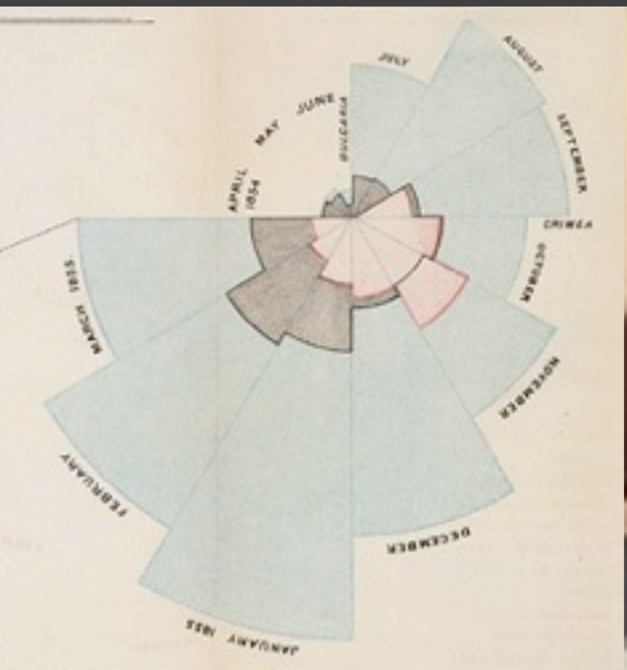
CSE512 :: 6 Feb 2014

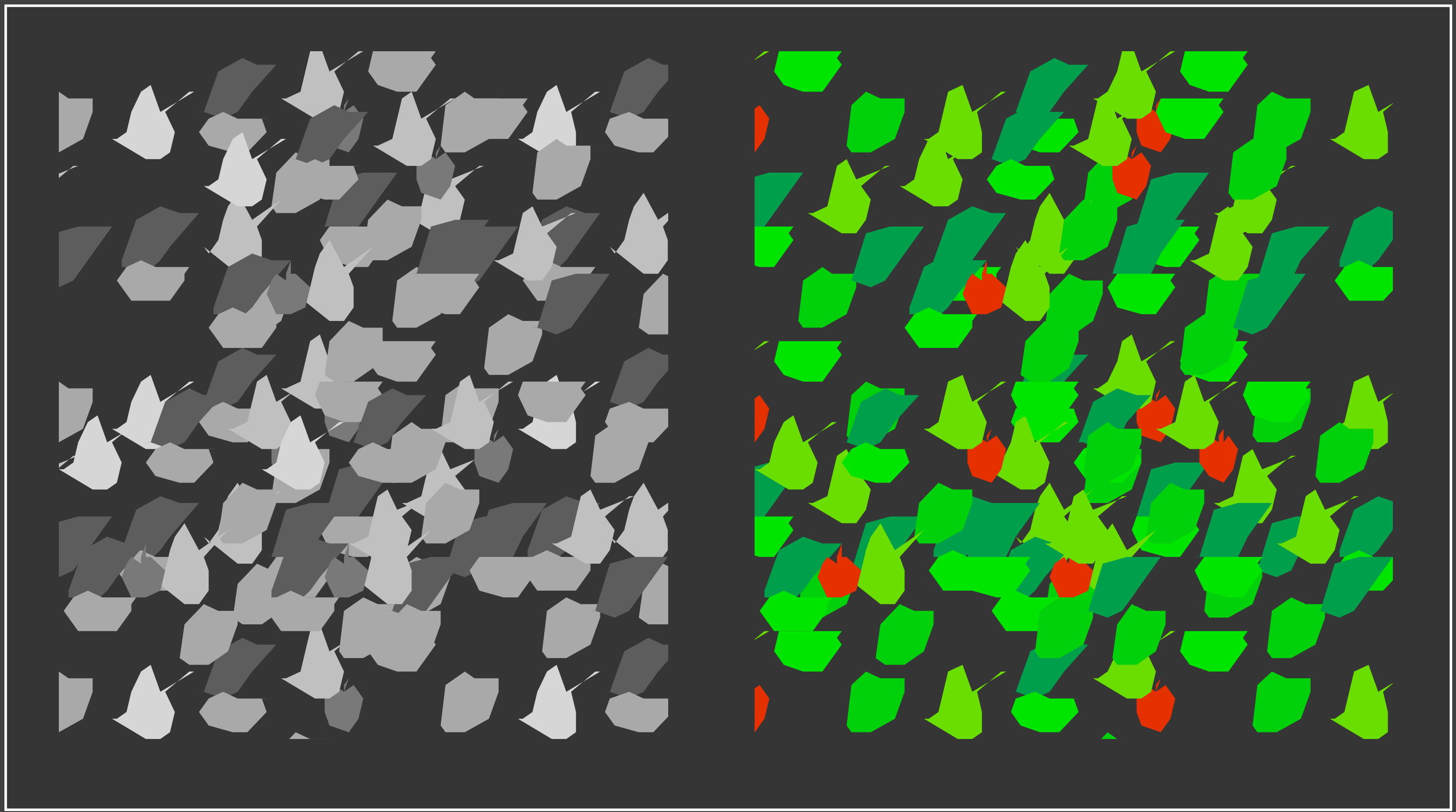
Color



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

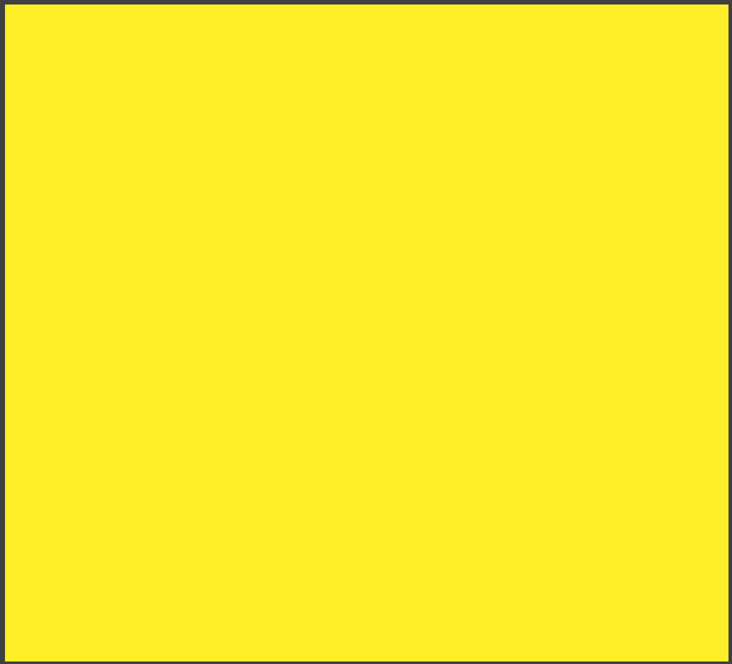
Color in Information Visualization

Nominal, Ordinal & Quantitative color encoding

Guidelines for color palette design

Perception of Color

What color is this?

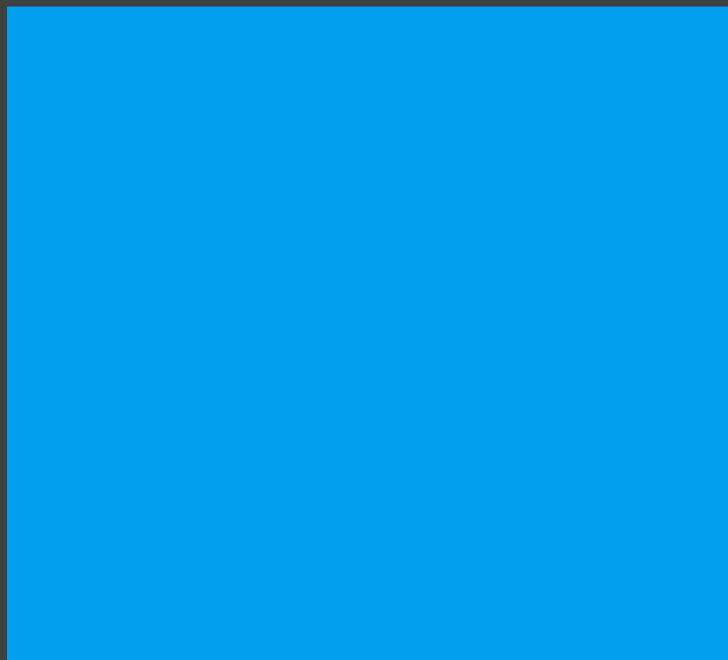


What color is this?

“Yellow”

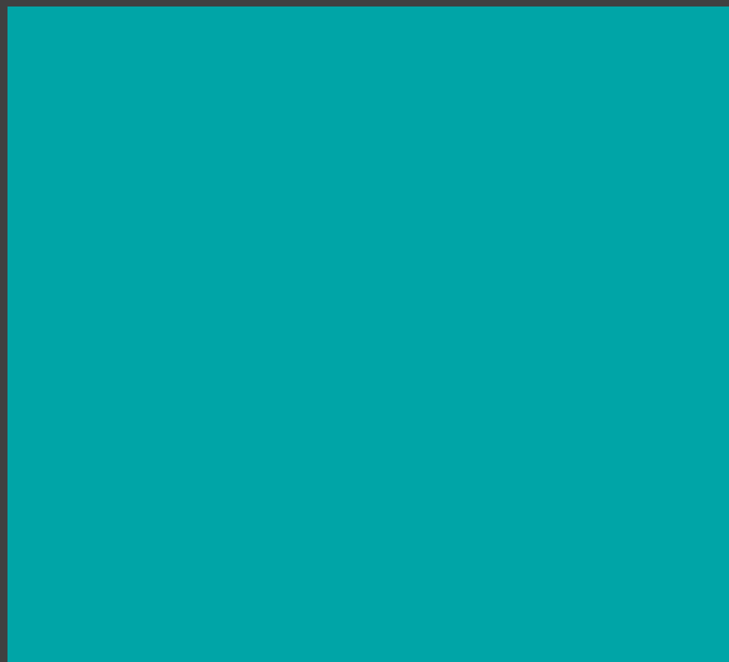
What color is this?

What color is this?



“Blue”

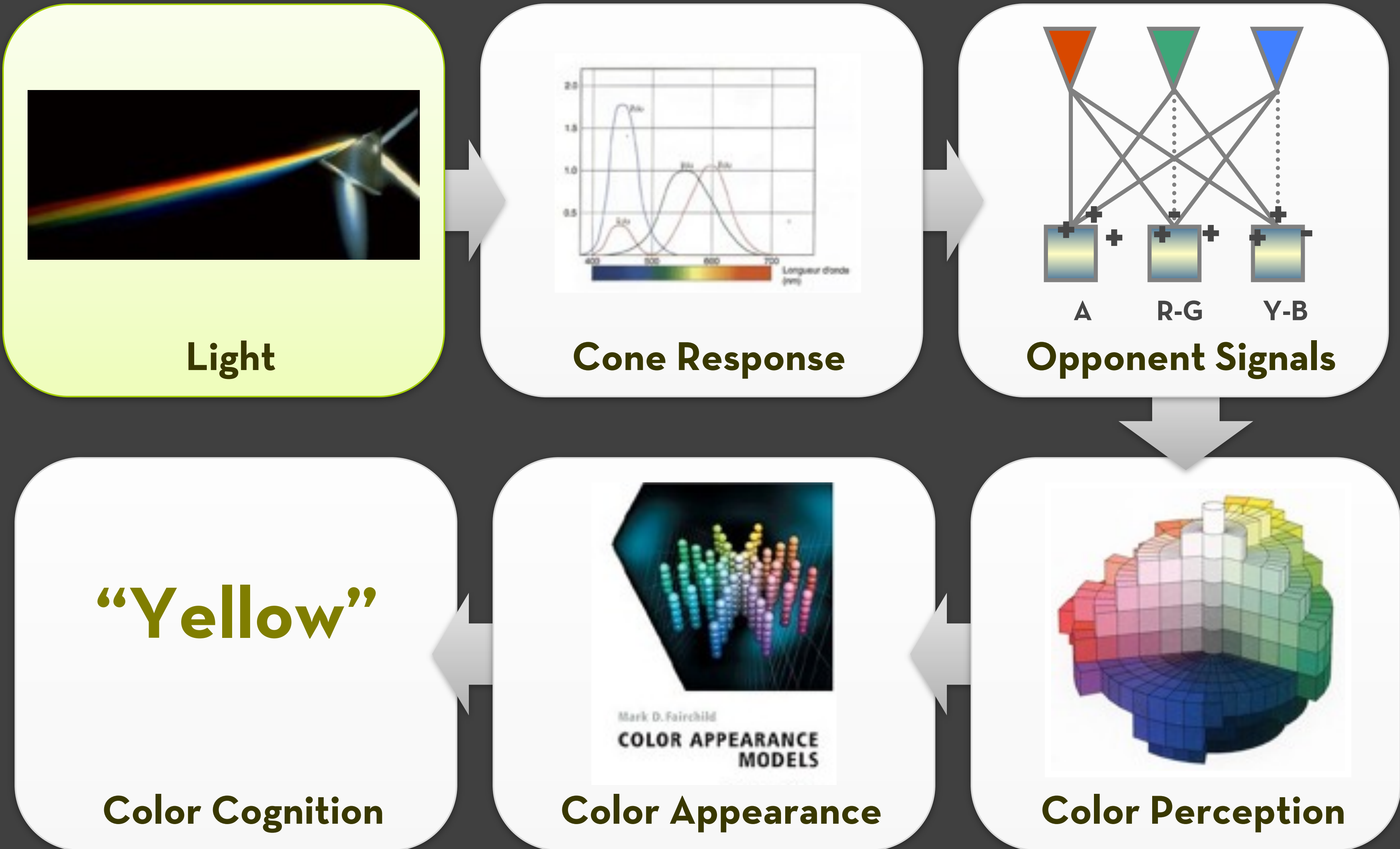
What color is this?



What color is this?

“Teal” ?

Perception of Color



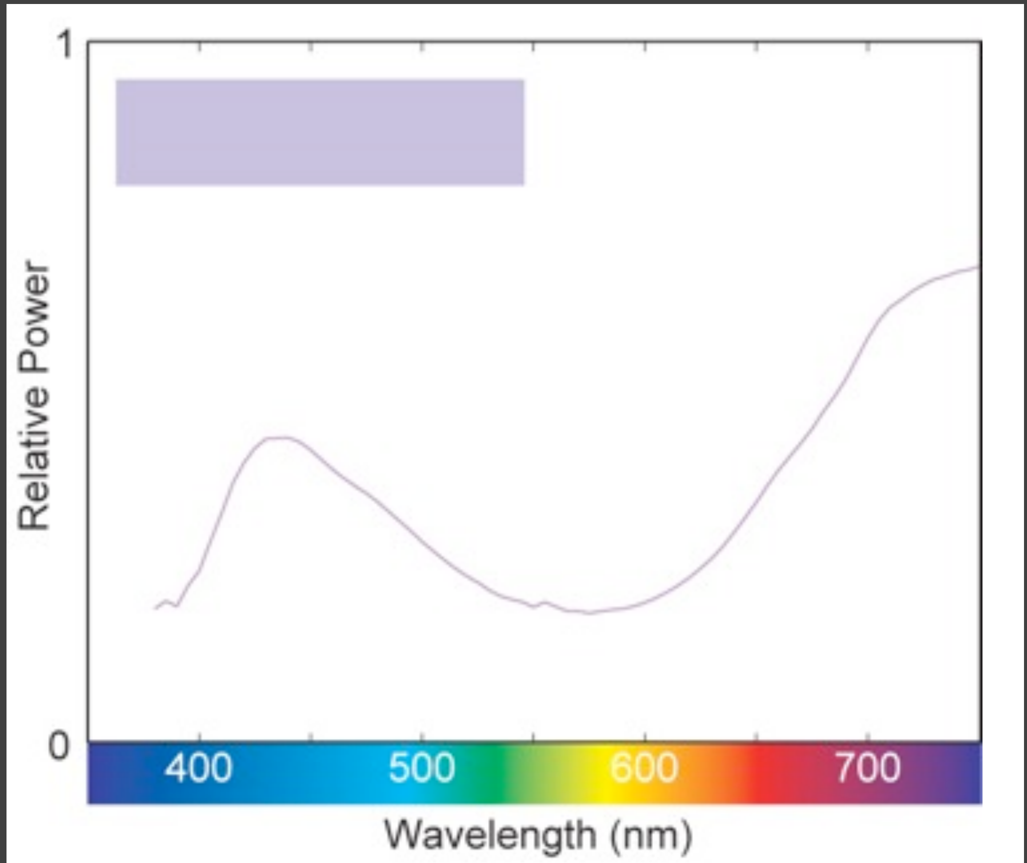
Physicist's view

Light as electromagnetic wave

Wavelength

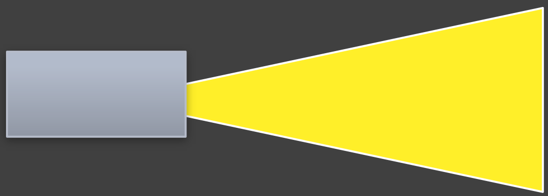
Energy or

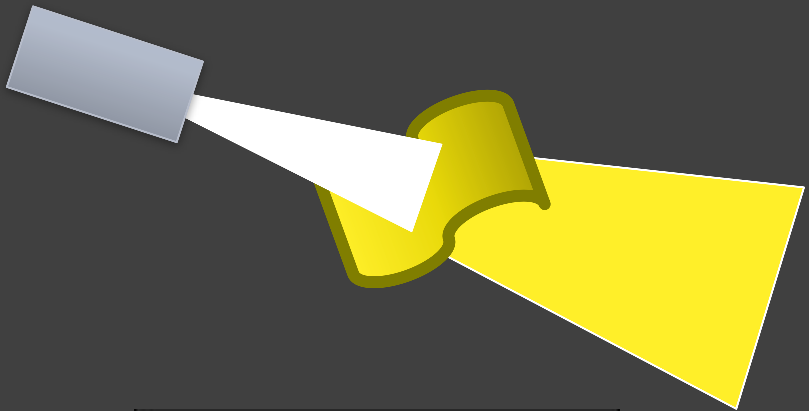
"Relative luminance"



A Field Guide to Digital Color, A.K. Peters

Emissive vs. reflective light



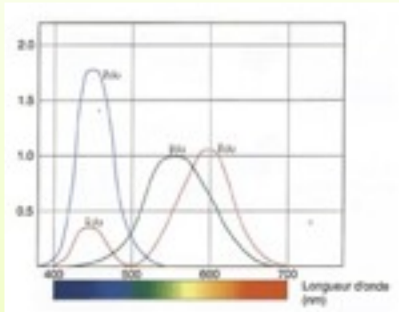


Additive
(digital displays)

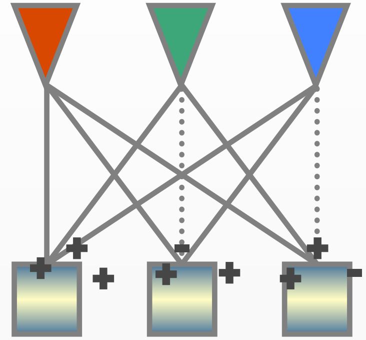
Subtractive
(print, e-paper)

Perception of Color

Light

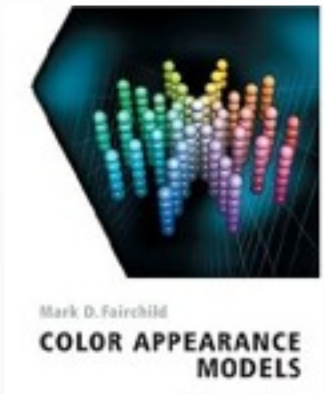


Cone Response



Opponent Signals

Color Perception

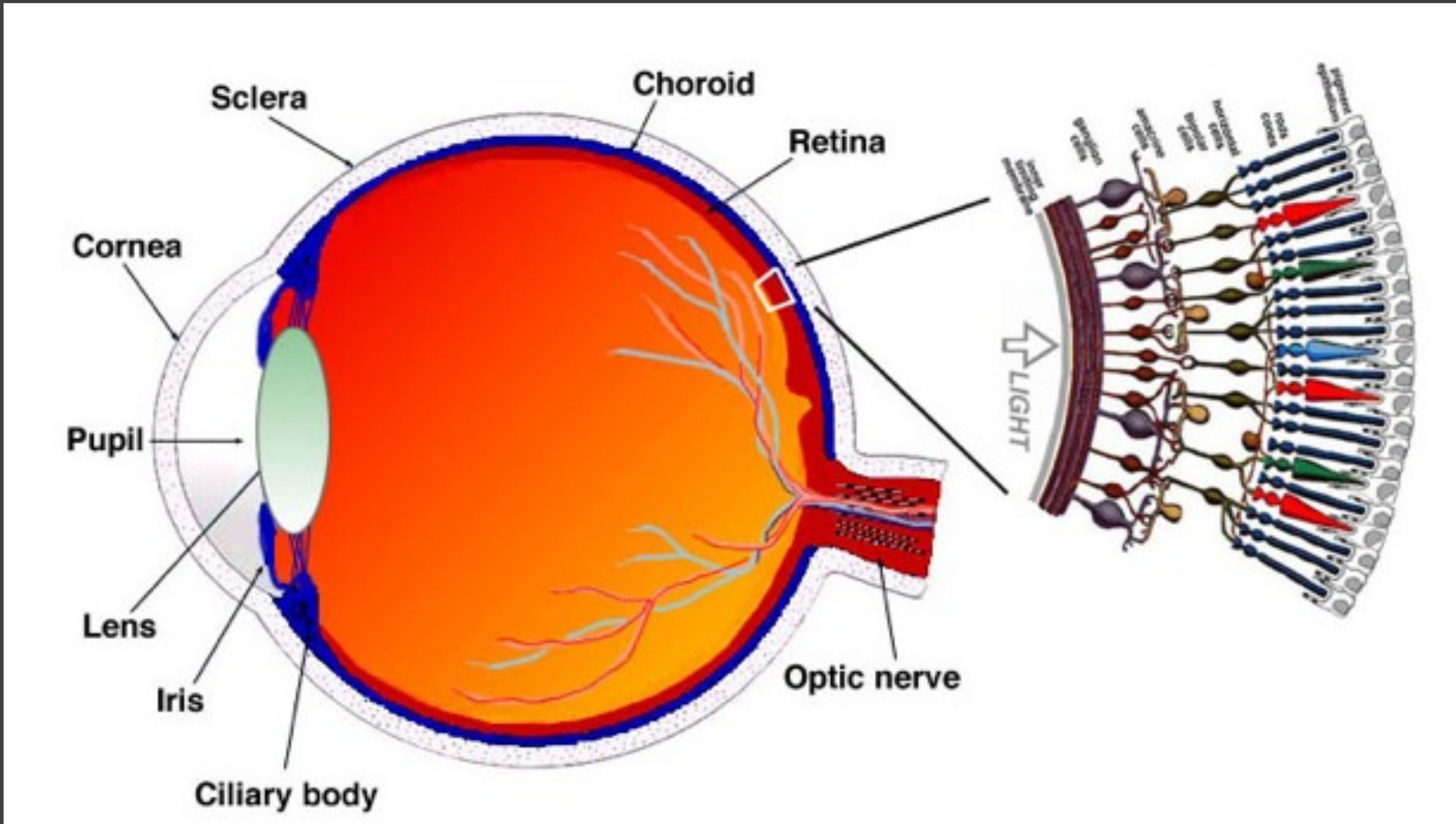


Color Appearance

"Yellow"

Color Cognition

Retina

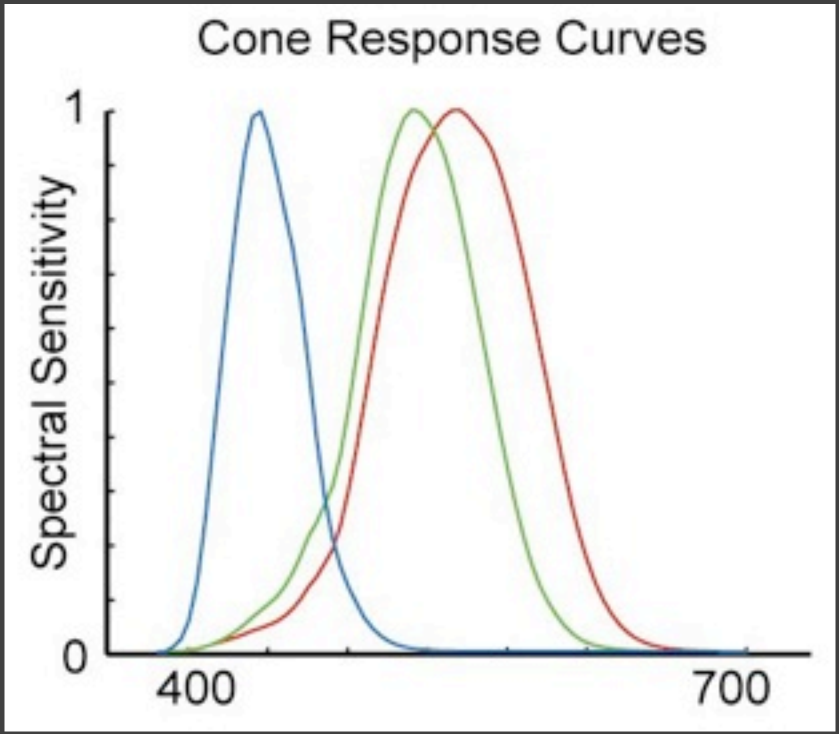


Simple Anatomy of the Retina, Helga Kolb

As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength



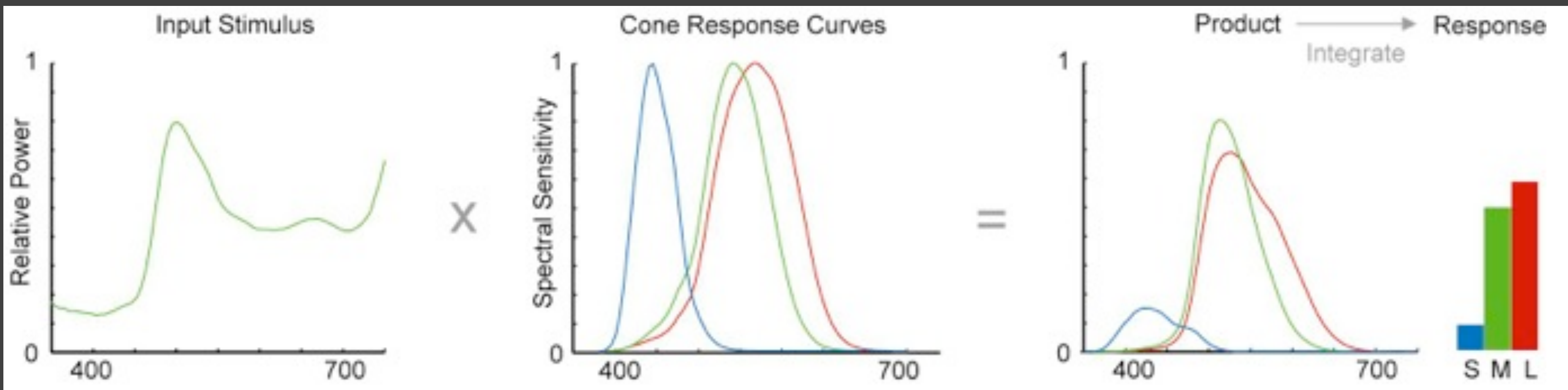
A Field Guide to Digital Color, Maureen Stone

As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength

Integration with input stimulus



A Field Guide to Digital Color, Maureen Stone

Effects of retina encoding

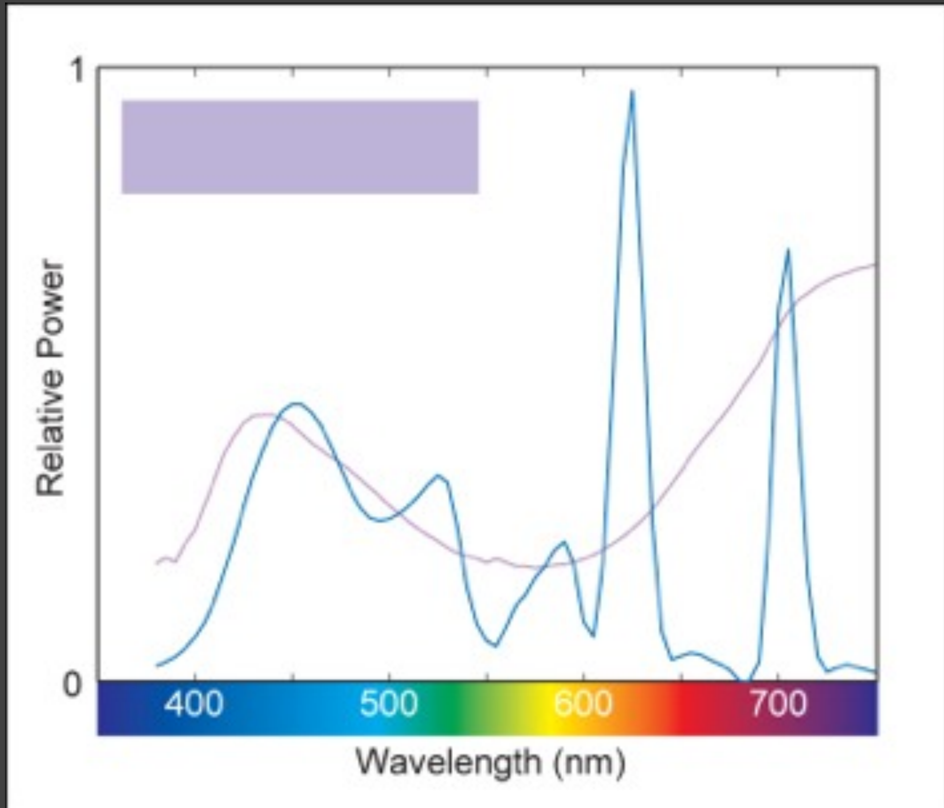
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. “metamers”).

“Tri-stimulus”

Computer displays

Digital scanners

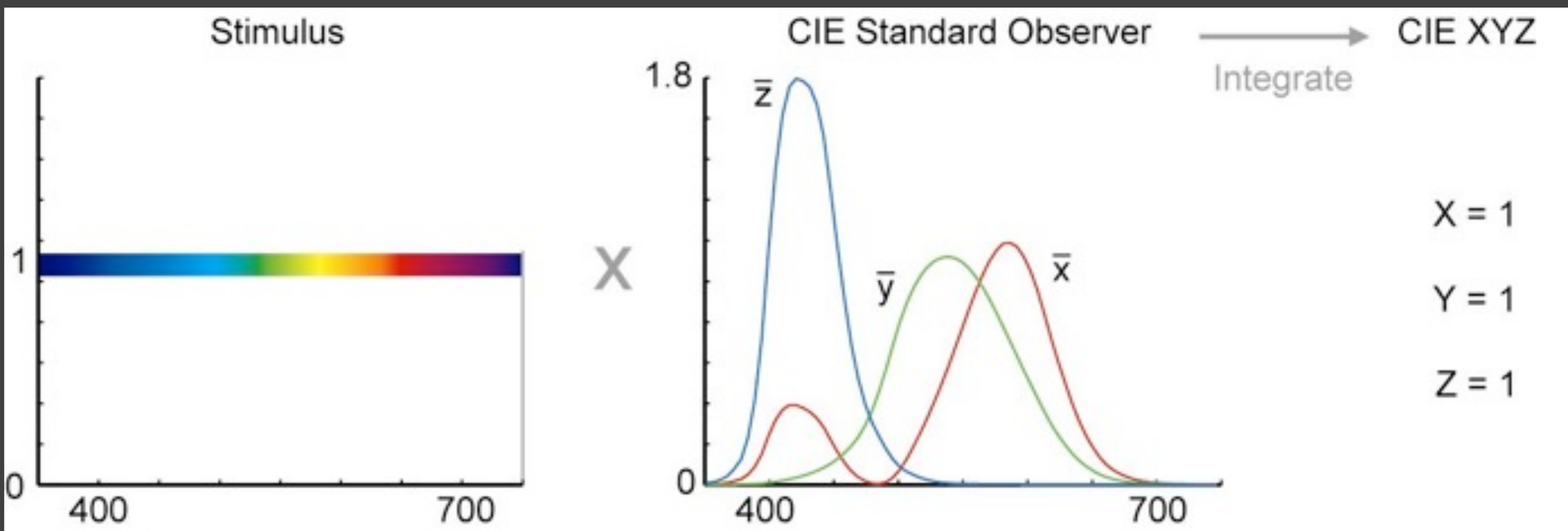
Digital cameras



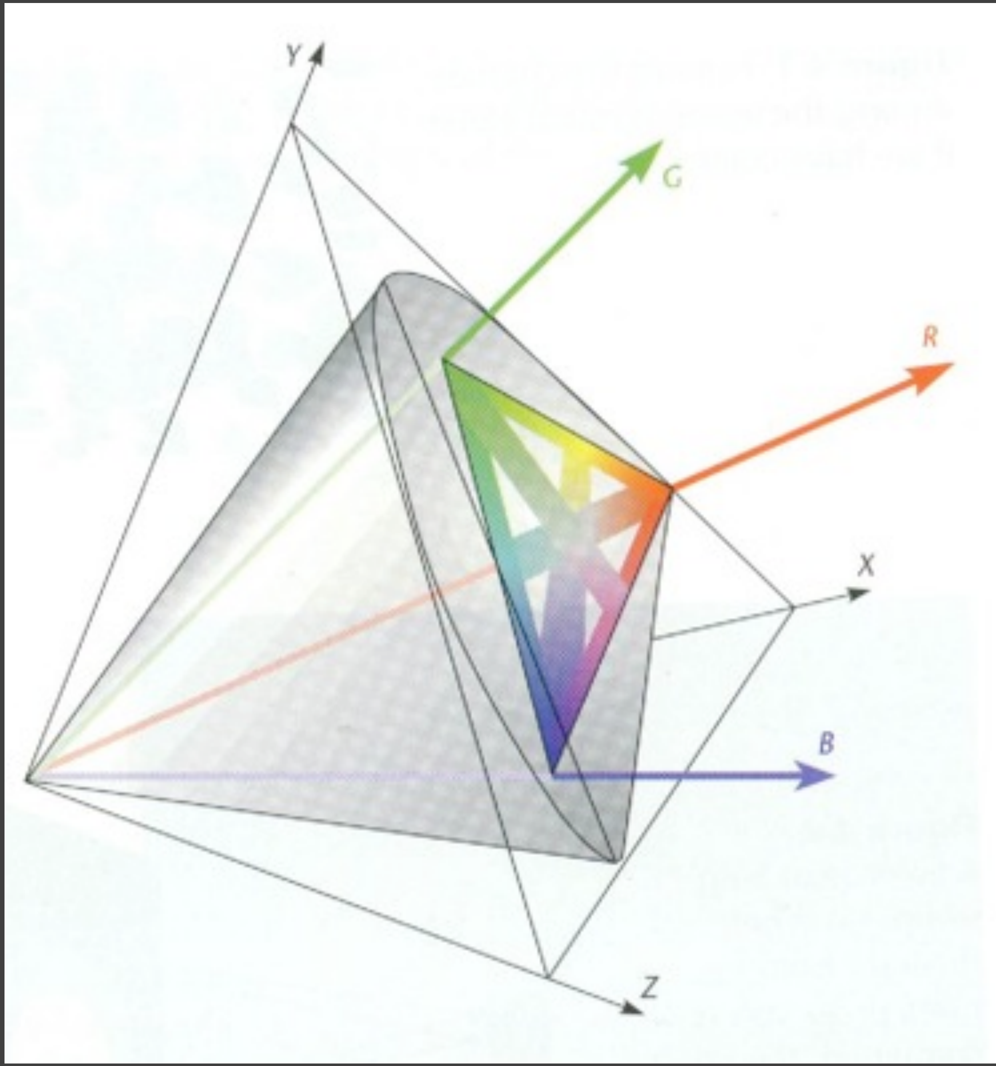
CIE XYZ color space

Standardized in 1931 to mathematically represent tri-stimulus response.

"Standard observer" response curves



CIE XYZ color space



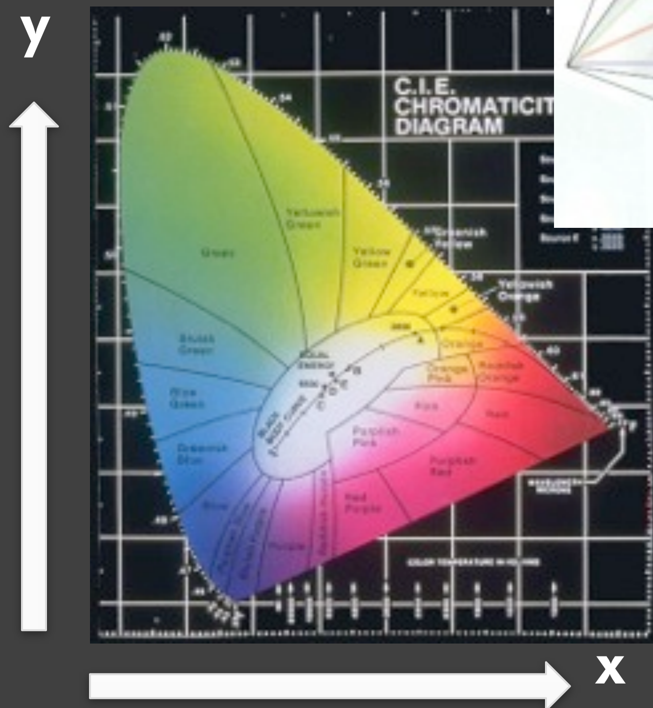
Colin Ware

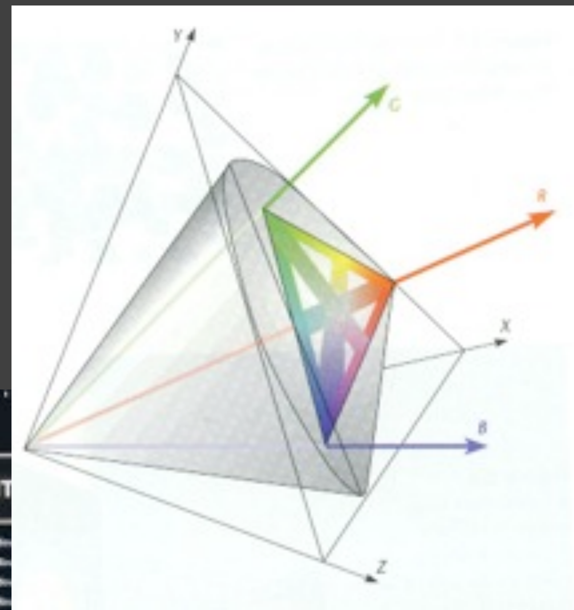
CIE chromaticity diagram

Colorfulness vs. Brightness

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

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

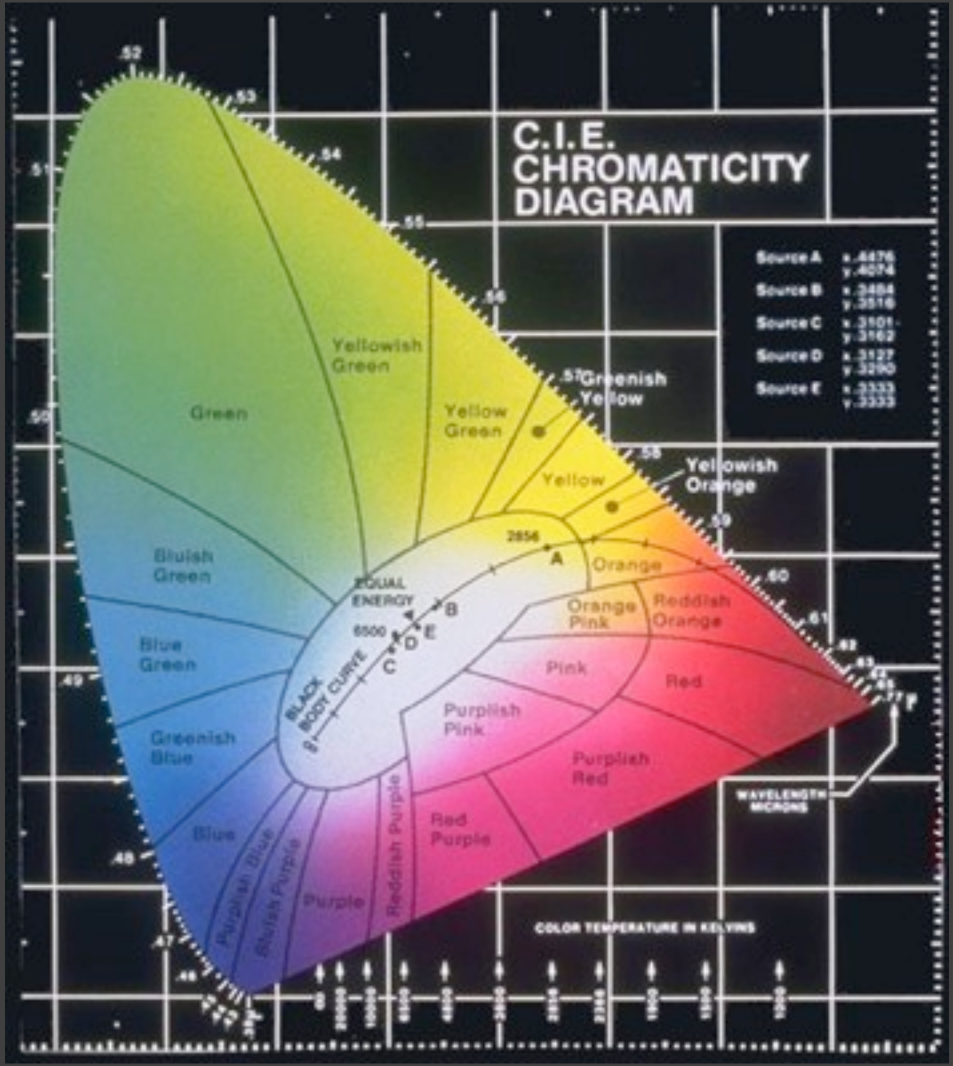




Colin Ware

CIE chromaticity diagram

- Spectrum locus
- Purple line
- Mixture of two lights appears as a straight line.



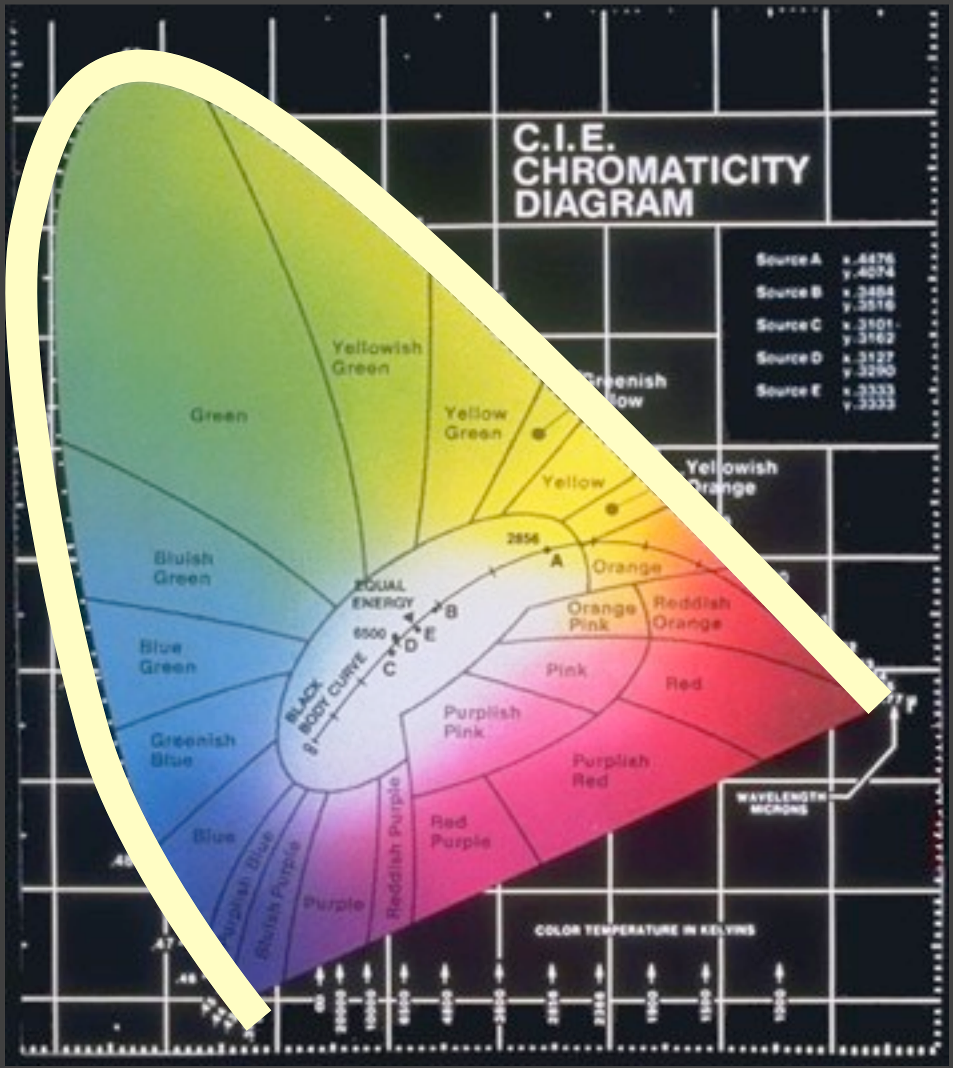
Courtesy of PhotoResearch, Inc.

CIE chromaticity diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.



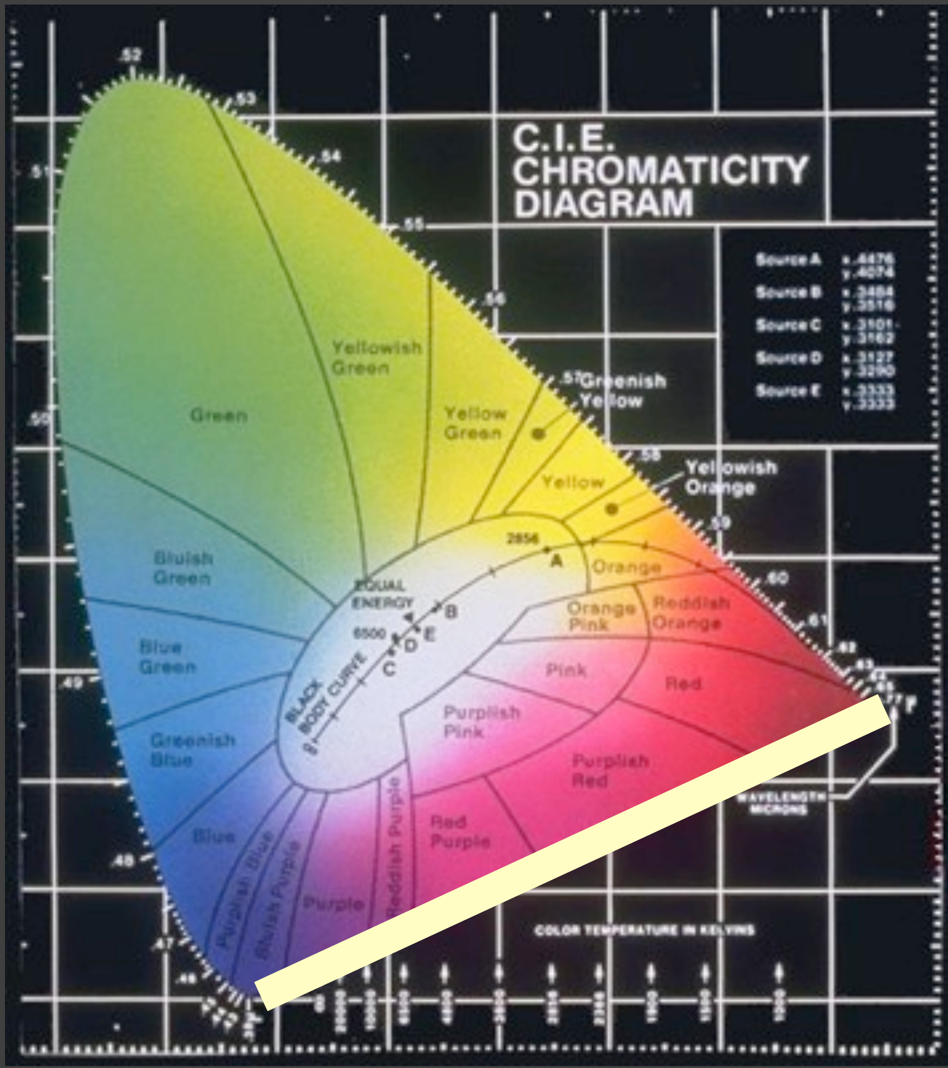
Courtesy of PhotoResearch, Inc.

CIE chromaticity diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.



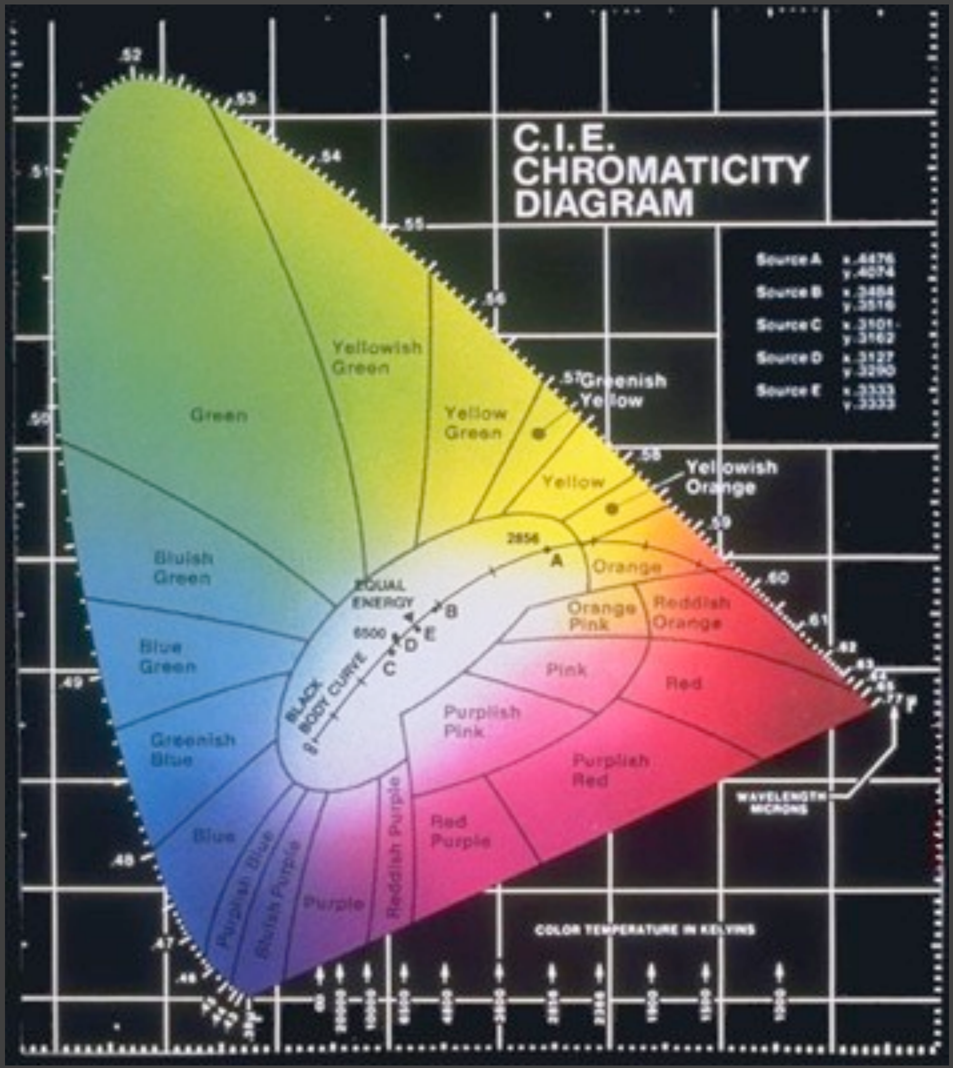
Courtesy of PhotoResearch, Inc.

CIE chromaticity diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.



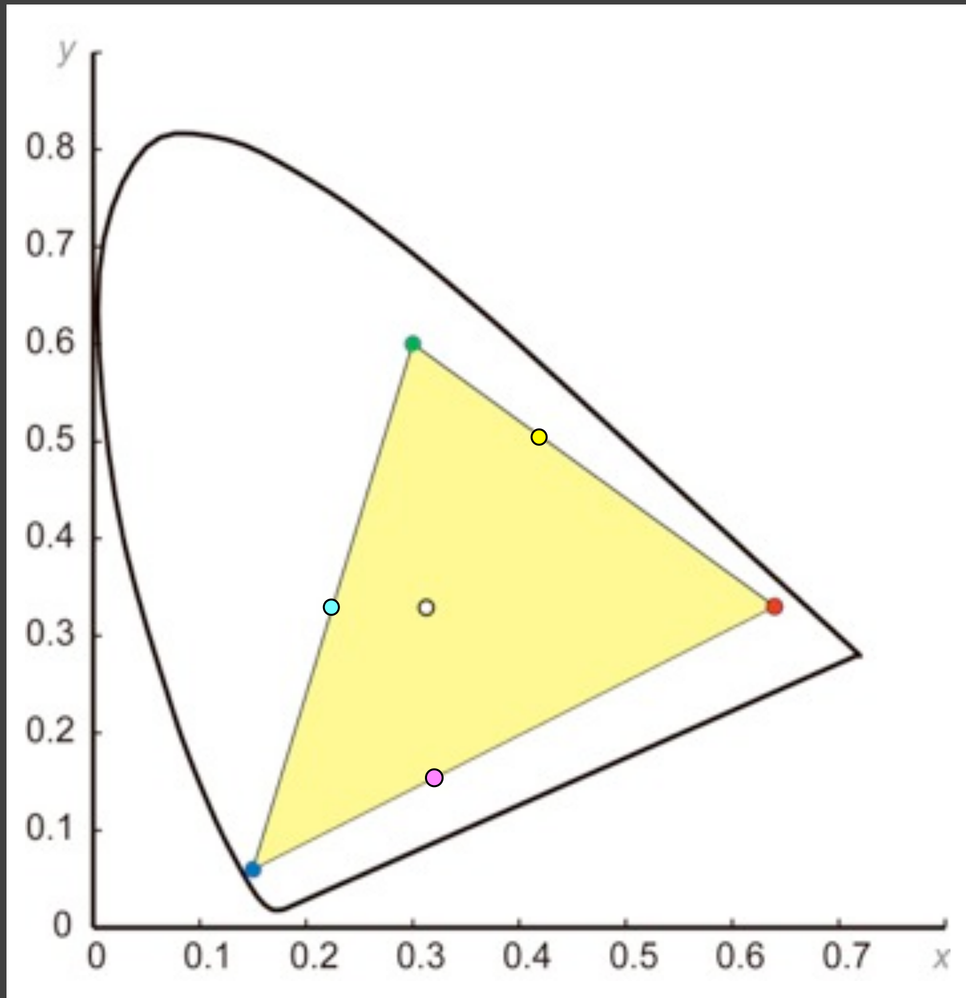
Courtesy of PhotoResearch, Inc.

Display gamuts

Typically defined by:

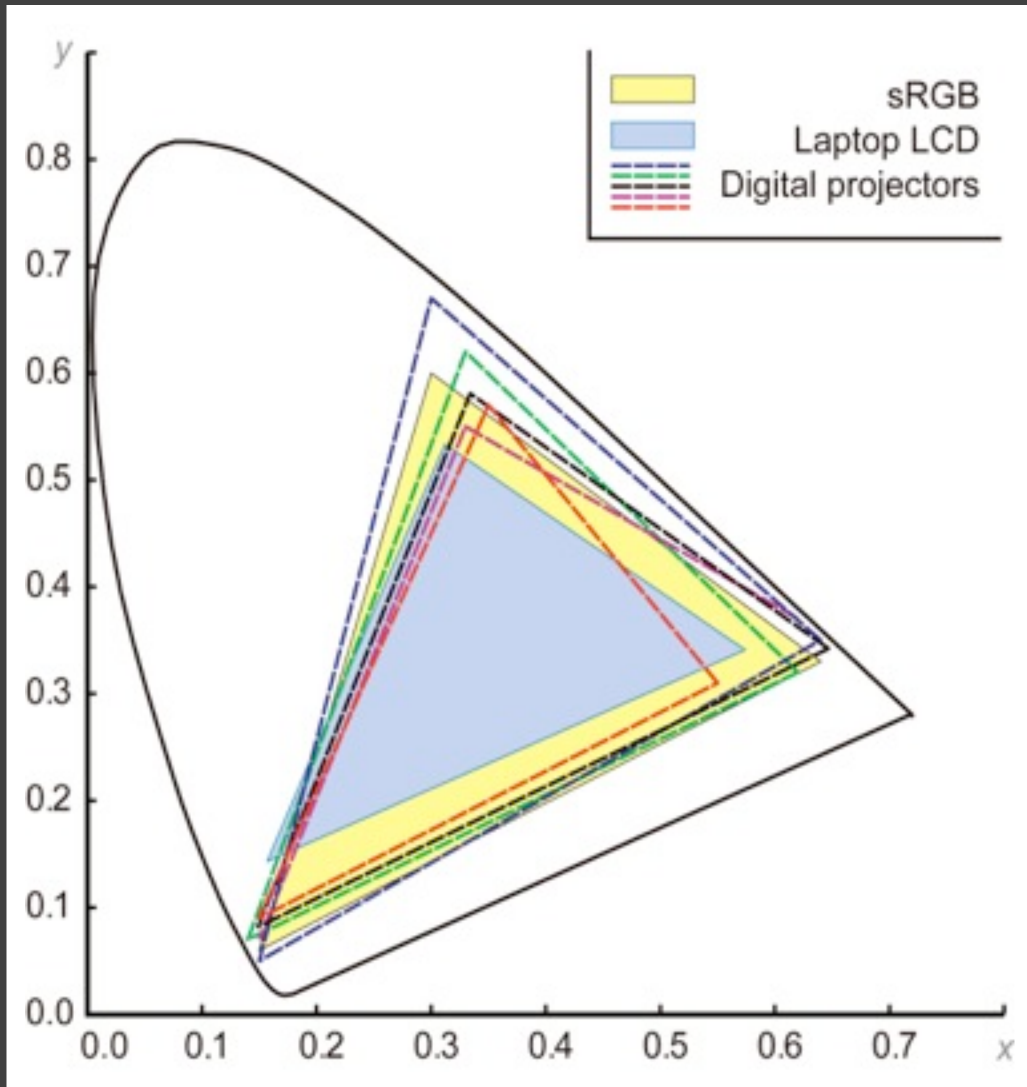
3 Colorants

Convex region



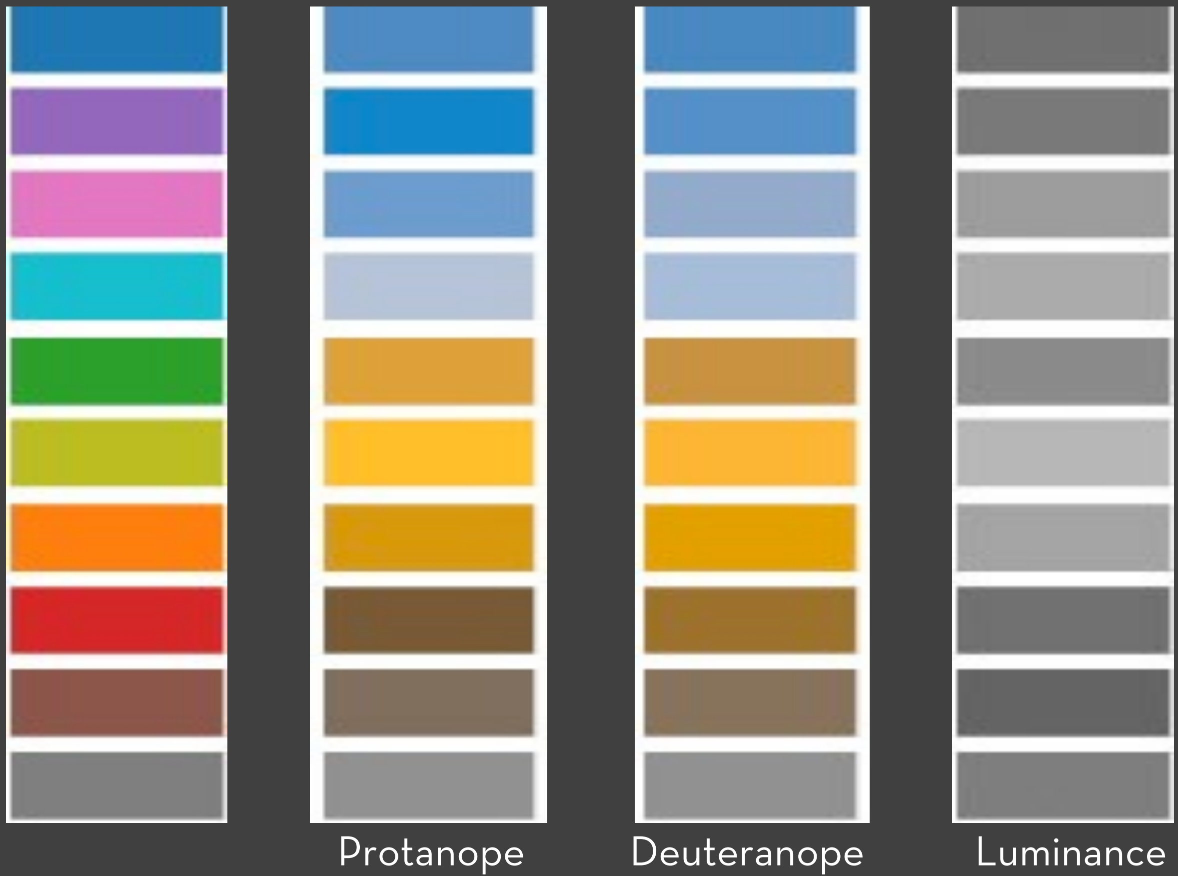
Display gamuts

Deviations from sRGB specification



Color blindness

Missing one or more retina cones or rods



VisCheck

Simulates color vision deficiencies

Web service or Photoshop plug-in

Robert Dougherty and Alex Wade

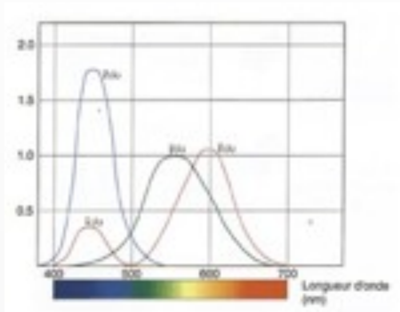
Deuteranope

Protanope

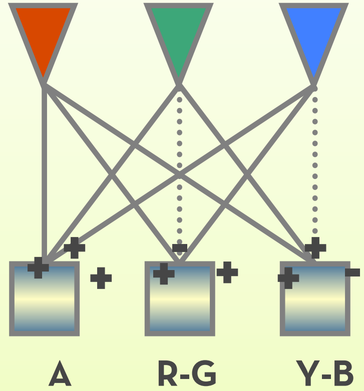
Tritanope

Perception of Color

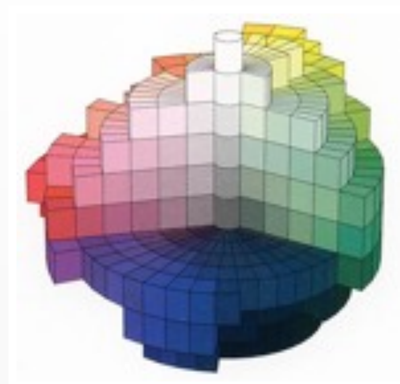
Light



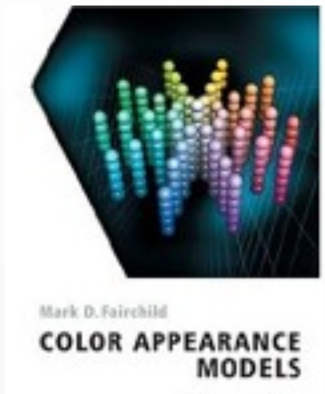
Cone Response



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

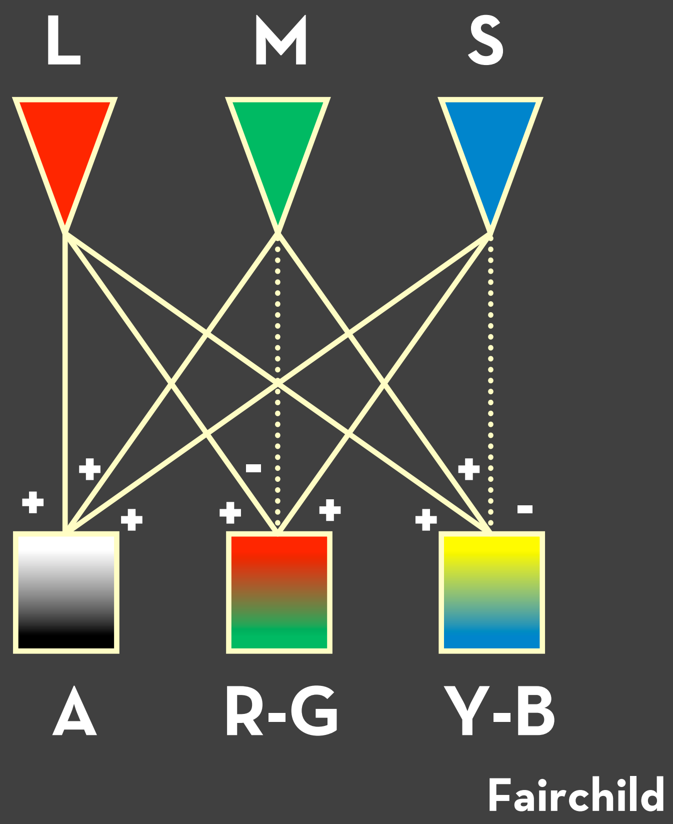
Opponent processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



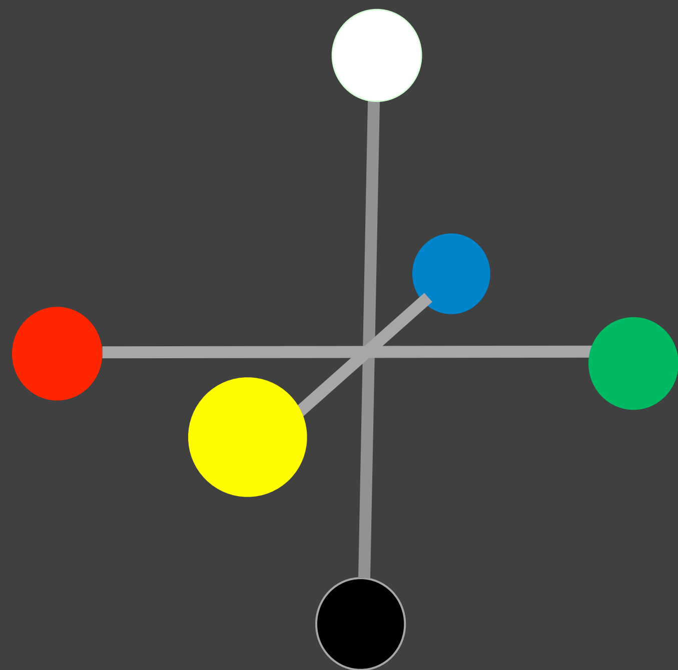
Opponent processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Opponent processing

LMS are combined to create:

Lightness

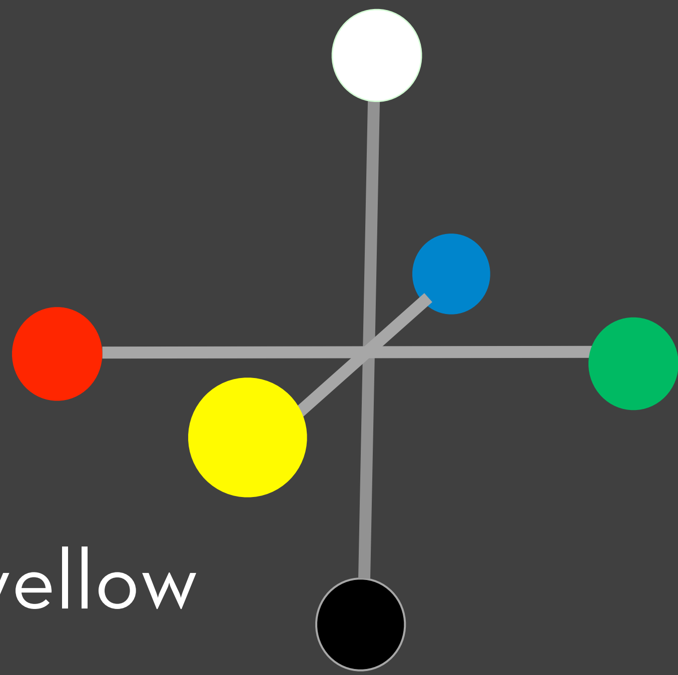
Red-green contrast

Yellow-blue contrast

Experiments:

No reddish green, no bluish yellow

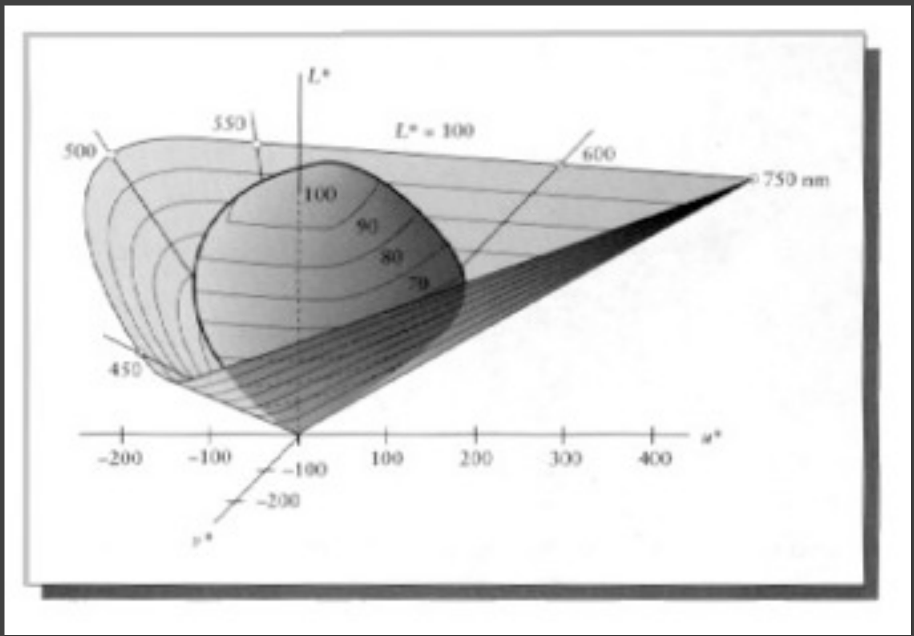
Color after images

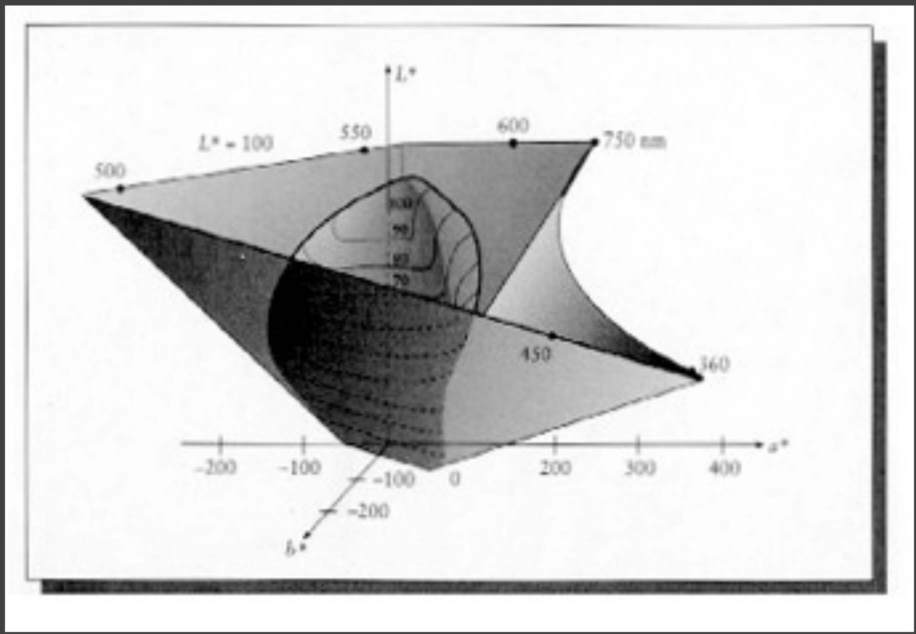


CIE LAB and LUV color spaces

Standardized in 1976 to mathematically represent opponent processing theory.

Non-linear transformation of CIE XYZ





Axes of CIE LAB

Correspond to opponent signals

L* = Luminance

a* = Red-green contrast

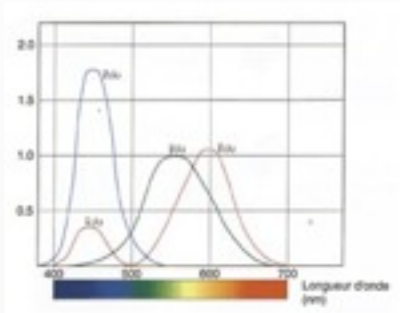
b* = Yellow-blue contrast

Scaling of axes to represent “color distance”

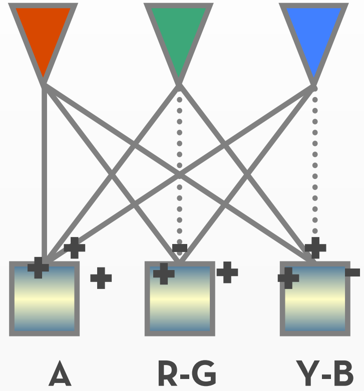
JND = Just noticeable difference (~2.3 units)

Perception of Color

Light

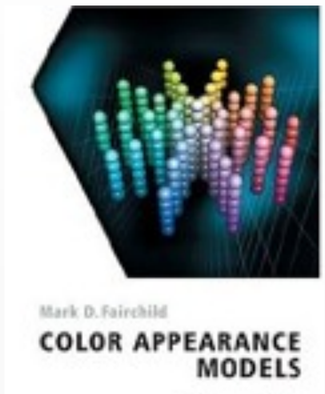


Cone Response



Opponent Signals

Color Perception



Color Appearance

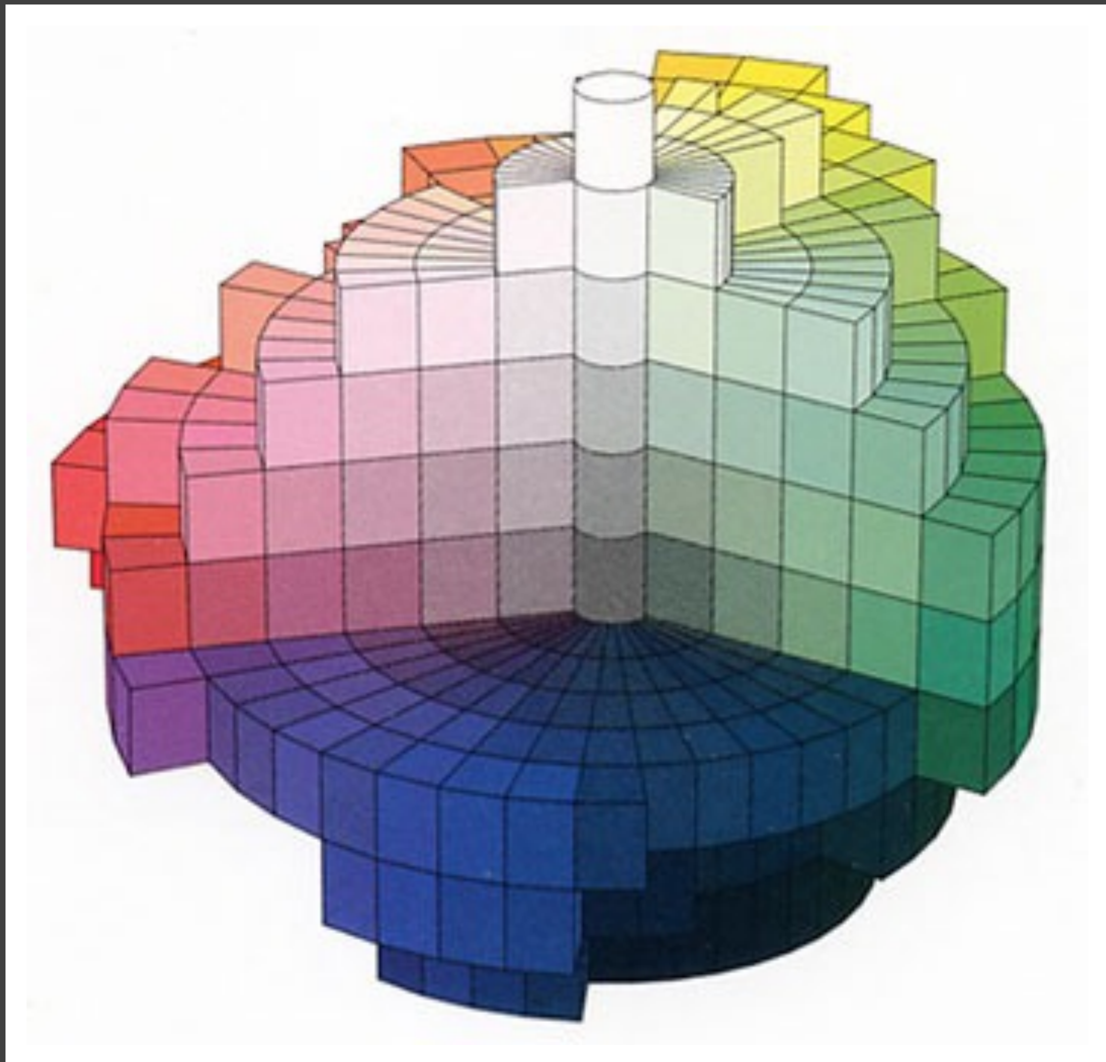
“Yellow”

Color Cognition

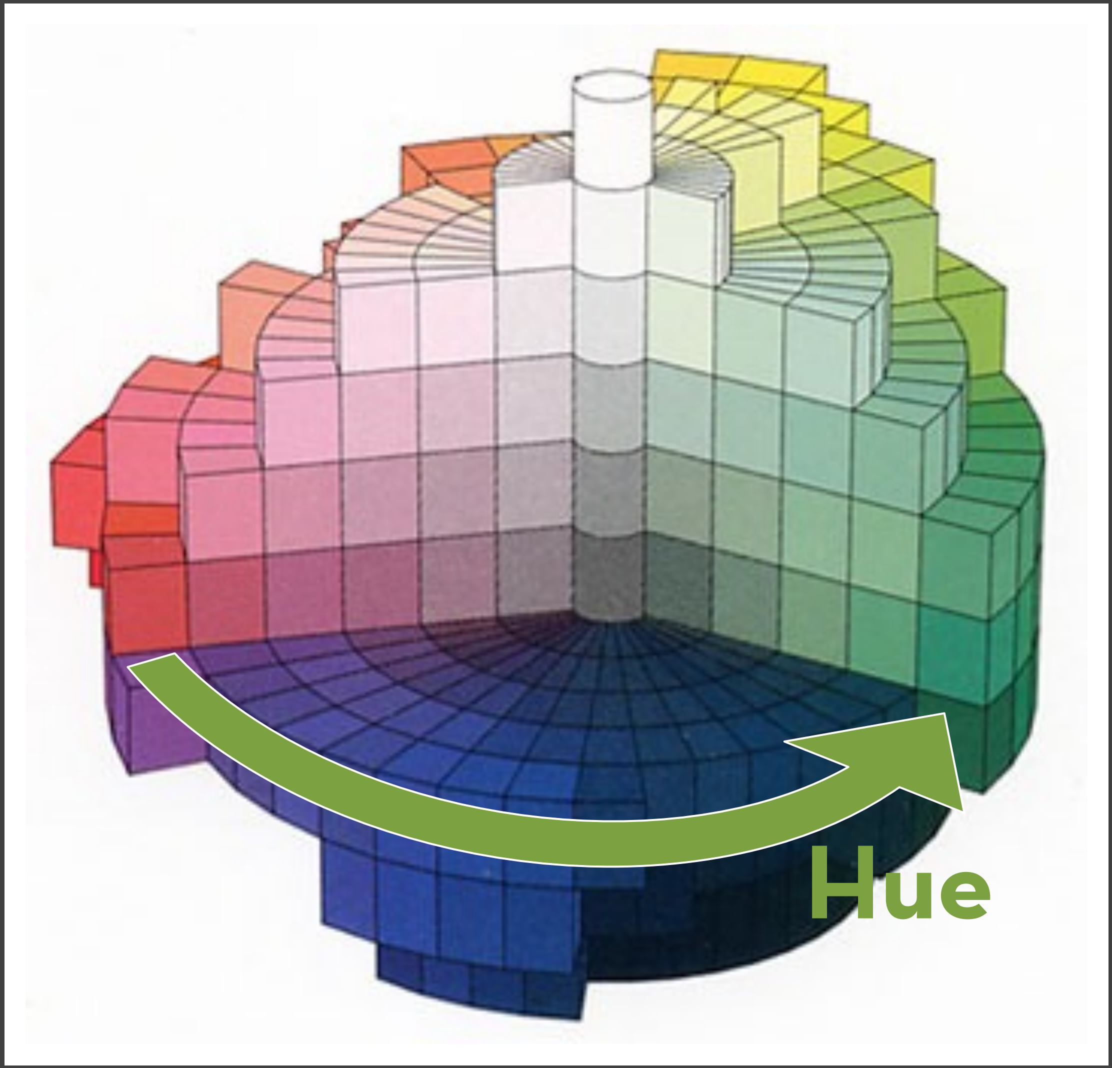
Albert Munsell

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

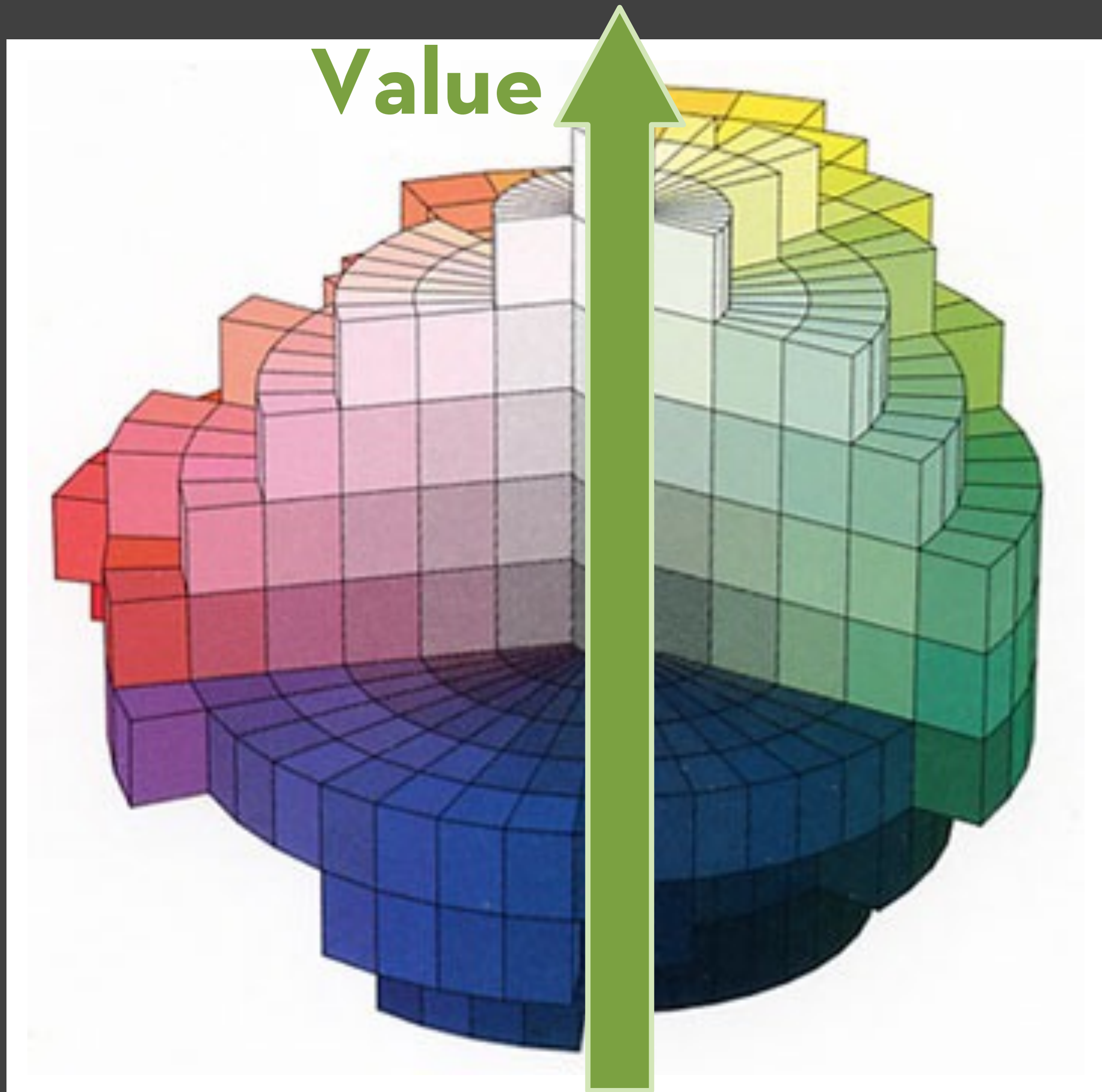
Hue, Value, Chroma



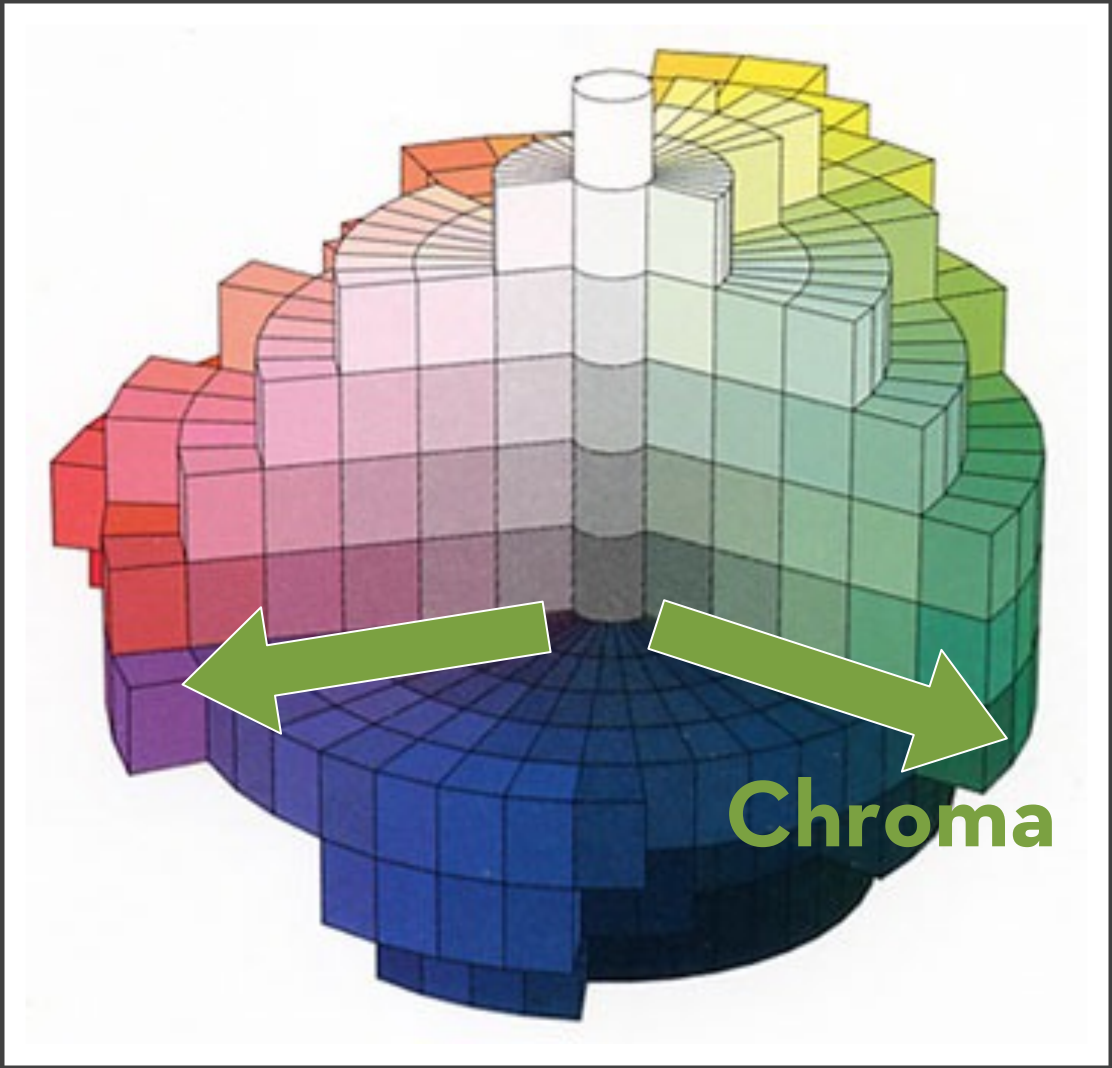
Hue, Value, Chroma



Hue, Value, Chroma



Hue, Value, Chroma



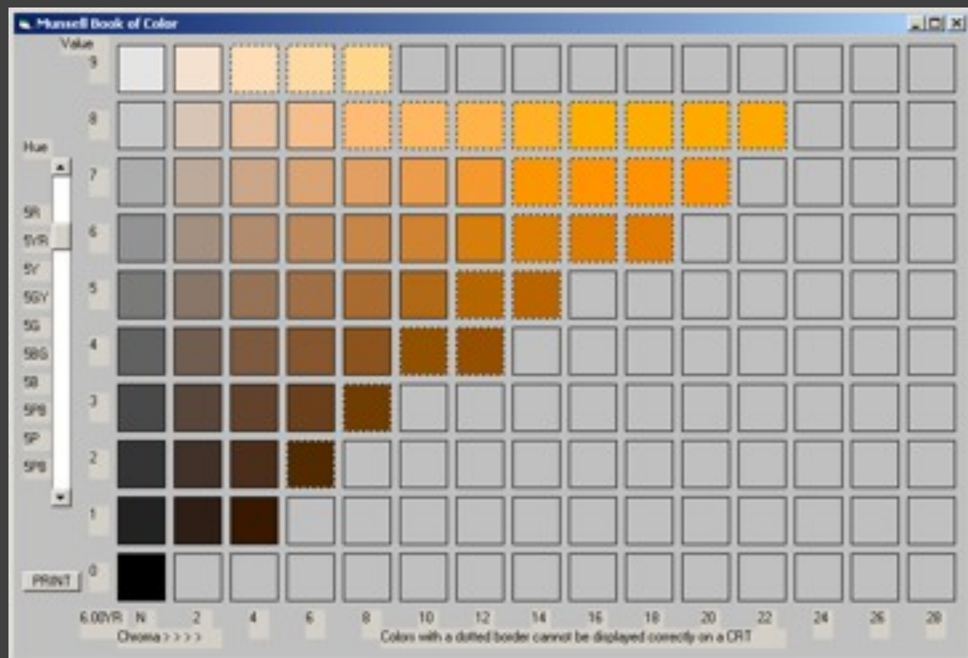
Munsell color system

Perceptually-based

Precisely reference a color

Intuitive dimensions

Look-up table (LUT)



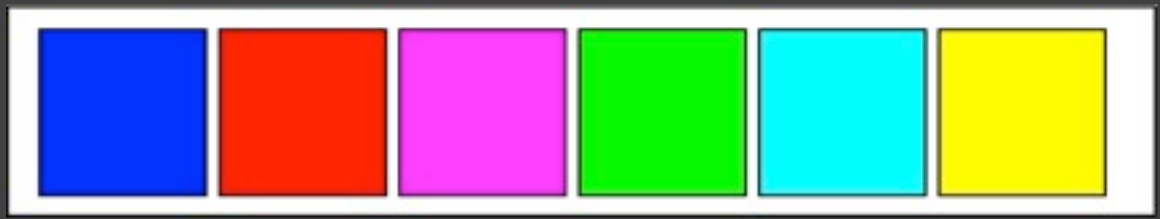
Munsell color system

Perceptual brightness

Color palette

Perceptual brightness

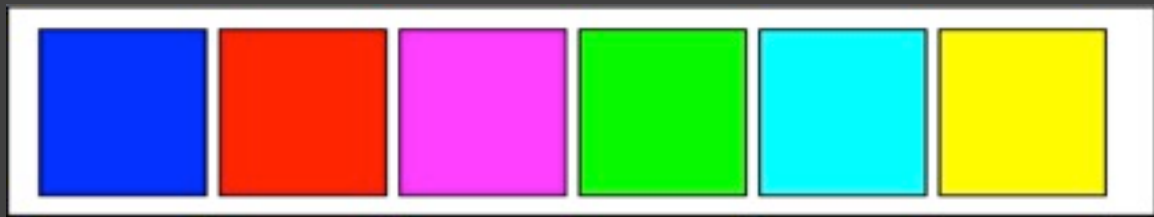
Color palette



HSL Lightness
(Photoshop)

Perceptual brightness

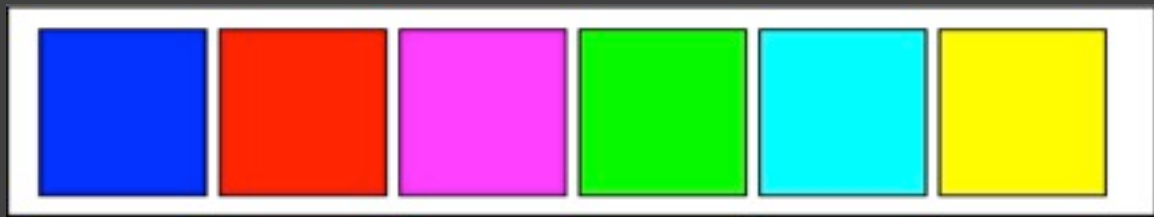
Color palette



Luminance Y
(CIE XYZ)

Perceptual brightness

Color palette



Munsell Value

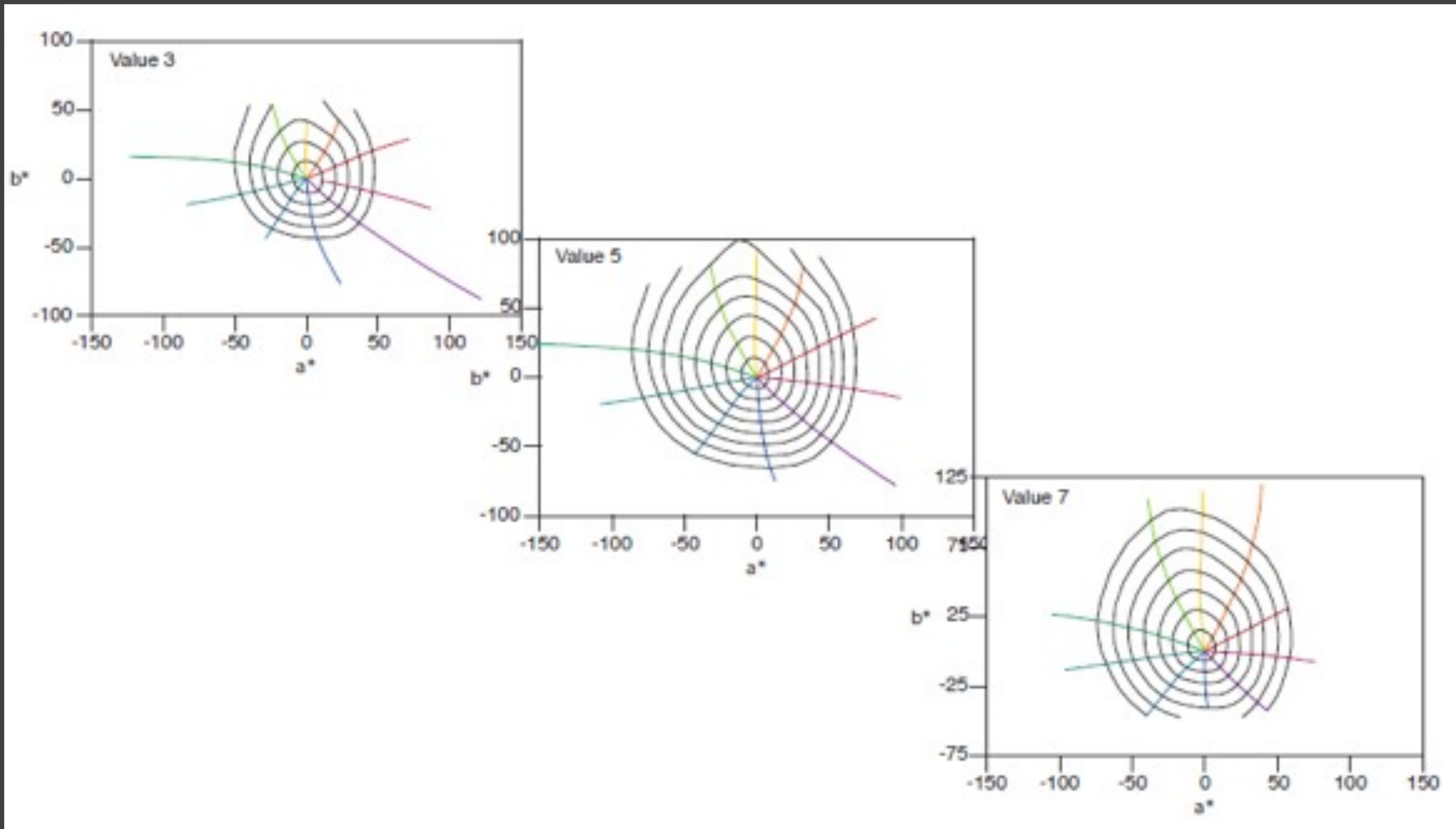
Perceptual brightness

Color palette

Munsell Value
L* (CIE LAB)

Perceptually-uniform color space

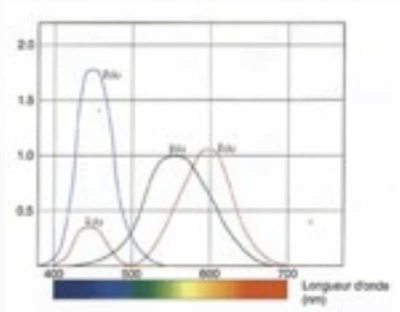
Munsell colors in CIE LAB coordinates



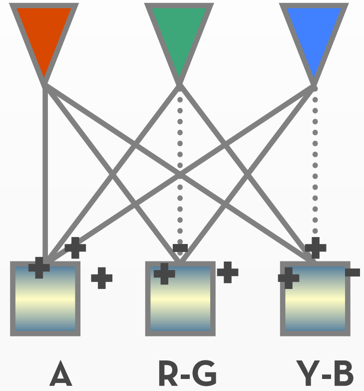
Mark Fairchild

Perception of Color

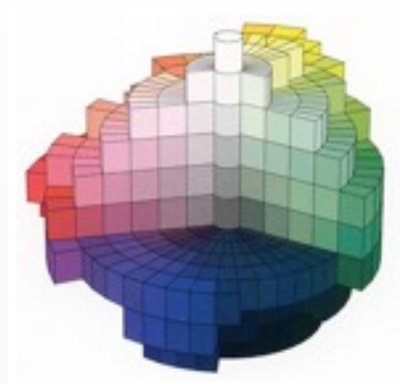
Light



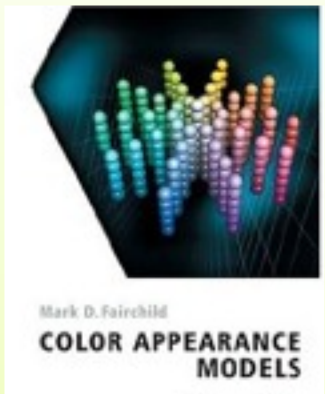
Cone Response



Opponent Signals



Color Perception



Color Appearance

“Yellow”

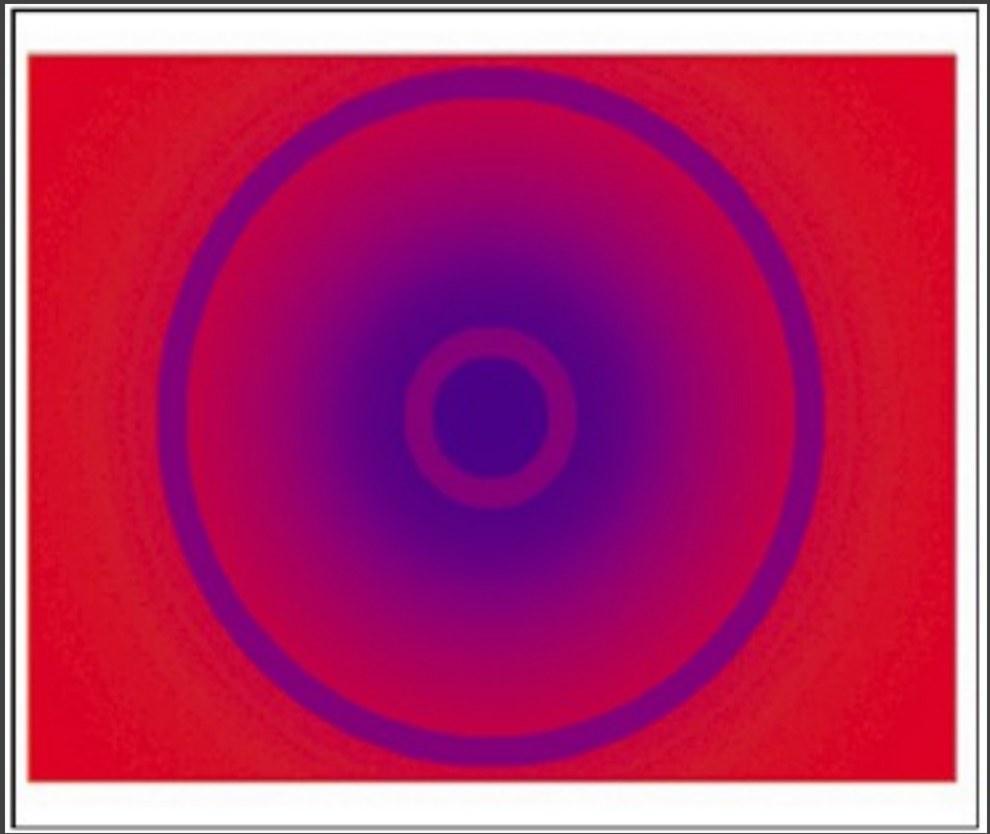
Color Cognition

Color Appearance

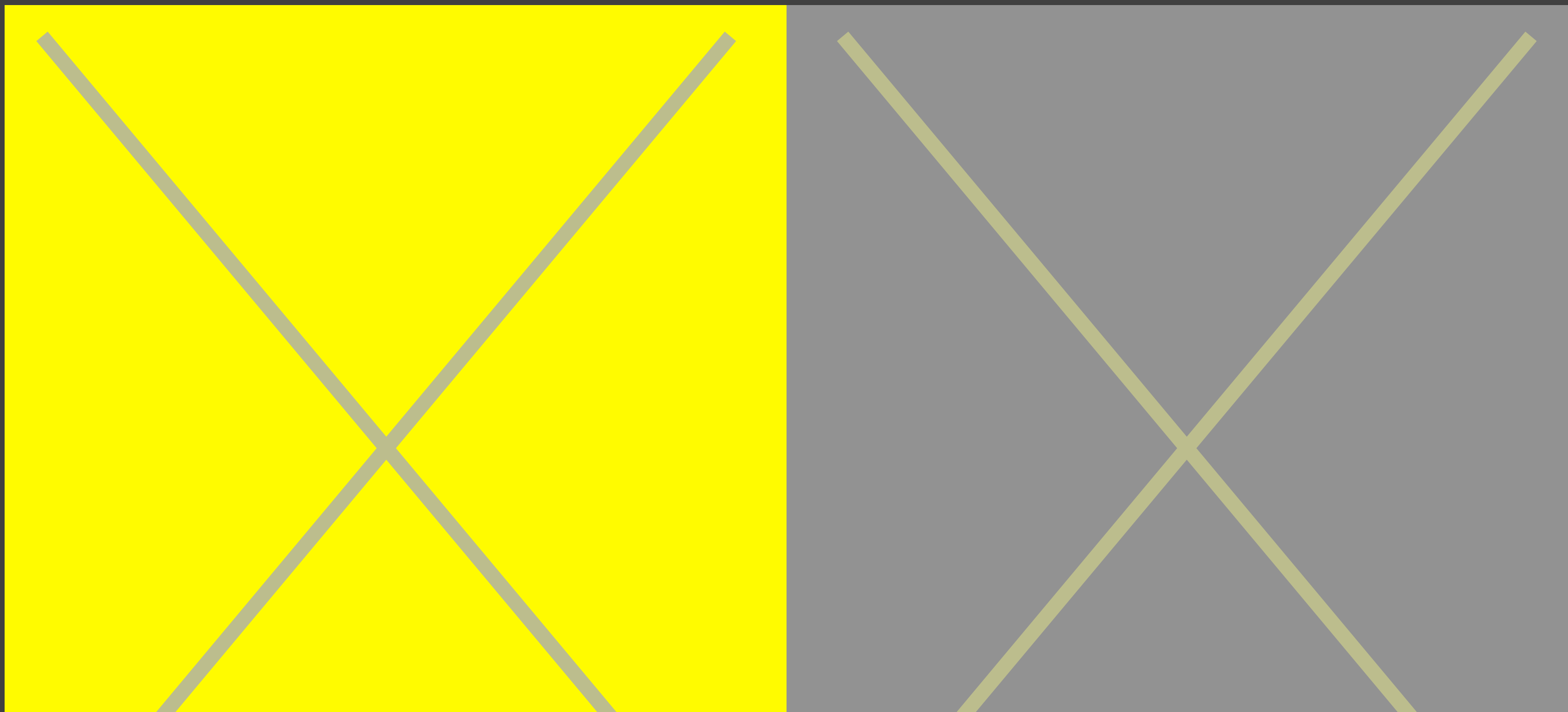
If we had a perceptually-uniform color space, can we predict how we perceive colors?

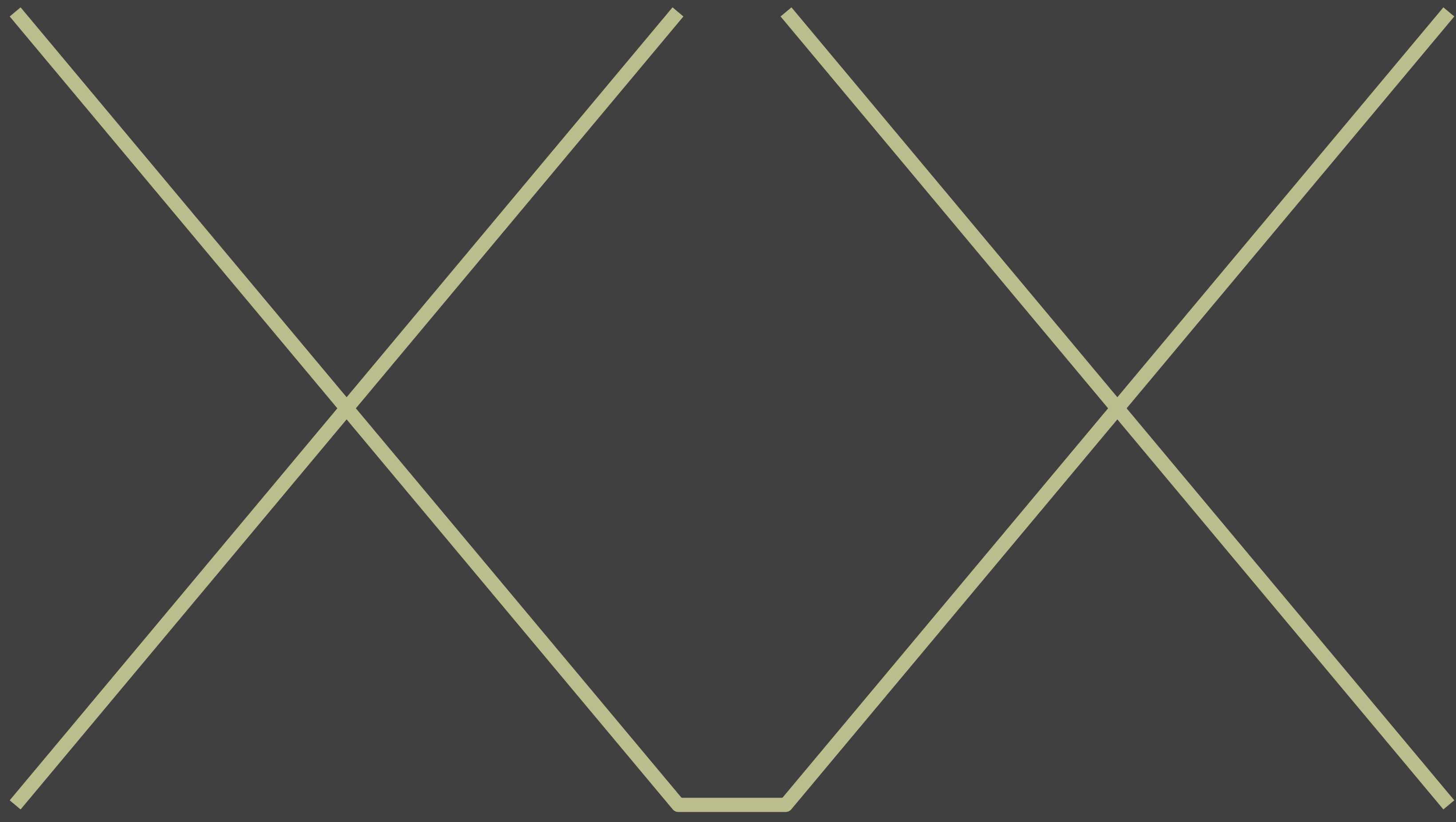
Simultaneous Contrast

The inner and outer thin rings are in fact the same physical purple.

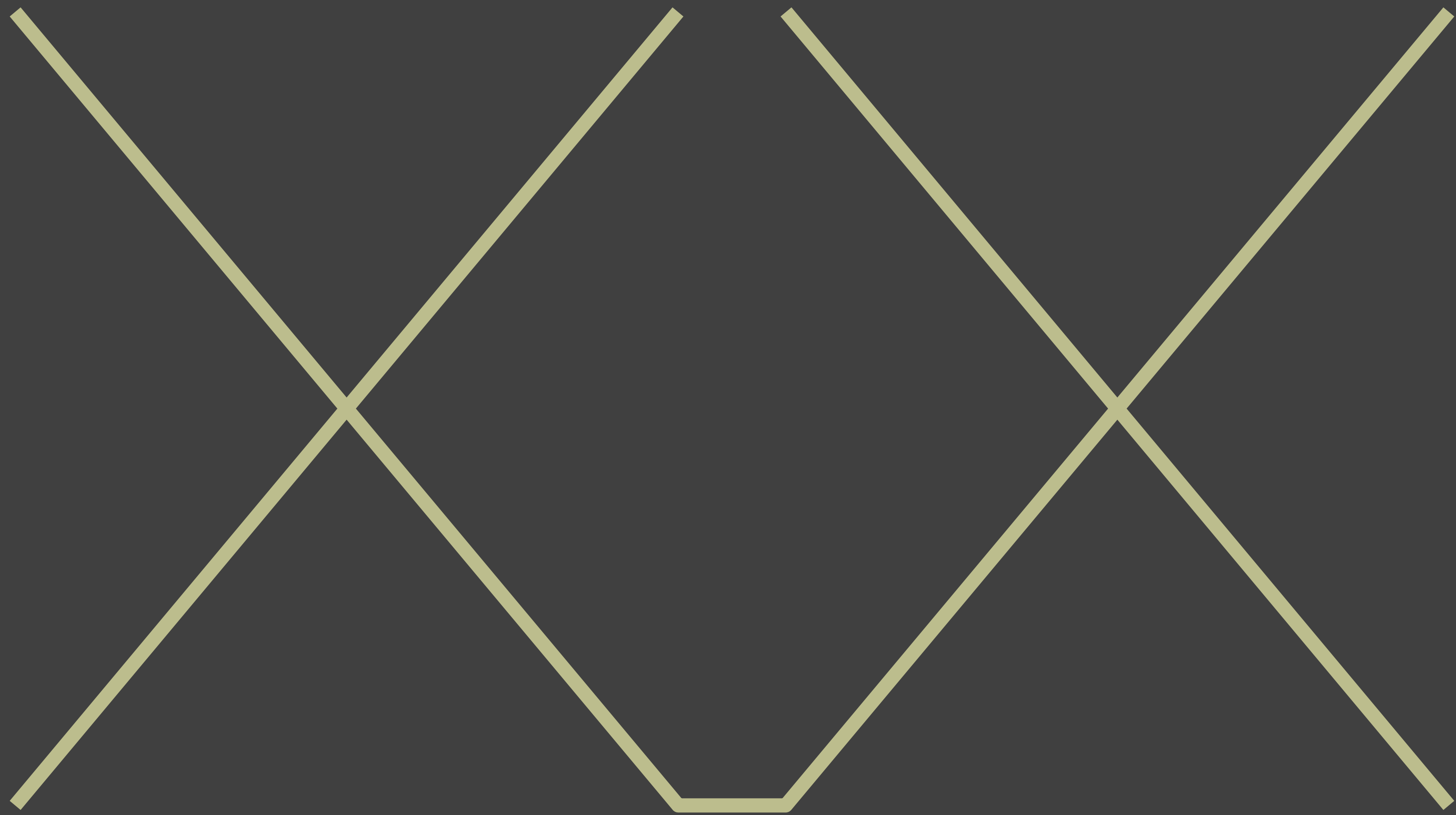


Donald MacLeod



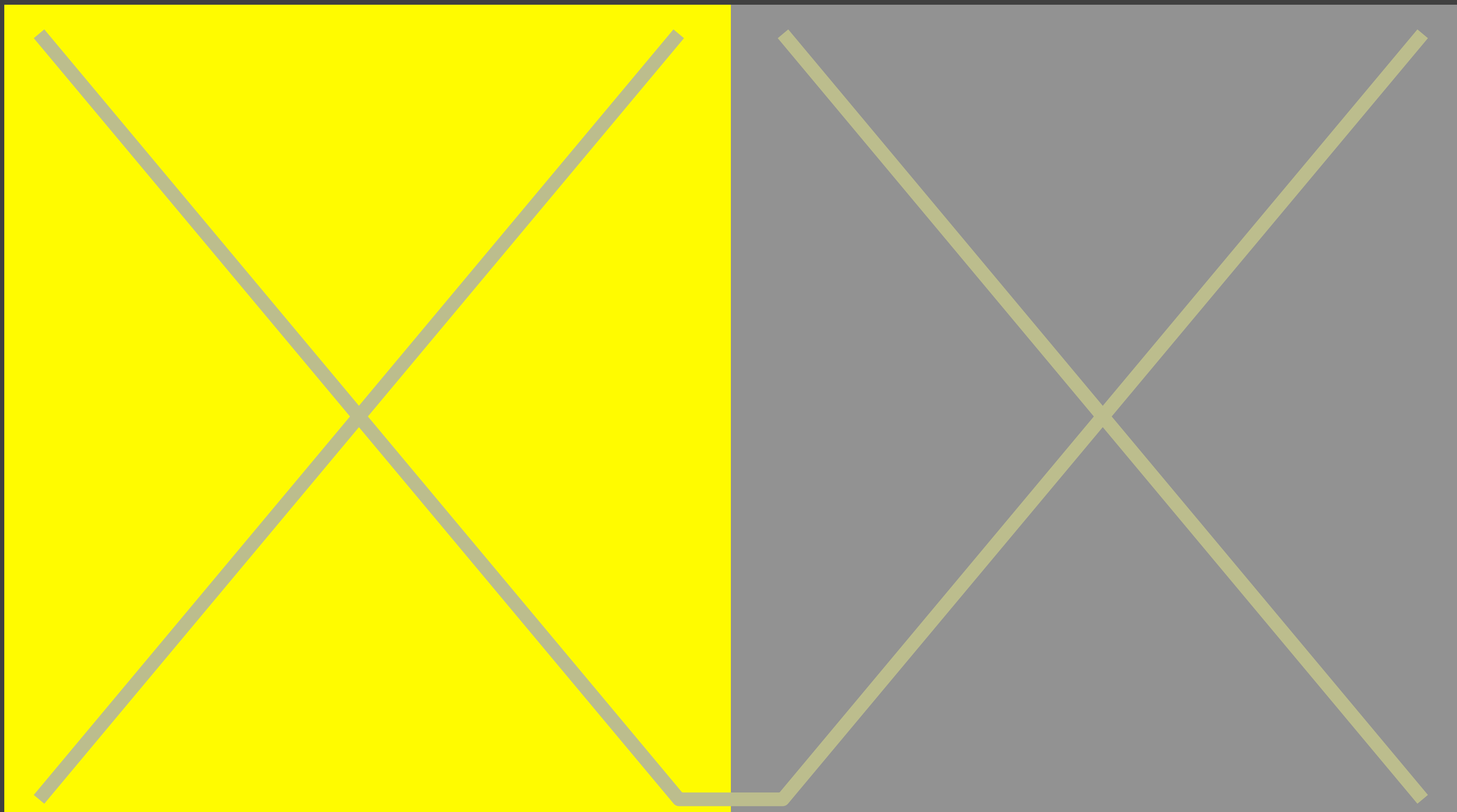


Simultaneous Contrast



Josef Albers

Simultaneous Contrast



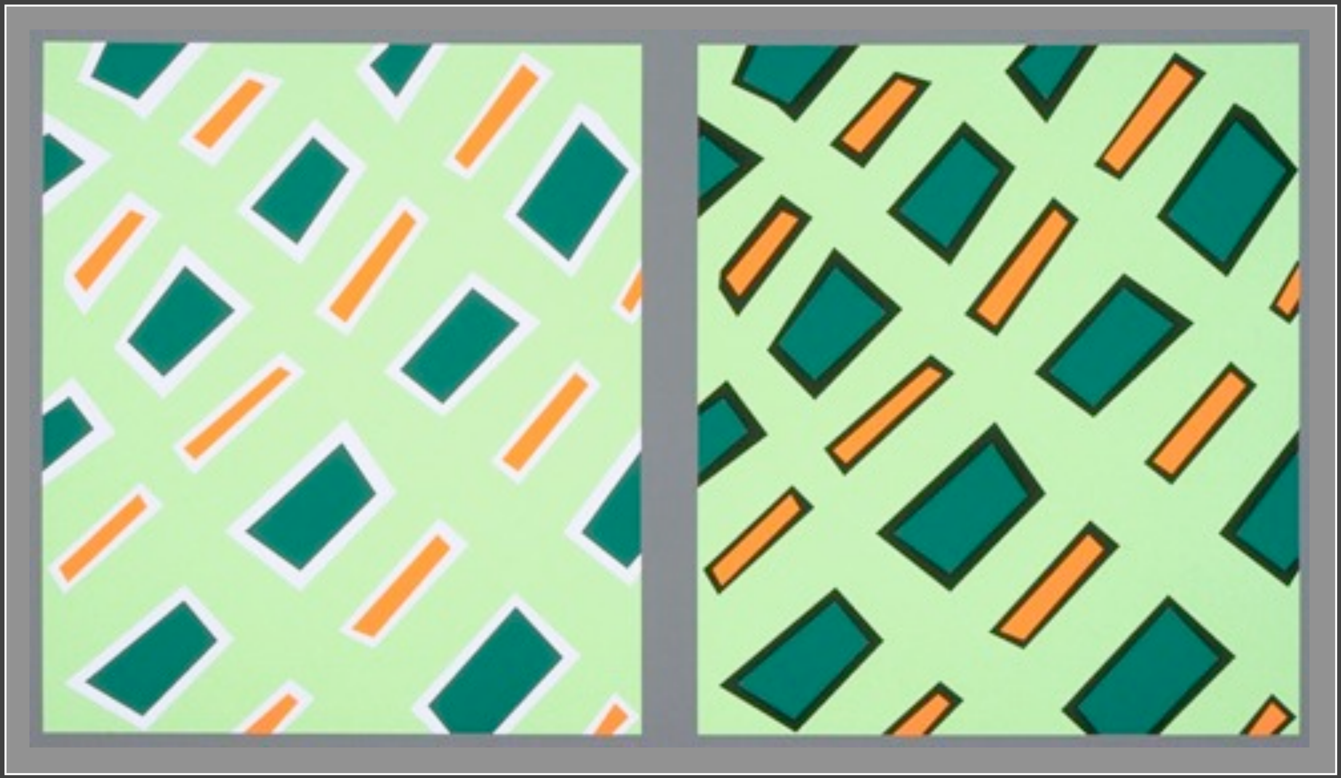
Josef Albers

Chromatic Adaptation

Chromatic Adaptation

Bezold effect

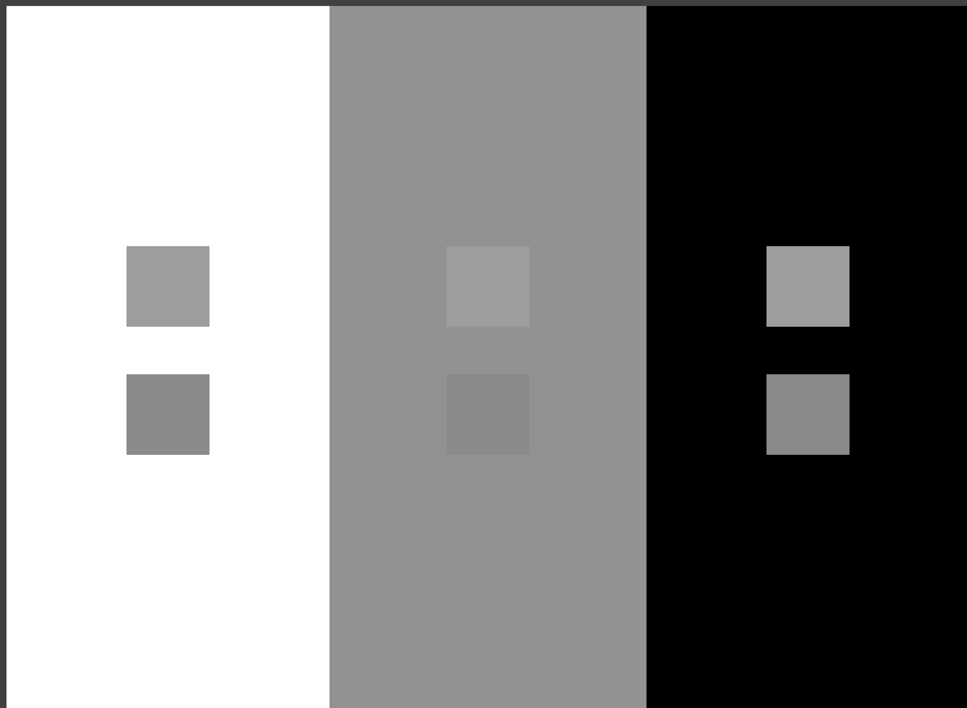
Color appearance depends adjacent colors



Color Appearance Tutorial by Maureen Stone

Crispening

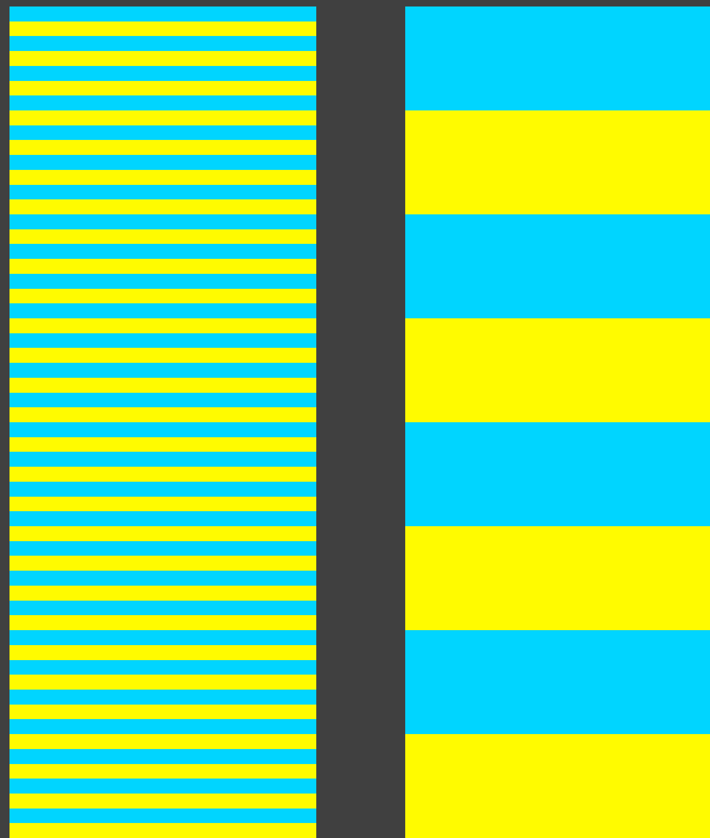
Perceived difference depends on background



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

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

Chromatic adaptation

Luminance adaptation

Simultaneous contrast

Spatial effects

Viewing angle

iCAM

iCAM models (2002)

Chromatic adaptation

Appearance scales

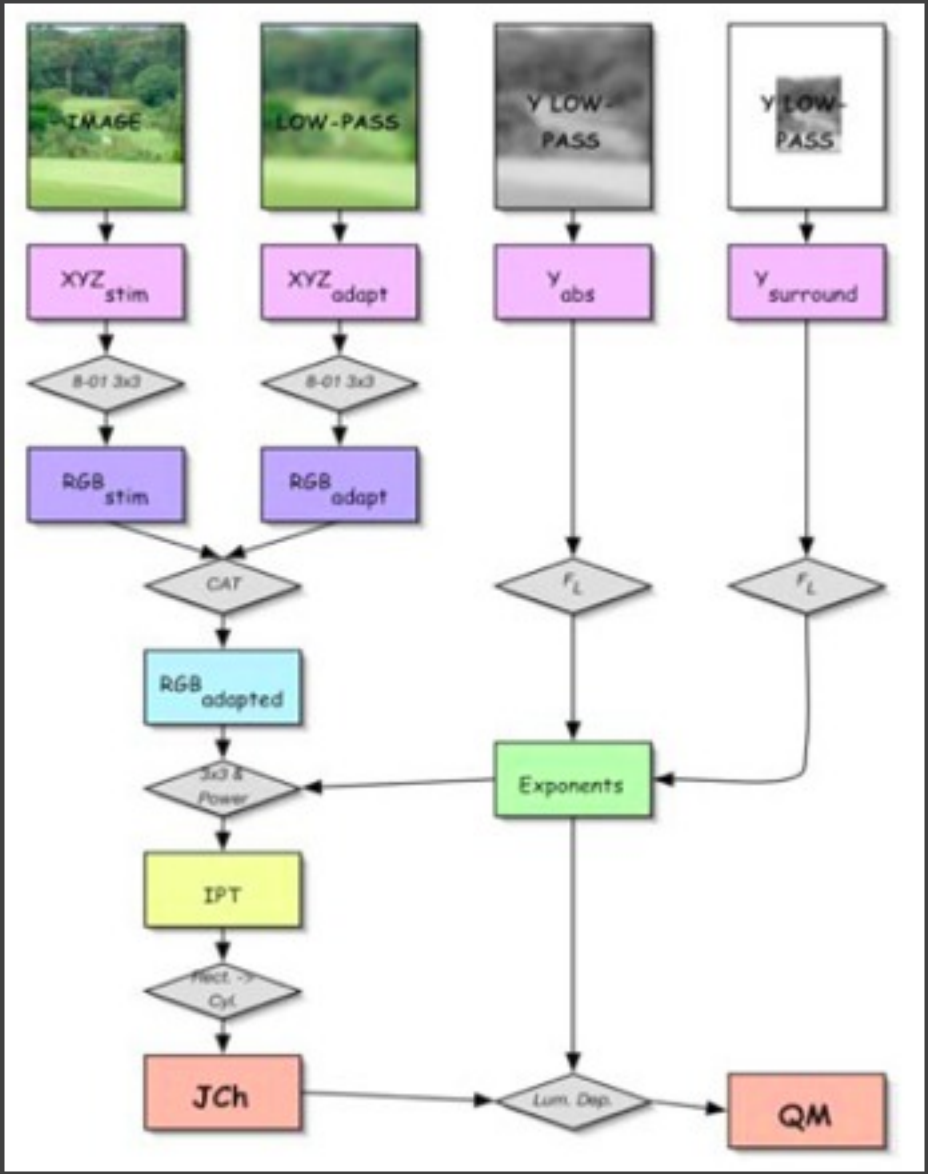
Color difference

Crispening

Spreading

HDR tone mapping

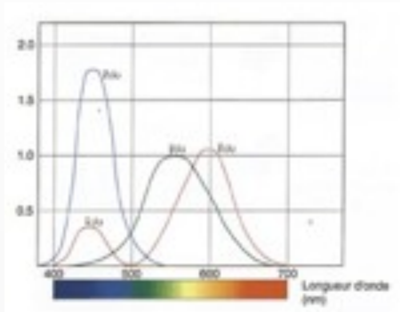
(see also CIECAM02)



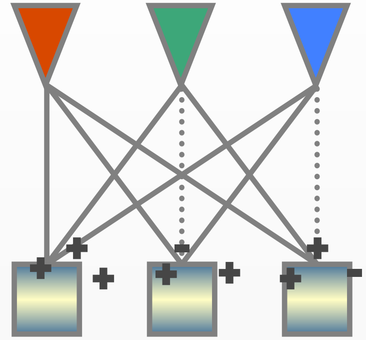
Mark Fairchild

Perception of Color

Light

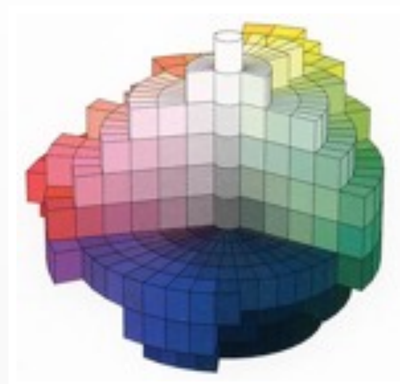


Cone Response

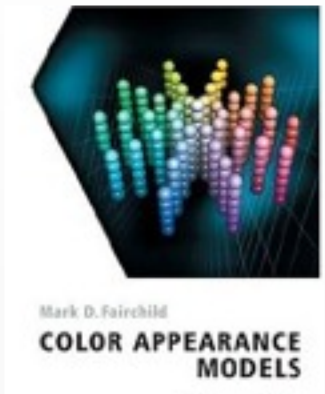


A R-G Y-B

Opponent Signals



Color Perception



Color Appearance

"Yellow"

Color Cognition

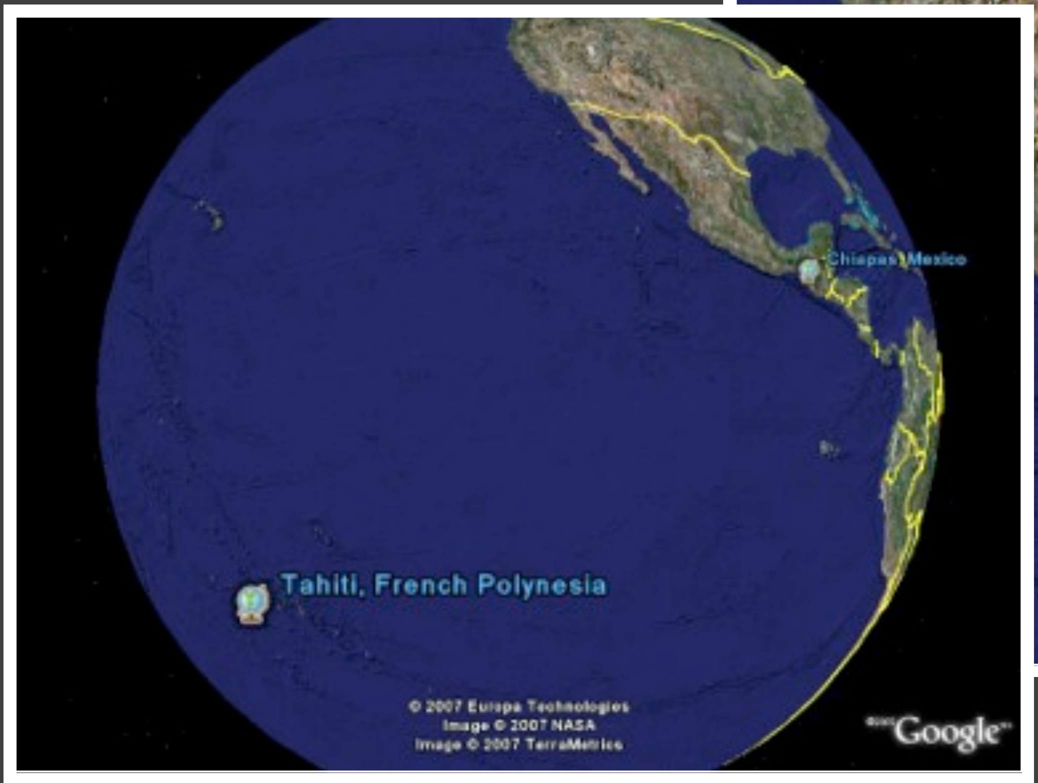
Colors according to XKCD…

Basic color terms

Chance discovery by Brent Berlin and Paul Kay.

Basic color terms

Chance discovery by Brent Berlin and Paul Kay.



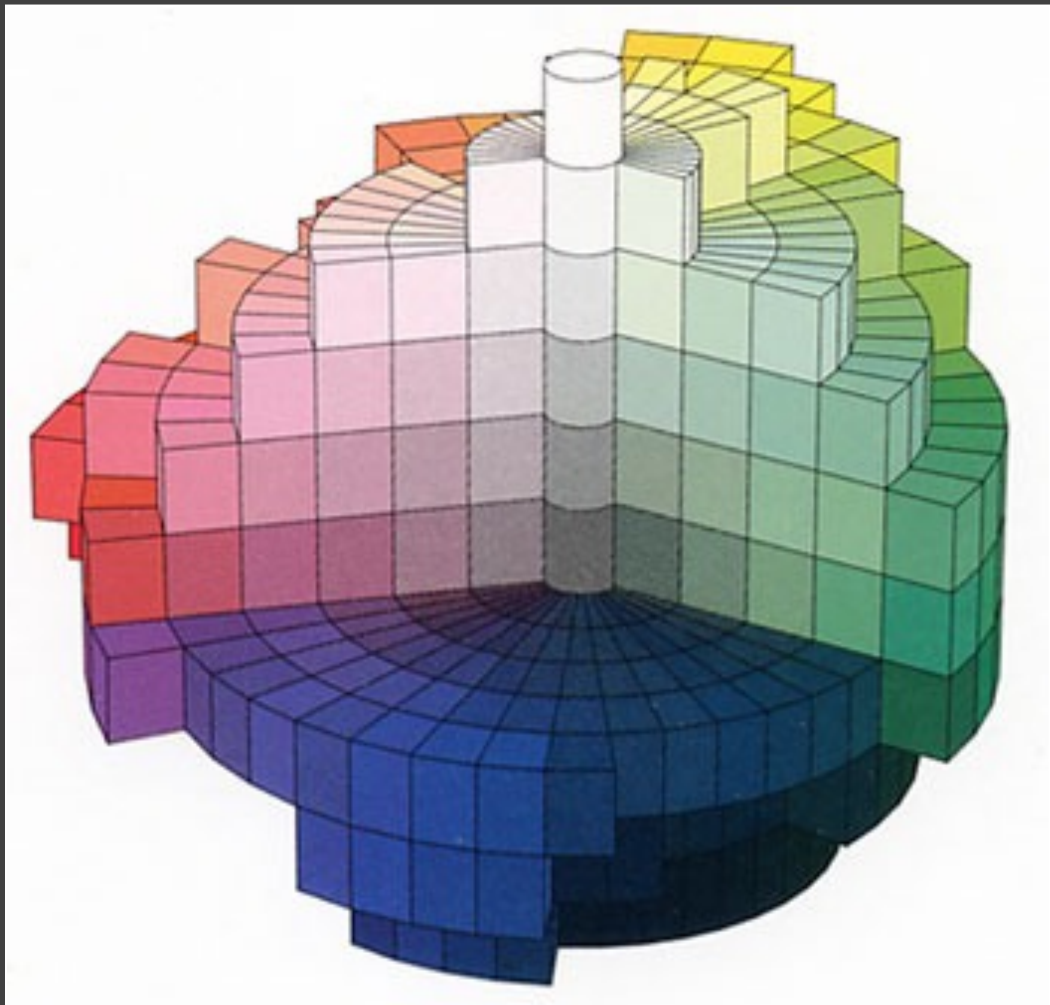
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.

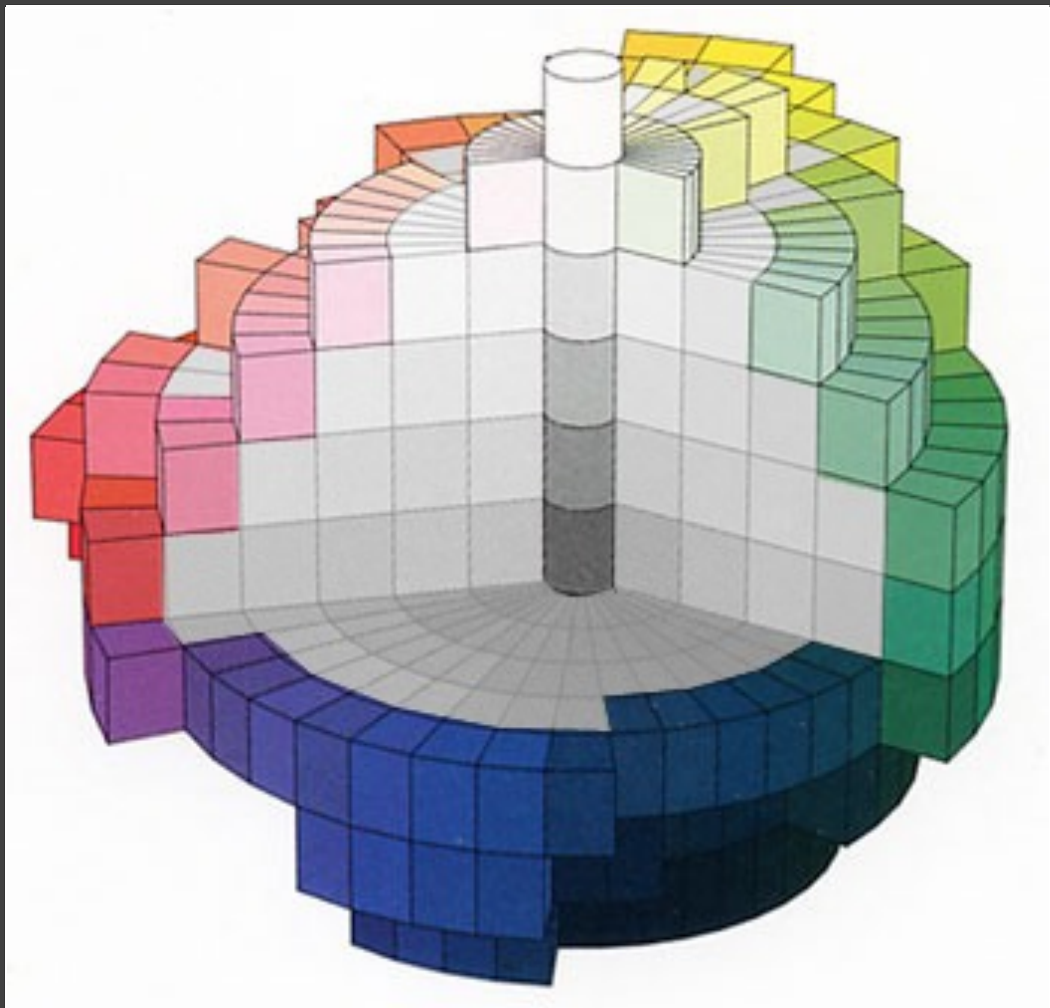
Initial study in 1969

- Surveyed speakers from 20 languages
- Literature from 69 languages

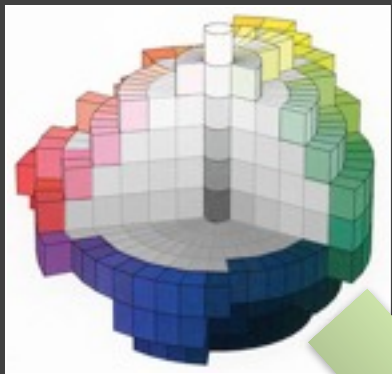
World color survey



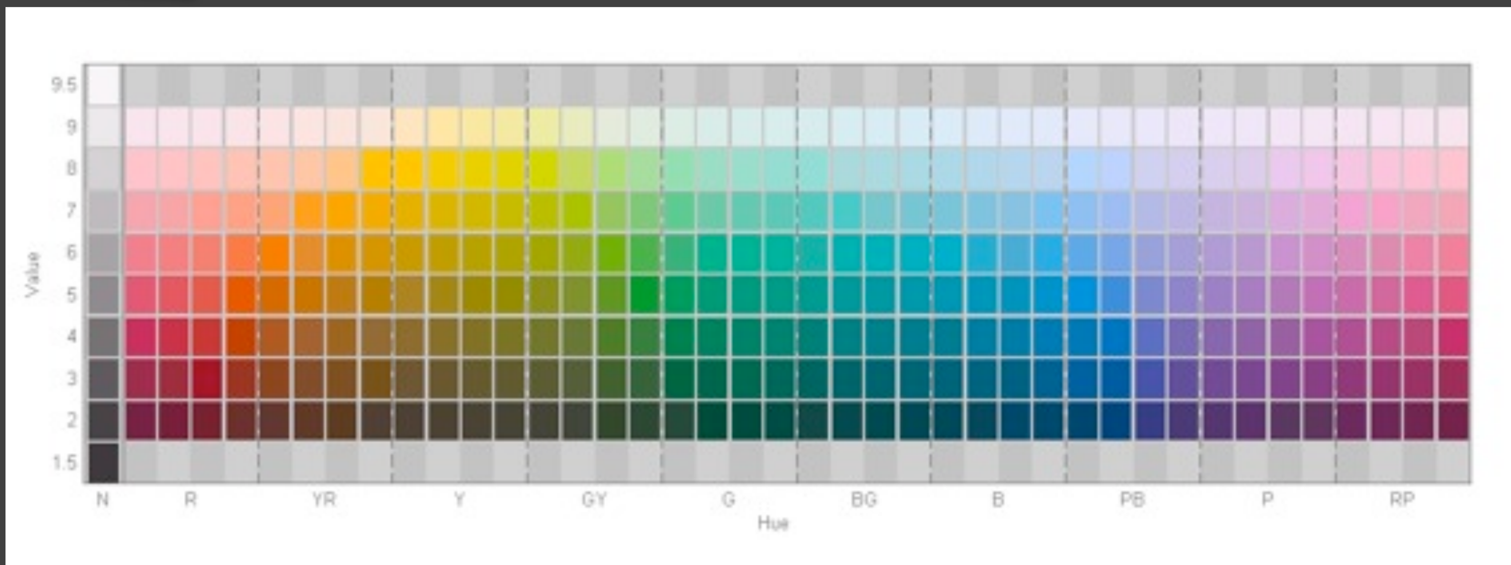
World color survey



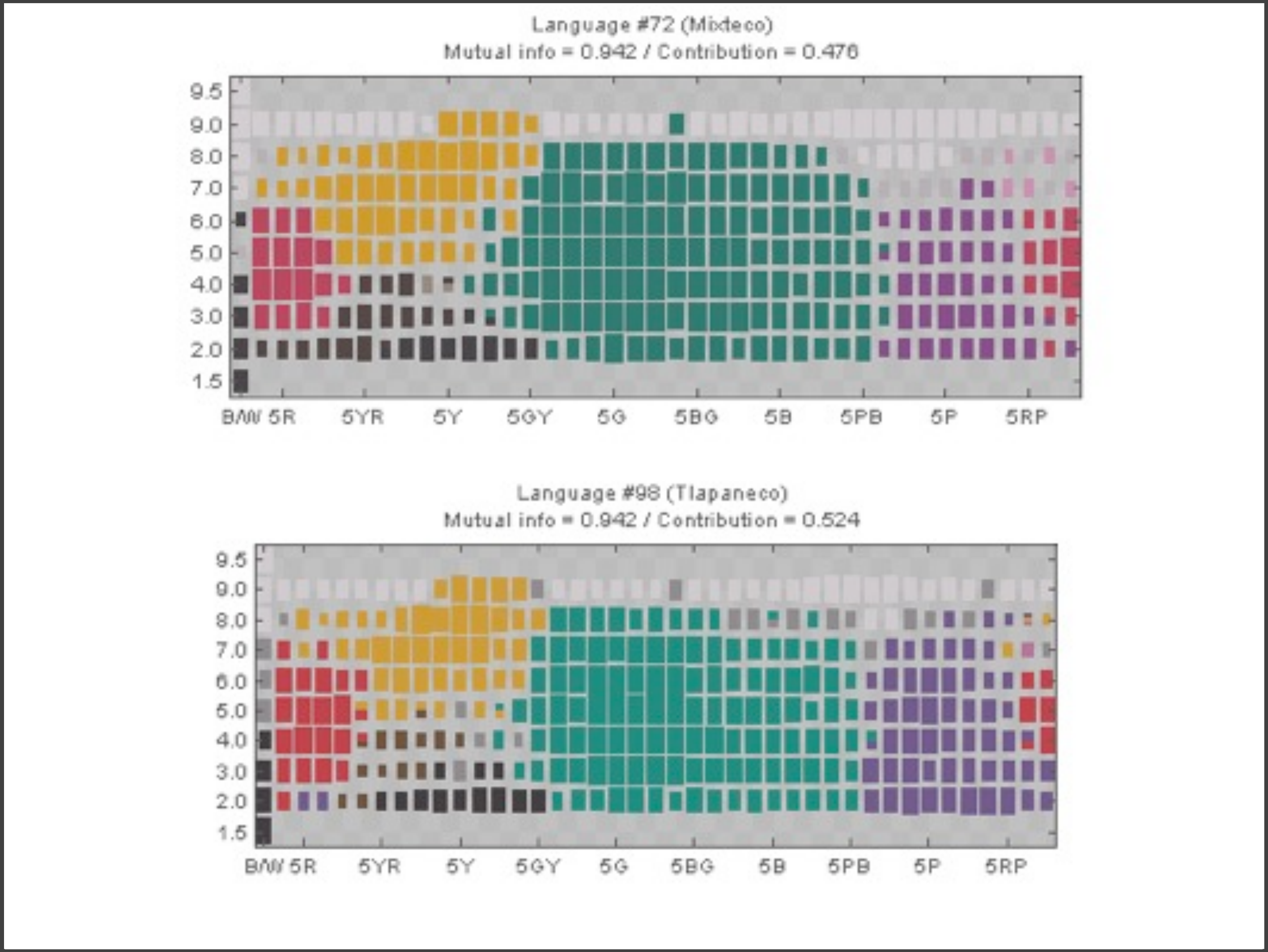
World color survey



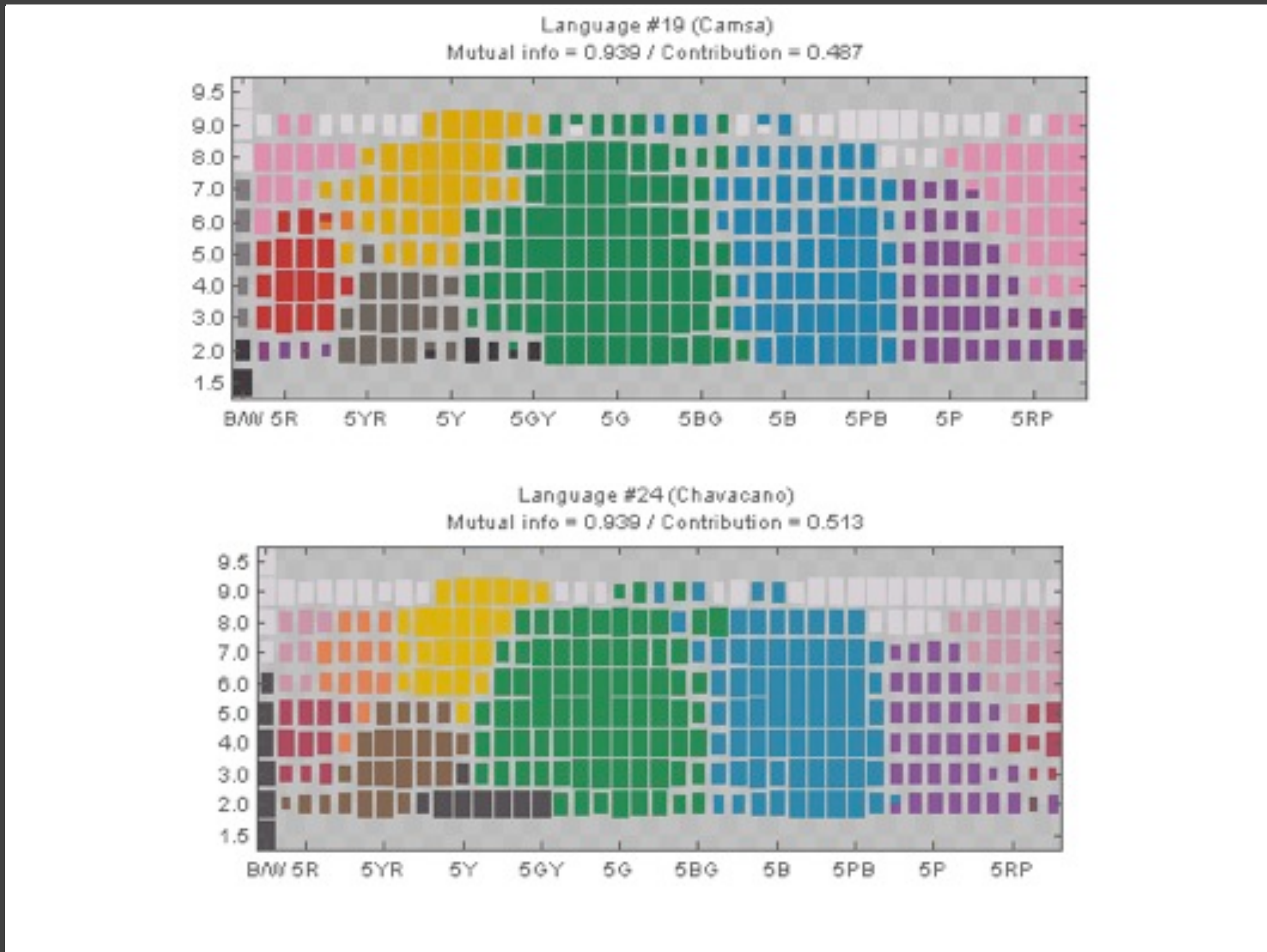
Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



Results from WCS



Results from WCS



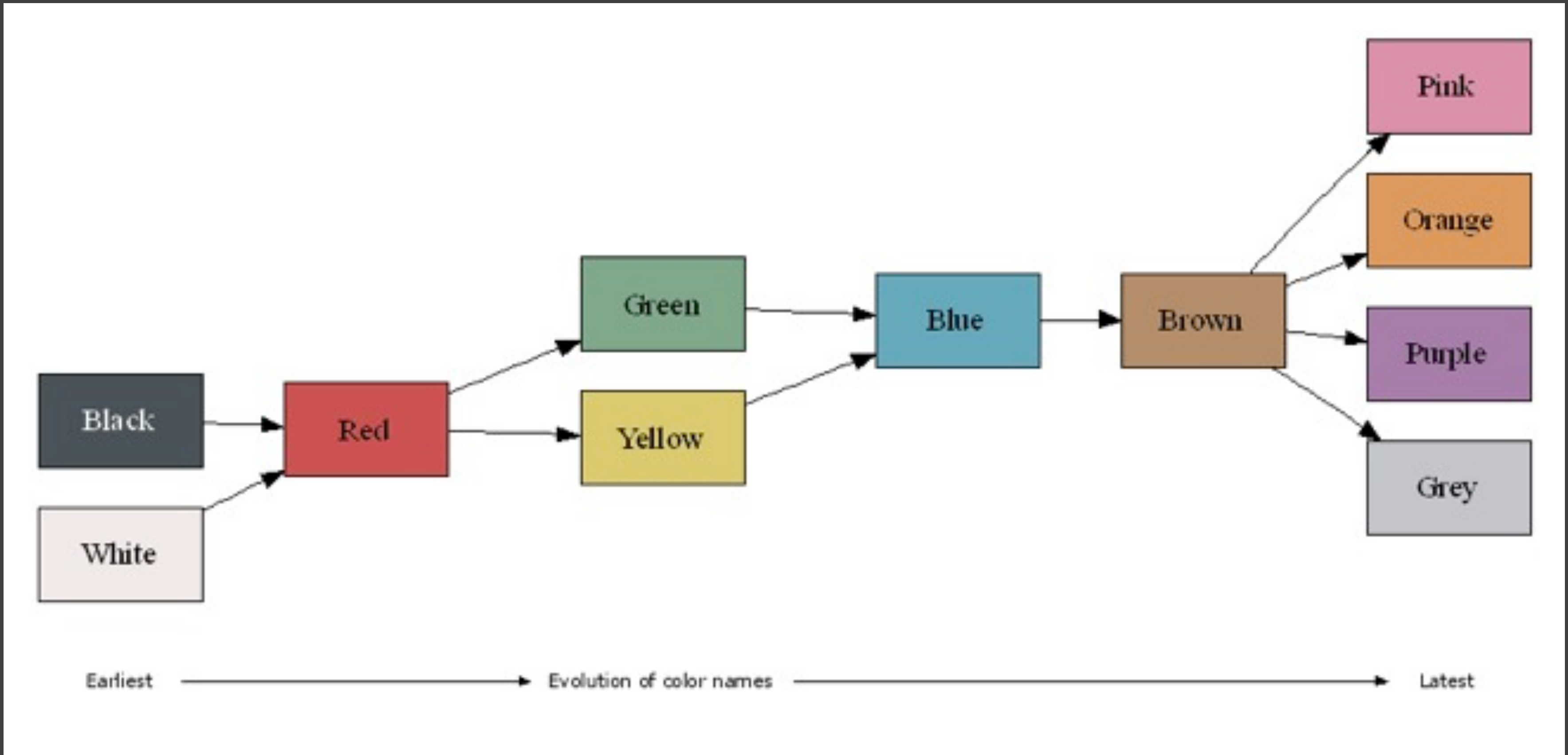
Universal (?) Basic Color Terms

Basic color terms recur across languages.

White	Red	Pink
Grey	Yellow	Brown
Black	Green	Orange
	Blue	Purple

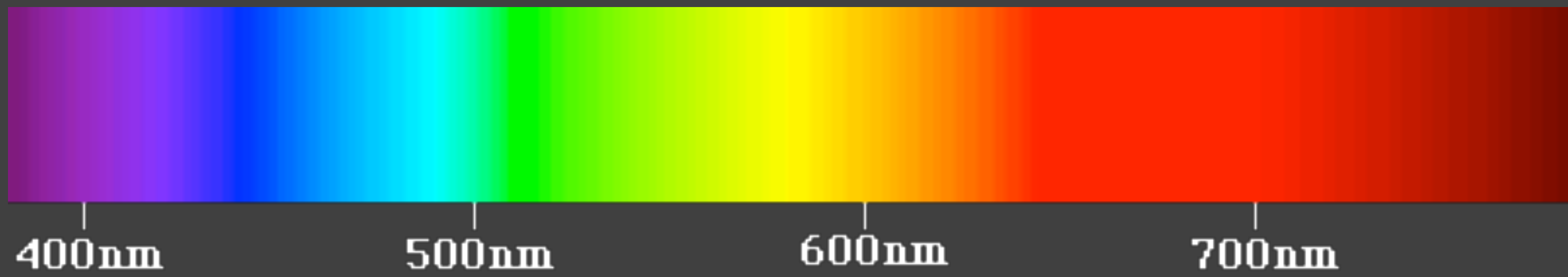
Evolution of Basic Color Terms

Proposed universal evolution across languages.



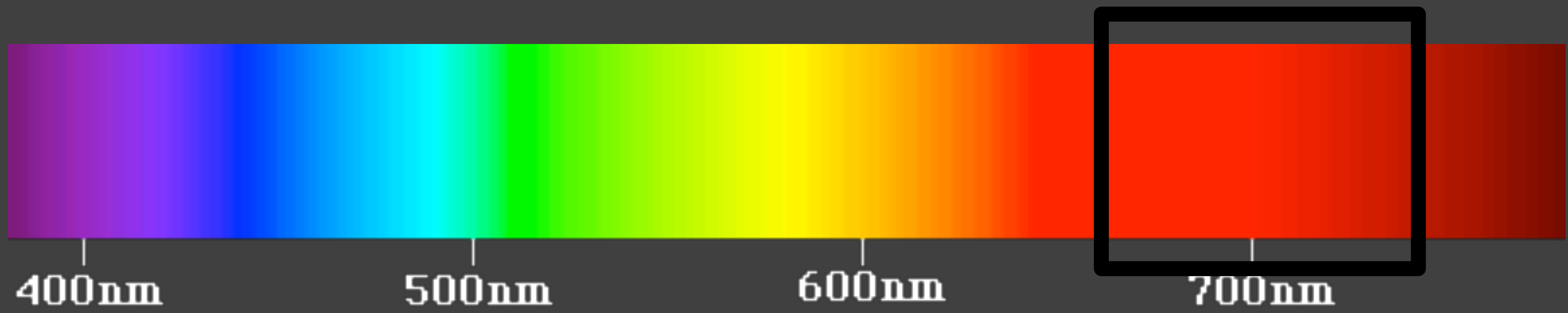
Rainbow color ramp

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



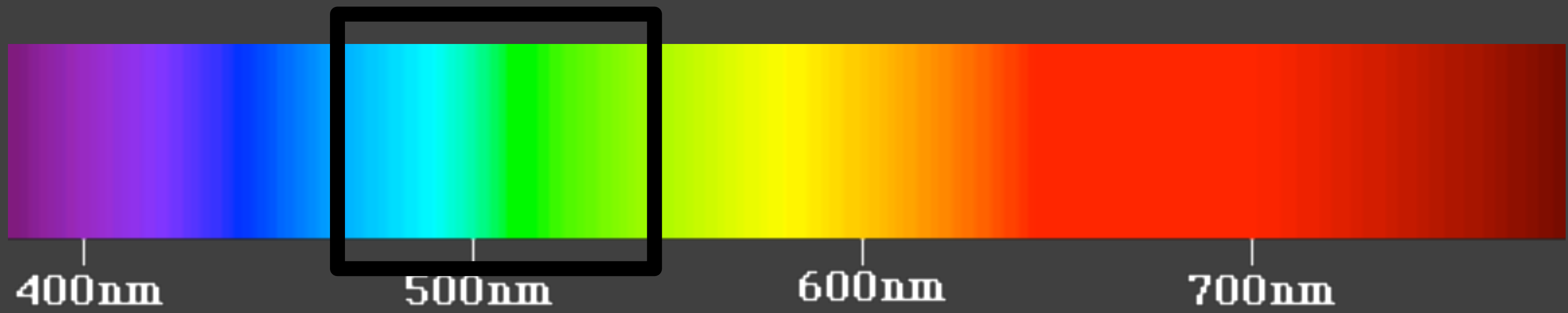
Rainbow color ramp

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



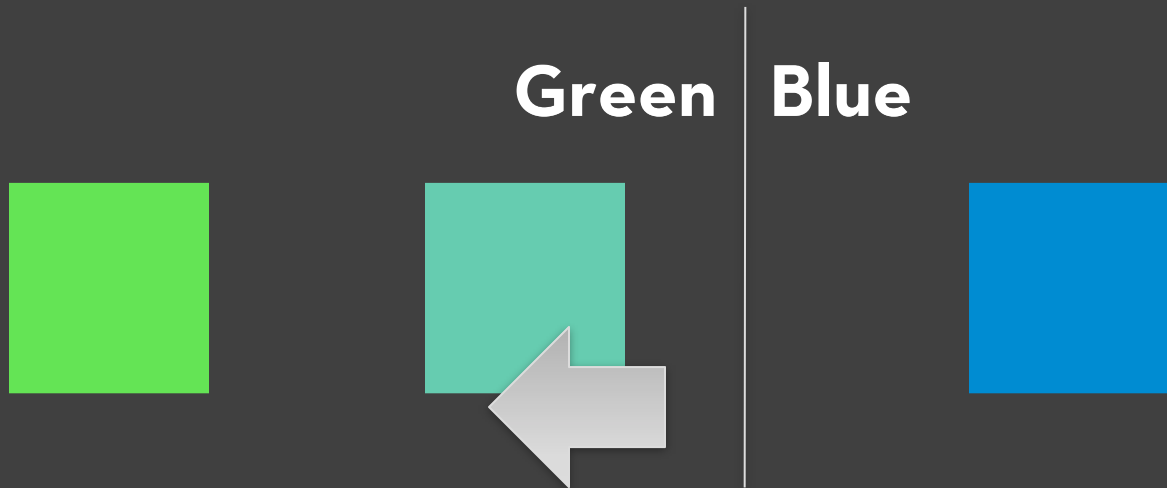
Rainbow color ramp

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



Naming affects color perception

Color name boundaries



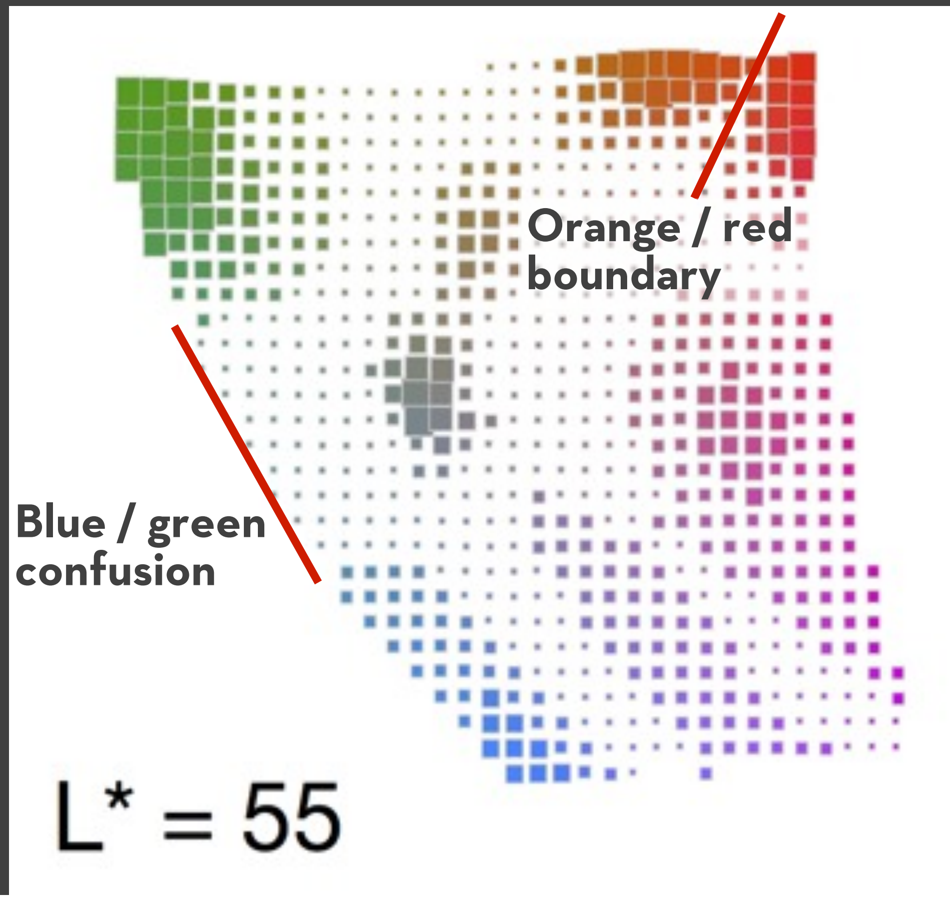
Color naming models [Chuang et al., Heer & Stone]

Model 3 million responses from XKCD survey

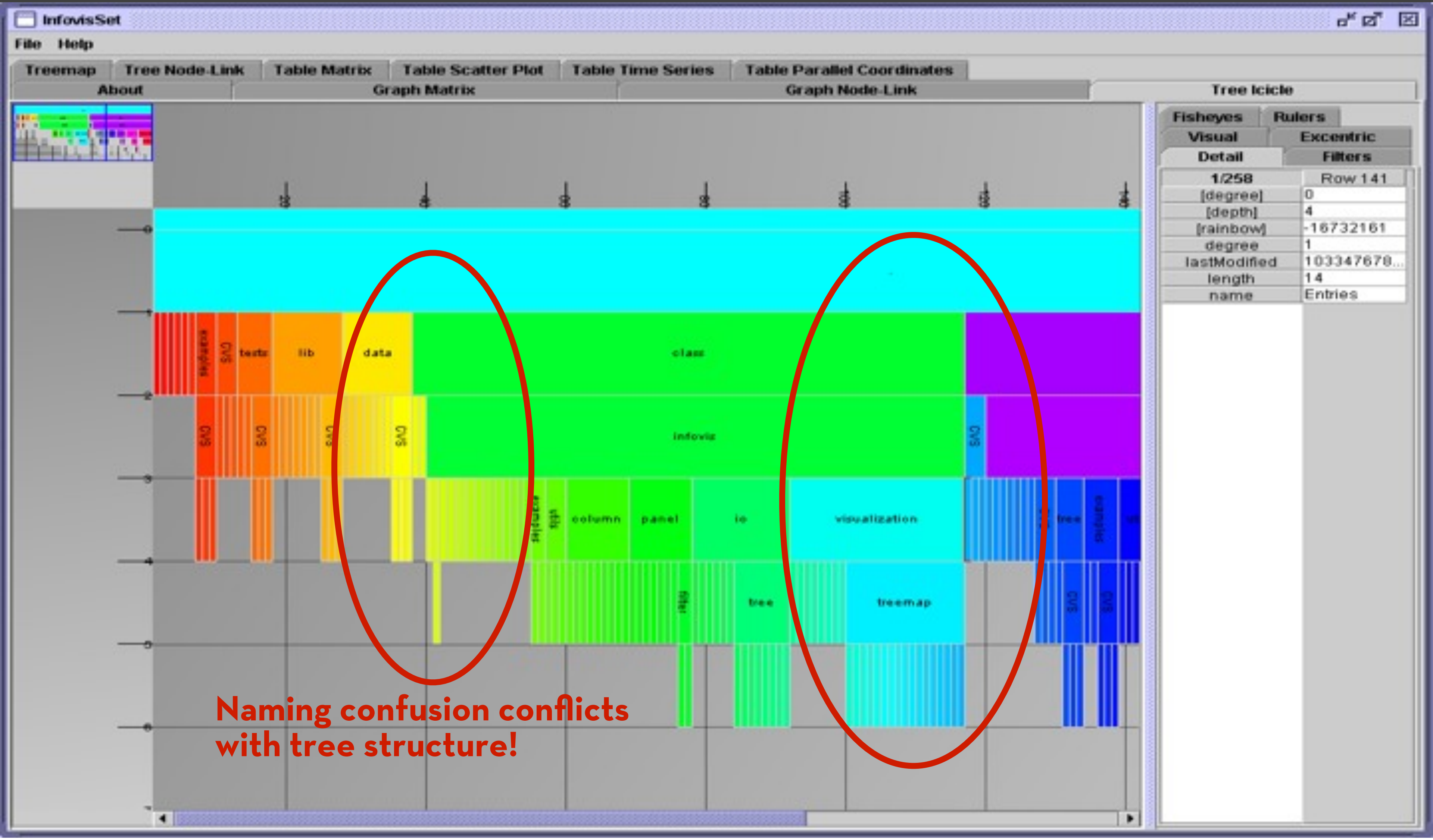
Bins in LAB space sized by *saliency*:

How much do people agree on color name?

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



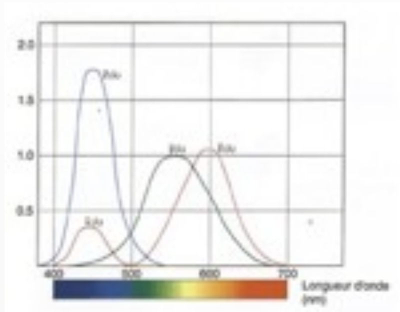
Icicle tree with colors



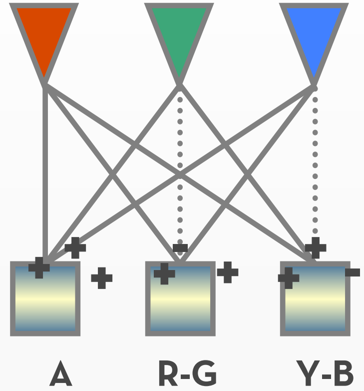
Naming confusion conflicts with tree structure!

Perception of Color

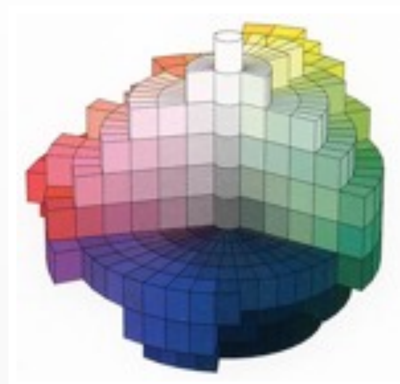
Light



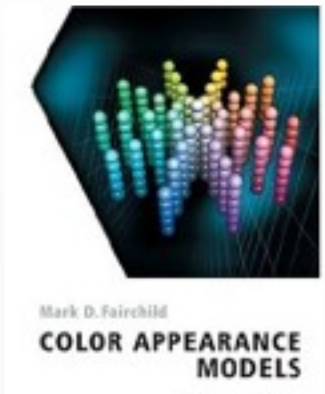
Cone Response



Opponent Signals



Color Perception



Color Appearance

“Yellow”

Color Cognition

Color in Data Visualization

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

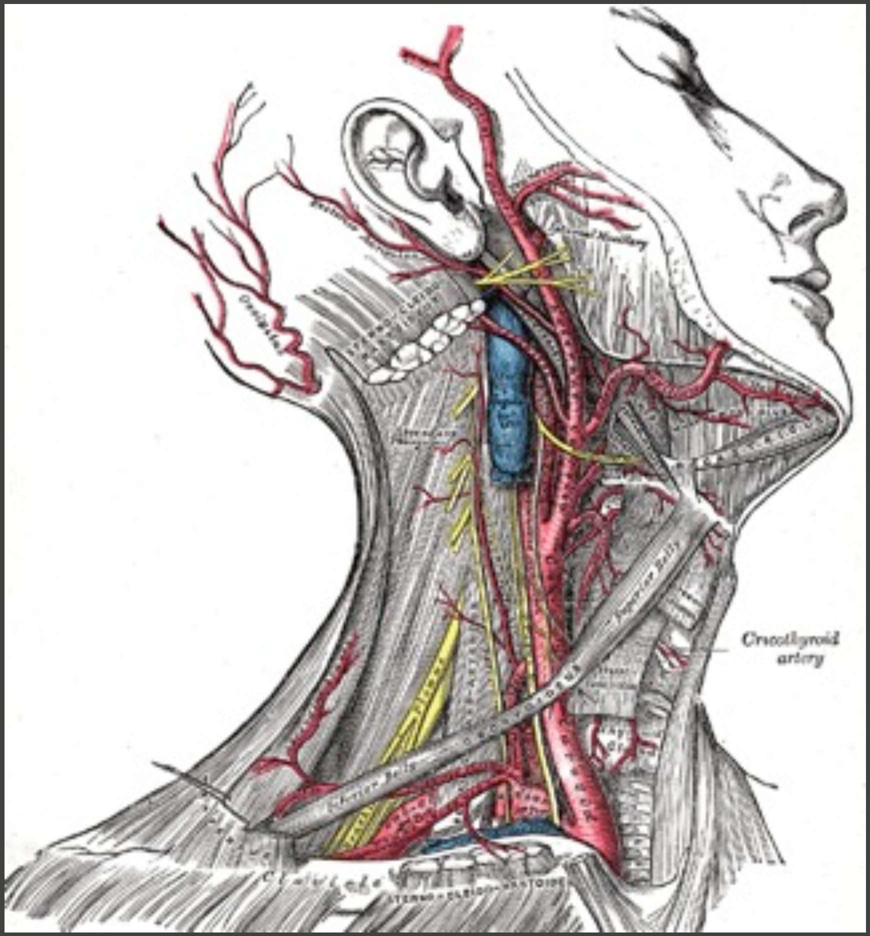
Beware of **bad interactions** (red/blue etc.)

Get it right in **black and white**

Respect the **color blind**

Categorical Color

Gray's anatomy

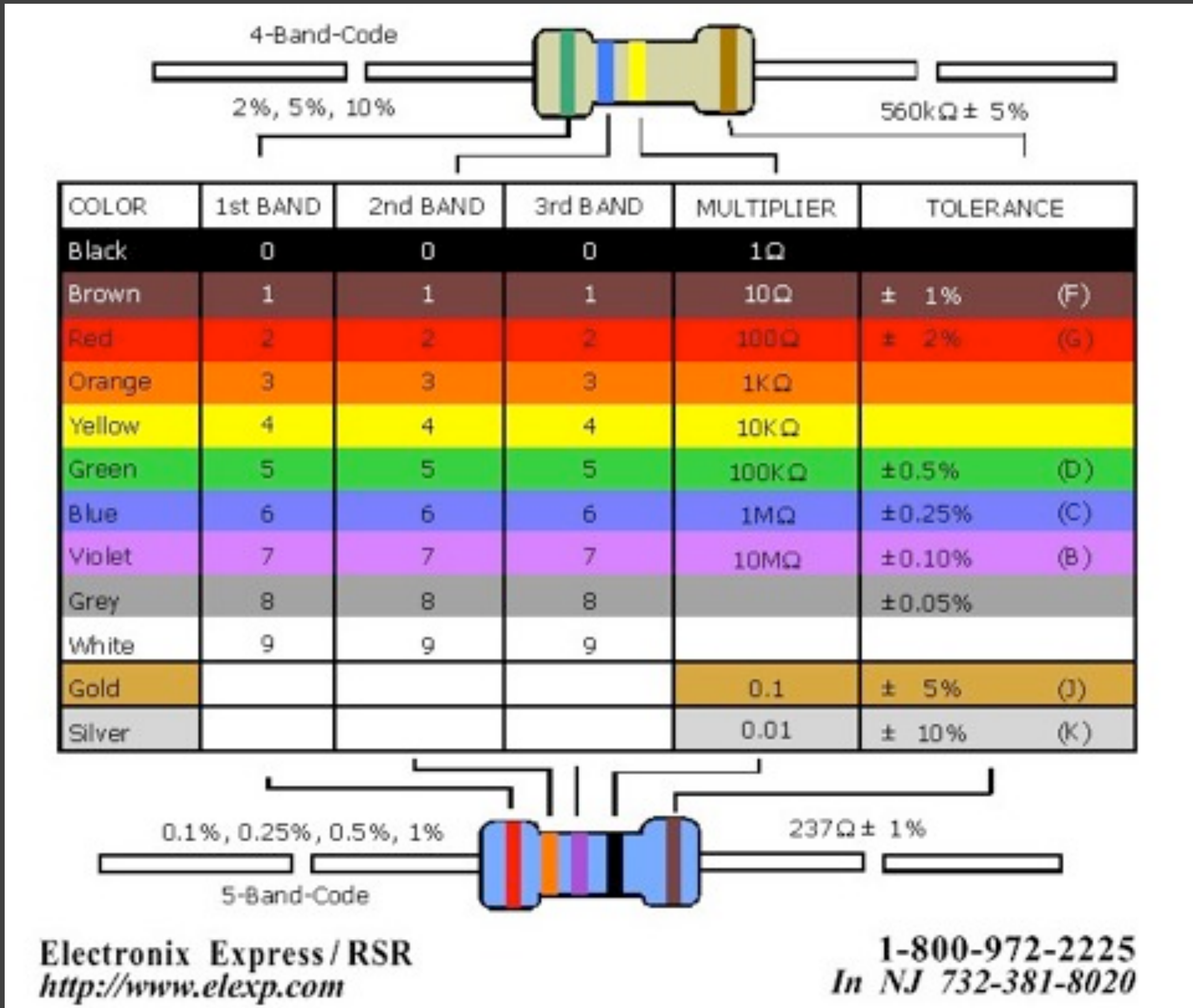


Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)

Molecular models

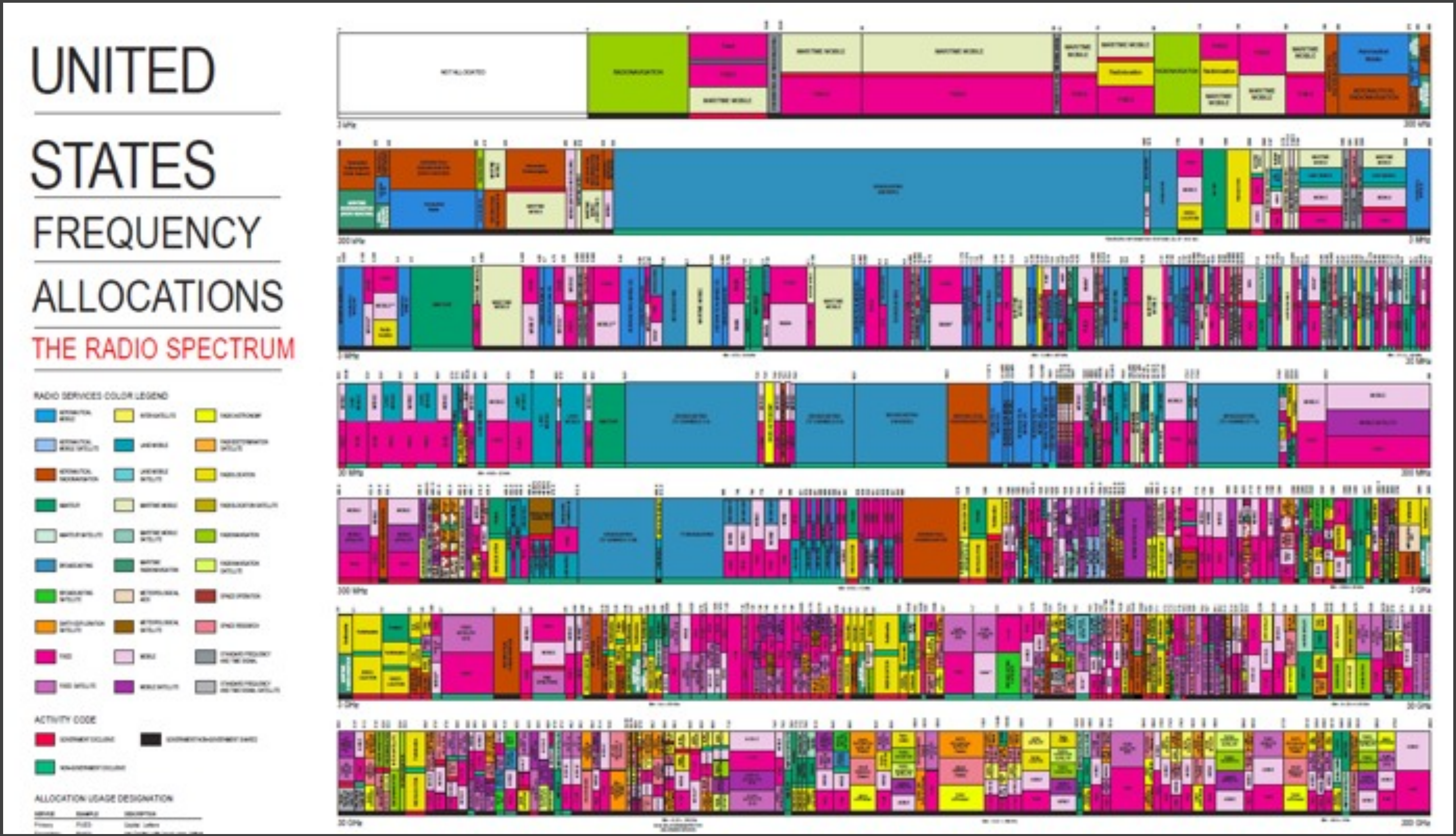
Organic Chemistry Molecular Model Set
http://www.indigo.com/models/gphmodel/62003.html

Resistor color codes

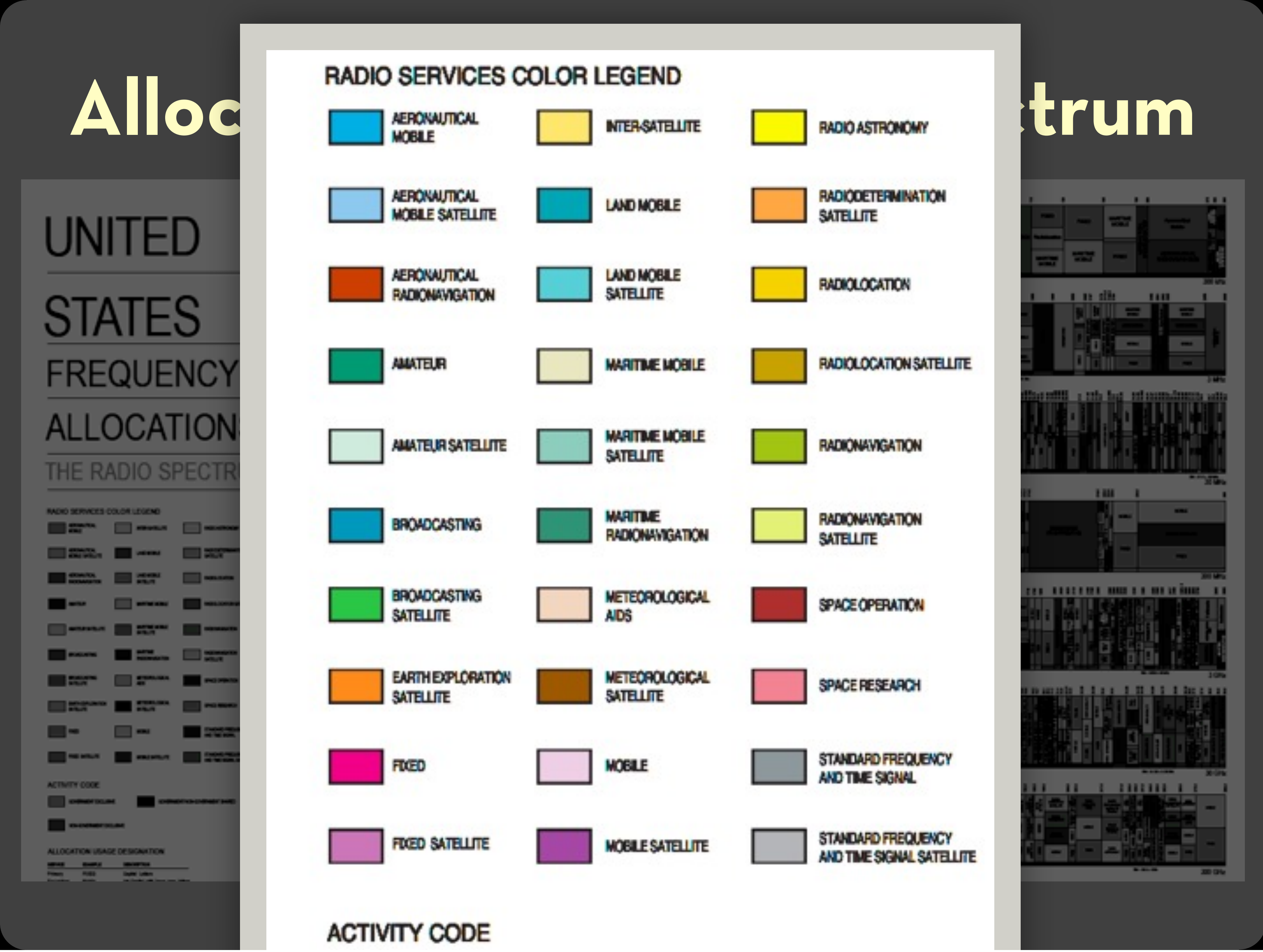


COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 2% (G)
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	±0.5% (D)
Blue	6	6	6	1MΩ	±0.25% (C)
Violet	7	7	7	10MΩ	±0.10% (B)
Grey	8	8	8		±0.05%
White	9	9	9		
Gold				0.1	± 5% (J)
Silver				0.01	± 10% (K)

Allocation of the radio spectrum



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



Alloc
trum
UNITED
STATES
FREQUENCY
ALLOCATION
THE RADIO SPECTR
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 MOBILE
RADIOLOCATION SATELLITE
AMATEUR SATELLITE
MARITIME MOBILE SATELLITE
RADIONAVIGATION
BROADCASTING
MARITIME RADIONAVIGATION
RADIONAVIGATION SATELLITE
BROADCASTING SATELLITE
METEOROLOGICAL AIDS
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
ACTIVITY CODE

Palette Design + Color Names

Minimize overlap and ambiguity of color names.

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 color names.

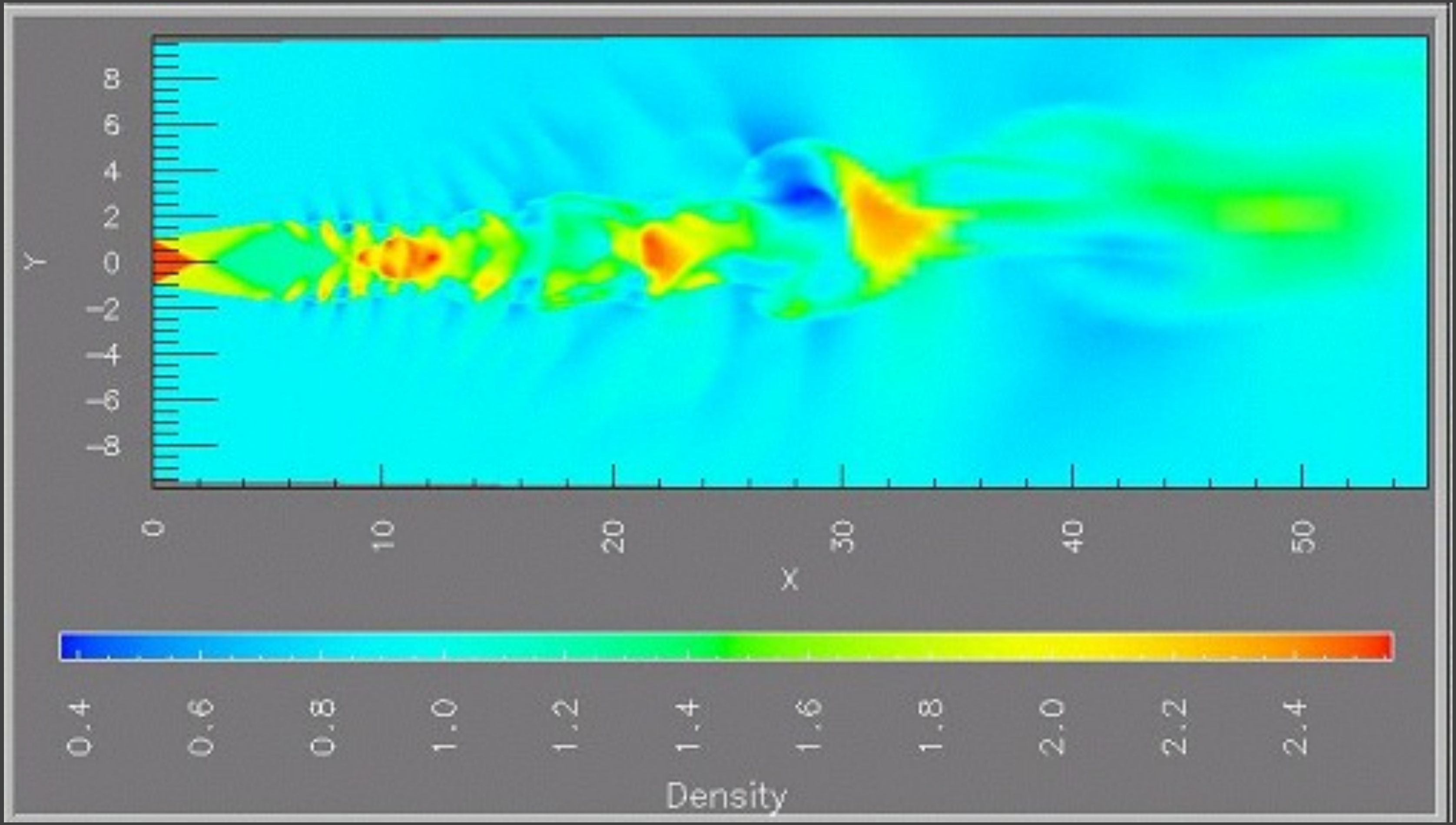
Color Name Distance

										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*	

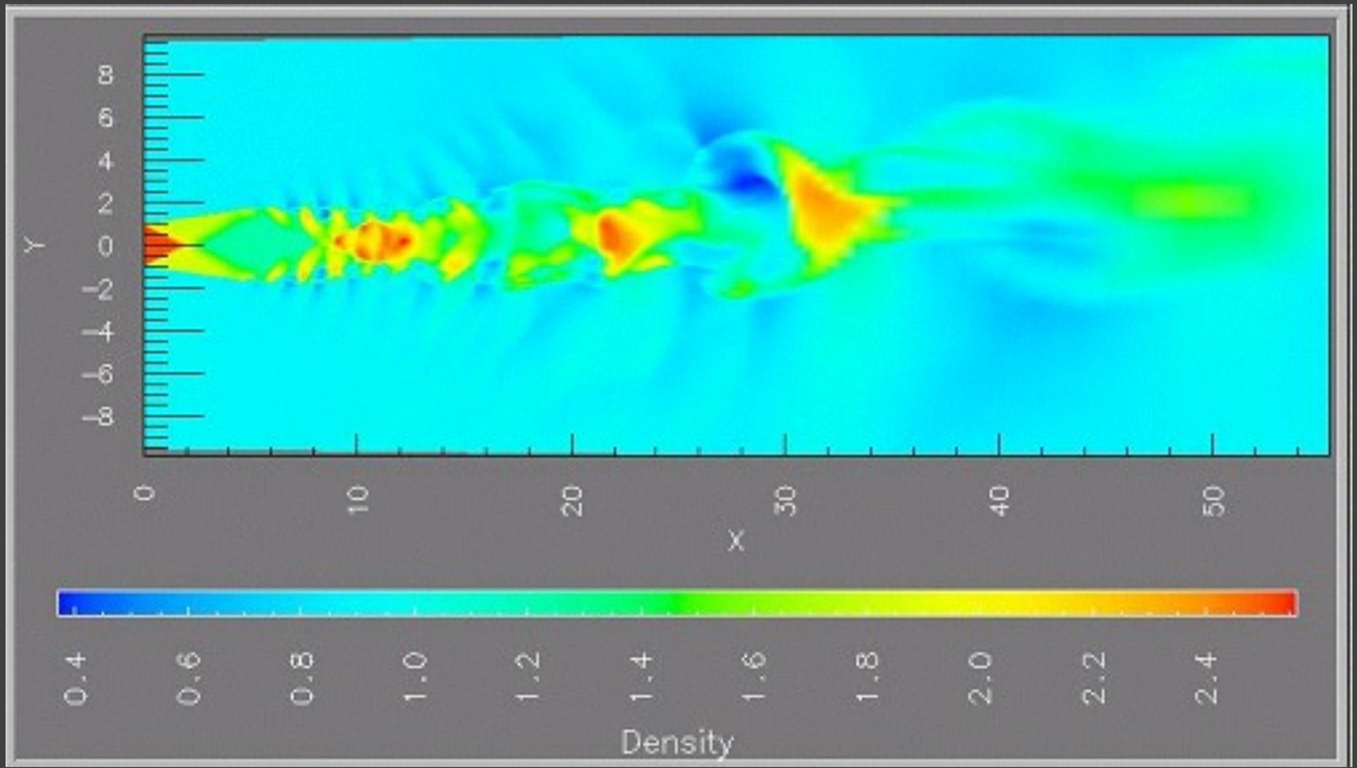
http://vis.stanford.edu/color-names

Quantitative Color

Default rainbow maps

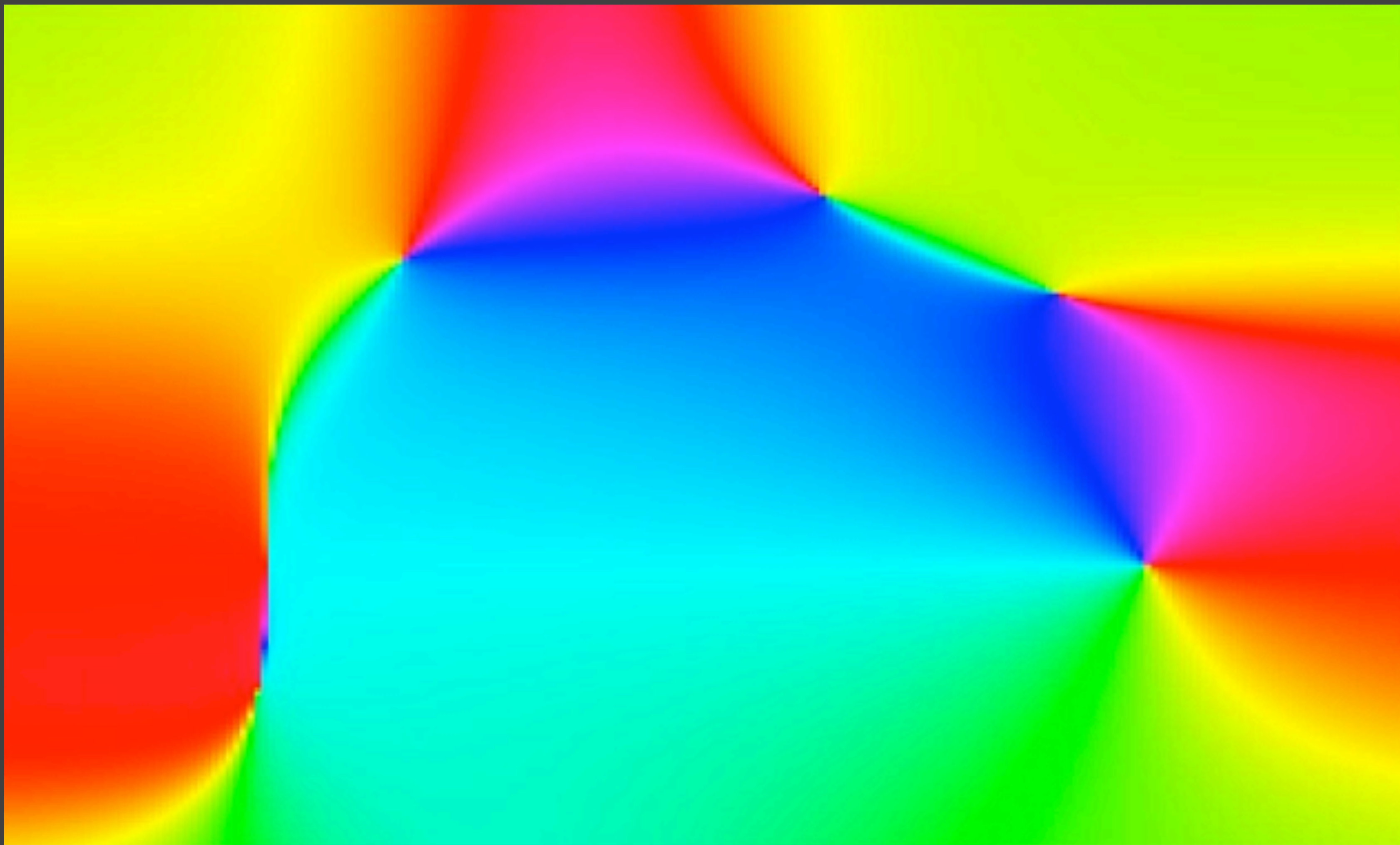


Avoid rainbow color maps!

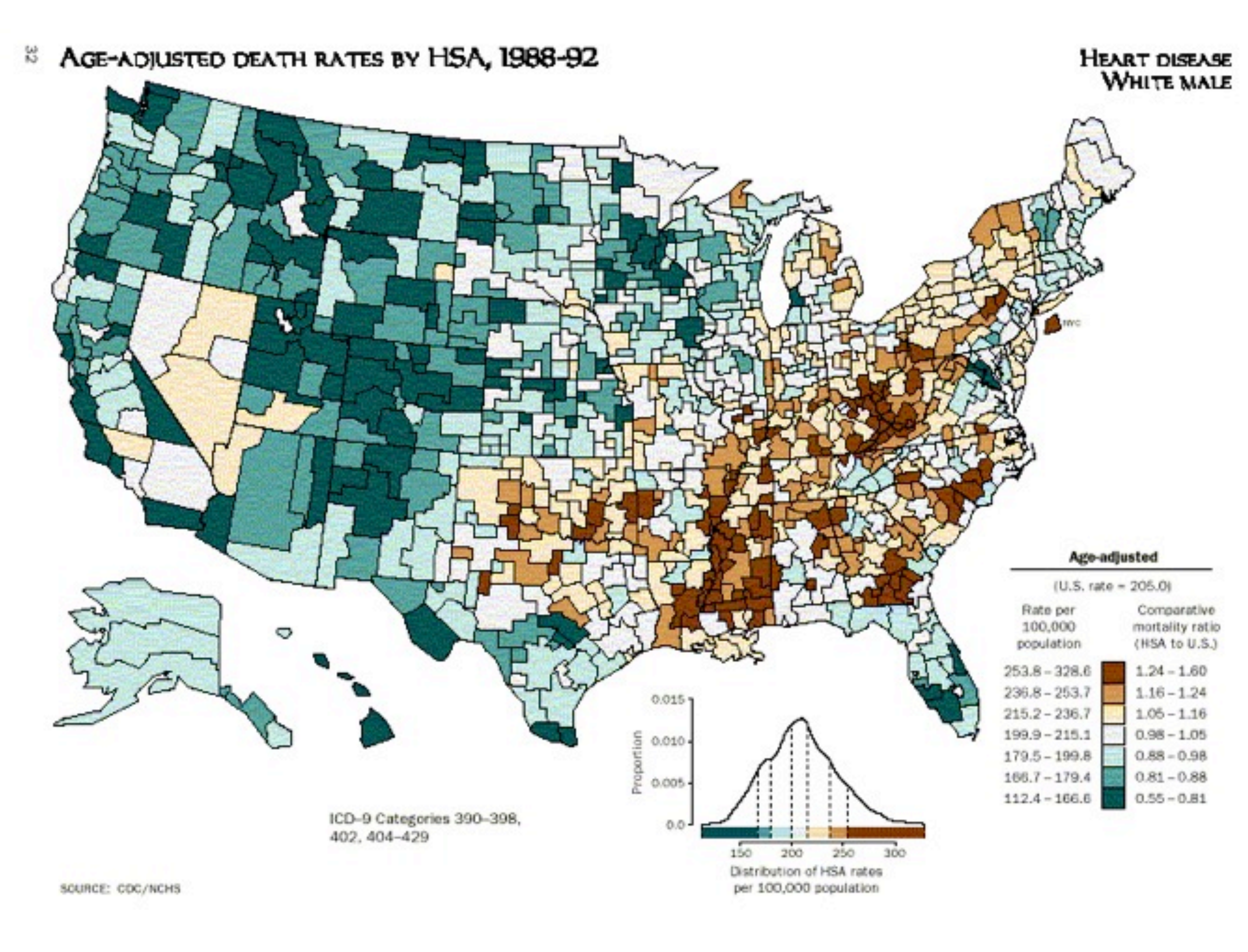


1. People segment colors into classes
2. Hues are not naturally ordered
3. Different lightness emphasizes certain scalar values
4. Low luminance colors (blue) hide high frequencies

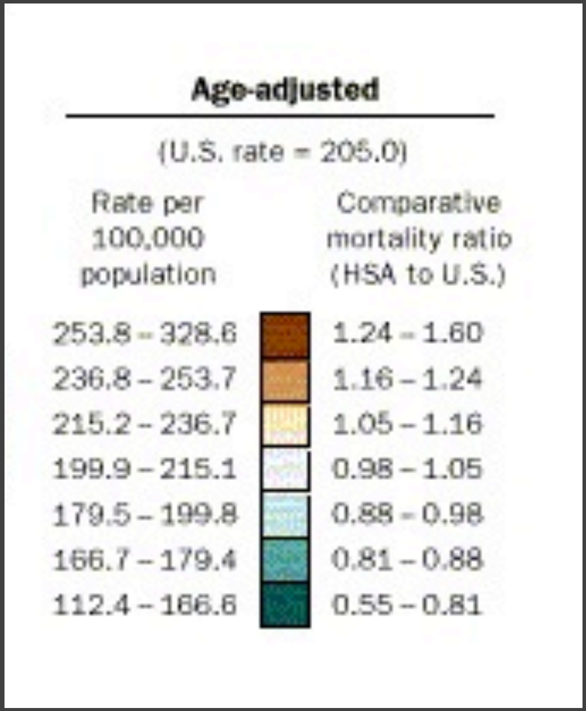
Singularity in Phase (M. Berry)

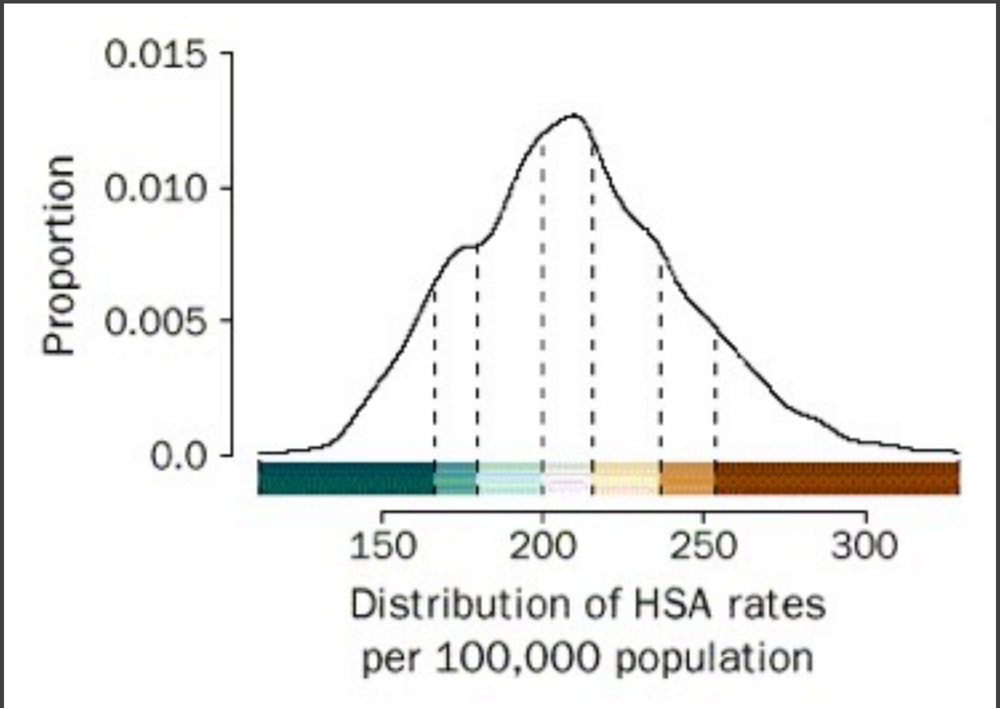


Phase is periodic ⇒ Hue circle which is also periodic


32
Age-adjusted death rates by HSA, 1988-92
Heart disease
White male
NYC
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
0.015
0.010
0.005
0.0
Proportion
150
200
250
300
Distribution of HSA rates per 100,000 population
ICD-9 Categories 390–398, 402, 404–429
SOURCE: CDC/NCHS

Classing quantitative data



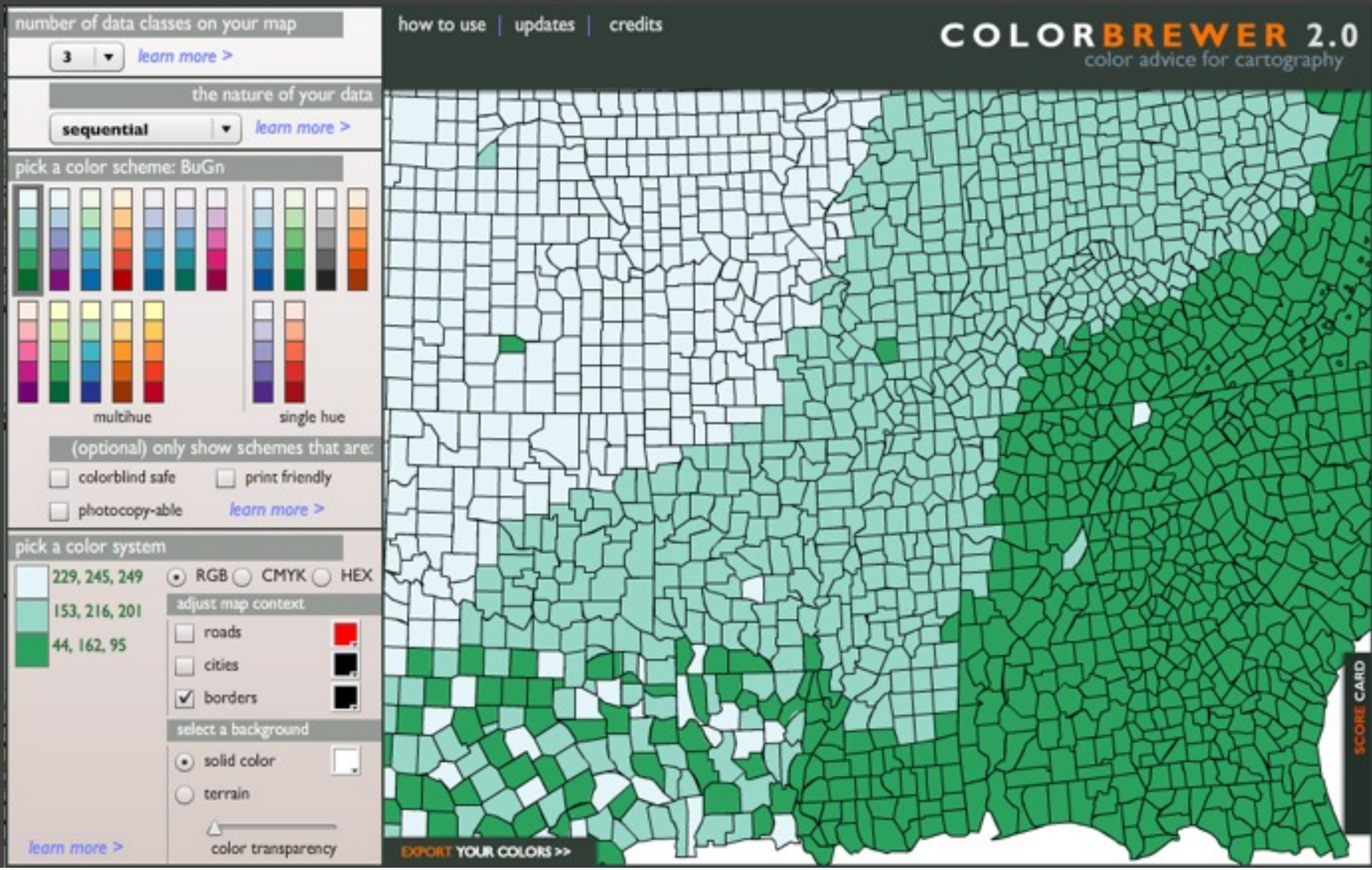


Age-adjusted mortality rates for the United States.

Classing quantitative data

1. Equal interval (arithmetic progression)
2. Quantiles *(recommended)*
3. Standard deviation
4. Classification [Jenks' "natural breaks"]
5. Equal area
6. Minimal length boundaries
7. Minimal gaps

ColorBrewer: Color advice for maps



Quantitative color encoding

Sequential color scale

Constrain hue, vary luminance/saturation

Map higher values to darker colors

Diverging color scale

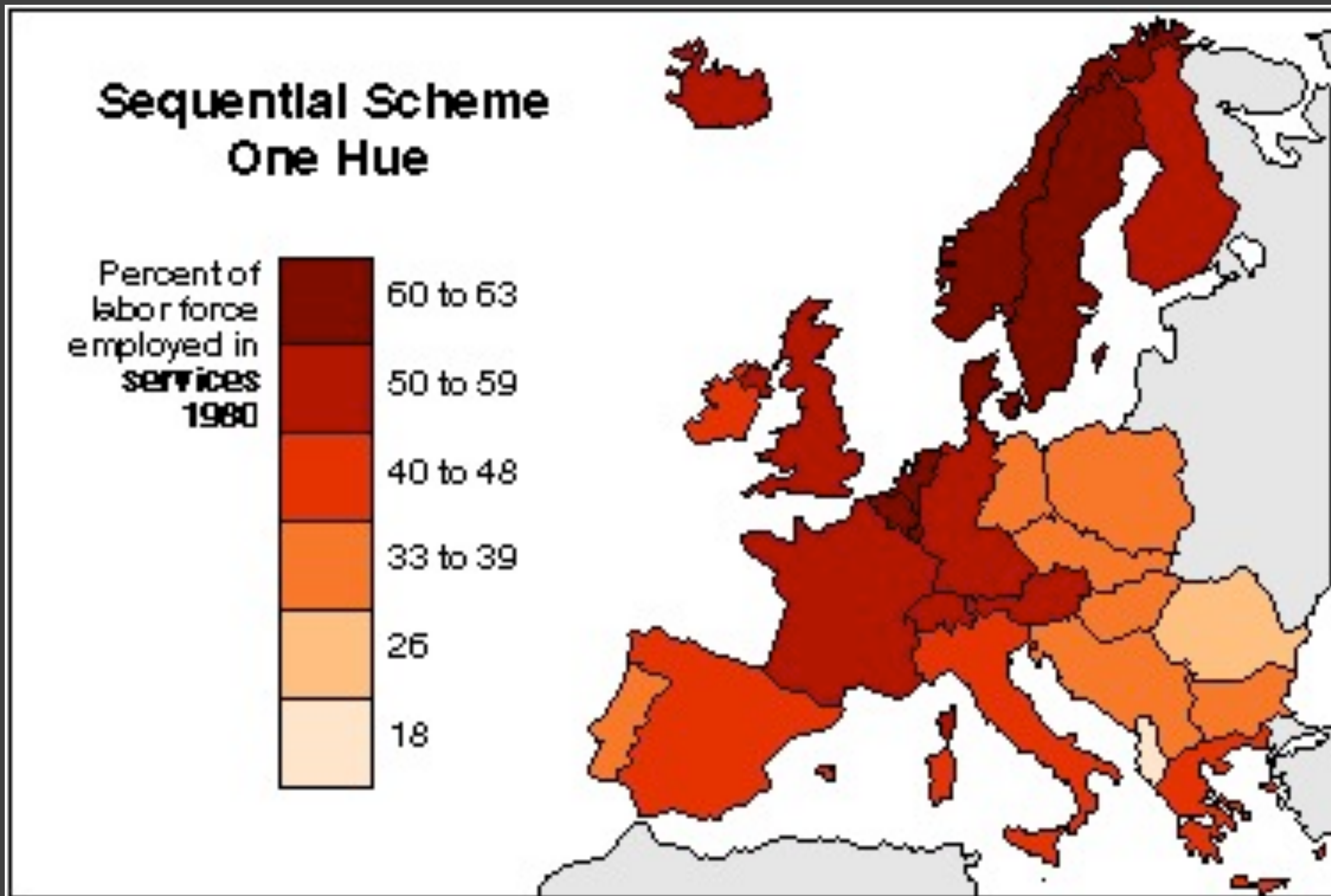
Useful when data has a meaningful "midpoint"

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

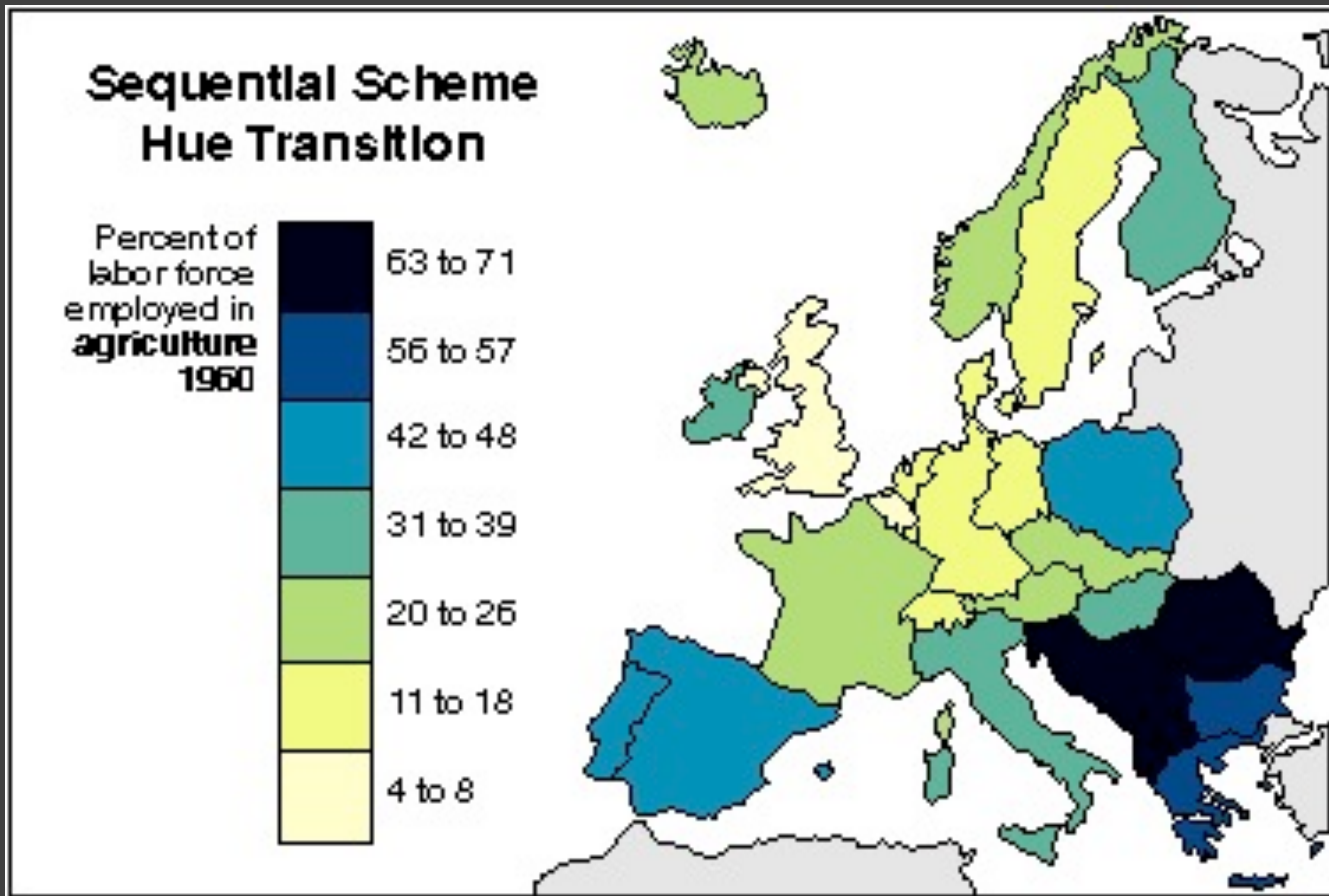
Use saturated colors for endpoints

Limit number of steps in color to 3-9

Sequential color scheme



Sequential color scheme



Design of sequential color scales

Hue-Lightness *(Recommended)*

Higher values mapped to darker colors

ColorBrewer schemes have 3-9 steps

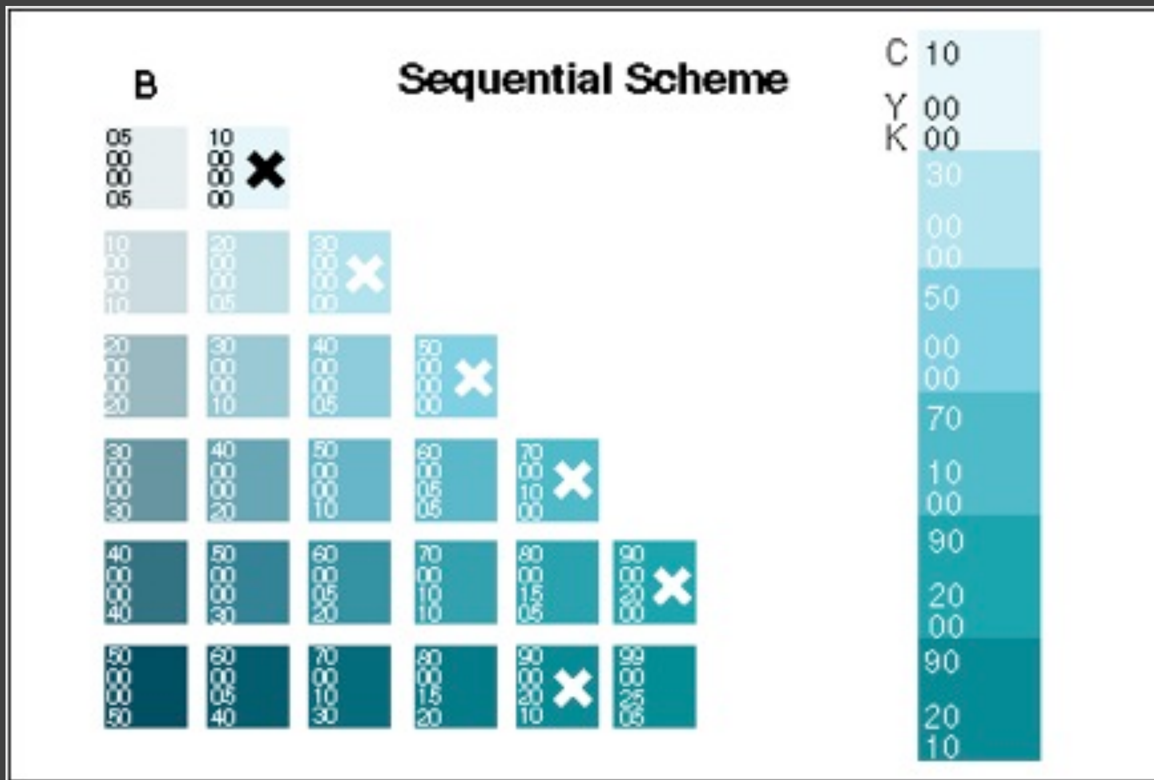
Hue Transition

Two hues

Neighboring hues interpolate better

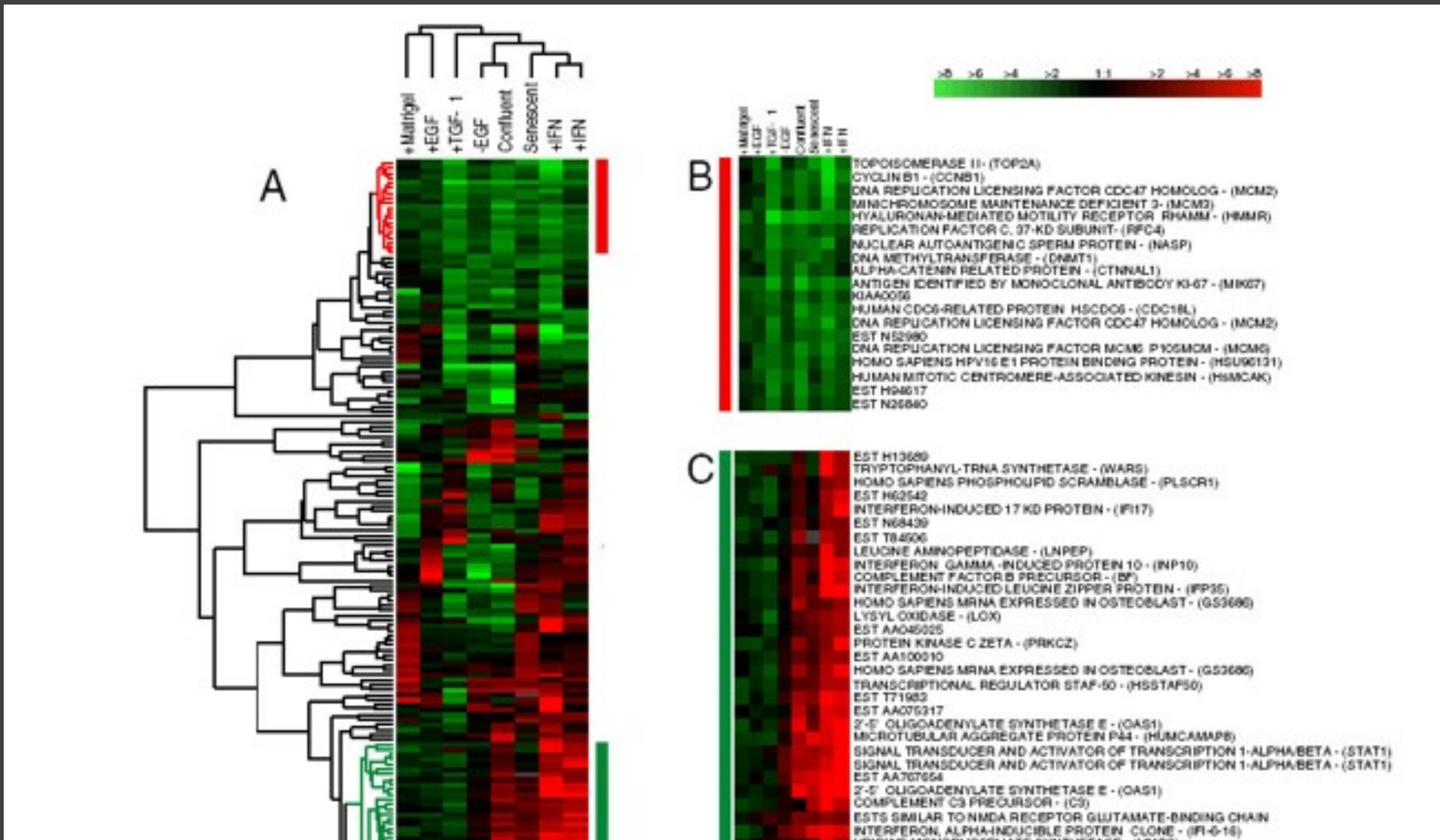
Couple with change in lightness

Design of sequential data scales

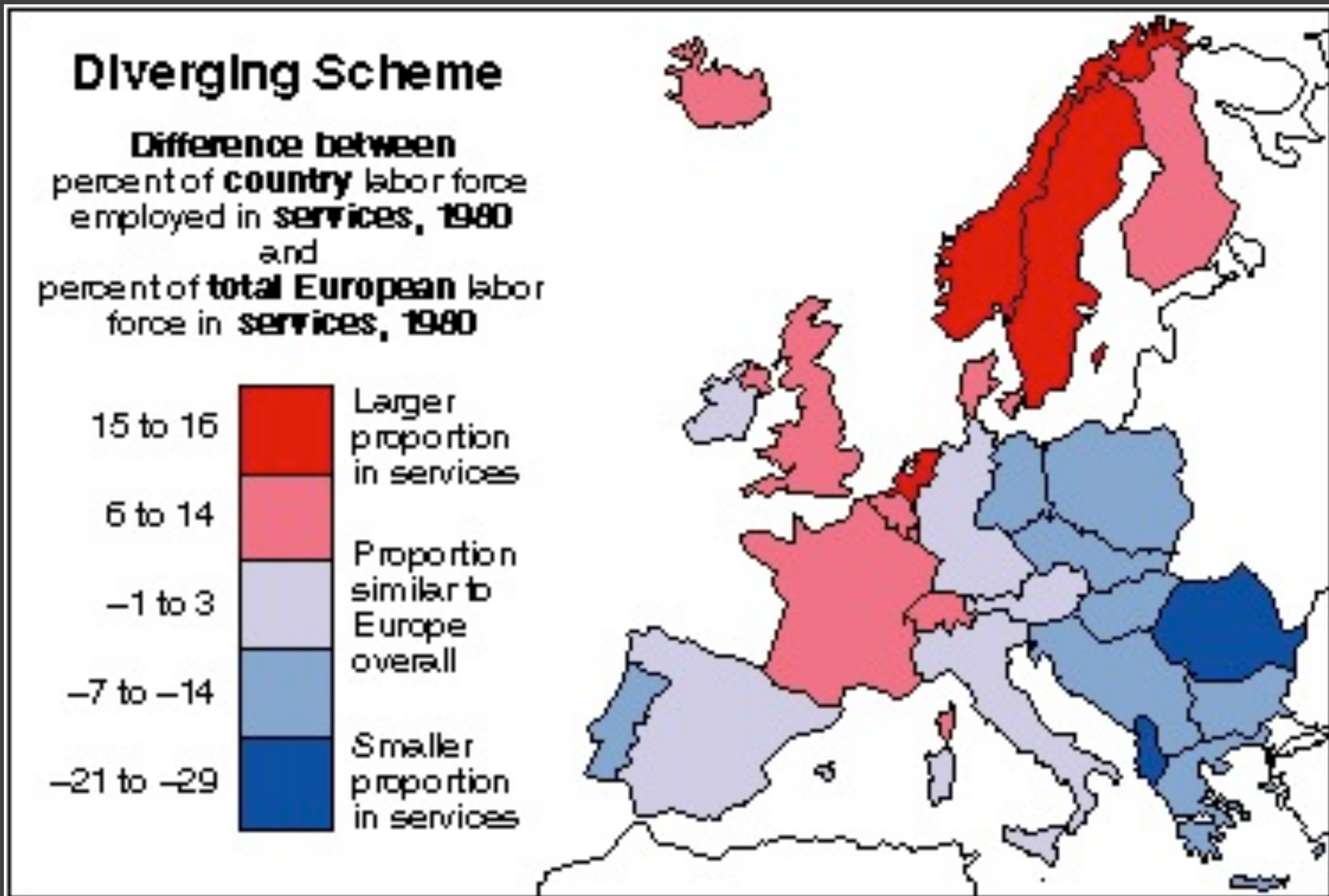


http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Diverging color scheme



Diverging color scheme

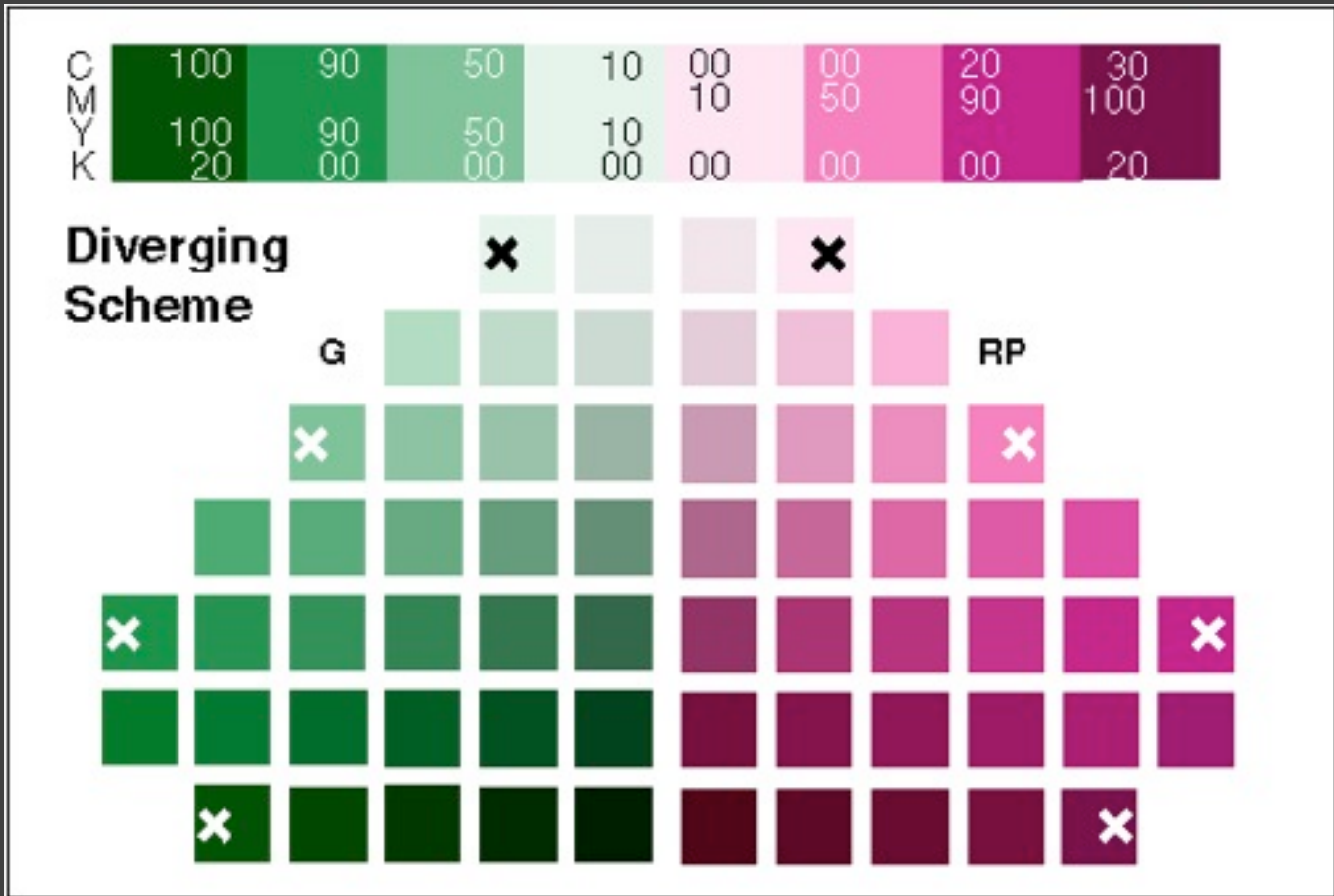


Diverging color scheme

Hue Transition

- Carefully handle midpoint
  - Critical class
    - Low, Average, High
    - ‘Average’ should be gray
  - Critical breakpoint
    - Defining value e.g. 0
    - Positive & negative should use different hues
- Extremes saturated, middle desaturated

Diverging color scheme



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

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

Beware of **bad interactions** (red/blue etc.)

Get it right in **black and white**

Respect the **color blind**