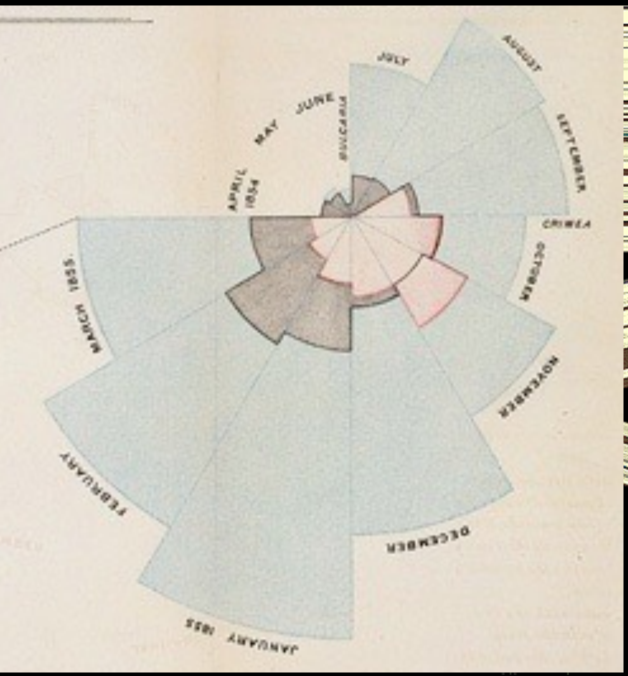
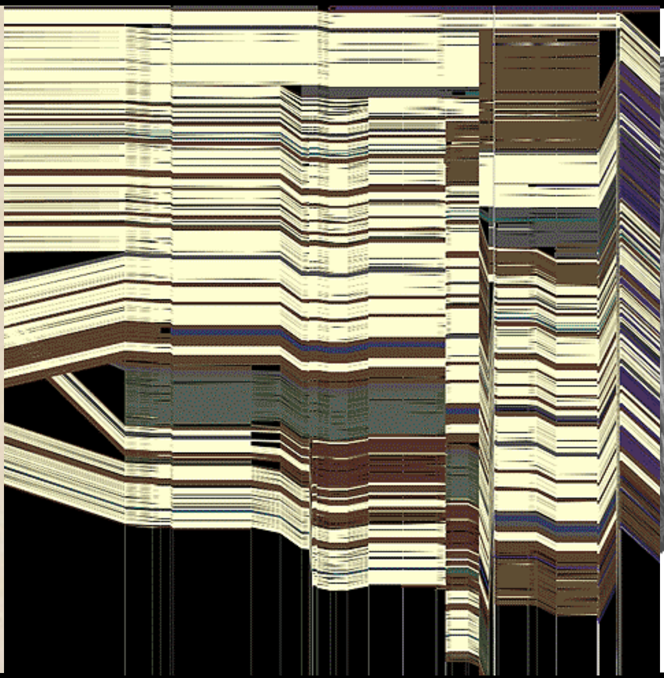
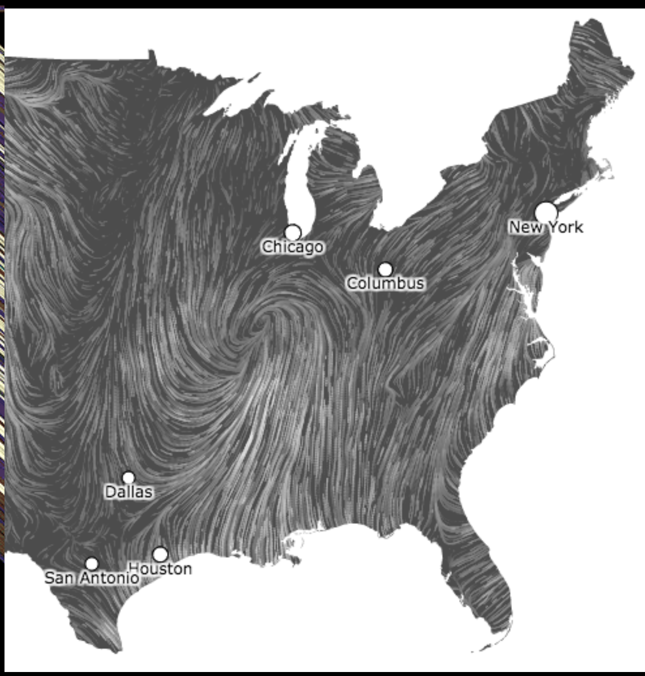
CSE 442 - Data Visualization

Color

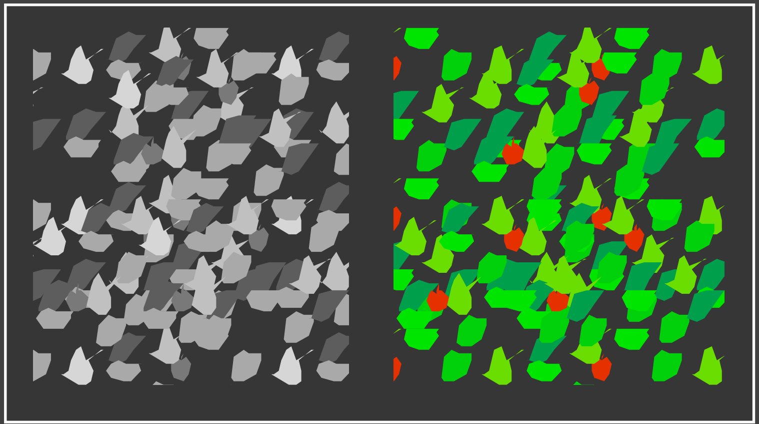






Jeffrey Heer University of Washington

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

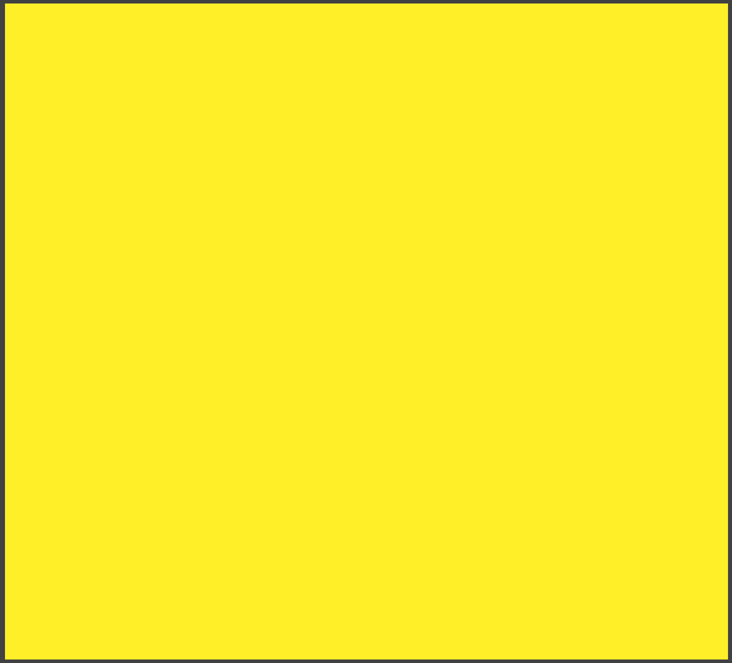
Categorical & Quantitative encoding

Guidelines for color palette design

Perception of Color

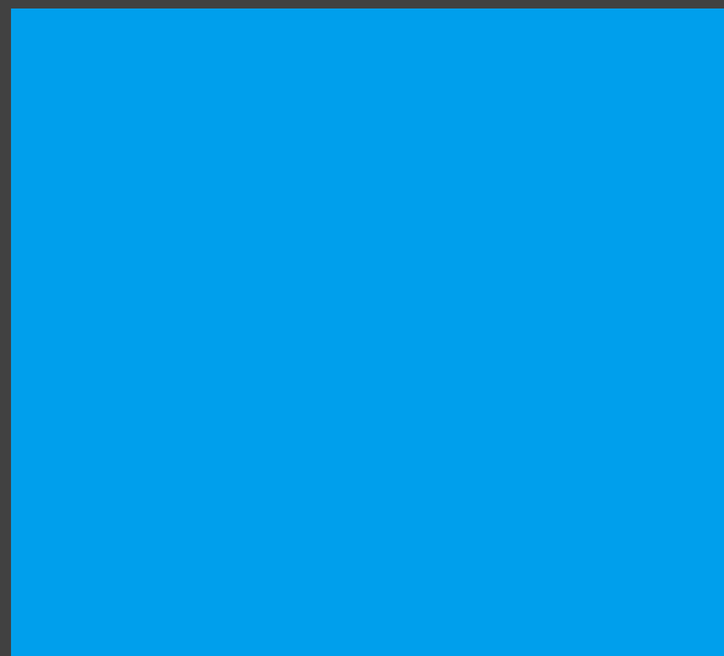
What color is this?

What color is this?



"Yellow"

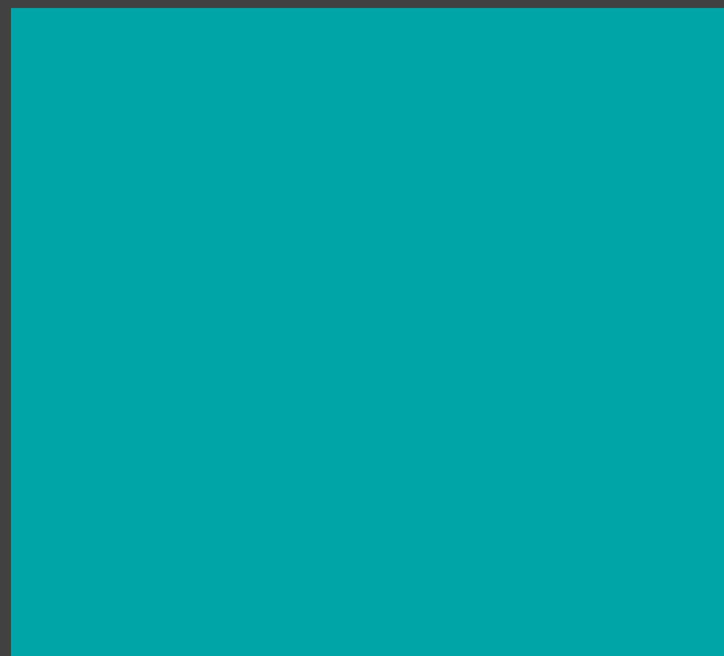
What color is this?



What color is this?

“Blue”

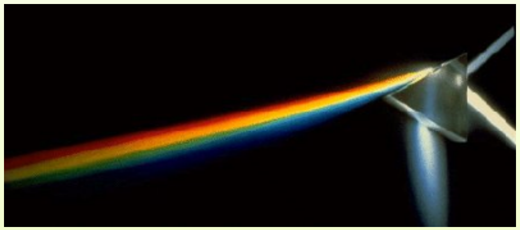
What color is this?



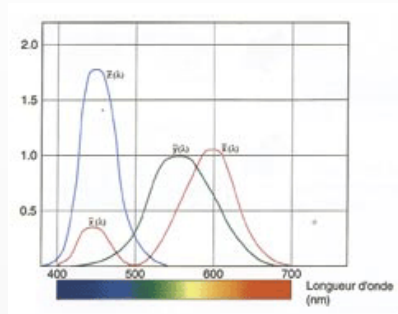
What color is this?

"Teal" ?

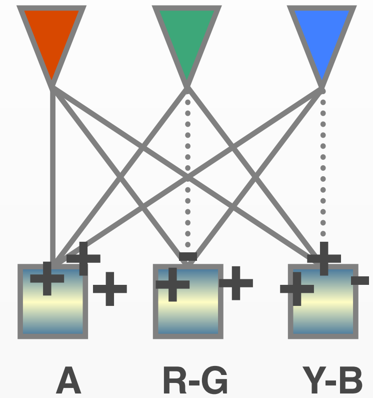
Perception of Color



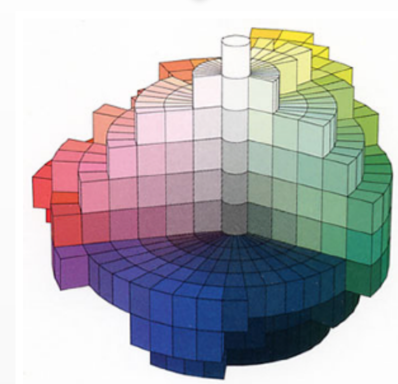
Light



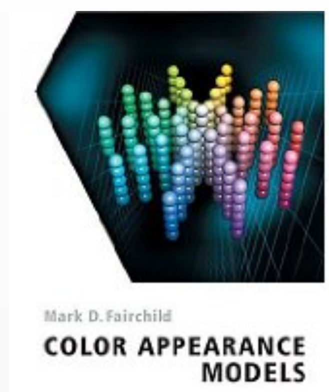
Cone Response



Opponent Signals



Color Perception



Color Appearance

"Yellow"

Color Cognition

Physicist’s View

Light as electromagnetic waves

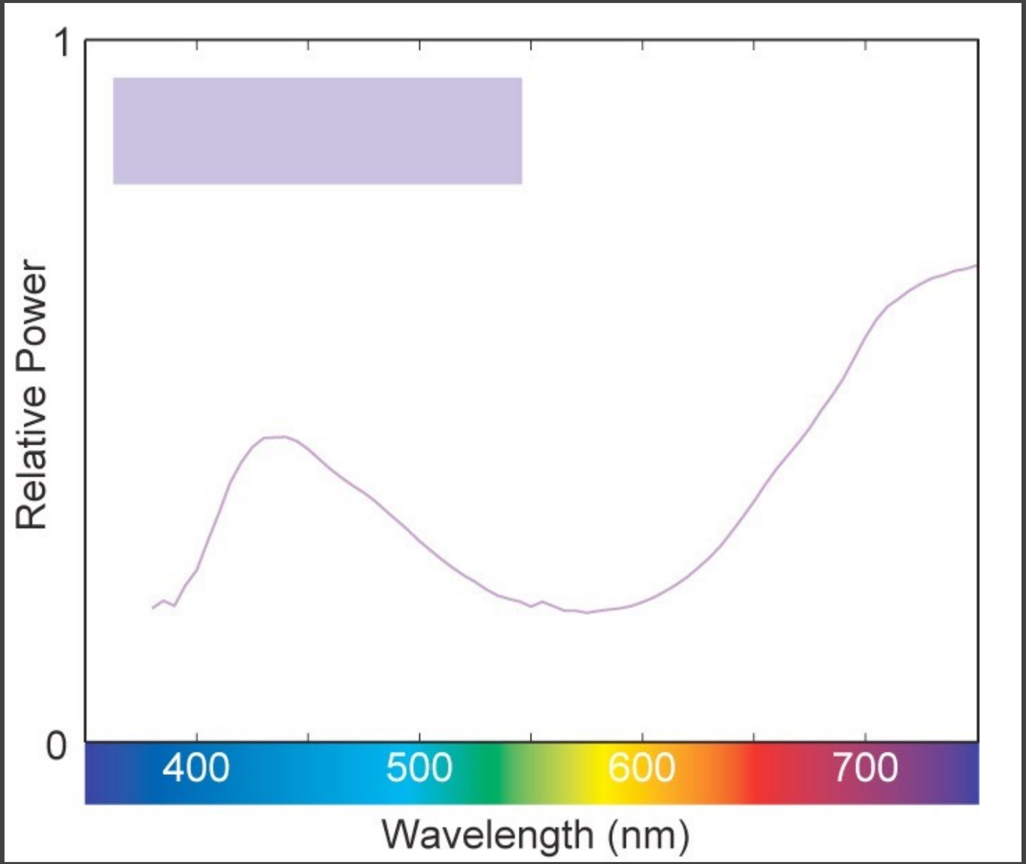
Wavelength

Visible spectrum is

370-730 nm

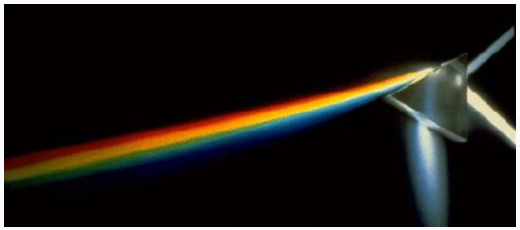
Power or

“Relative luminance”



A Field Guide to Digital Color, M. Stone

Perception of Color



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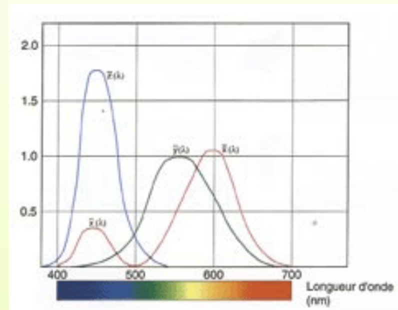

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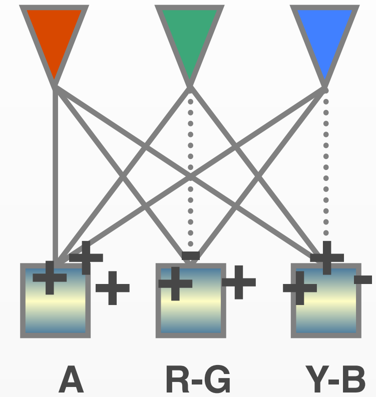
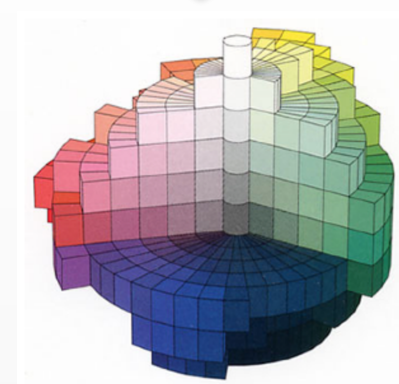
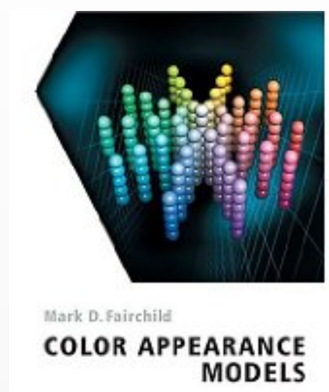


Opponent Signals



Color Perception

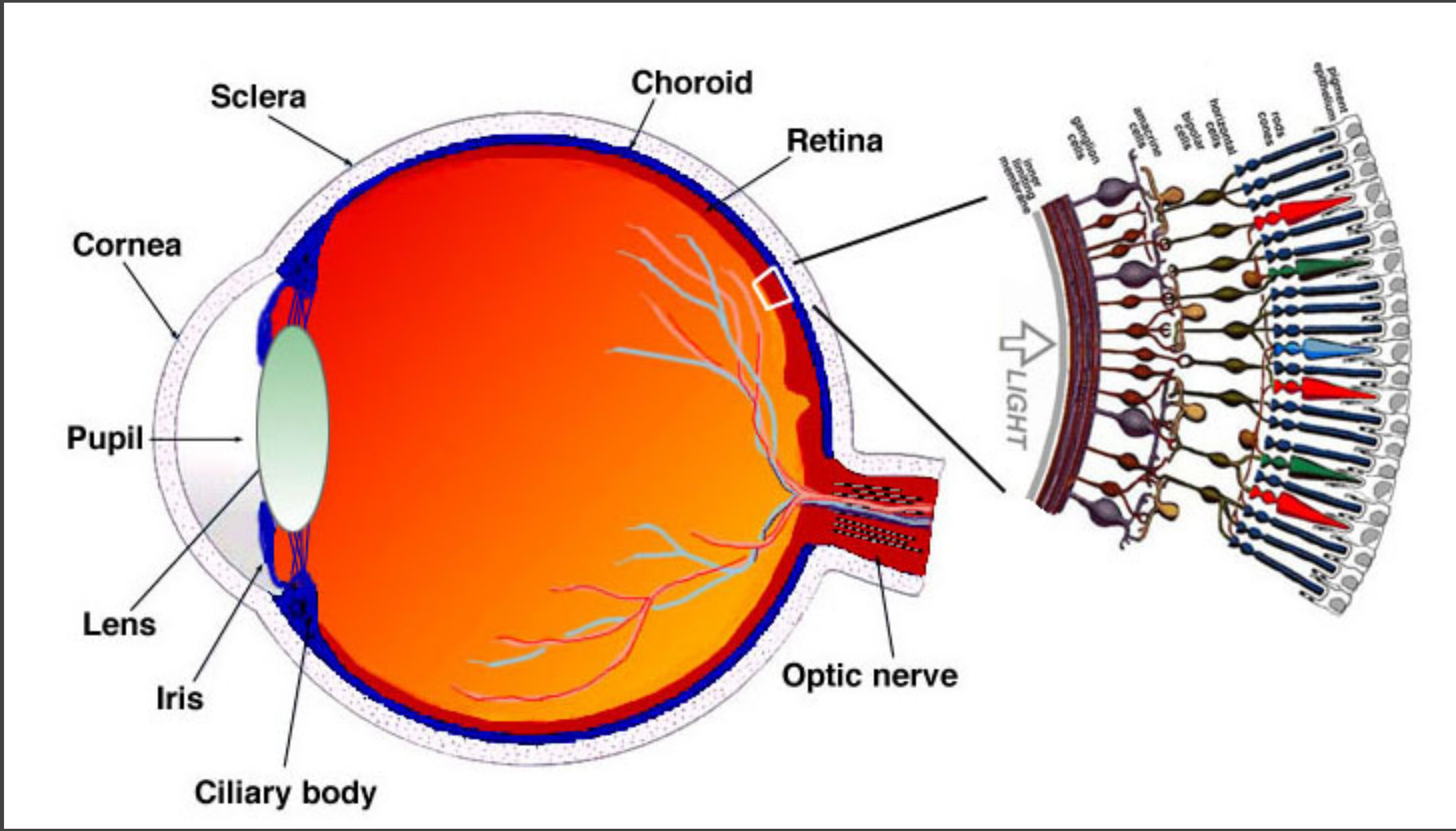


Color Appearance

“Yellow”

Color Cognition

Retina

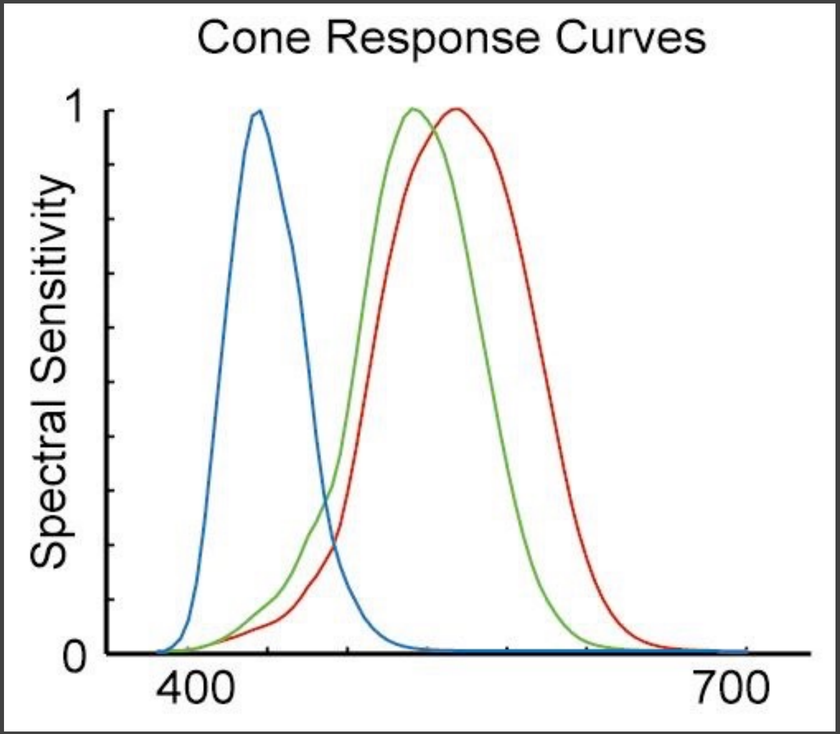


Simple Anatomy of the Retina, Helga Kolb

As light enters our retina…

LMS (Long, Middle, Short) Cones

Sensitive to different wavelengths



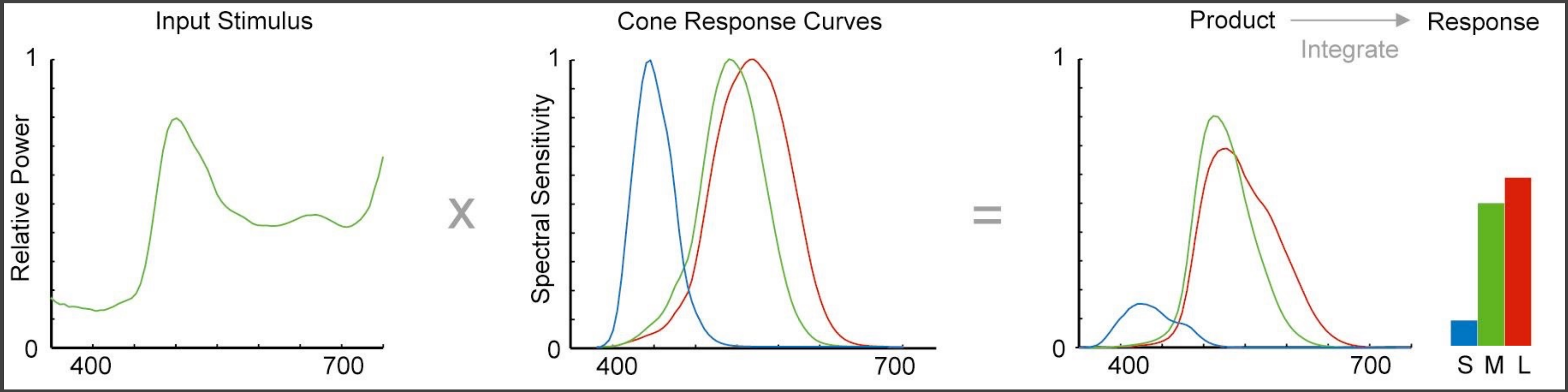
A Field Guide to Digital Color, M. Stone

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

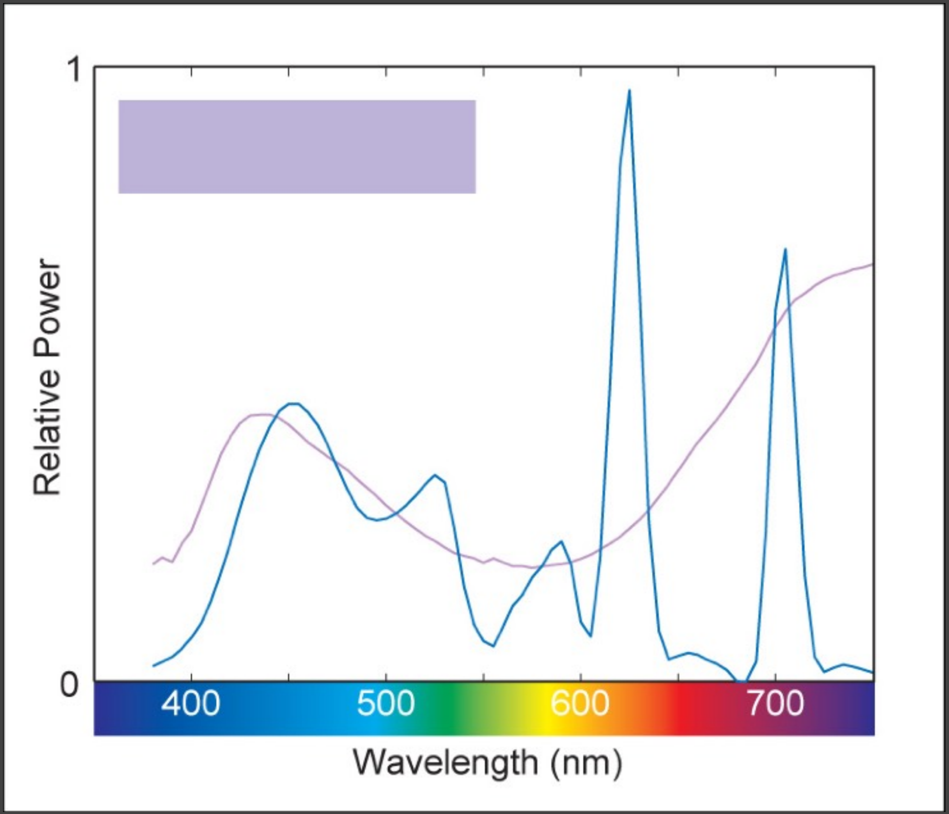
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

"Tri-stimulus"

Computer displays

Digital scanners

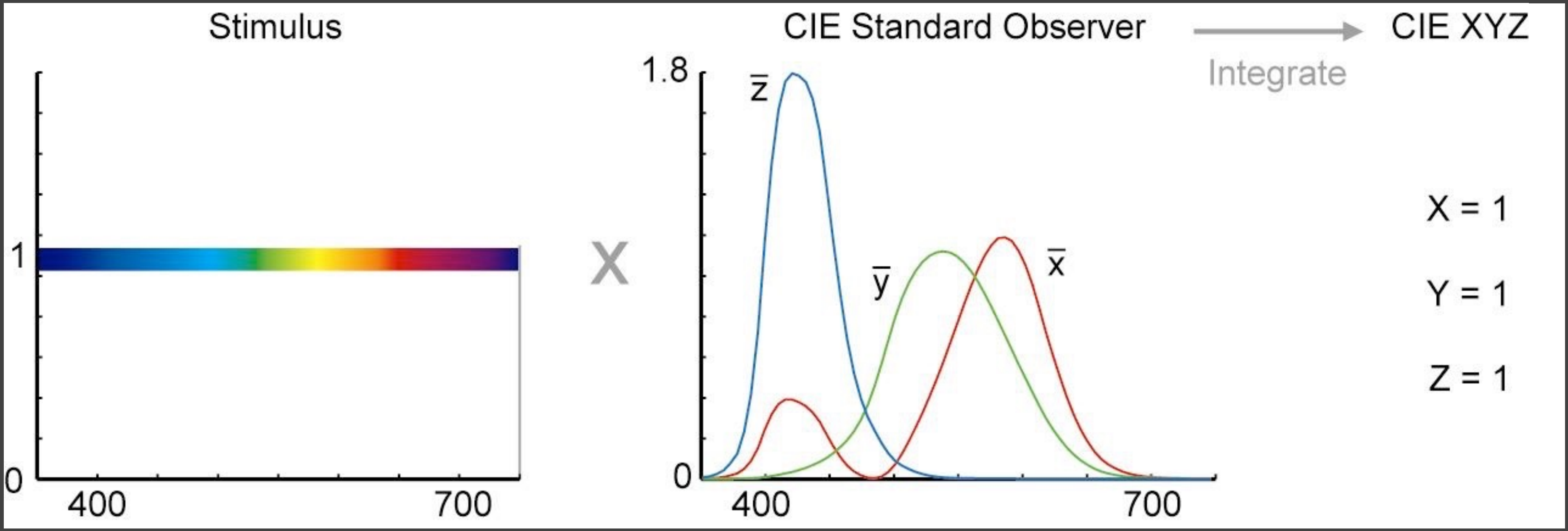
Digital cameras



CIE XYZ Color Space

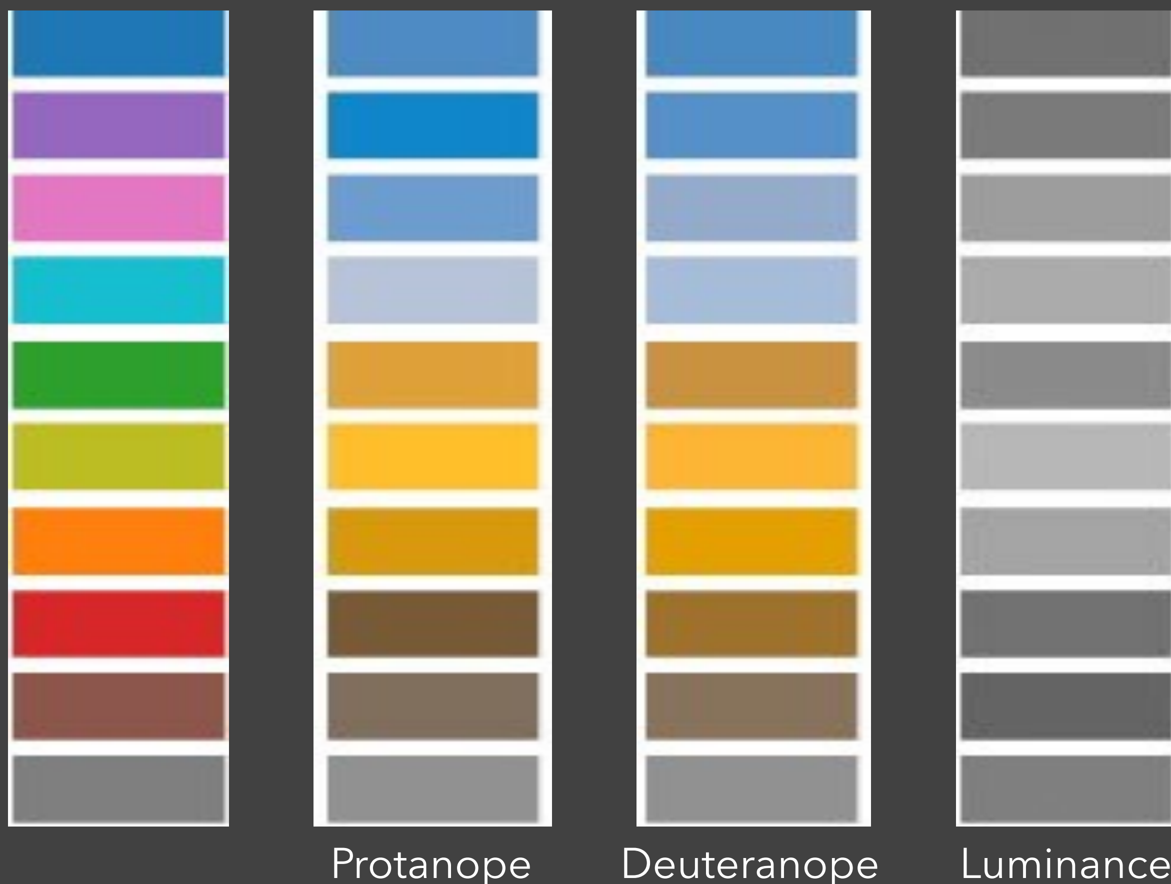
Standardized in 1931 to mathematically represent tri-stimulus response from cones on the retina.

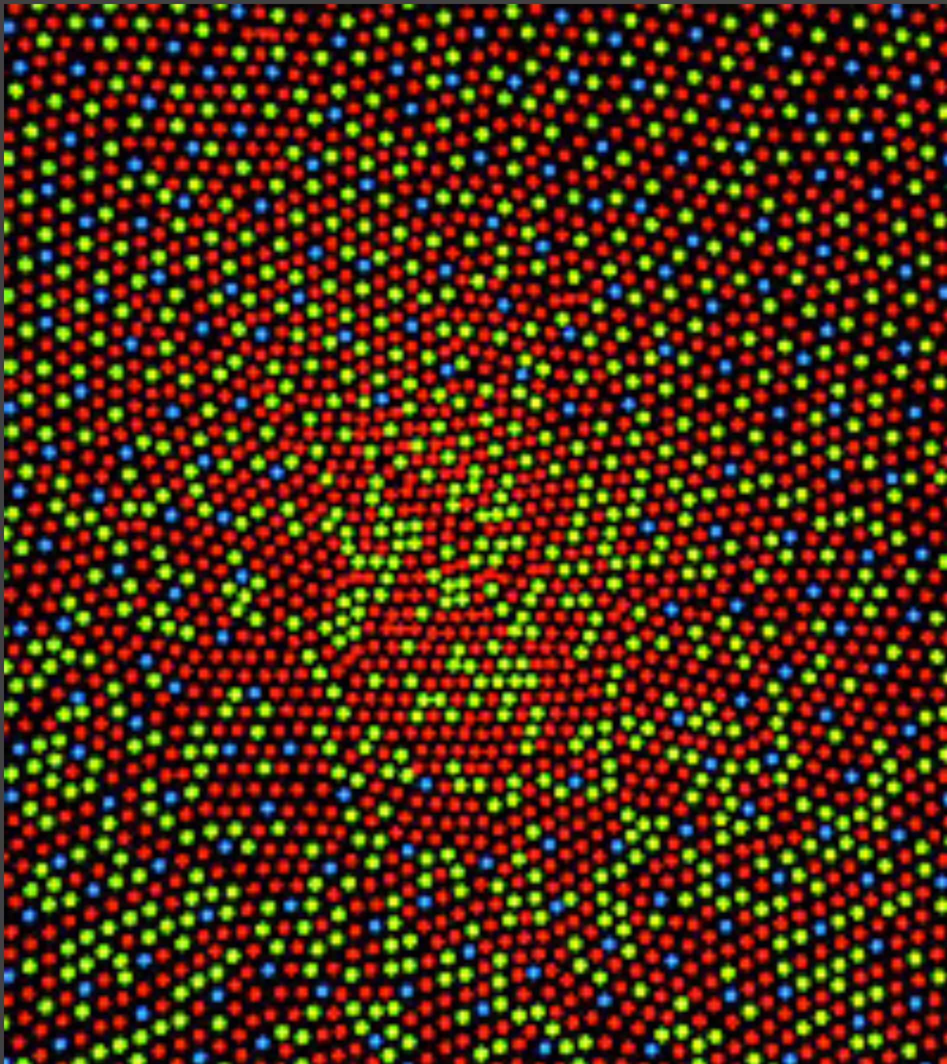
"Standard observer" response curves



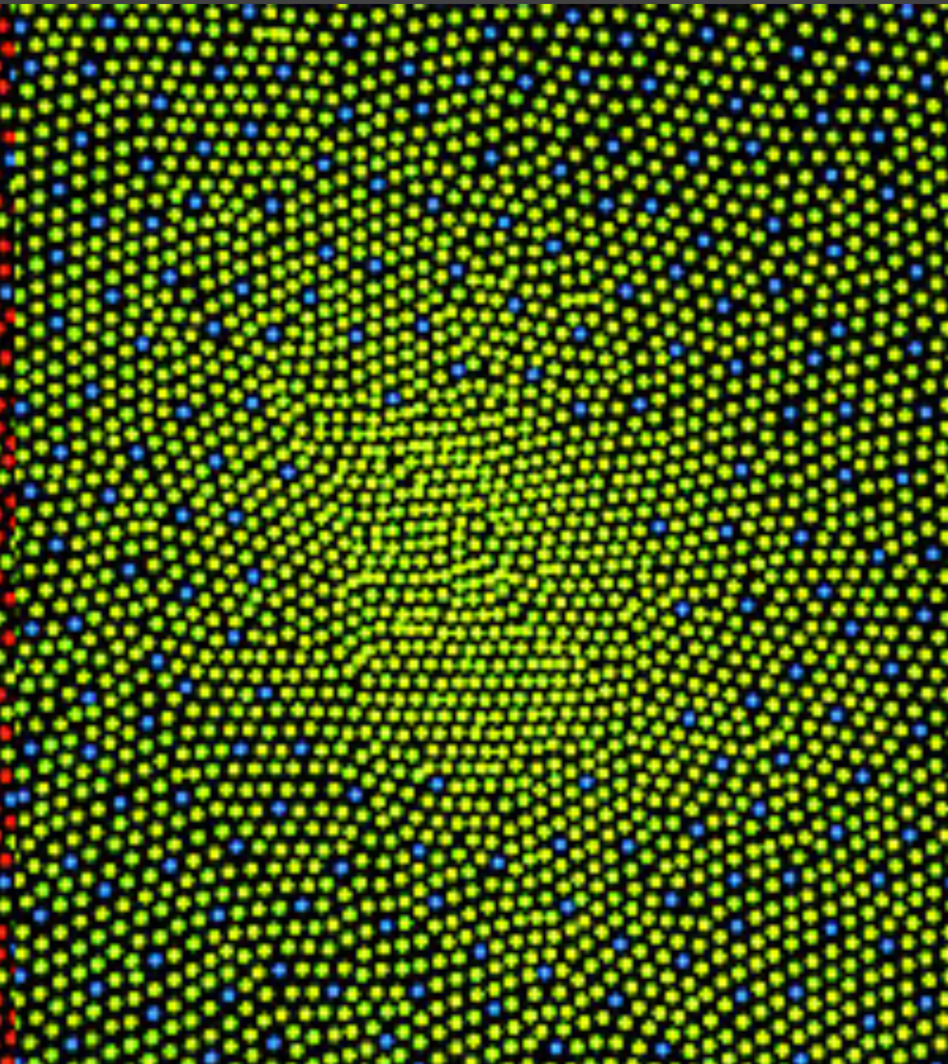
Color Vision Deficiency (CVD)

Missing one or more cones or rods in retina.





Normal Retina



Protanopia

Color Vision Simulators

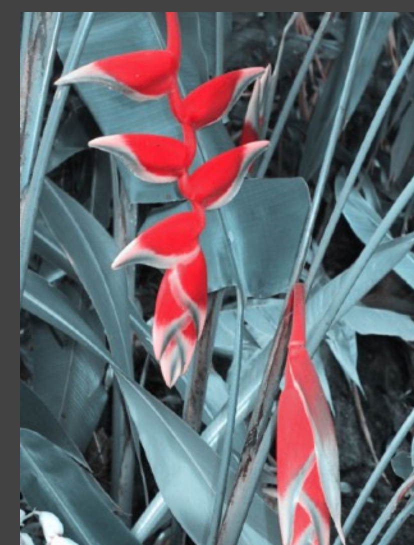
Simulate color vision deficiencies

Browser plug-ins

Photoshop plug-ins, etc.

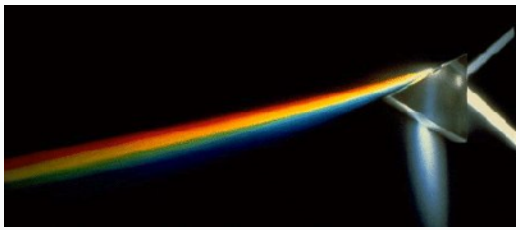
Deuteranope

Protanope

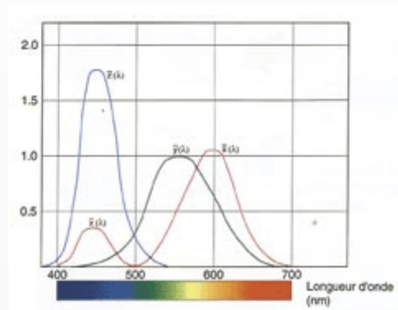


Tritanope

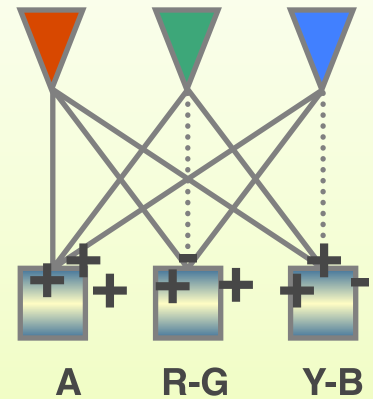
Perception of Color



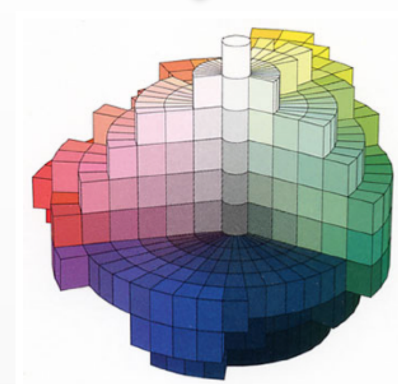
Light



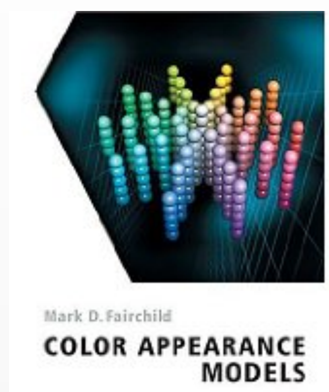
Cone Response



Opponent Signals



Color Perception



Color Appearance

“Yellow”

Color Cognition

Primary Colors

To paint "all colors":
Leonardo da Vinci, circa 1500 described in his notebooks a list of simple colors…

Yellow
Blue
Green
Red

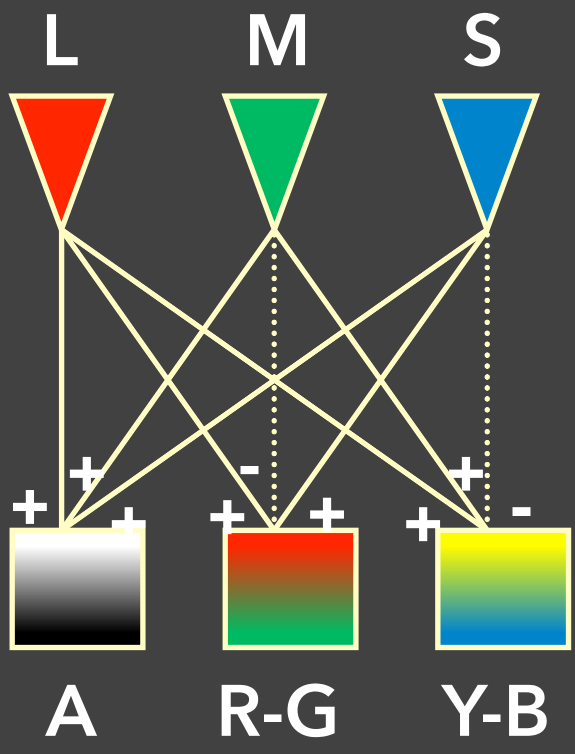
Opponent Processing Theory

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



[Fairchild]

Opponent Processing Theory

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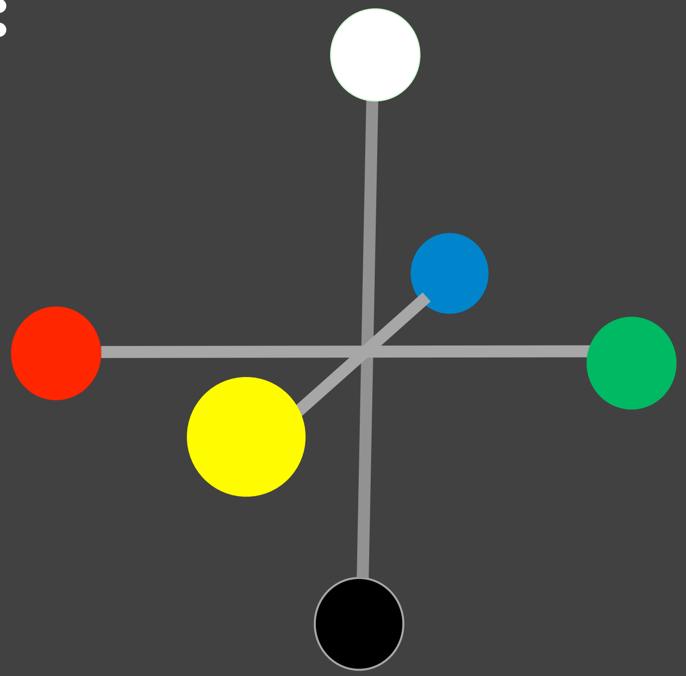

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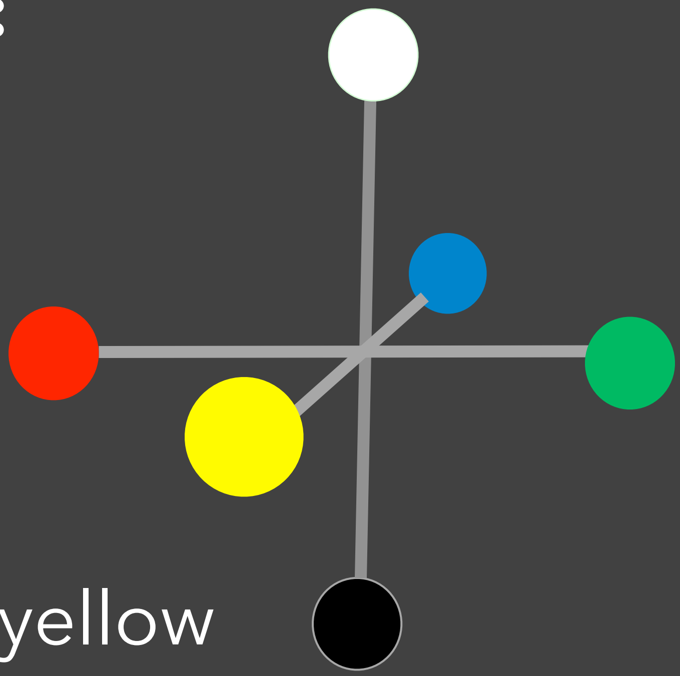


Experiments:

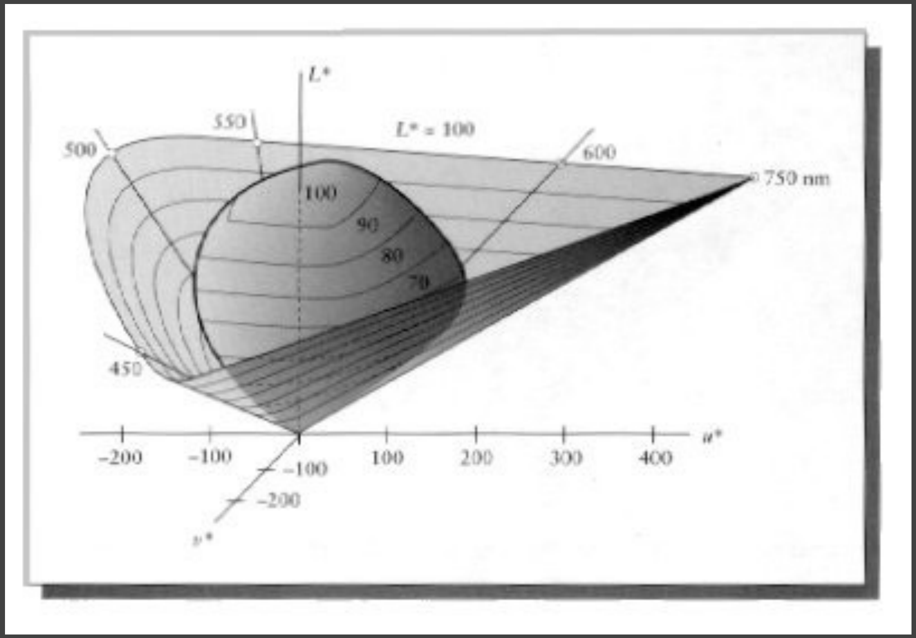
No reddish-green, no blueish-yellow

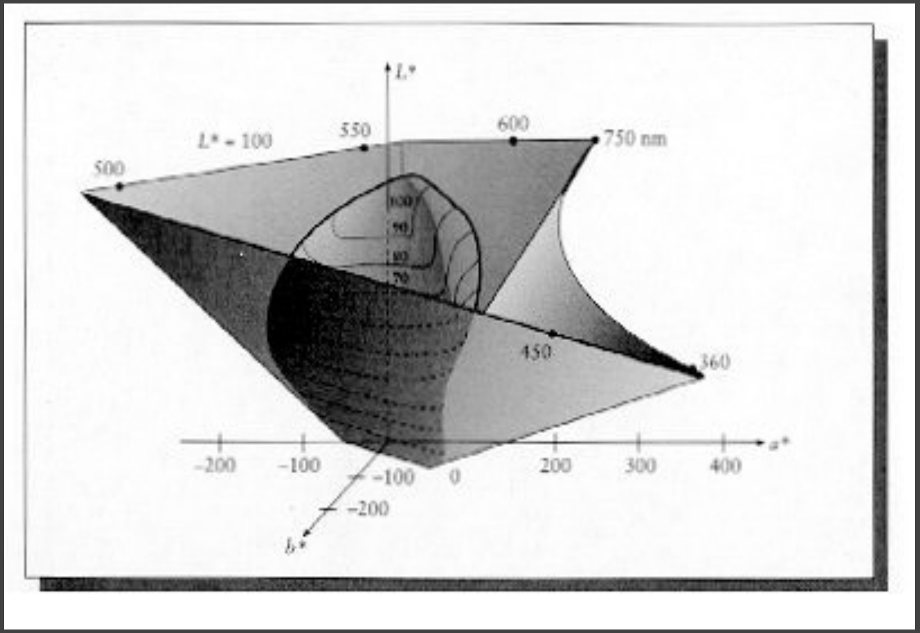
Color after images

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

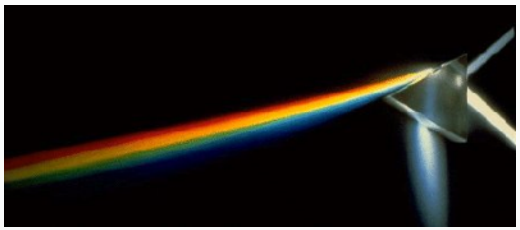
Much more perceptually uniform than sRGB!

Scaling of axes to represent "color distance"

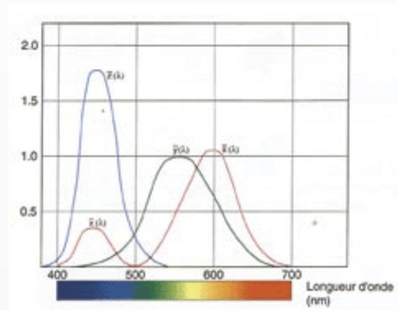
JND = Just noticeable difference (~2.3 units)

D3 + Vega include LAB color space support!

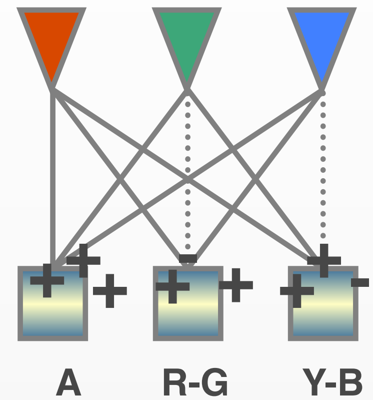
Perception of Color



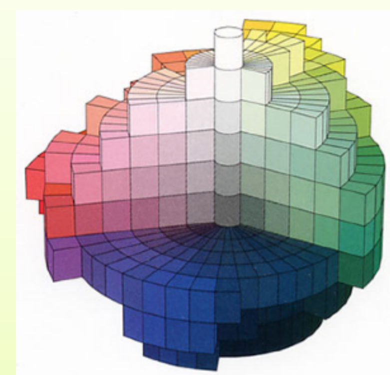
Light



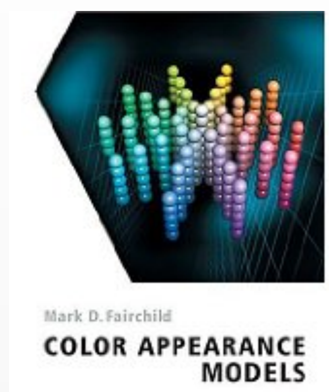
Cone Response



Opponent Signals



Color Perception



Color Appearance

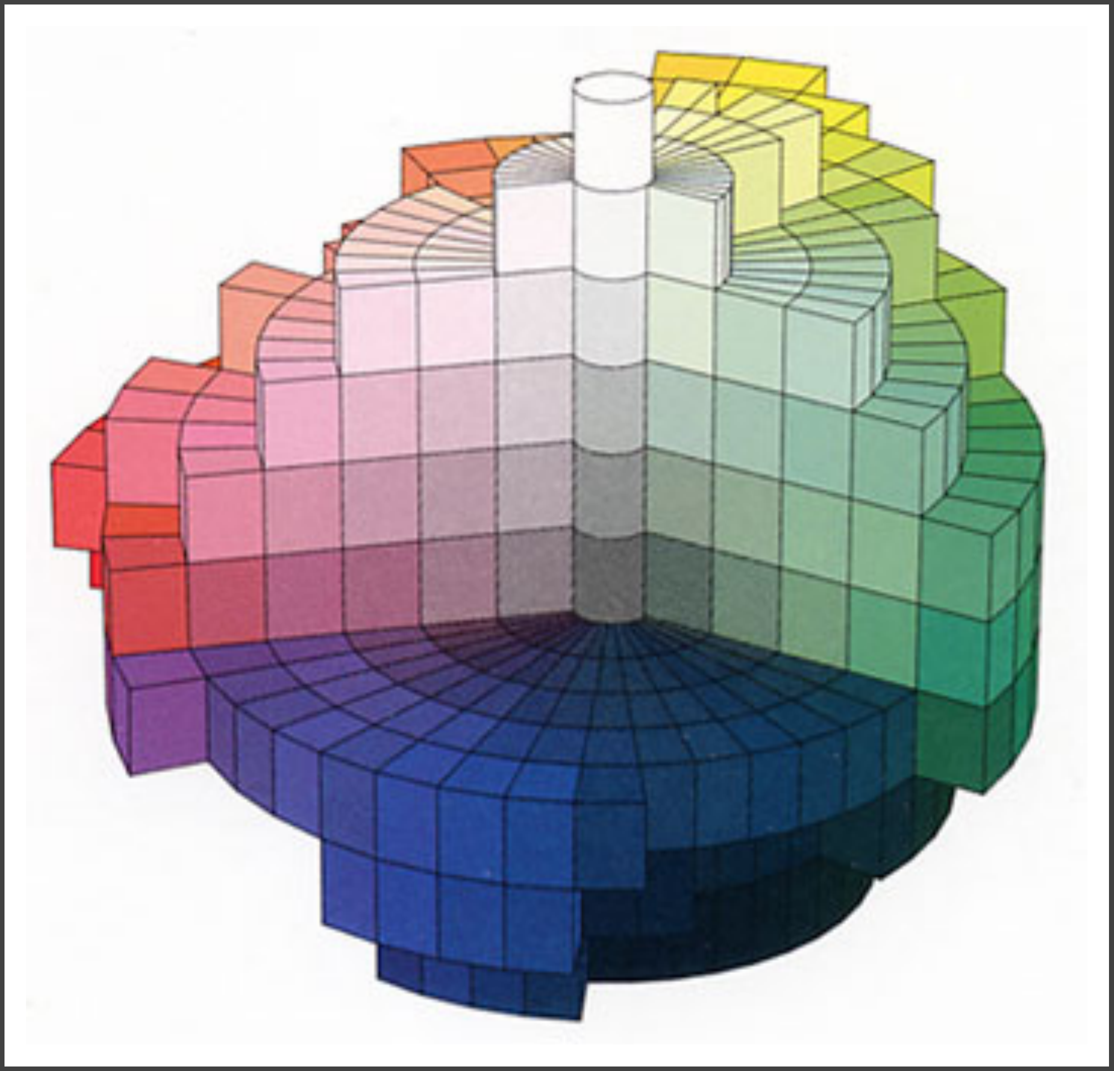
“Yellow”

Color Cognition

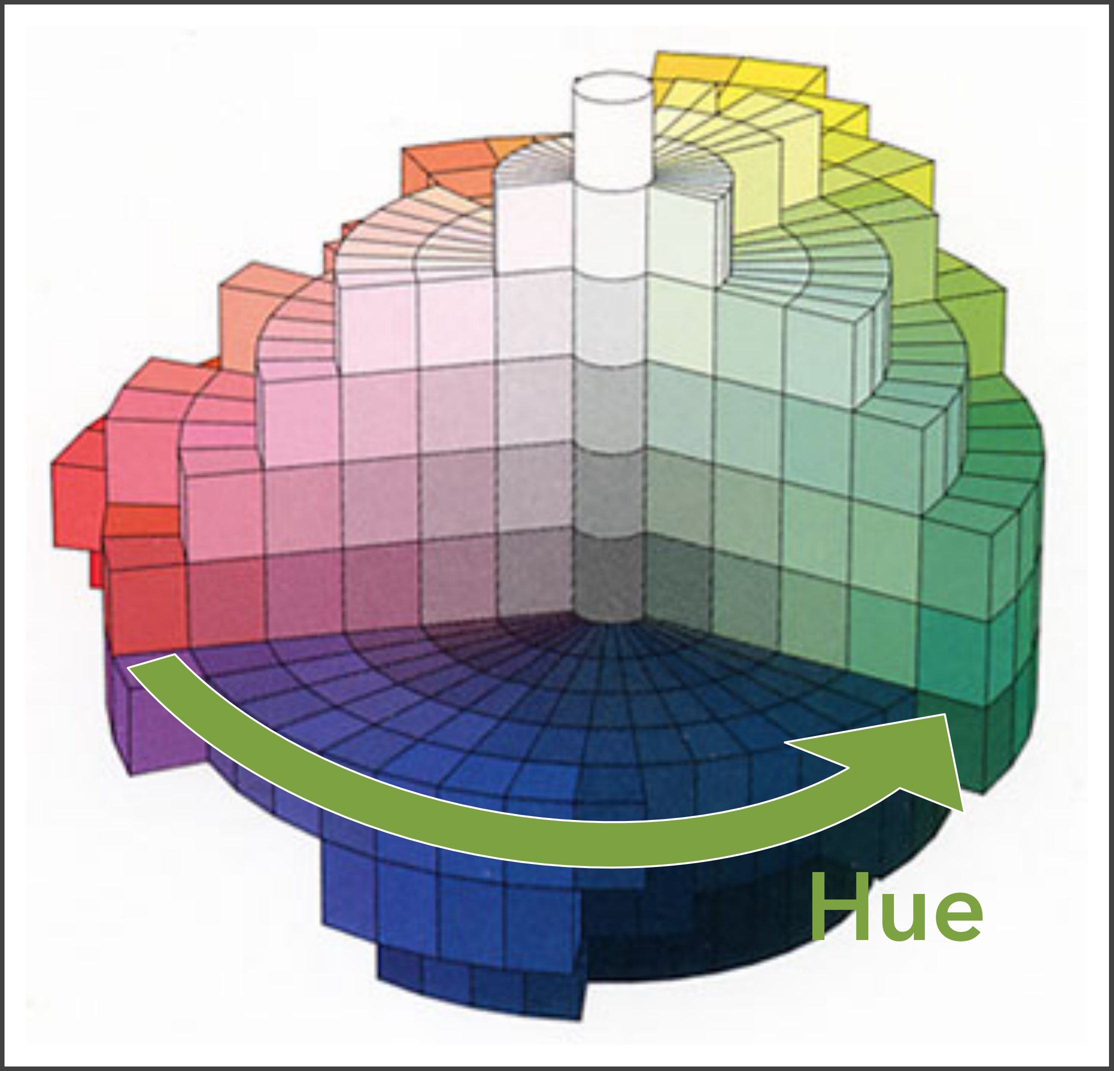
Albert Munsell

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

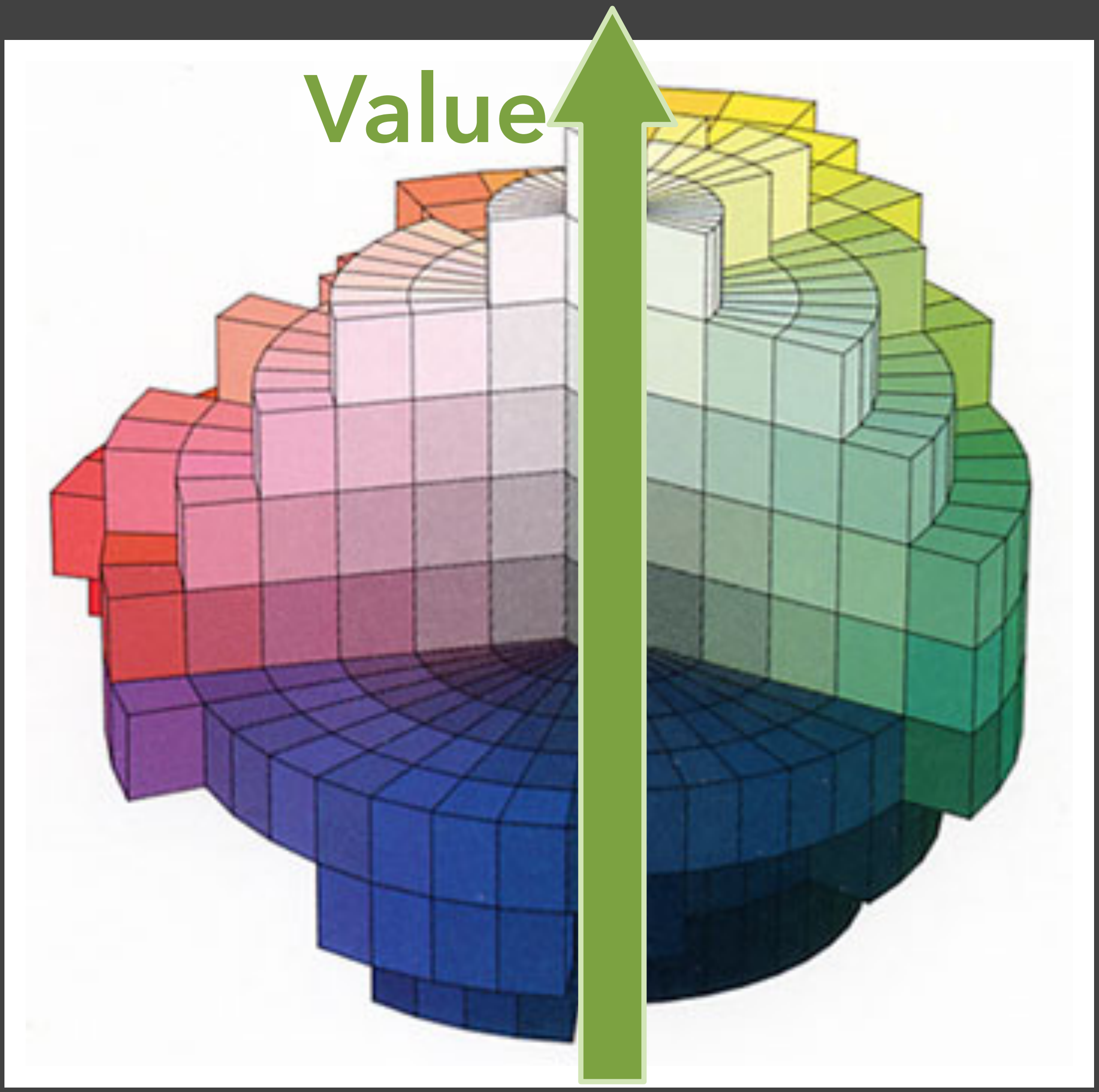
Hue, Value, and Chroma



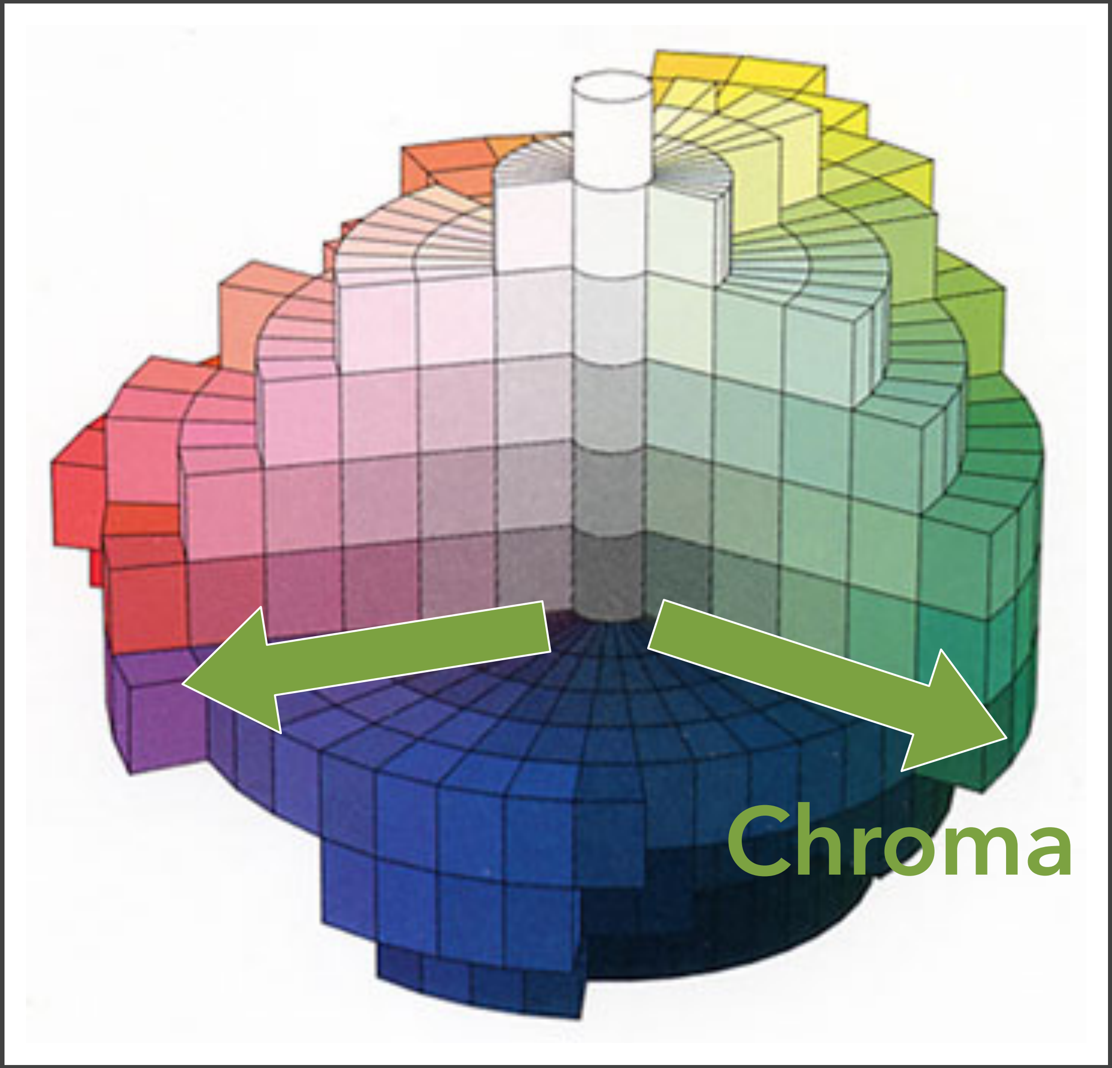
Hue, Value and Chroma



Hue, Value and Chroma



Hue, Value and Chroma



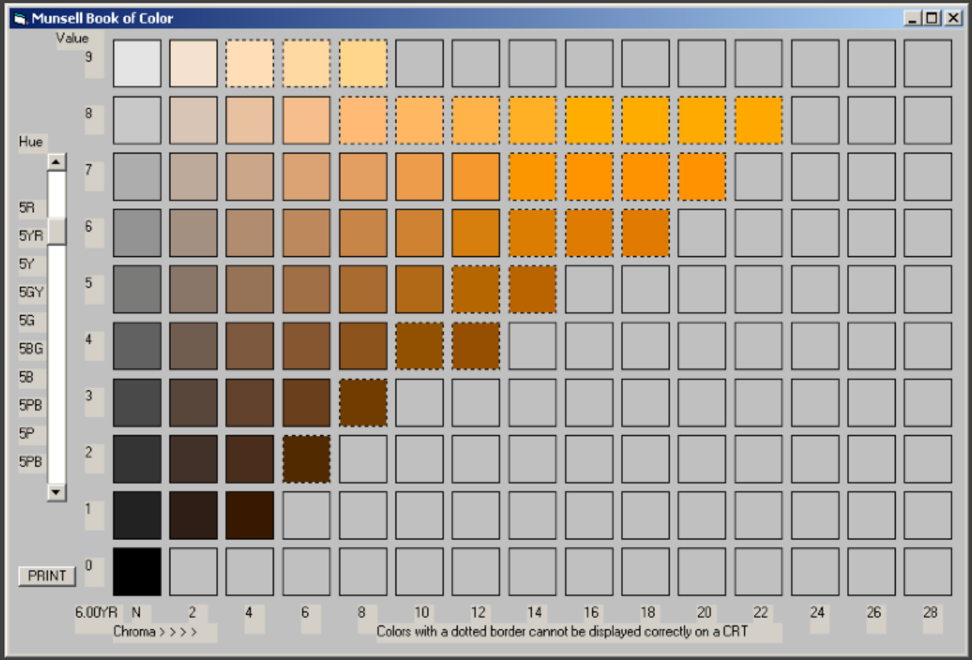
Munsell Color System

Perceptually-based

Precisely reference a color

Intuitive dimensions

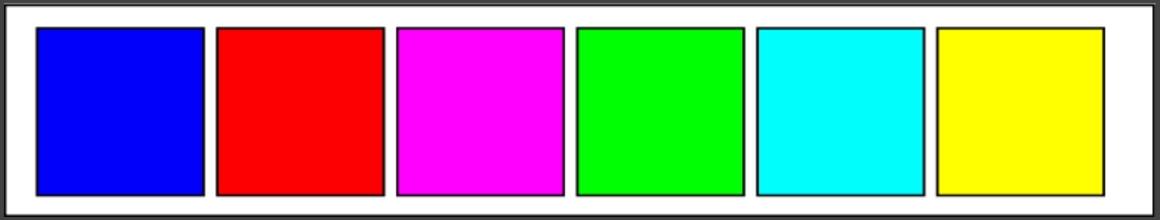
Look-up table (LUT)



Munsell Color System

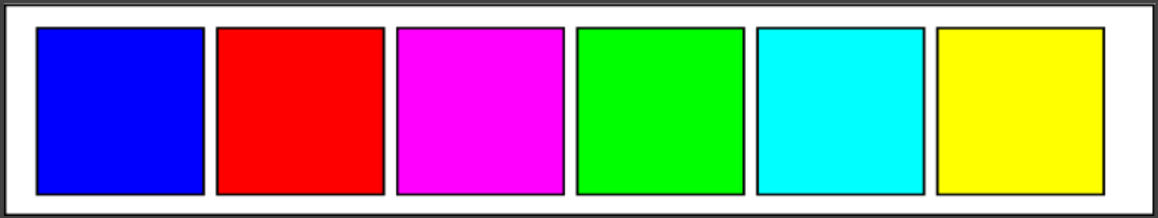
Perceptual Brightness

Color palette



Perceptual Brightness

Color palette



HSL Lightness
(Photoshop)

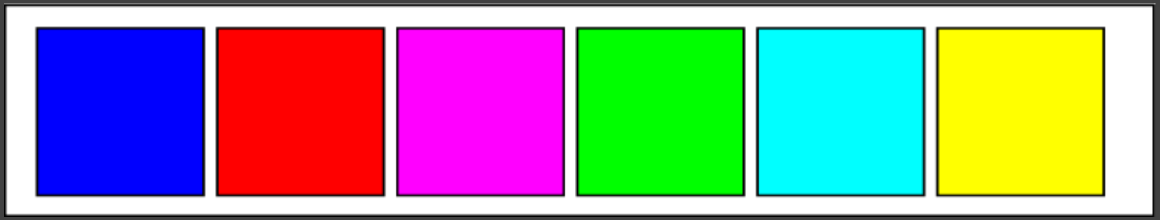
Perceptual Brightness

Color palette

Luminance Y
(CIE XYZ)

Perceptual Brightness

Color palette



Munsell Value

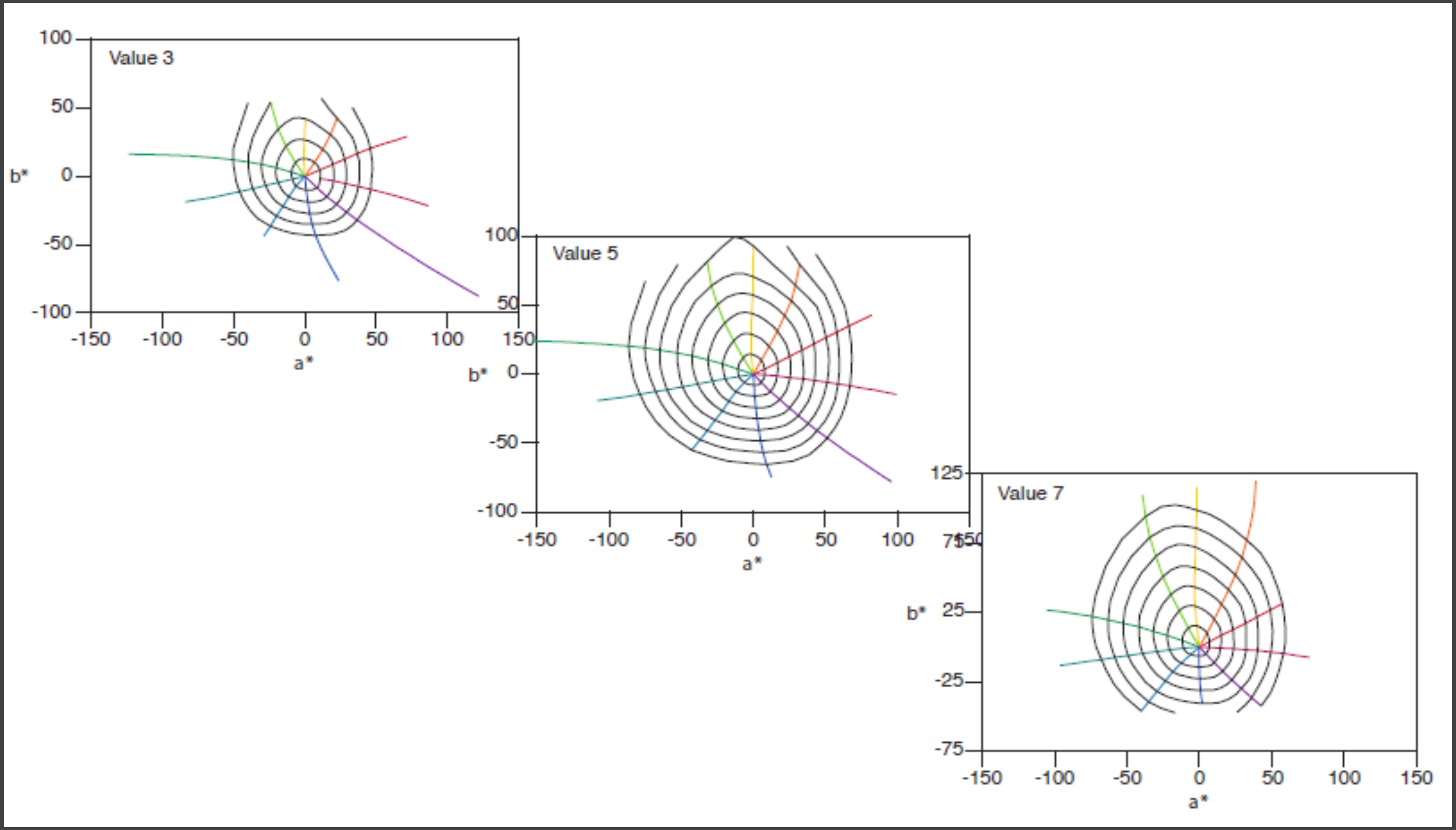
Perceptual Brightness

Color palette

Munsell Value
L* (CIE LAB)

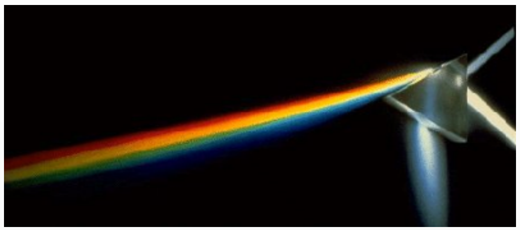
Perceptually-Uniform Color Space

Munsell colors in CIE LAB coordinates

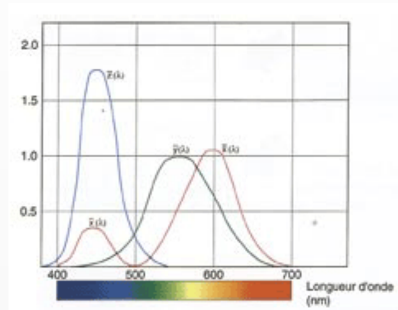


Mark Fairchild

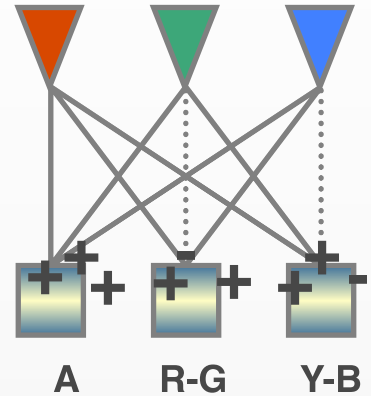
Perception of Color



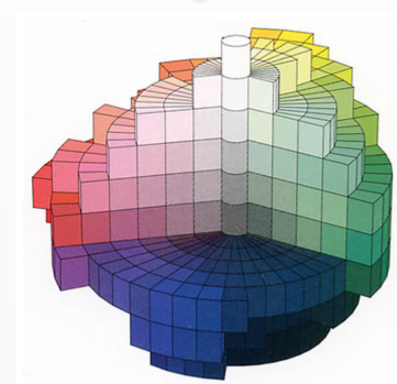
Light



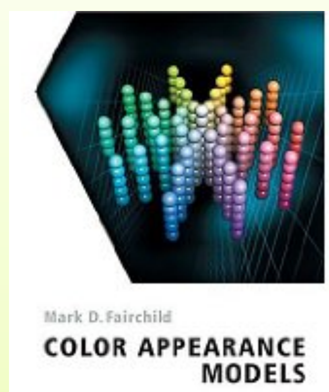
Cone Response



Opponent Signals



Color Perception



Color Appearance

"Yellow"

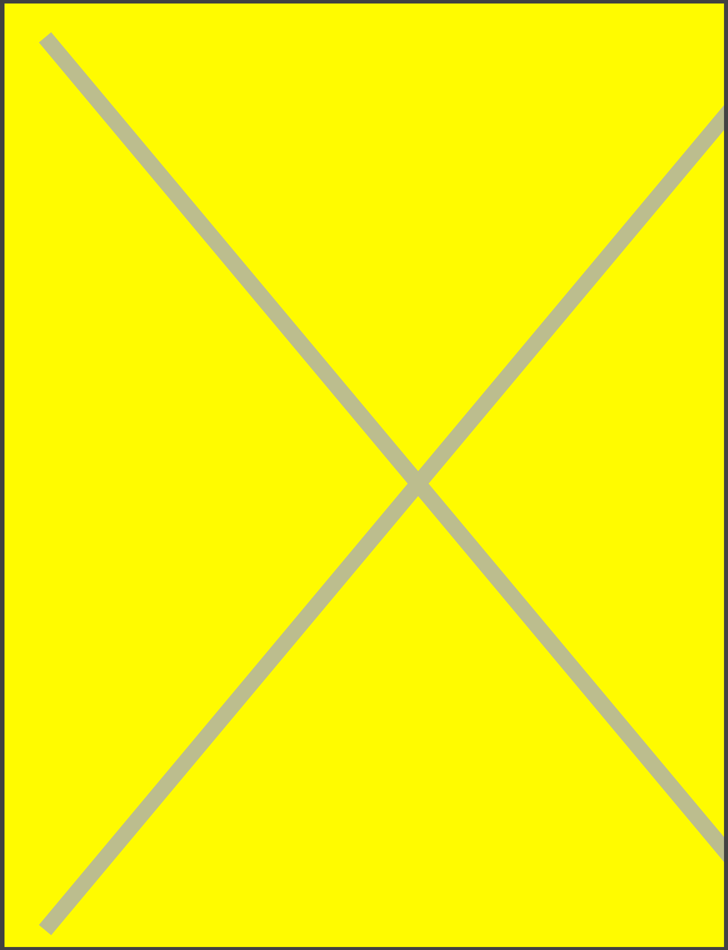
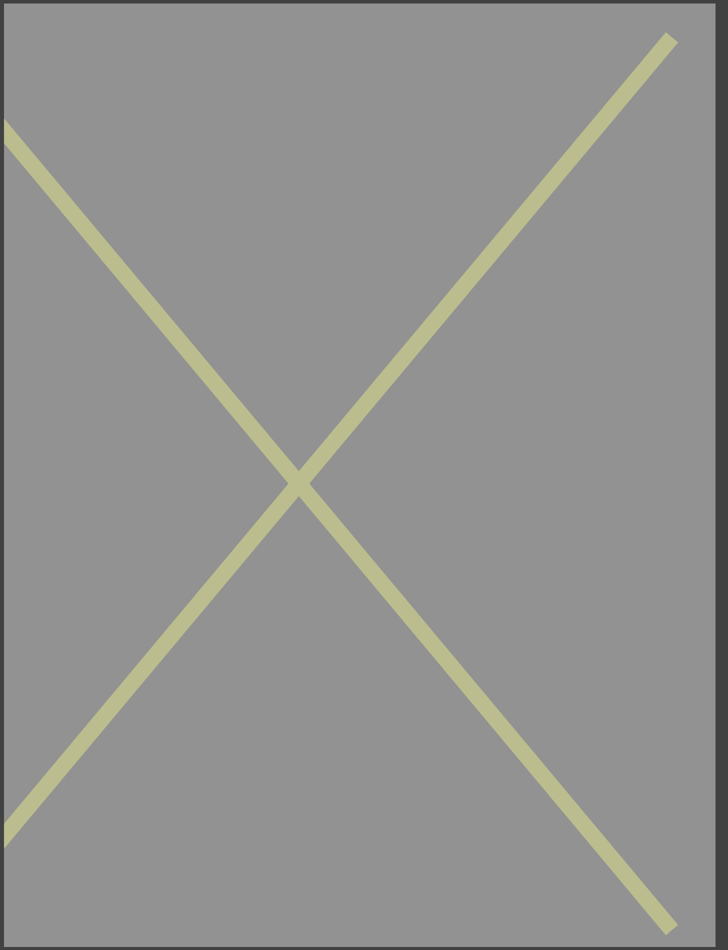
Color Cognition

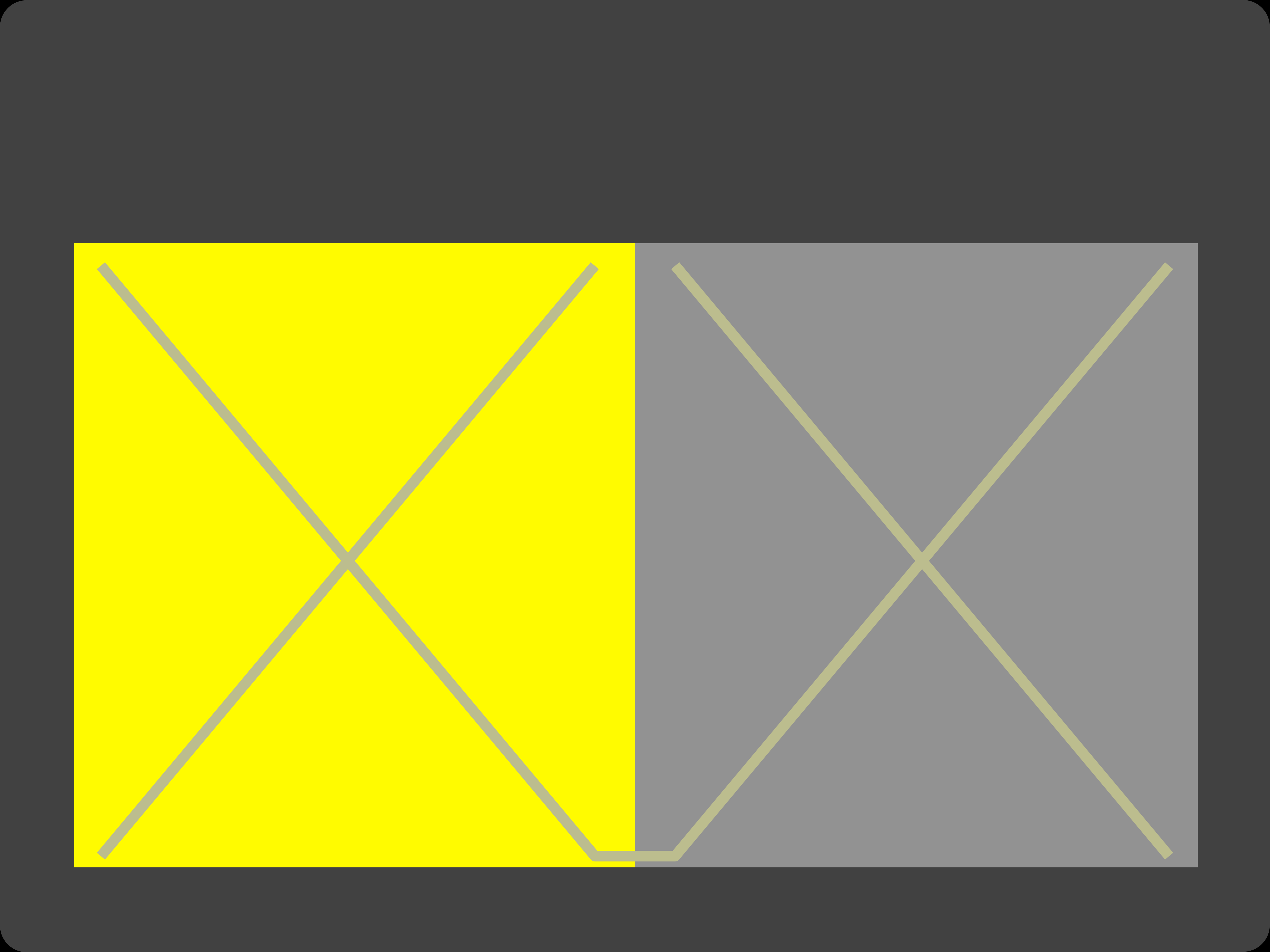
Color Appearance

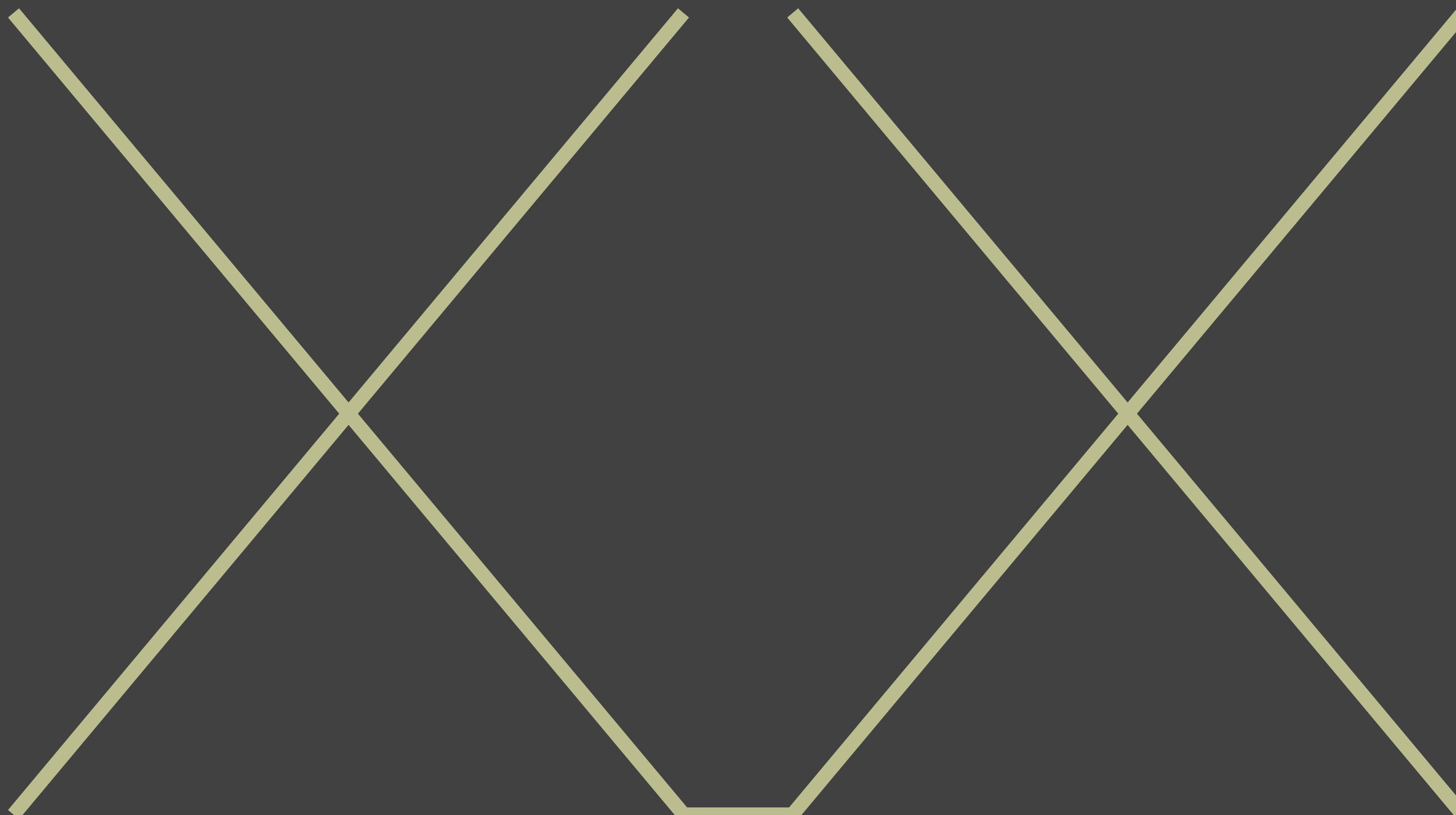
If we have a perceptually-uniform color space, can we predict how we perceive colors?

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

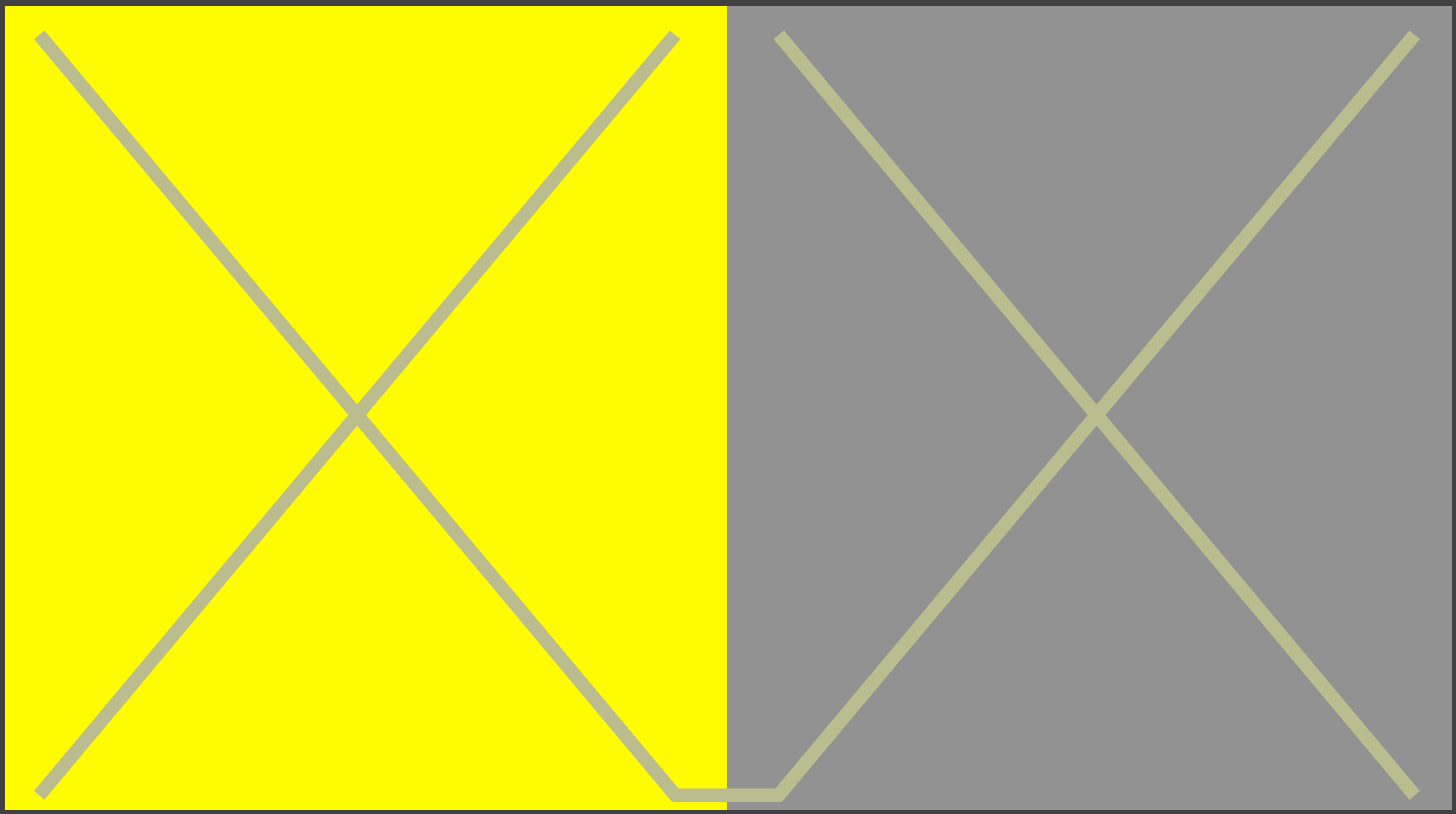
- Josef Albers, *Interaction of Color*





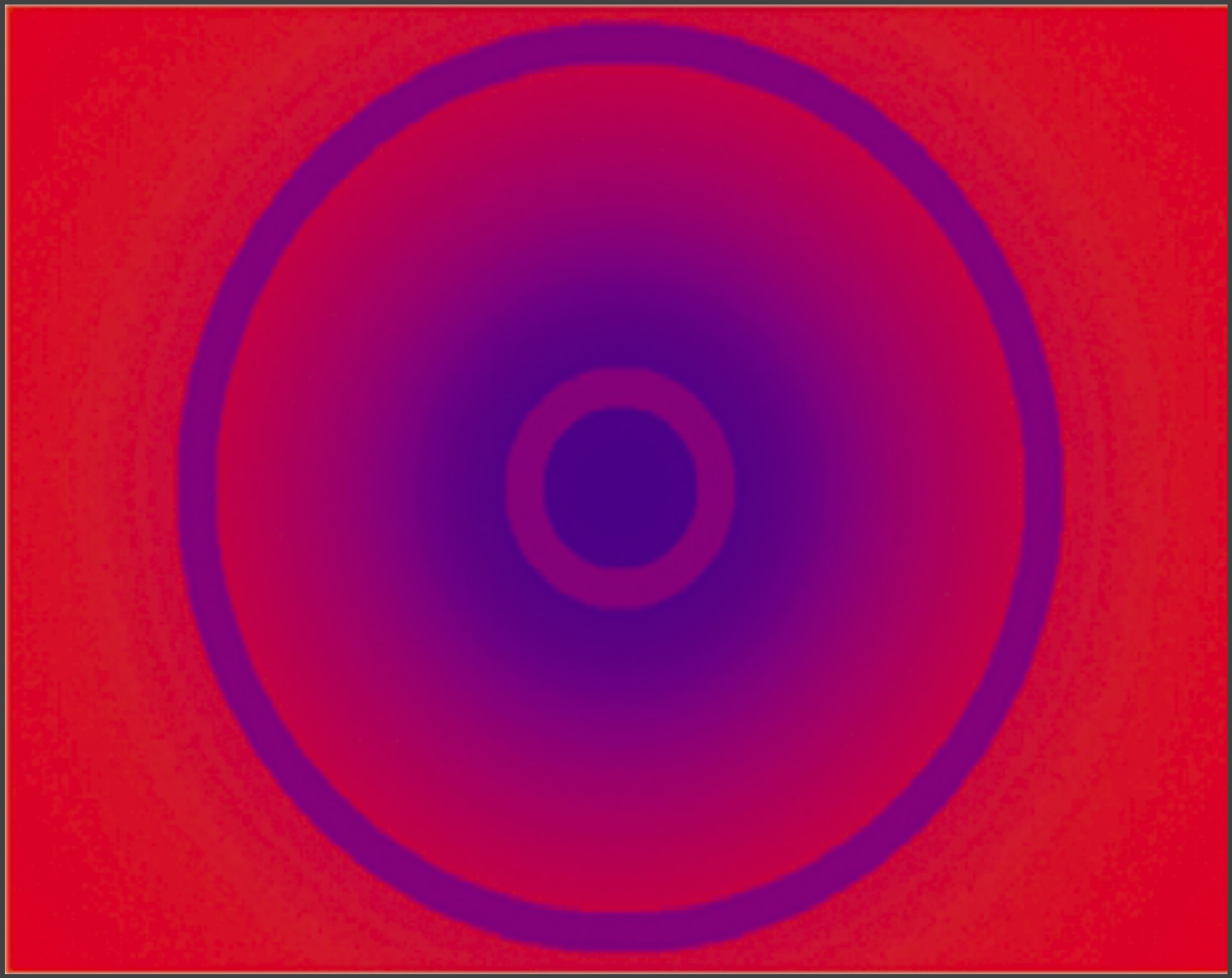
Simultaneous Contrast



Josef Albers

Simultaneous Contrast

Inner & outer rings are the same physical purple.



Donald MacLeod

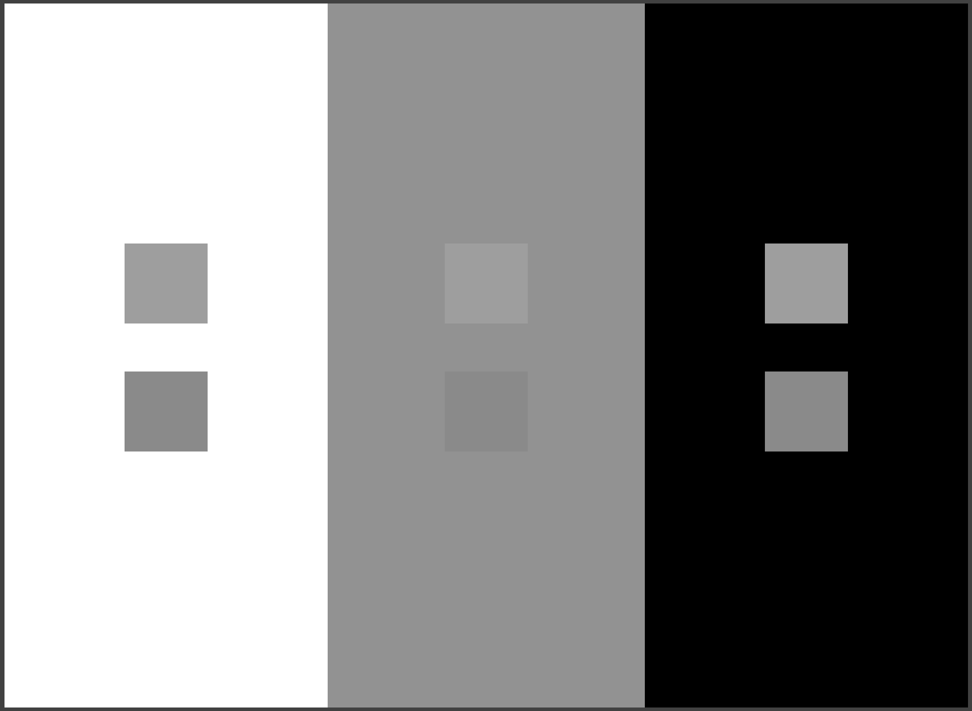
Bezold Effect

Color appearance depends on adjacent colors

Color Appearance Tutorial by Maureen Stone

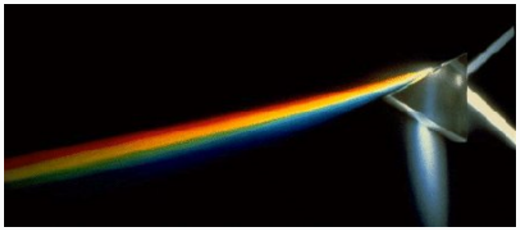
Crispening

Perceived difference depends on background

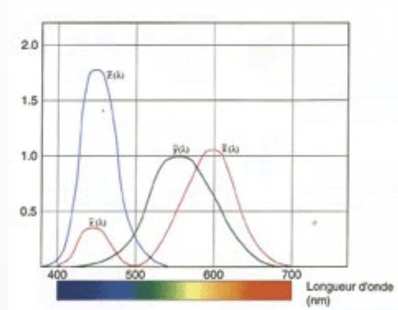


Color Appearance Models, Fairchild

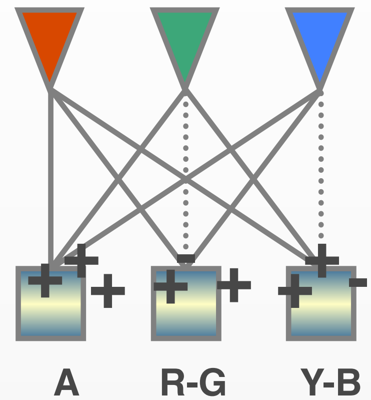
Perception of Color



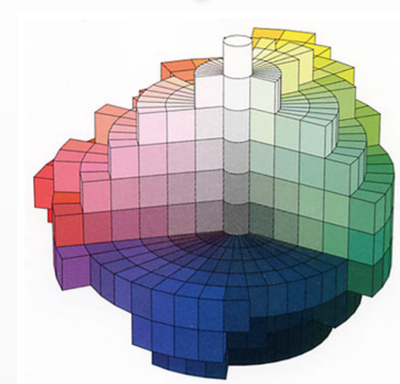
Light



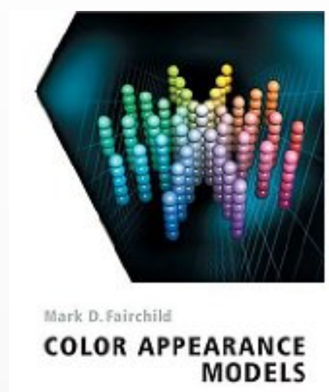
Cone Response



Opponent Signals



Color Perception



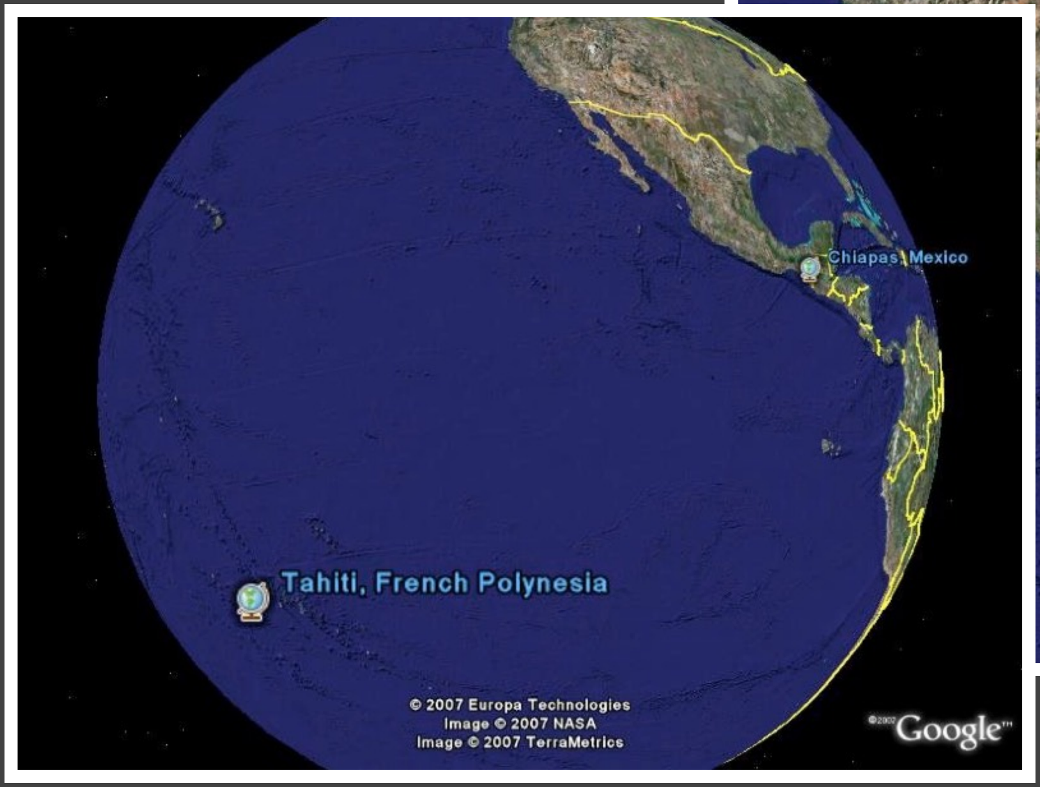
Color Appearance

"Yellow"

Color Cognition

Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.



Basic Color Terms

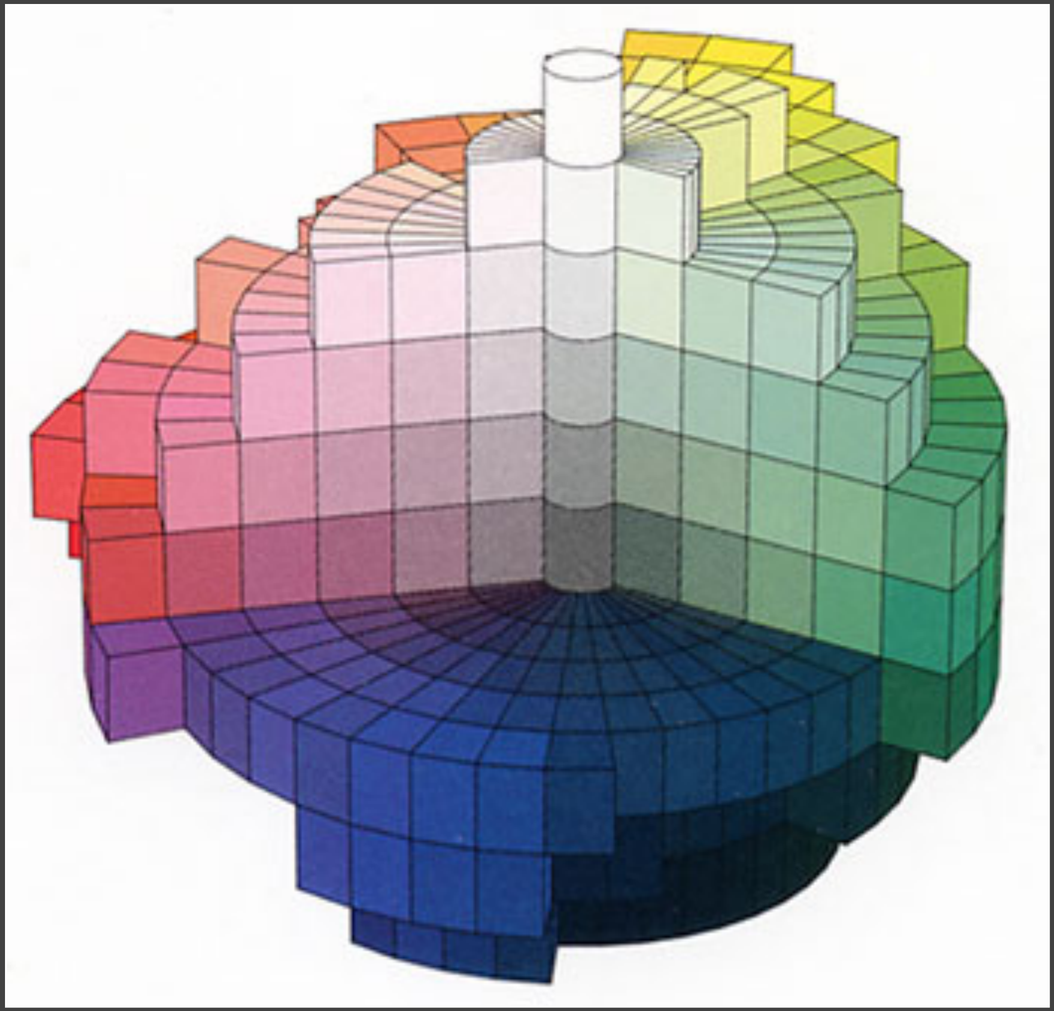
Chance discovery by Brent Berlin and Paul Kay.

Initial study in 1969

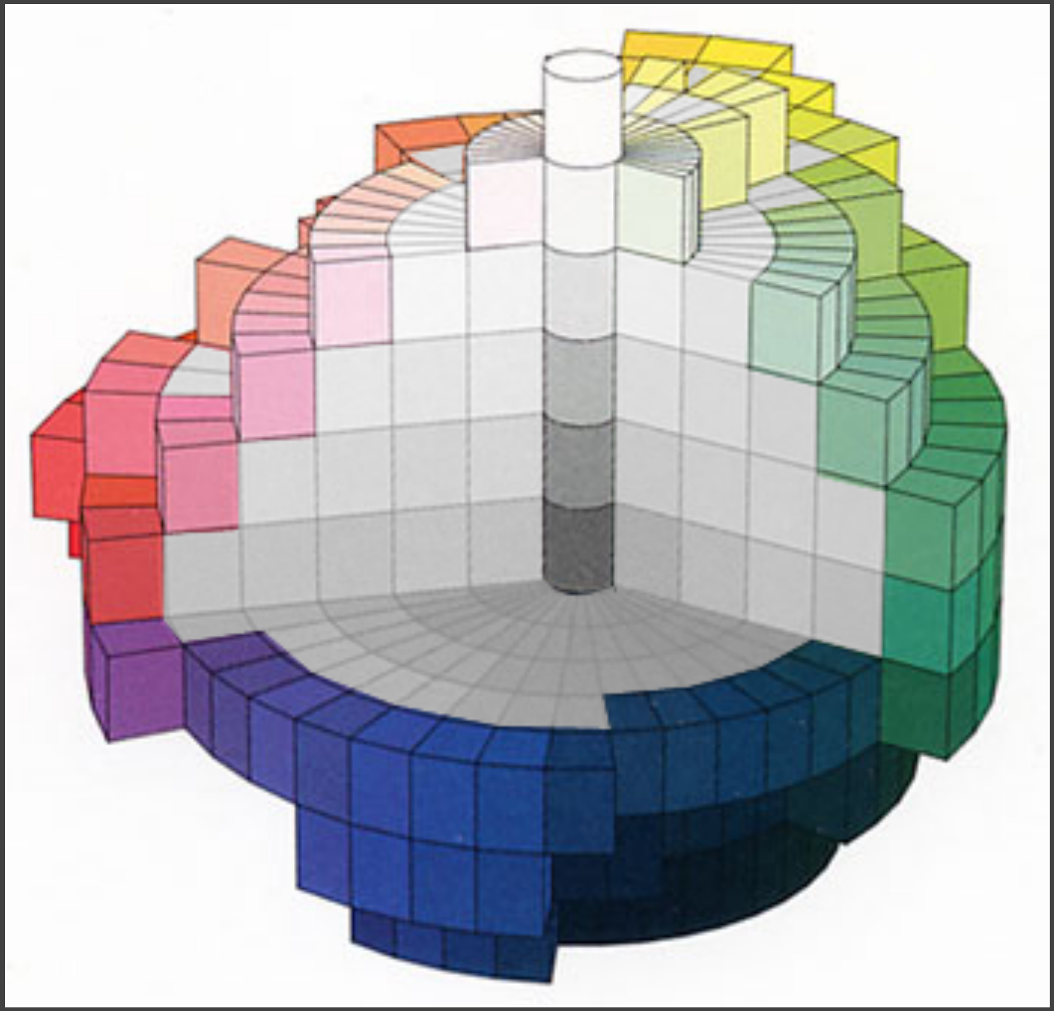
Surveyed speakers from 20 languages

Literature from 69 languages

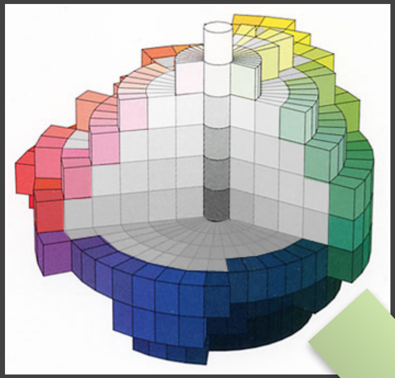
World Color Survey



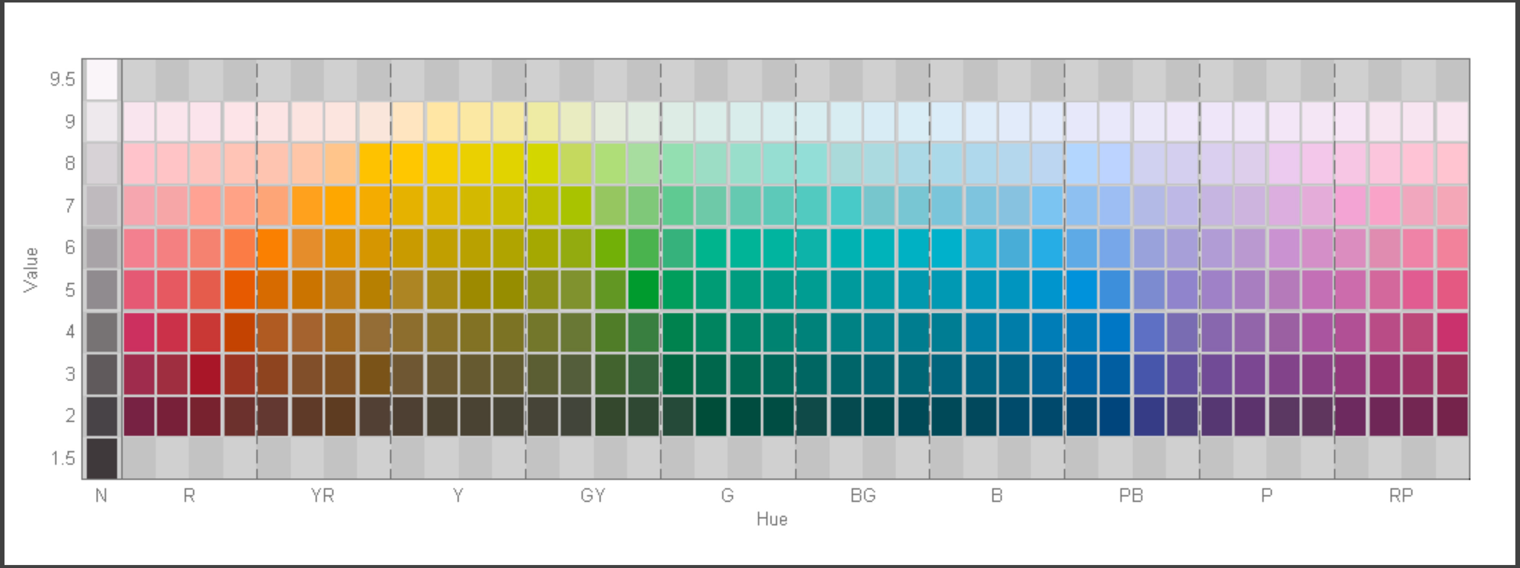
World Color Survey



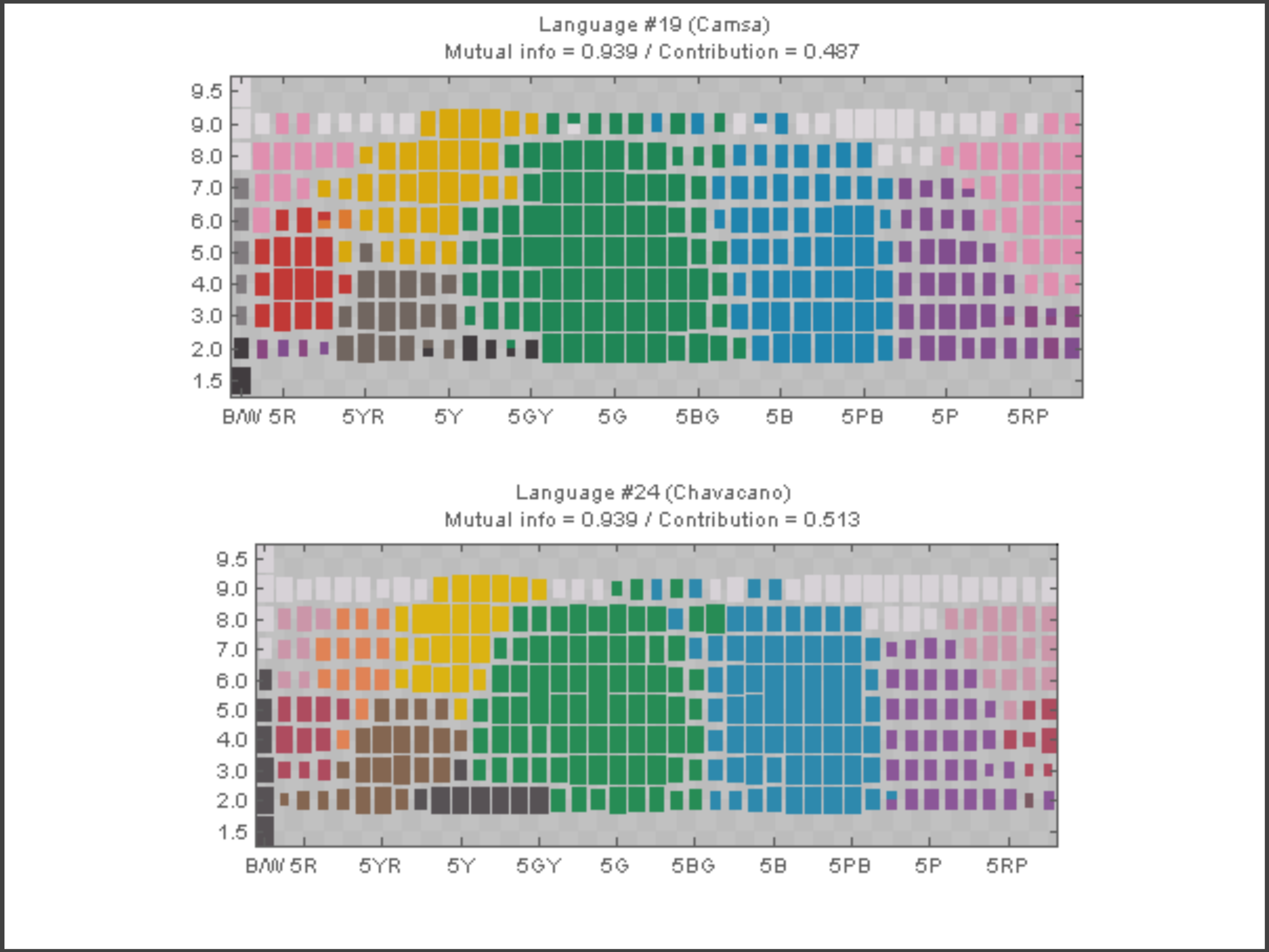
World Color Survey



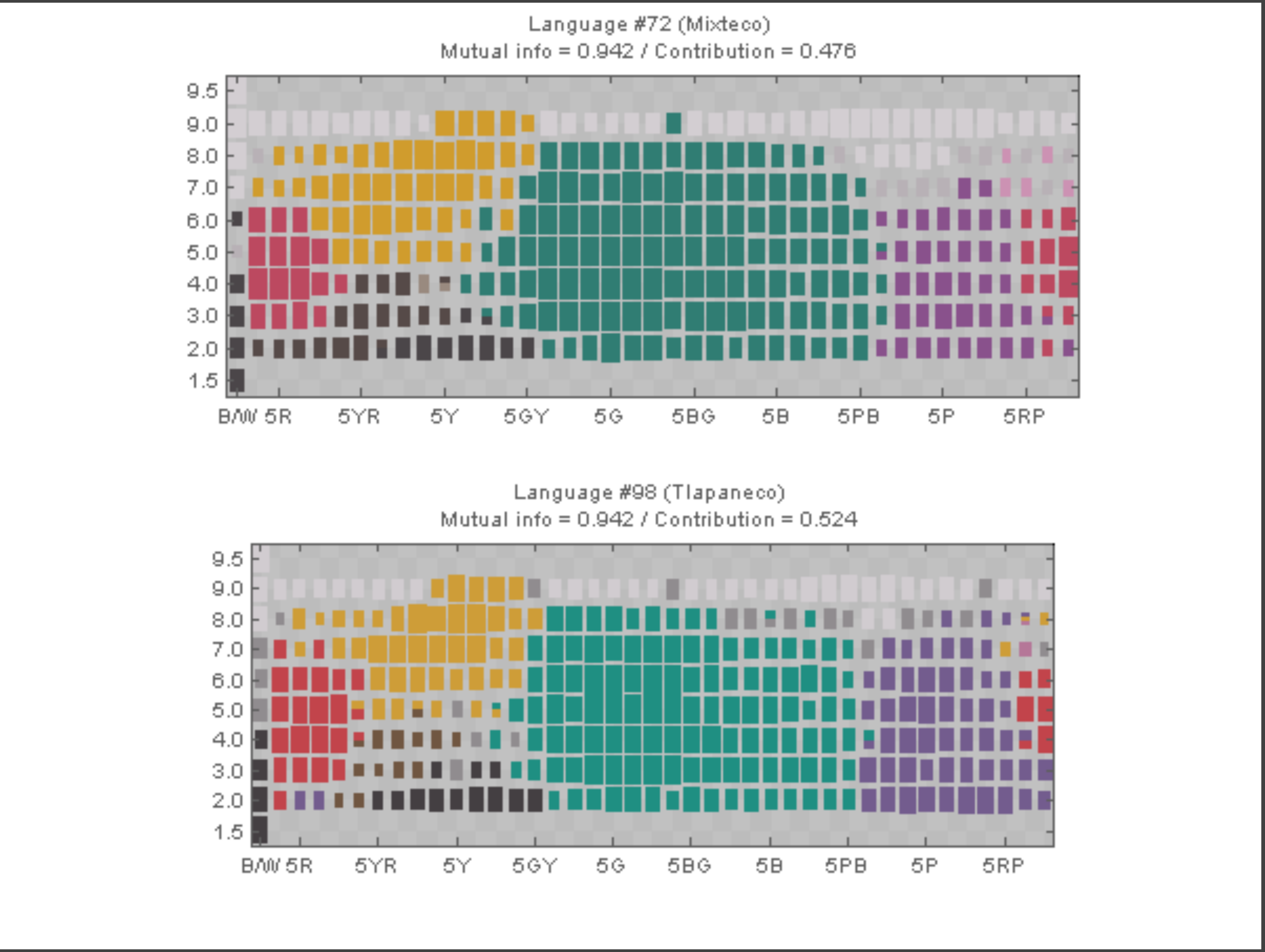
Naming information from 2,616 speakers from 110 languages on 330 Munsell color chips



Results from WCS



Results from WCS



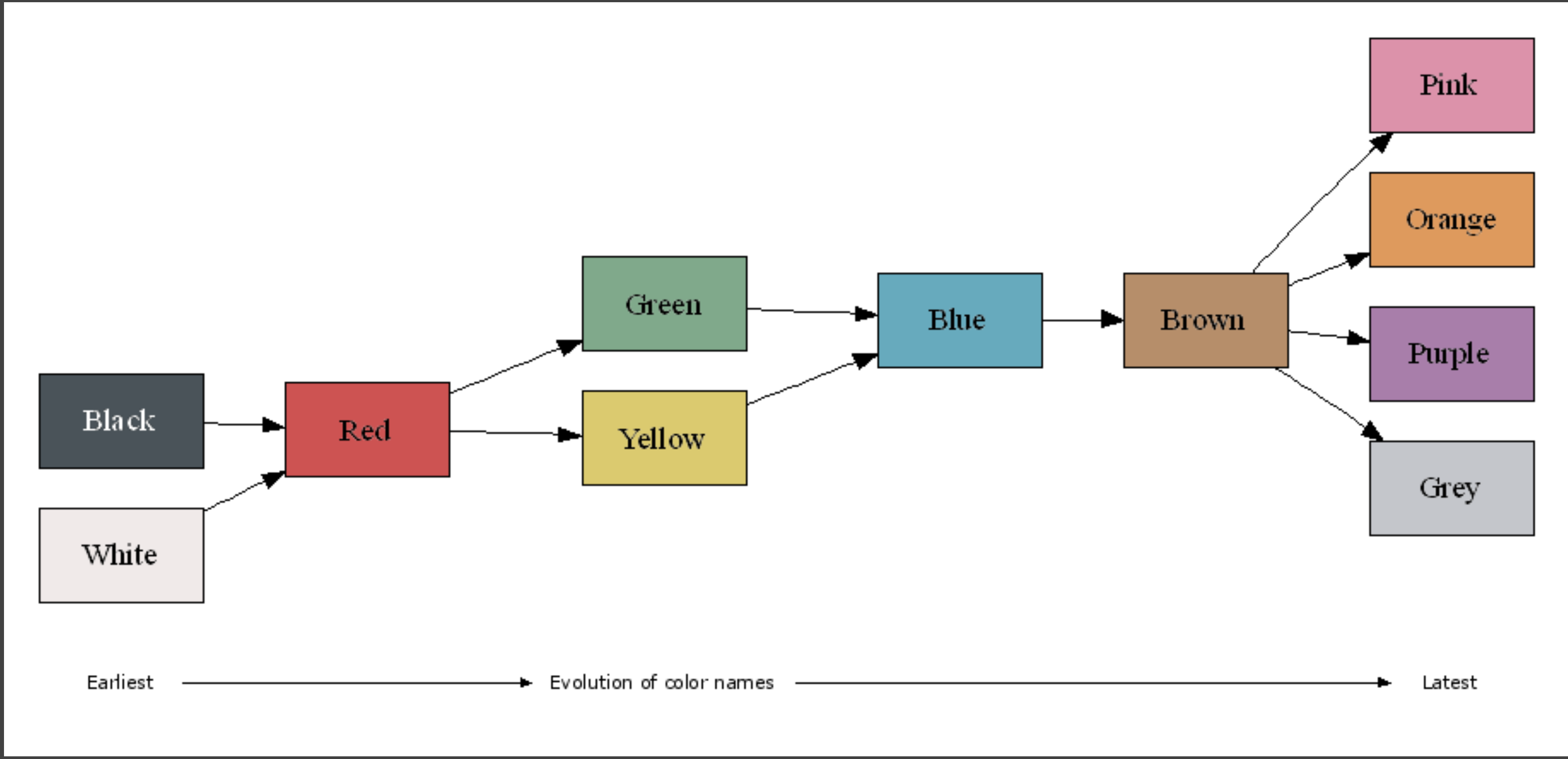
Universal (?) Basic Color Terms

Basic color terms recur across languages.

White	Red	Pink
Grey	Yellow	Brown
Black	Green	Orange
	Blue	Purple

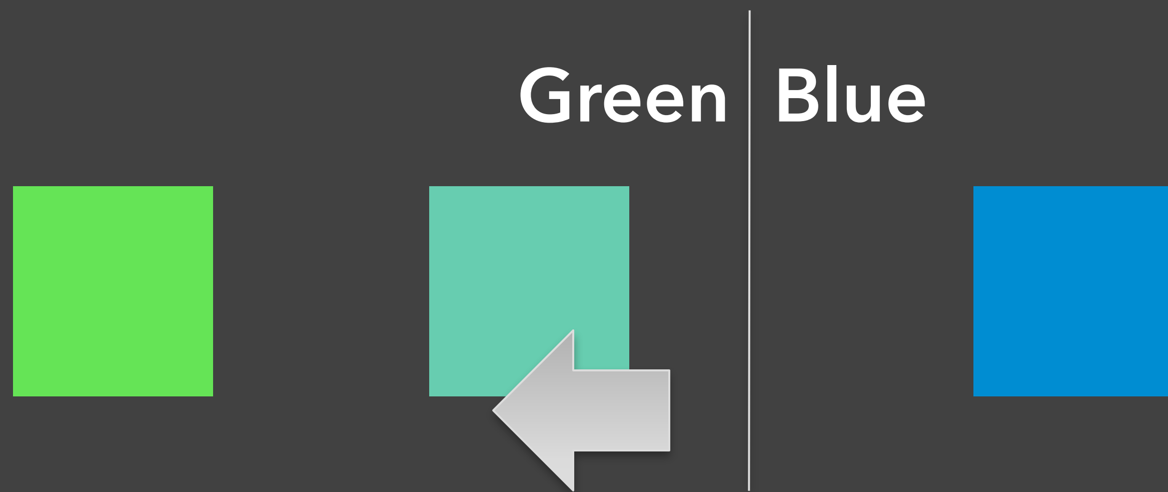
Evolution of Basic Color Terms

Proposed term evolution across languages.



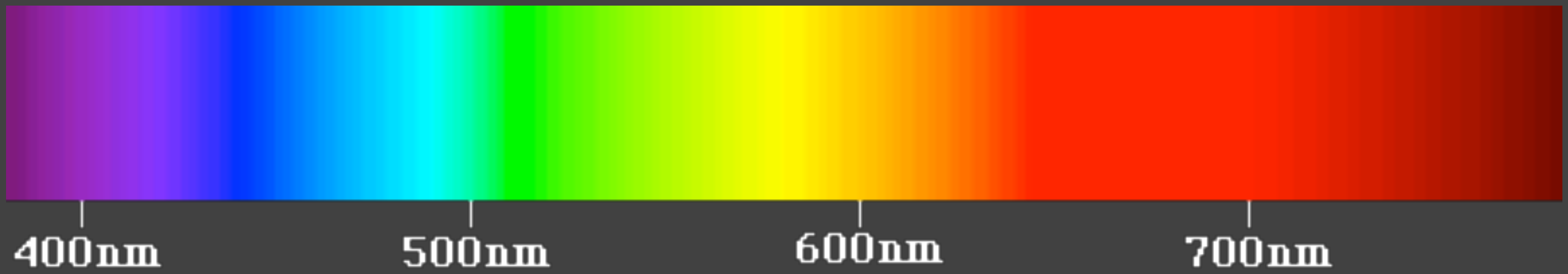
Naming Effects Color Perception

Color name boundaries



Rainbow Color Map

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



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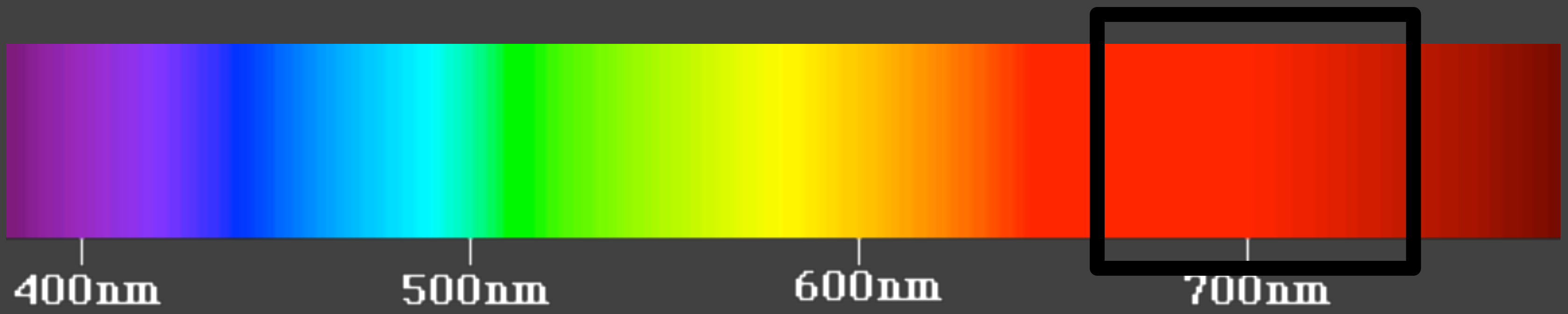

Rainbow Color Map

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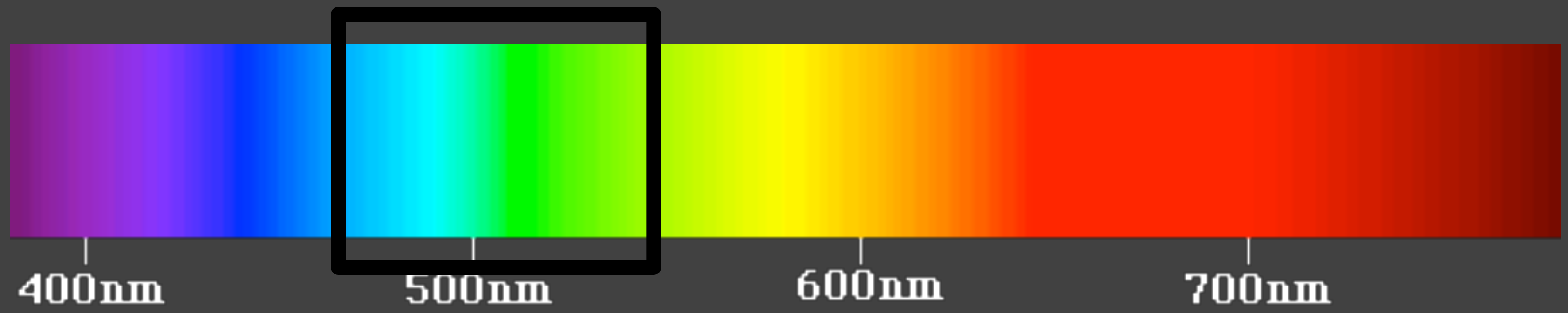
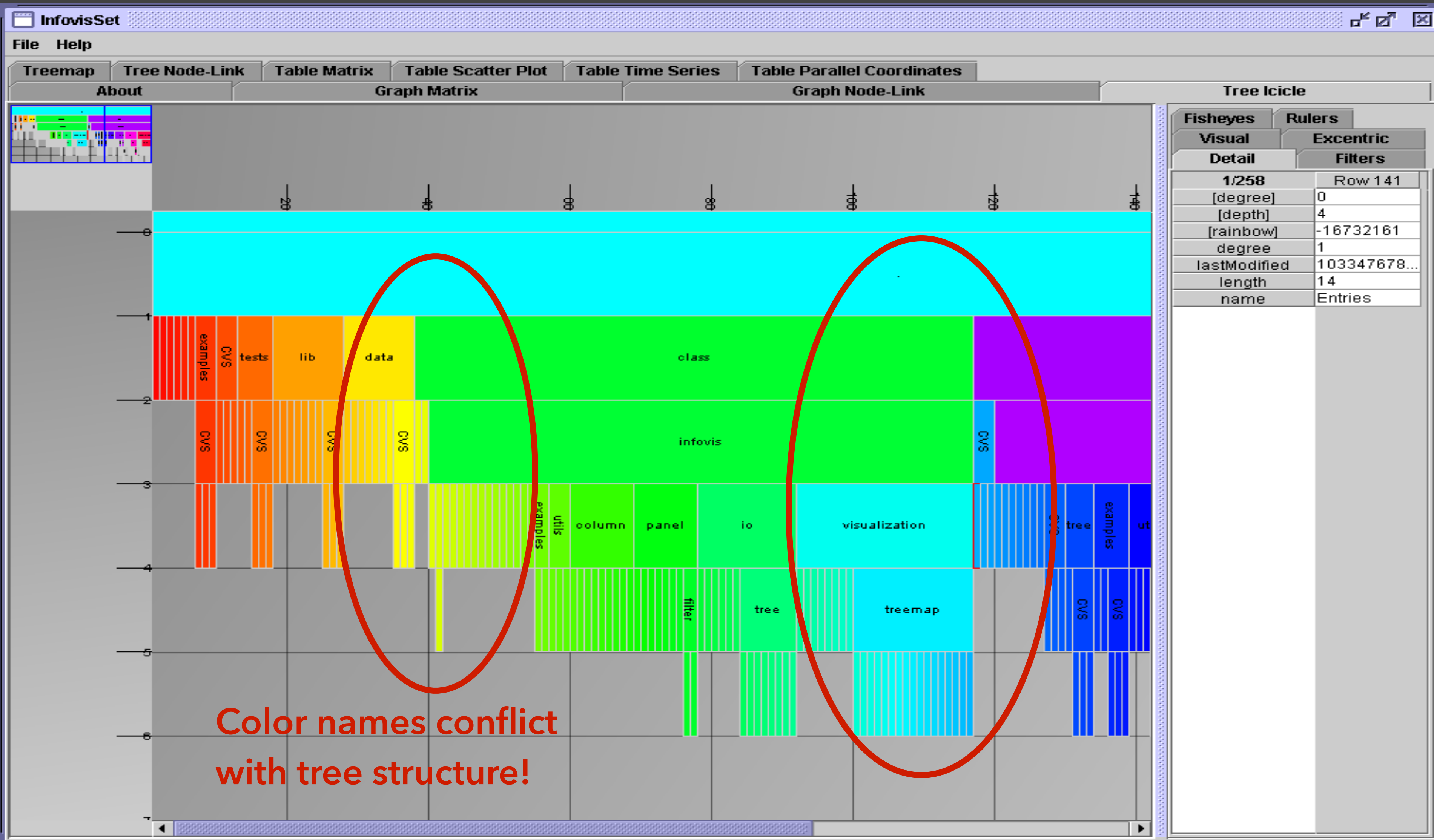


Icicle Tree with Rainbow Coloring



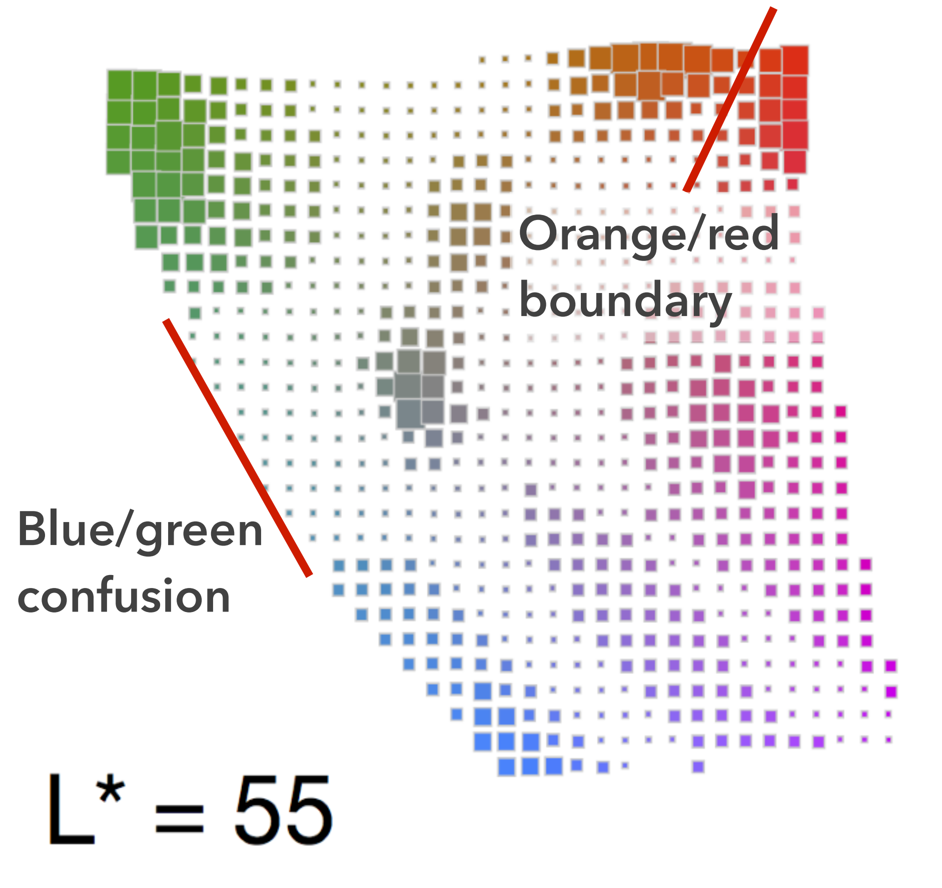
Color Naming Models [Heer & Stone '12]

Model 3 million responses from XKCD survey

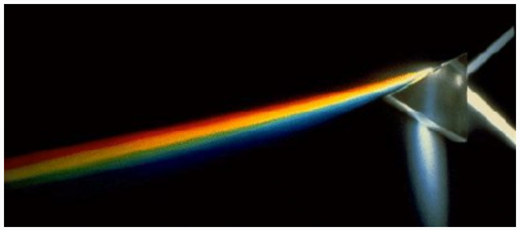
Bins in LAB space sized by *saliency*:

How much do people agree on color name?

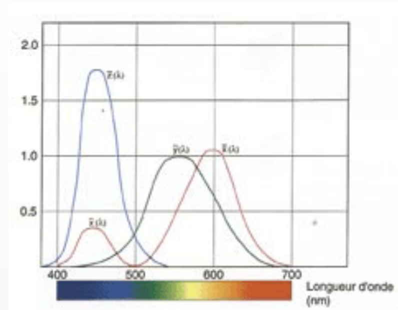
Modeled by entropy of *p(name | color)*



Perception of Color



Light



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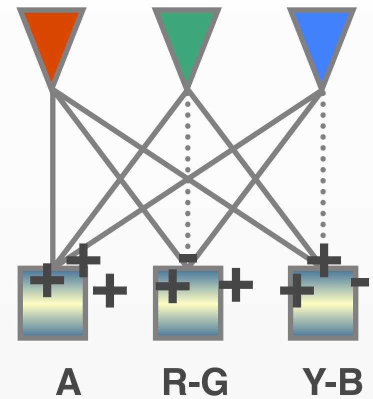

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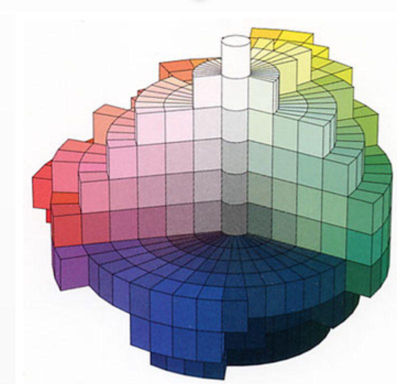
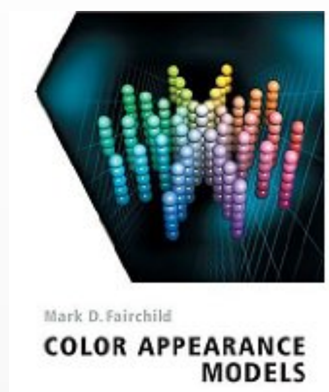


Color Perception



Color Appearance

“Yellow”

Color Cognition

Designing Colormaps

Colormap Design Considerations

Perceptually distinguishable colors

Value distance matches perceptual distance

Colors and concepts properly align

Aesthetically pleasing, intriguing

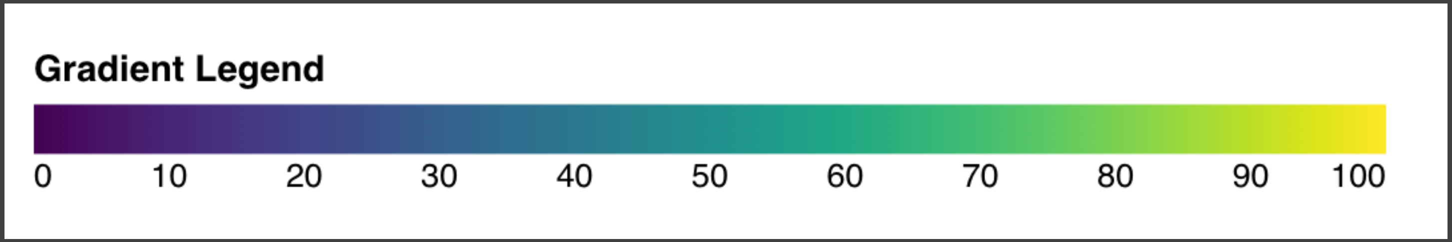
Respect color vision deficiencies

Should survive printing to black & white

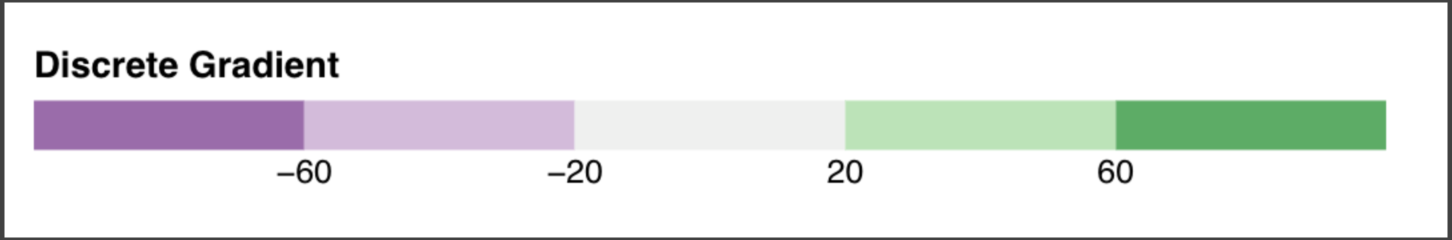
Don’t overwhelm people’s capability!

Discrete (Binary, Categorical)

Continuous (Sequential, Diverging, Cyclic)

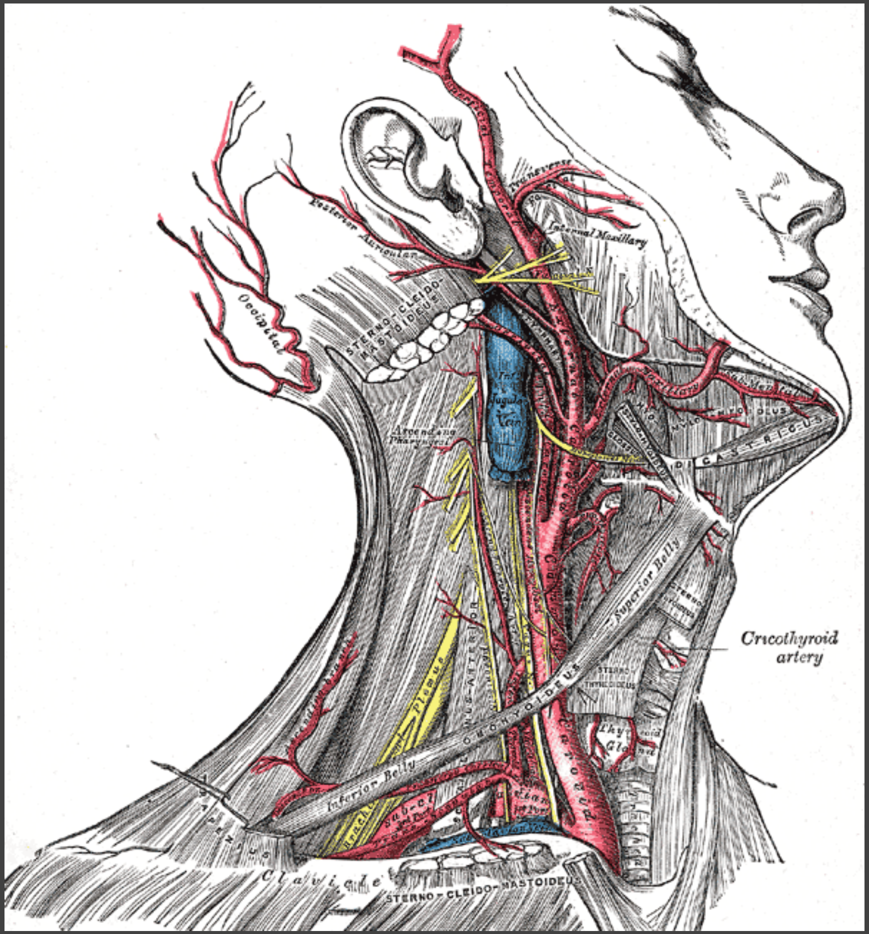


Discretized Continuous



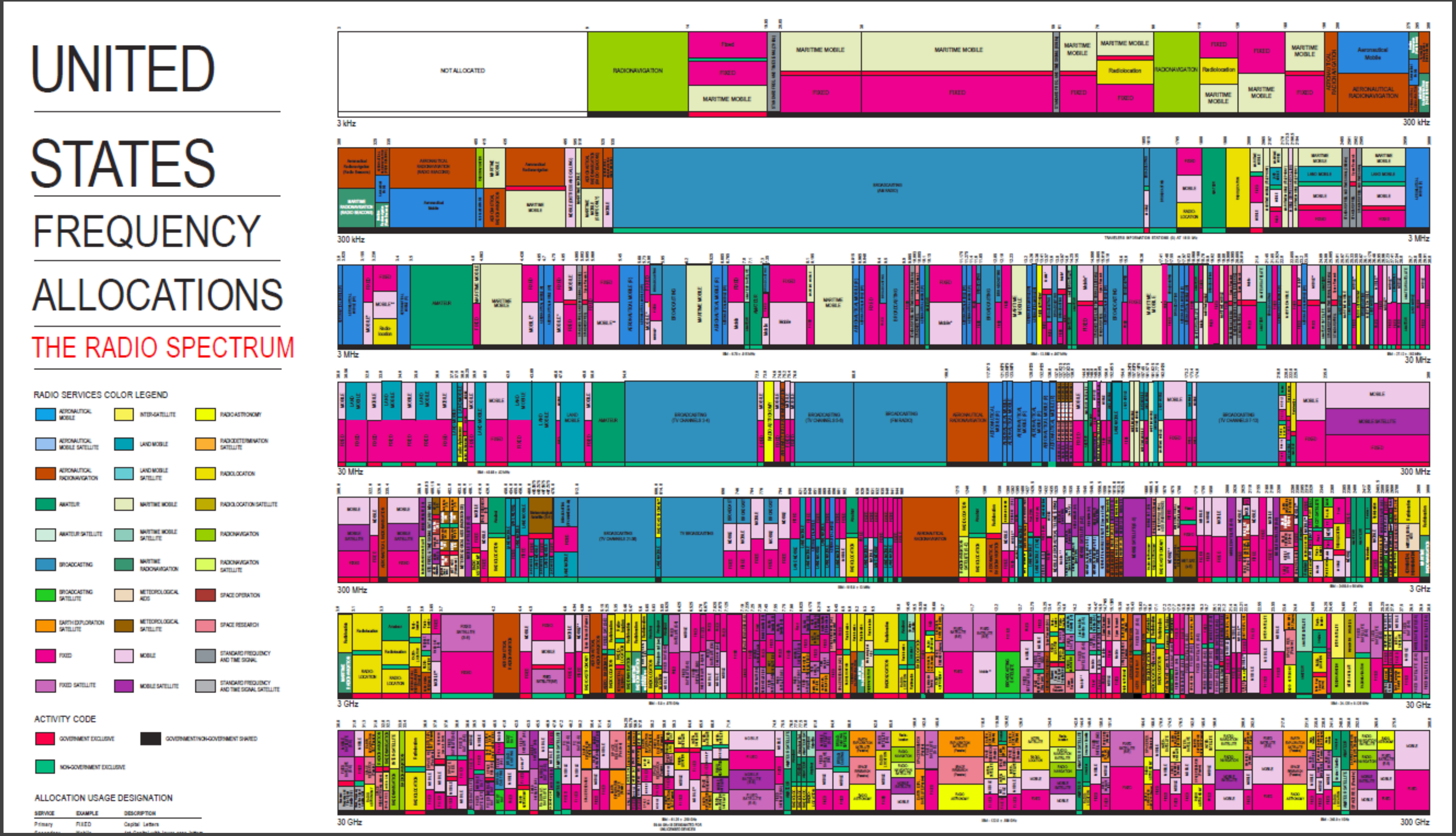
Categorical Color

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



http://www.ntia.doc.gov/osmhome/allochrt.html

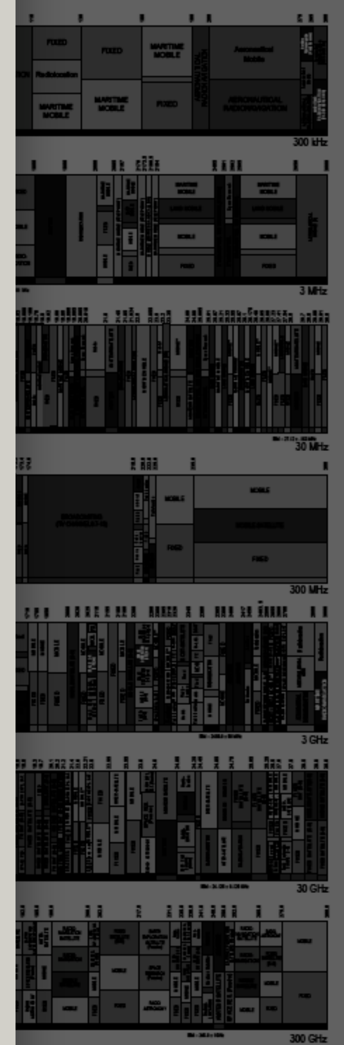
Alloca… …rum

UNITED STATES FREQUENCY ALLOCATION… THE RADIO SPECTRU…

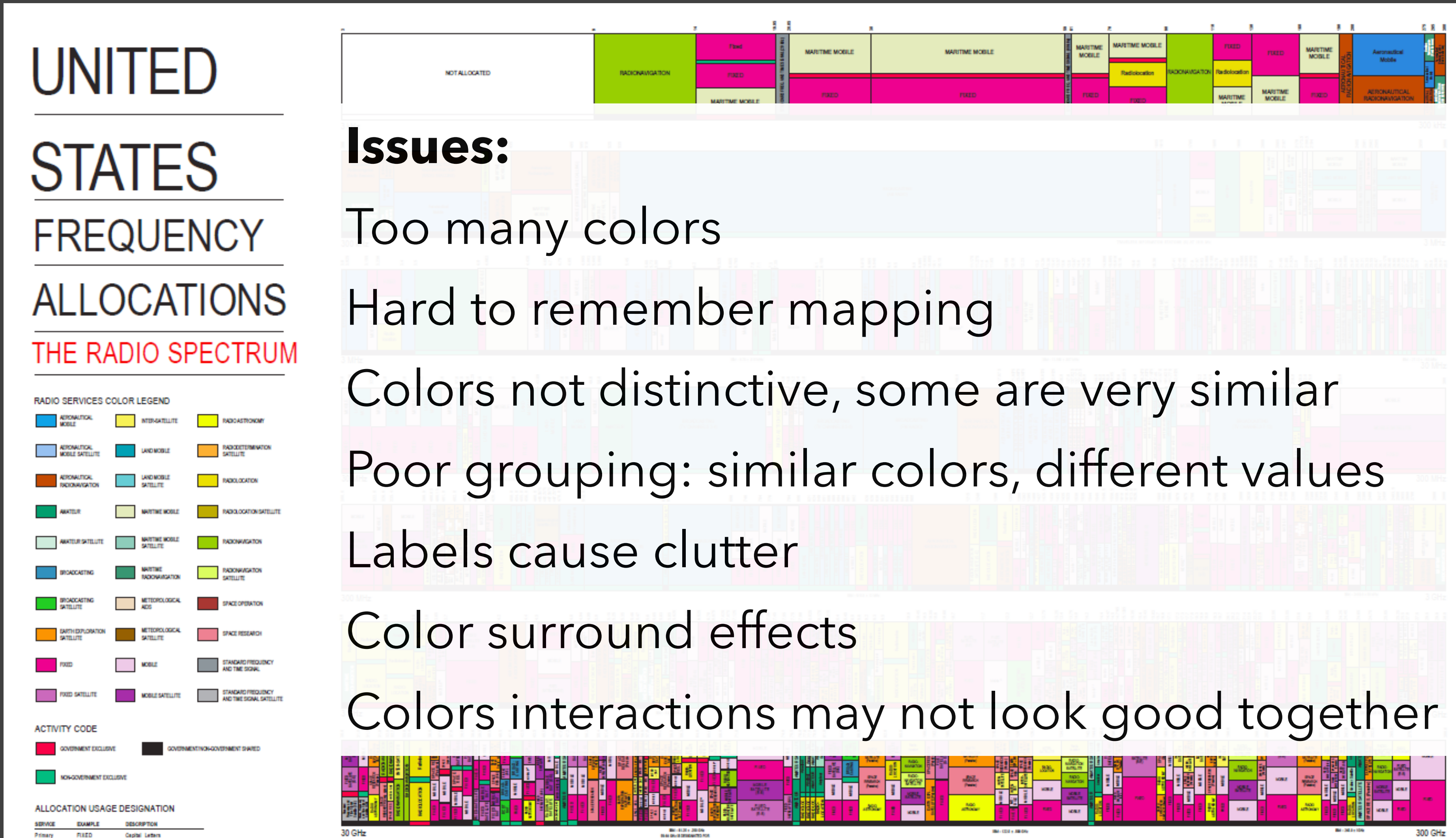
RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL AIDS
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE



Allocation of the Radio Spectrum



Issues:

Too many colors

Hard to remember mapping

Colors not distinctive, some are very similar

Poor grouping: similar colors, different values

Labels cause clutter

Color surround effects

Colors interactions may not look good together

http://www.ntia.doc.gov/osmhome/allochrt.html

Palette Design & Color Names

Minimize overlap and ambiguity of colors.

Color Name Distance										Salience	Name
0.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.20	.47	**blue** 62.9%
1.00	0.00	1.00	0.97	1.00	1.00	1.00	1.00	0.96	1.00	.90	**orange** 93.9%
1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.90	0.99	.67	**green** 79.8%
1.00	0.97	1.00	0.00	1.00	0.95	0.99	1.00	1.00	1.00	.66	**red** 80.4%
0.98	1.00	1.00	1.00	0.00	0.96	0.91	0.97	1.00	0.99	.47	**purple** 51.4%
1.00	1.00	1.00	0.95	0.96	0.00	0.97	0.93	0.98	1.00	.37	**brown** 54.0%
1.00	1.00	1.00	0.99	0.91	0.97	0.00	1.00	1.00	1.00	.58	**pink** 71.7%
1.00	1.00	1.00	1.00	0.97	0.93	1.00	0.00	1.00	1.00	.67	**grey** 79.4%
1.00	0.96	0.90	1.00	1.00	0.98	1.00	1.00	0.00	1.00	.18	**yellow** 31.2%
0.20	1.00	0.99	1.00	0.99	1.00	1.00	1.00	1.00	0.00	.25	**blue** 25.4%
Tableau-10								*Average*	*0.97*	.52	

http://vis.stanford.edu/color-names

Palette Design & Color Names

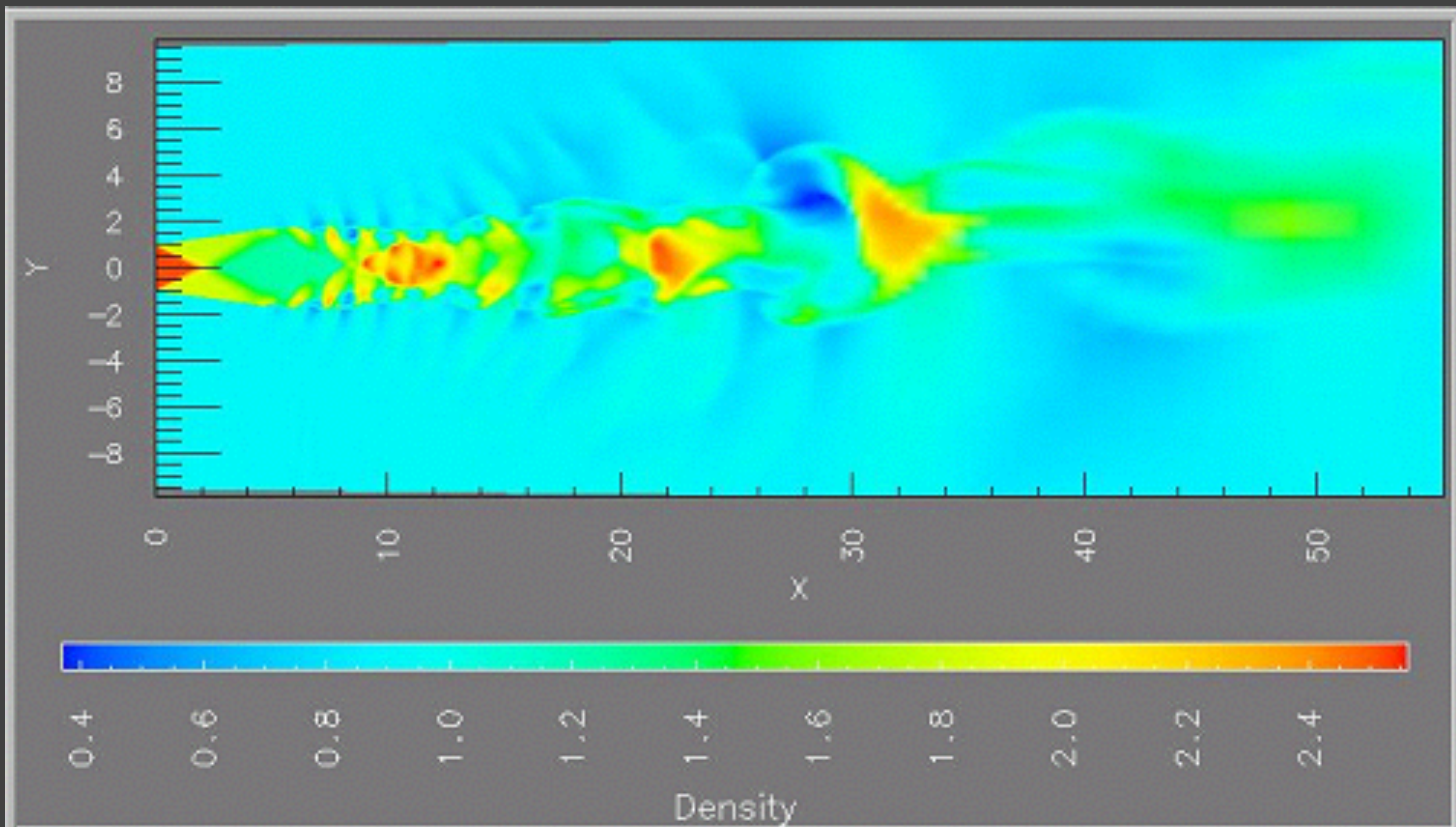
Minimize overlap and ambiguity of colors.

Color Name Distance										Salience	Name
0.00	1.00	1.00	0.89	0.07	1.00	0.35	0.99	1.00	0.89	.30	**blue** 50.5%
1.00	0.00	0.99	1.00	1.00	0.92	1.00	0.84	0.98	0.99	.21	**red** 27.8%
1.00	0.99	0.00	1.00	0.98	1.00	1.00	1.00	0.17	1.00	.34	**green** 36.8%
0.89	1.00	1.00	0.00	0.98	1.00	0.71	0.93	1.00	0.32	.55	**purple** 67.3%
0.07	1.00	0.98	0.98	0.00	1.00	0.36	1.00	0.97	0.95	.20	**blue** 36.6%
1.00	0.92	1.00	1.00	1.00	0.00	1.00	0.97	0.99	1.00	.39	**orange** 51.9%
0.35	1.00	1.00	0.71	0.36	1.00	0.00	0.95	0.92	0.42	.13	**blue** 15.7%
0.99	0.84	1.00	0.93	1.00	0.97	0.95	0.00	0.98	0.85	.16	**pink** 29.4%
1.00	0.98	0.17	1.00	0.97	0.99	0.92	0.98	0.00	0.97	.12	**green** 21.7%
0.89	0.99	1.00	0.32	0.95	1.00	0.42	0.85	0.97	0.00	.30	**purple** 23.9%
Excel-10								*Average*	*0.87*	*.27*	

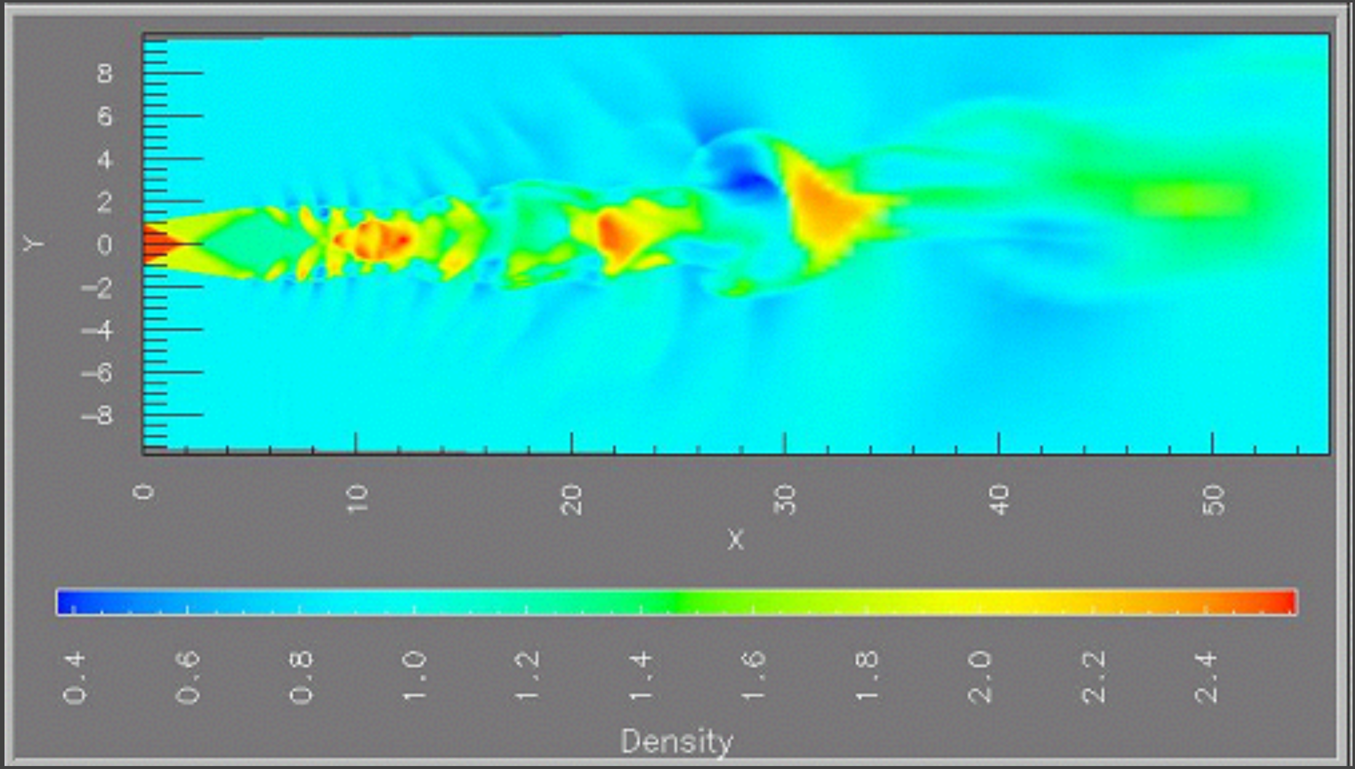
http://vis.stanford.edu/color-names

Quantitative Color

Rainbow Color Maps

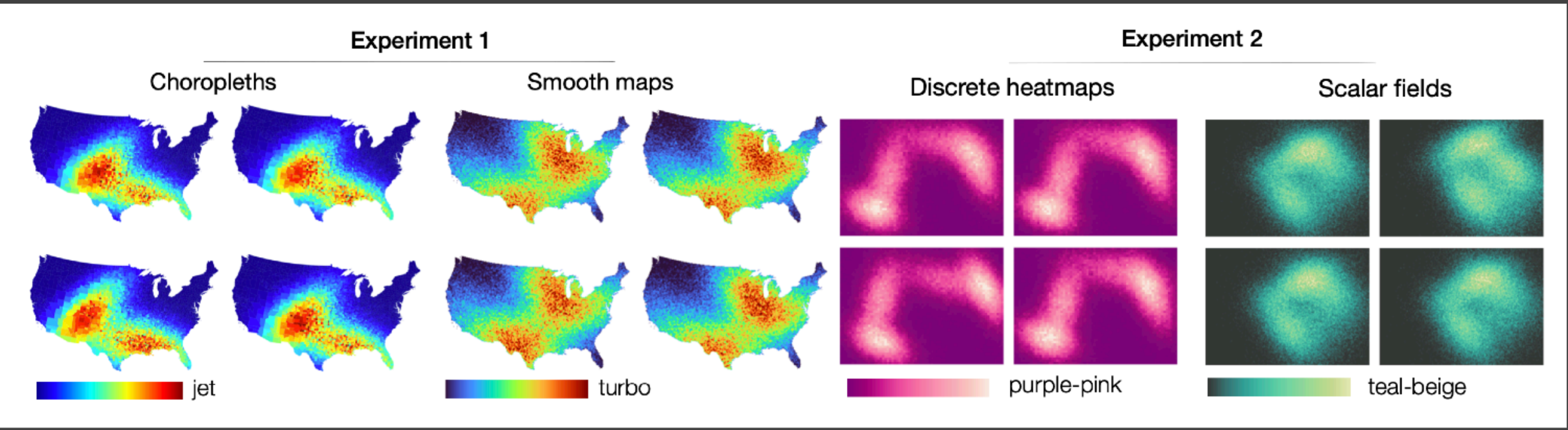


Be wary of naïve rainbows?



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?



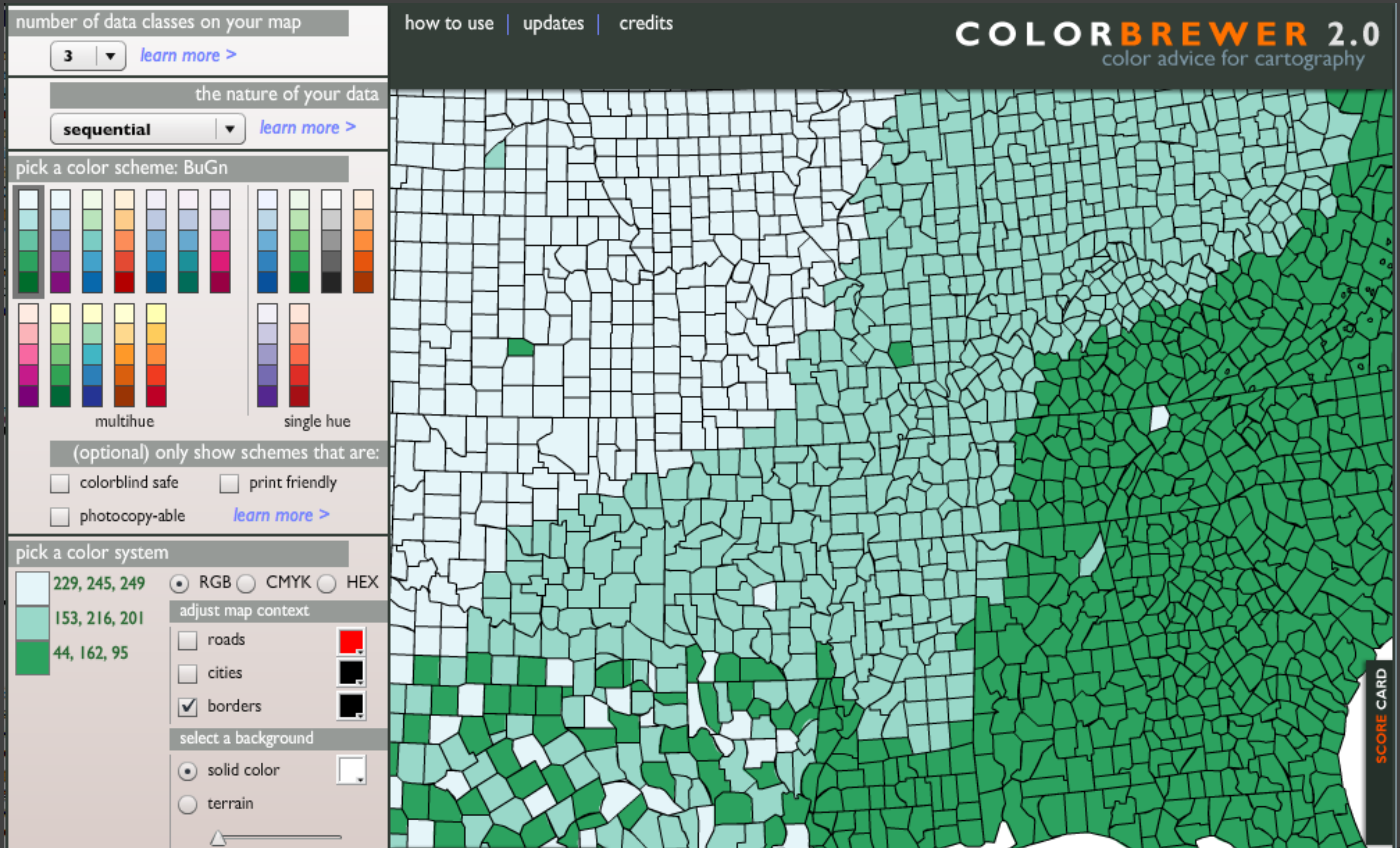
Reda et al. '21: Color Nameability Predicts Inference Accuracy in Spatial Visualizations

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

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

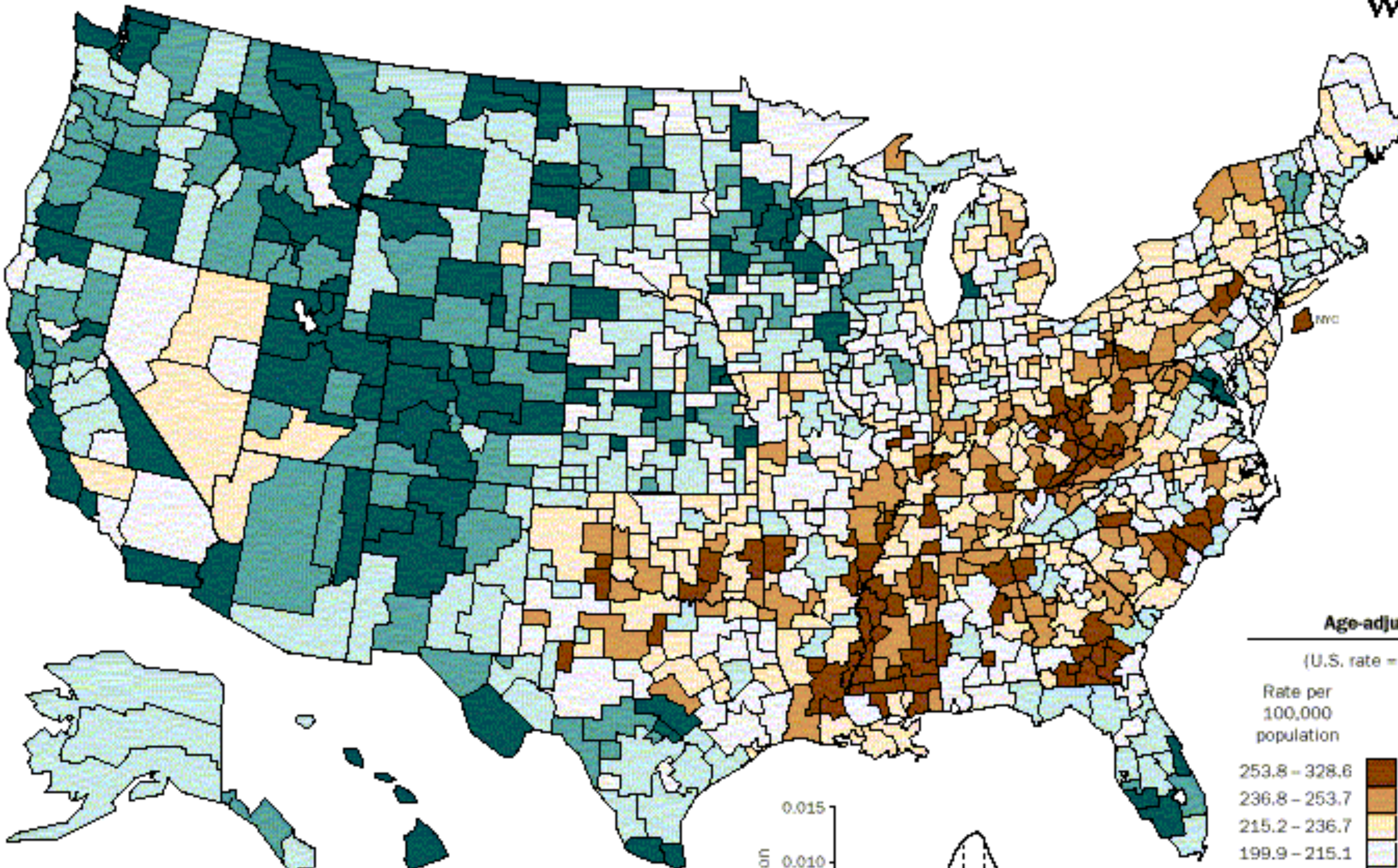
Task matters!

Steps, rather than Gradients?



Age-adjusted death rates by HSA, 1988-92

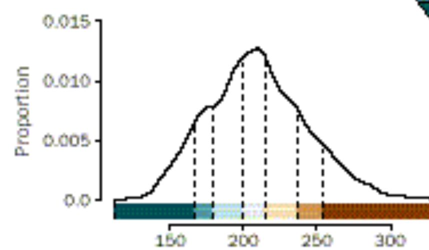
Heart disease
White male



Age-adjusted

(U.S. rate = 205.0)

Rate per 100,000 population	Comparative mortality ratio (HSA to U.S.)
253.8 – 328.6	1.24 – 1.60
236.8 – 253.7	1.16 – 1.24
215.2 – 236.7	1.05 – 1.16
199.9 – 215.1	0.98 – 1.05
179.5 – 199.8	0.88 – 0.98
166.7 – 179.4	0.81 – 0.88
112.4 – 166.6	0.55 – 0.81

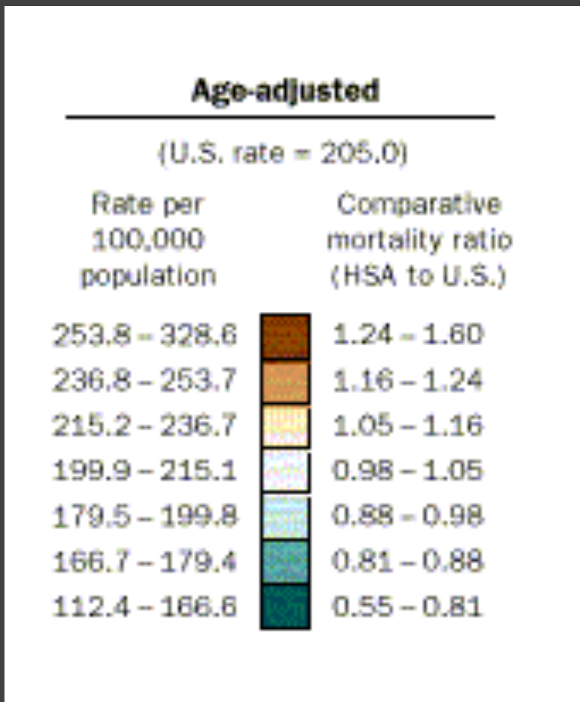


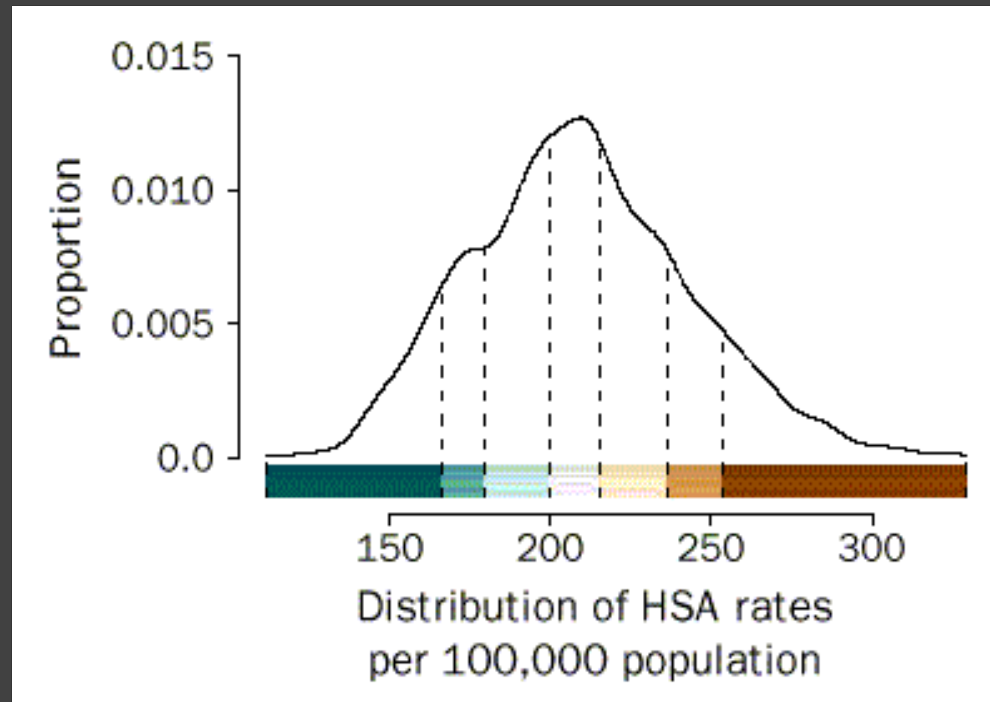
Distribution of HSA rates per 100,000 population

ICD–9 Categories 390–398, 402, 404–429

SOURCE: CDC/NCHS

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

Quantitative Color Encoding

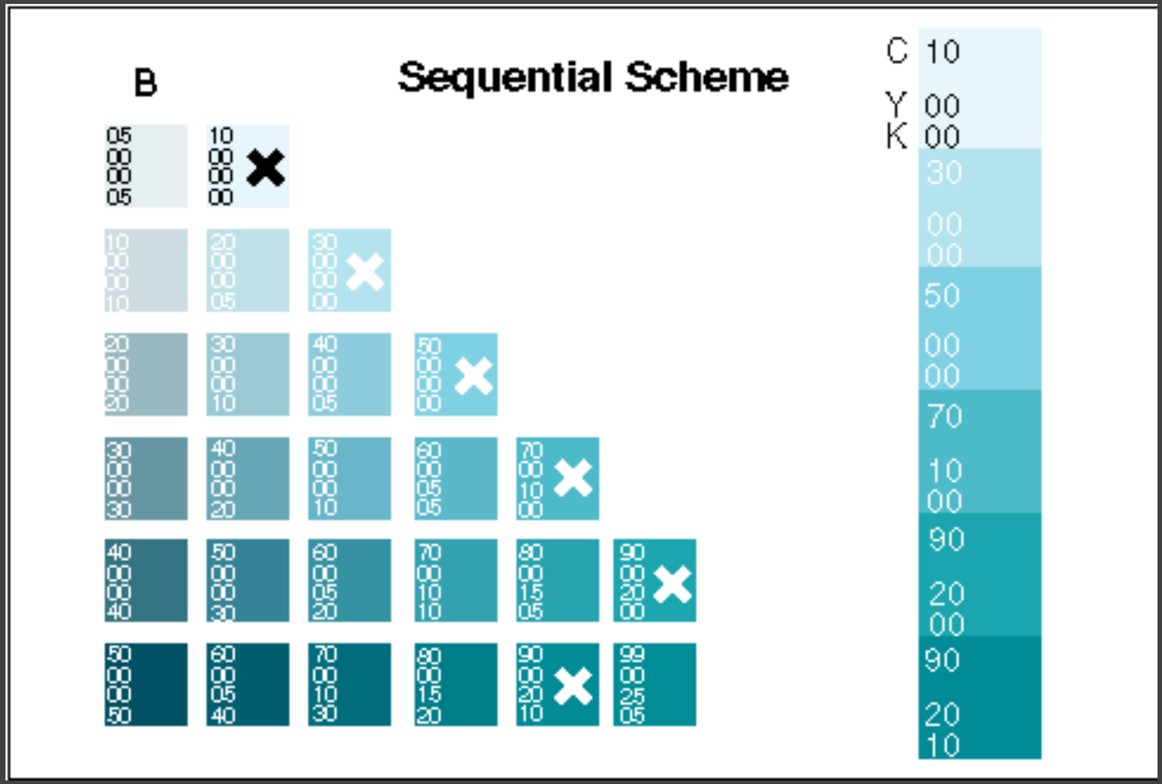
Sequential color scale

Ramp in luminance, possibly also hue

Higher value -> darker color (or vice versa)

Sequential Scales: Single-Hue

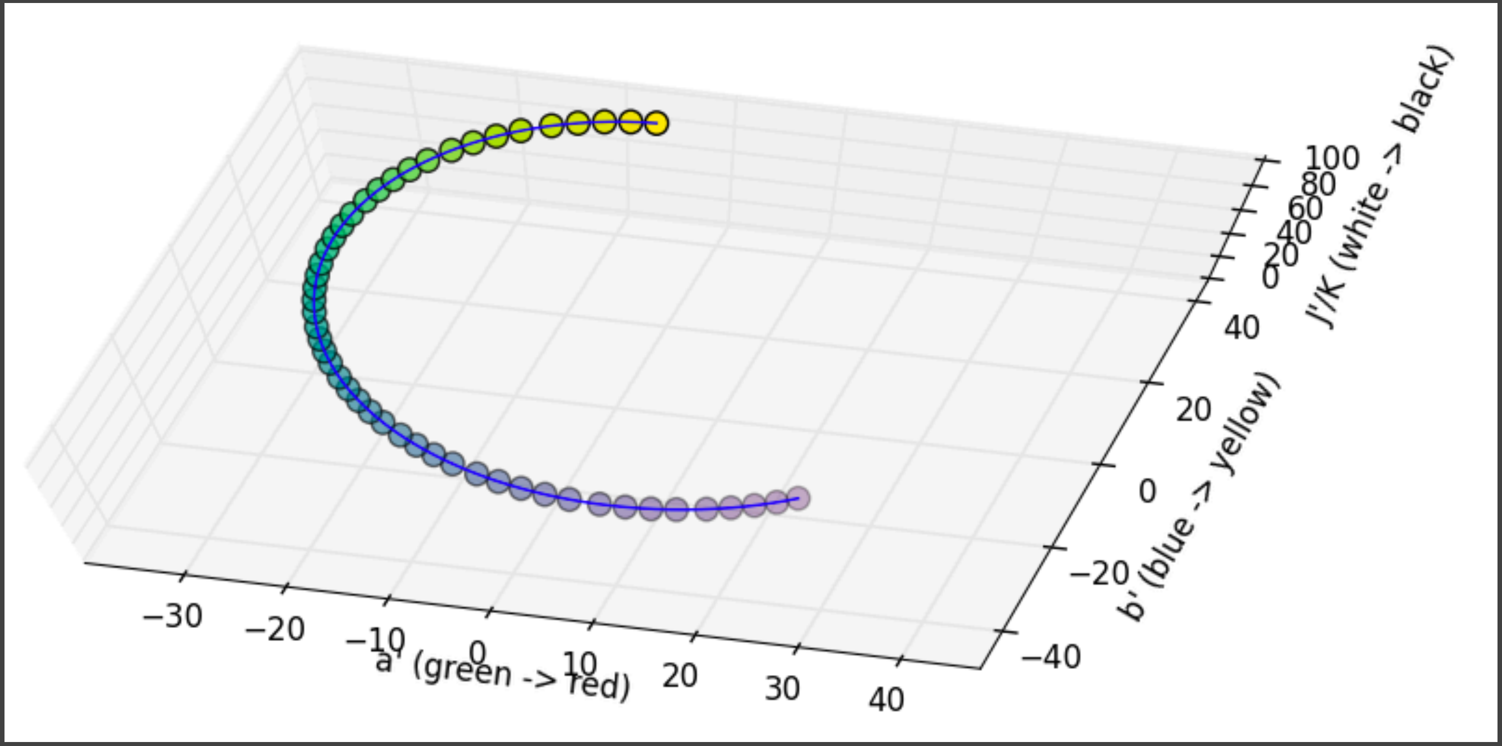
Ramp primarily in luminance, subtle hue difference



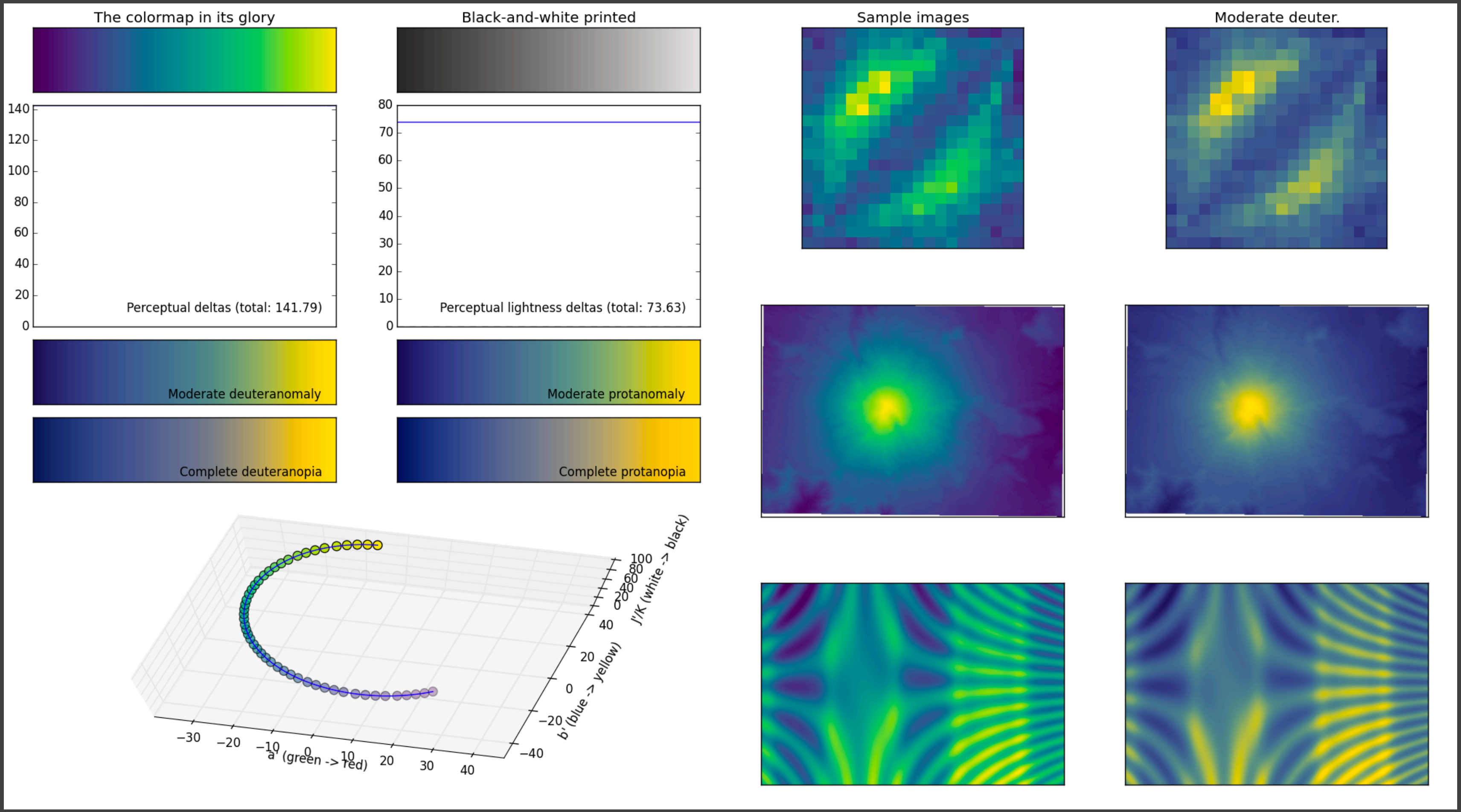
http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Sequential Scales: Multi-Hue

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



Sequential Scales: Multi-Hue



Viridis, https://bids.github.io/colormap/

Quantitative Color Encoding

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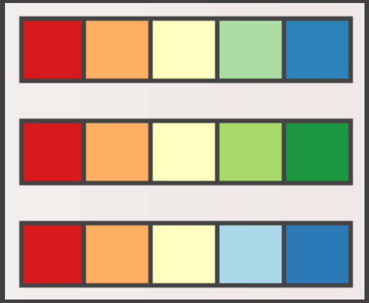
Higher value -> darker color (or vice versa)

Diverging color scale

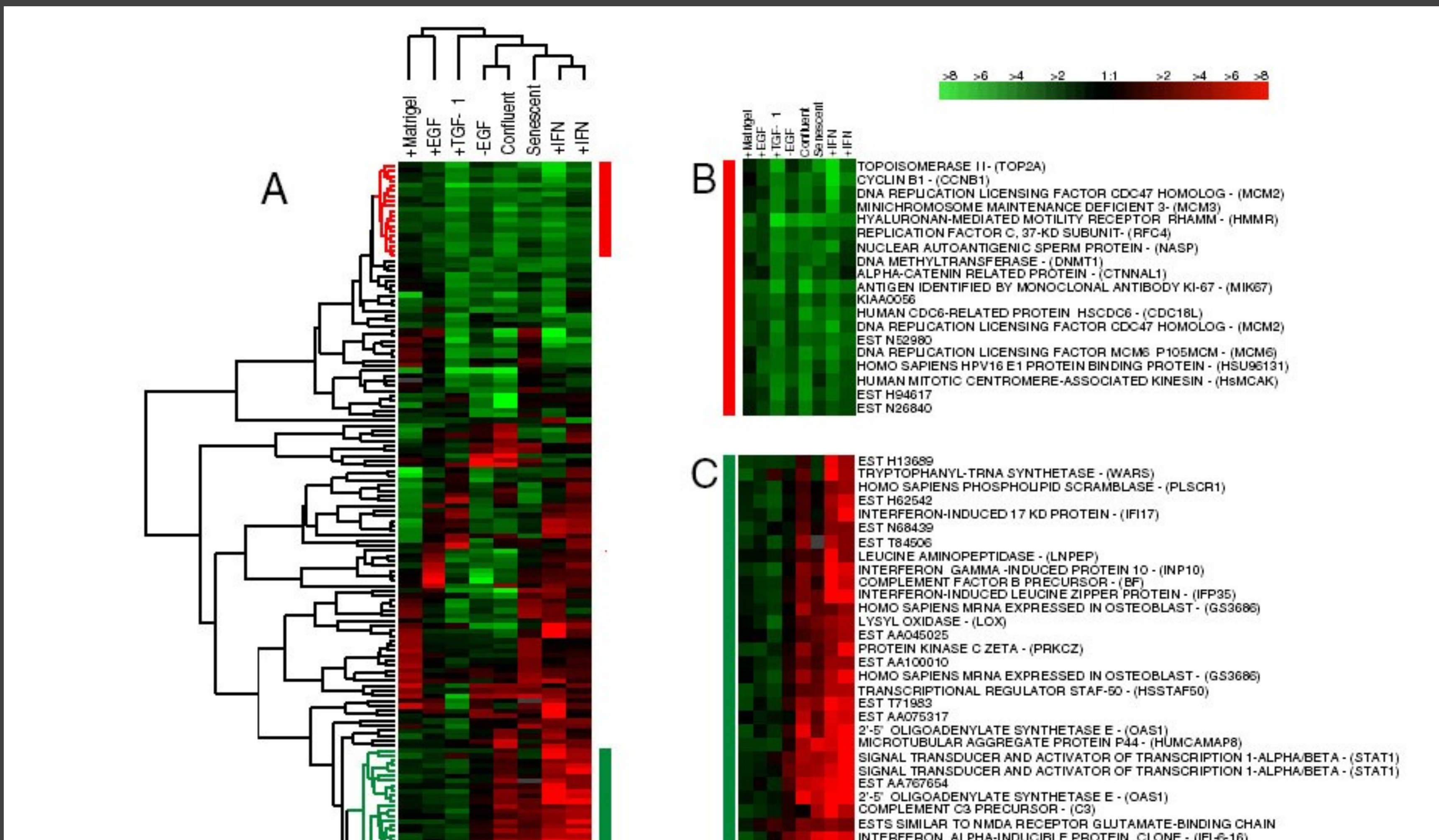


Useful when data has meaningful "midpoint"

Use neutral color (e.g., grey) for midpoint

Use saturated colors for endpoints

Diverging Color Scheme



Designing Diverging Scales

Hue Transition

Carefully Handle Midpoint

Choose classes of values

Low, Average, High - Average should be gray

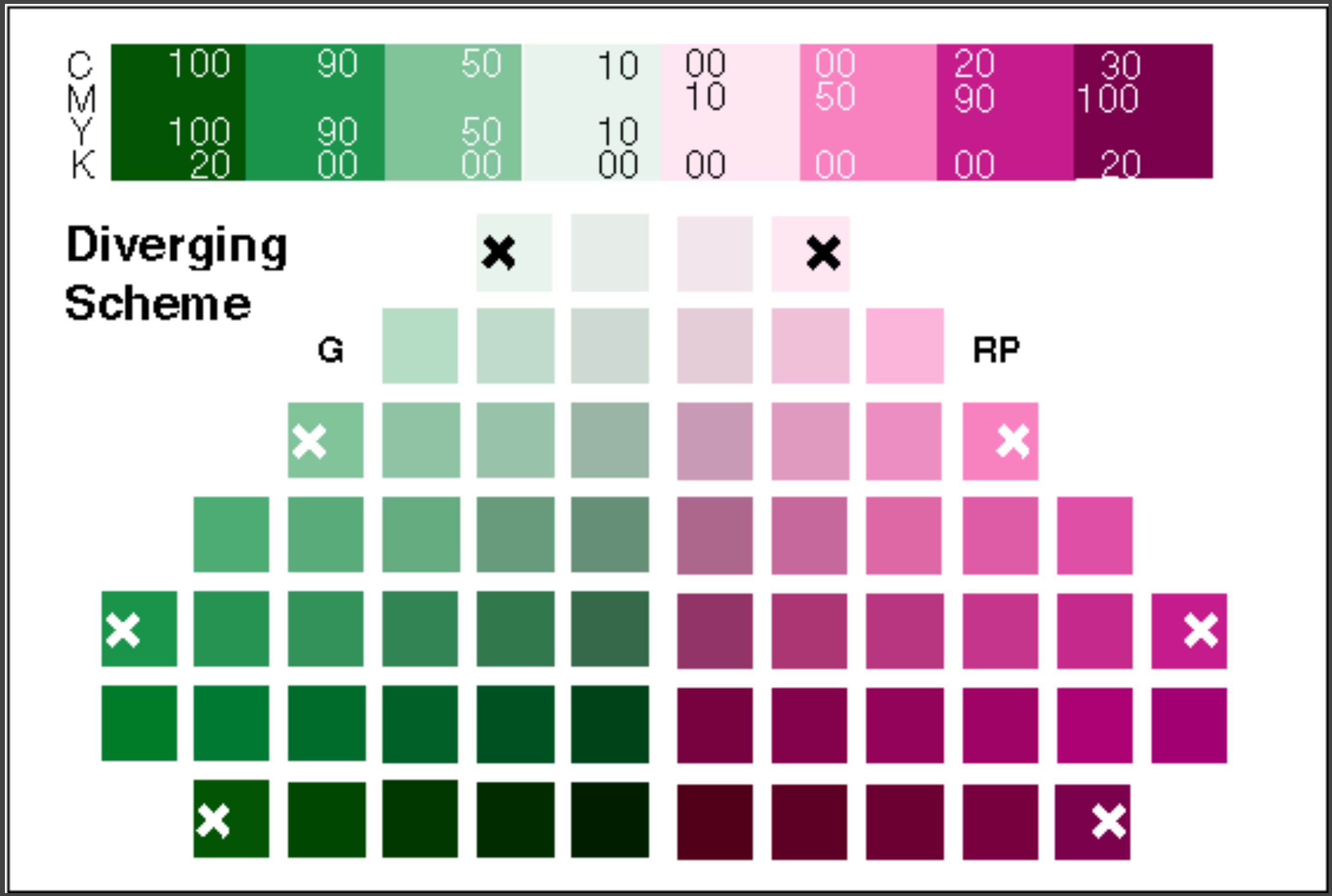
Critical Breakpoint

Defining value e.g., 0

Positive & negative should use different hues

Extremes saturated, middle desaturated

Designing Diverging Scales



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

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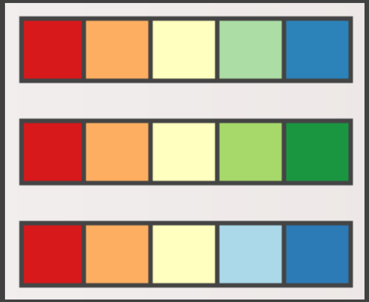

Limit number of steps in color to 3-9

Why?

Quantitative Color Encoding

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

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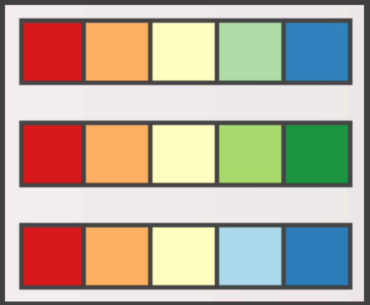

Limit number of steps in color to 3-9

Avoid simultaneous contrast, hold mappings in memory

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 people with **color vision deficiency**

Take advantage of **perceptual color spaces**

Color is cultural and a matter of taste!