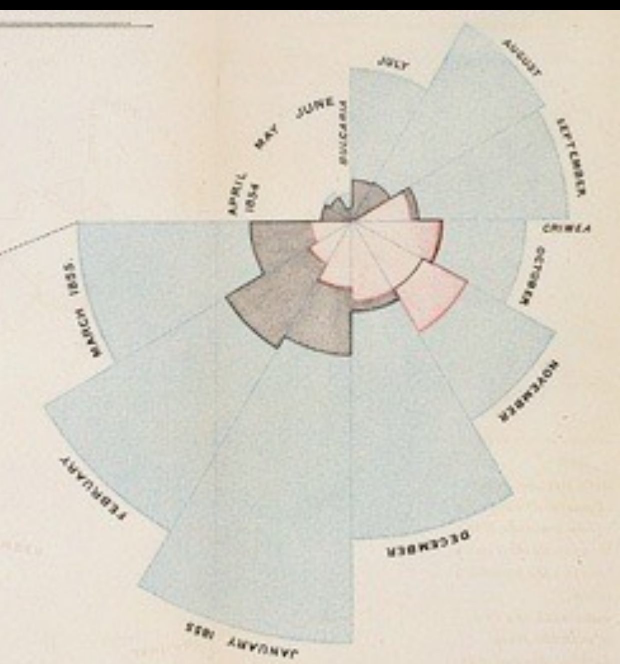
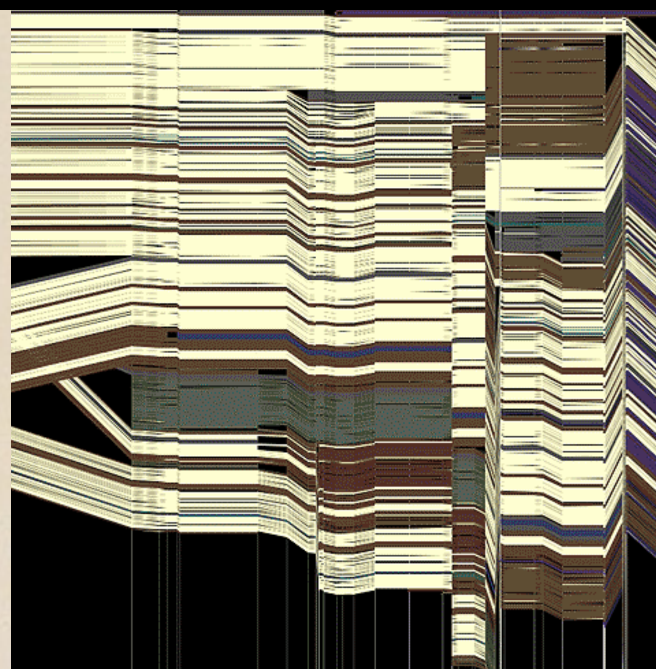
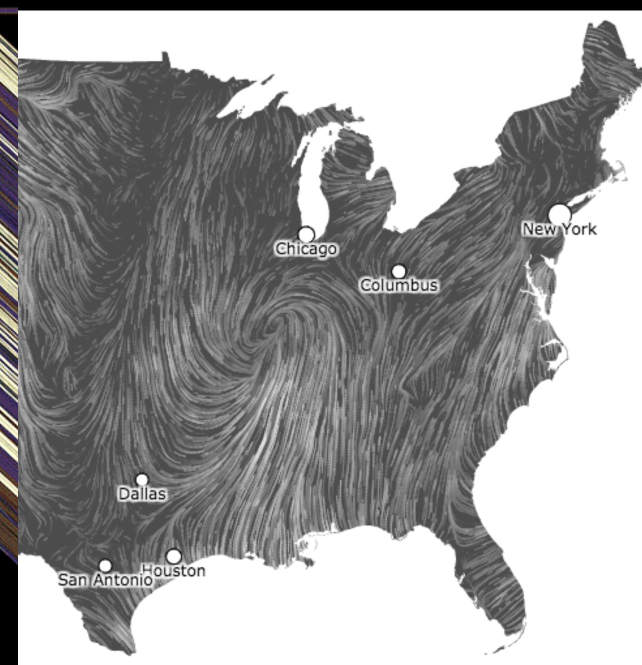
CSE 442 - Data Visualization

Color



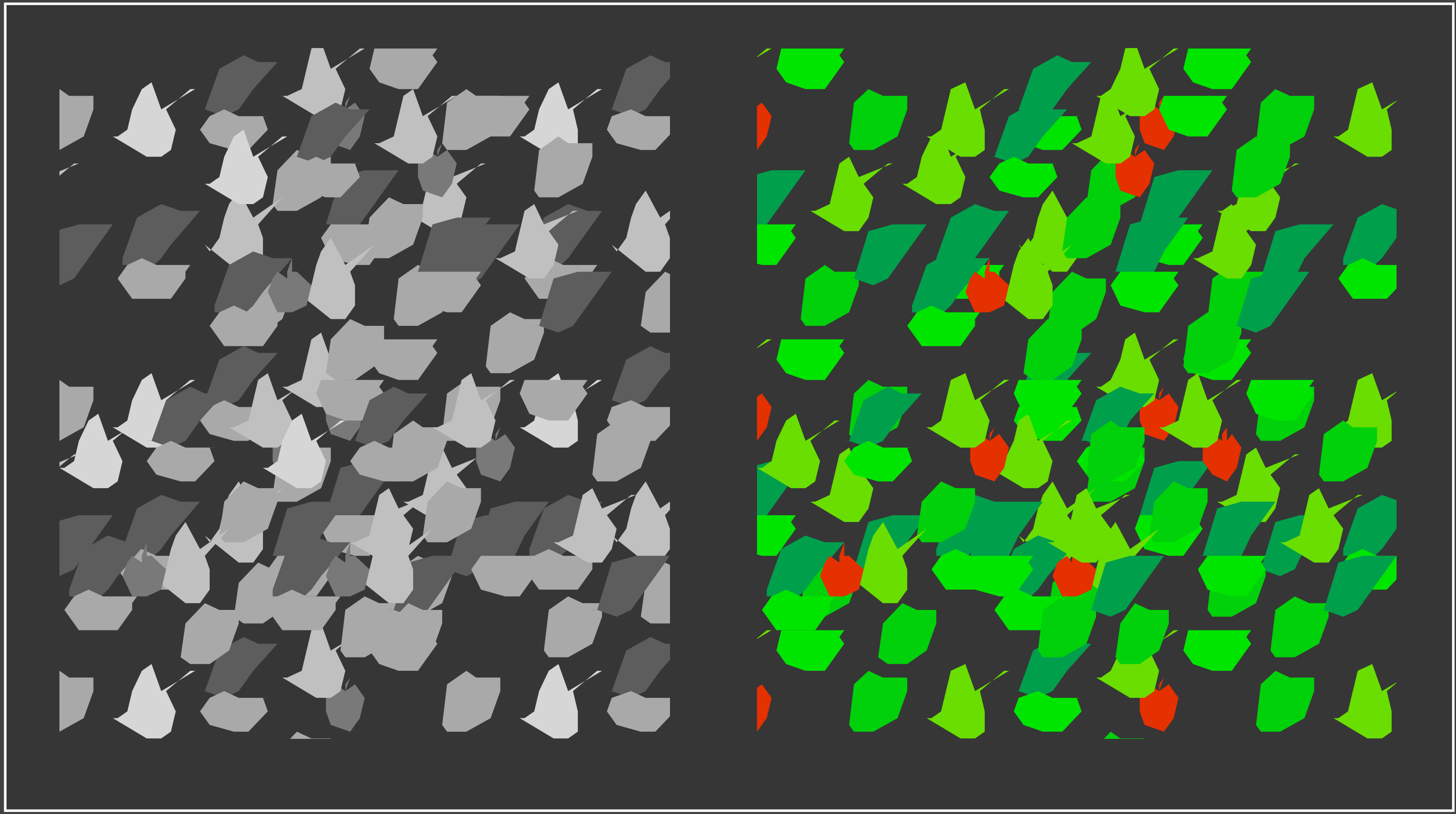




Jeffrey Heer University of Washington

Color in Visualization

Identify, Group, Layer, Highlight



Colin Ware

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

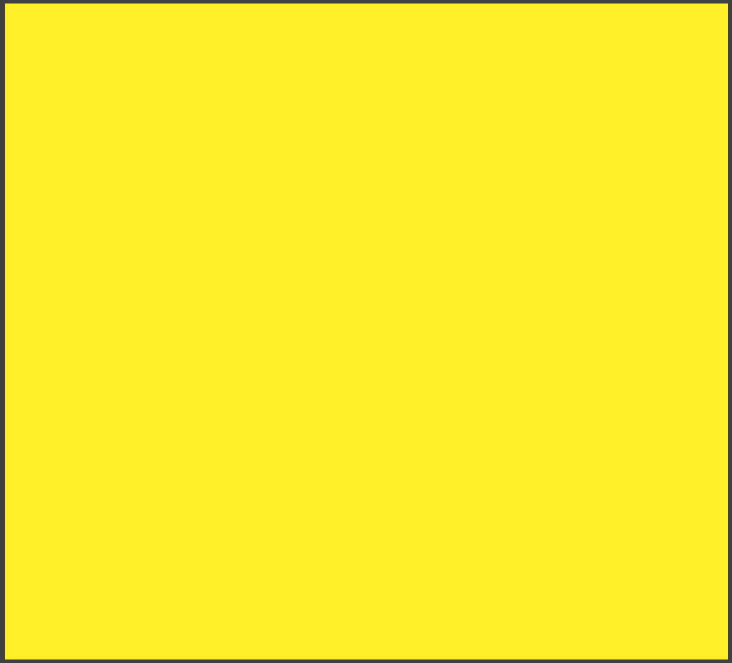
Categorical & Quantitative encoding

Guidelines for color palette design

Perception of Color

What color is this?

What color is this?



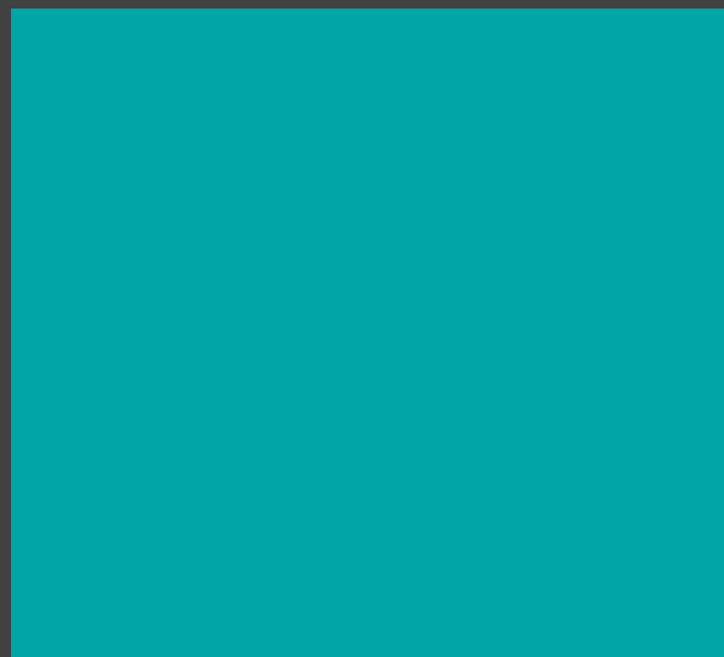
"Yellow"

What color is this?

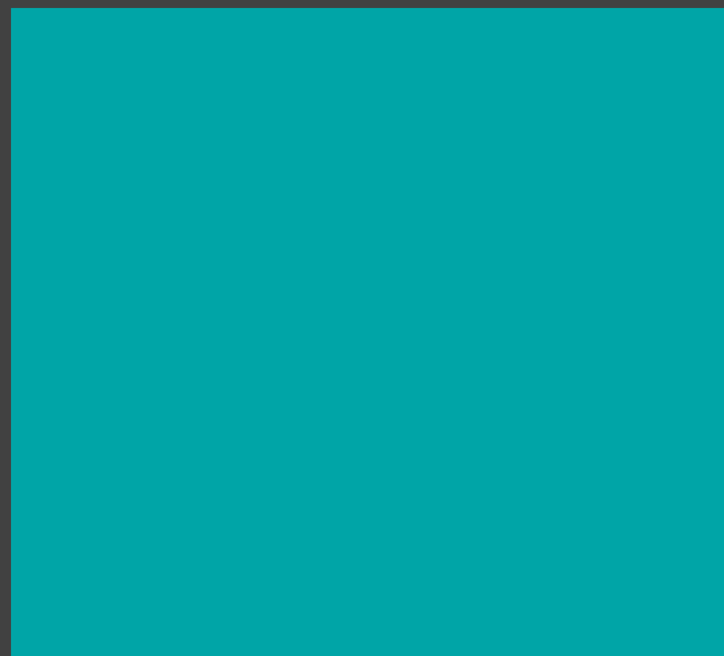
What color is this?

"Blue"

What color is this?

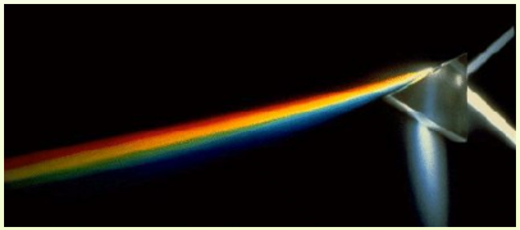


What color is this?

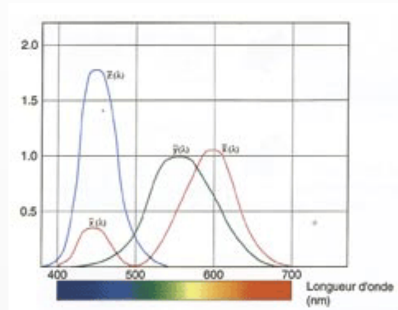


"Teal" ?

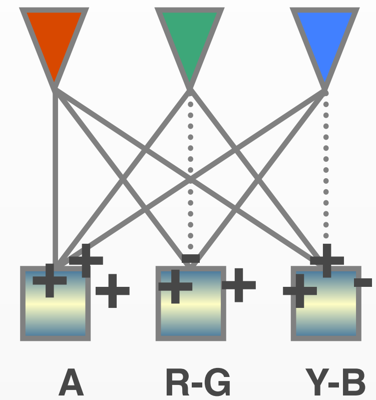
Perception of Color



Light



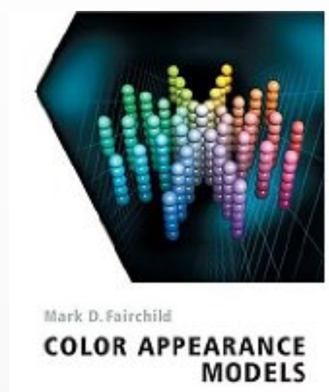
Cone Response



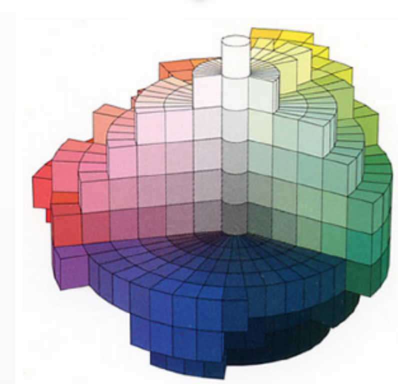
Opponent Signals

“Yellow”

Color Cognition



Color Appearance



Color Perception

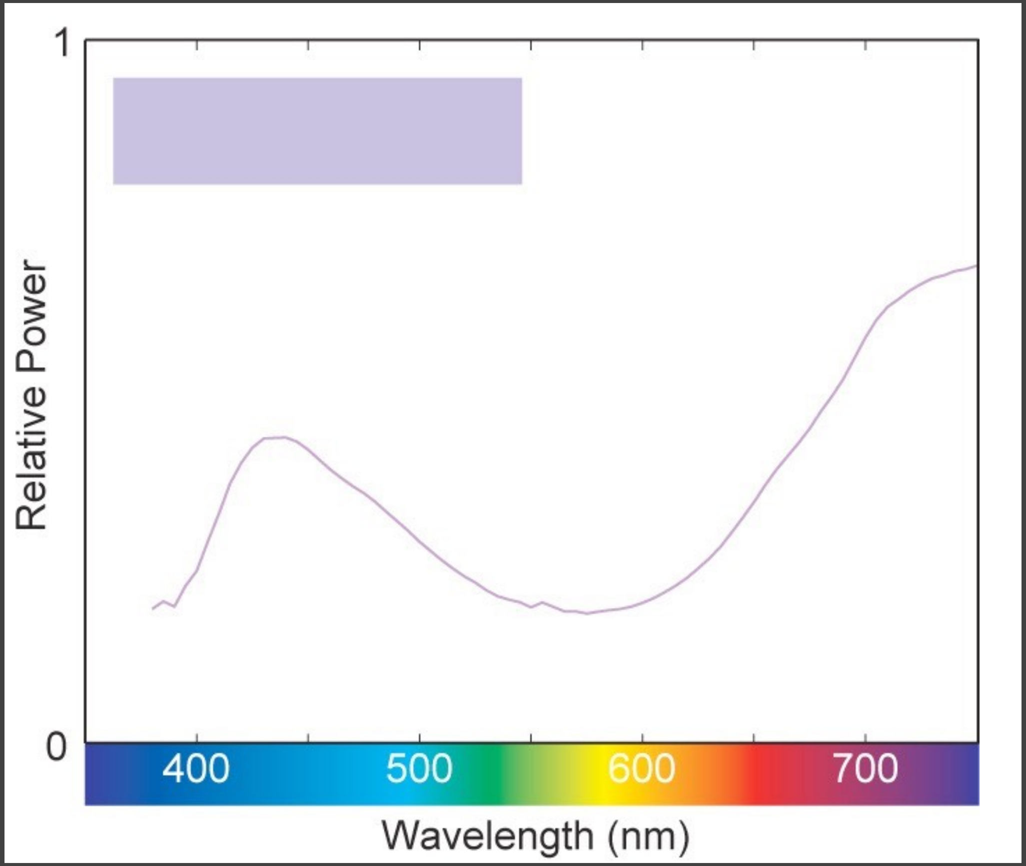
Physicist's View

Light as electromagnetic waves

Wavelength

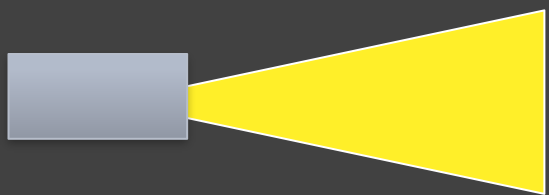
Visible spectrum is 370-730 nm

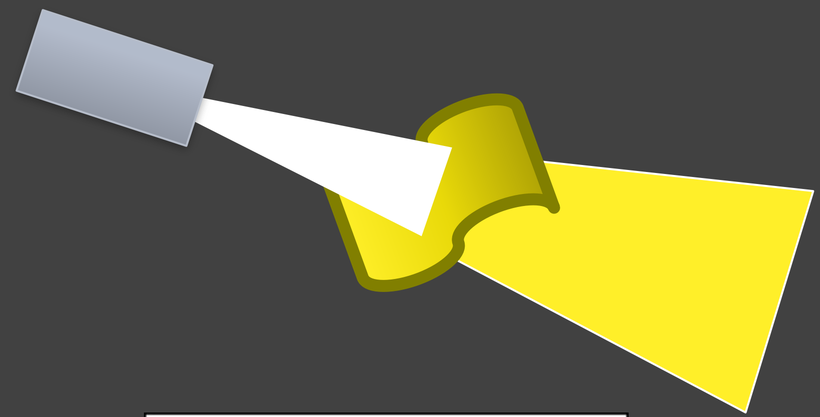
Power or "Relative luminance"



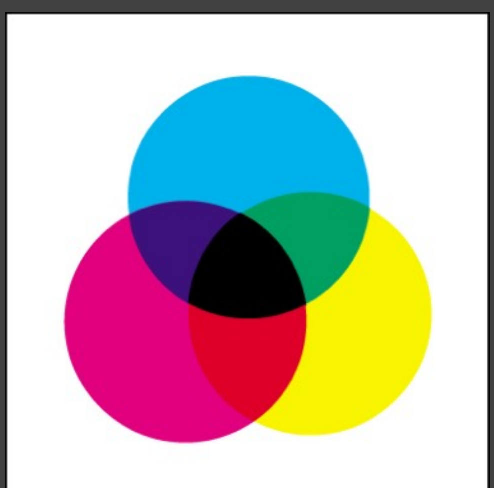
A Field Guide to Digital Color, M. Stone

Emissive vs. Reflective Light



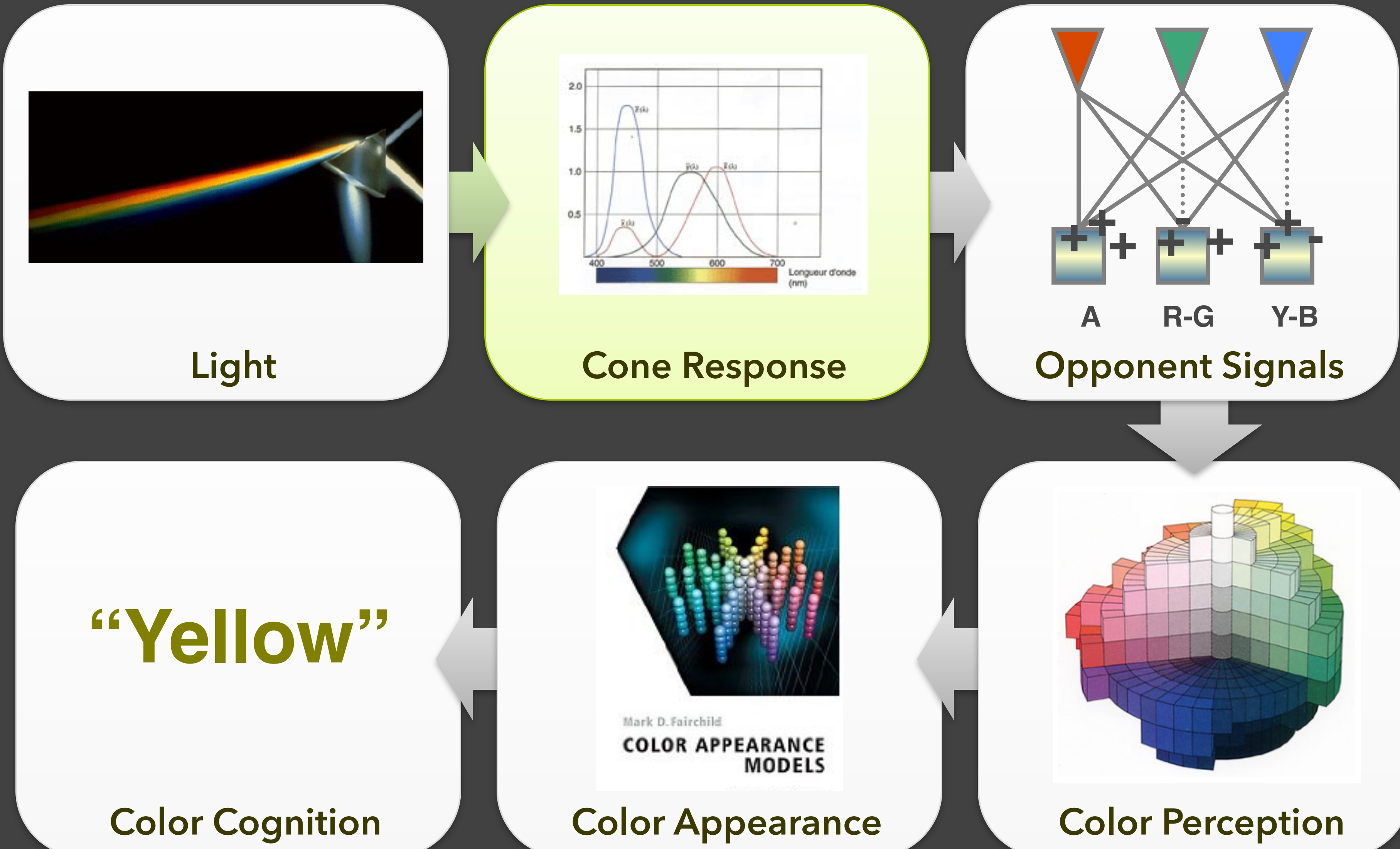


Additive
(digital displays)

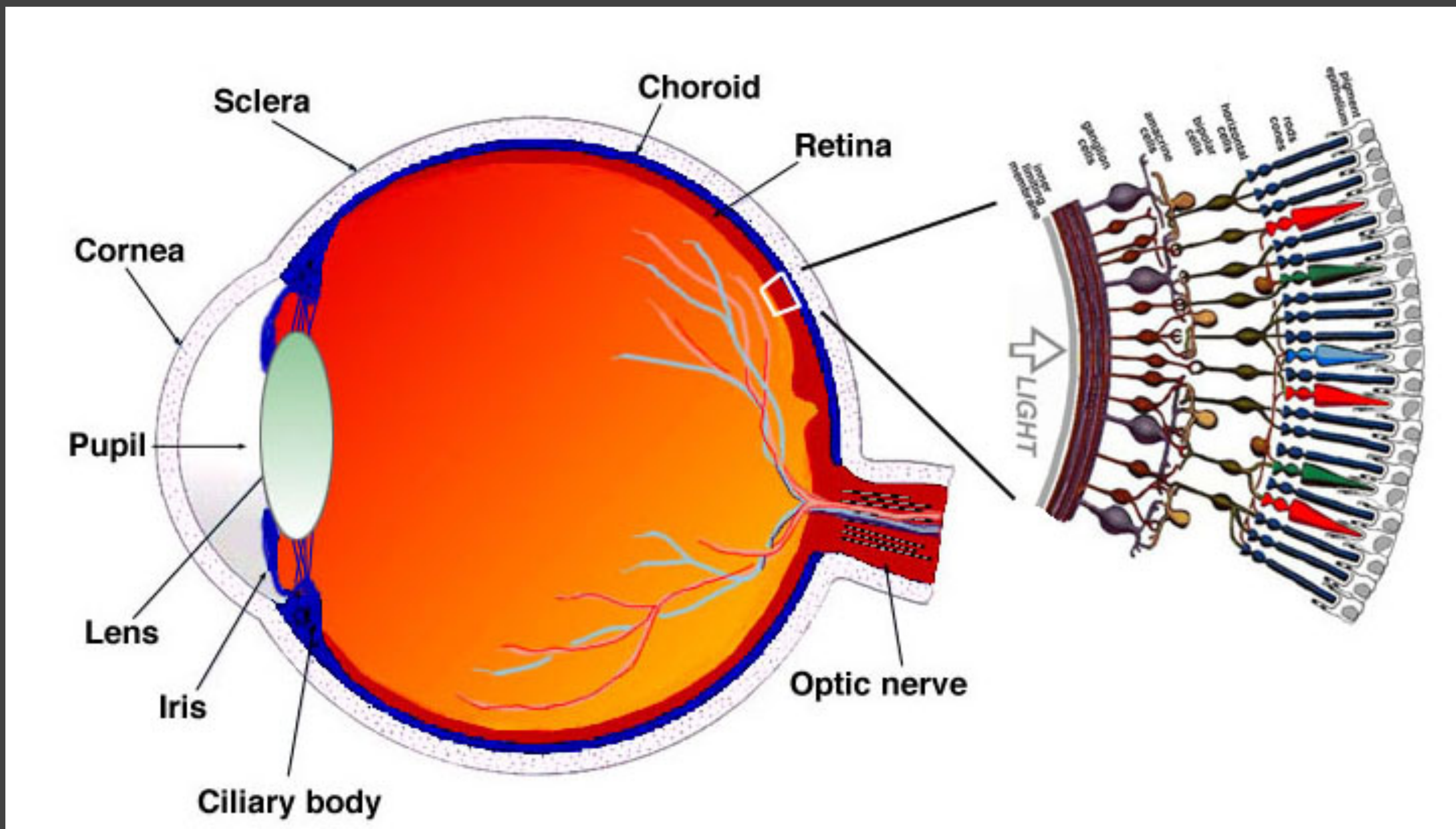


Subtractive
(print, e-paper)

Perception of Color



Retina

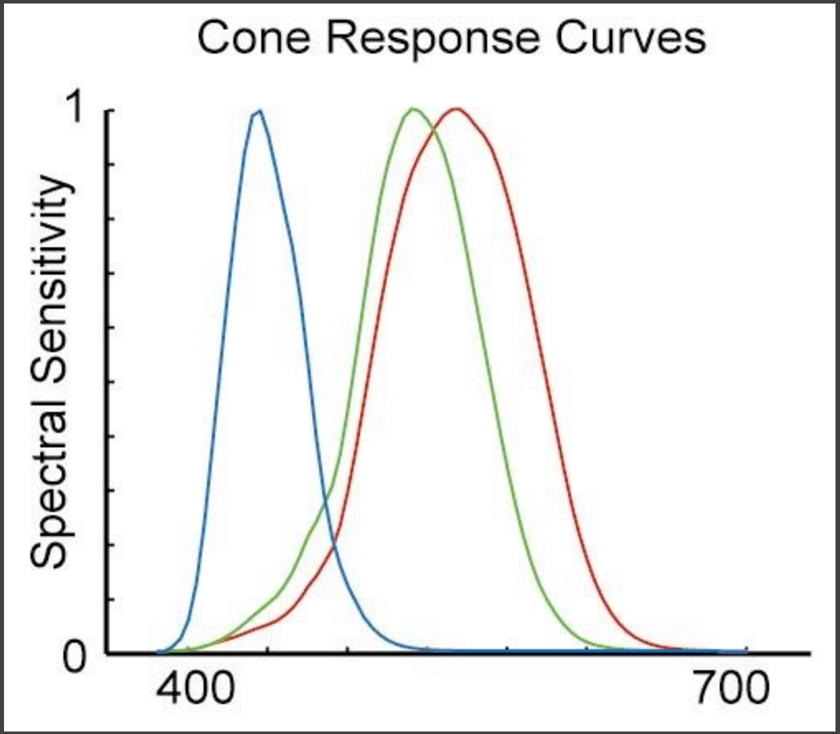


Simple Anatomy of the Retina, Helga Kolb

As light enters our retina…

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength



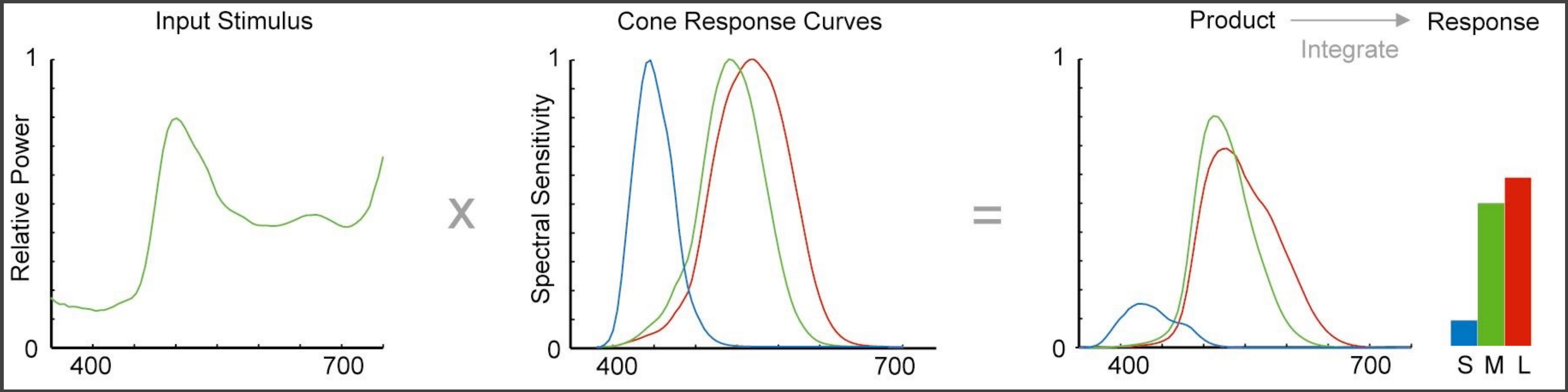
A Field Guide to Digital Color, M. Stone

As light enters our retina…

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength

Integration with input stimulus



A Field Guide to Digital Color, M. Stone

Effects of Retina Encoding

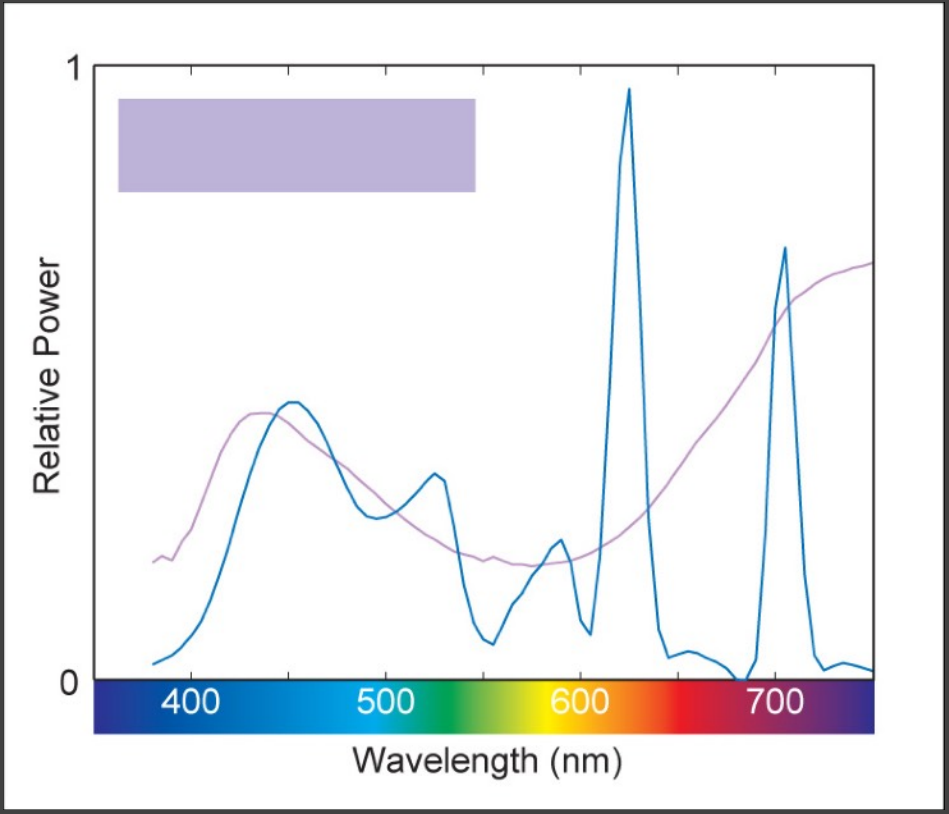
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

"Tri-stimulus"

Computer displays

Digital scanners

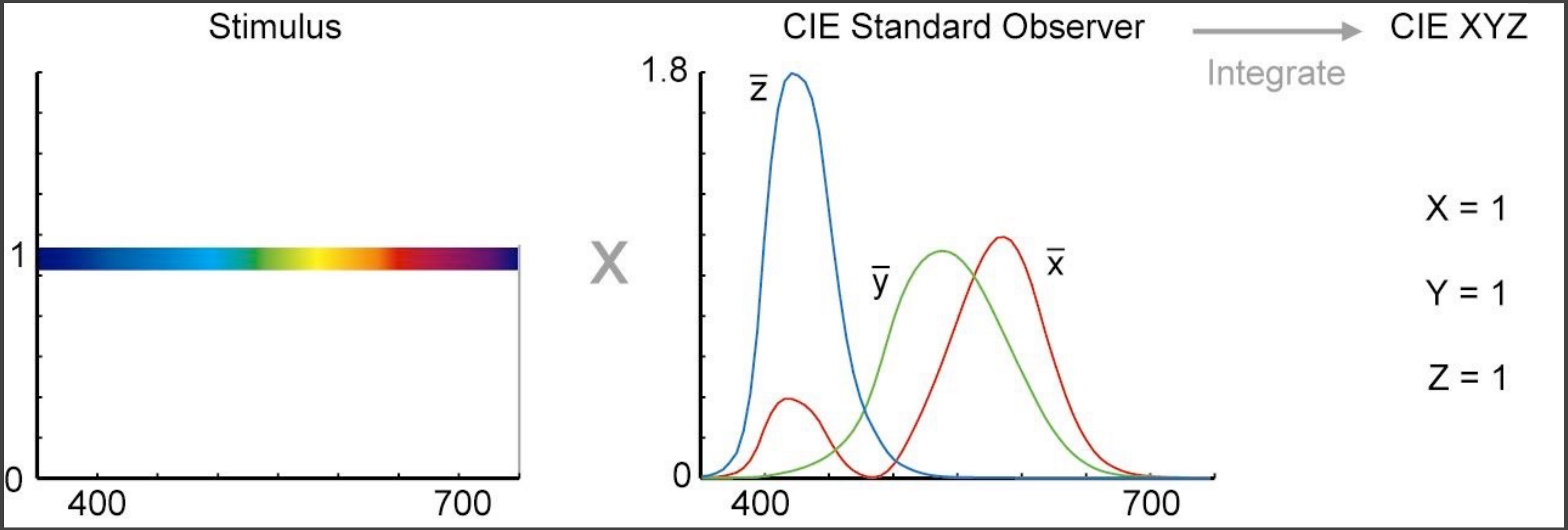
Digital cameras



CIE XYZ Color Space

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

"Standard observer" response curves

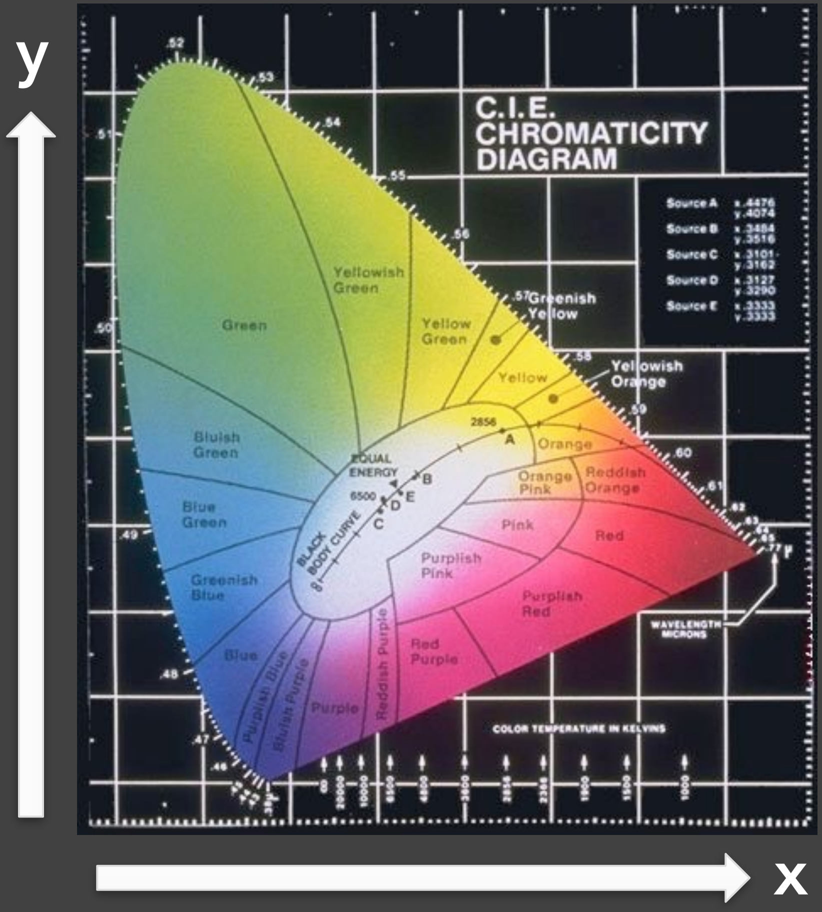


CIE Chromaticity Diagram

Colorfulness vs. Brightness

x = X / (X+Y+Z)

y = Y / (X+Y+Z)

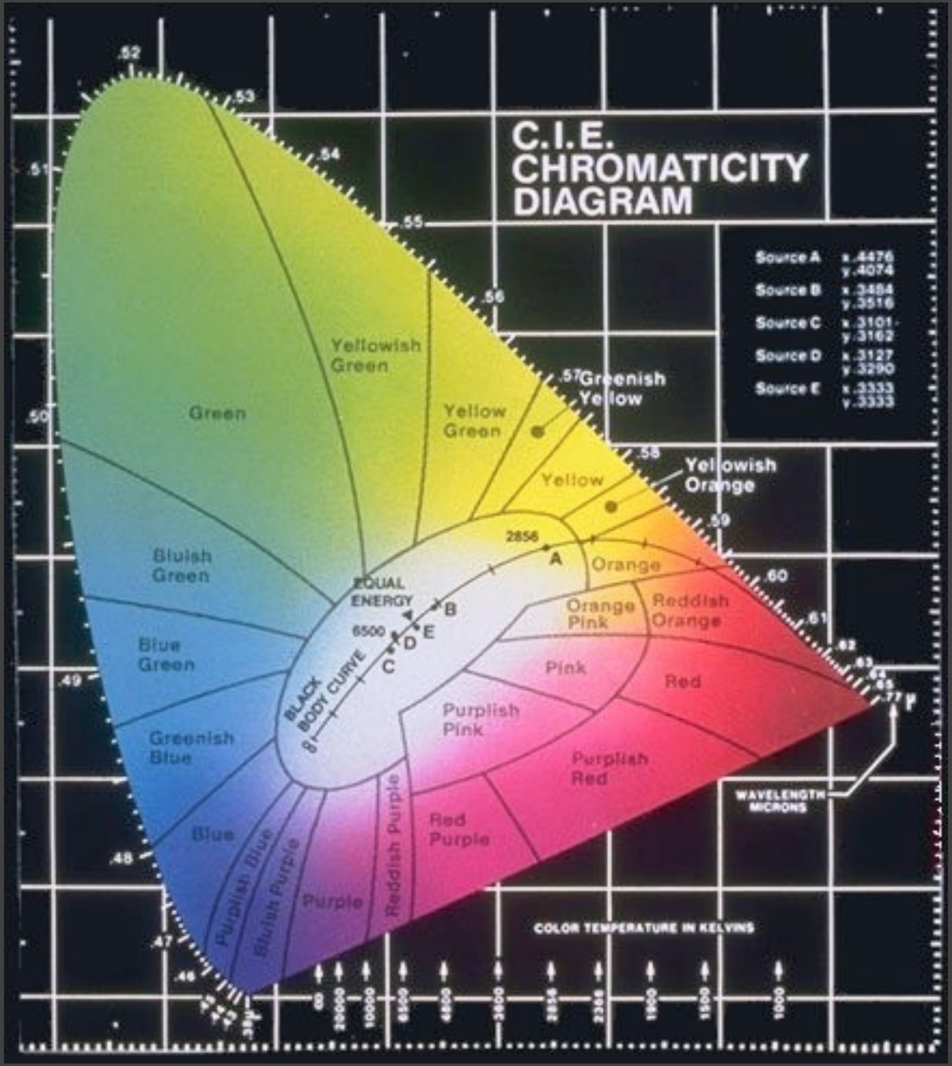


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.



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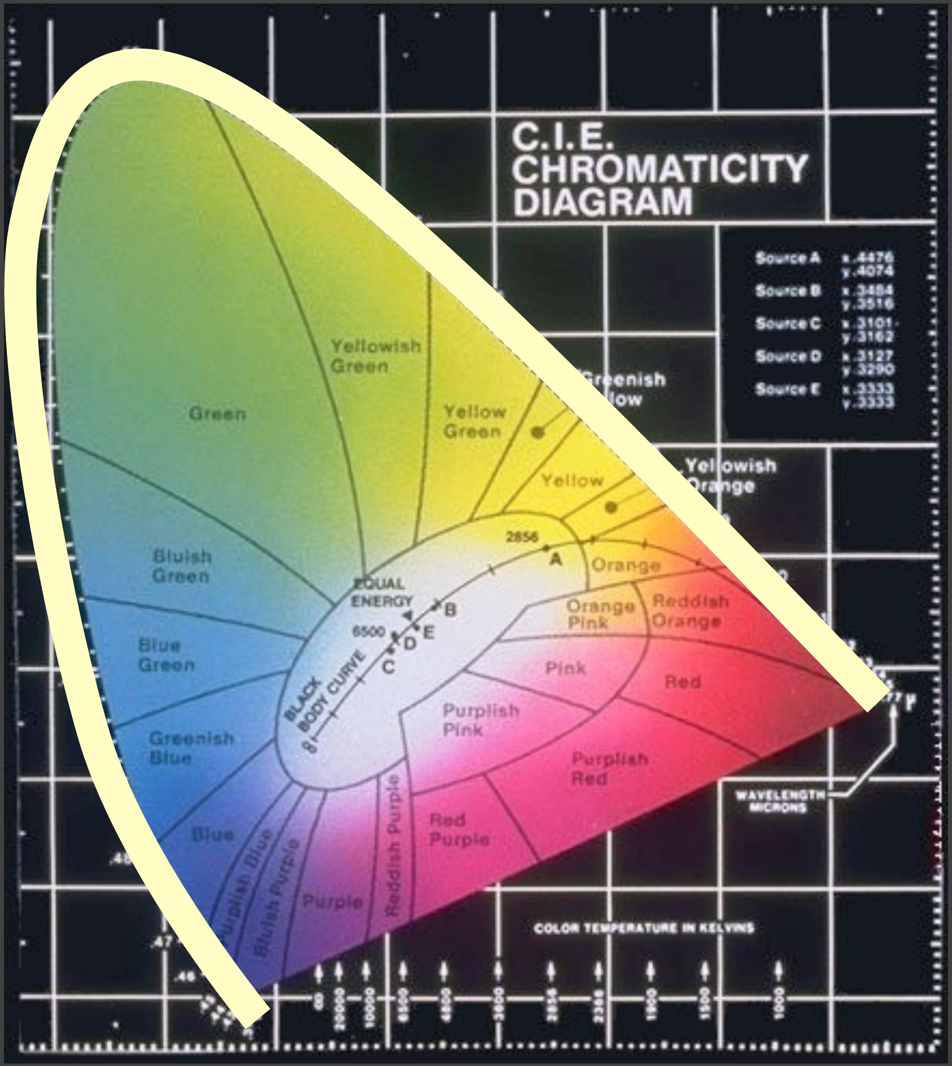

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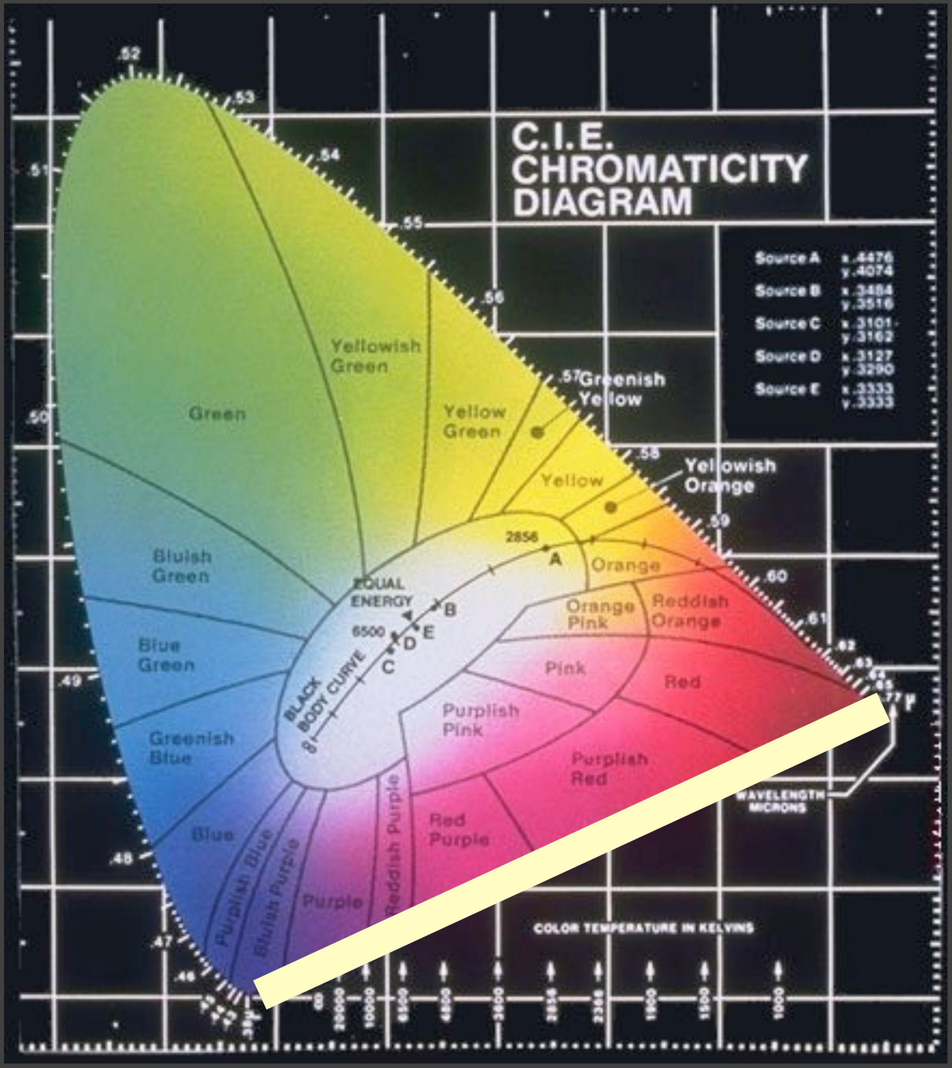

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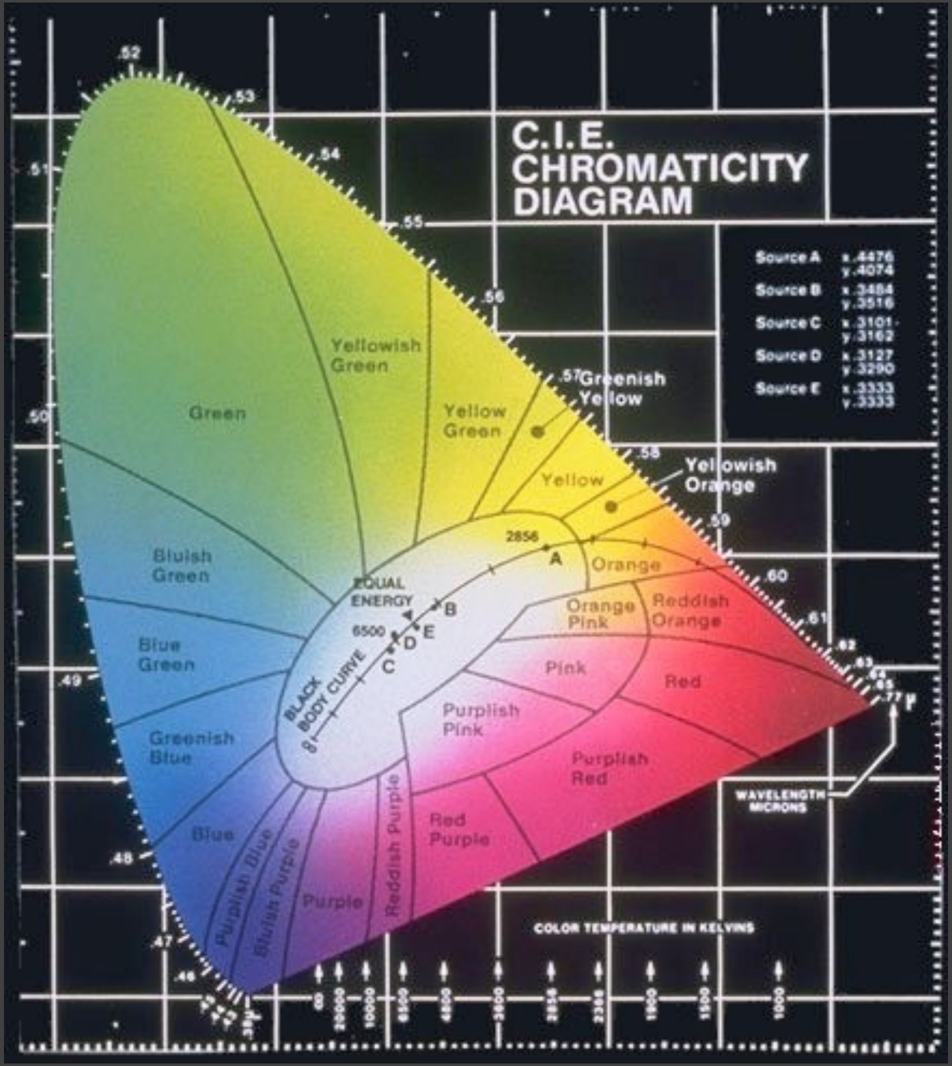
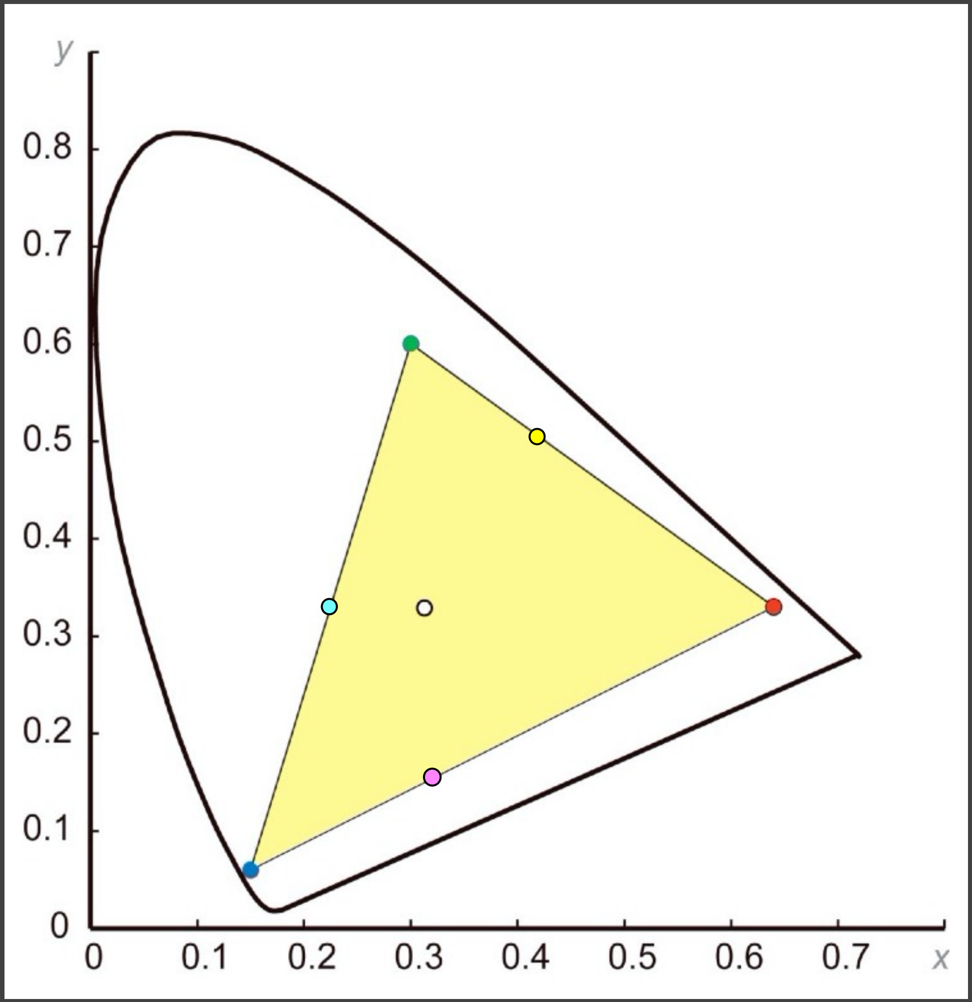


Display Gamuts

Typically defined by:

3 Colorants

Convex region

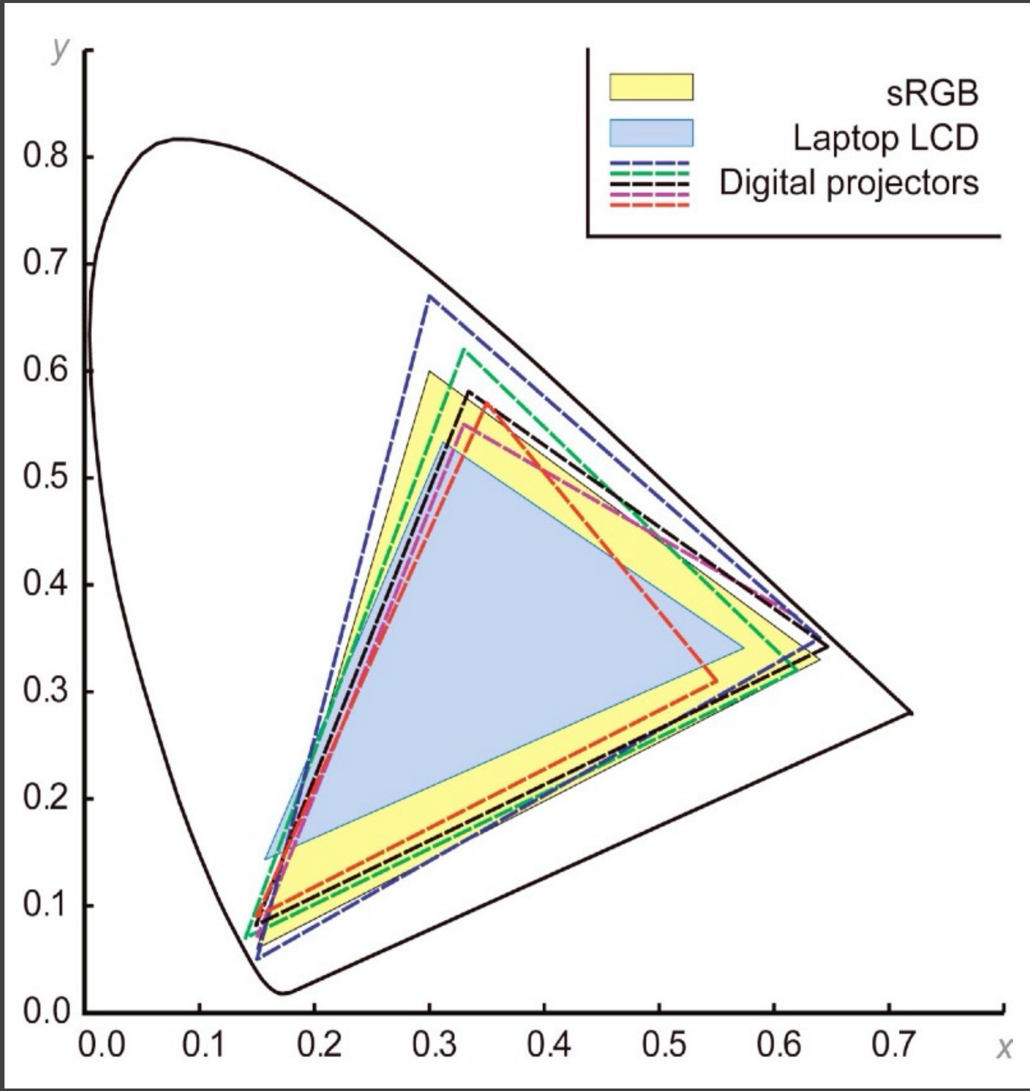


Display Gamuts

Deviations from sRGB specification

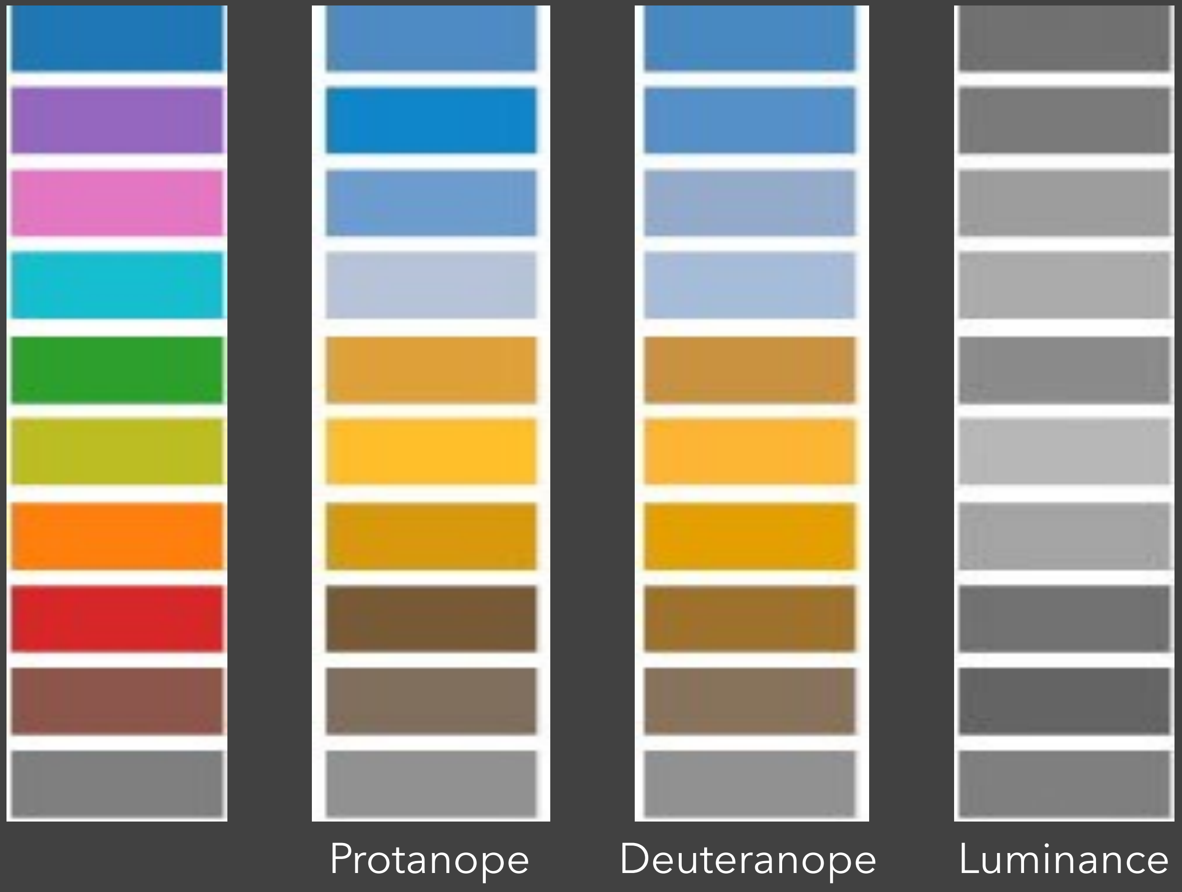
Example:
(R, G, B) coordinates ranging from 0-255.

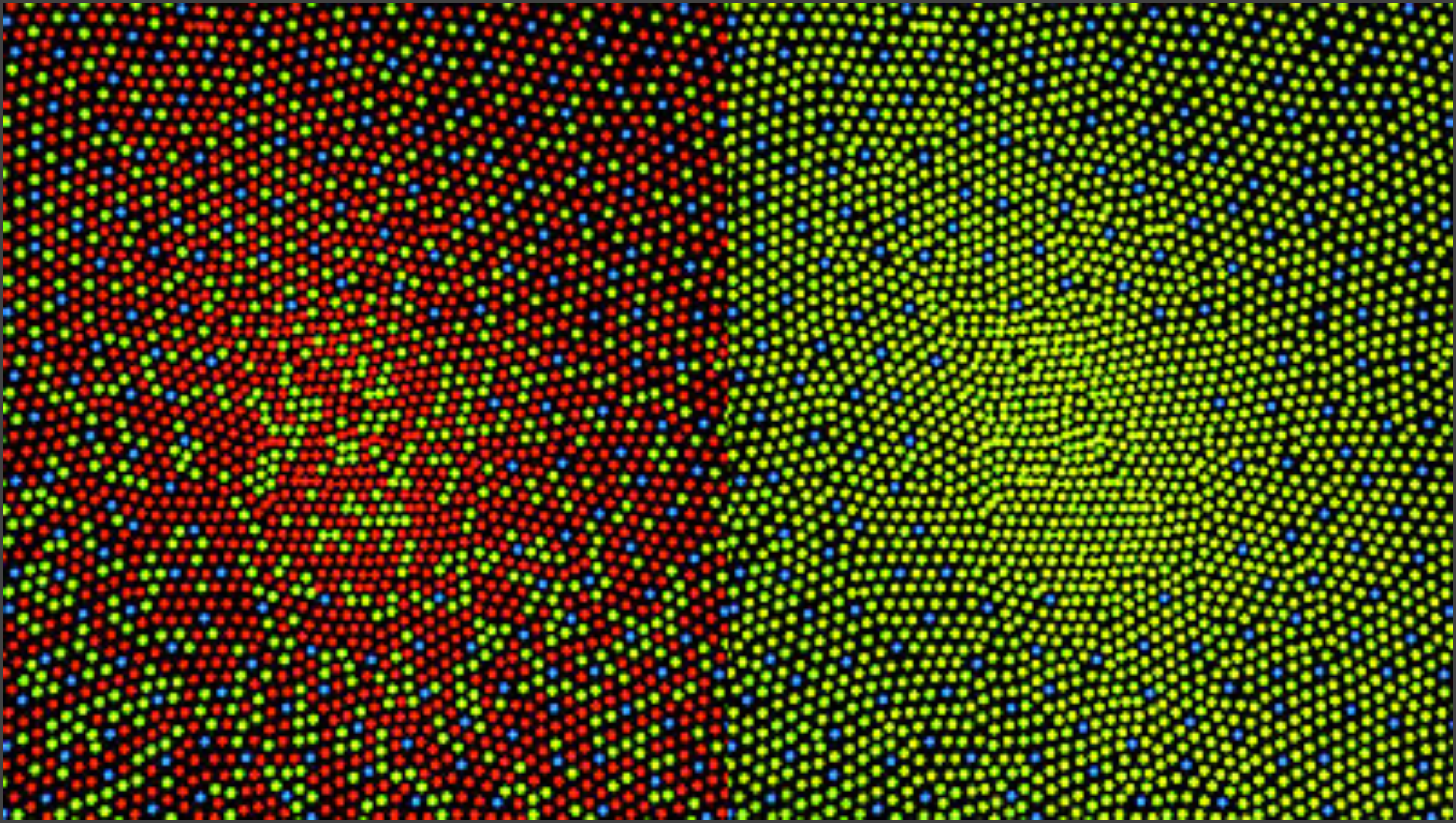
Displays may produce different colors for a coord!



Color Vision Deficiency (CVD)

Missing one or more cones or rods in retina.





Normal Retina

Protanopia

Color Vision Simulators

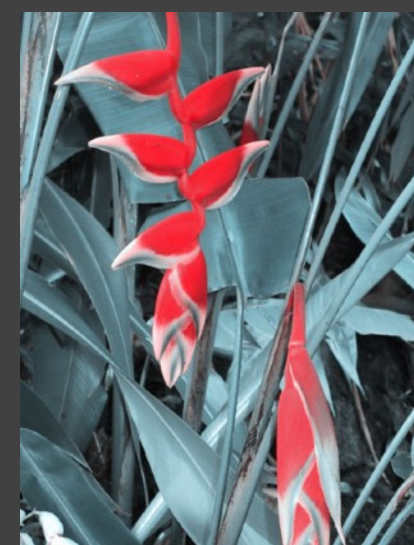
Simulate color vision deficiencies

Browser plug-ins

Photoshop plug-ins, etc.

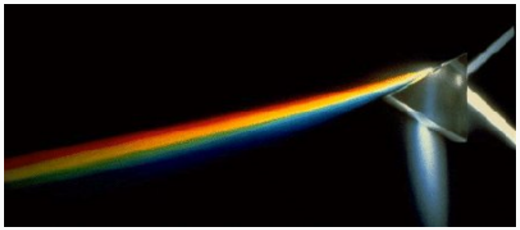
Deuteranope

Protanope

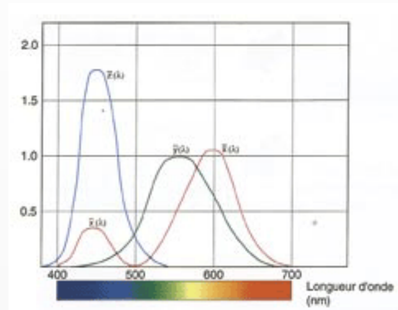


Tritanope

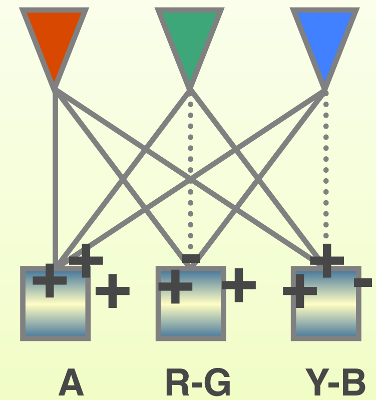
Perception of Color



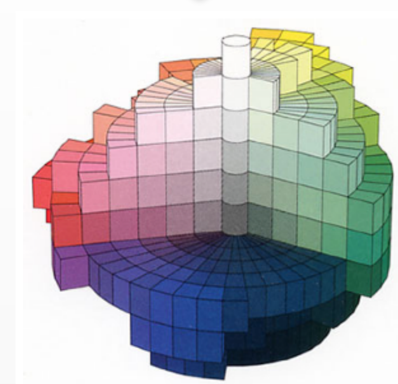
Light



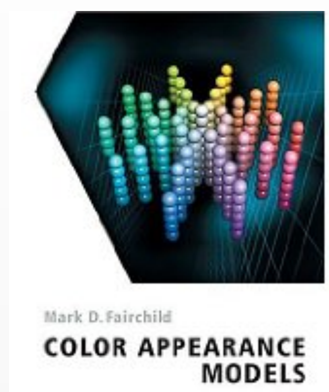
Cone Response



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

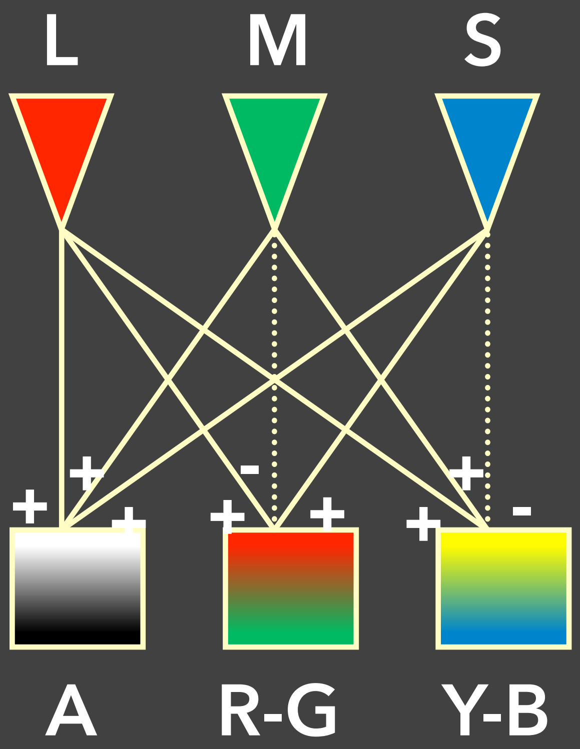
Opponent Processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



[Fairchild]

Opponent Processing

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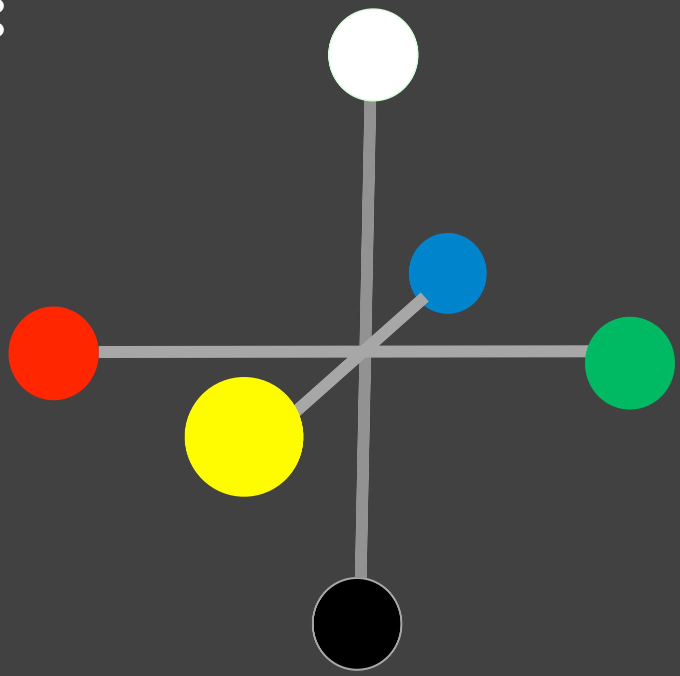


Opponent Processing

LMS are combined to create:

Lightness

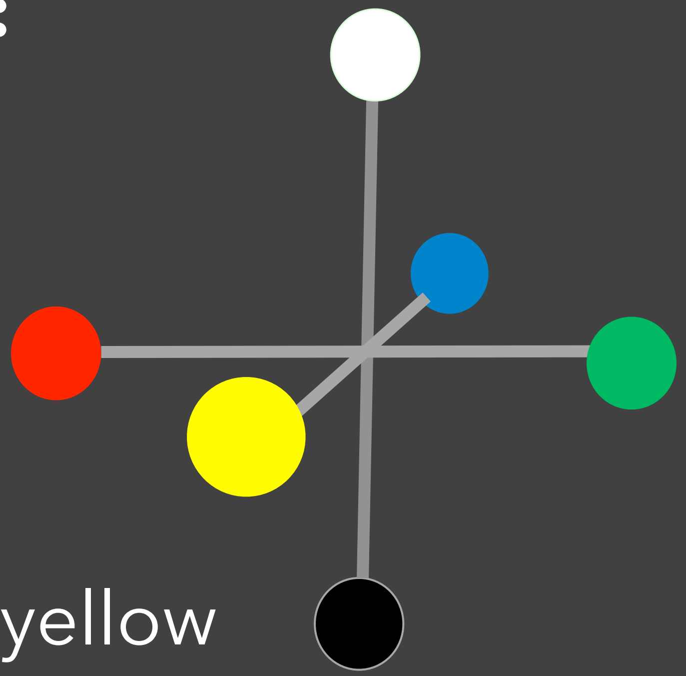
Red-green contrast

Yellow-blue contrast

Experiments:

No reddish-green, no blueish-yellow

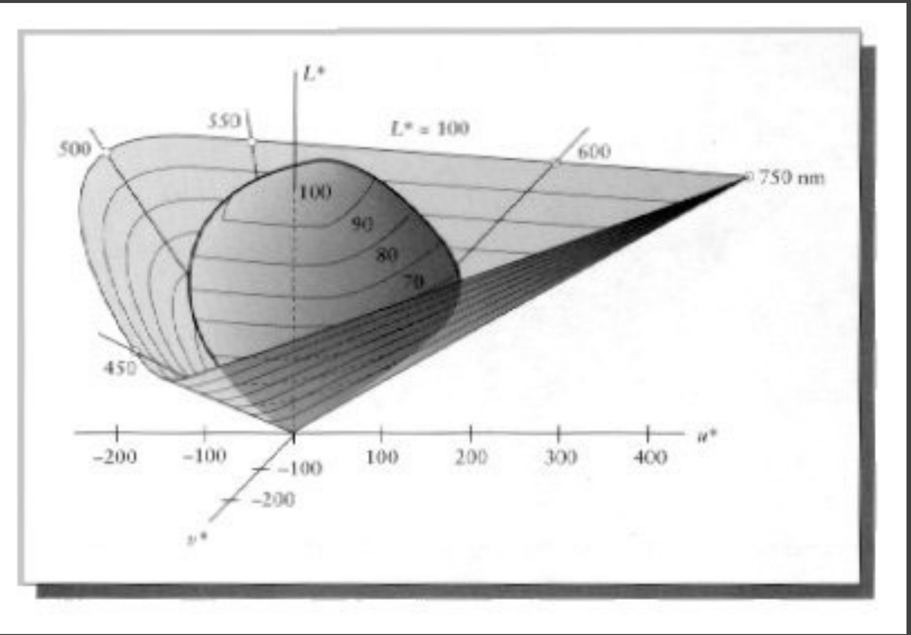
Color after images

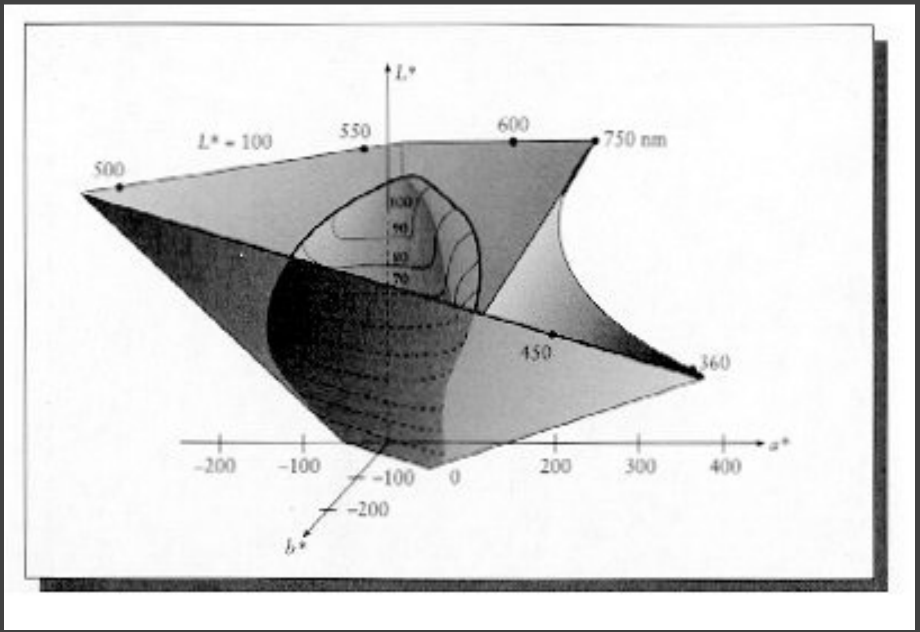


CIE LAB and LUV Color Spaces

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

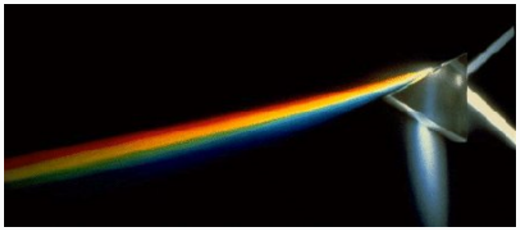
Much more perceptually uniform than sRGB!

Scaling of axes to represent “color distance”

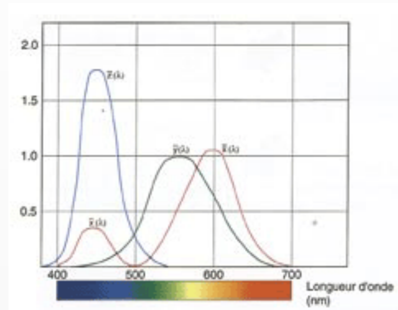
JND = Just noticeable difference (~2.3 units)

D3 + Vega include LAB color space support!

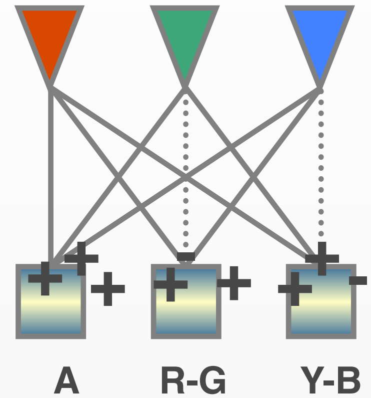
Perception of Color



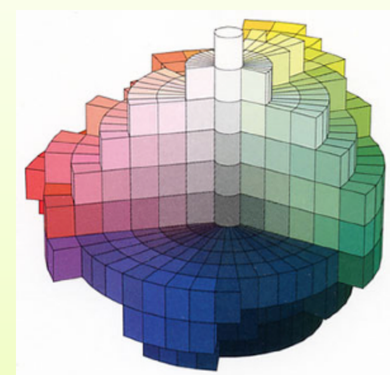
Light



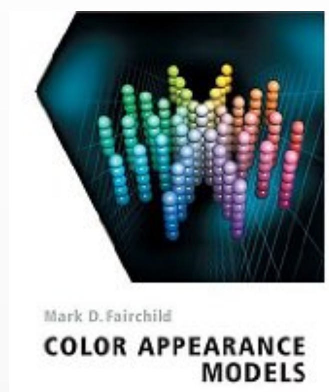
Cone Response



Opponent Signals



Color Perception



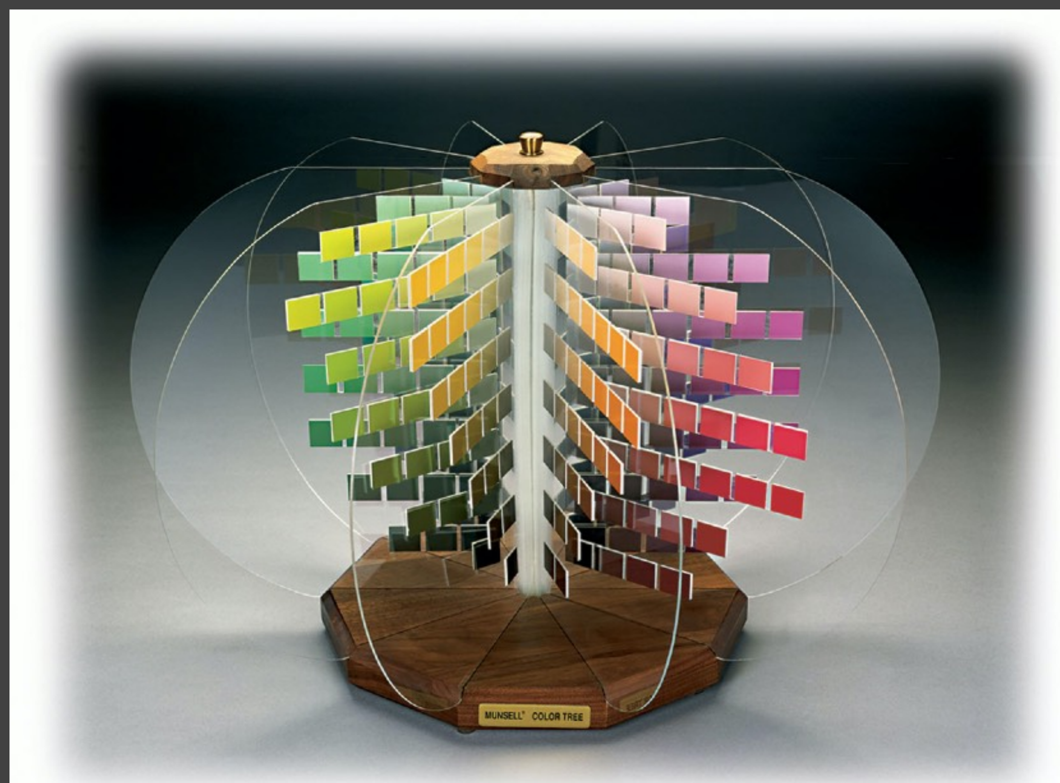
Color Appearance

“Yellow”

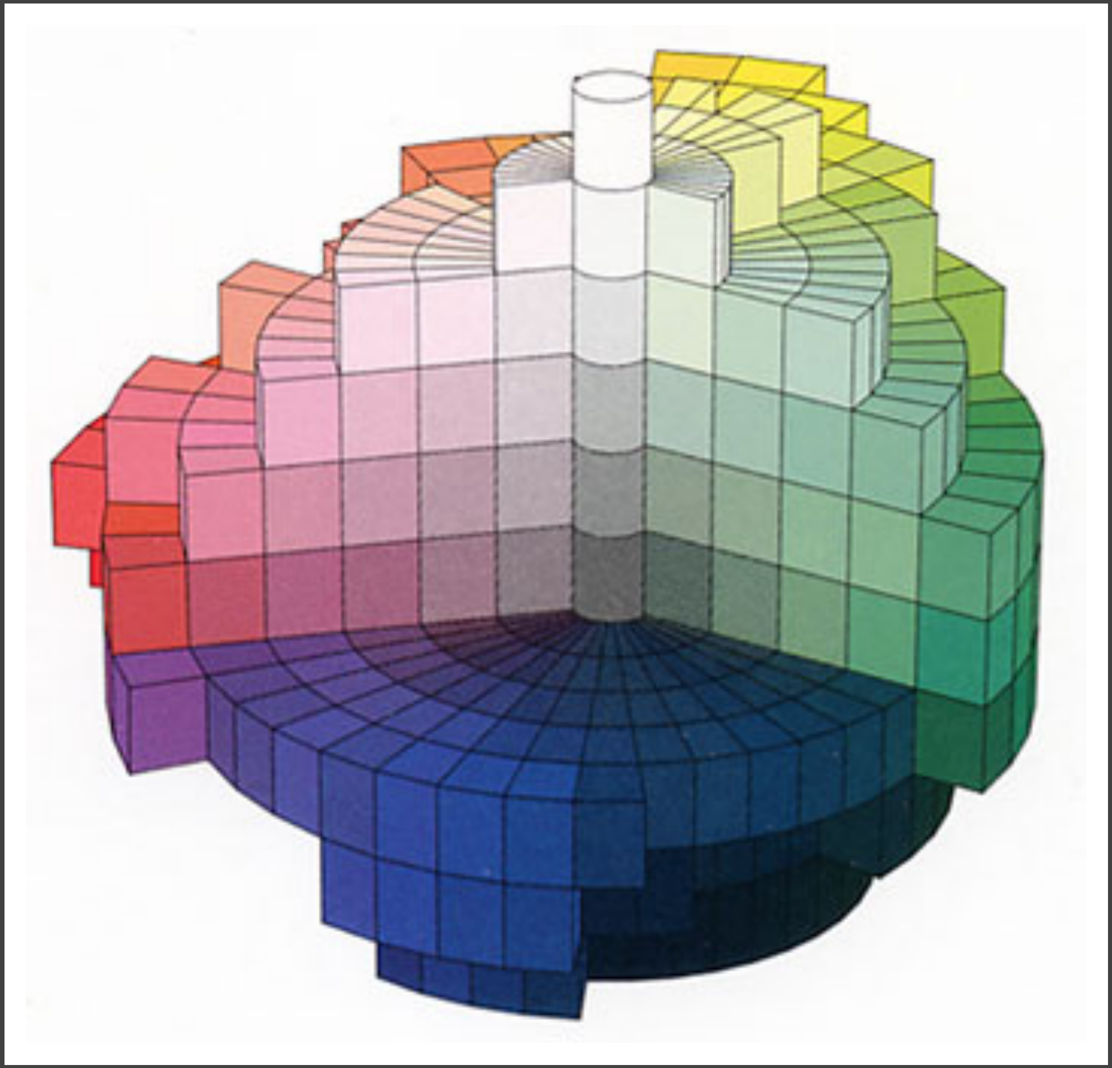
Color Cognition

Albert Munsell

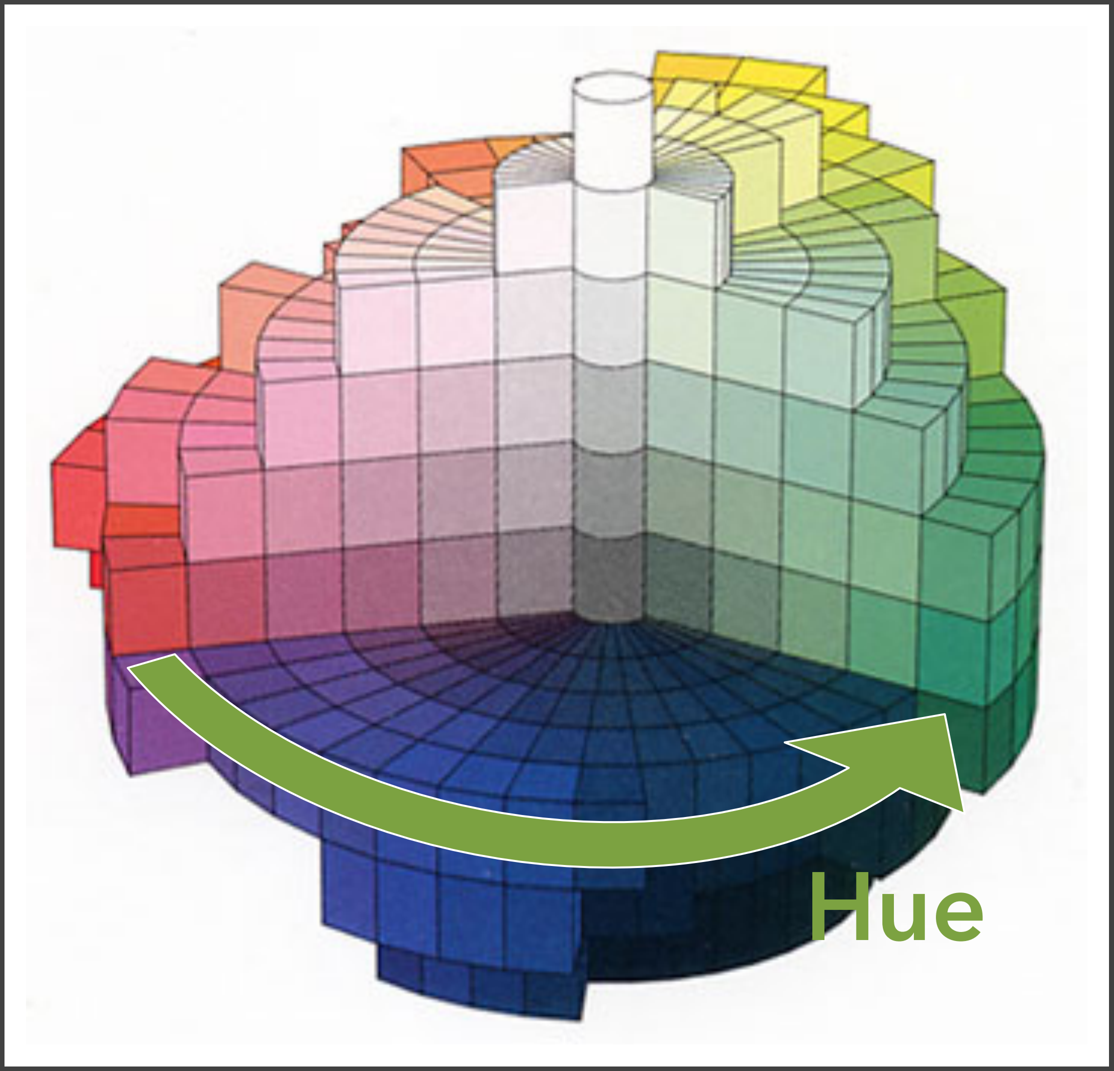
Developed the first perceptual color system based on his experience as an artist (1905).



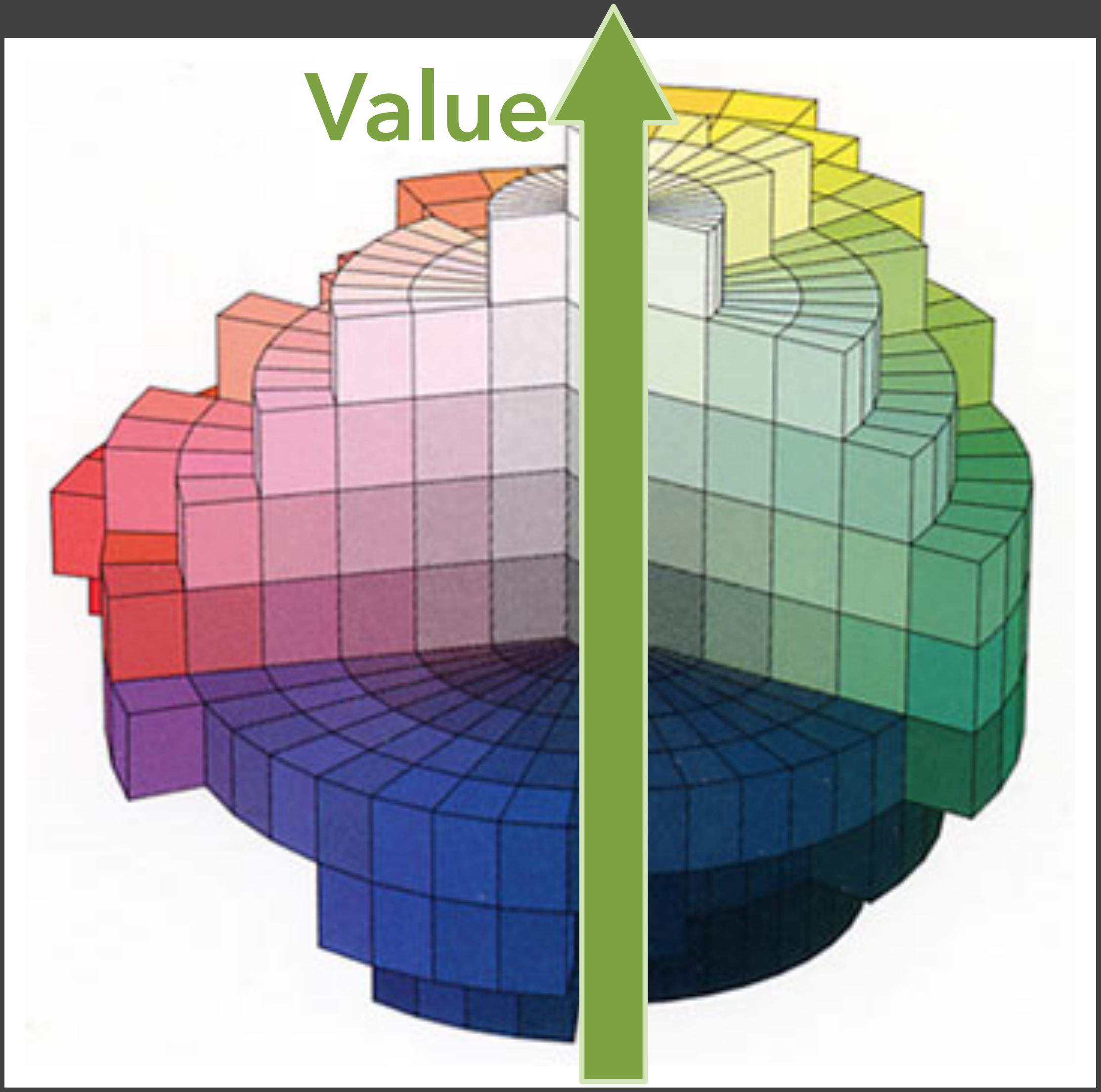
Hue, Value, and Chroma



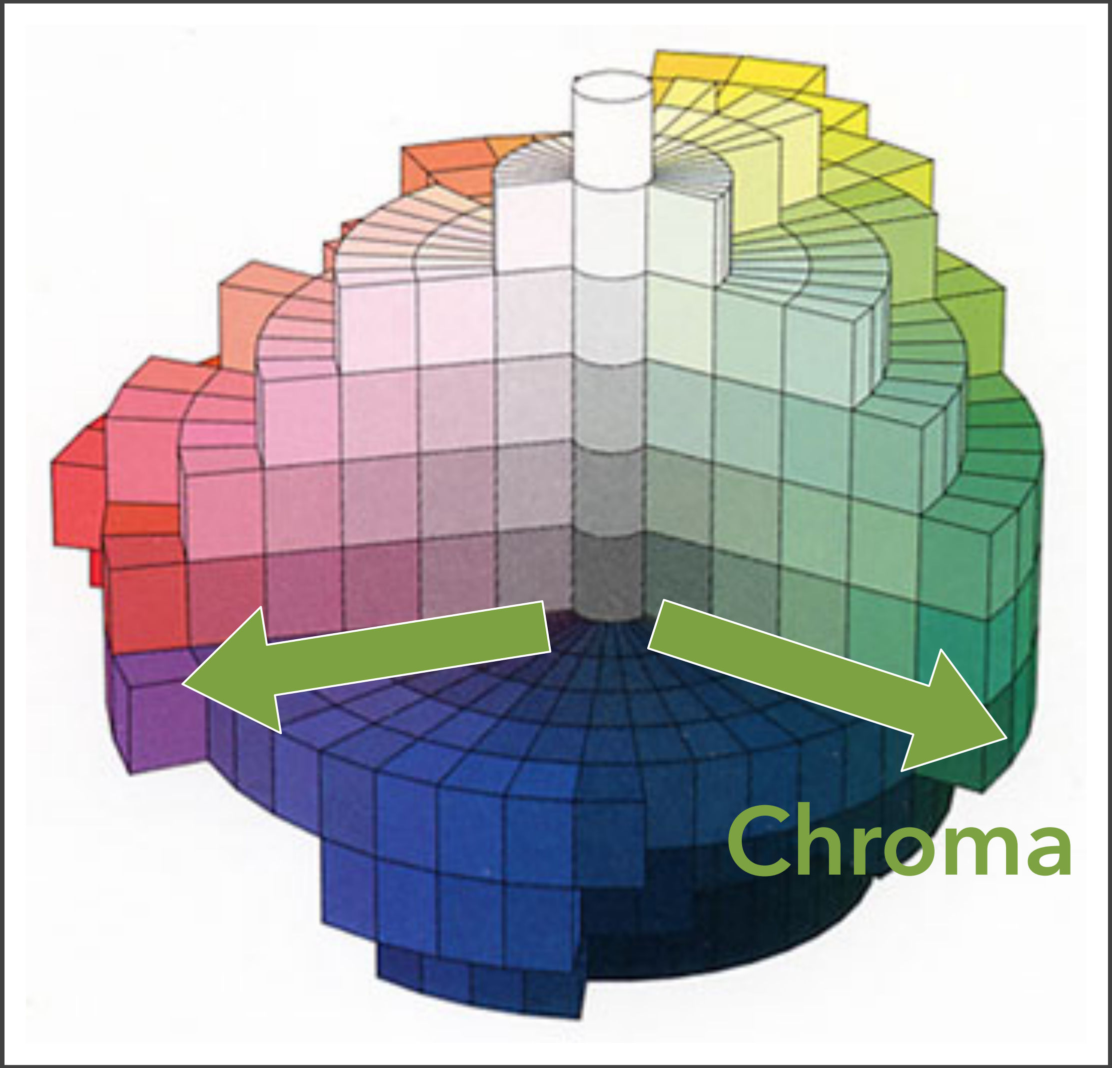
Hue, Value and Chroma



Hue, Value and Chroma



Hue, Value and Chroma



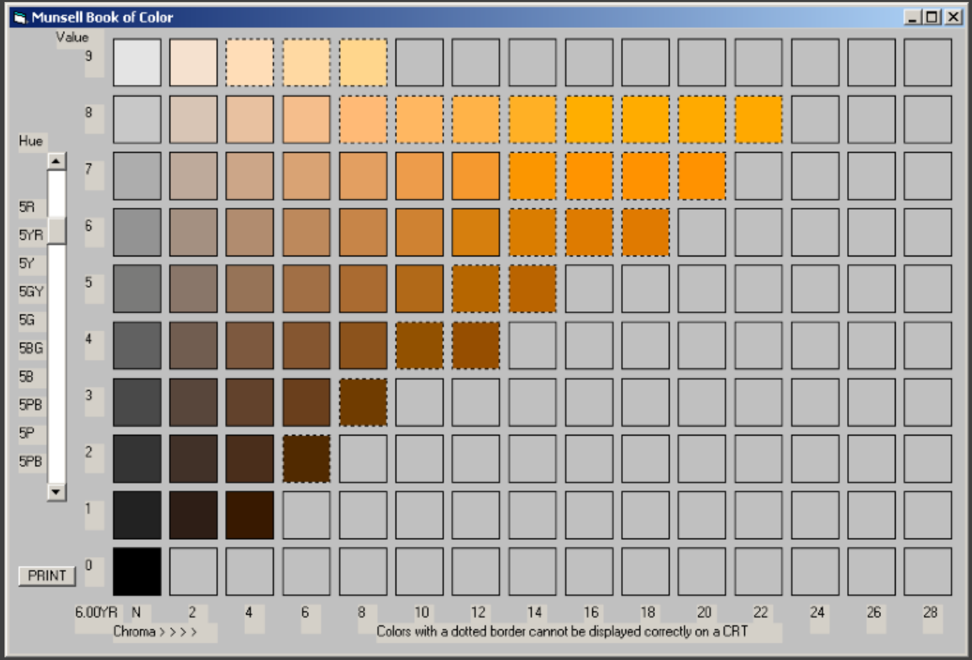
Munsell Color System

Perceptually-based

Precisely reference a color

Intuitive dimensions

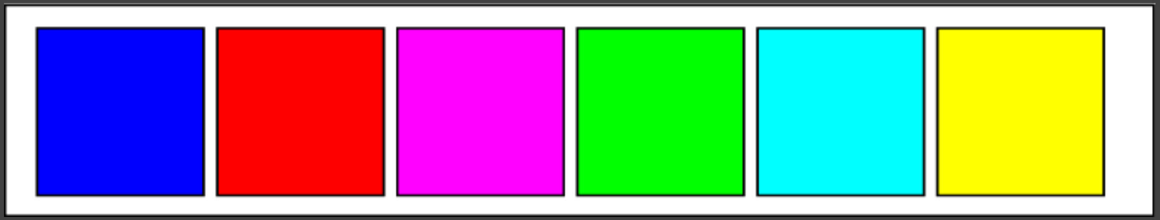
Look-up table (LUT)



Munsell Color System

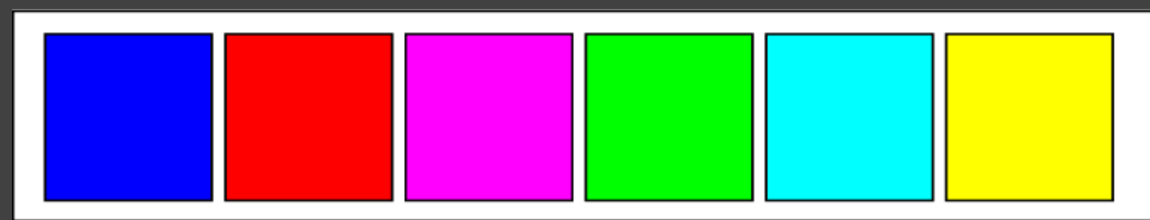
Perceptual Brightness

Color palette



Perceptual Brightness

Color palette



HSL Lightness
(Photoshop)

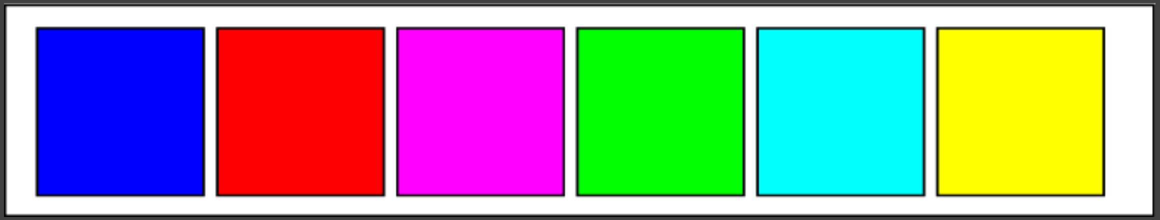
Perceptual Brightness

Color palette

Luminance Y
(CIE XYZ)

Perceptual Brightness

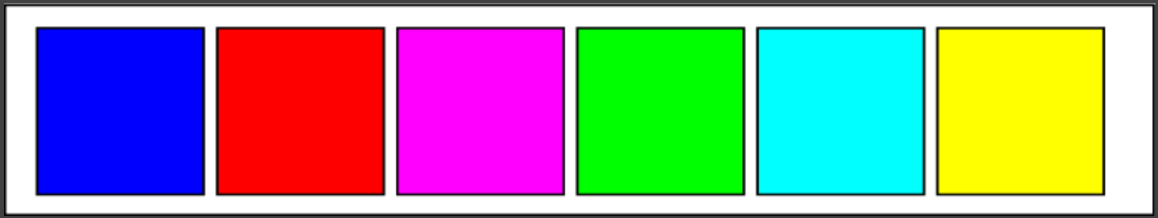
Color palette



Munsell Value

Perceptual Brightness

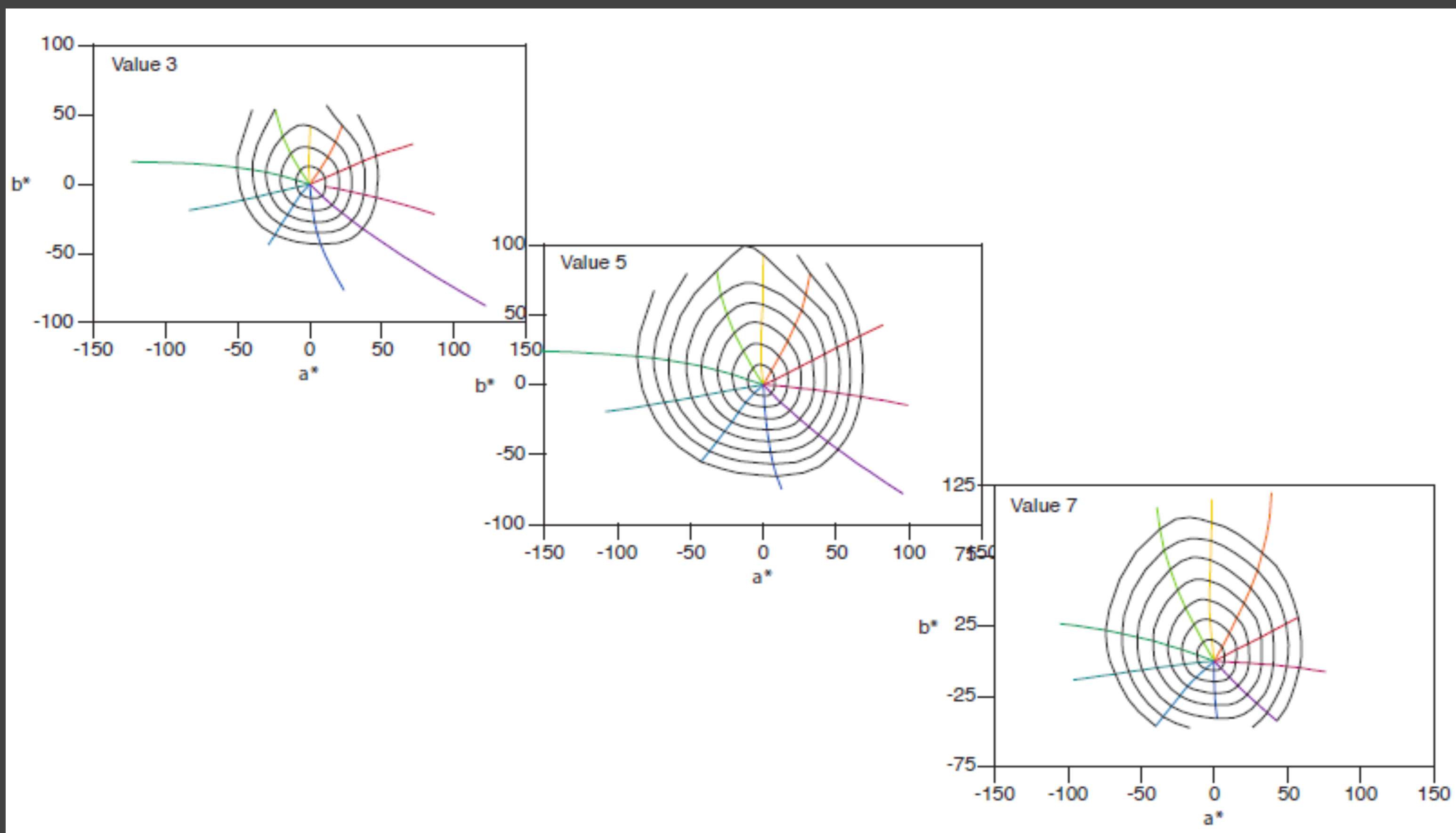
Color palette



Munsell Value
L* (CIE LAB)

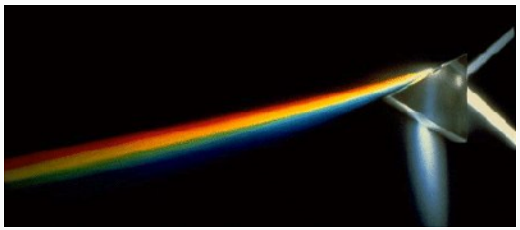
Perceptually-Uniform Color Space

Munsell colors in CIE LAB coordinates

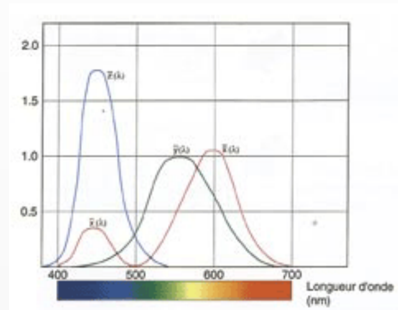


Mark Fairchild

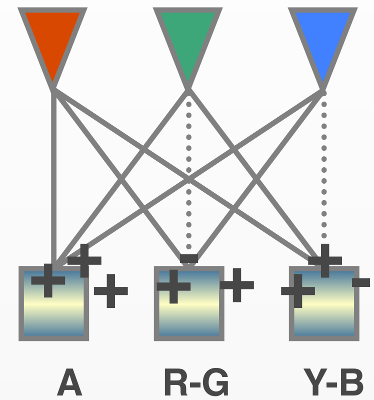
Perception of Color



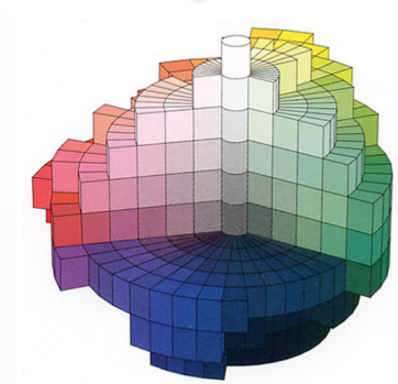
Light



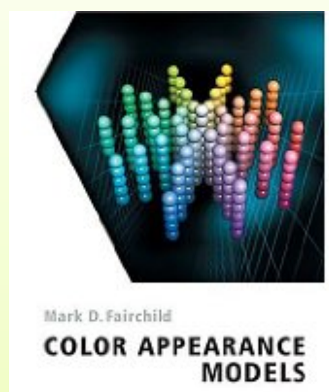
Cone Response



Opponent Signals



Color Perception



Color Appearance

"Yellow"

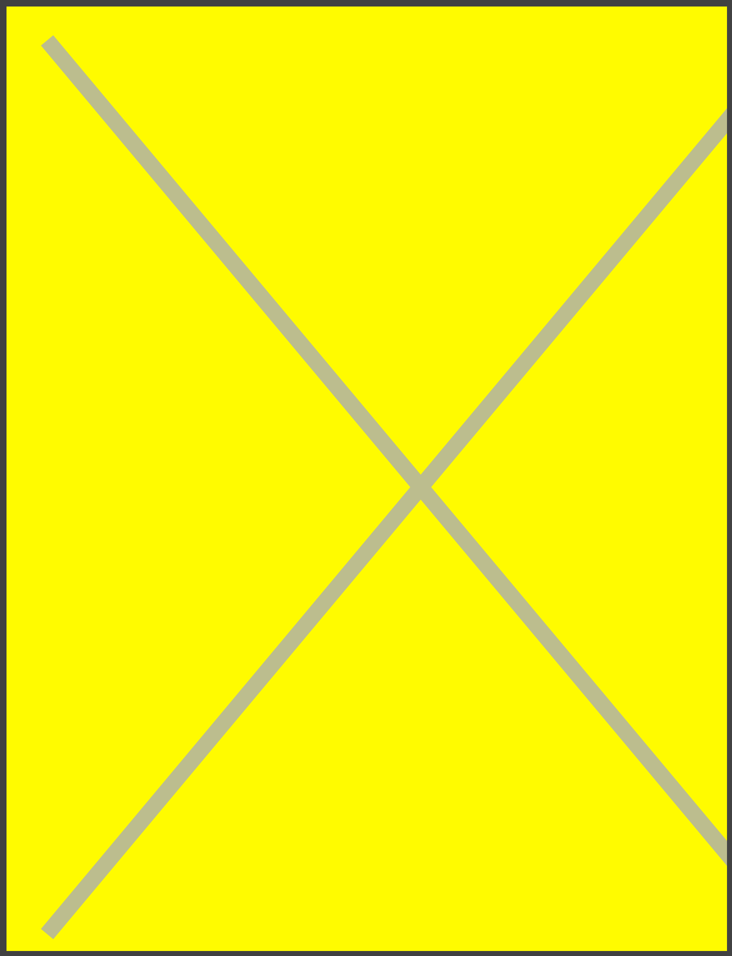
Color Cognition

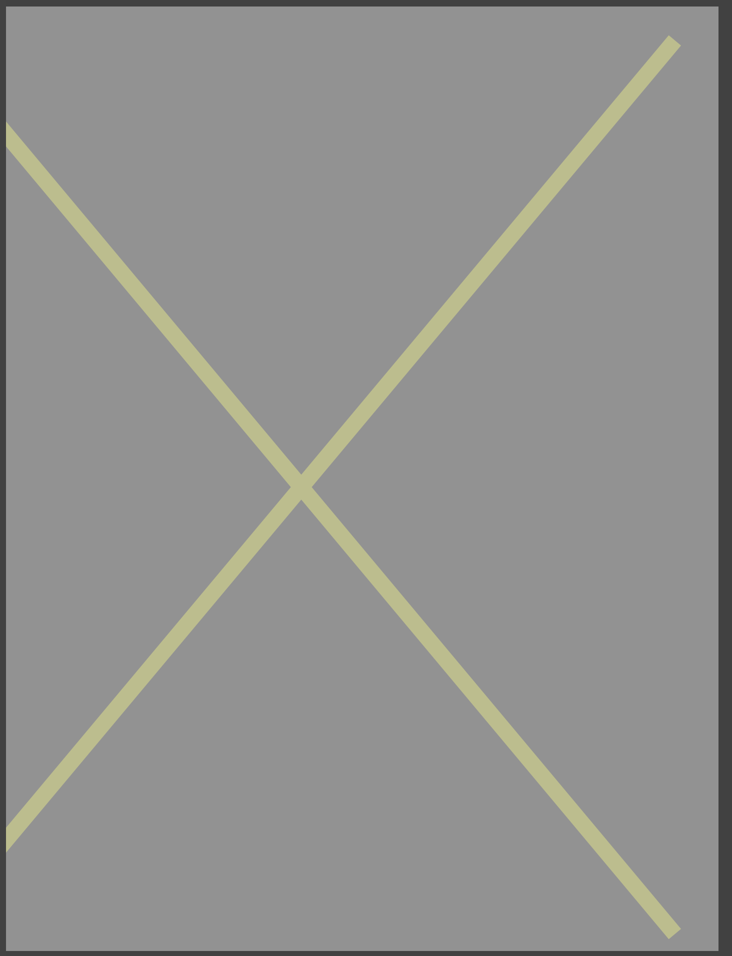
Color Appearance

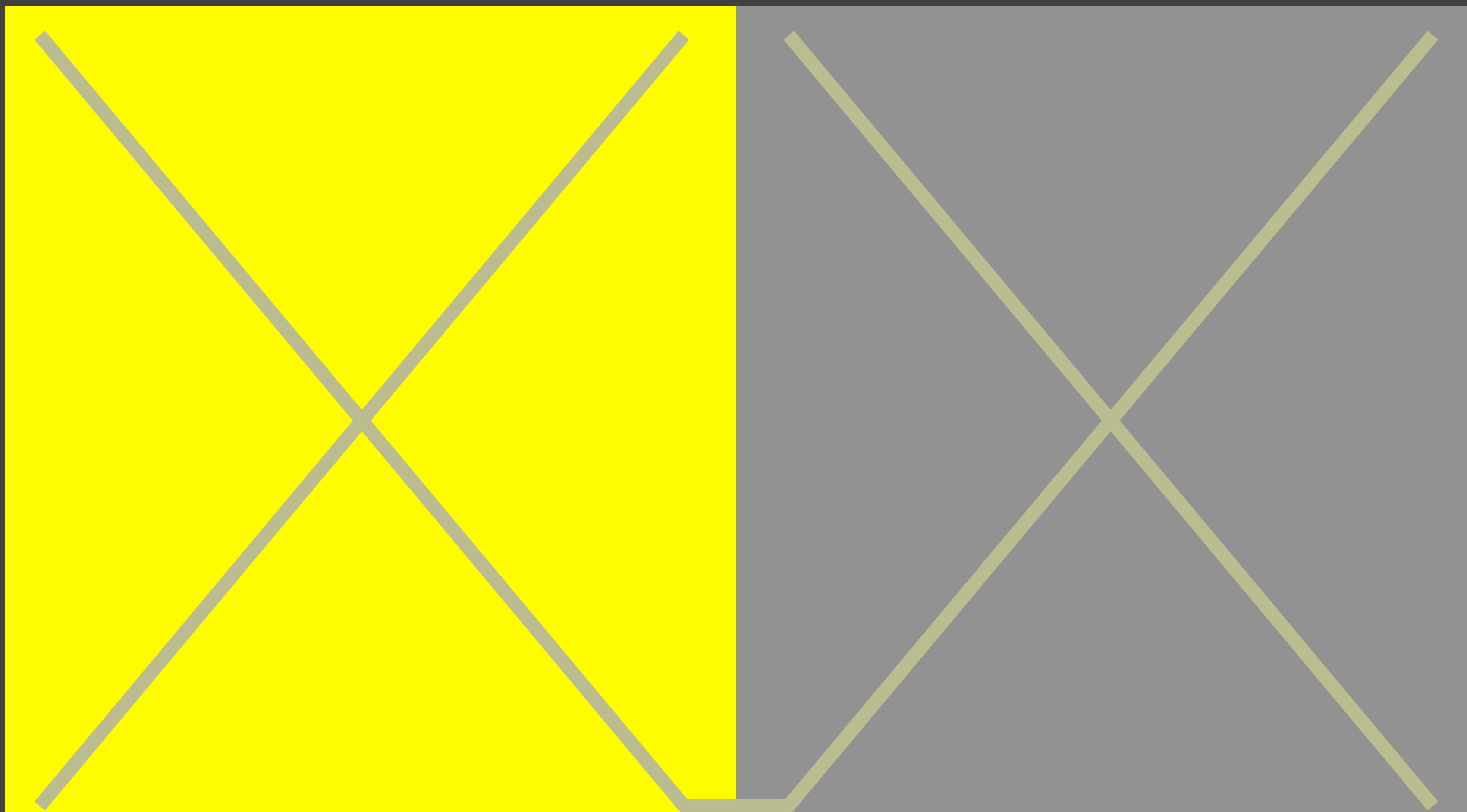
If we have a perceptually-uniform color space, can we predict how we perceive colors?

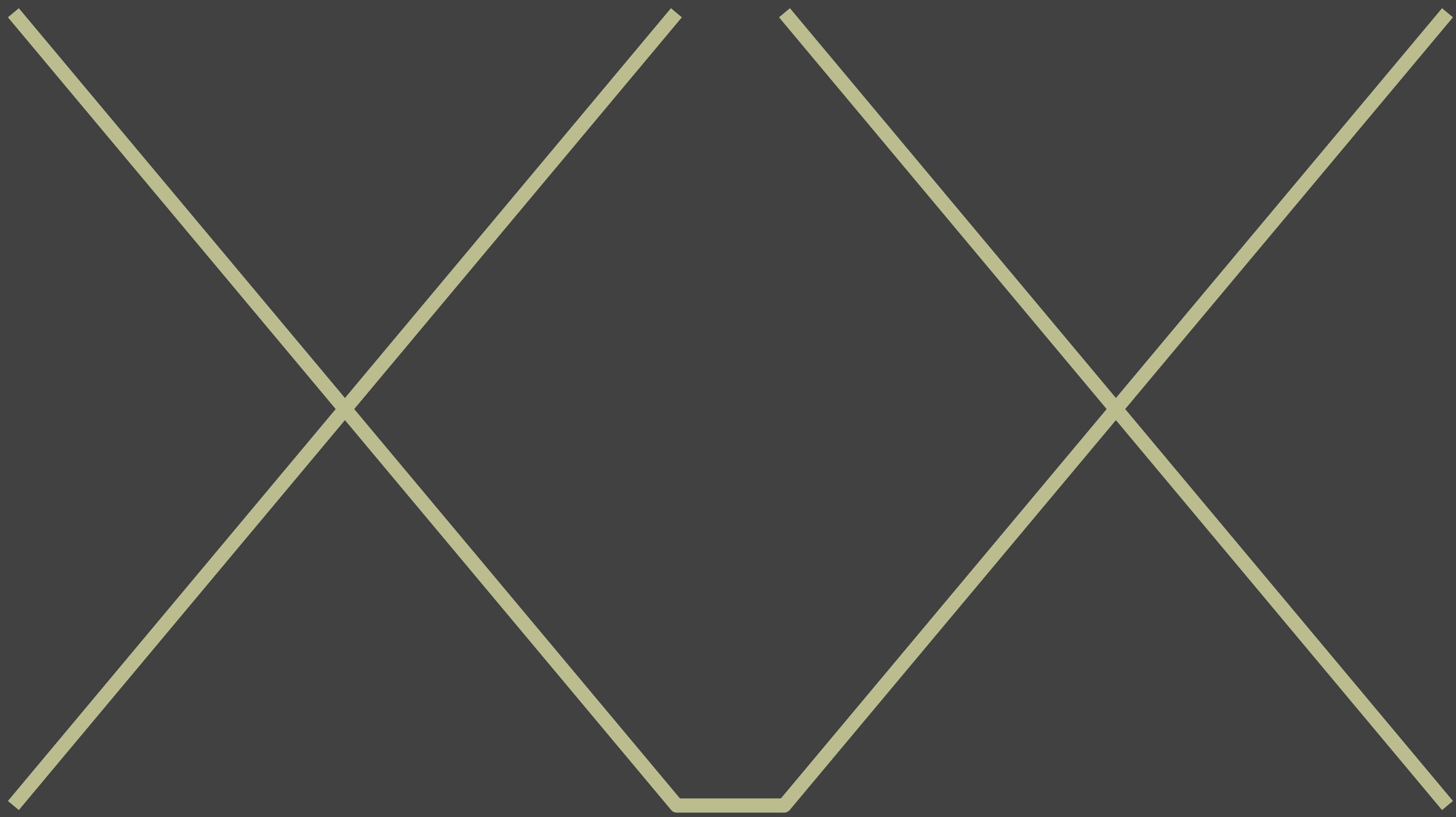
“In order to use color effectively it is necessary to recognize that it deceives continually.”

- Josef Albers, *Interaction of Color*

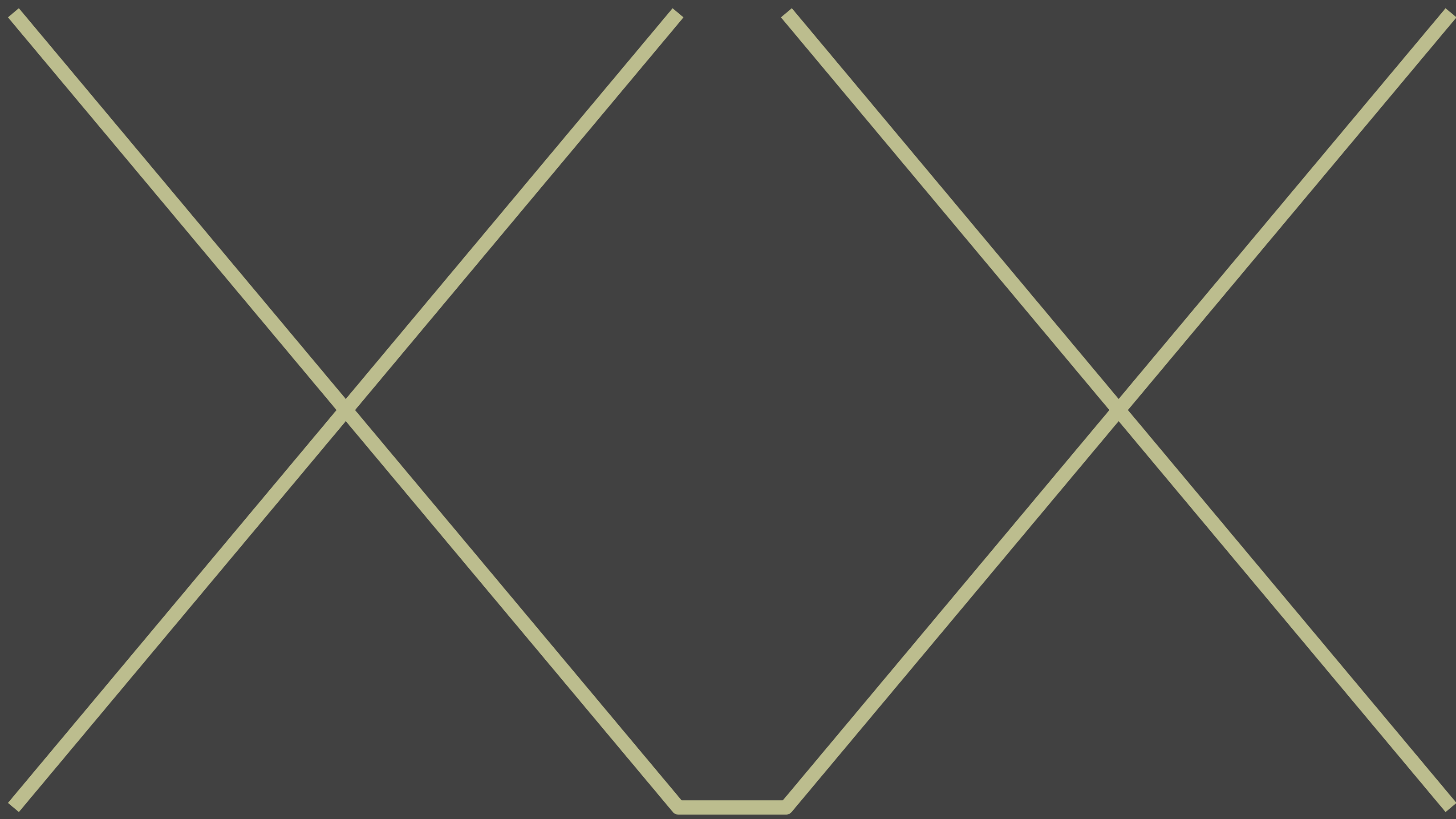






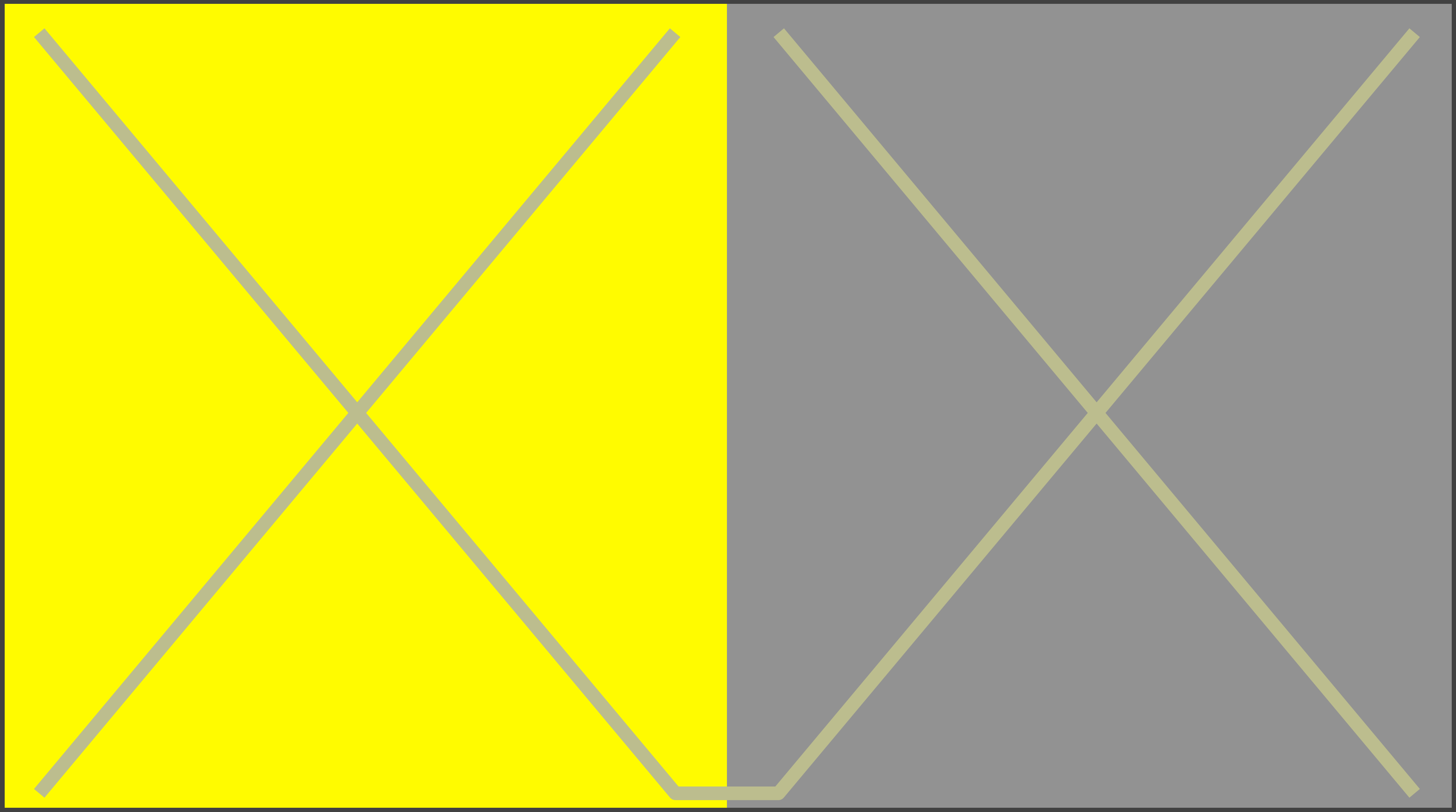


Simultaneous Contrast



Josef Albers

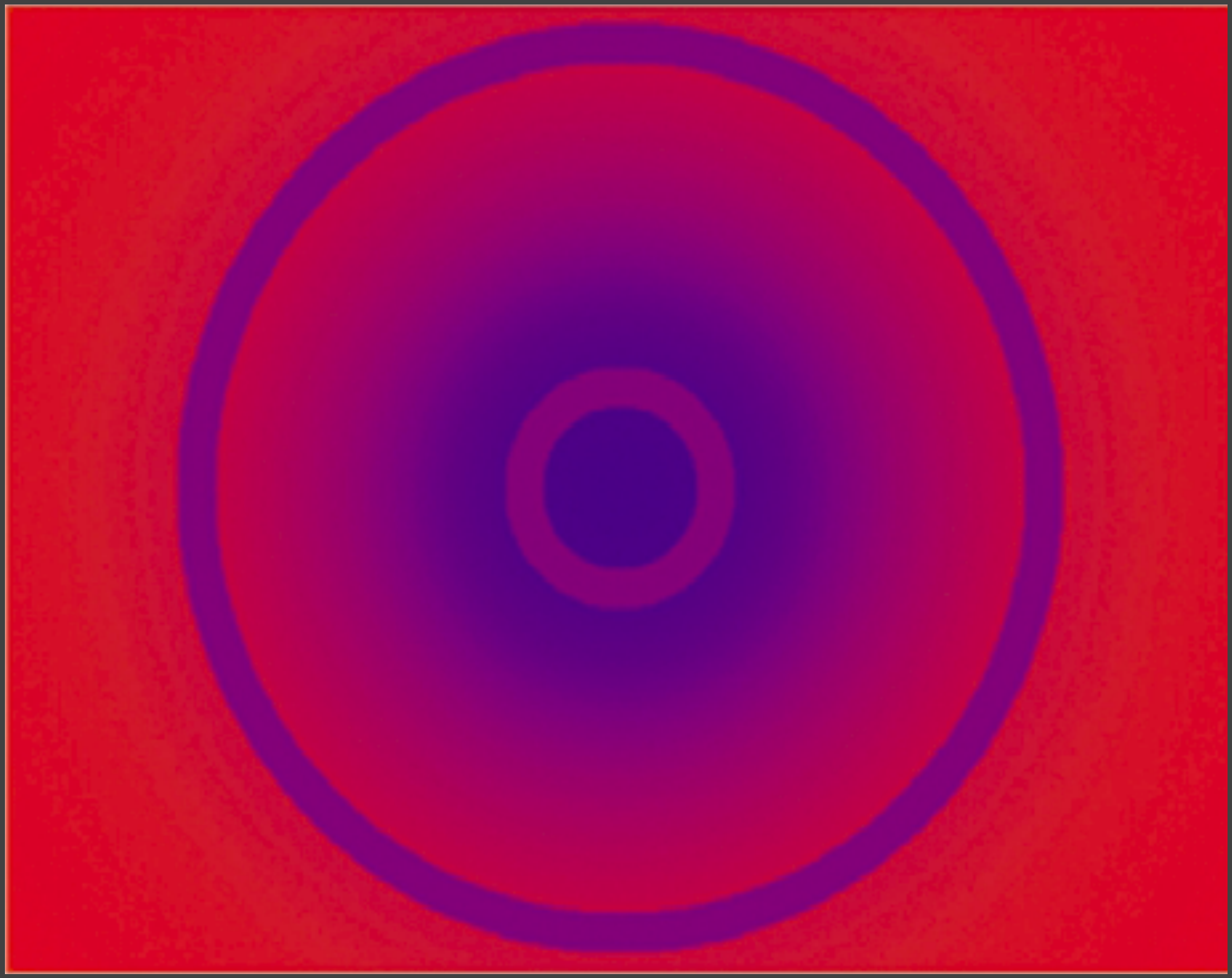
Simultaneous Contrast



Josef Albers

Simultaneous Contrast

Inner & outer rings are the same physical purple.



Donald MacLeod

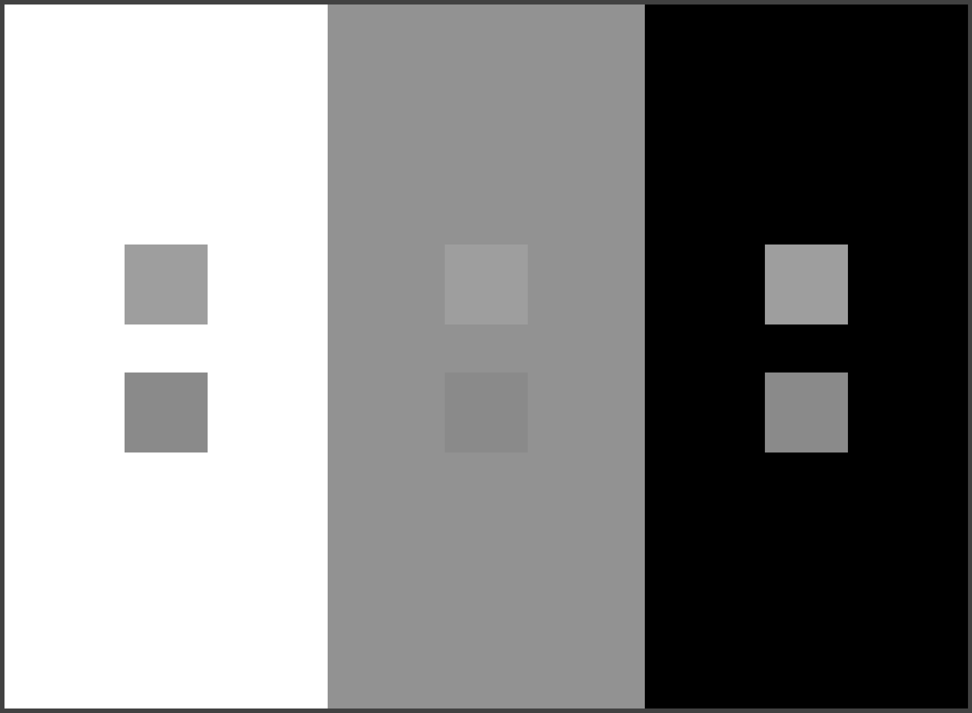
Bezold Effect

Color appearance depends on adjacent colors

Color Appearance Tutorial by Maureen Stone

Crispening

Perceived difference depends on background



Color Appearance Models, Fairchild

Spreading

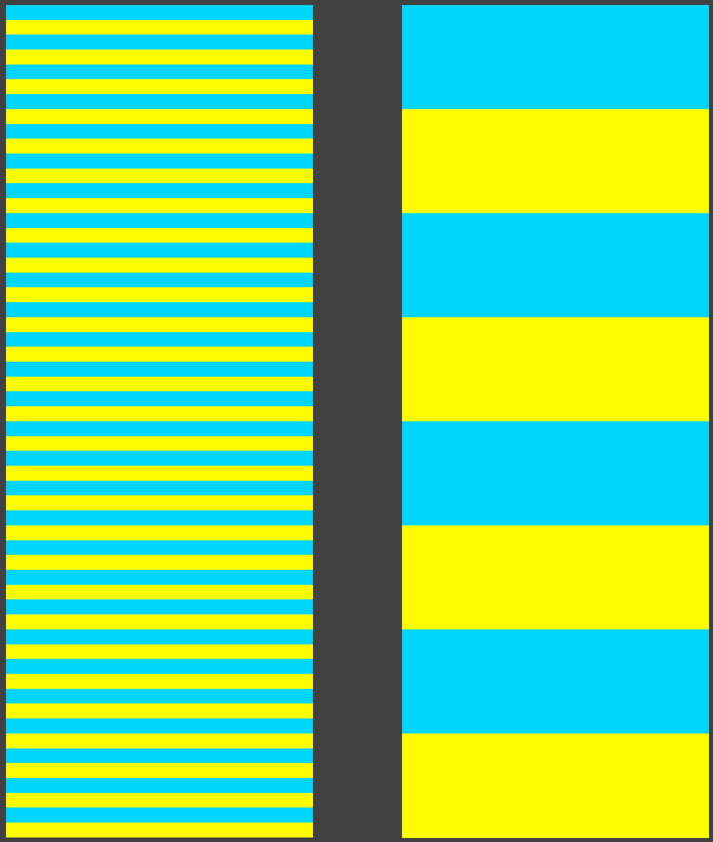
Spatial frequency

The paint chip problem

Small text, lines, glyphs

Image colors

Adjacent colors blend



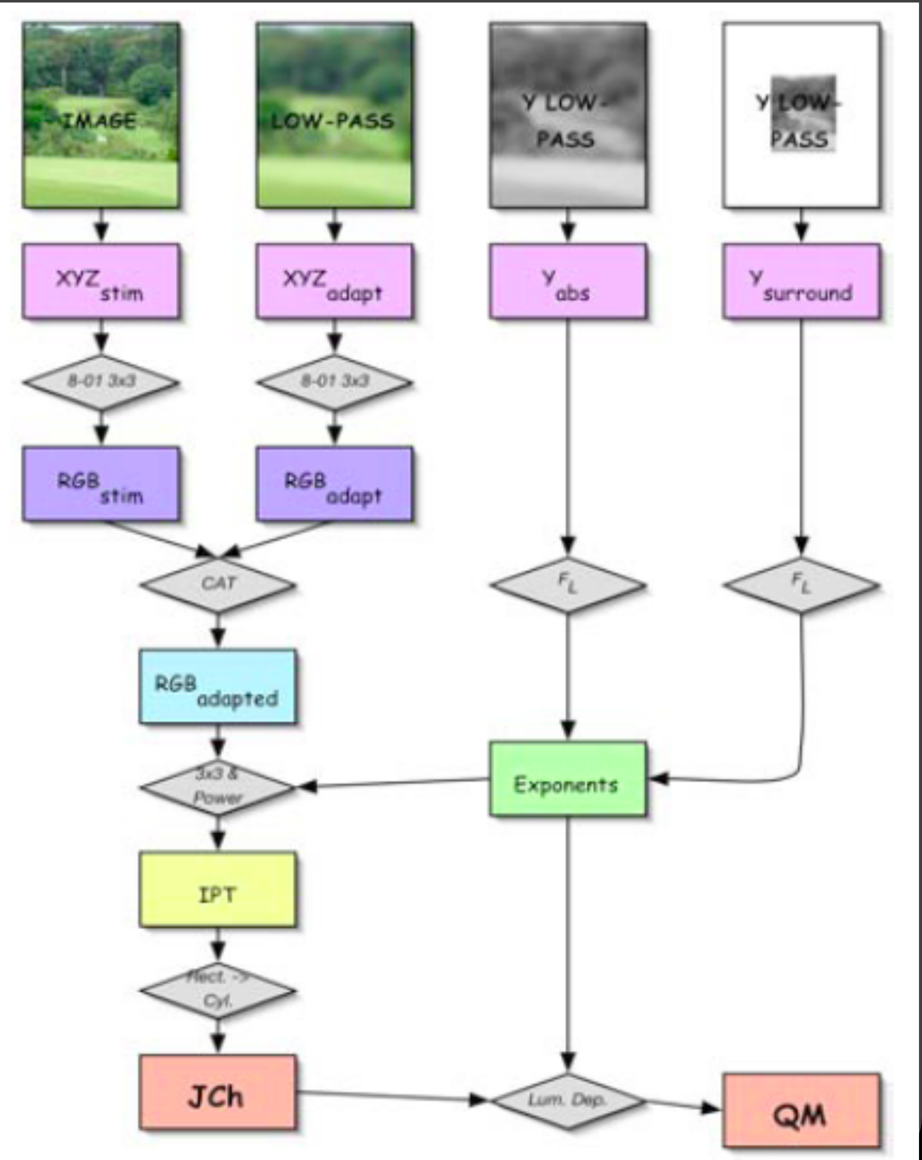
Foundations of Vision, Brian Wandell

Color Appearance Models (CIECAM'02)

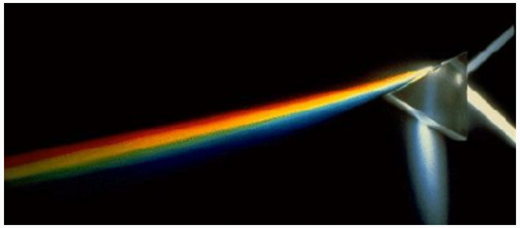
From color *spaces* to *appearance models*…

Chromatic adaptation
Appearance scales
Color difference
Crispening
Spreading
HDR tone mapping

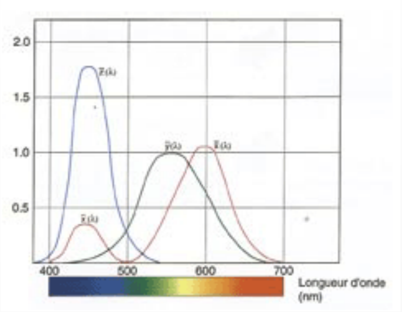
[Fairchild]



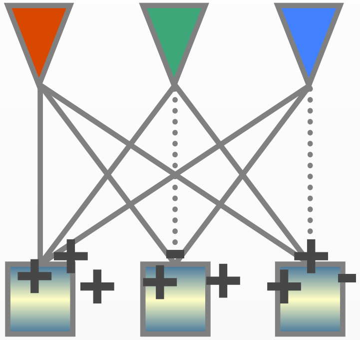
Perception of Color



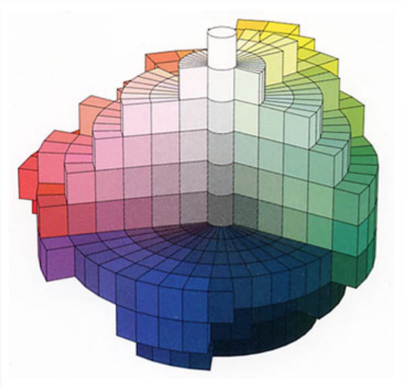
Light



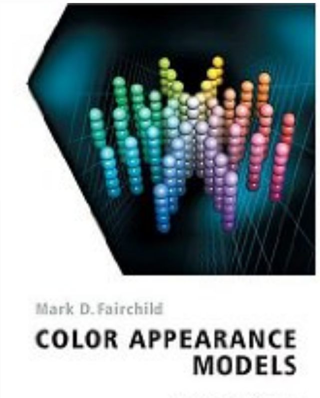
Cone Response



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.

Basic Color Terms

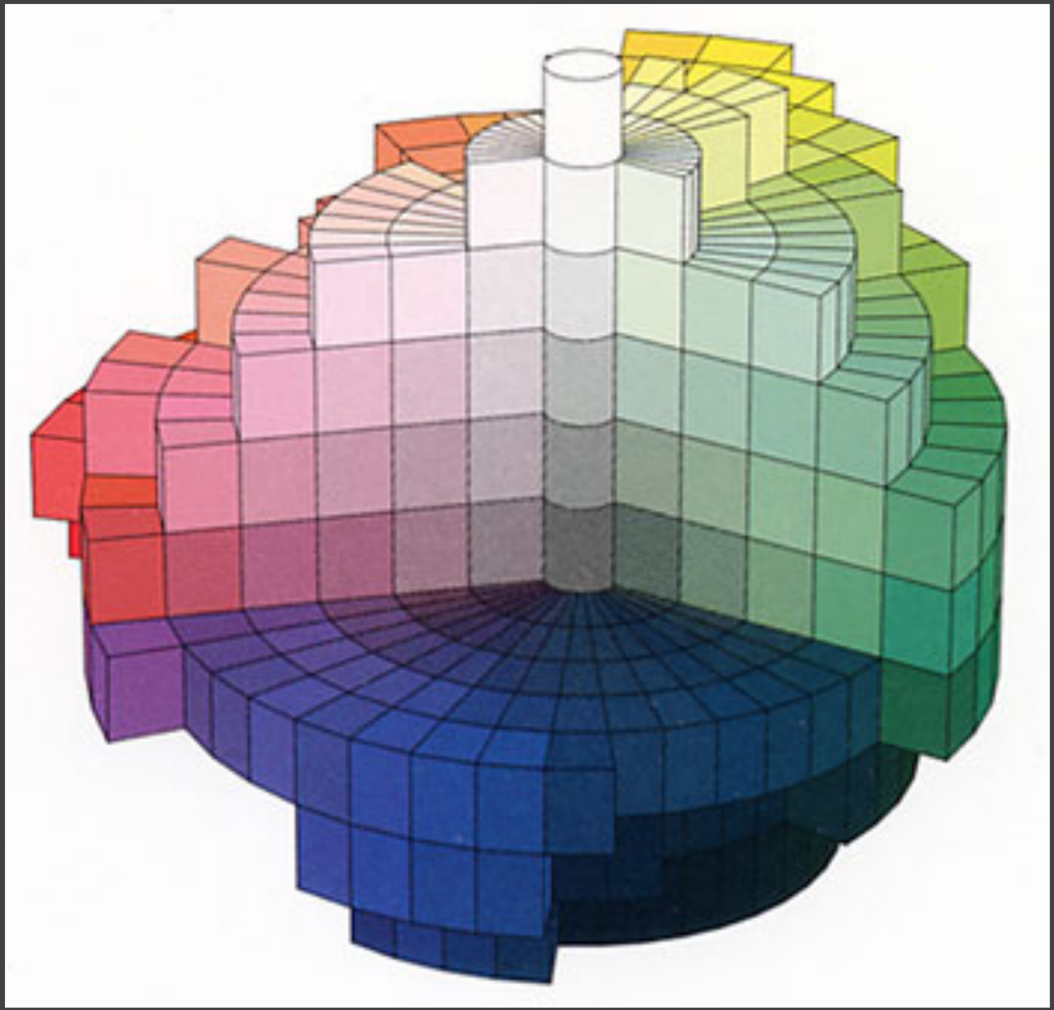
Chance discovery by Brent Berlin and Paul Kay.

Initial study in 1969

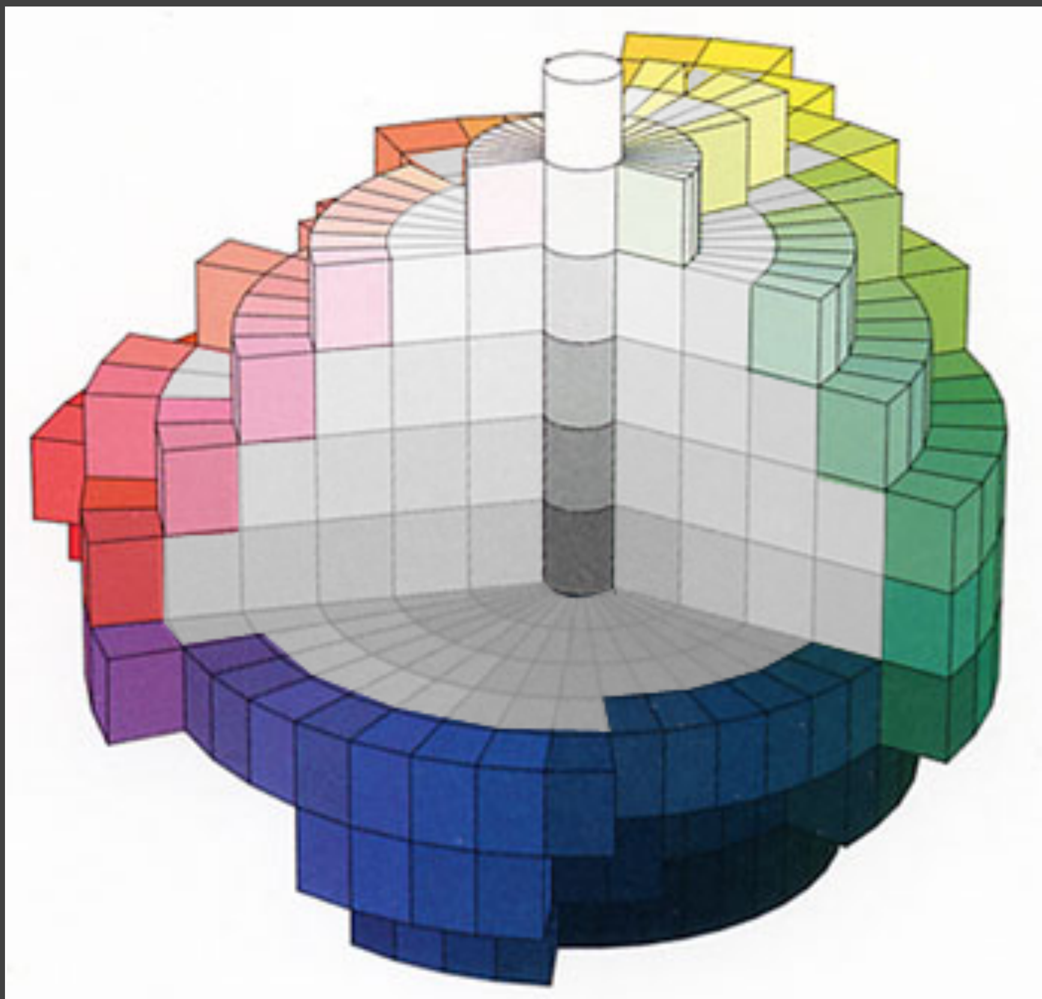
Surveyed speakers from 20 languages

Literature from 69 languages

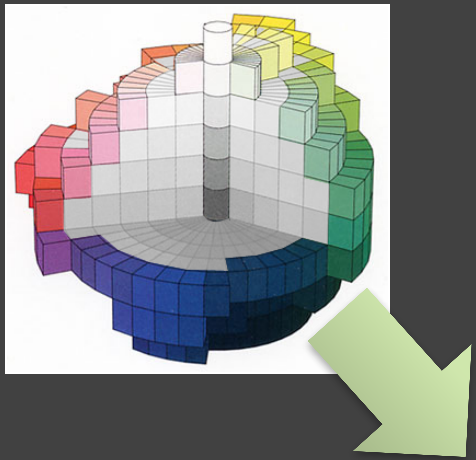
World Color Survey



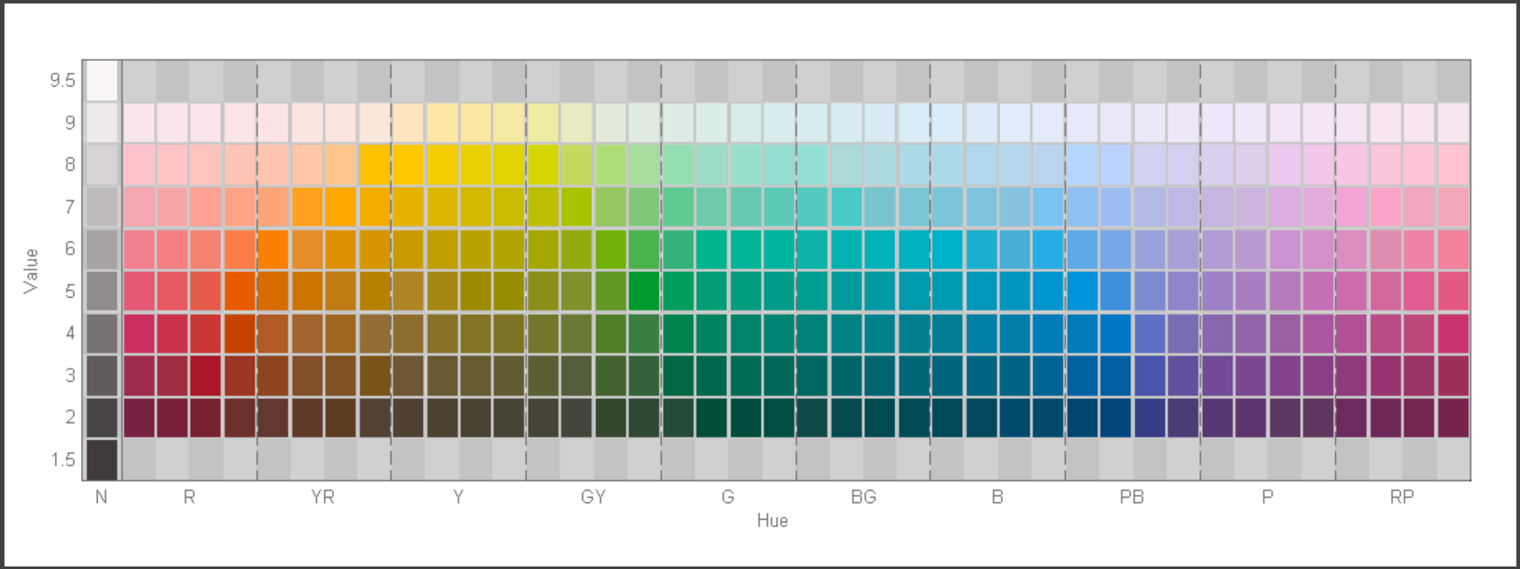
World Color Survey



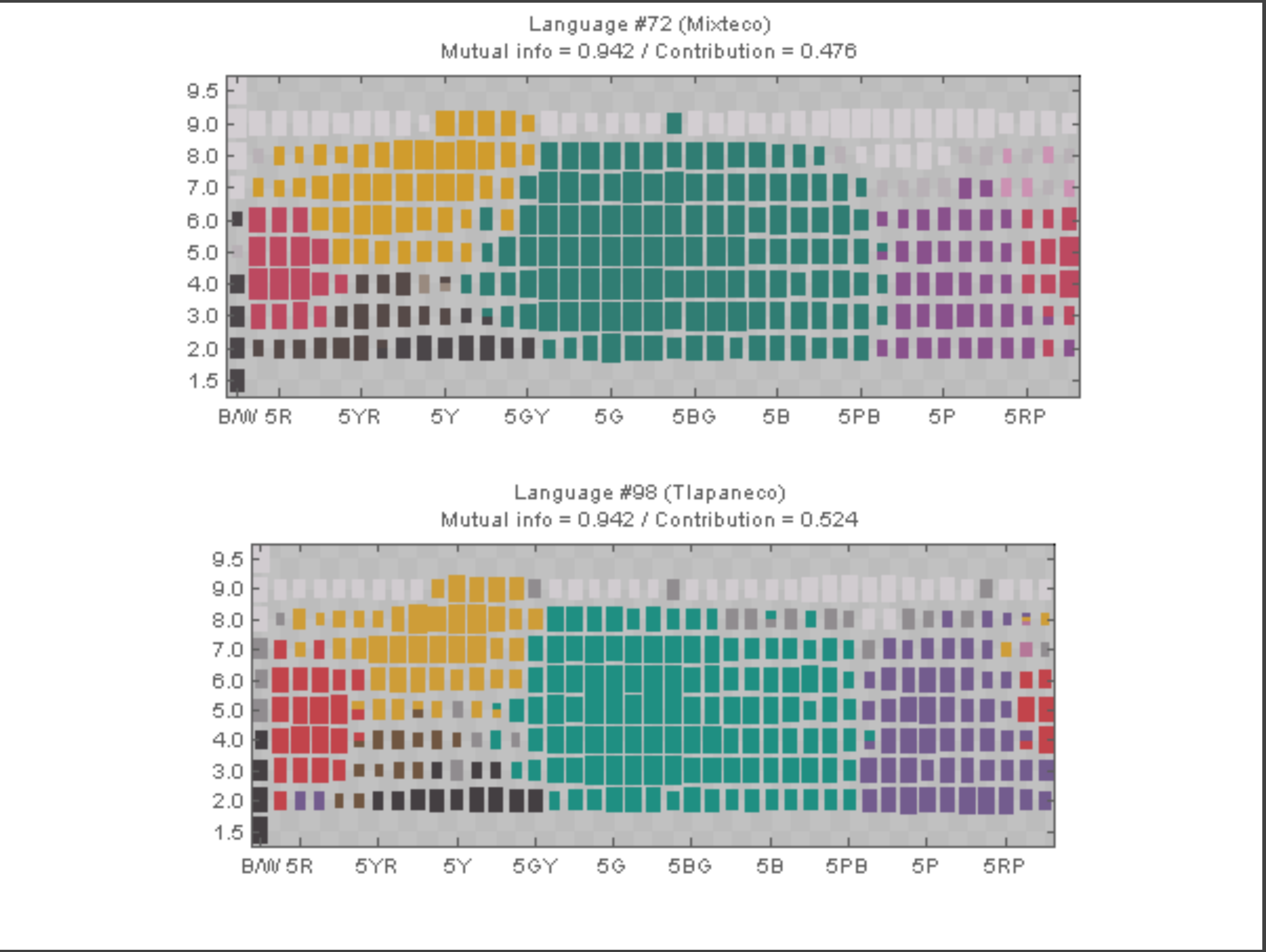
World Color Survey



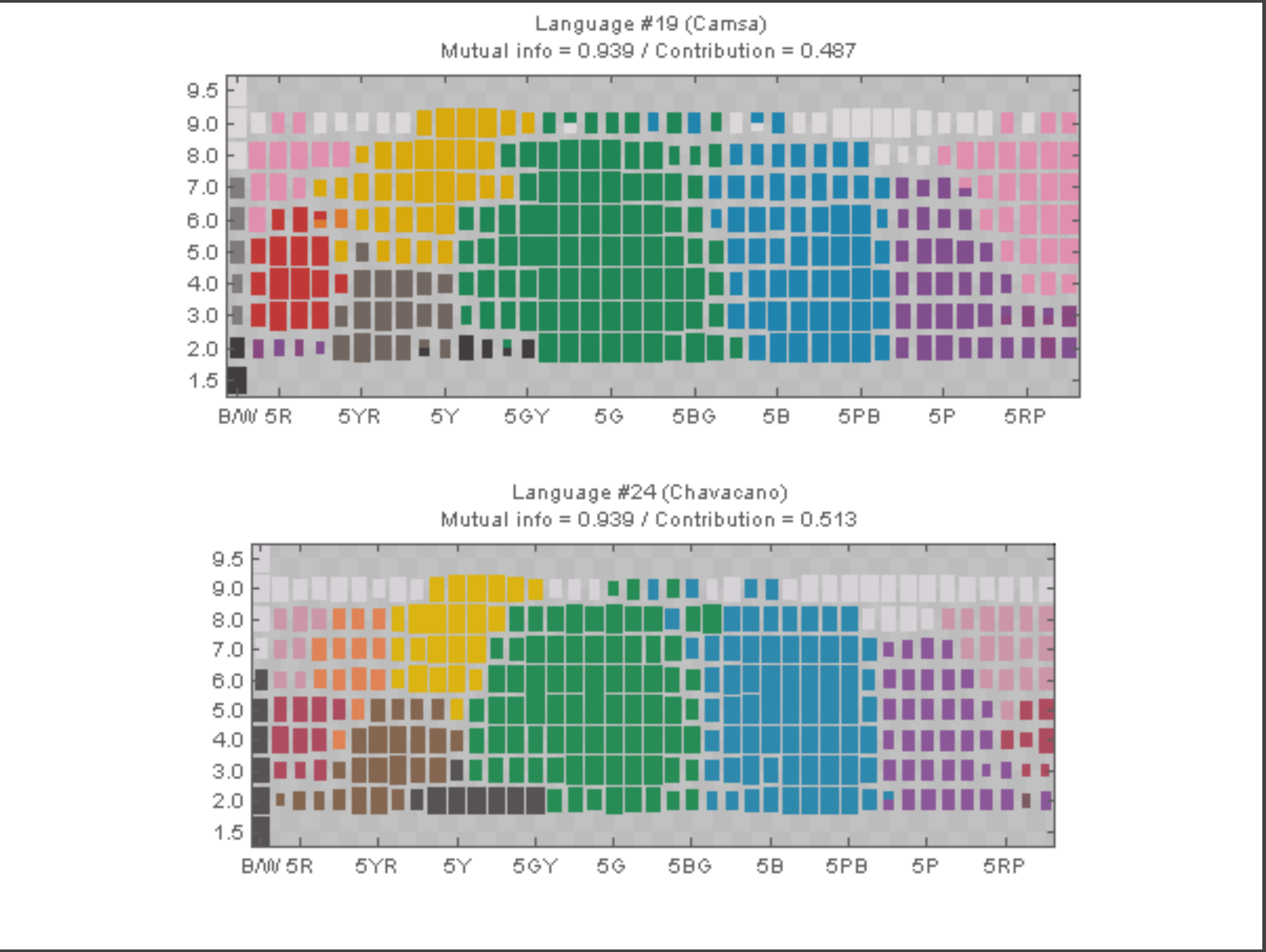
Naming information from 2,616 speakers from 110 languages on 330 Munsell color chips



Results from WCS



Results from WCS



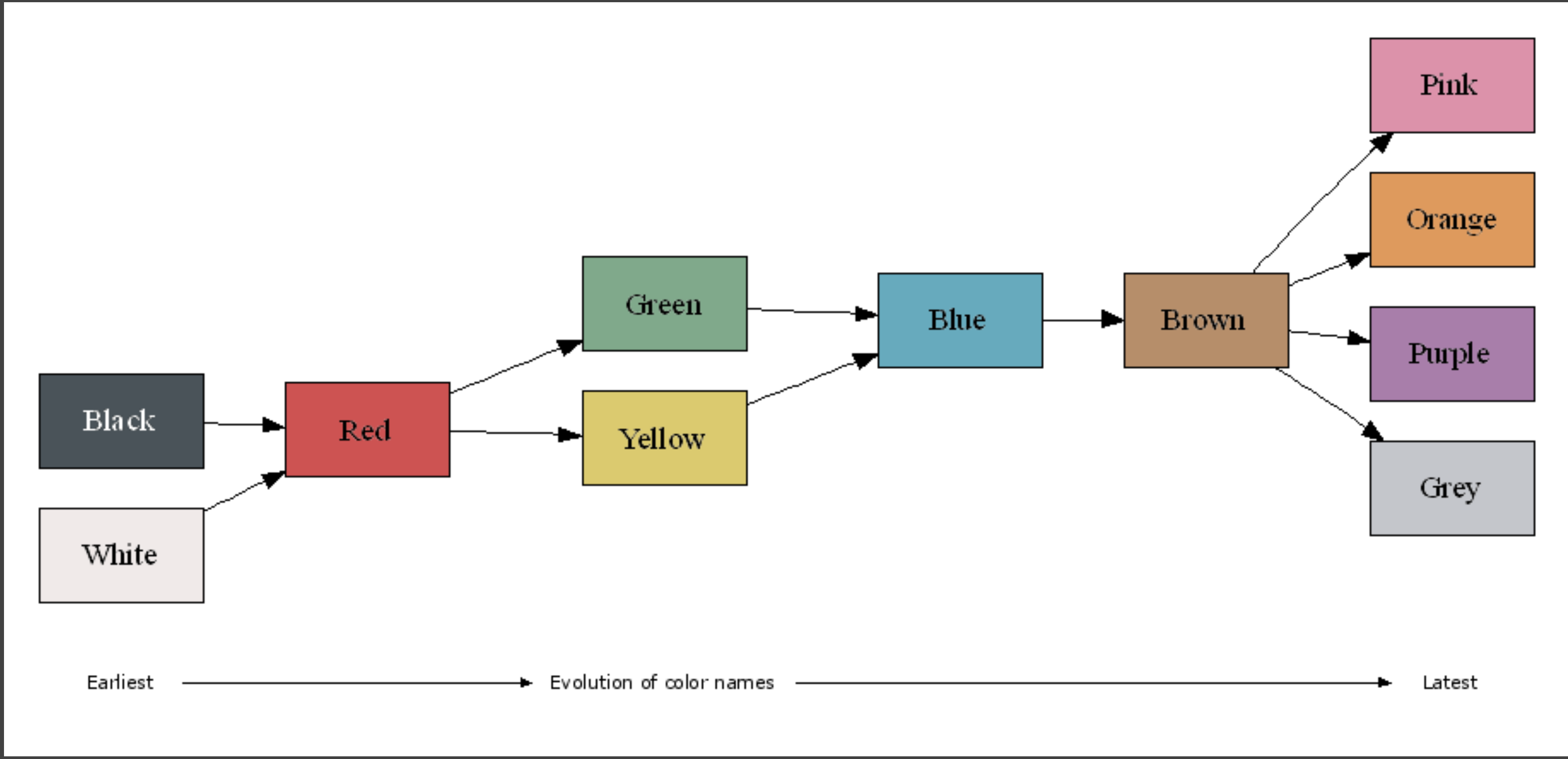
Universal (?) Basic Color Terms

Basic color terms recur across languages.

White	Red	Pink
Grey	Yellow	Brown
Black	Green	Orange
	Blue	Purple

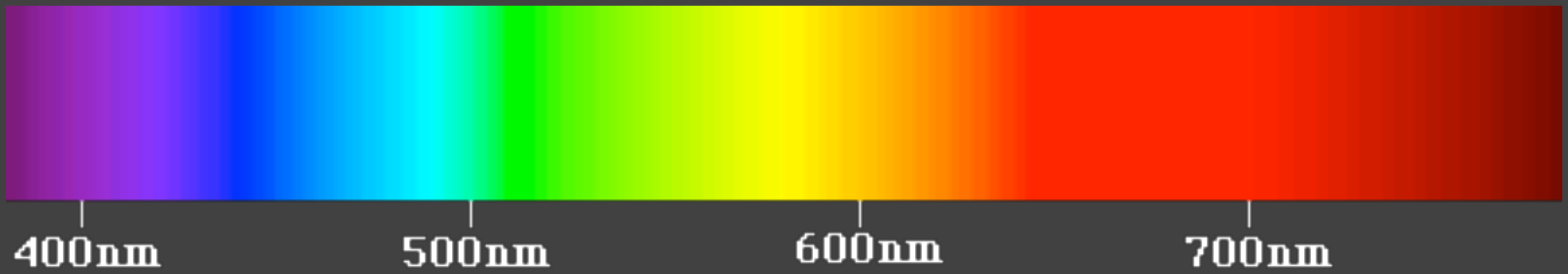
Evolution of Basic Color Terms

Proposed universal evolution across languages.



Rainbow Color Map

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



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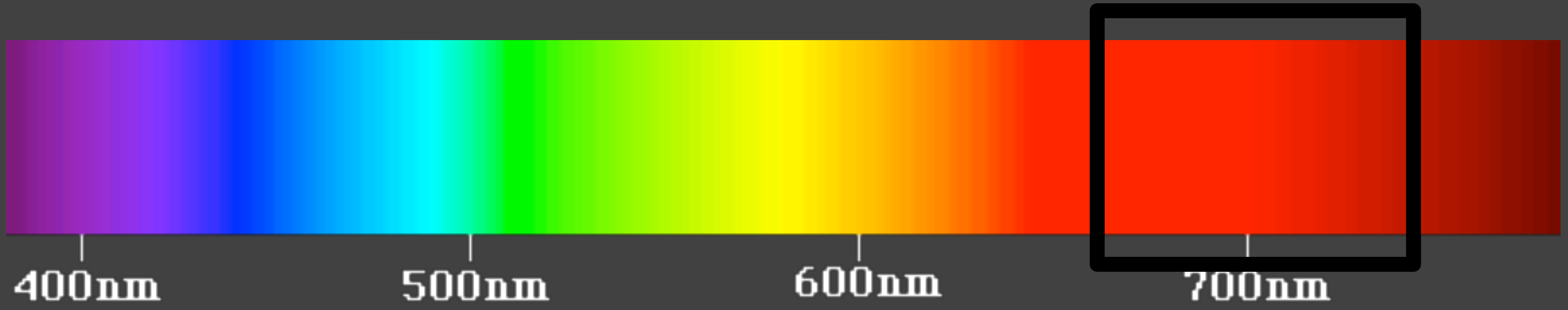

Rainbow Color Map

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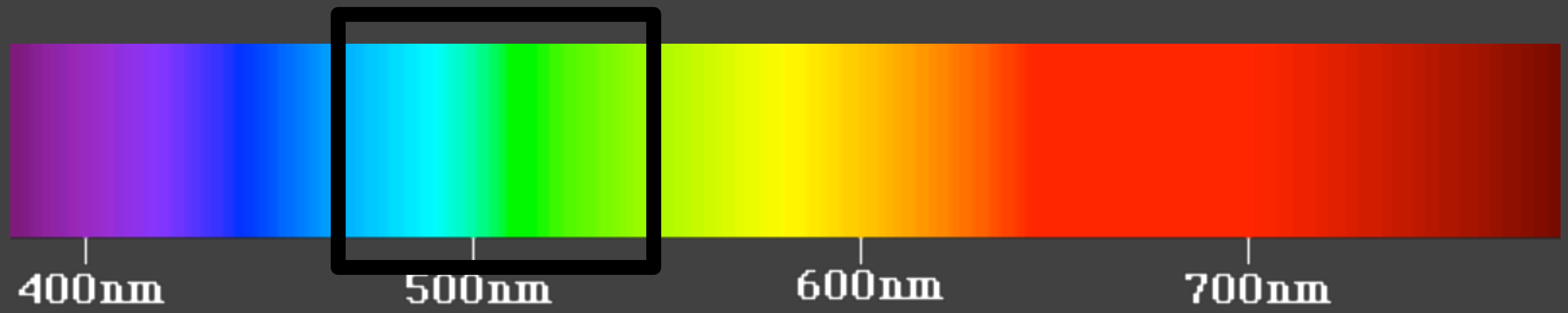
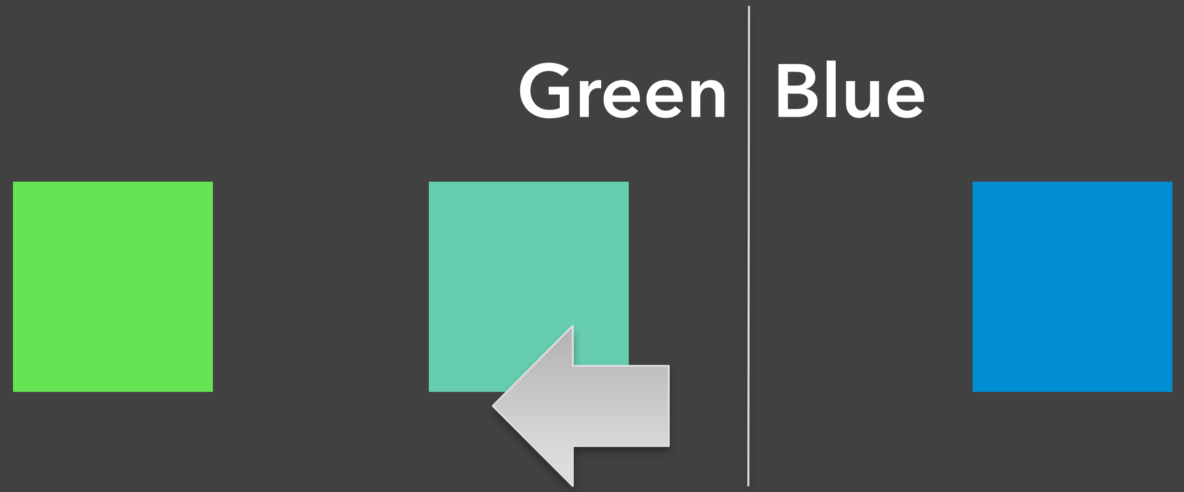
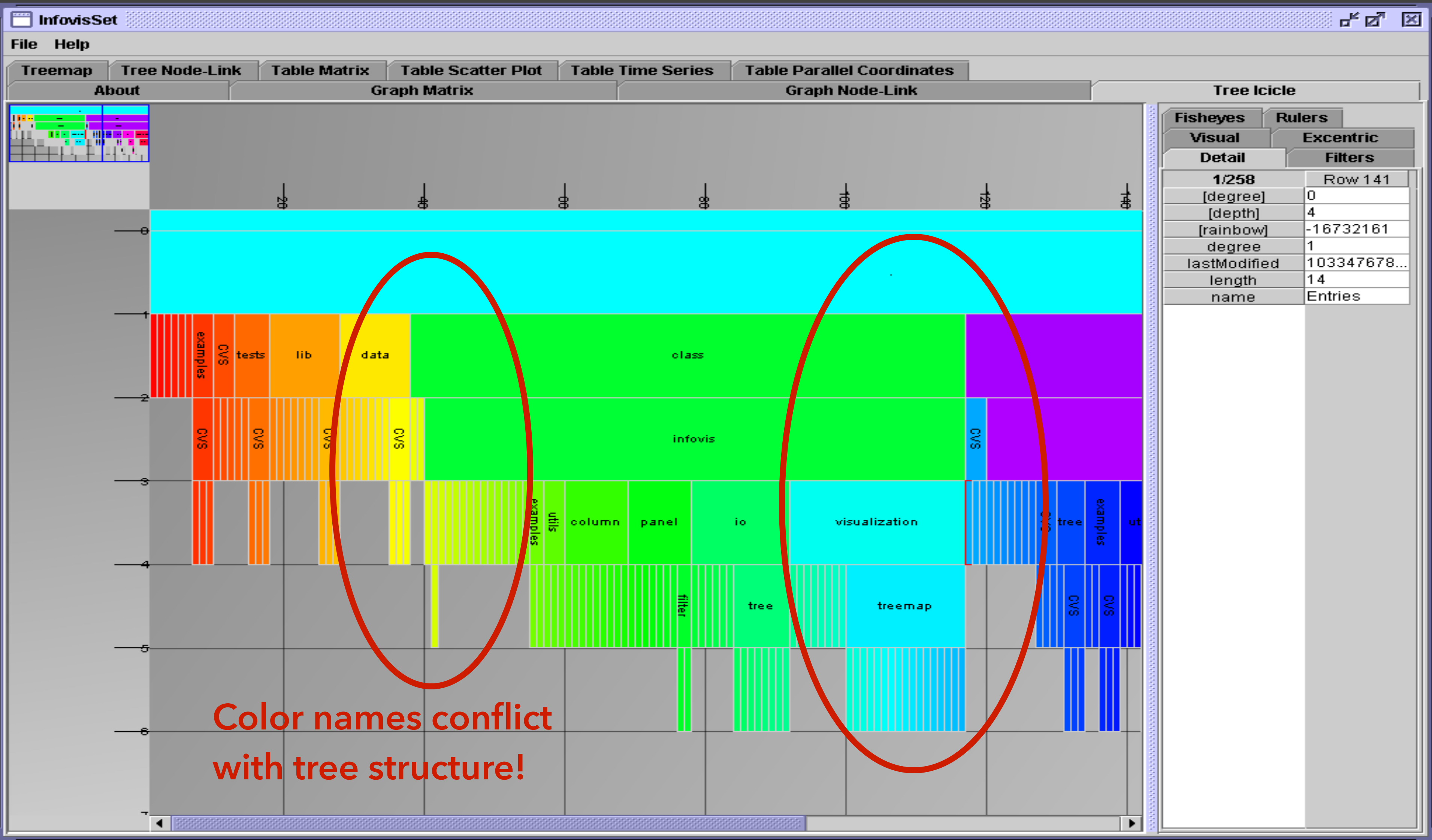


Naming Effects Color Perception

Color name boundaries



Icicle Tree with Rainbow Coloring



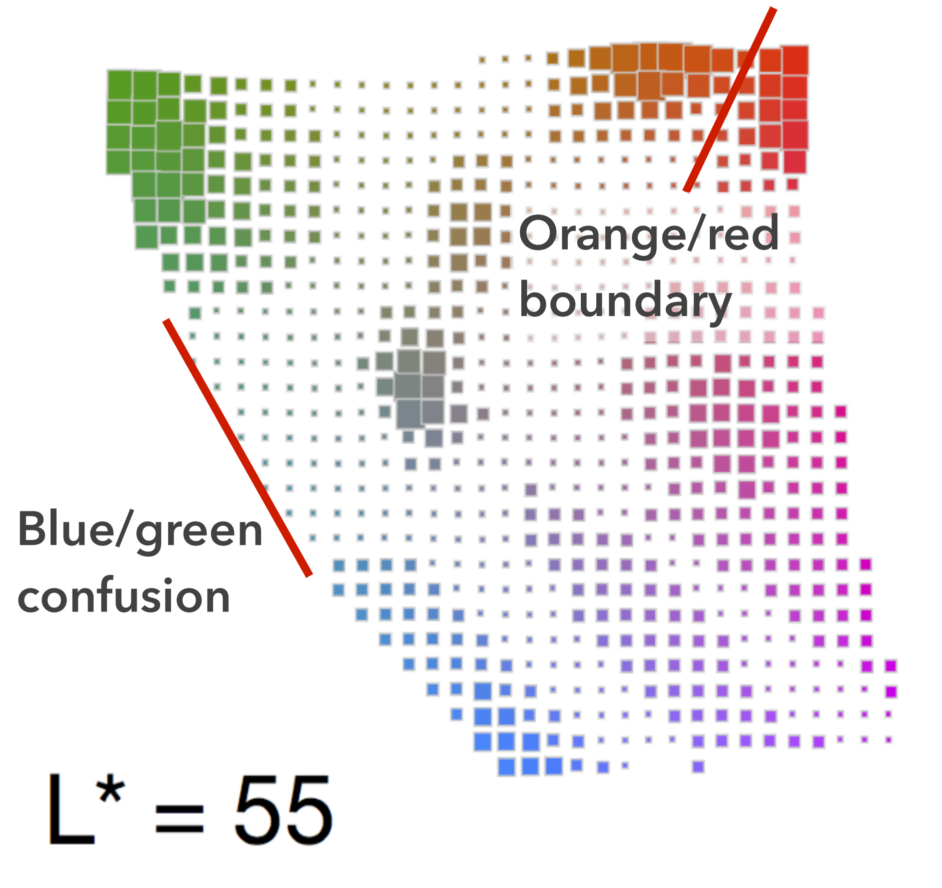
Color Naming Models [Heer & Stone '12]

Model 3 million responses from XKCD survey

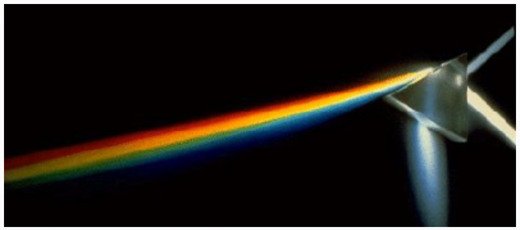
Bins in LAB space sized by *saliency*:

How much do people agree on color name?

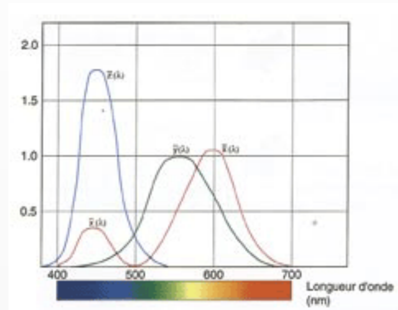
Modeled by entropy of *p(name | color)*



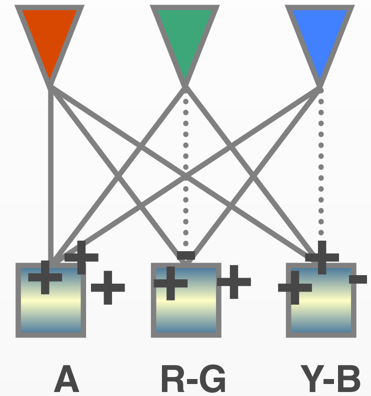
Perception of Color



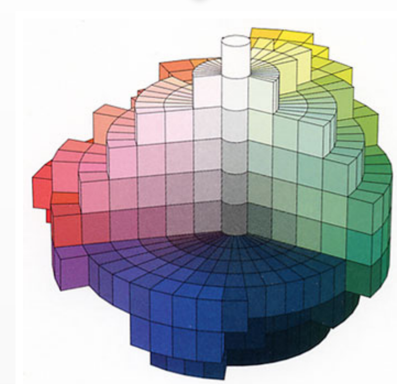
Light



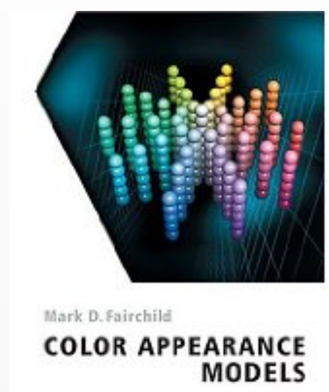
Cone Response



Opponent Signals



Color Perception



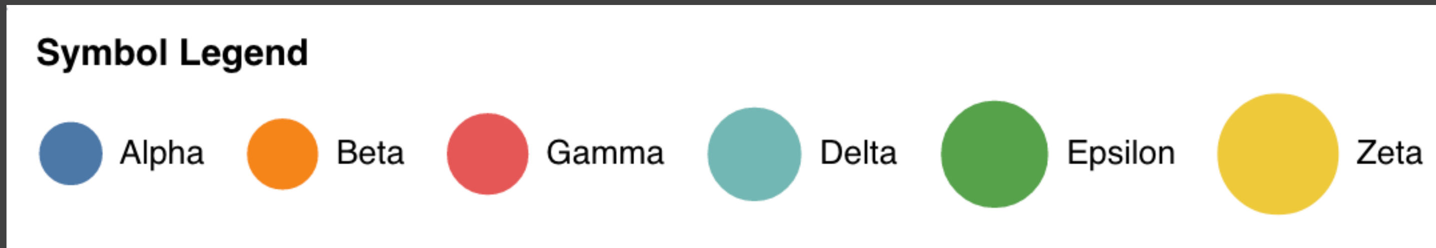
Color Appearance

"Yellow"

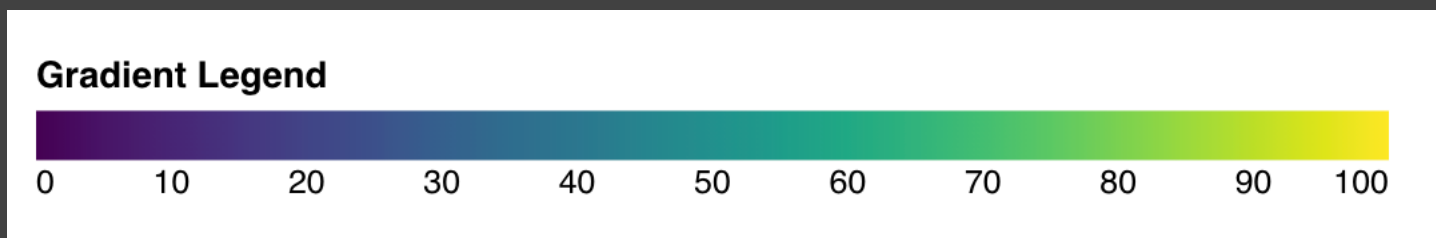
Color Cognition

Designing Colormaps

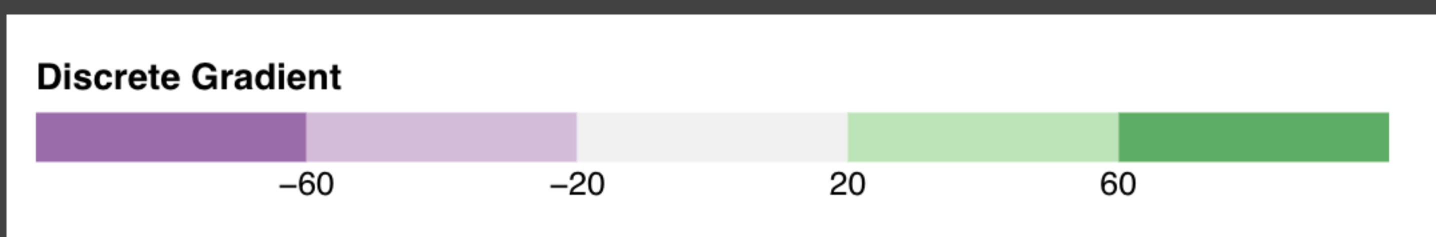
Discrete (Binary, Categorical)



Continuous (Sequential, Diverging, Cyclic)



Discretized Continuous



Colormap Design Considerations

Perceptually distinguishable colors

Value distance matches perceptual distance

Colors and concepts properly align

Aesthetically pleasing, intriguing

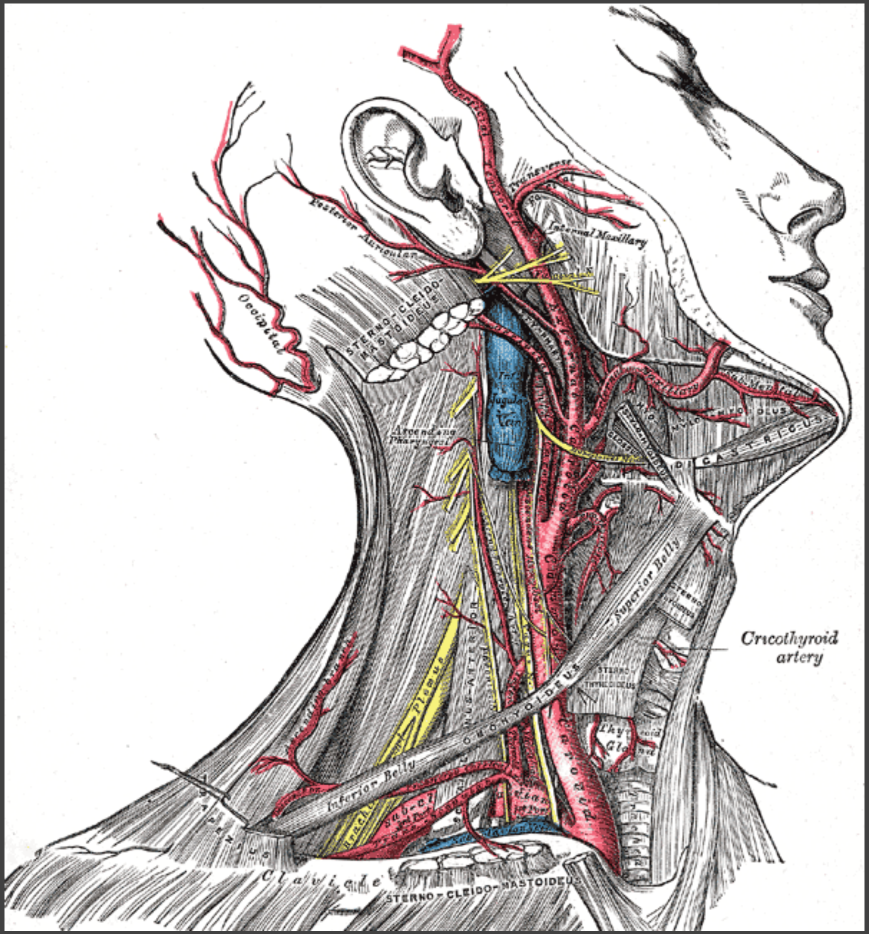
Respect color vision deficiencies

Should survive printing to black & white

Don’t overwhelm people’s capability!

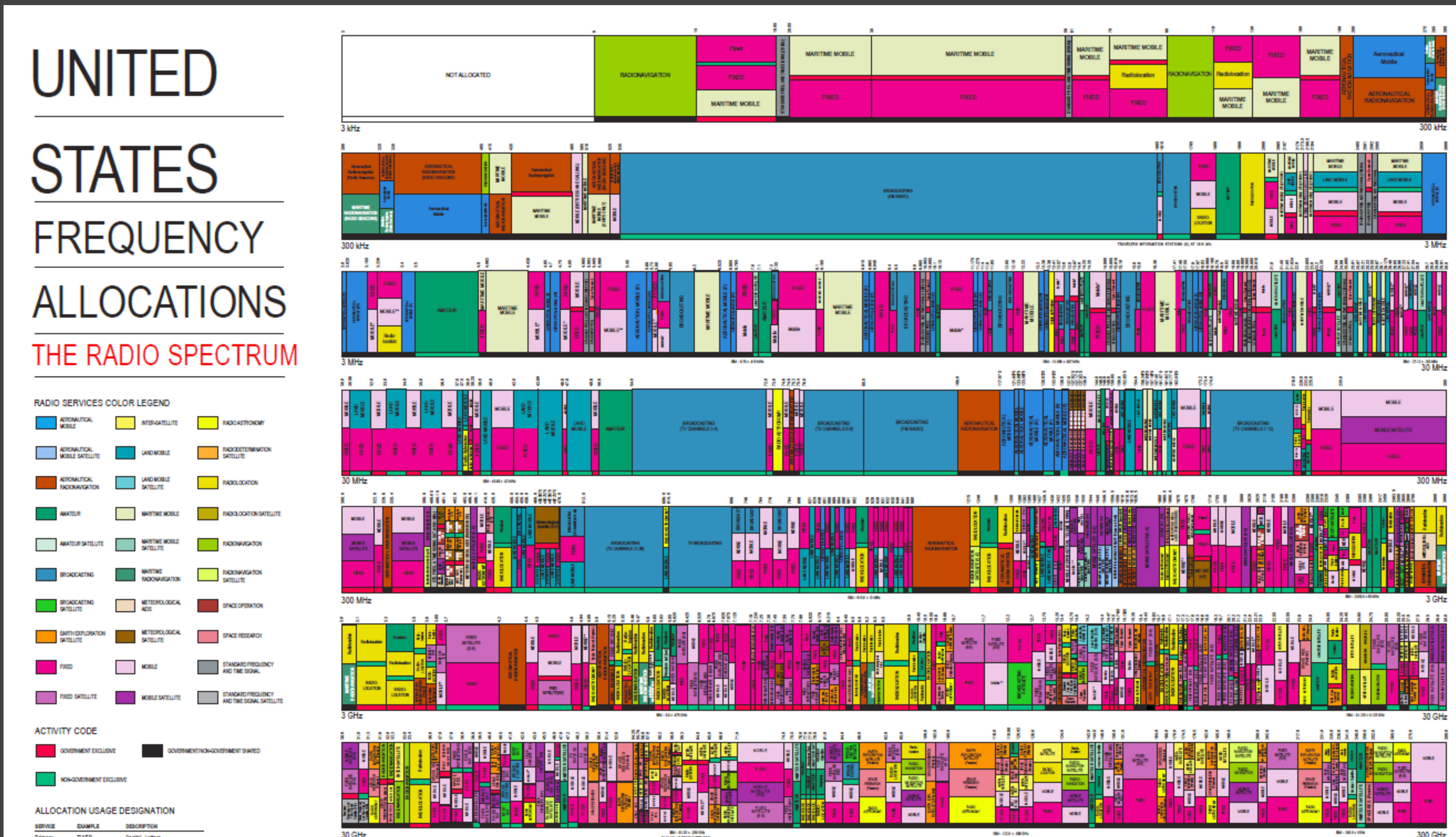
Categorical Color

Gray's Anatomy



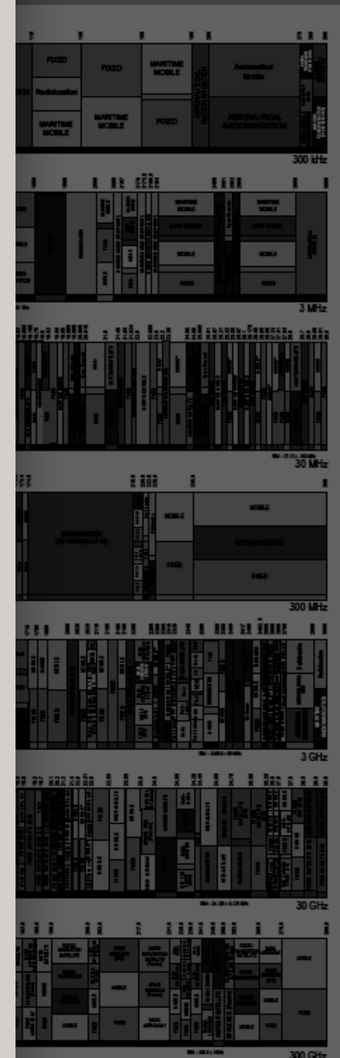
Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)

Allocation of the Radio Spectrum



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

Alloc… rum

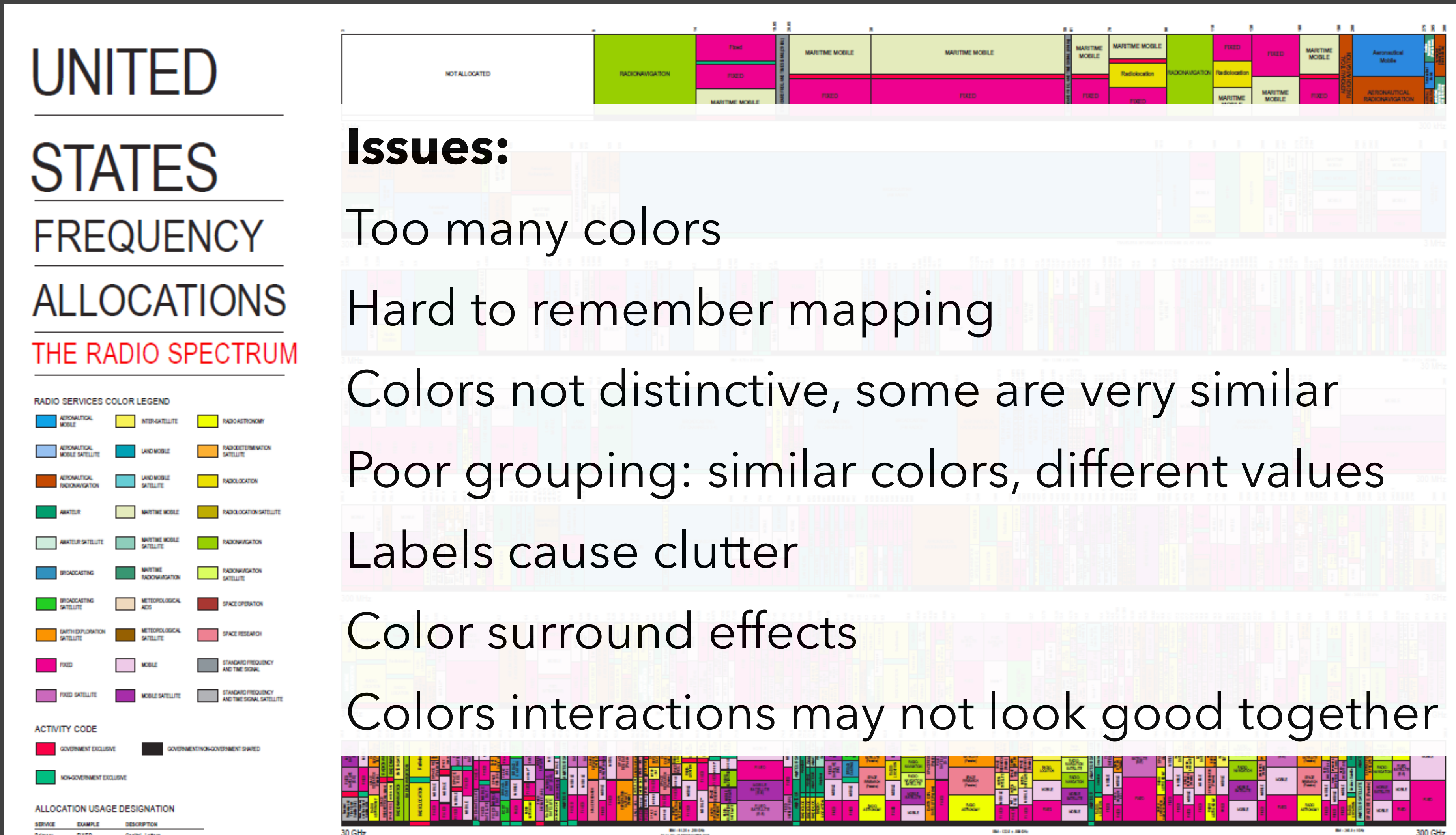


RADIO SERVICES COLOR LEGEND

- 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

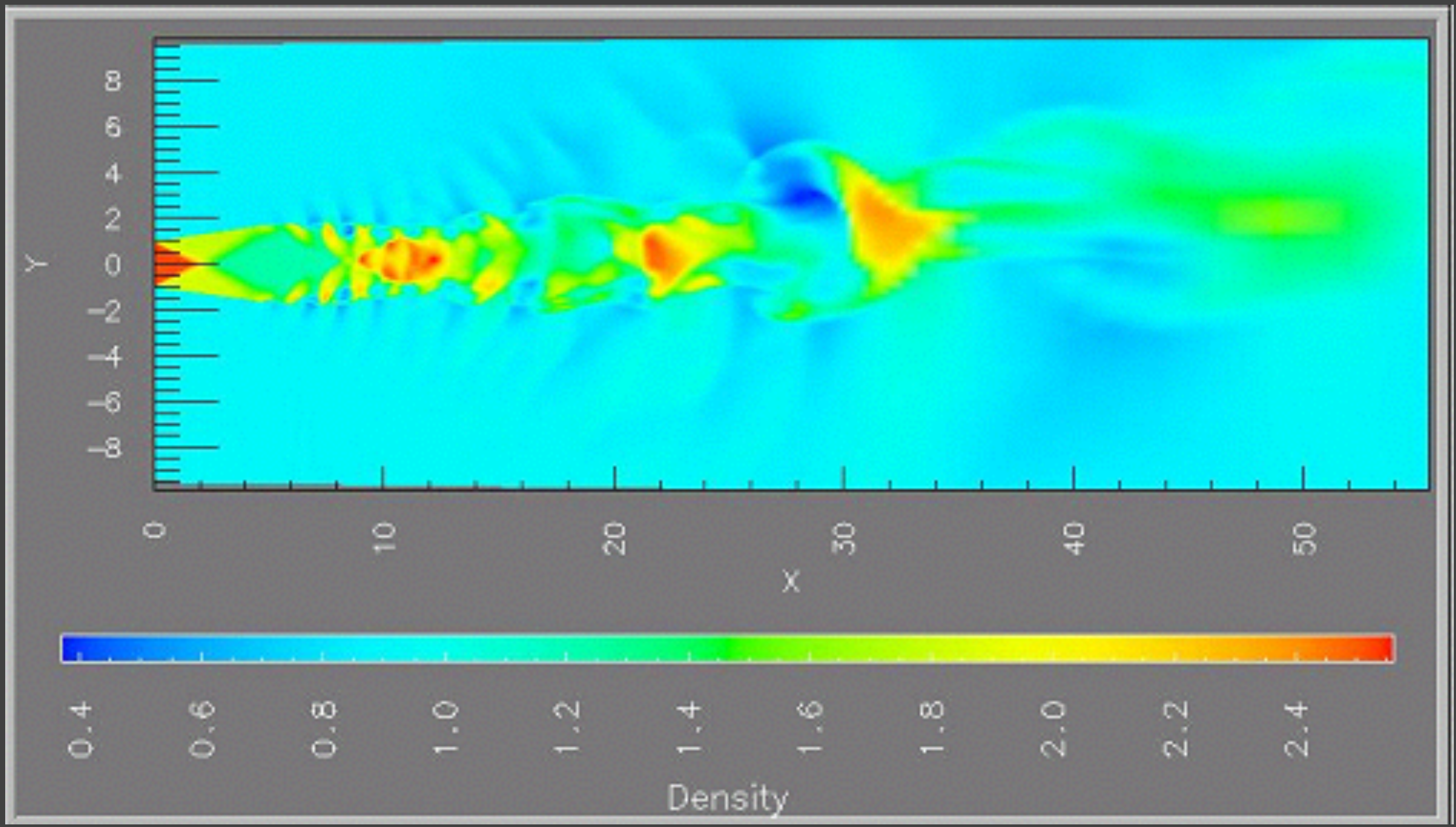
Minimize overlap and ambiguity of colors.

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*	

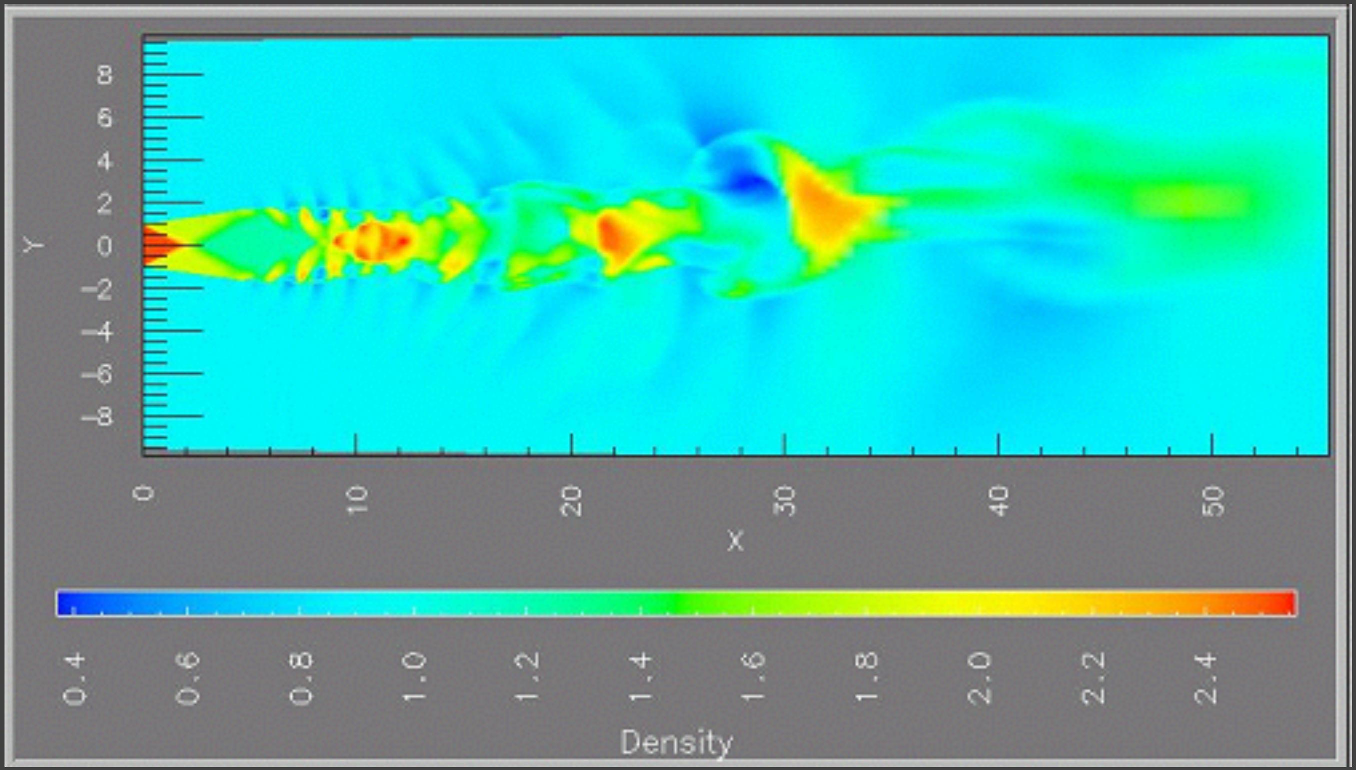
http://vis.stanford.edu/color-names

Quantitative Color

Rainbow Color Maps

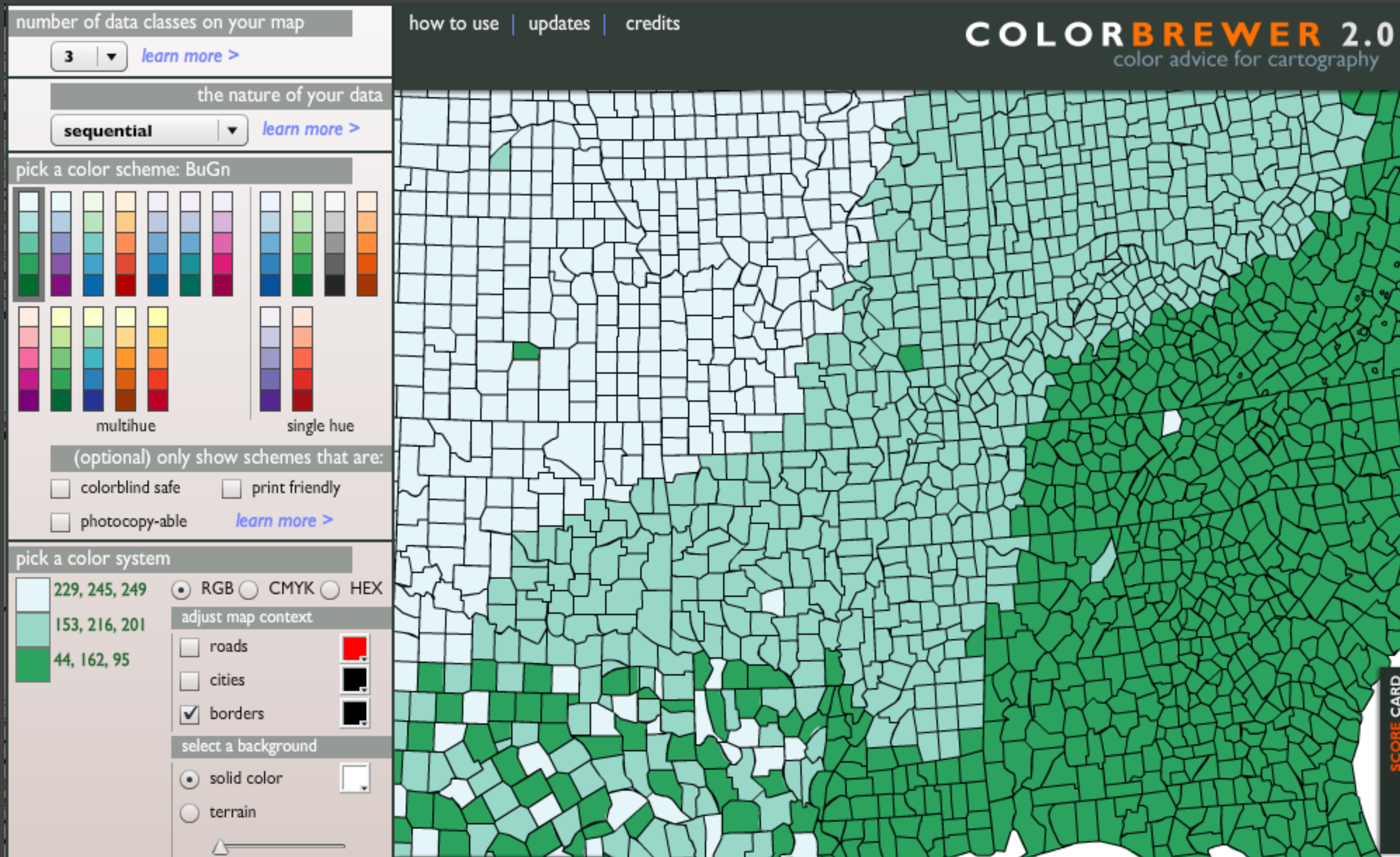


Be Wary of Naïve Rainbows!



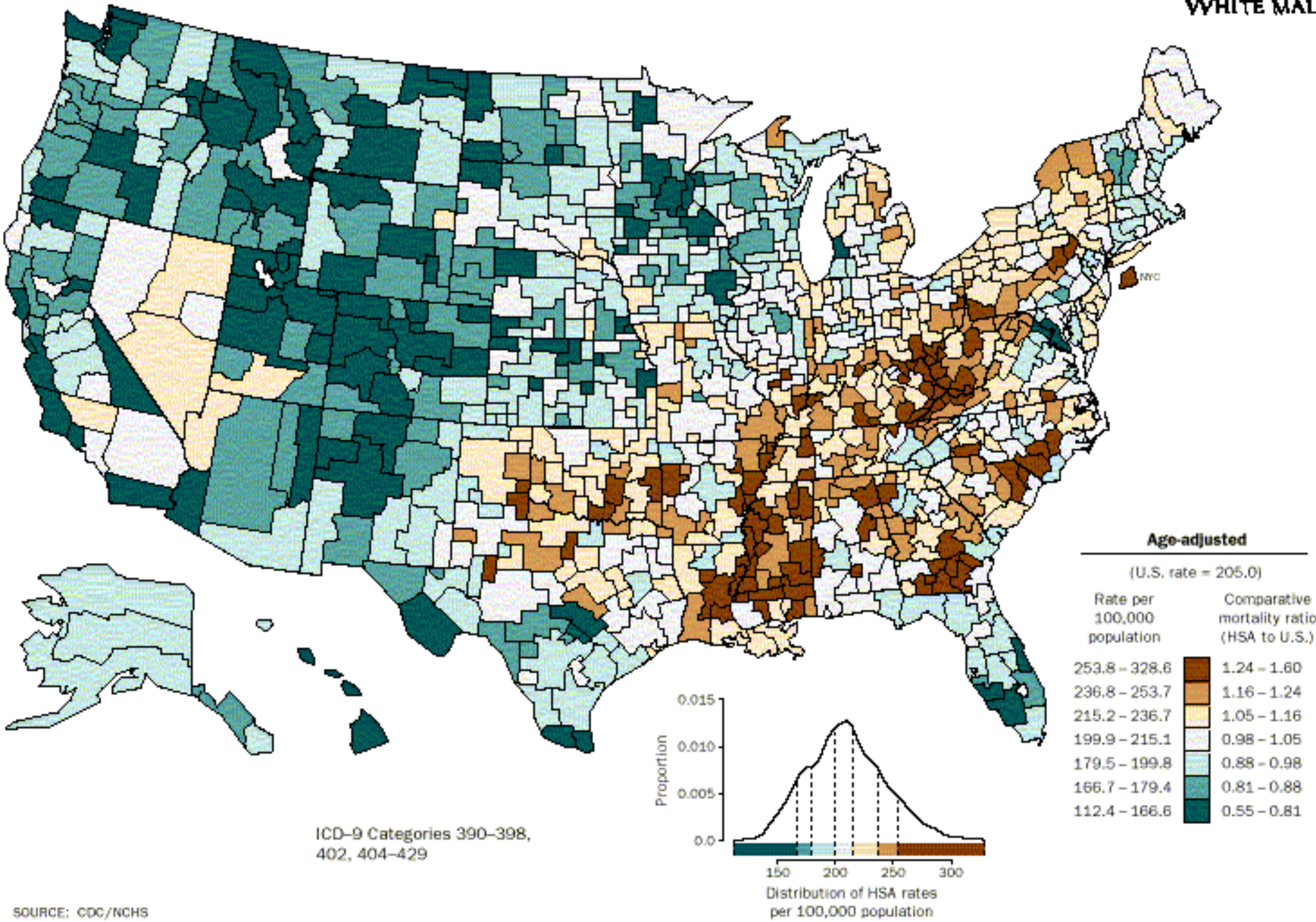
1. Hues are not naturally ordered
2. People segment colors into classes, perceptual banding
3. Naive rainbows are unfriendly to color blind viewers
4. Some colors are less effective at high spatial frequencies

Color Brewer: Palettes for Maps



Age-adjusted death rates by HSA, 1988-92

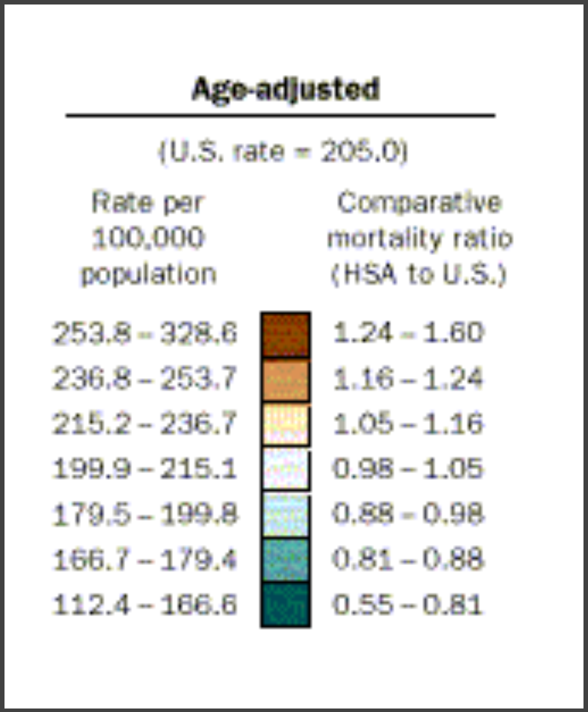
Heart disease
White male

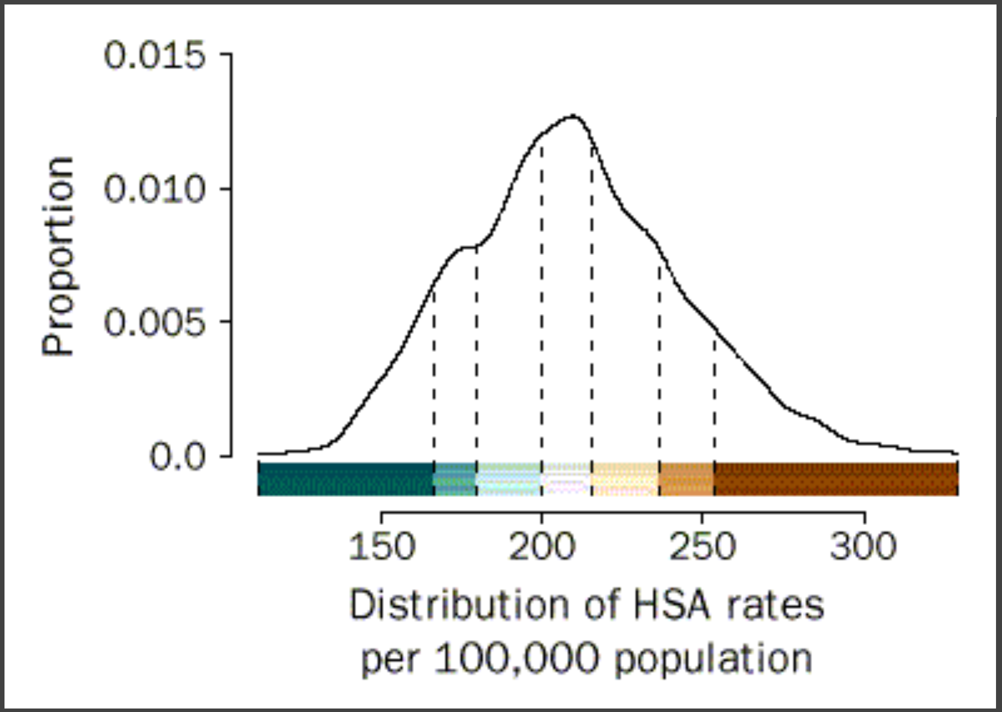


ICD–9 Categories 390–398, 402, 404–429

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)

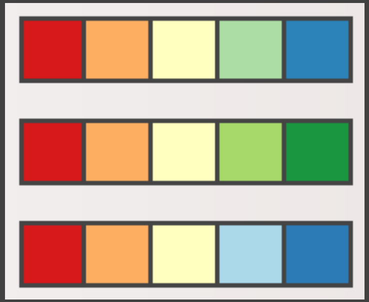
Quantitative Color Encoding

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

Use saturated colors for endpoints

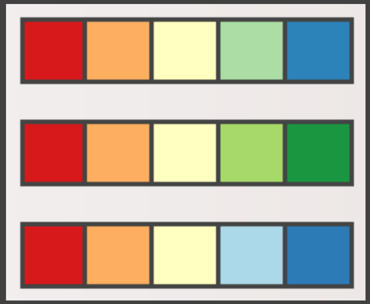
Quantitative Color Encoding

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

Use saturated colors for endpoints

Limit number of steps in color to 3-9

Why?

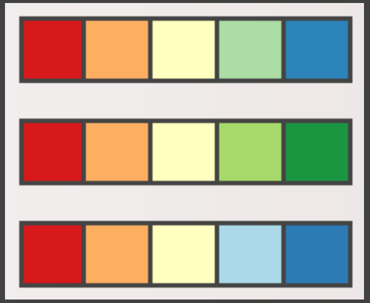
Quantitative Color Encoding

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

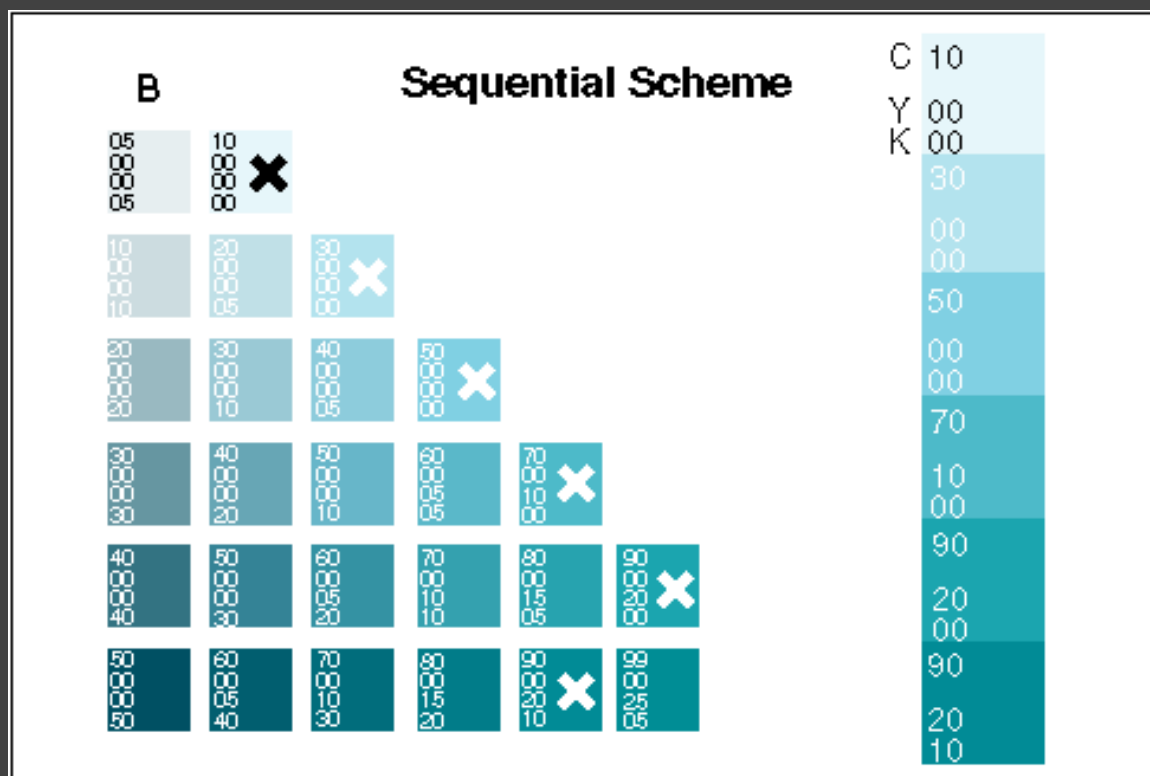
Use saturated colors for endpoints

Limit number of steps in color to 3-9

Avoid simultaneous contrast, hold mappings in memory

Sequential Scales: Single-Hue

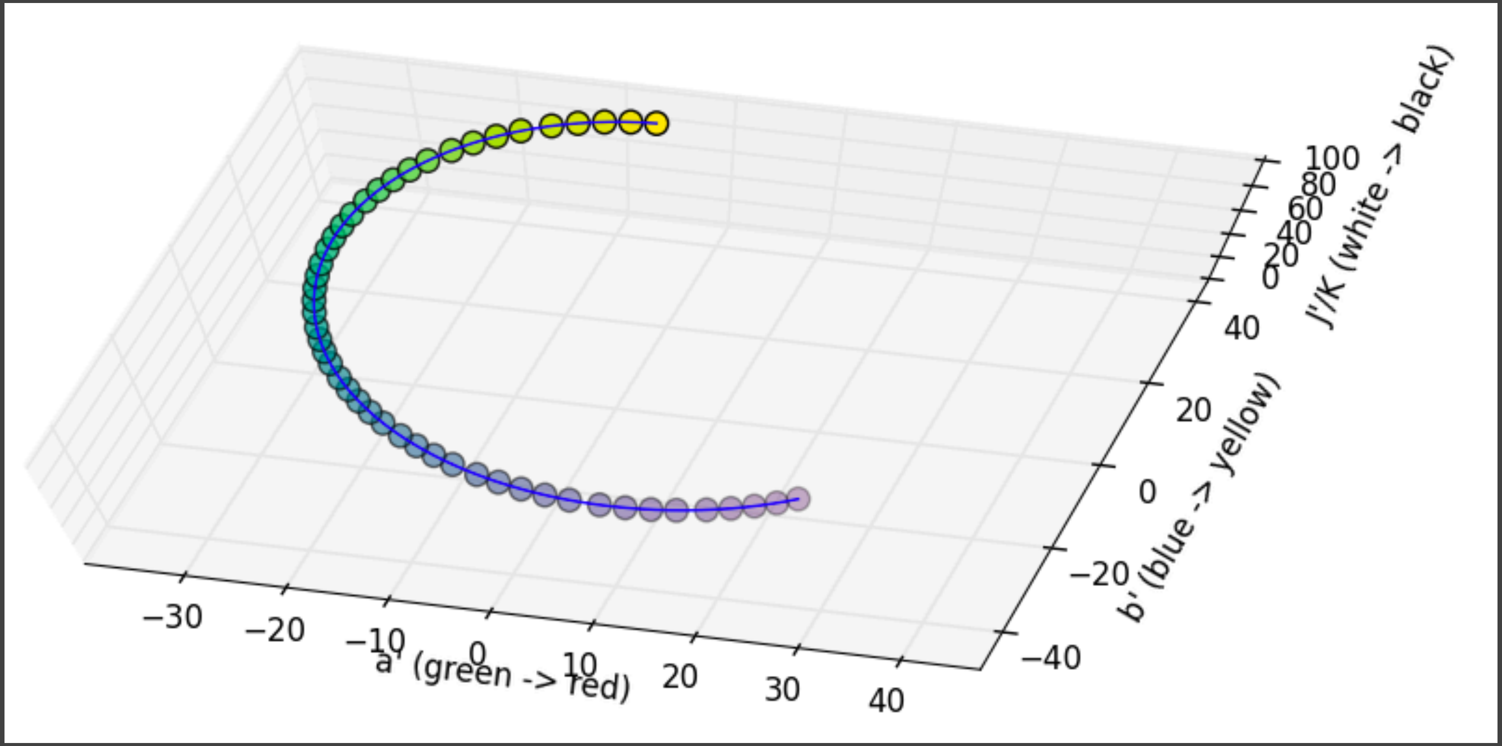
Ramp primarily in luminance, subtle hue difference



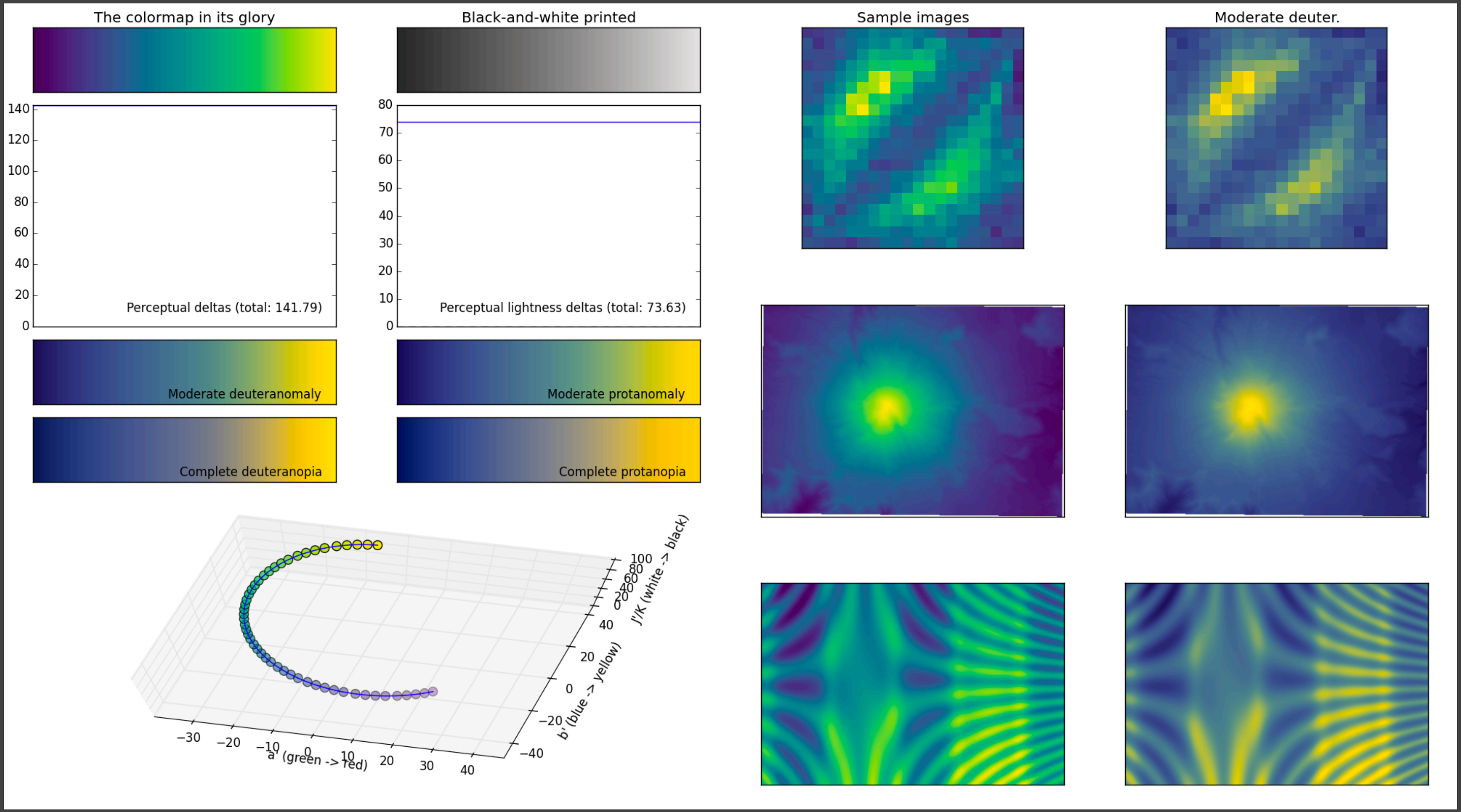
http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Sequential Scales: Multi-Hue

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

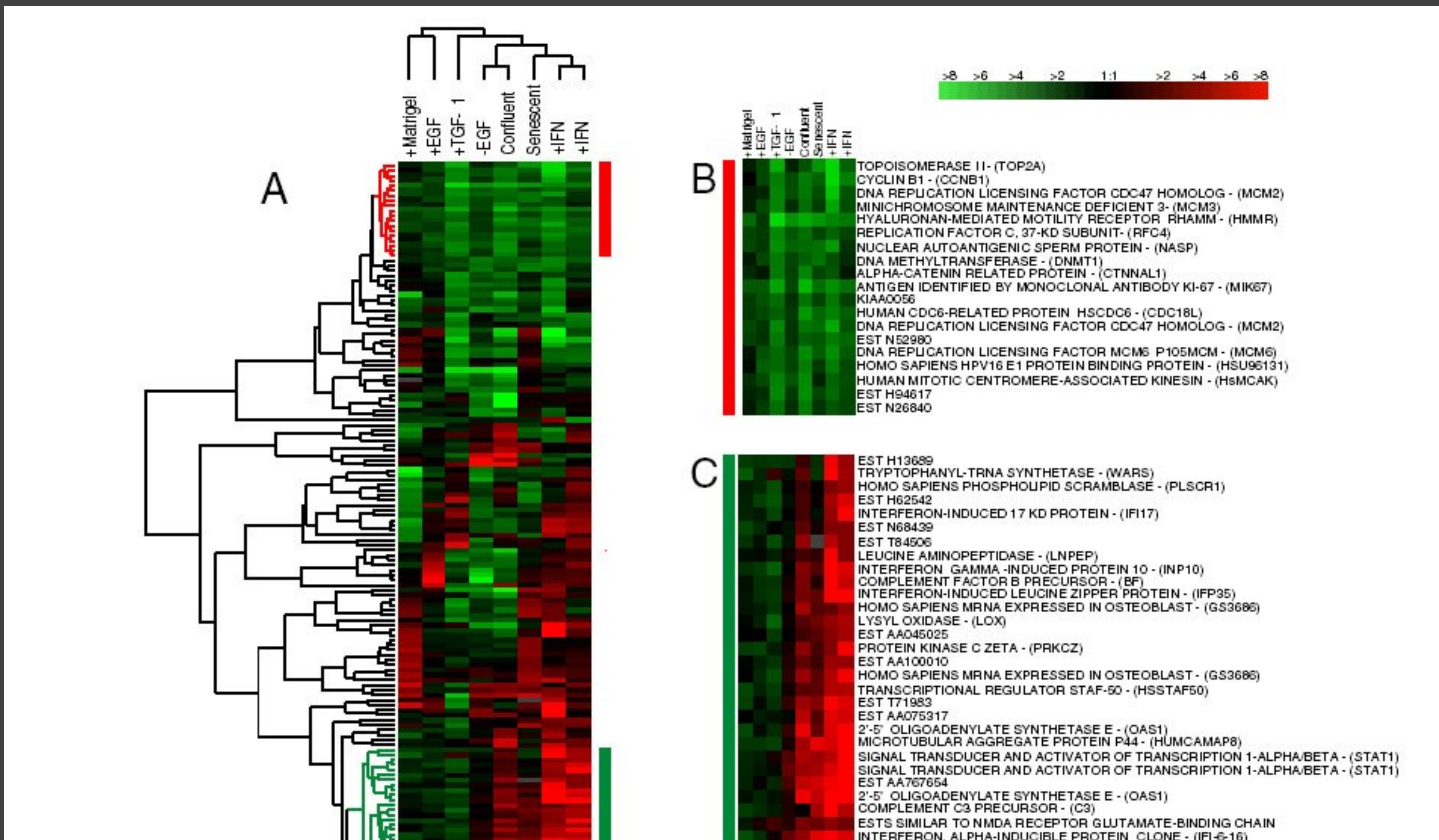


Sequential Scales: Multi-Hue

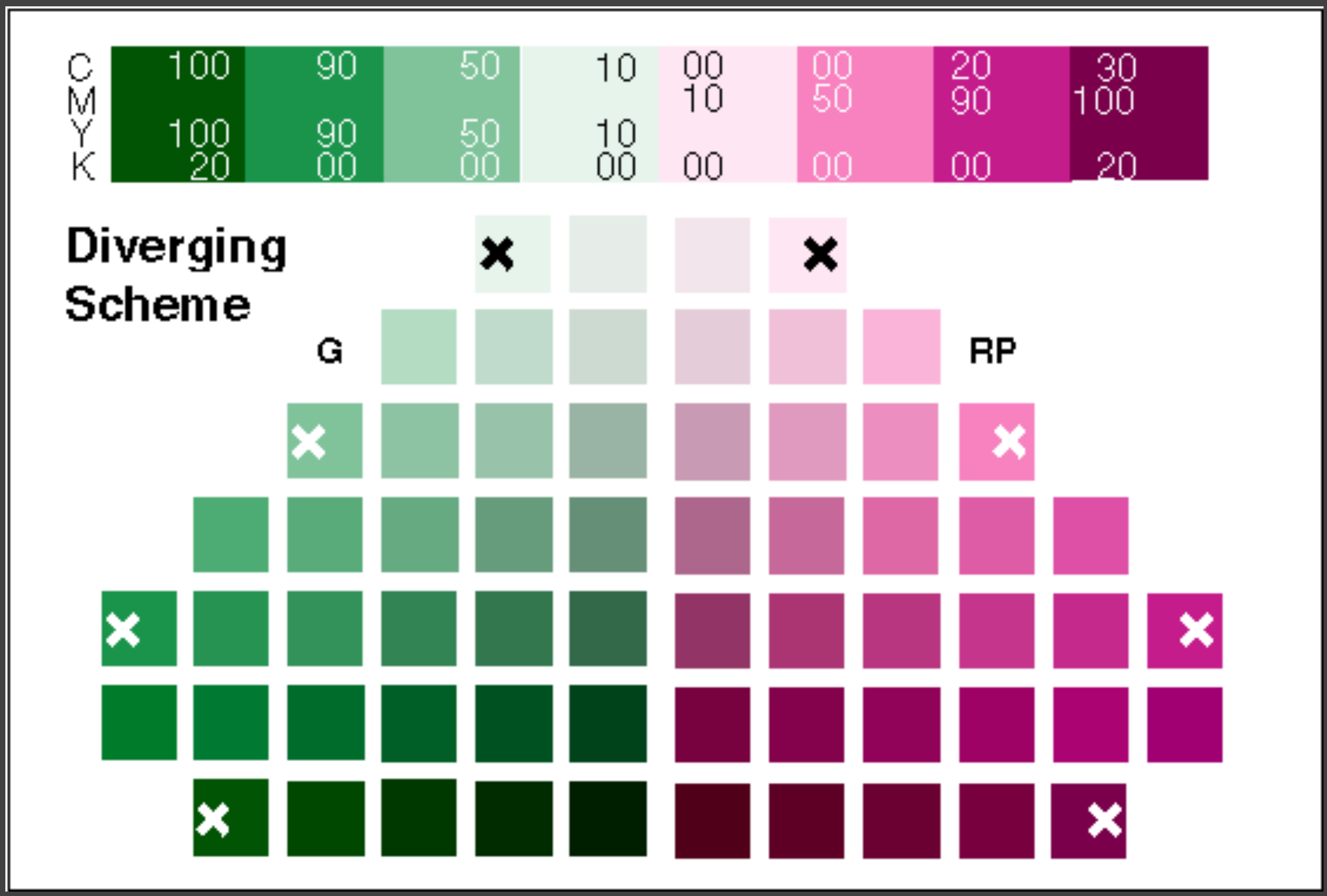


Viridis, https://bids.github.io/colormap/

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!