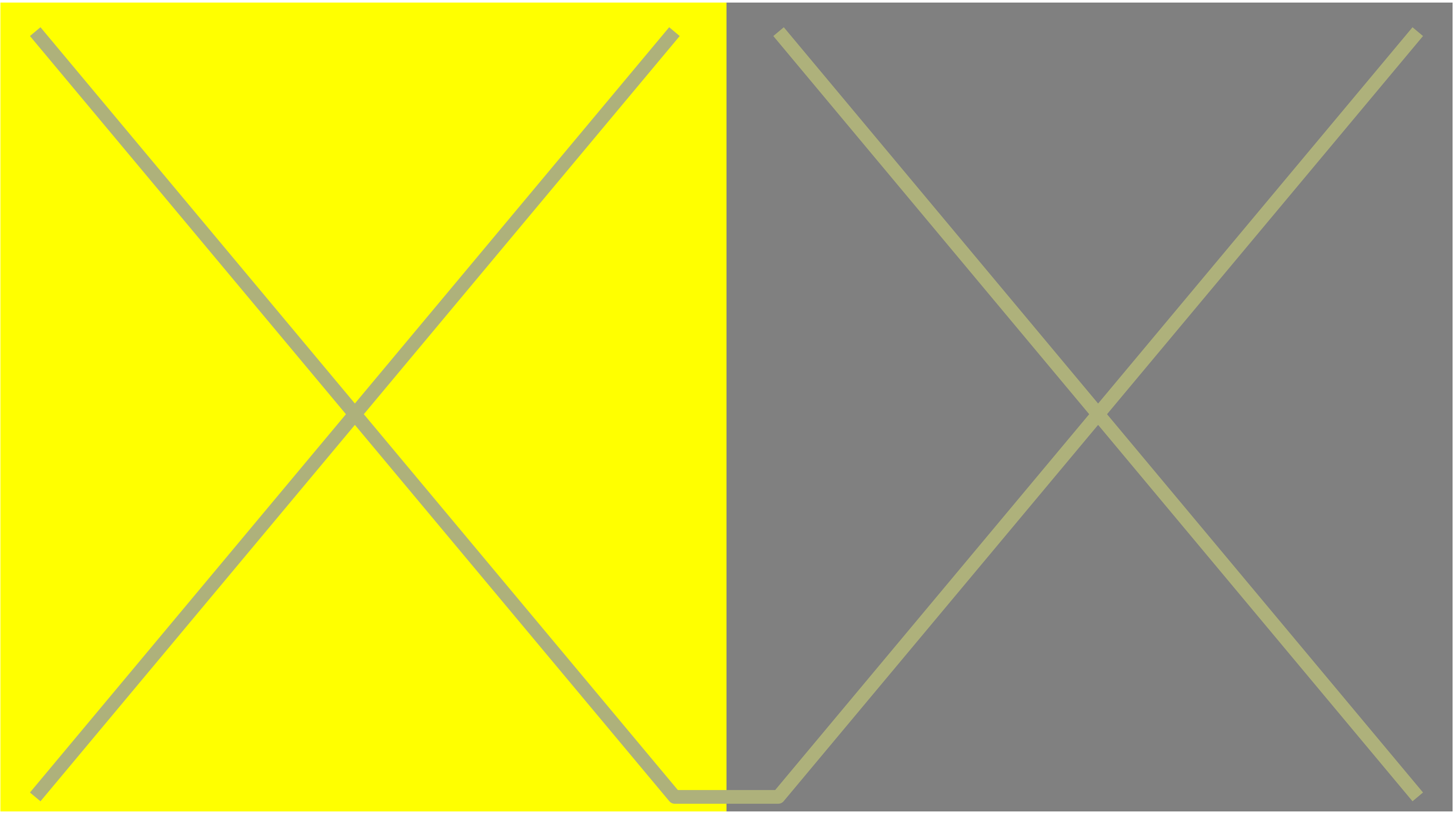
Color Perception in Context

- remember the Mach band effect



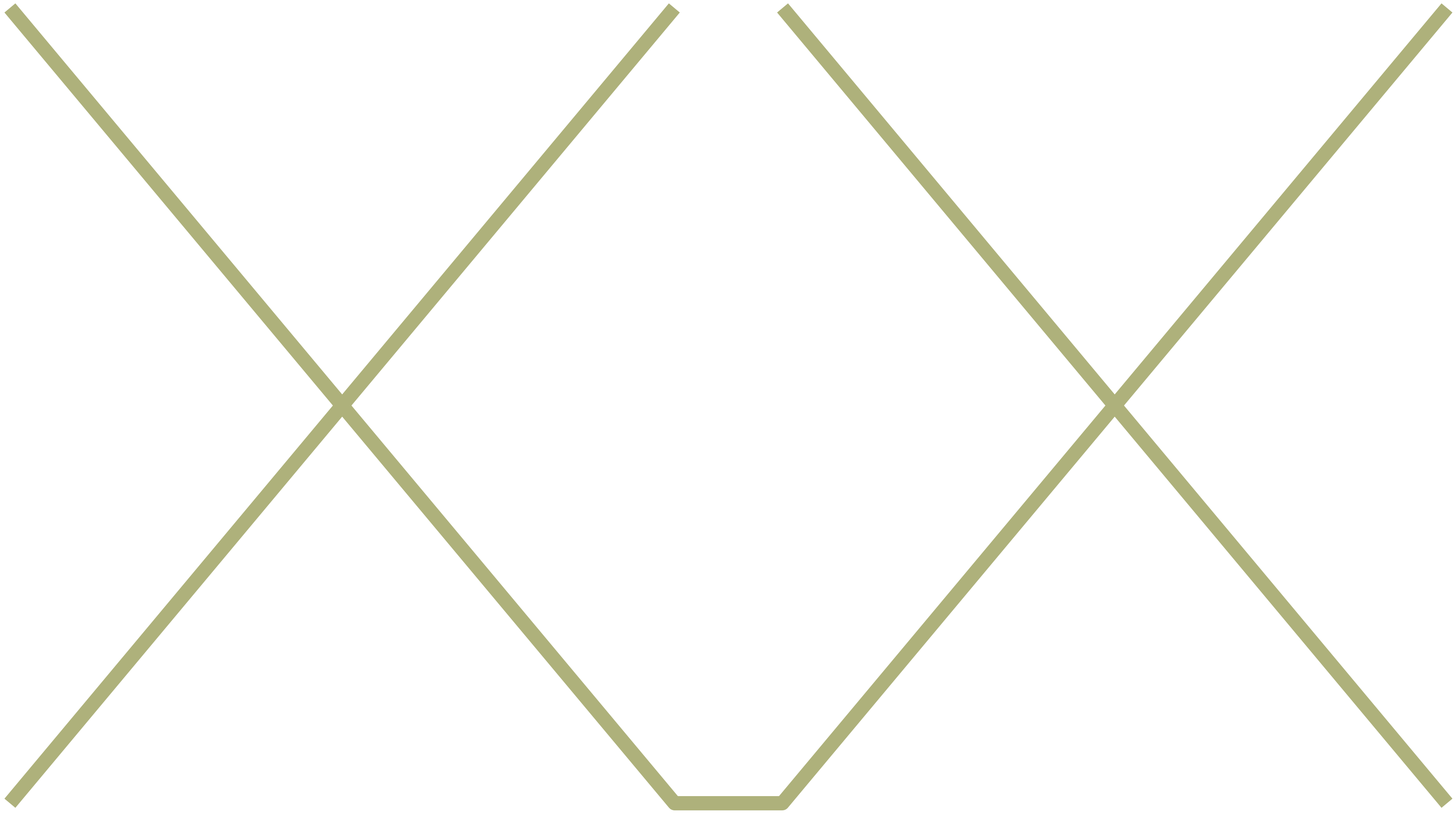
Angel (2000)

Simultaneous Contrast



Josef Albers

Simultaneous Contrast

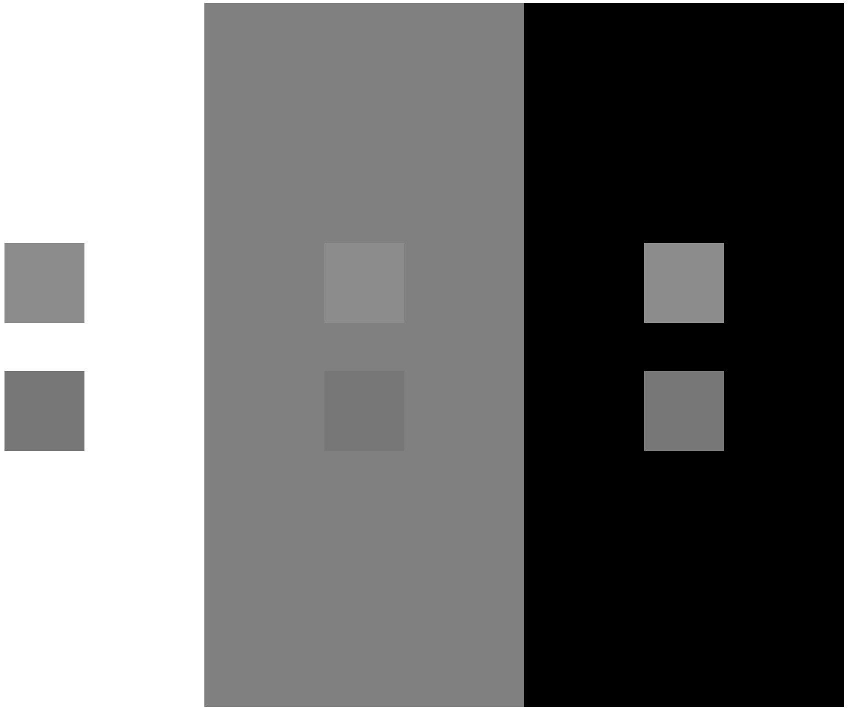


Josef Albers

Color Perception: Bezold Effect

Color Perception: Crispening

Perceived difference depends on background



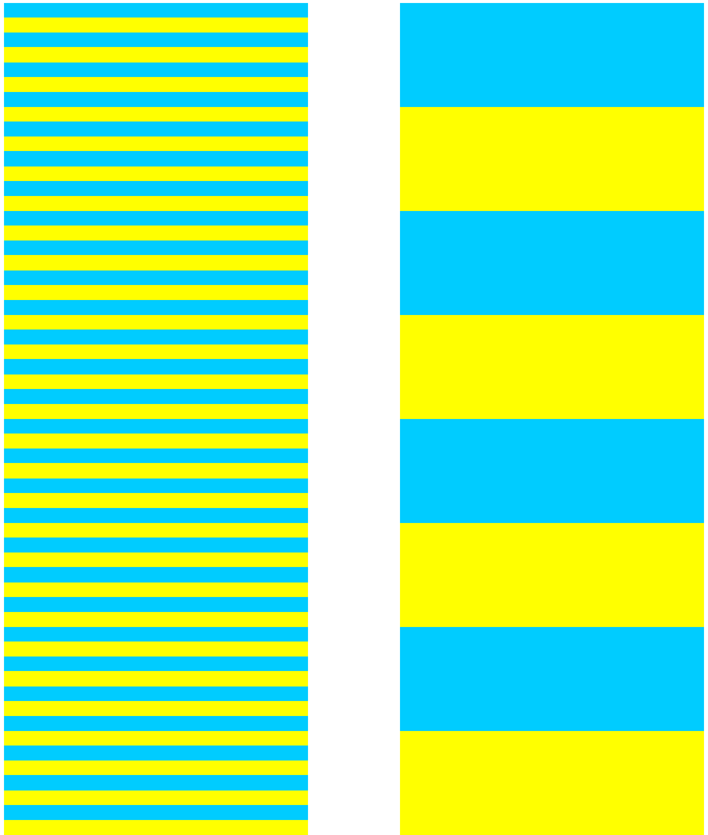
From Fairchild, *Color Appearance Models*

Color Perception: Spreading

Spatial frequency

- The paint chip problem
- Small text, lines, glyphs
- Image colors

Adjacent colors blend



Redrawn from *Foundations of Vision*
© Brian Wandell, Stanford University

Color Perception in Context

Image source: The Journal of Neuroscience, October 1, 1999, 19(19):8542–8551 An Empirical Explanation of the Cornsweet Effect.

Color Perception in Context

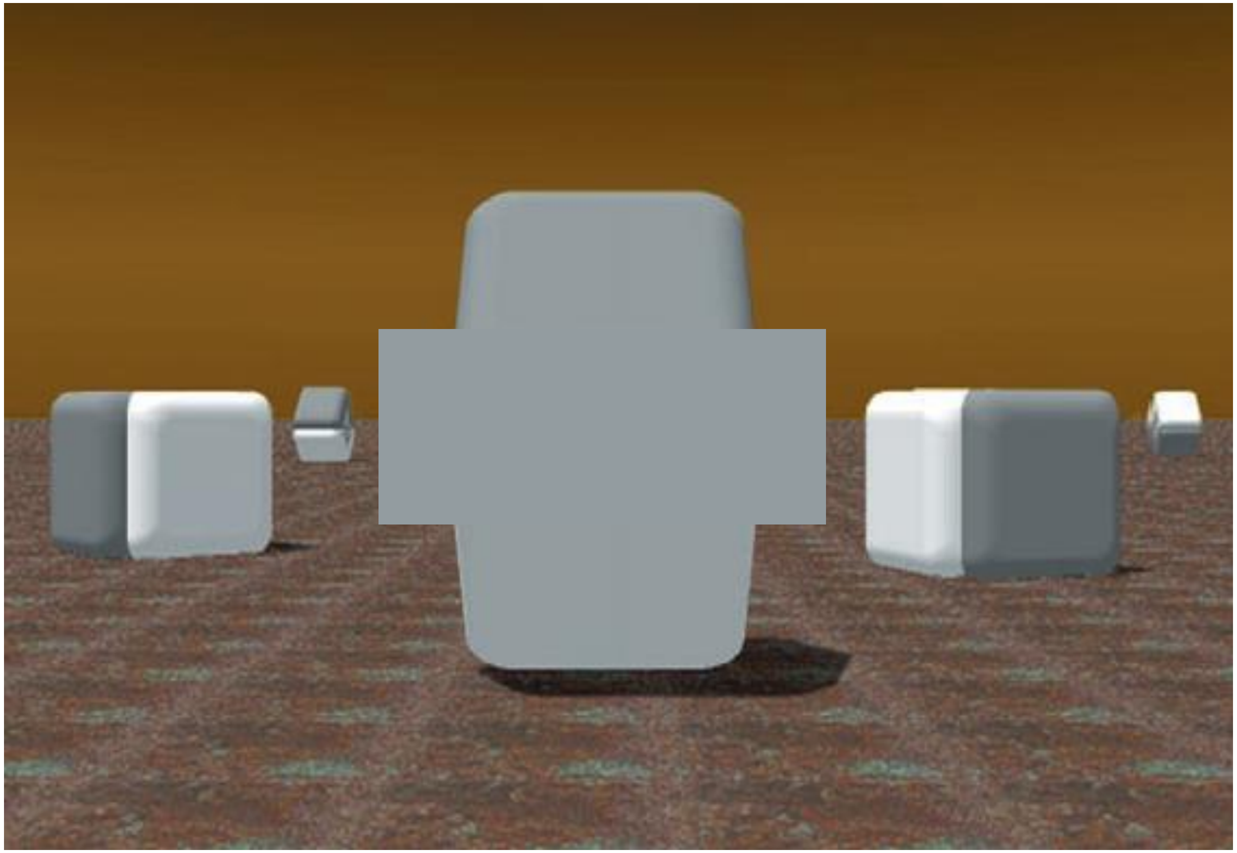
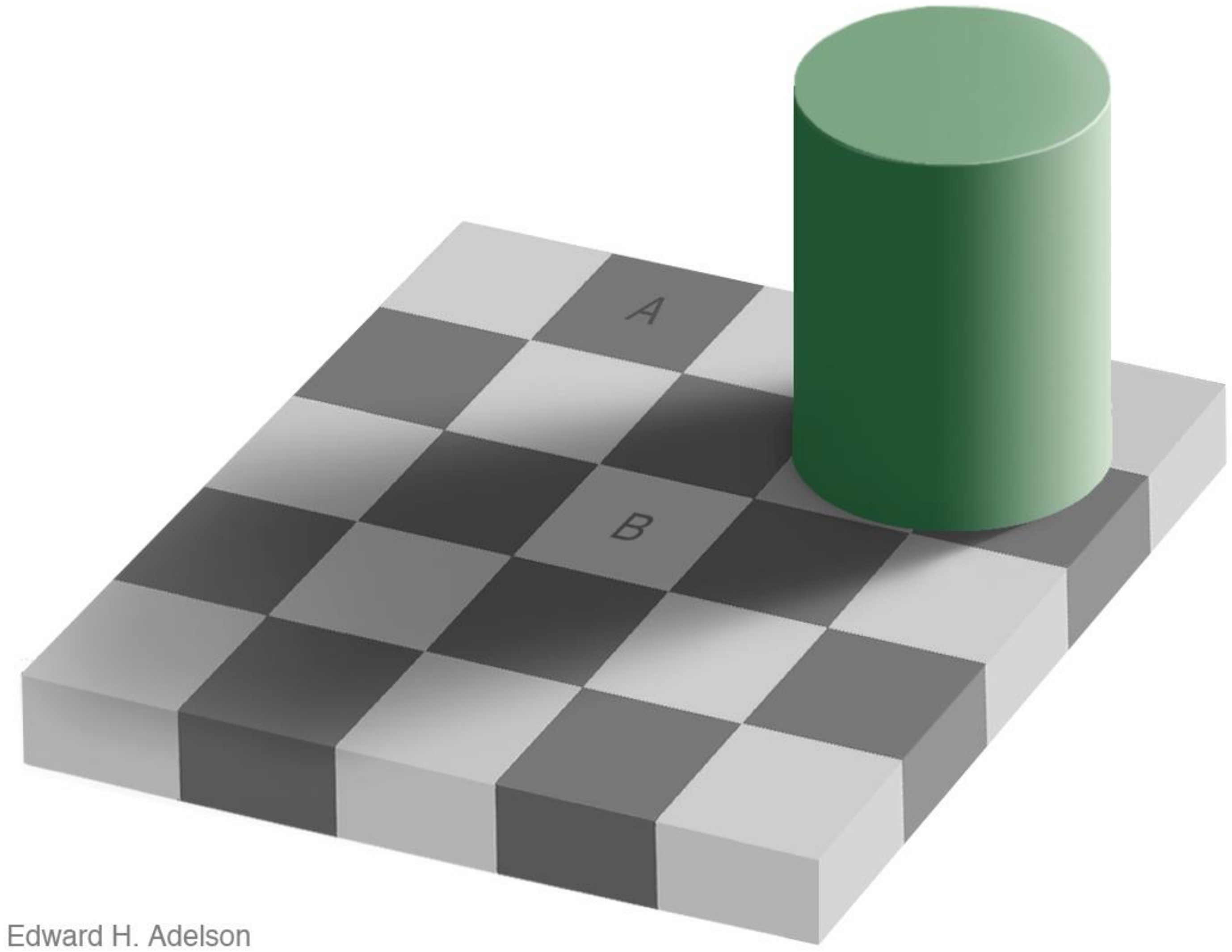
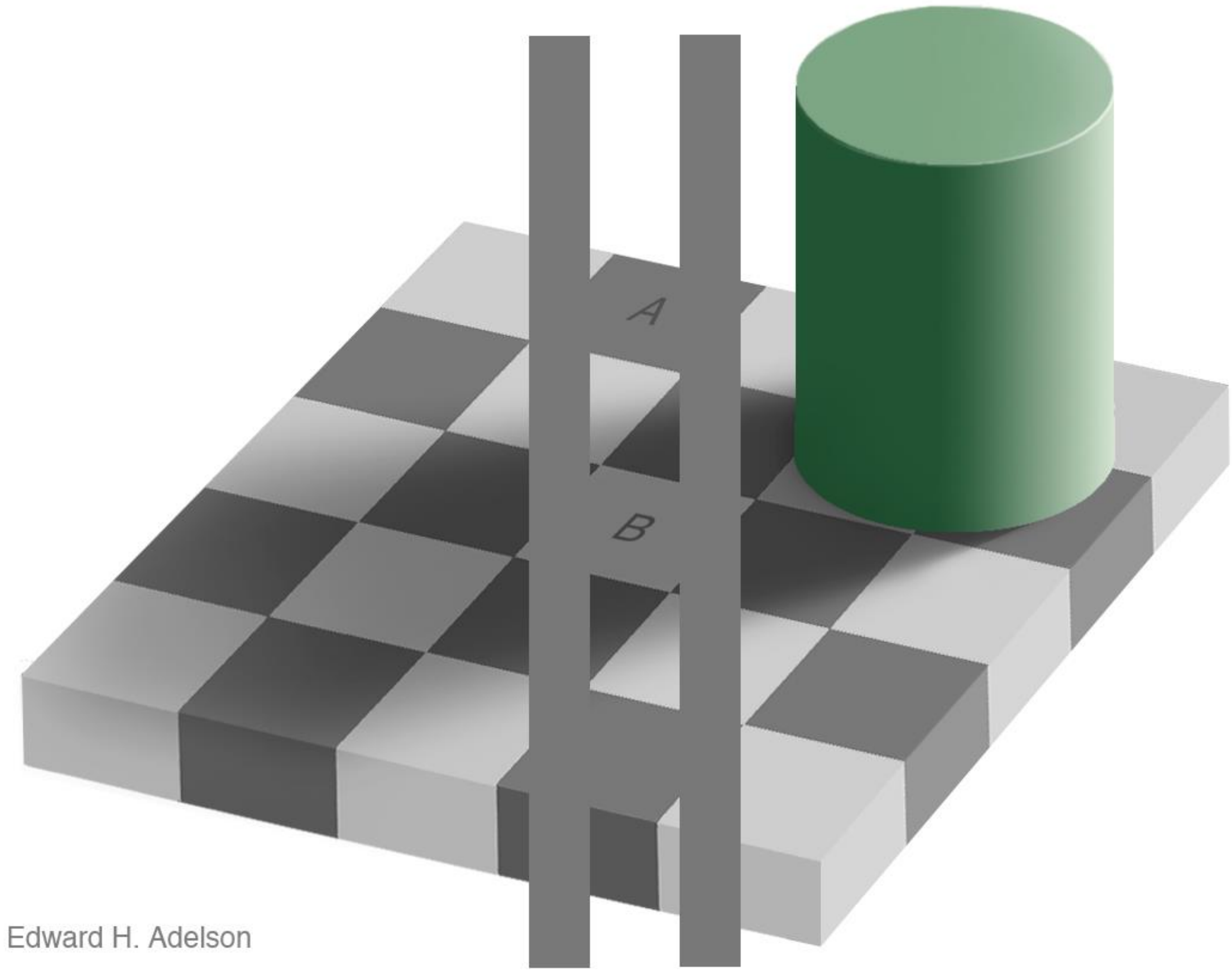


Image source: The Journal of Neuroscience, October 1, 1999, 19(19):8542–8551 [An Empirical Explanation of the Cornsweet Effect.]

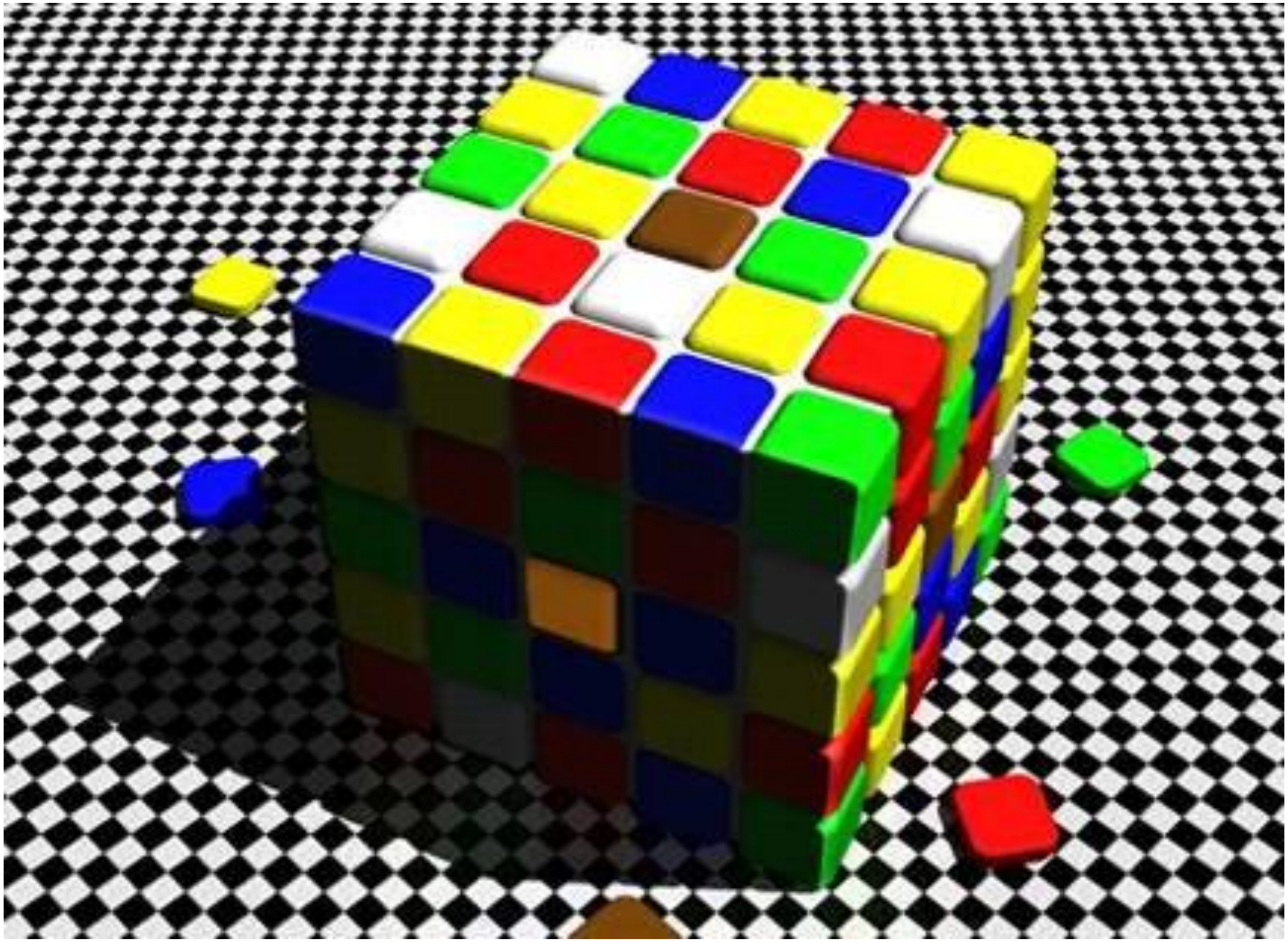
Color Perception in Context



Color Perception in Context



Color Perception in Context



Color Perception in Context

Color Naming

Color Perception: Color Naming

“Yellow”

Color Perception: Color Naming

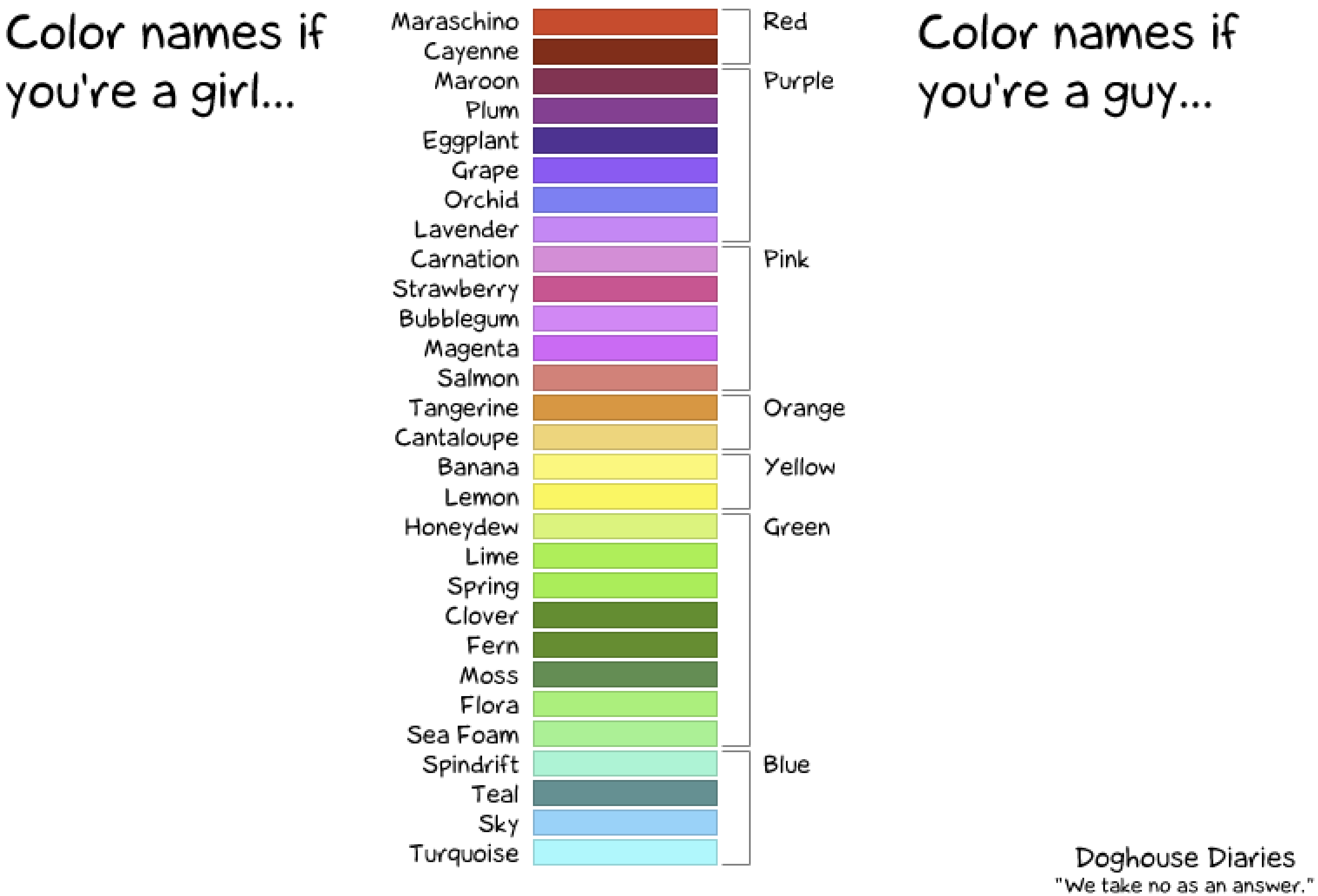
“Blue”

Color Perception: Color Naming

“Teal ?”

“Turquoise ?”   “Blue-Green ?”   “Sarcelle ?”

Color according to gender?



Color according to XKCD

A crowdsourced color-labeling game

~5 million colors

~222,500 user sessions

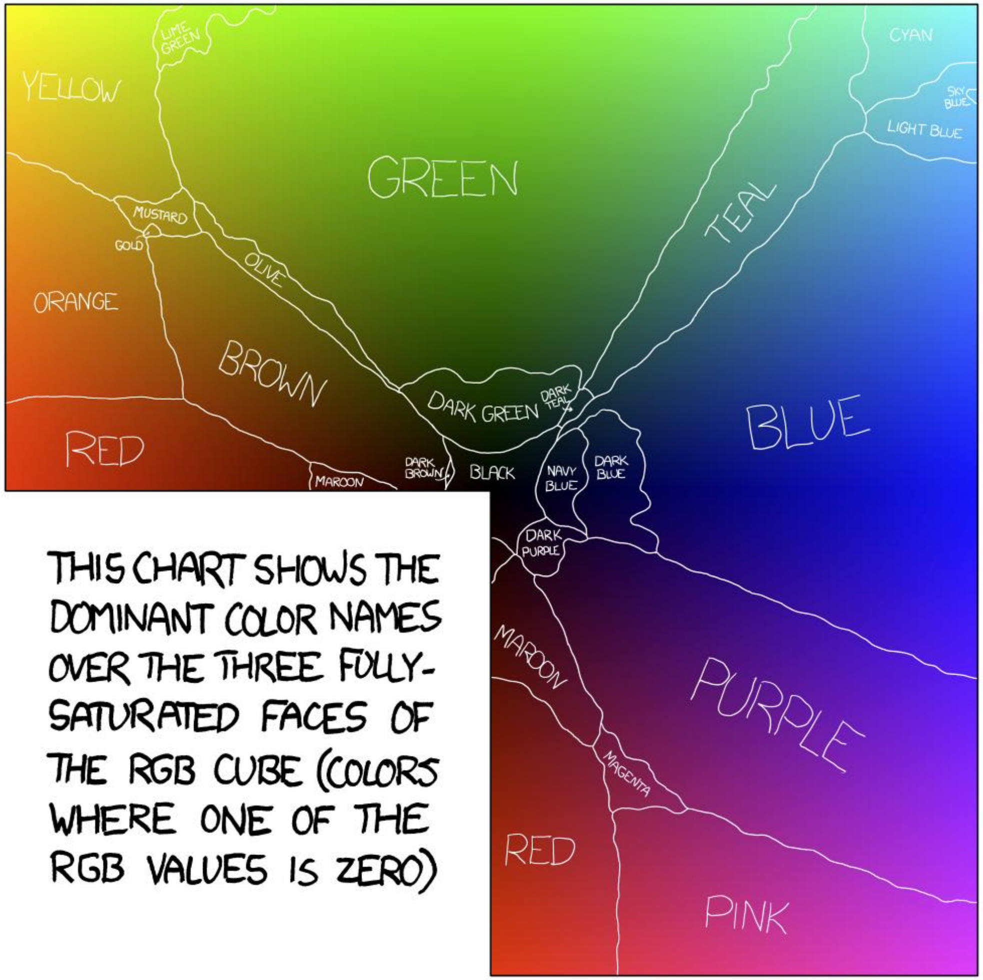
http://blog.xkcd.com/2010/05/03/color-survey-results/

Color according to XKCD

Color Naming

We associate and group colors together, often using the name we assign to the colors

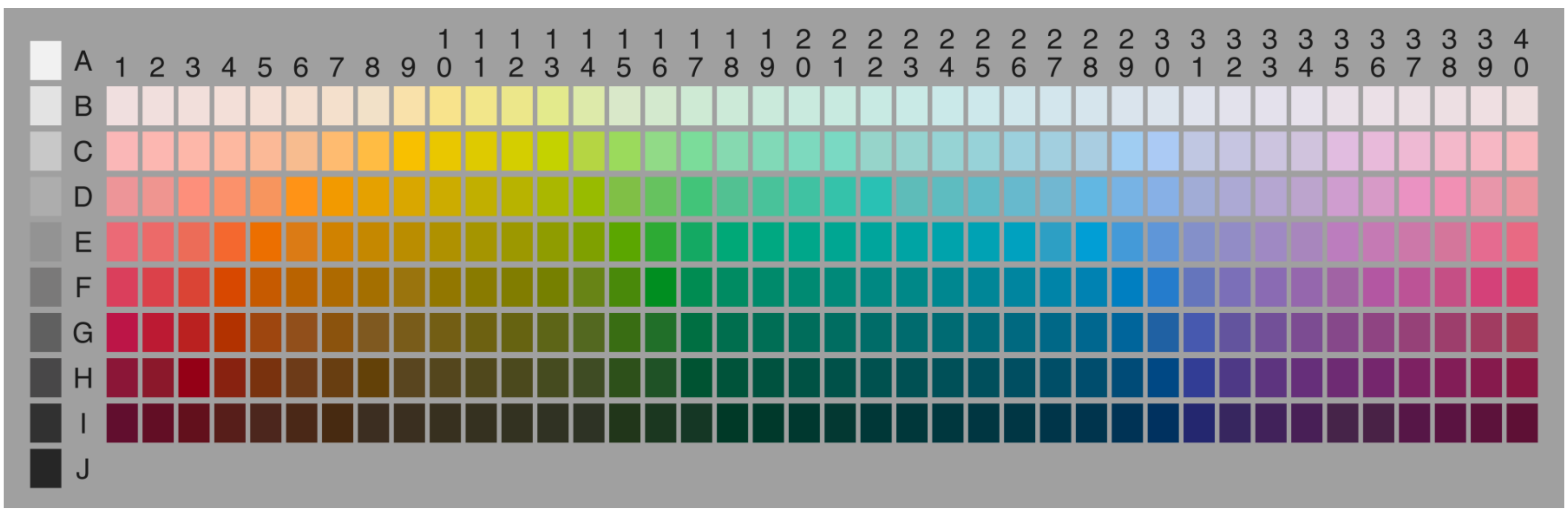
Are there natural boundaries?



xkcd

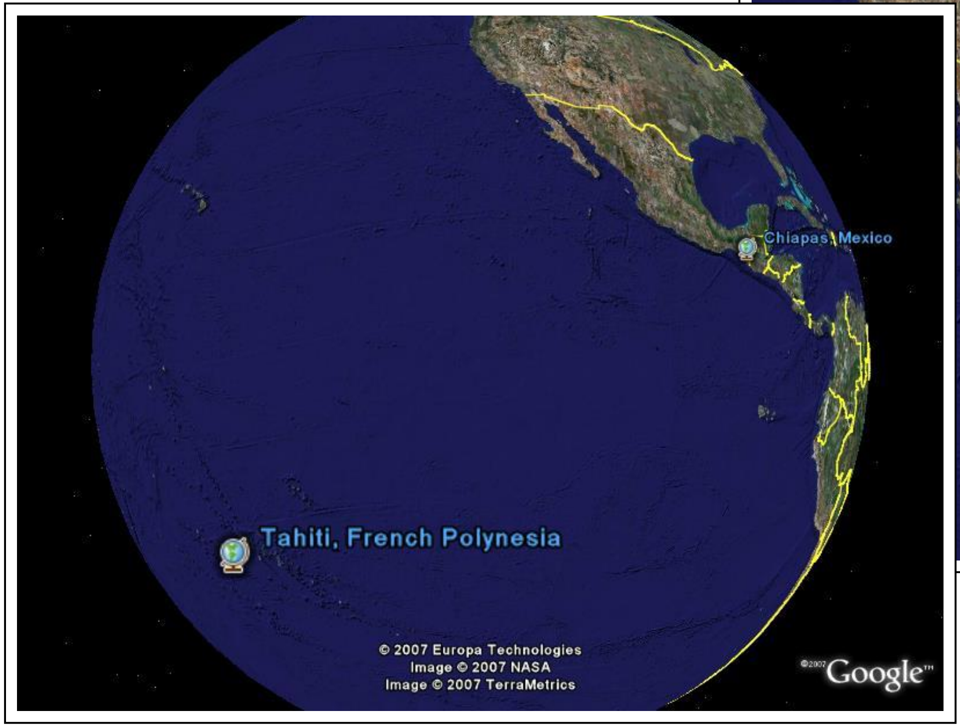
Basic Color Terms: World Color Survey

- Brent Berlin & Paul Kay 1969:
  Surveyed 2616 speakers of 110 languages using 330 different color chips

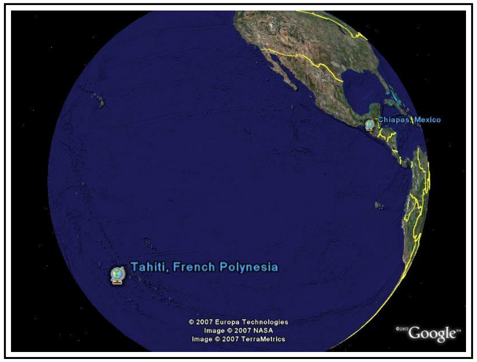


Basic Color Terms: World Color Survey

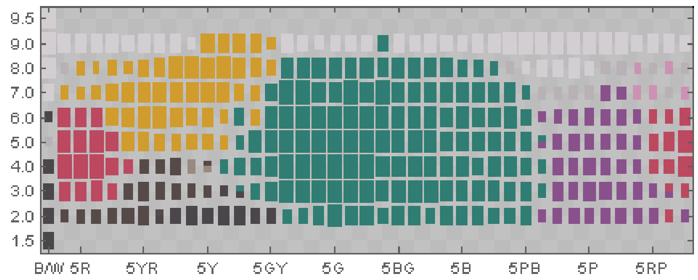
- Brent Berlin & Paul Kay 1969
- let's look at two specific places



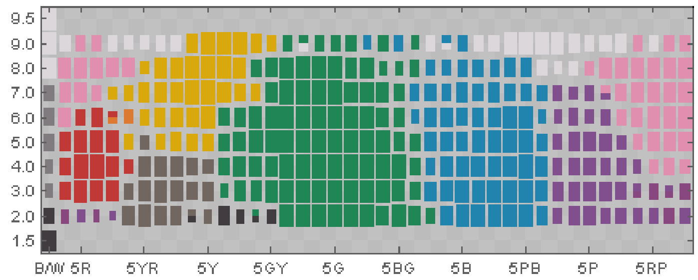
Results from WCS



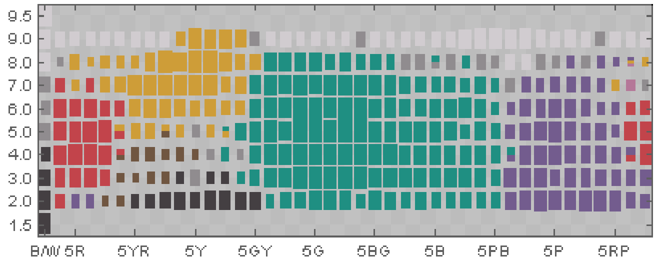
Language #72 (Mixteco)
Mutual info = 0.942 / Contribution = 0.476



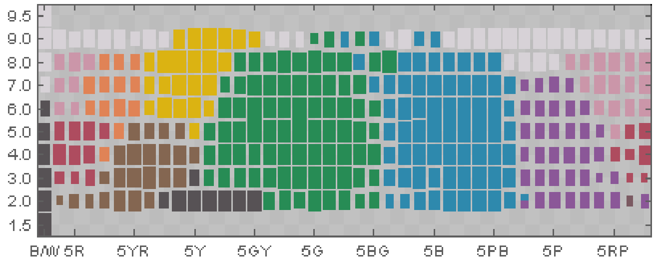
Language #19 (Camsa)
Mutual info = 0.939 / Contribution = 0.487



Language #98 (Tlapaneco)
Mutual info = 0.942 / Contribution = 0.524



Language #24 (Chavacano)
Mutual info = 0.939 / Contribution = 0.513

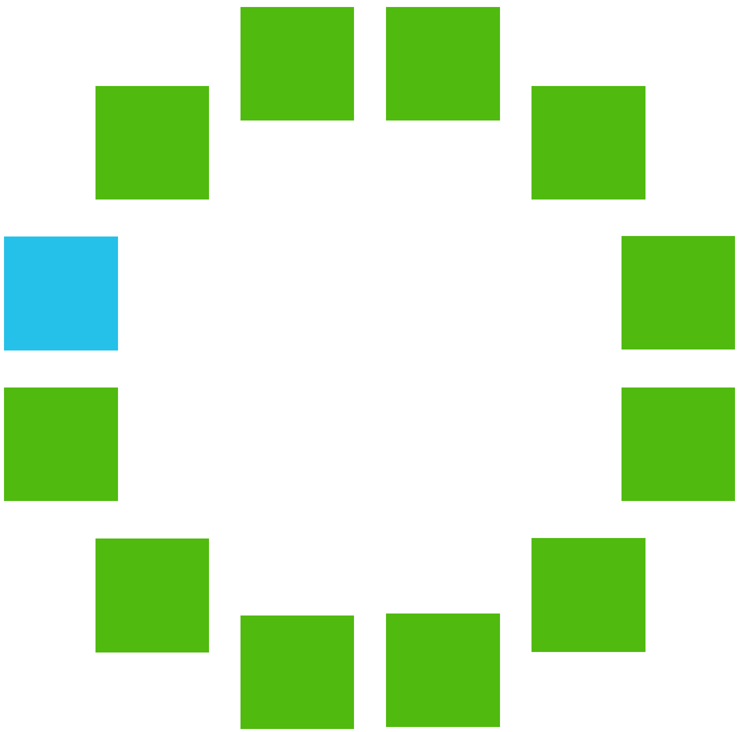


But language-color interaction

- Himba tribe in Namibia – only few color words:
  - **zoozu**: most dark colors (red, blue, green, violet)
  - **vapa**: white, also some yellow
  - **borou**: some green & blue colors
  - **dumbu**: many green but also red colors

But language-color interaction

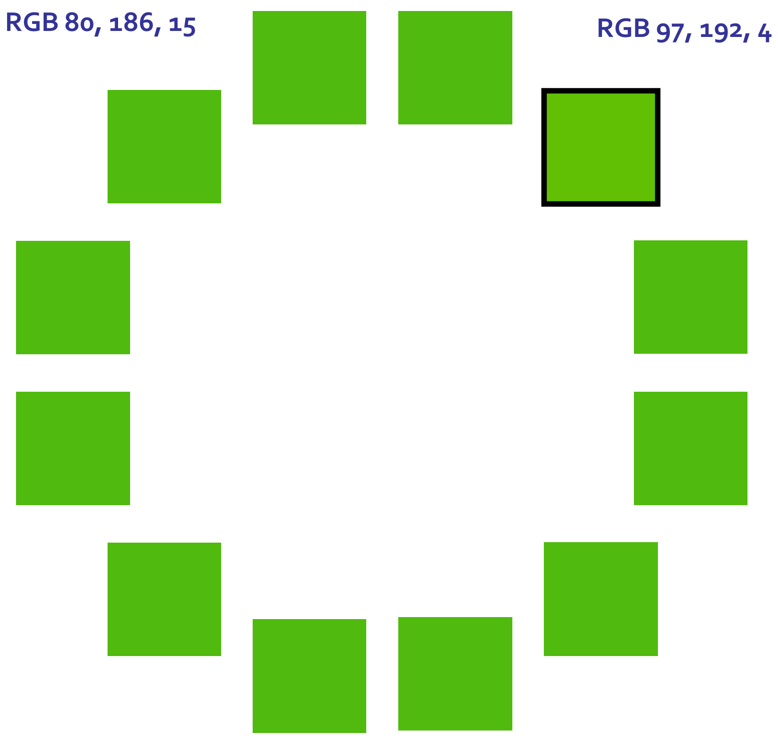
- experiment: how long to find a differing color?

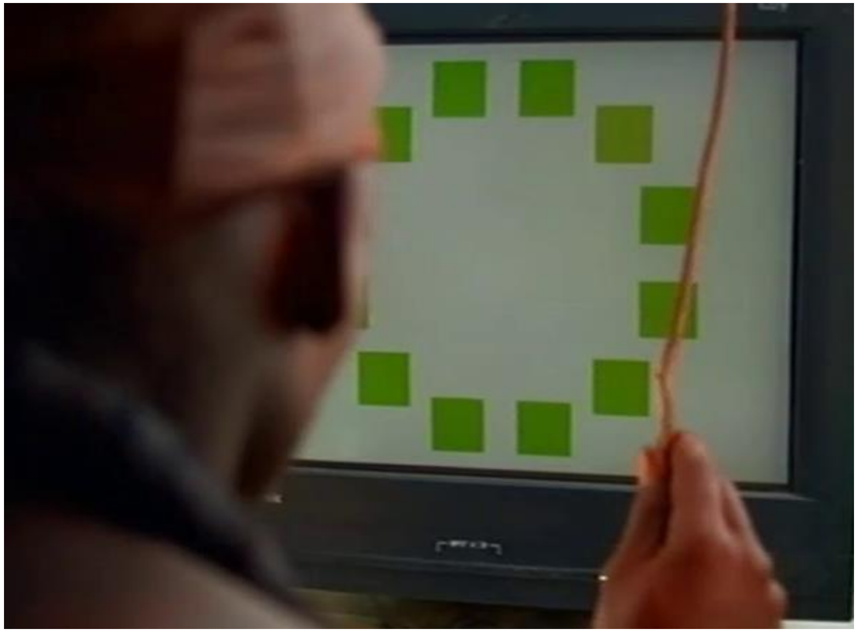


difficult to impossible for Himba people

But language-color interaction

- experiment: how long to find a differing color?





© BBC

easy for Himba people: different words for both types of green

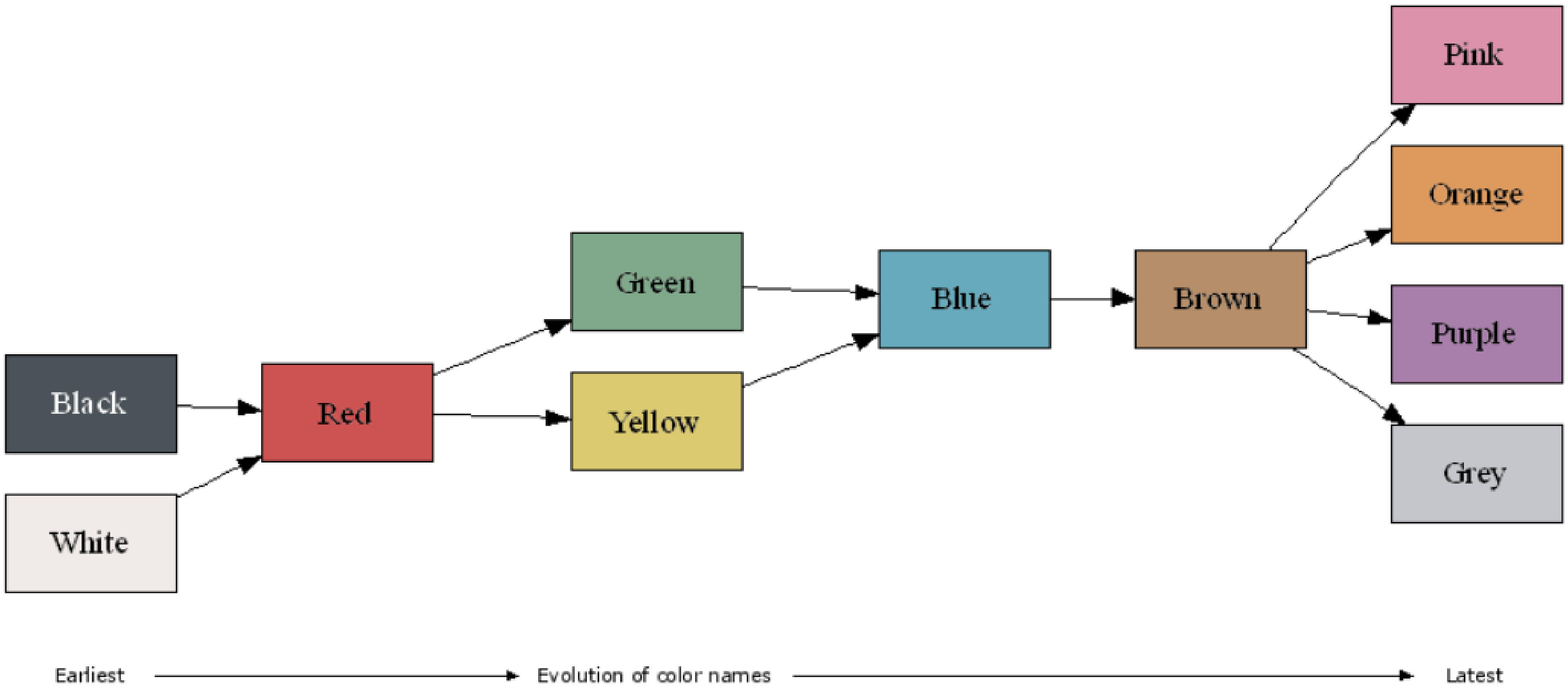
Universal (?) Basic Color Terms

basic color terms that recur across (many) languages

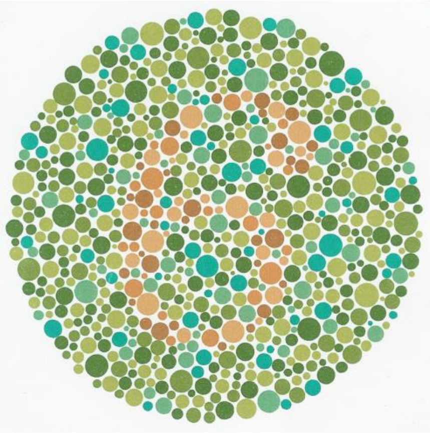
White	Red	Pink
Grey	Yellow	Brown
Black	Green	Orange
	Blue	Purple

Evolution of Basic Color Terms

proposed universal evolution of color names across languages



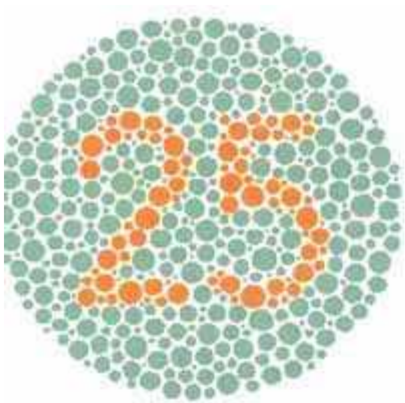
Color Deficiency

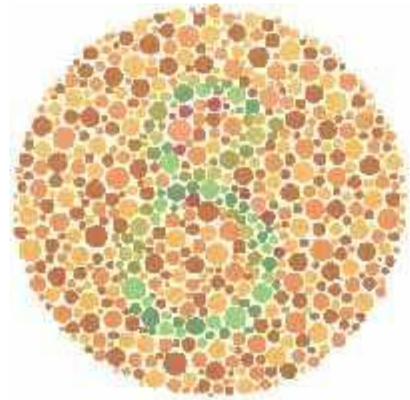


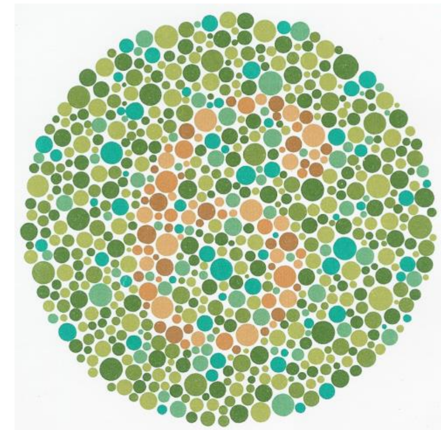
Color Deficiency

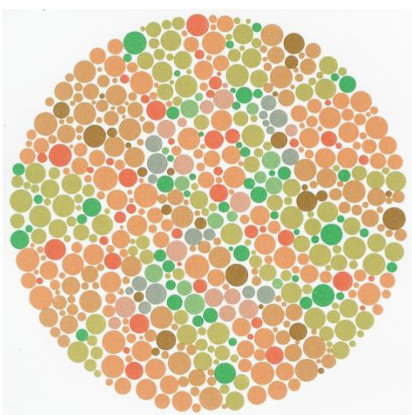
- ca. 7% of male population color-deficient
- mostly red-green color deficiency (Deuteranopy or Protanopy); other forms as well (e.g., Tritanope, very rare)
- avoid red-green color contrasts for visualization purposes!
- side note: there are (very, very few) people with more than three cone types

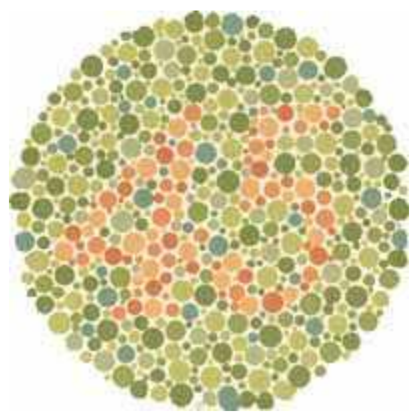
Color Deficiency Test

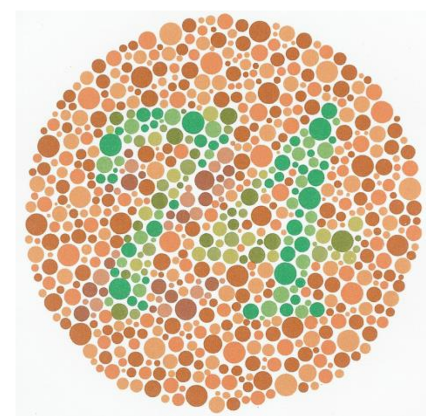




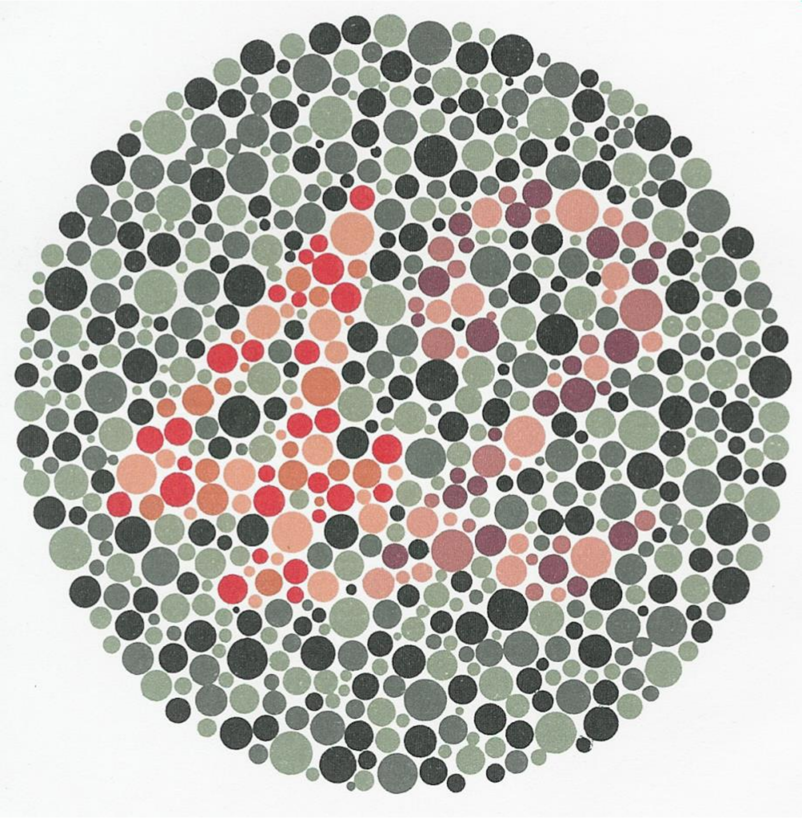


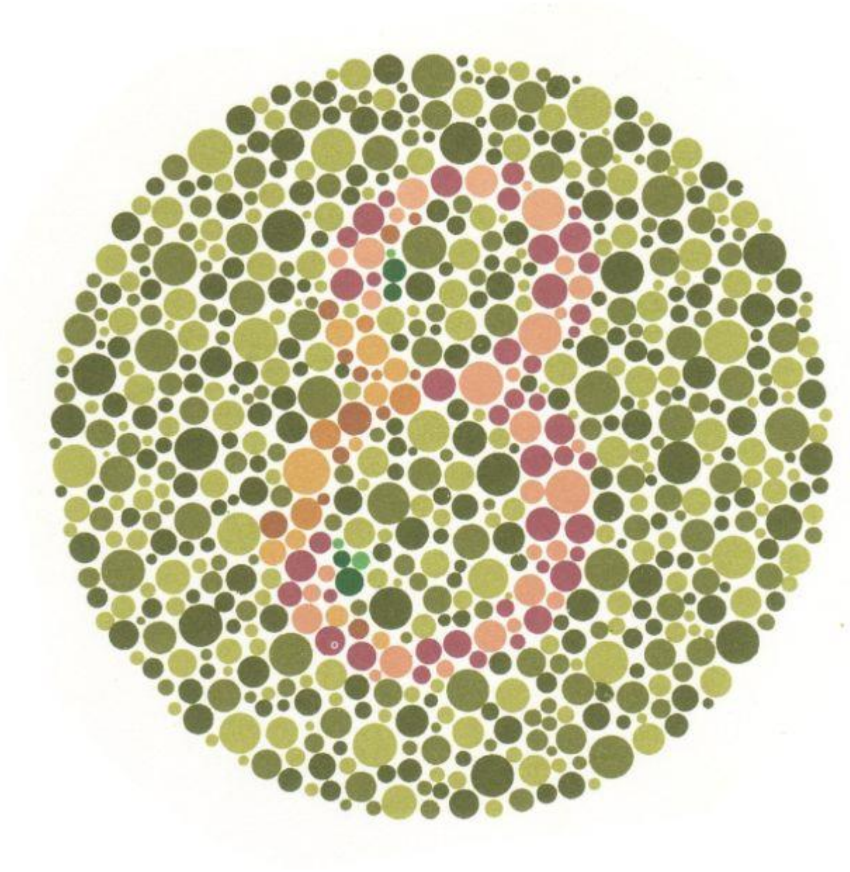






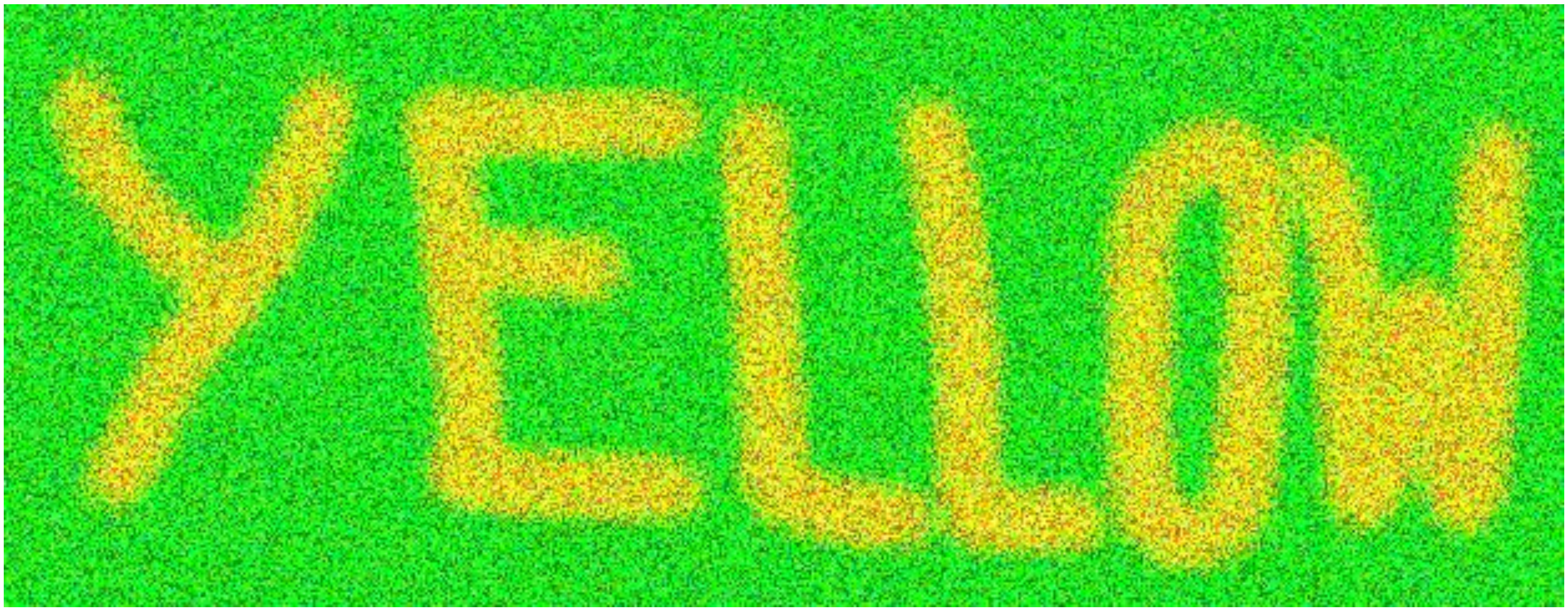
Color Deficiency Test





Color Deficiency

Color Deficiency



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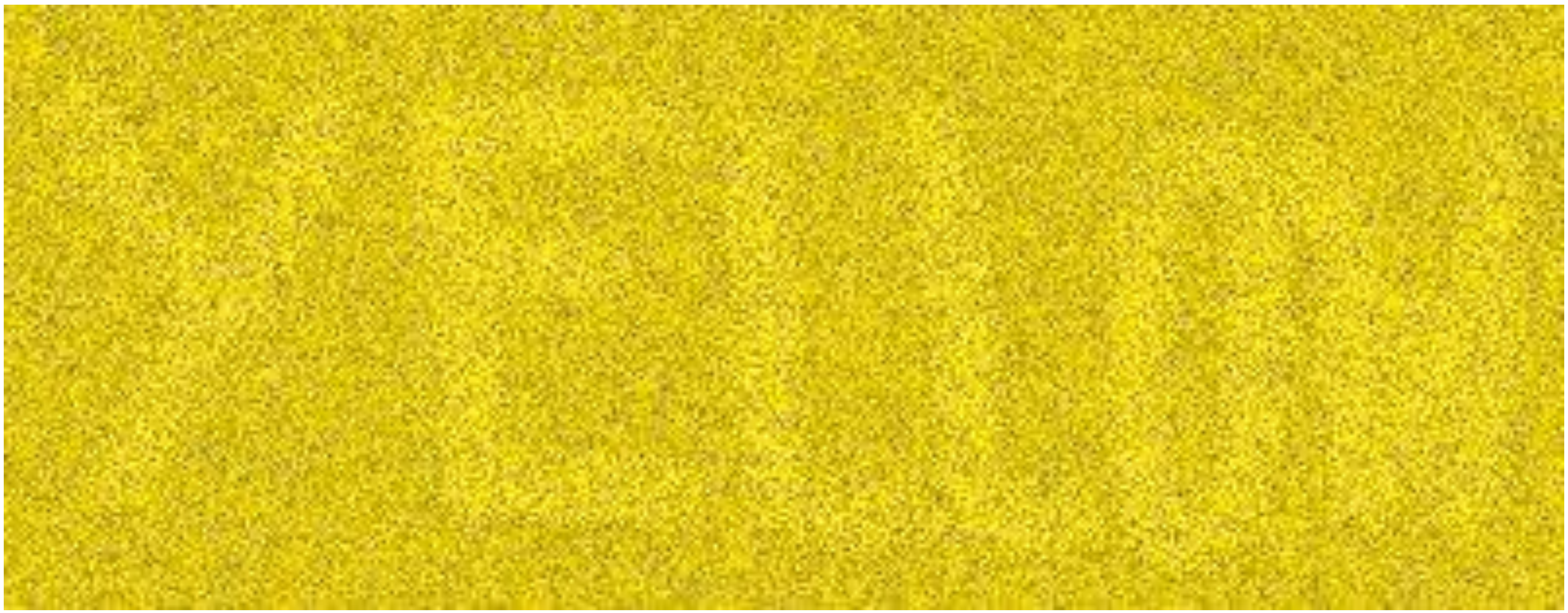
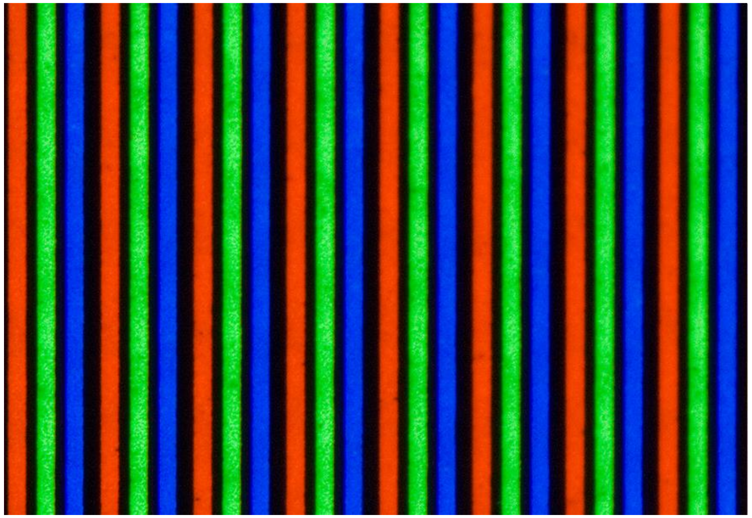
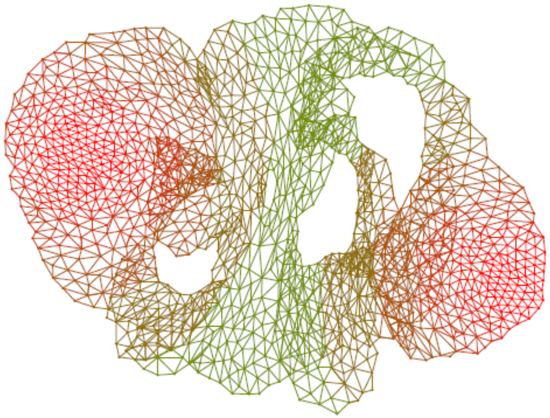
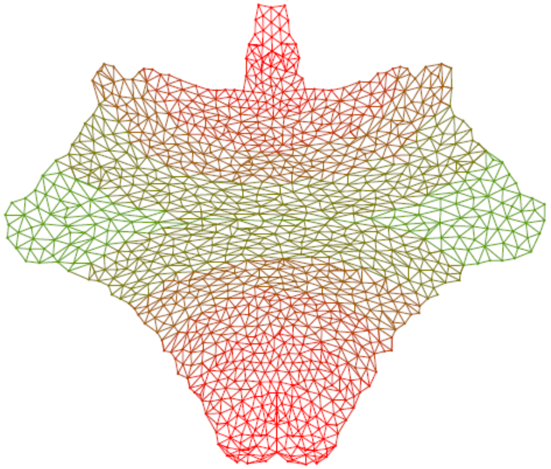
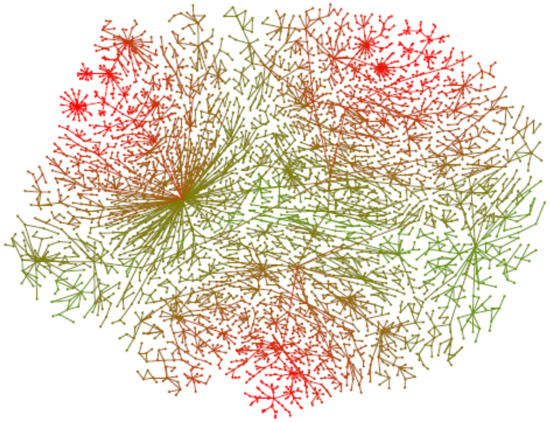
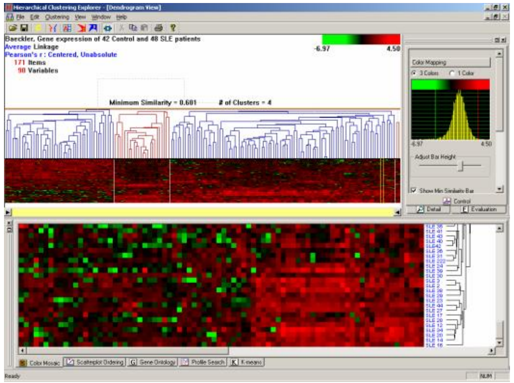
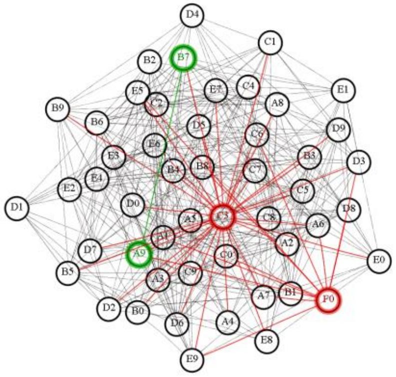
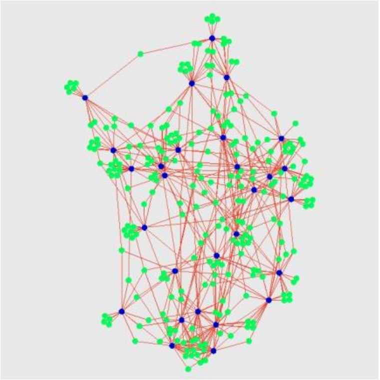
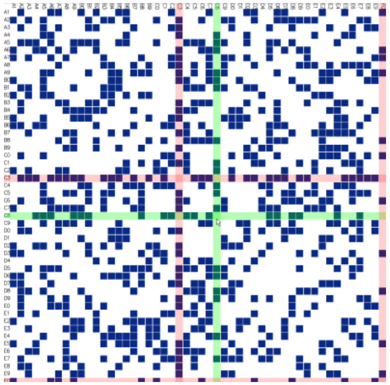


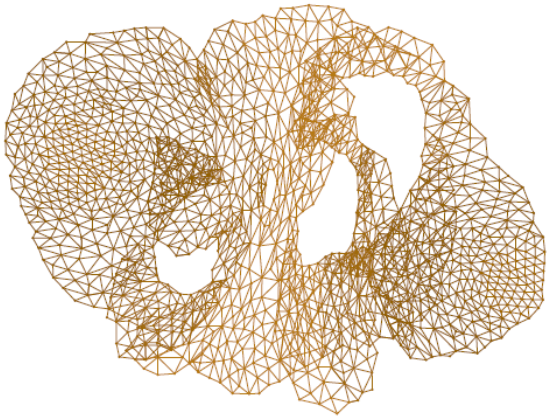
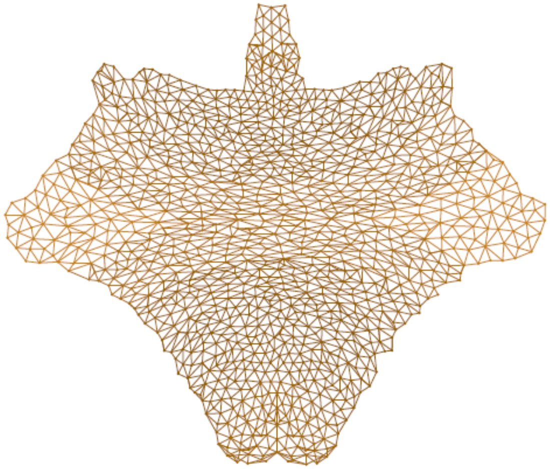
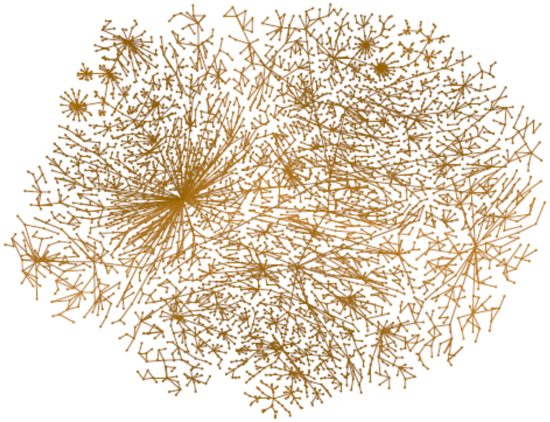
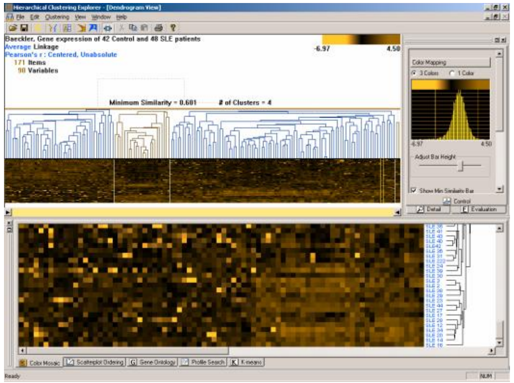
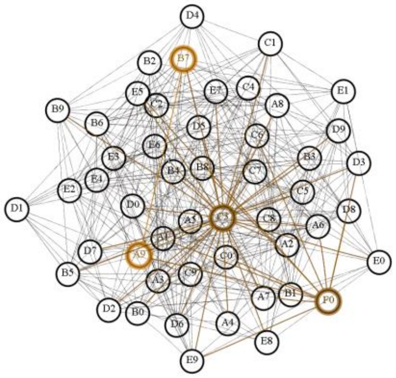
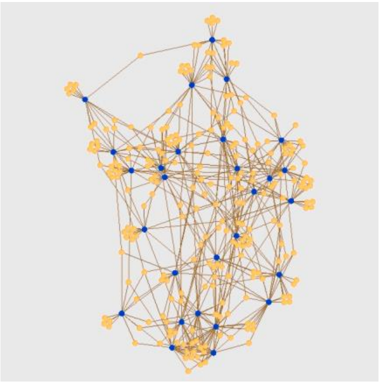
Color Deficiency



Examples from VIS/InfoVis 2004

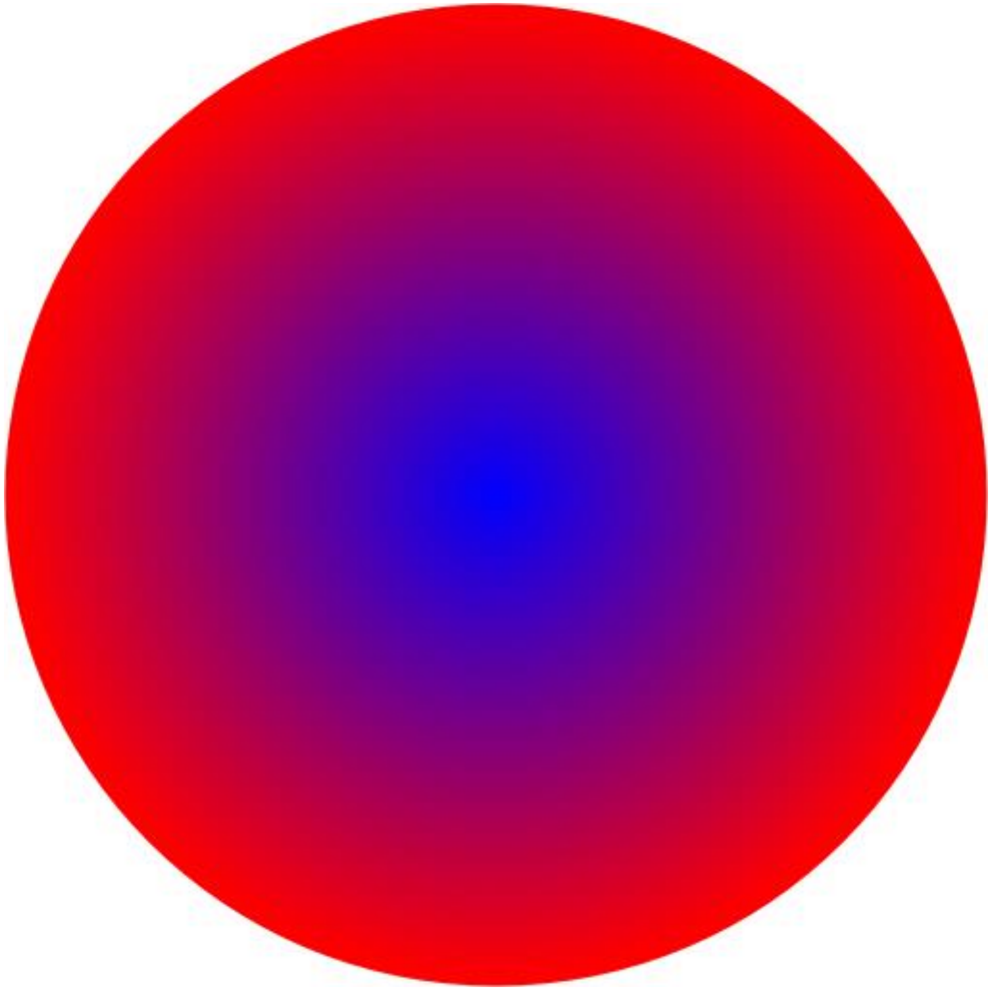








Examples from VIS/InfoVis 2004

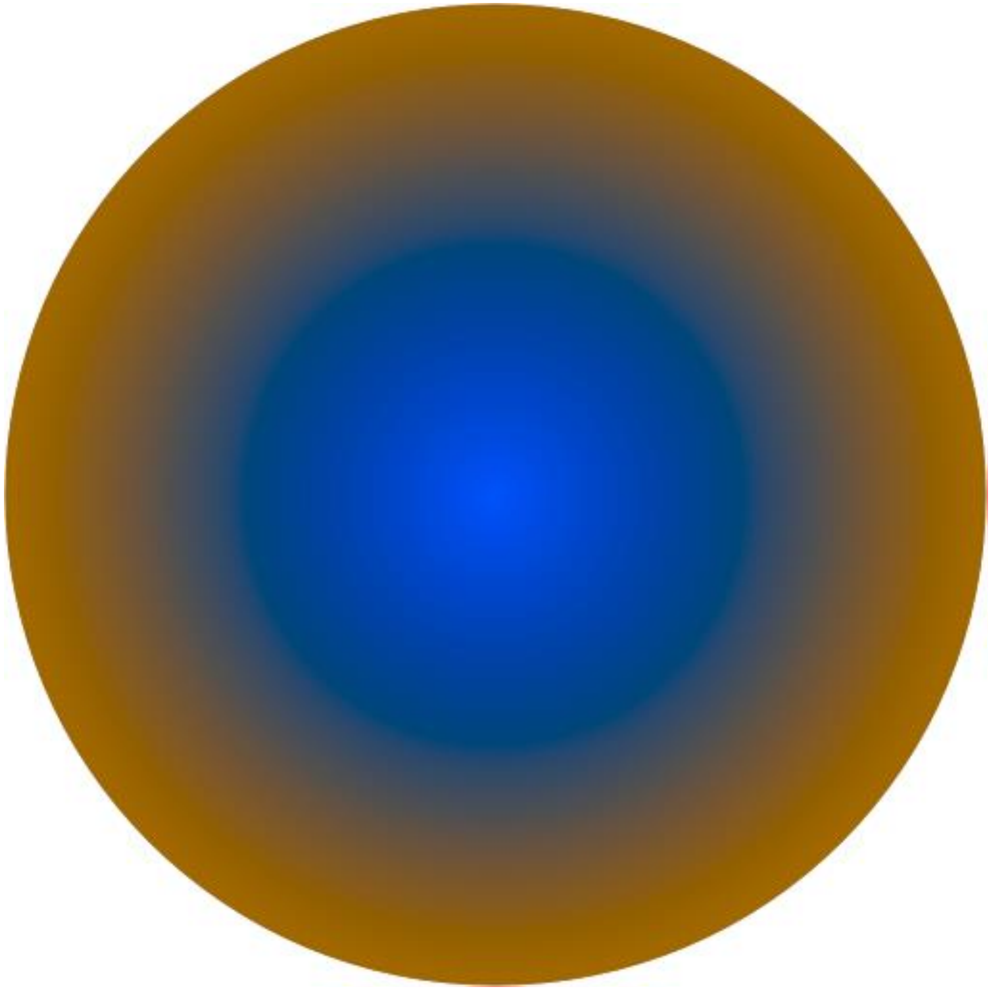








things have not really improved over the years:
Angerbauer et al. 2022 (CHI), **https://doi.org/10.1145/3491102.3502133**

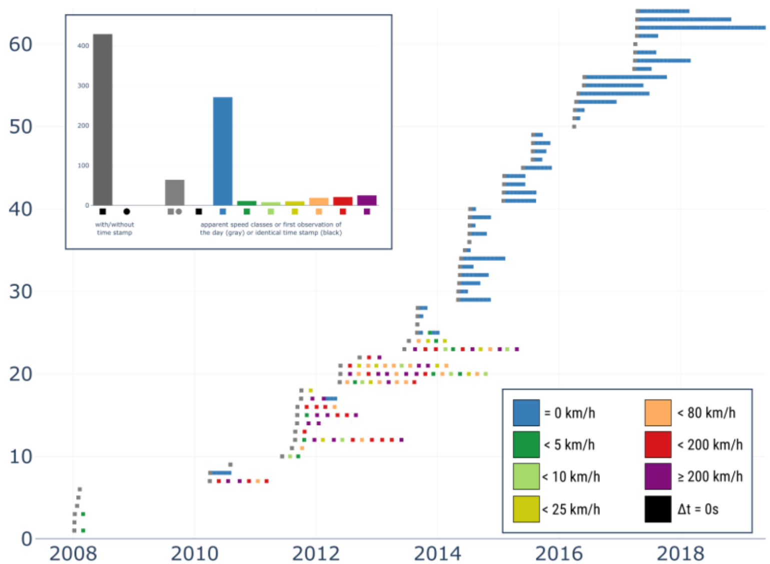
Better: Red-Blue Contrast



Better: Red-Blue Contrast



Or: Provide Alternative Mappings



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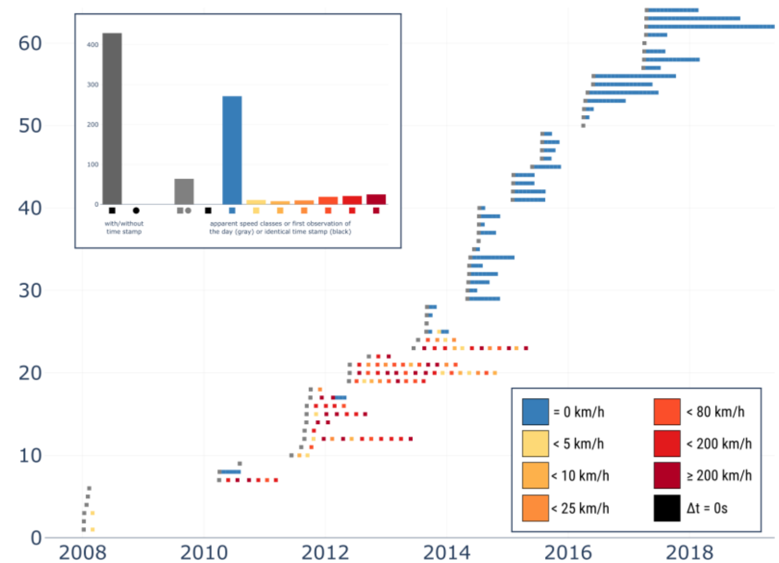
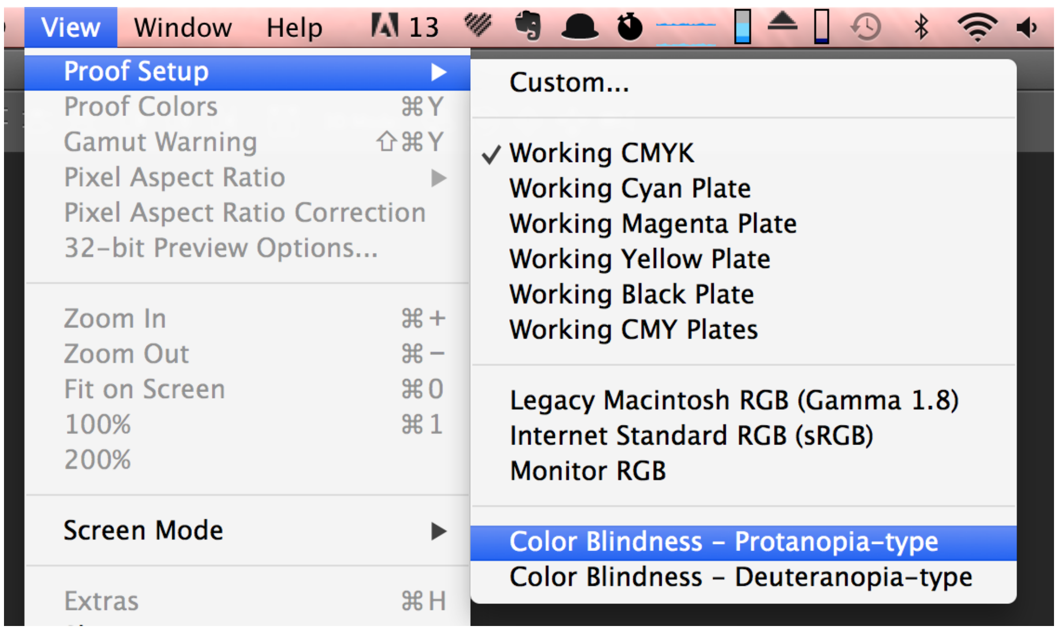


Check Your Visualizations!

When possible, avoid red-green color contrasts, in particular for visualization purposes.



To test your visualizations, use proofing modes in PhotoShop and GIMP, or try VisCheck
http://www.vischeck.com/

Summary

- color perception sufficiently similar in humans to be standardized
- 3 color values are sufficient to mix colors
- different type of color models
- RGB and CMYK most commonly used
- most color models cannot represent all perceivable colors
- color depends on context
- color deficiency