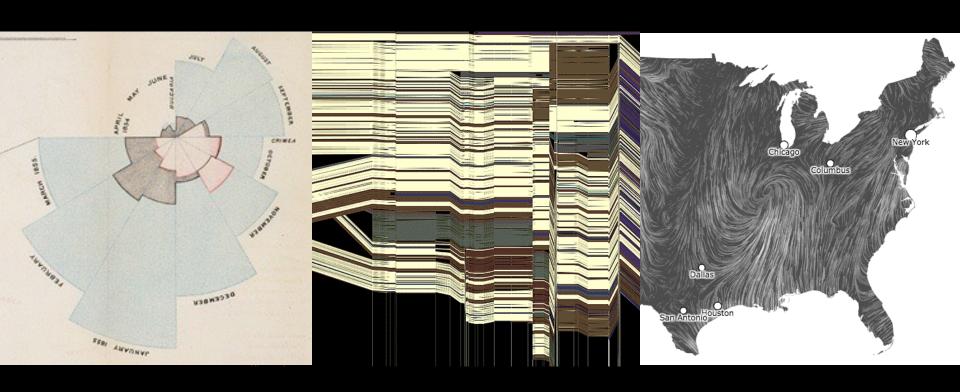
CSE 512 - Data Visualization

Color



Jeffrey Heer University of Washington

Purpose of Color

To label
To measure
To represent and imitate
To enliven and decorate

"Above all, do no harm." - Edward Tufte

Topics

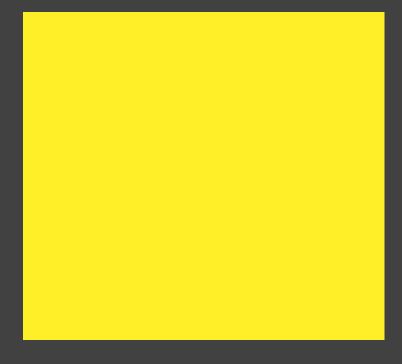
Perception of Color

Light, Visual system, Mental models

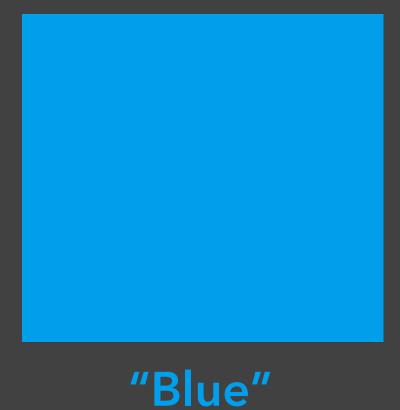
Color in Information Visualization

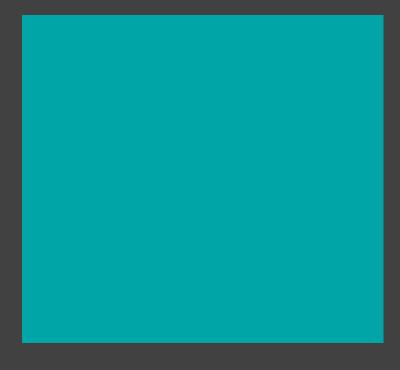
Categorical & Quantitative encoding Guidelines for color palette design

Perception of Color



"Yellow"



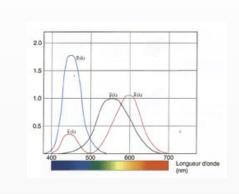


"Teal" ?

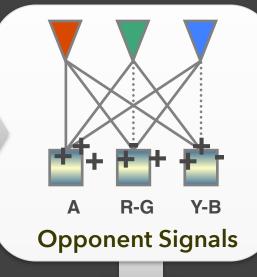
Perception of Color



Light

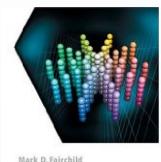


Cone Response



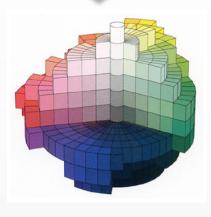
"Yellow"

Color Cognition



COLOR APPEARANCE MODELS

Color Appearance



Color Perception

Physicist's View

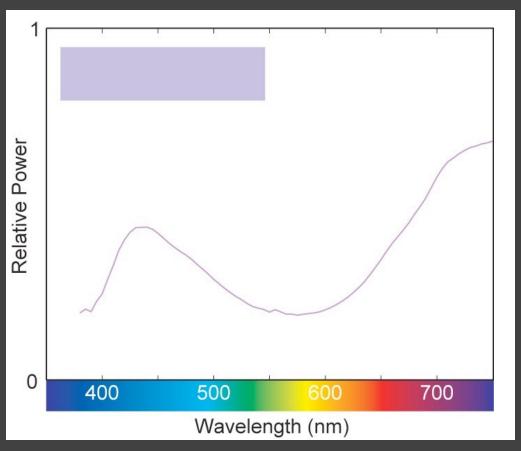
Light as electromagnetic waves

Wavelength

Visible spectrum is 370-730 nm

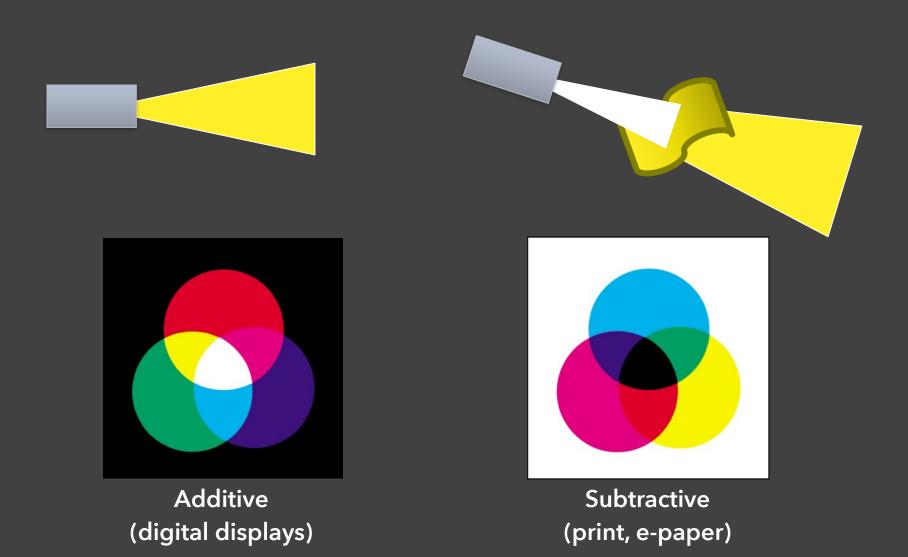
Power or

"Relative luminance"



A Field Guide to Digital Color, M. Stone

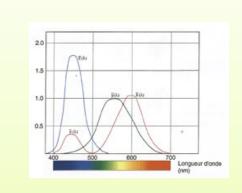
Emissive vs. Reflective Light



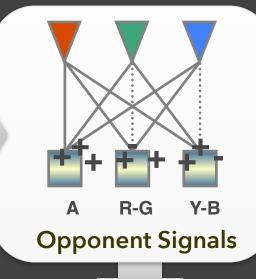
Perception of Color



Light



Cone Response



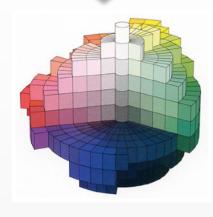
"Yellow"

Color Cognition



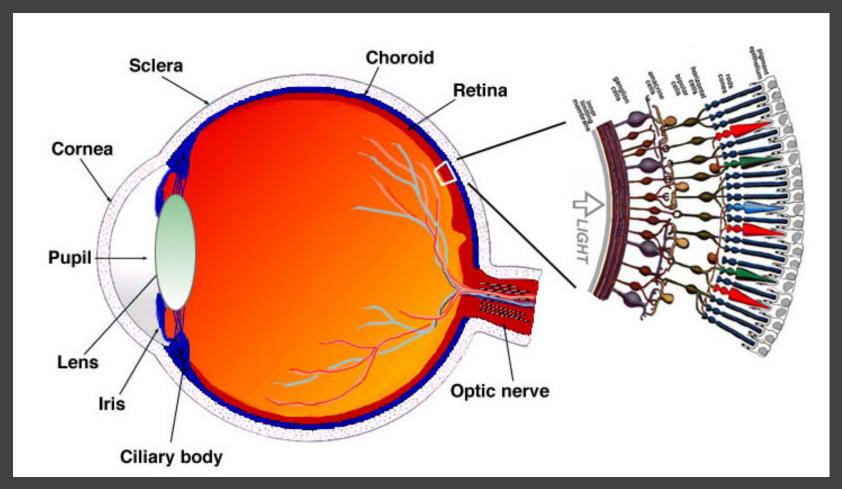
COLOR APPEARANCE MODELS

Color Appearance



Color Perception

Retina

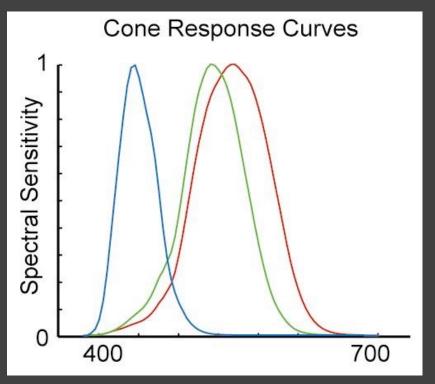


Simple Anatomy of the Retina, Helga Kolb

As light enters our retina...

LMS (Long, Middle, Short) Cones

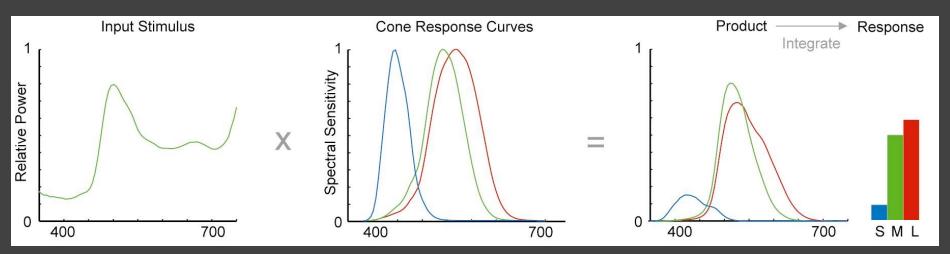
Sensitive to different wavelengths



A Field Guide to Digital Color, M. Stone

As light enters our retina...

LMS (Long, Middle, Short) Cones
Sensitive to different wavelengths
Integration with input stimulus



A Field Guide to Digital Color, M. Stone

Effects of Retina Encoding

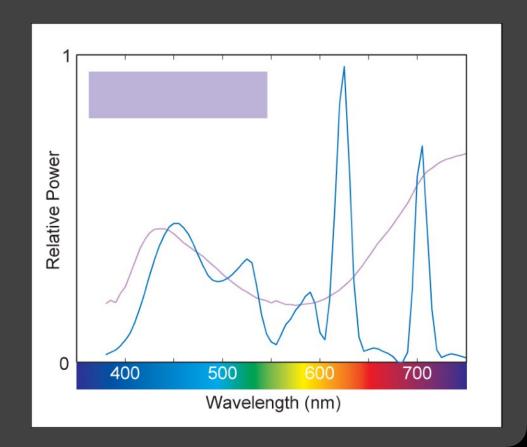
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

"Tri-stimulus"

Computer displays

Digital scanners

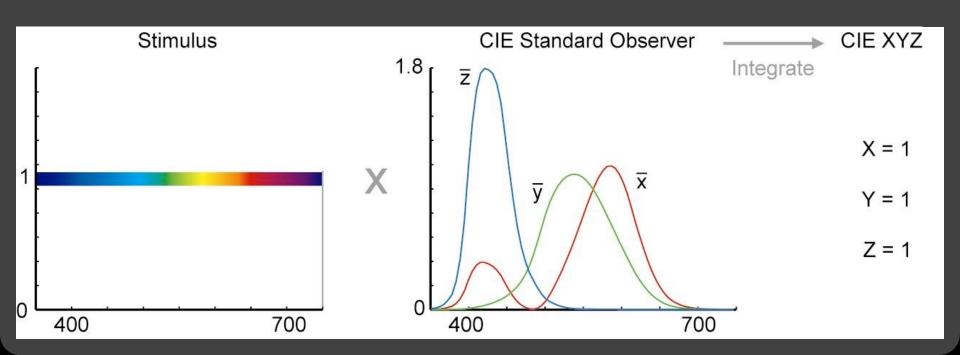
Digital cameras



CIE XYZ Color Space

Standardized in 1931 to mathematically represent tri-stimulus response from cones on the retina.

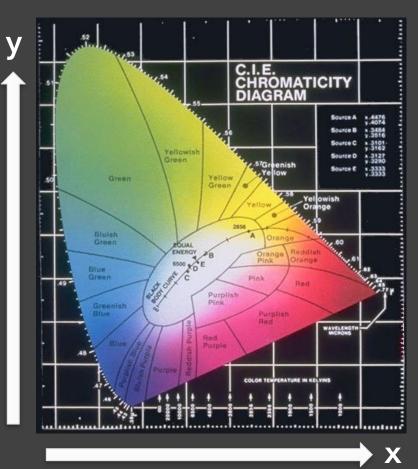
"Standard observer" response curves



Colorfulness vs. Brightness

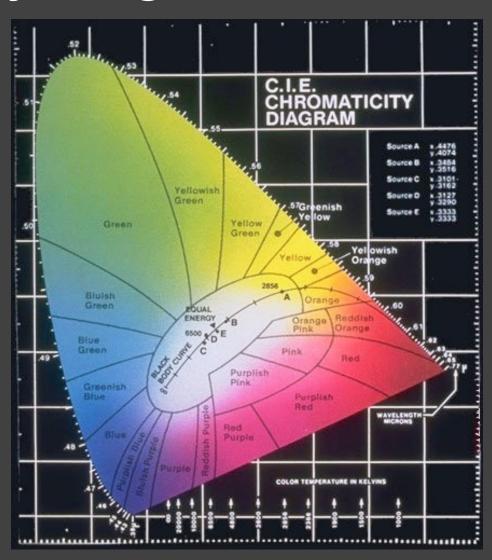
$$x = X / (X+Y+Z)$$

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



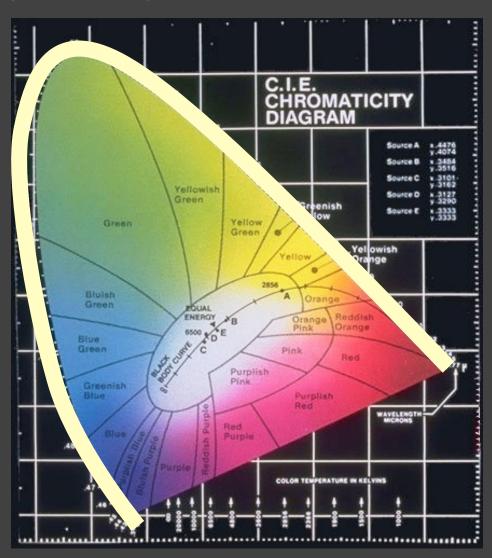
Spectrum locus

Purple line



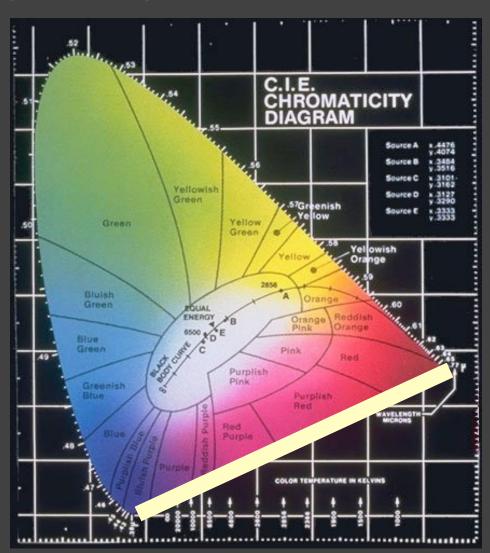
Spectrum locus

Purple line



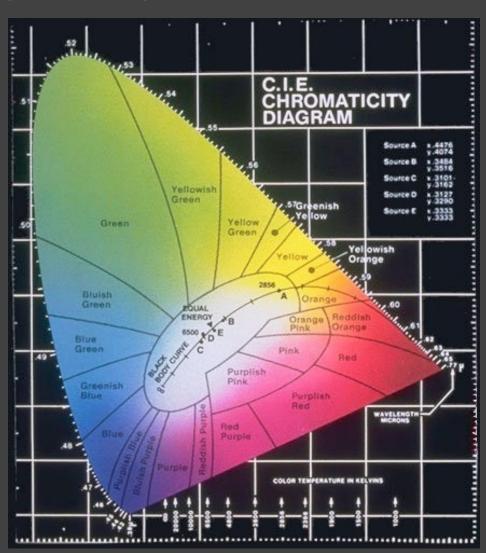
Spectrum locus

Purple line



Spectrum locus

Purple line

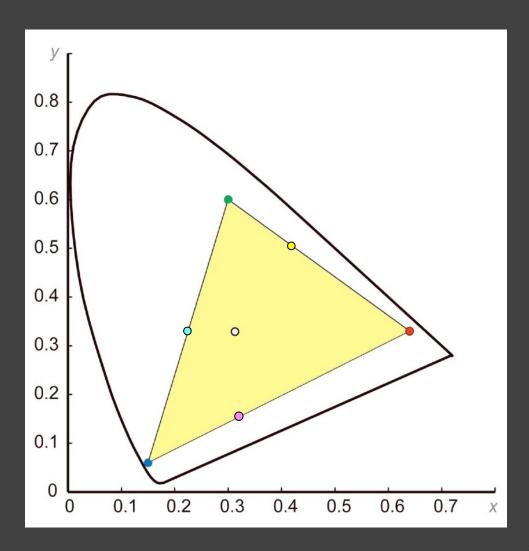


Display Gamuts

Typically defined by:

3 Colorants

Convex region



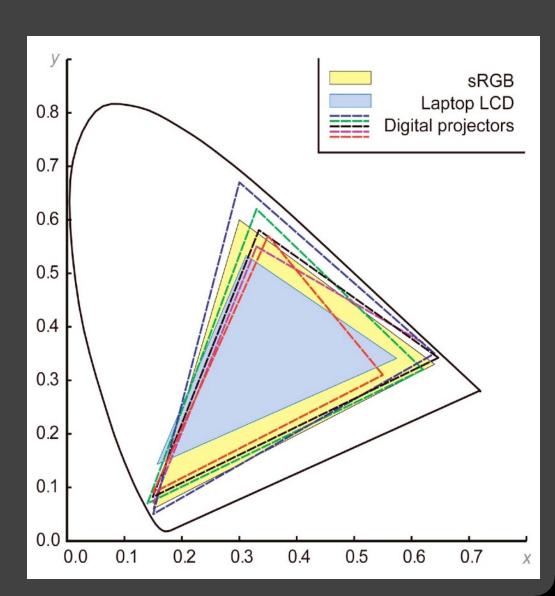
Display Gamuts

Deviations from sRGB specification

Example:

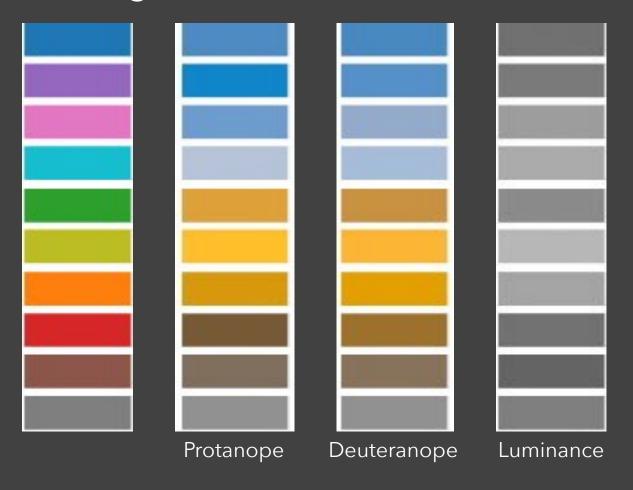
(R, G, B) coordinates ranging from 0-255.

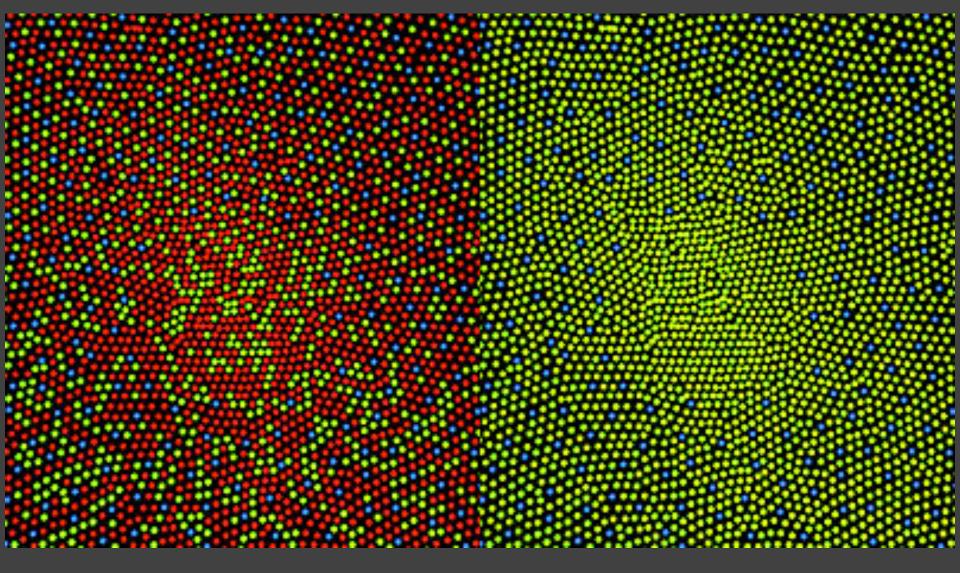
Displays may produce different colors for a coord!



Color Vision Deficiency (CVD)

Missing one or more cones or rods in retina.





Normal Retina

Protanopia

Color Vision Simulators

Simulate color vision deficiencies

Browser plug-ins Photoshop plug-ins, etc.









<u>Prot</u>anope

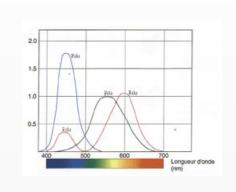


Tritanope

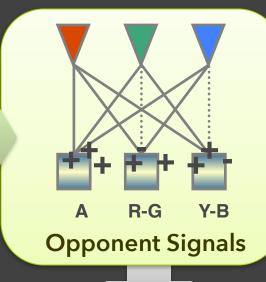
Perception of Color



Light



Cone Response



"Yellow"

Color Cognition

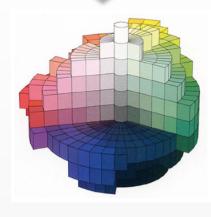


Mark D. Fairchild

COLOR APPEARANCE

MODELS

Color Appearance



Color Perception

Primary Colors

To paint "all colors":

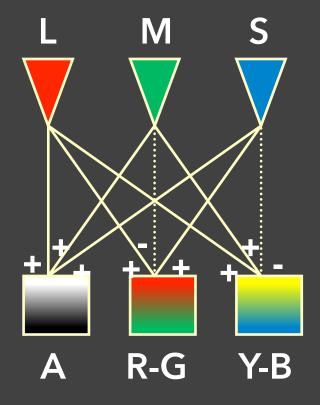
Leonardo da Vinci, circa 1500 described in his notebooks a list of simple colors...

Yellow Blue Green Red

Opponent Processing

LMS are combined to create:

Lightness Red-green contrast Yellow-blue contrast



[Fairchild]

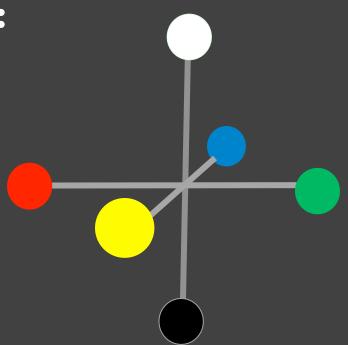
Opponent Processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Opponent Processing

LMS are combined to create:

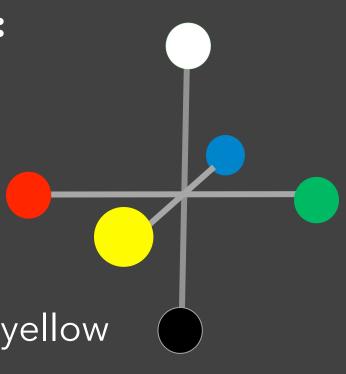
Lightness

Red-green contrast

Yellow-blue contrast

Experiments:

No reddish-green, no blueish-yellow Color after images



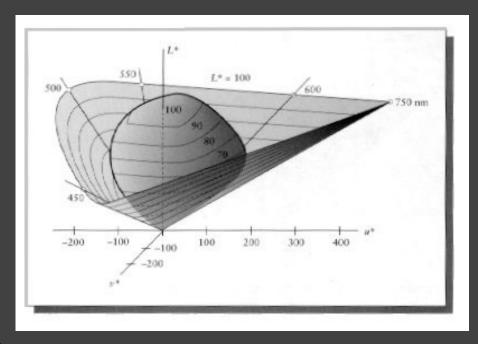


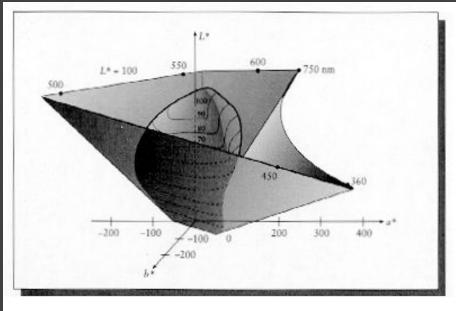


CIE LAB and LUV Color Spaces

Standardized in 1976 to mathematically represent opponent processing theory.

Non-linear transformation of CIE XYZ





CIE LAB Color Space

Axes correspond to opponent signals

L* = Luminance

a* = Red-green contrast

b* = Yellow-blue contrast

Much more perceptually uniform than sRGB!

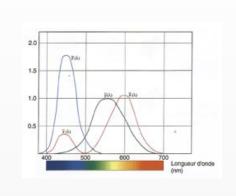
Scaling of axes to represent "color distance" JND = Just noticeable difference (~2.3 units)

D3 + Vega include LAB color space support!

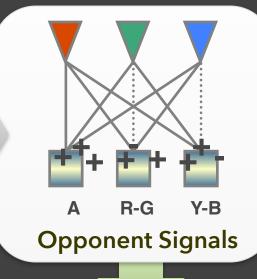
Perception of Color



Light

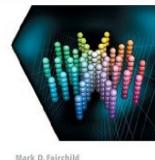


Cone Response



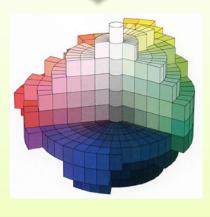
"Yellow"

Color Cognition



COLOR APPEARANCE MODELS

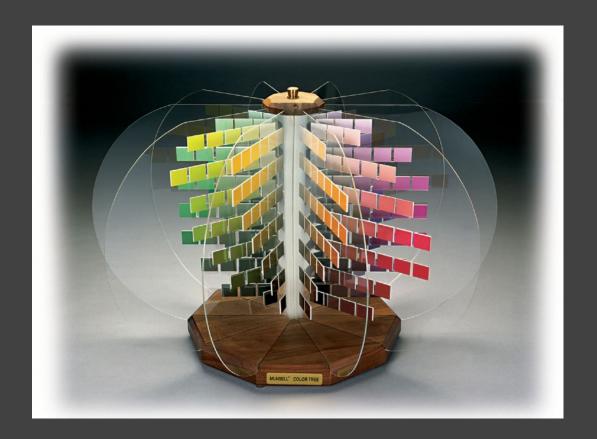
Color Appearance



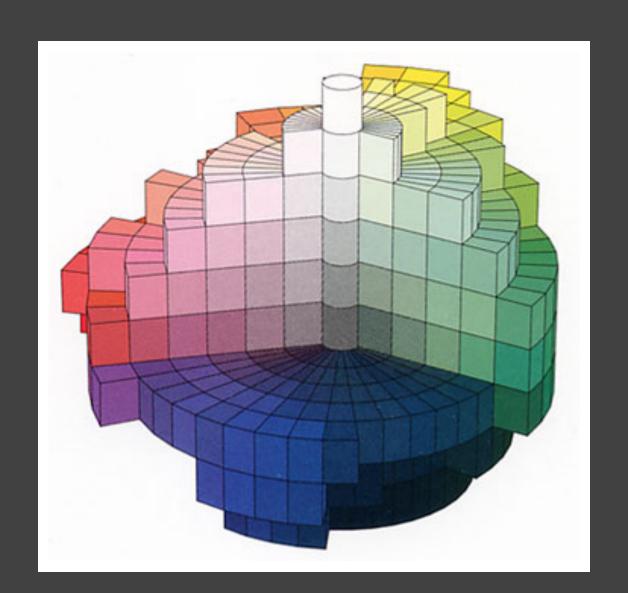
Color Perception

Albert Munsell

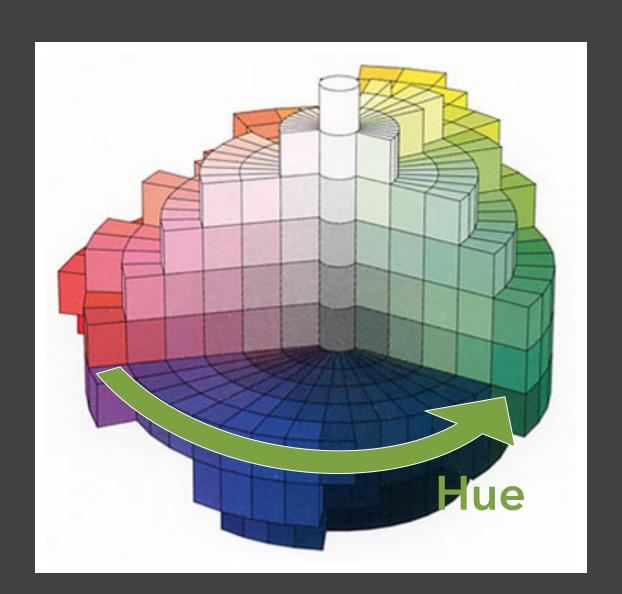
Developed the first perceptual color system based on his experience as an artist (1905).



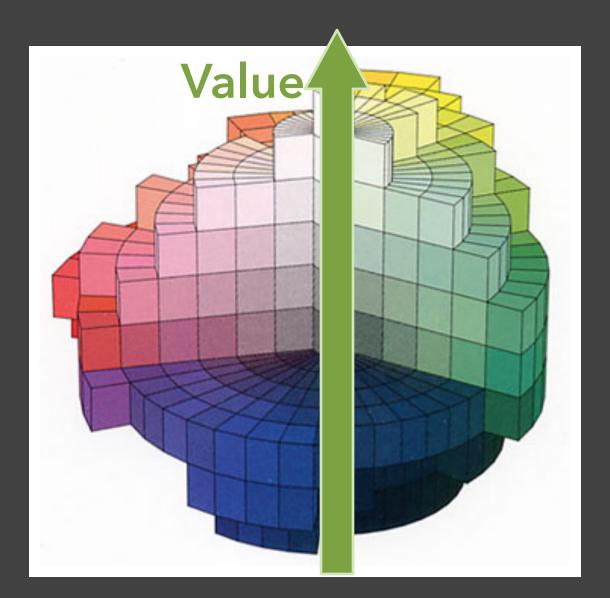
Hue, Value, and Chroma



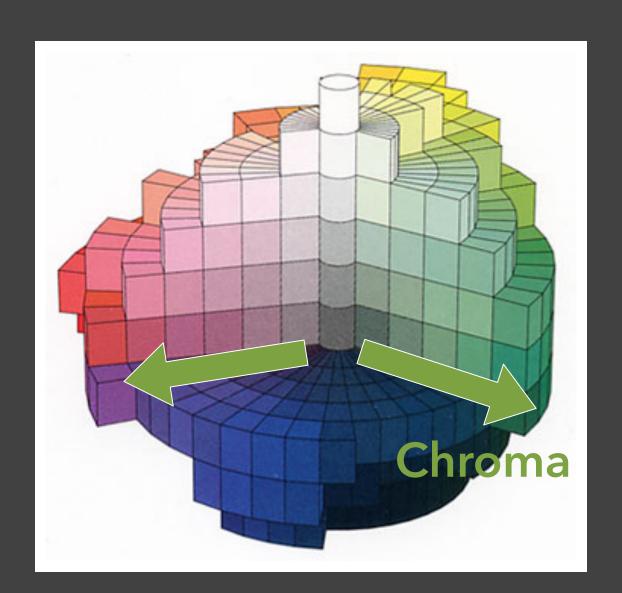
Hue, Value and Chroma



Hue, Value and Chroma



Hue, Value and Chroma



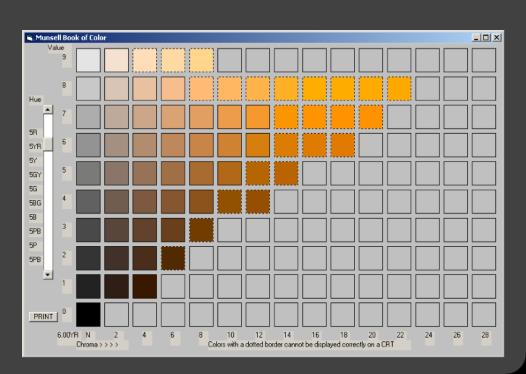
Munsell Color System

Perceptually-based

Precisely reference a color

Intuitive dimensions

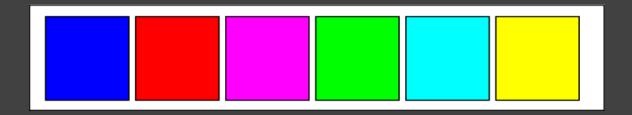
Look-up table (LUT)



Munsell Color System



Color palette



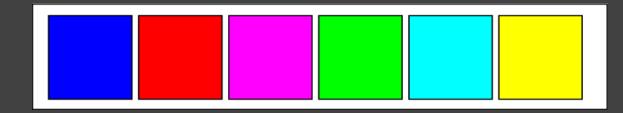
Color palette



HSL Lightness (Photoshop)



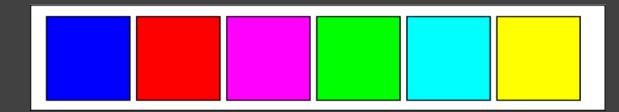
Color palette



Luminance Y (CIE XYZ)



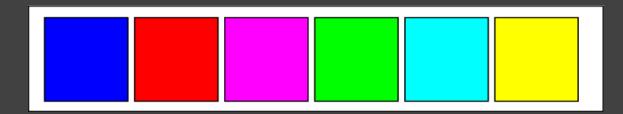
Color palette



Munsell Value



Color palette

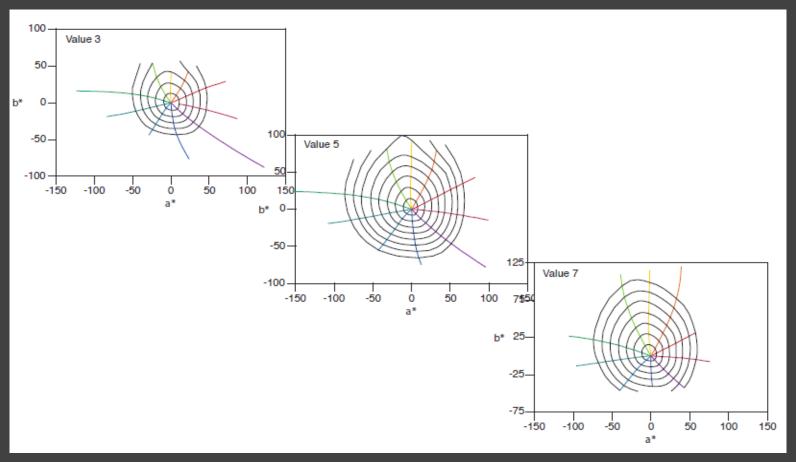


Munsell Value L* (CIE LAB)



Perceptually-Uniform Color Space

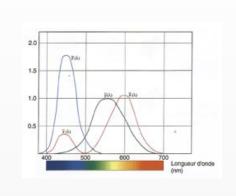
Munsell colors in CIE LAB coordinates



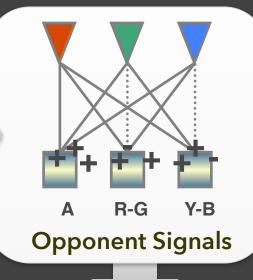
Perception of Color



Light

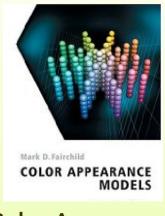


Cone Response



"Yellow"

Color Cognition



Color Appearance



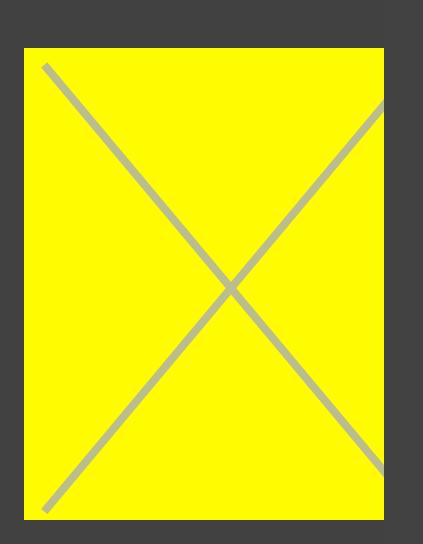
Color Perception

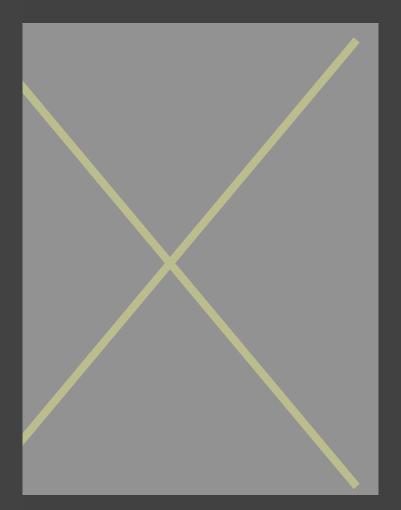
Color Appearance

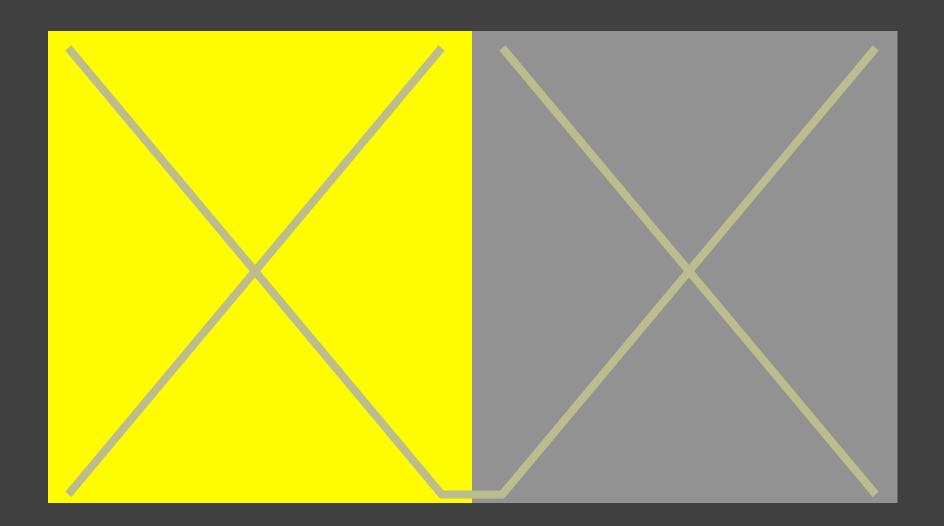
If we have a perceptually-uniform color space, can we predict how we perceive colors?

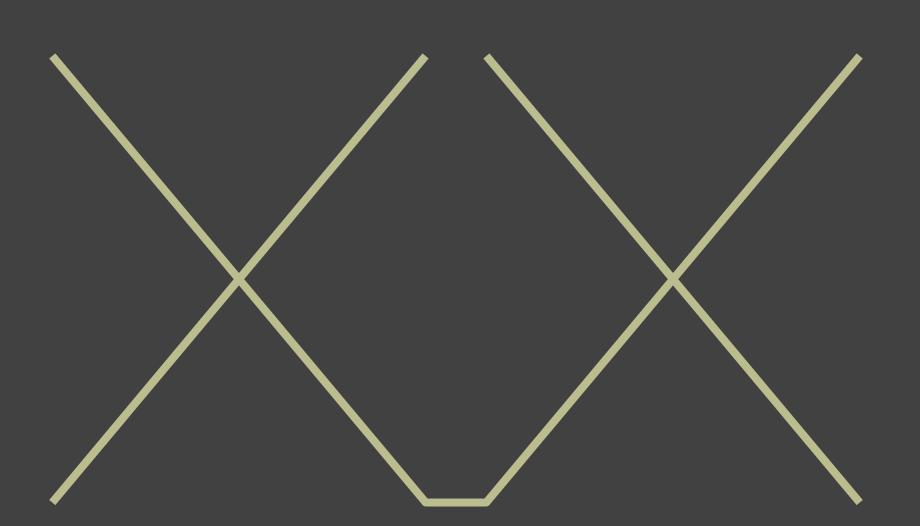
"In order to use color effectively it is necessary to recognize that it deceives continually."

- Josef Albers, Interaction of Color

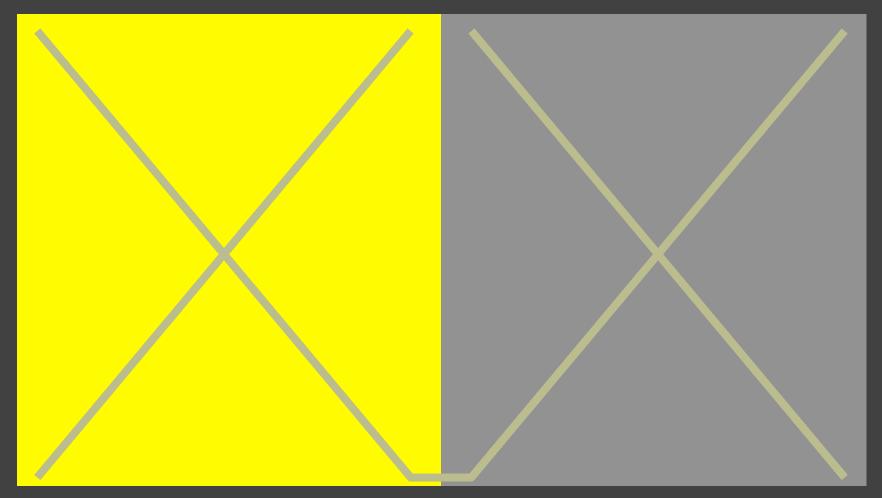






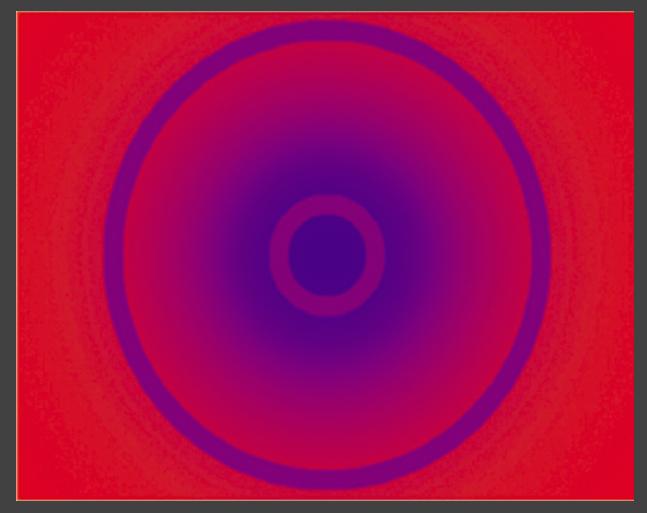


Simultaneous Contrast



Simultaneous Contrast

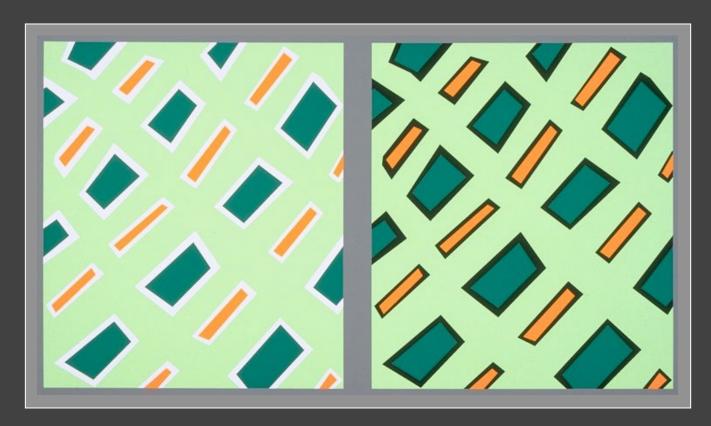
Inner & outer rings are the same physical purple.



Donald MacLeod

Bezold Effect

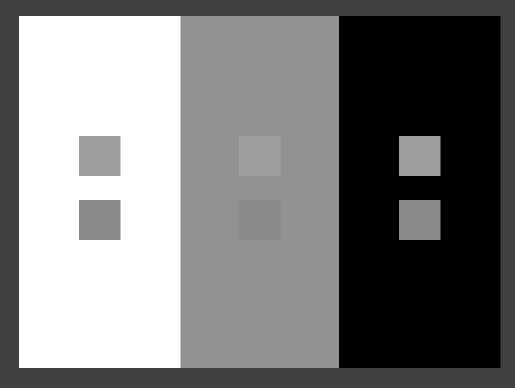
Color appearance depends on adjacent colors



Color Appearance Tutorial by Maureen Stone

Crispening

Perceived difference depends on background

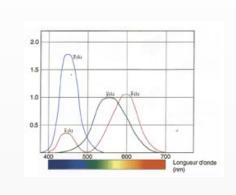


Color Appearance Models, Fairchild

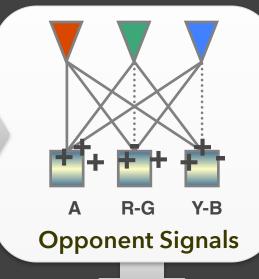
Perception of Color



Light



Cone Response



"Yellow"

Color Cognition

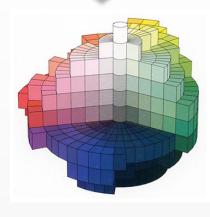


Mark D. Fairchild

COLOR APPEARANCE

MODELS

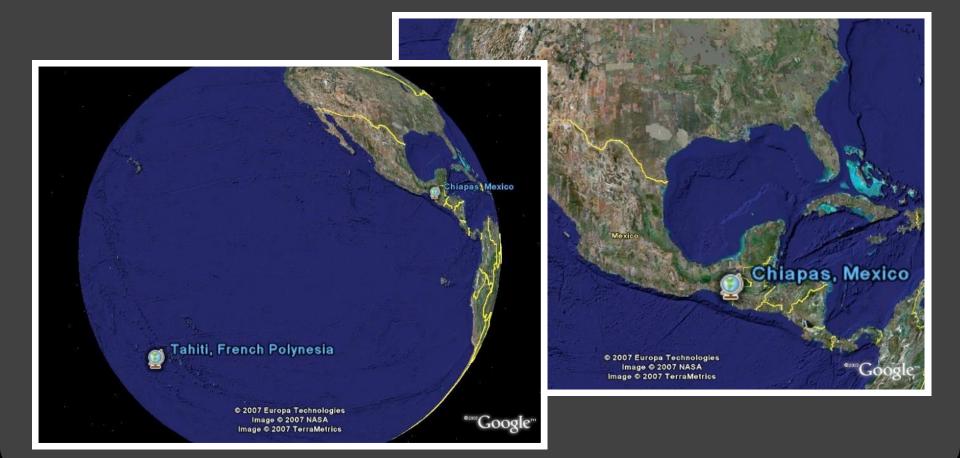
Color Appearance



Color Perception

Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.



Basic Color Terms

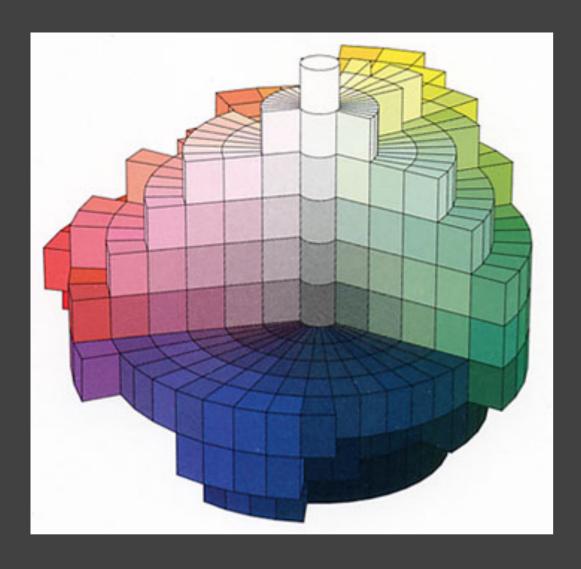
Chance discovery by Brent Berlin and Paul Kay.

Initial study in 1969

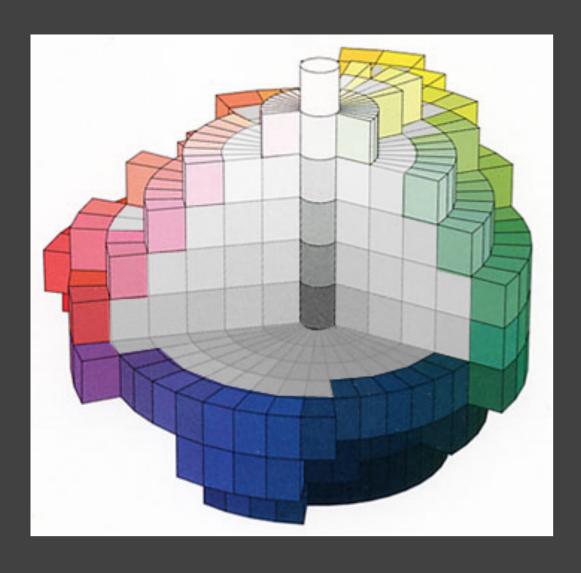
Surveyed speakers from 20 languages

Literature from 69 languages

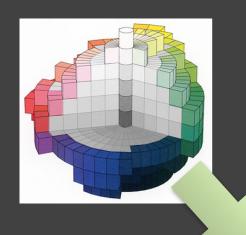
World Color Survey



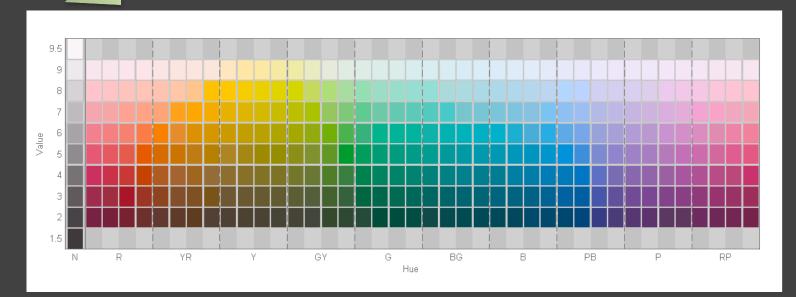
World Color Survey



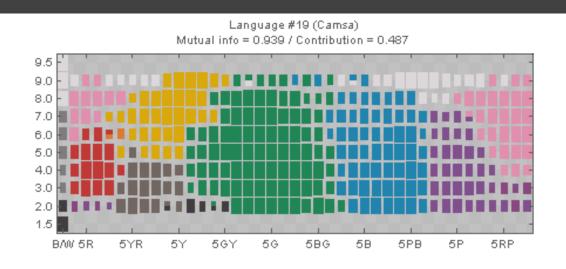
World Color Survey

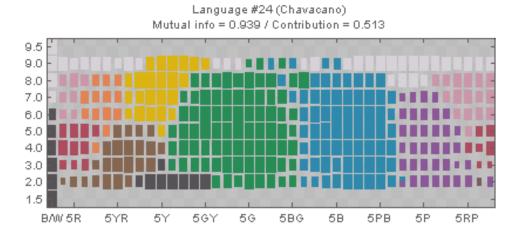


Naming information from 2,616 speakers from 110 languages on 330 Munsell color chips

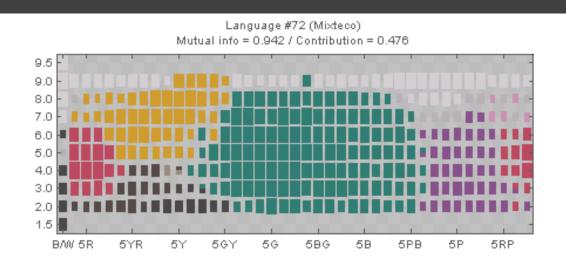


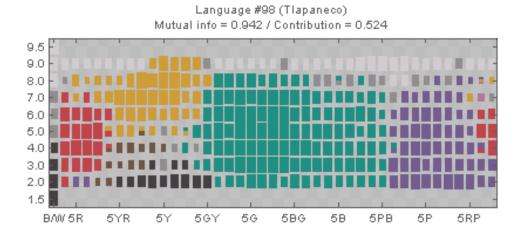
Results from WCS





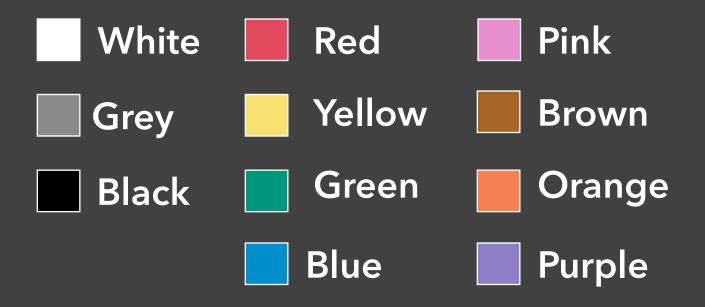
Results from WCS





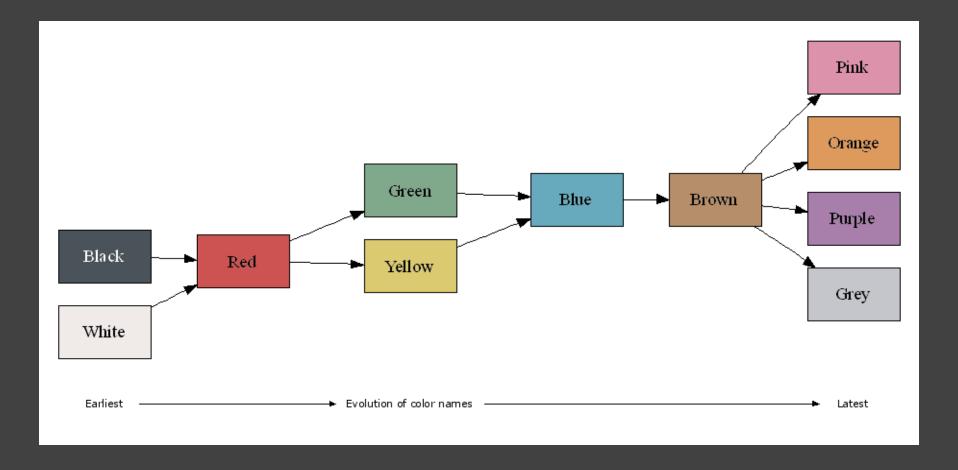
Universal (?) Basic Color Terms

Basic color terms recur across languages.



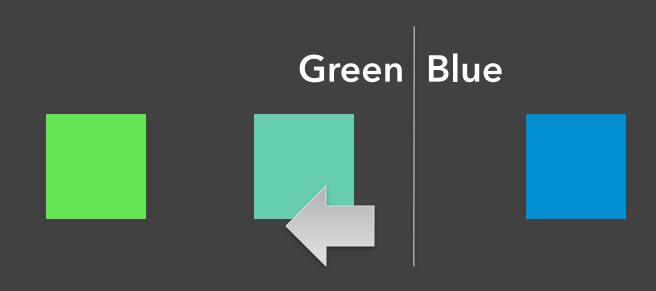
Evolution of Basic Color Terms

Proposed term evolution across languages.



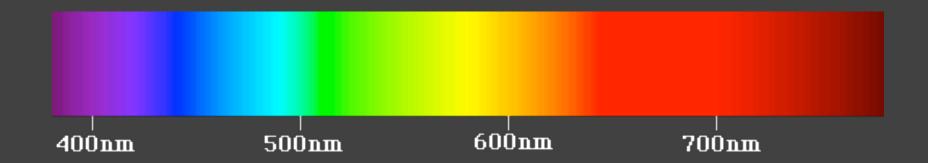
Naming Effects Color Perception

Color name boundaries



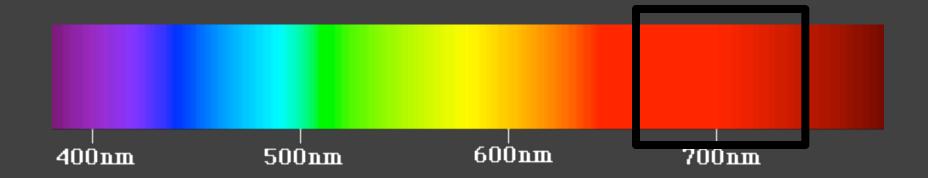
Rainbow Color Map

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



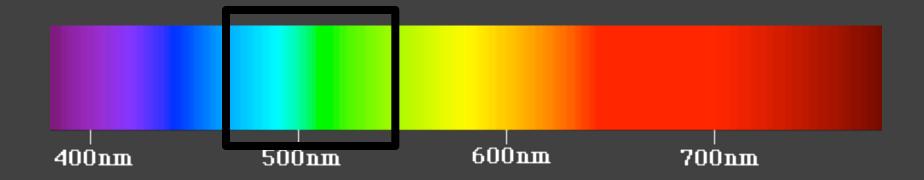
Rainbow Color Map

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

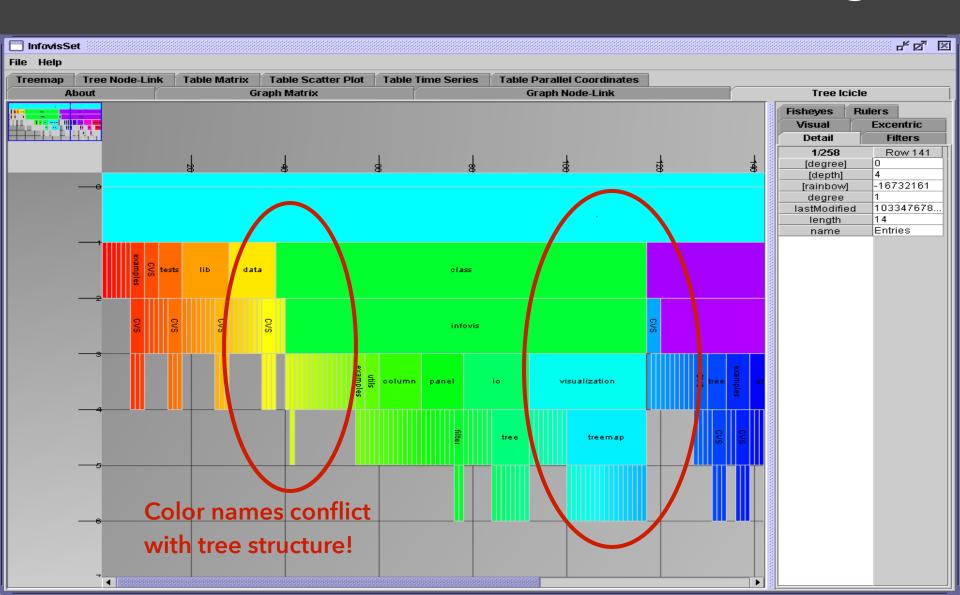


Rainbow Color Map

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



Icicle Tree with Rainbow Coloring



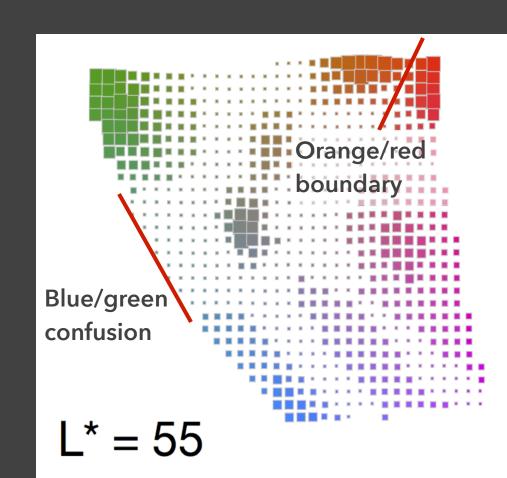
Color Naming Models [Heer & Stone '12]

Model 3 million responses from XKCD survey

Bins in LAB space sized by *saliency*:

How much do people agree on color name?

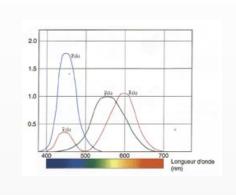
Modeled by entropy of *p*(*name* | *color*)



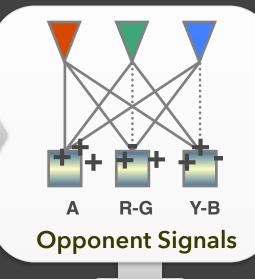
Perception of Color



Light



Cone Response



"Yellow"

Color Cognition



COLOR APPEARANCE MODELS

Color Appearance



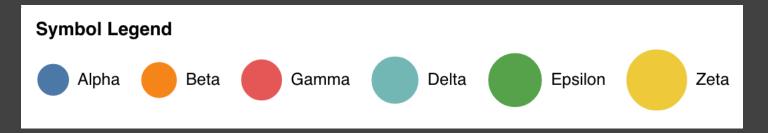
Color Perception

Designing Colormaps

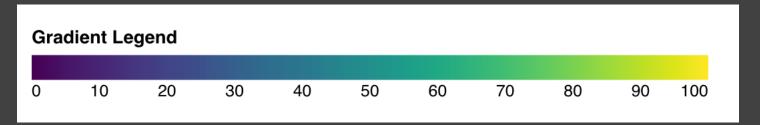
Colormap Design Considerations

Perceptually distinguishable colors Value distance matches perceptual distance Colors and concepts properly align Aesthetically pleasing, intriguing Respect color vision deficiencies Should survive printing to black & white Don't overwhelm people's capability!

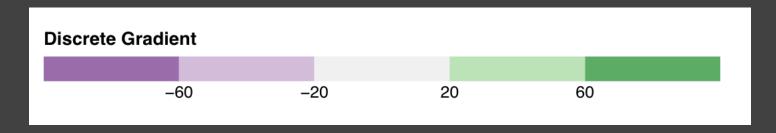
Discrete (Binary, Categorical)



Continuous (Sequential, Diverging, Cyclic)

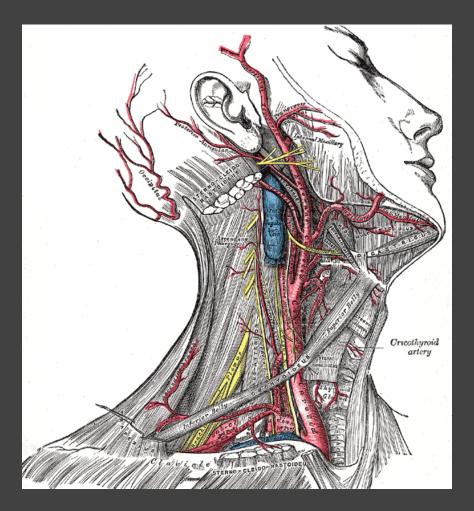


Discretized Continuous



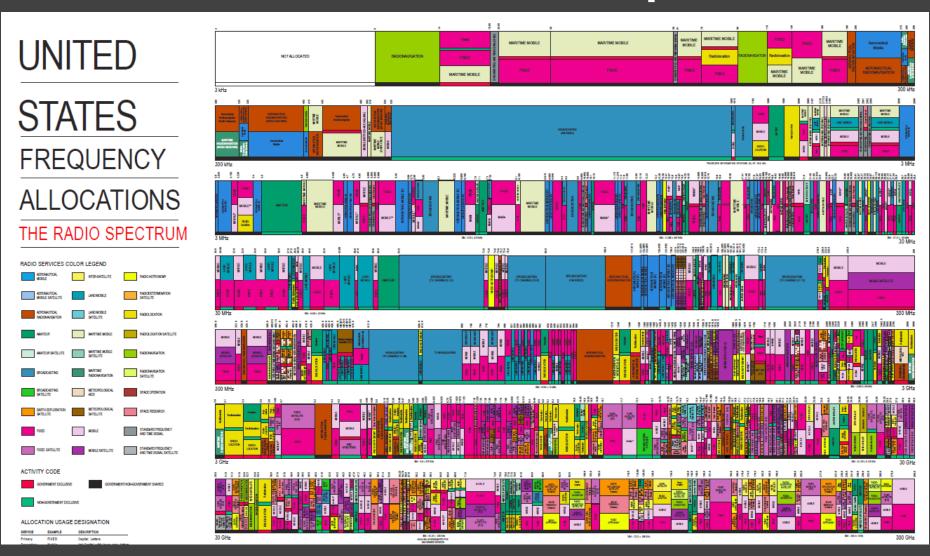
Categorical Color

Gray's Anatomy



Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)

Allocation of the Radio Spectrum



Alloca

UNITED

STATES **FREQUENCY**

ALLOCATION

THE RADIO SPECTS

- RADIO SERVICES COLOR LEGEND

RADIO SERVICES COLOR LEGEND

AERONAUTICAL MOBILE



INTER-SATELLITE



RADIO ASTRONOMY

AERONAUTICAL MOBILE SATELLITE

LAND MOBILE



RADIODETERMINATION SATELLITE

AERONAUTICAL RADIONAVIGATION

LAND MOBILE SATELLITE

RADIOLOCATION

AMATEUR

MARITIME MÓBILE



RADIOLOCATION SATELLITE



AMATEUR SATELLITE



MARITIME MÓBILE SATELLITE



PADIONAVIGATION



BROADCASTING



MARITIME **RADIONAVIGATION**



RADIONAVIGATION SATELLITE



BROADCASTING SATELLITE



METEOROLOGICAL



SPACE OPERATION



EARTH EXPLORATION SATELLITE



METEOROLOGICAL SATELLITE



SPACE RESEARCH



FIXED



MOBILE



STANDARD FREQUENCY AND TIME SIGNAL



FIXED SATELLITE

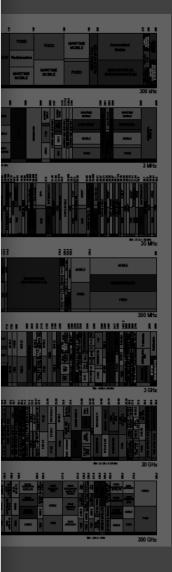


MOBILE SATELLITE



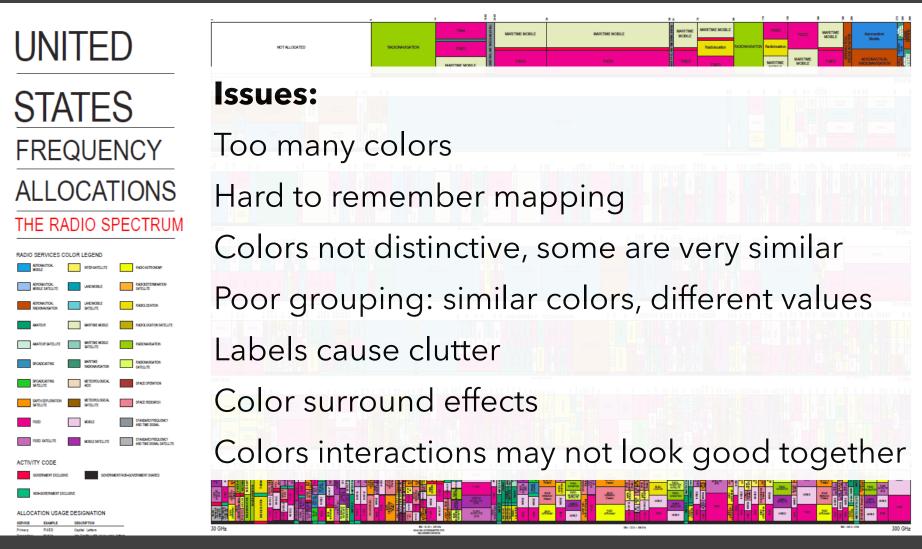
STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

rum



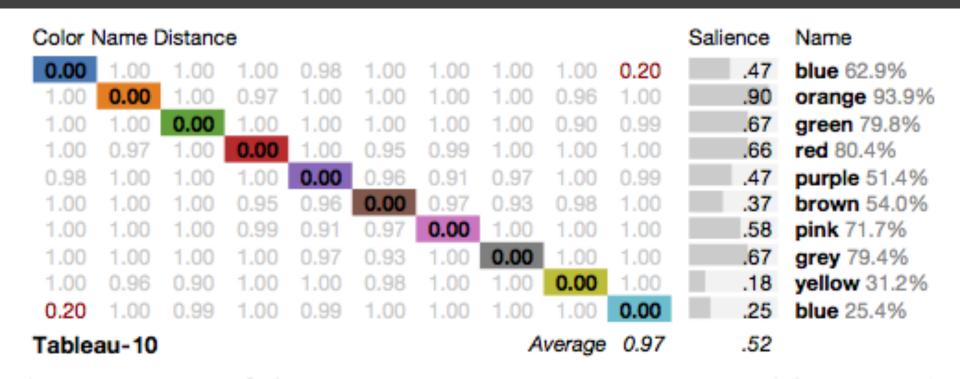
ACTIVITY CODE

Allocation of the Radio Spectrum



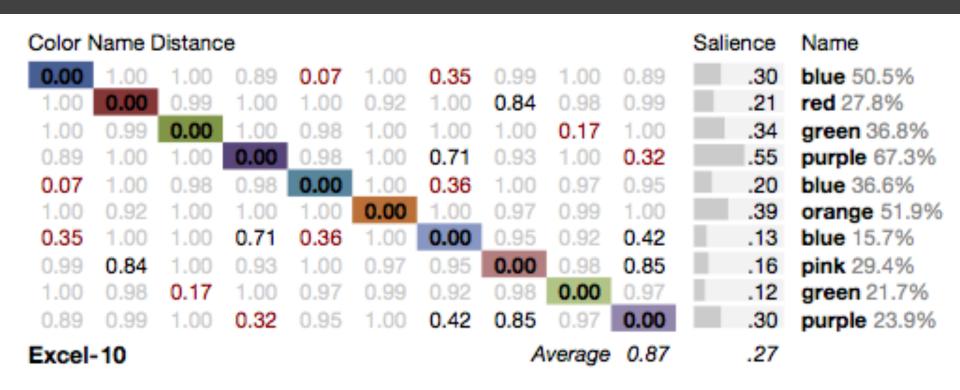
Palette Design & Color Names

Minimize overlap and ambiguity of colors.



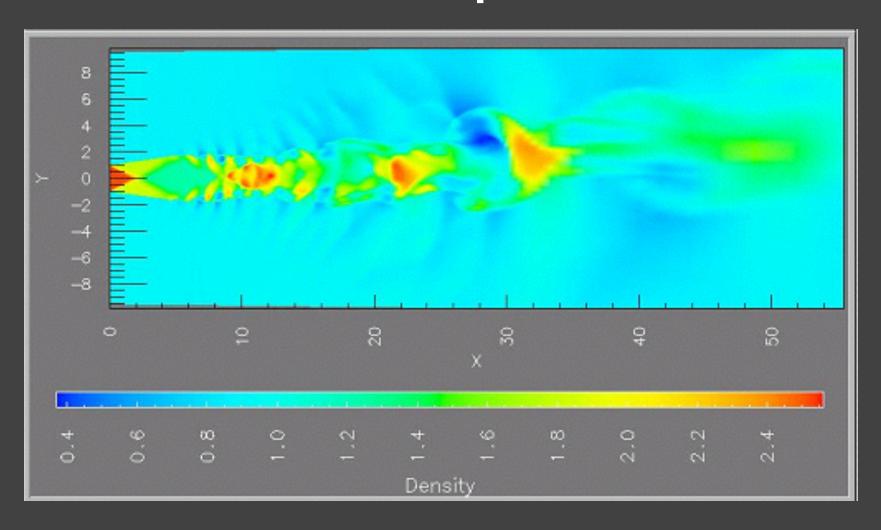
Palette Design & Color Names

Minimize overlap and ambiguity of colors.

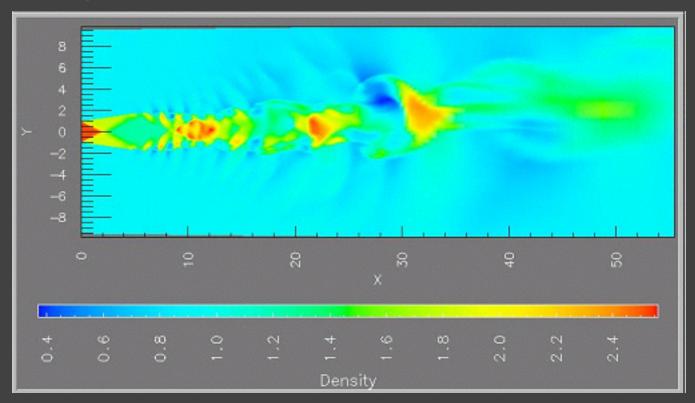


Quantitative Color

Rainbow Color Maps

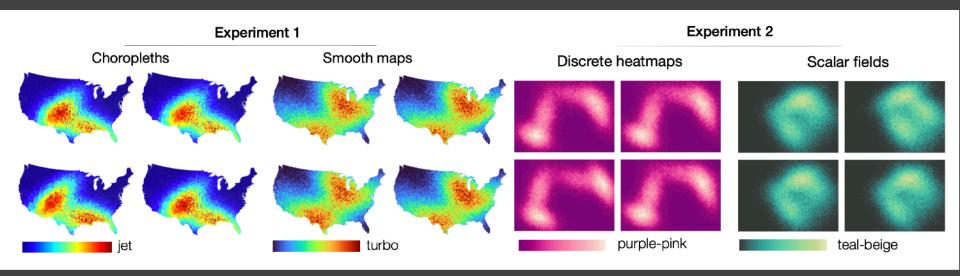


Be wary of naïve rainbows?



- 1. Naive rainbows are unfriendly to color blind viewers
- 2. Hues are not naturally ordered
- 3. Some colors are less effective at high spatial frequencies
- 4. People segment colors into classes -> perceptual banding

But rainbow helpful for inference?



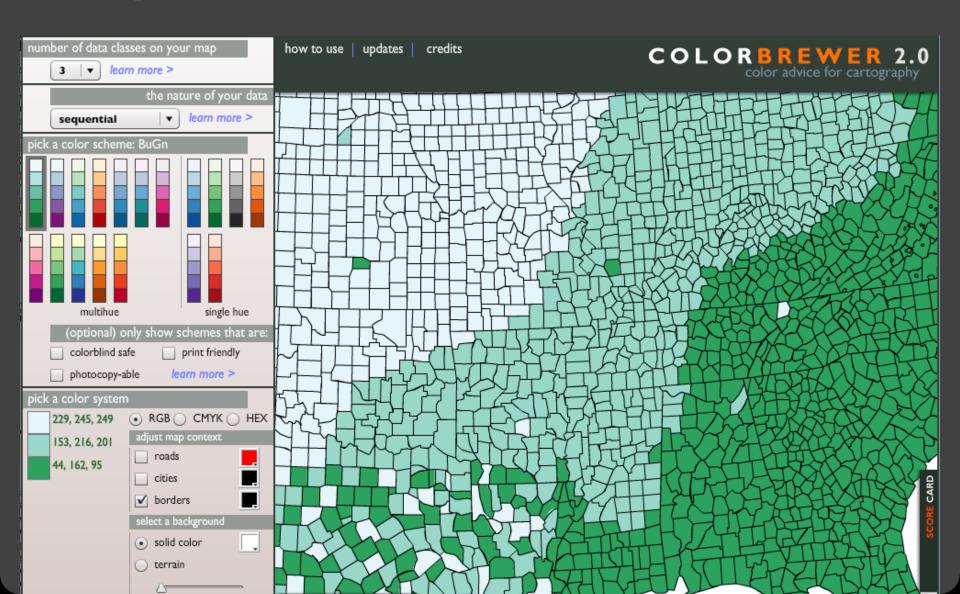
Reda et al. '21: Color Nameability Predicts Inference Accuracy in Spatial Visualizations

Rainbow found ineffective for *value comparison* [Liu '18]...

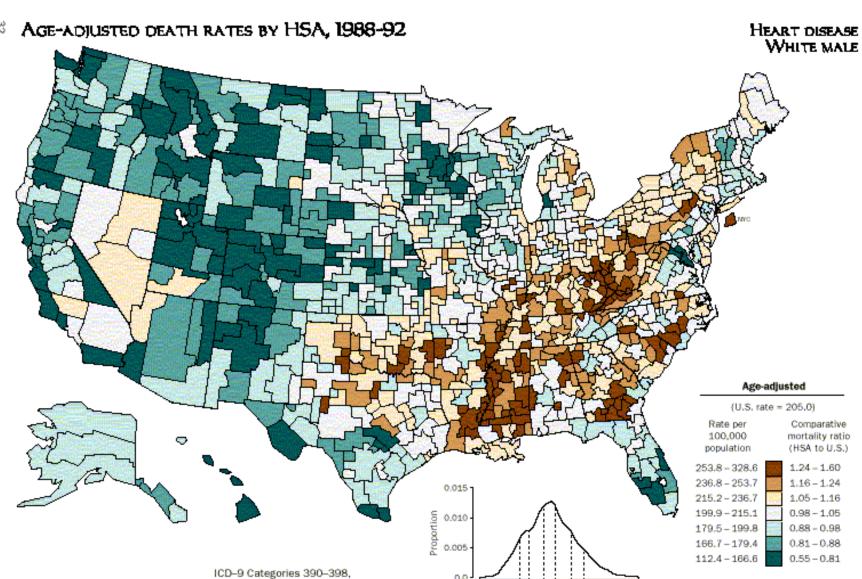
...but color name salience found to improve performance on *inference task* of distinguishing distributions [Reda '21]

Task matters!

Steps, rather than Gradients?





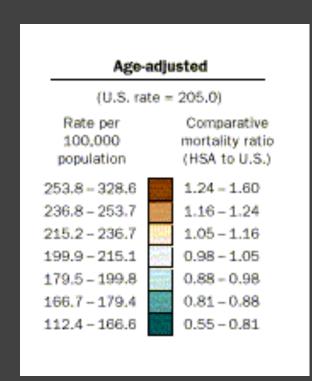


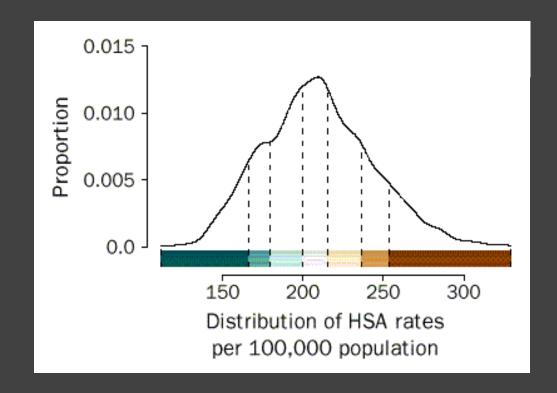
200 Distribution of HSA rates per 100,000 population

SOURCE: CDC/NCHS

402, 404-429

Classing Quantitative Data





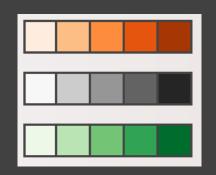
Age-adjusted mortality rates for the United States. Common option: break into 5 or 7 quantiles.

Classing Quantitative Data

- 1. Equal interval (arithmetic progression)
- 2. Quantiles (recommended)
- 3. Standard deviations
- 4. Clustering (Jenks' natural breaks / 1D K-Means)
 Minimize within group variance
 - Maximize between group variance

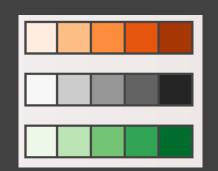
Sequential color scale

Ramp in luminance, possibly also hue Higher value -> darker color (or vice versa)



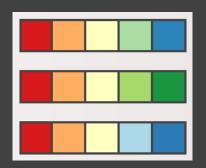
Sequential color scale

Ramp in luminance, possibly also hue
Higher value -> darker color (or vice versa)



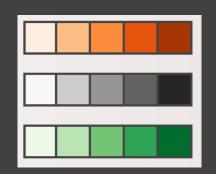
Diverging color scale

Useful when data has meaningful "midpoint" Use neutral color (e.g., grey) for midpoint Use saturated colors for endpoints



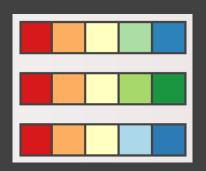
Sequential color scale

Ramp in luminance, possibly also hue Higher value -> darker color (or vice versa)



Diverging color scale

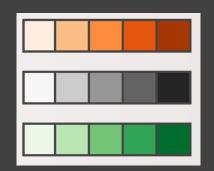
Useful when data has meaningful "midpoint" Use neutral color (e.g., grey) for midpoint Use saturated colors for endpoints



Limit number of steps in color to 3-9 *Why?*

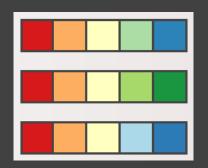
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Diverging color scale

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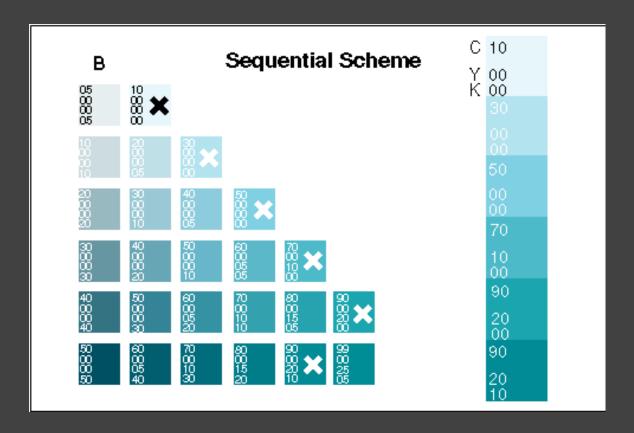


Limit number of steps in color to 3-9

Avoid simultaneous contrast, hold mappings in memory

Sequential Scales: Single-Hue

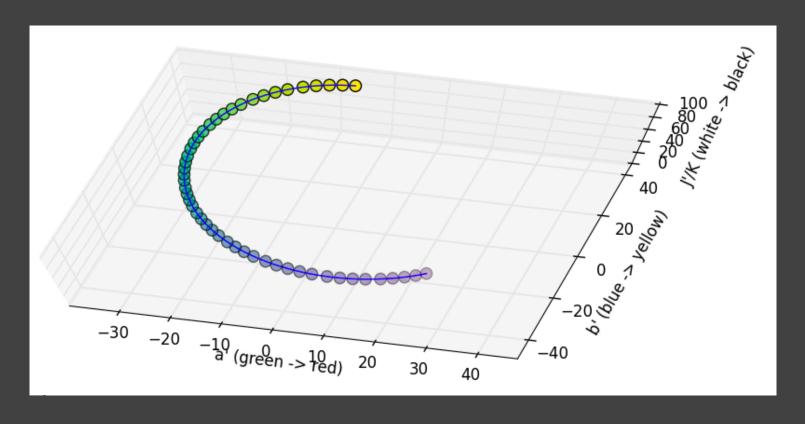
Ramp primarily in luminance, subtle hue difference



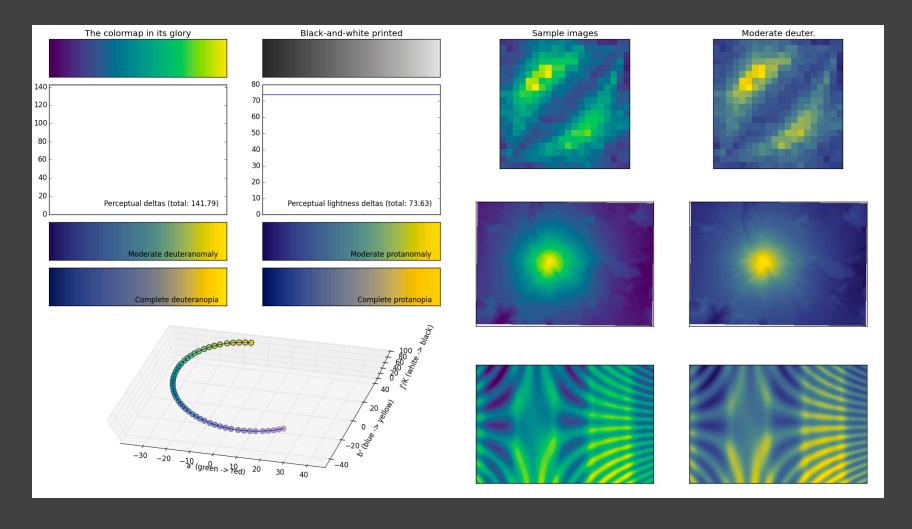
http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Sequential Scales: Multi-Hue

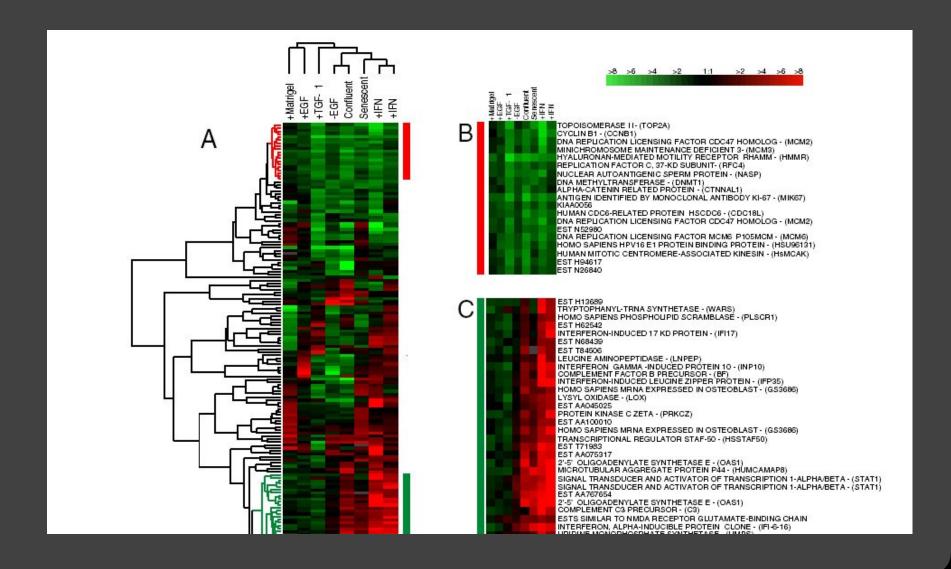
Ramp luminance & hue in perceptual color space Avoid contrasts subject to color blindness!



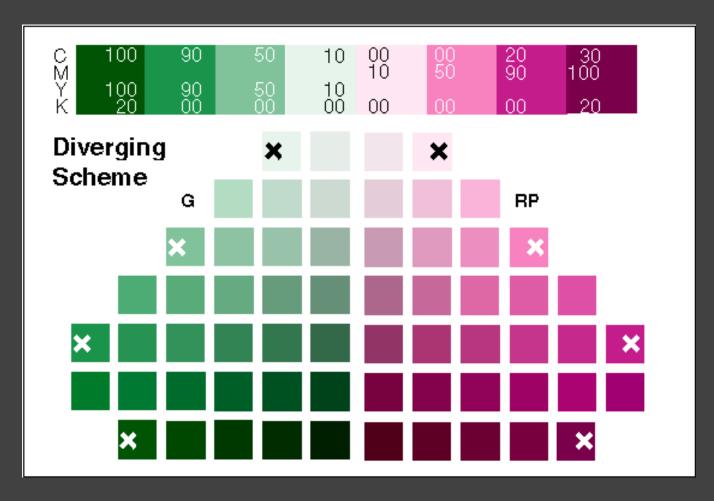
Sequential Scales: Multi-Hue



Diverging Color Scheme



Designing Diverging Scales



http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Designing Diverging Scales

Hue Transition

Carefully Handle Midpoint

Choose classes of values

Low, Average, High - Average should be gray

Critical Breakpoint

Defining value e.g., 0

Positive & negative should use different hues

Extremes saturated, middle desaturated

Hints for the Colorist

Use **only a few** colors (~6 ideal)

Colors should be distinctive and named

Strive for color harmony (natural colors?)

Use cultural conventions; appreciate symbolism

Get it right in black and white

Respect the color blind

Take advantage of perceptual color spaces

Color is cultural and a matter of taste!