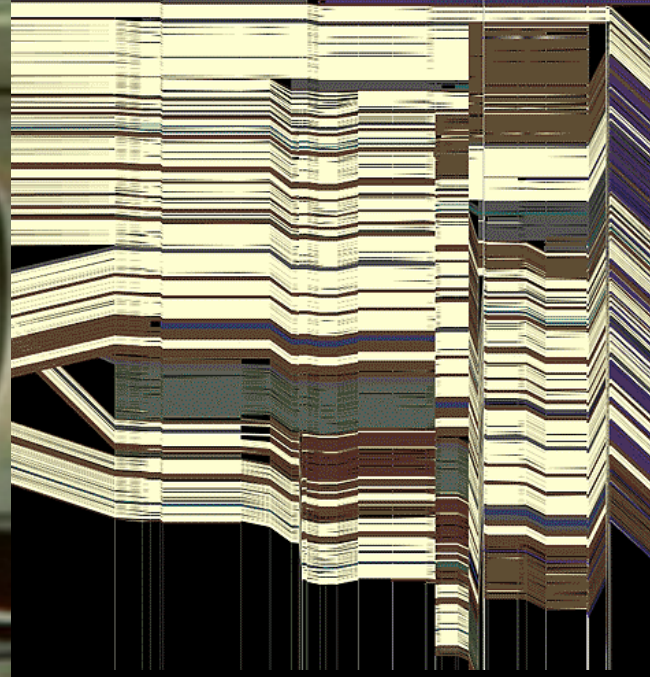
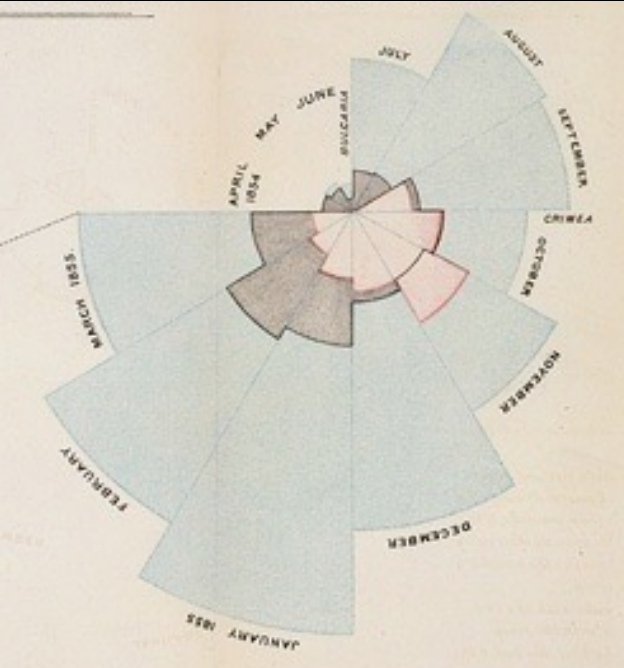


CSE 512 - Data Visualization

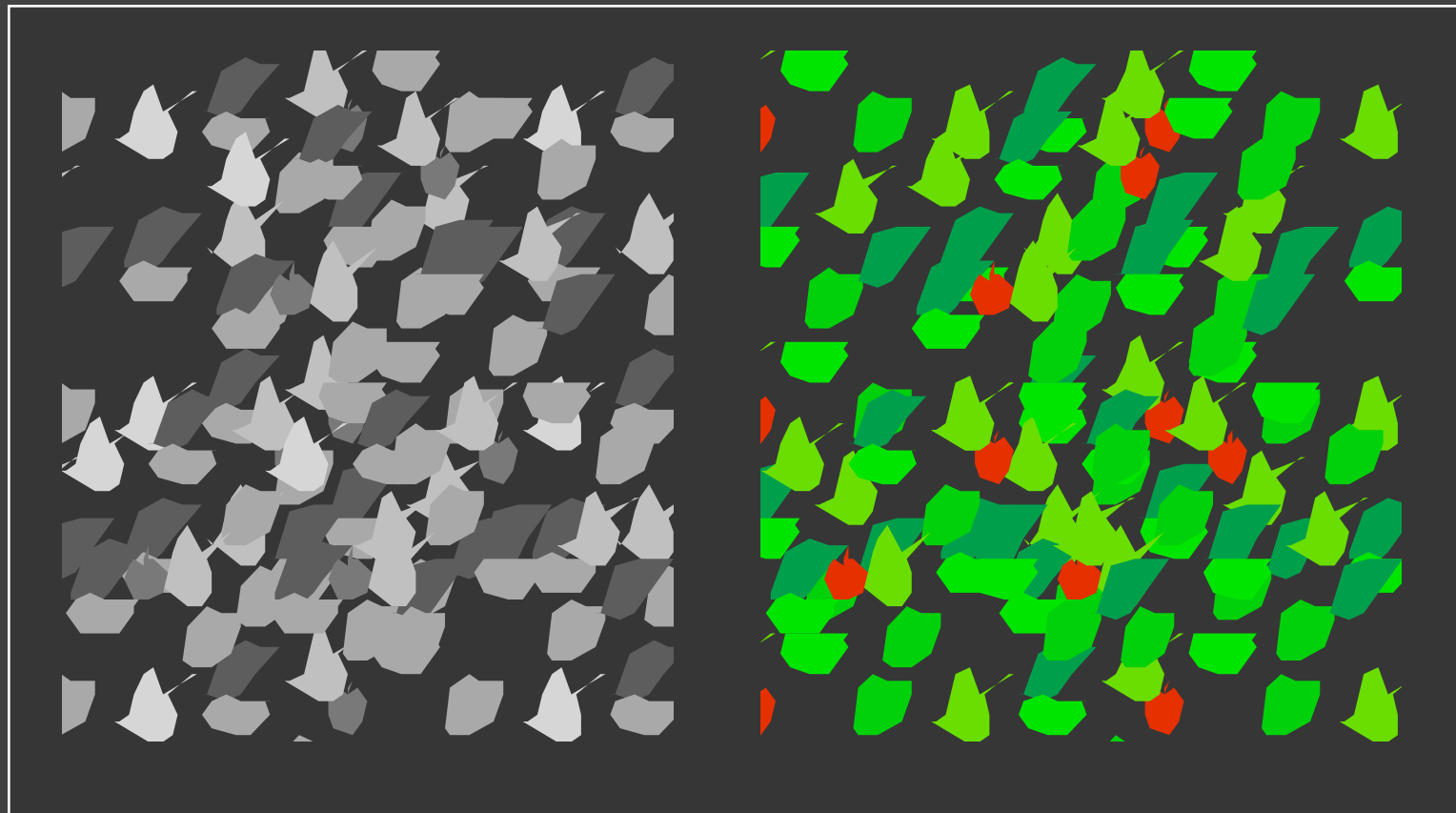
Color



Jeffrey Heer University of Washington

Color in Visualization

Identify, Group, Layer, Highlight



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 encoding

Guidelines for color palette design

Perception of Color

What color is this?

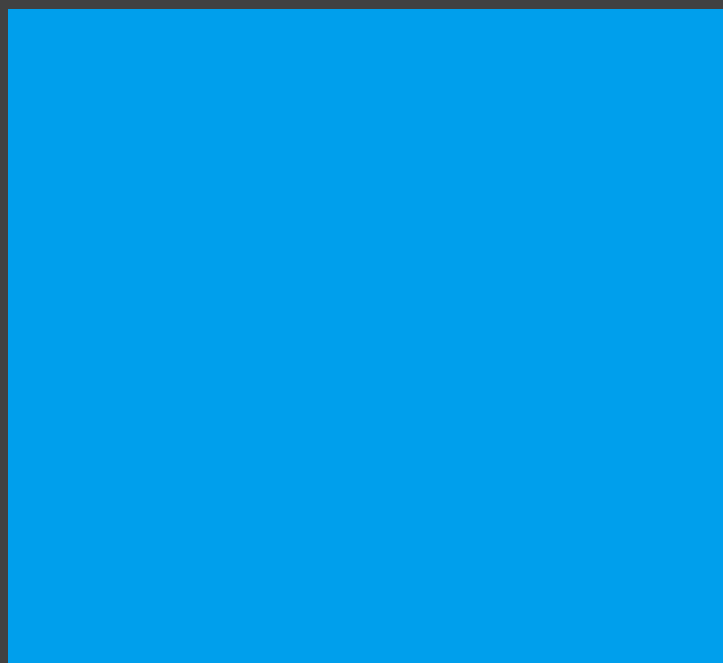


What color is this?

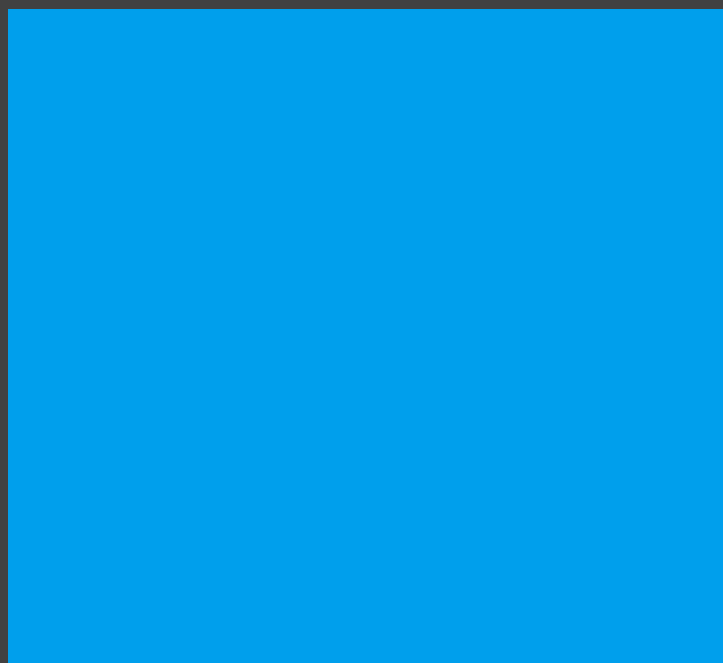


"Yellow"

What color is this?

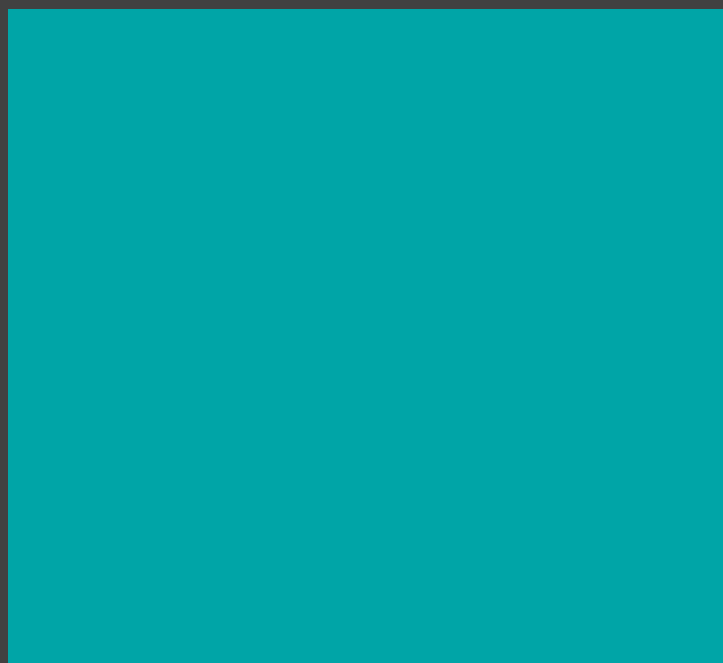


What color is this?



"Blue"

What color is this?



What color is this?

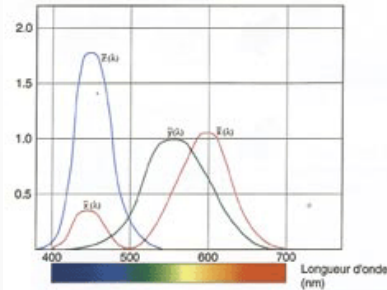


"Teal" ?

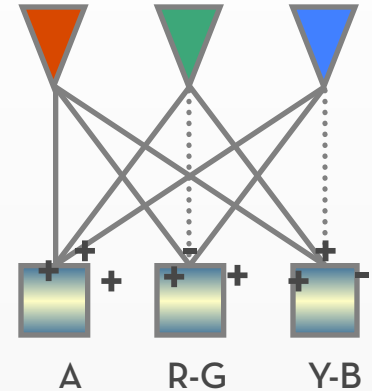
Perception of Color



Light



Cone Response



Opponent Signals

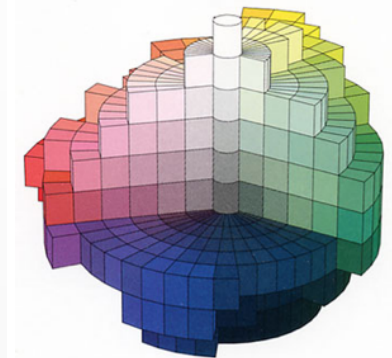
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE
MODELS

Color Appearance



Color Perception

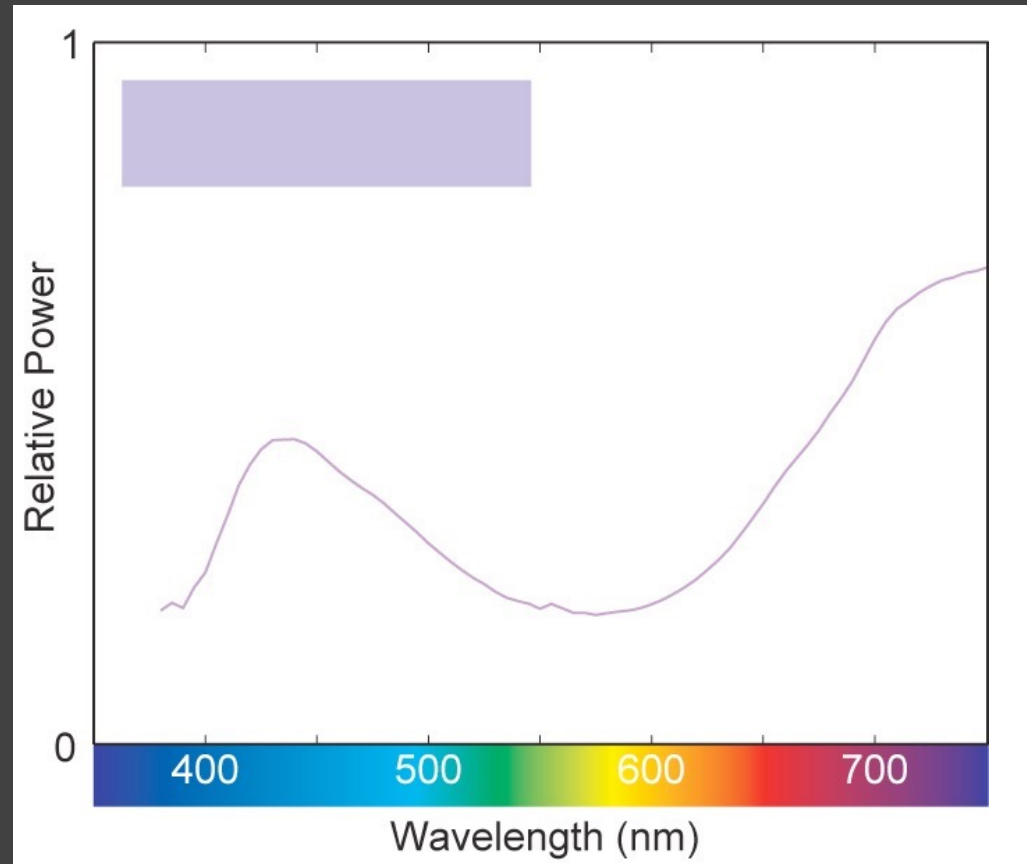
Physicist's View

Light as electromagnetic wave

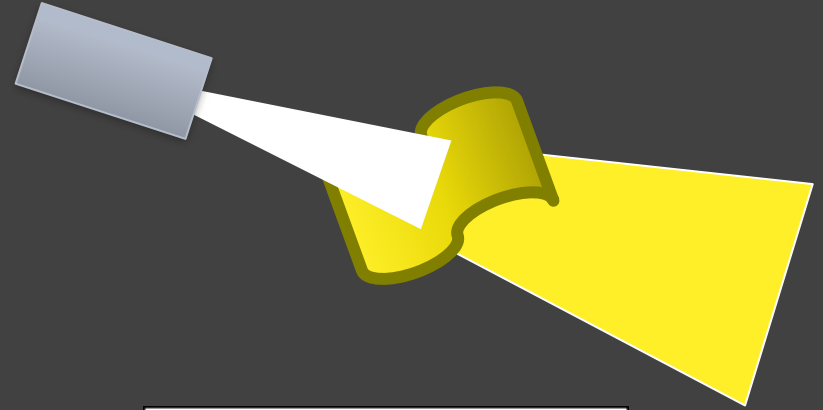
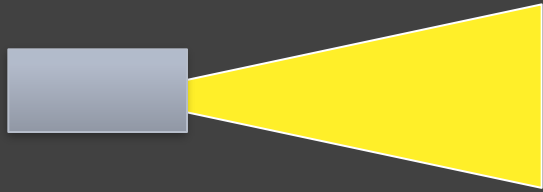
Wavelength

Energy or

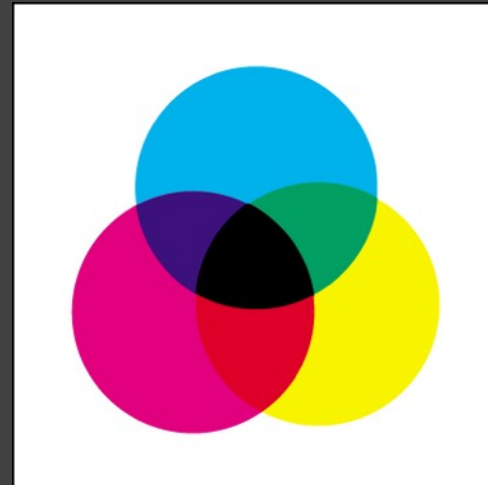
"Relative luminance"



Emissive vs. Reflective Light



Additive
(digital displays)

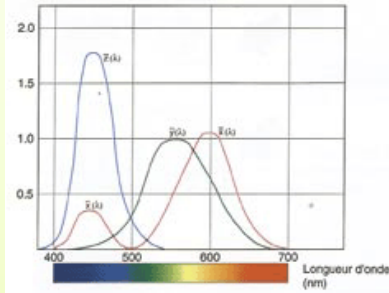


Subtractive
(print, e-paper)

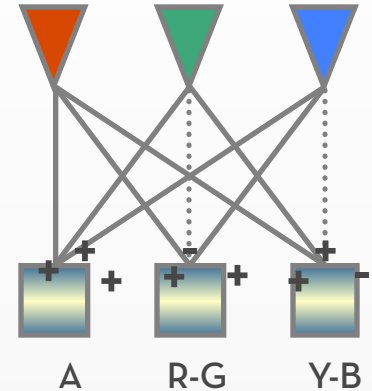
Perception of Color



Light



Cone Response



Opponent Signals

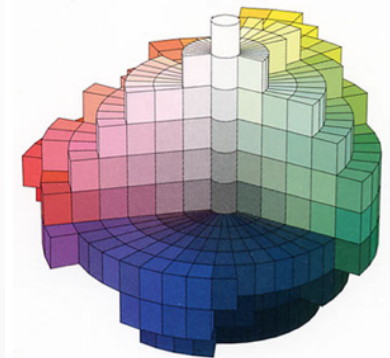
“Yellow”

Color Cognition



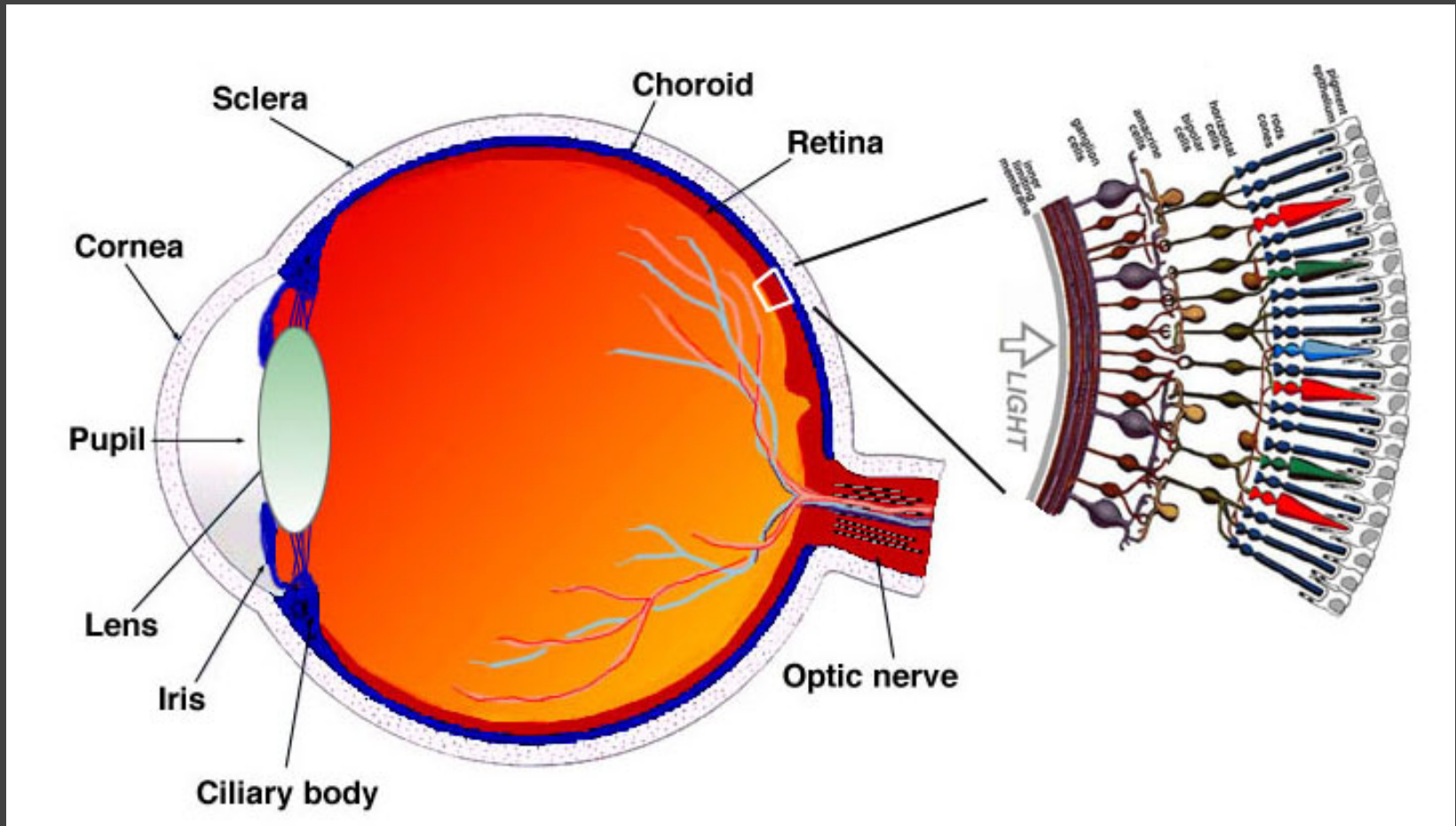
Mark D. Fairchild
COLOR APPEARANCE
MODELS

Color Appearance



Color Perception

Retina

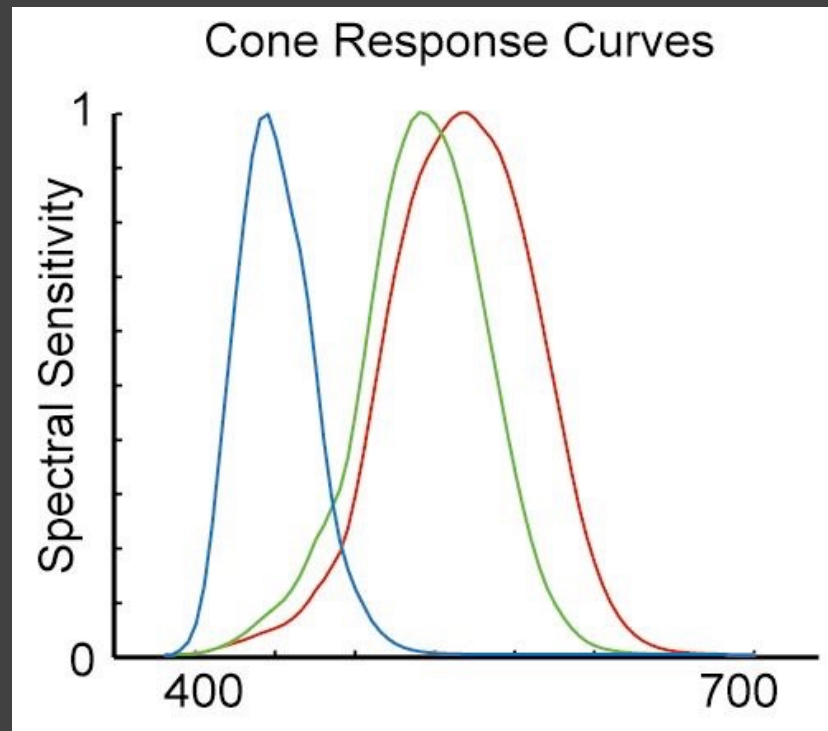


Simple Anatomy of the Retina, Helga Kolb

As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength

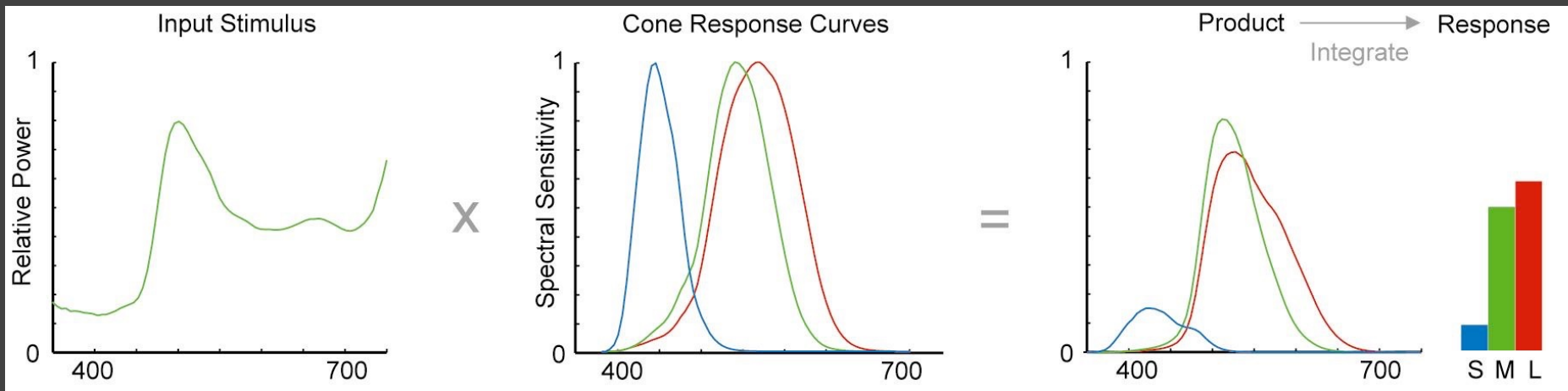


As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength

Integration with input stimulus



Effects of Retina Encoding

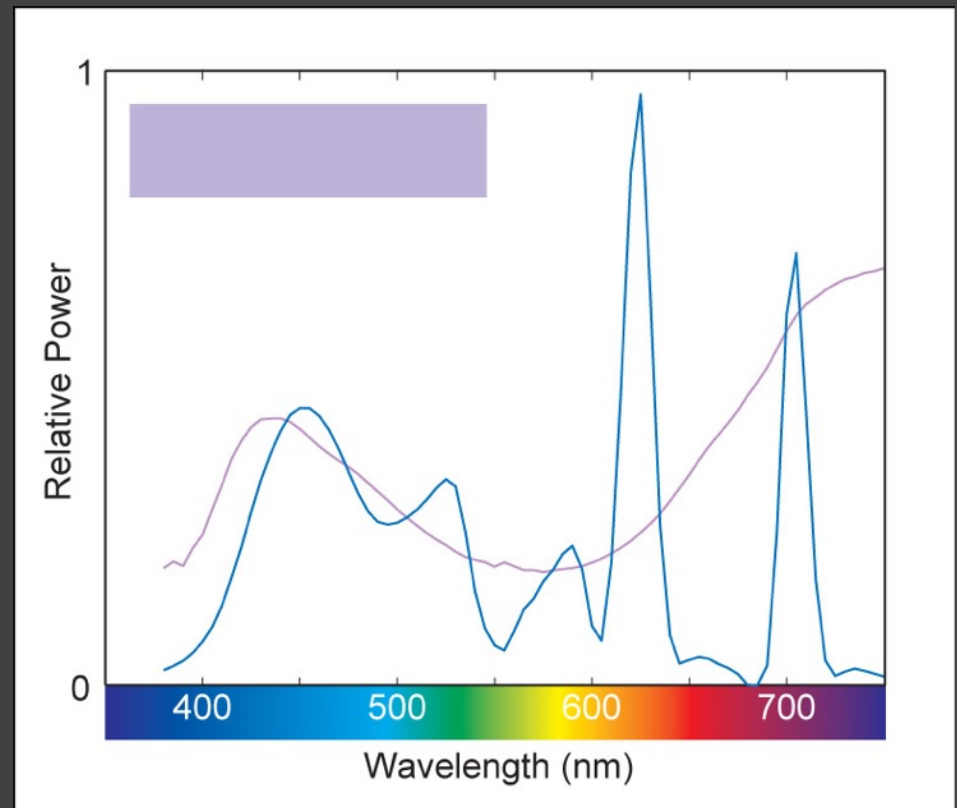
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

"Tri-stimulus"

Computer displays

Digital scanners

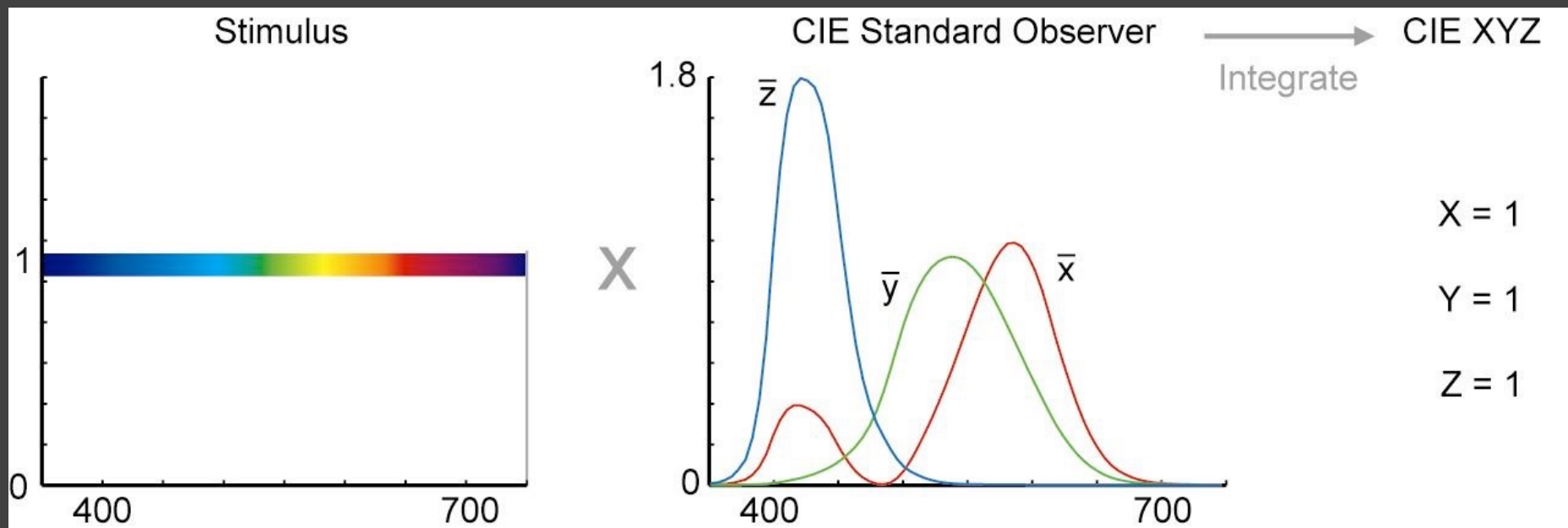
Digital cameras



CIE XYZ Color Space

Standardized in 1931 to mathematically represent tri-stimulus response.

“Standard observer” response curves



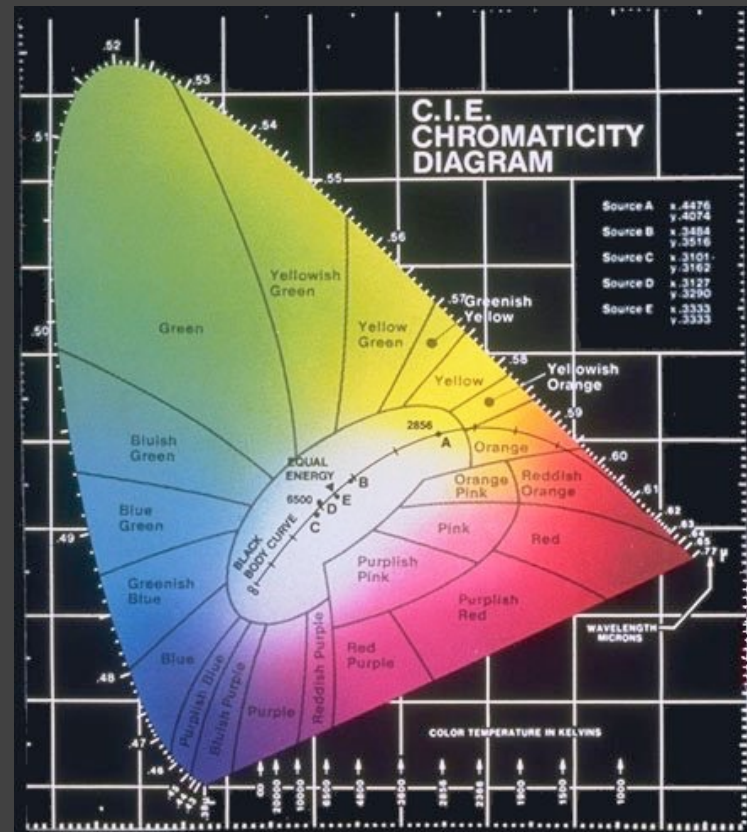
CIE Chromaticity Diagram

Colorfulness vs. Brightness

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

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

y



x

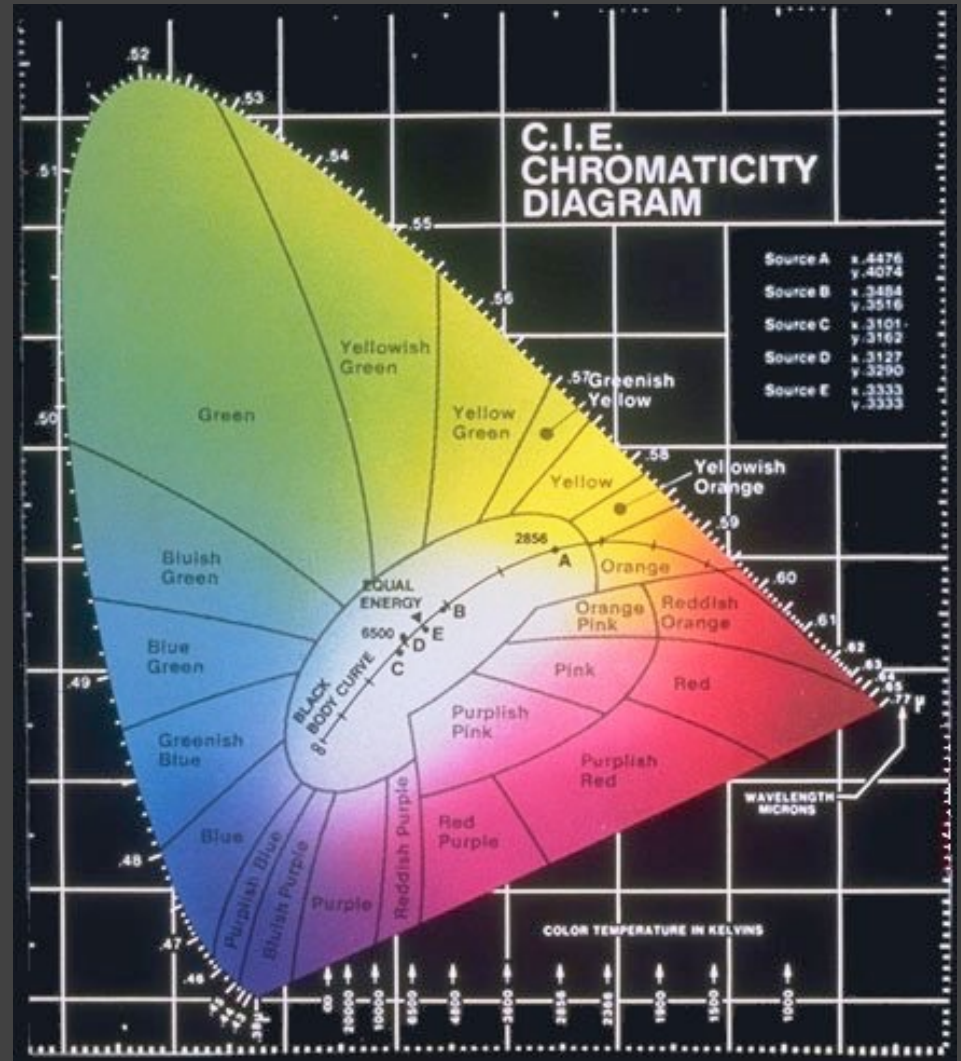


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

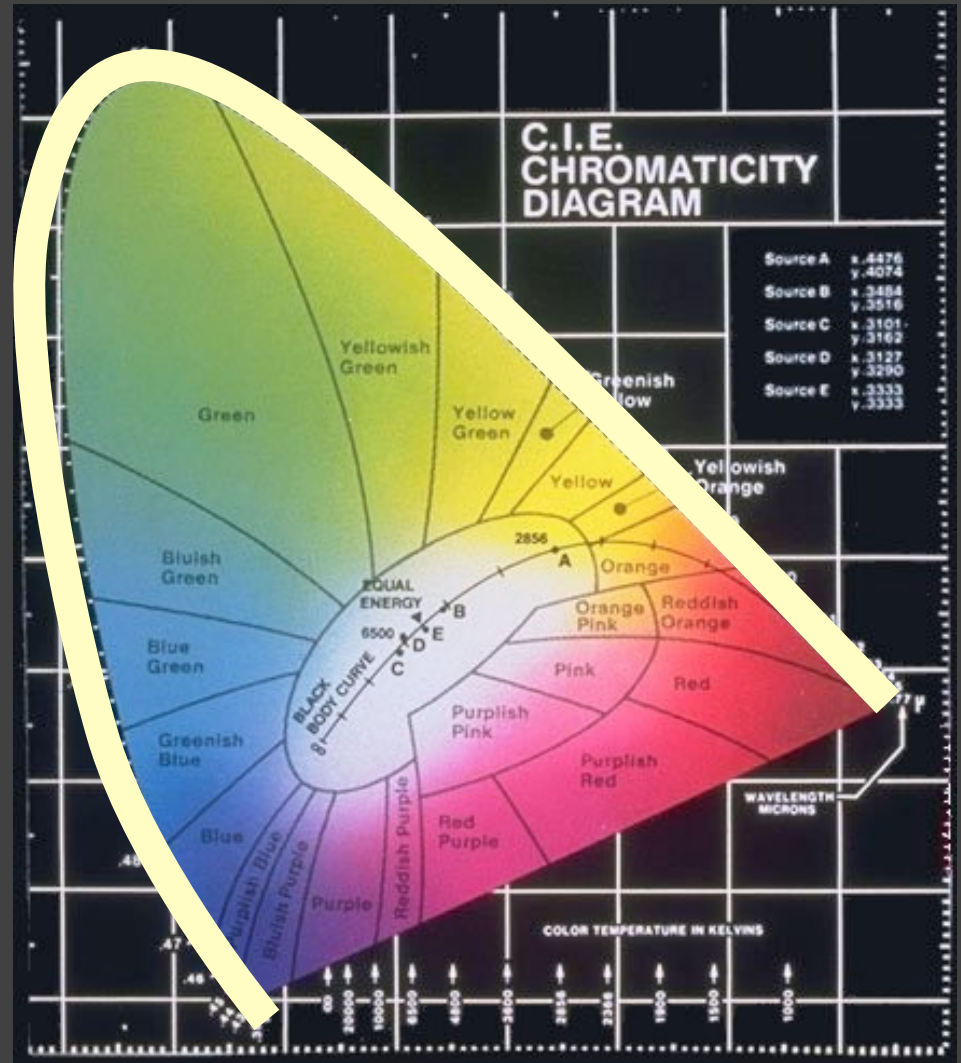


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

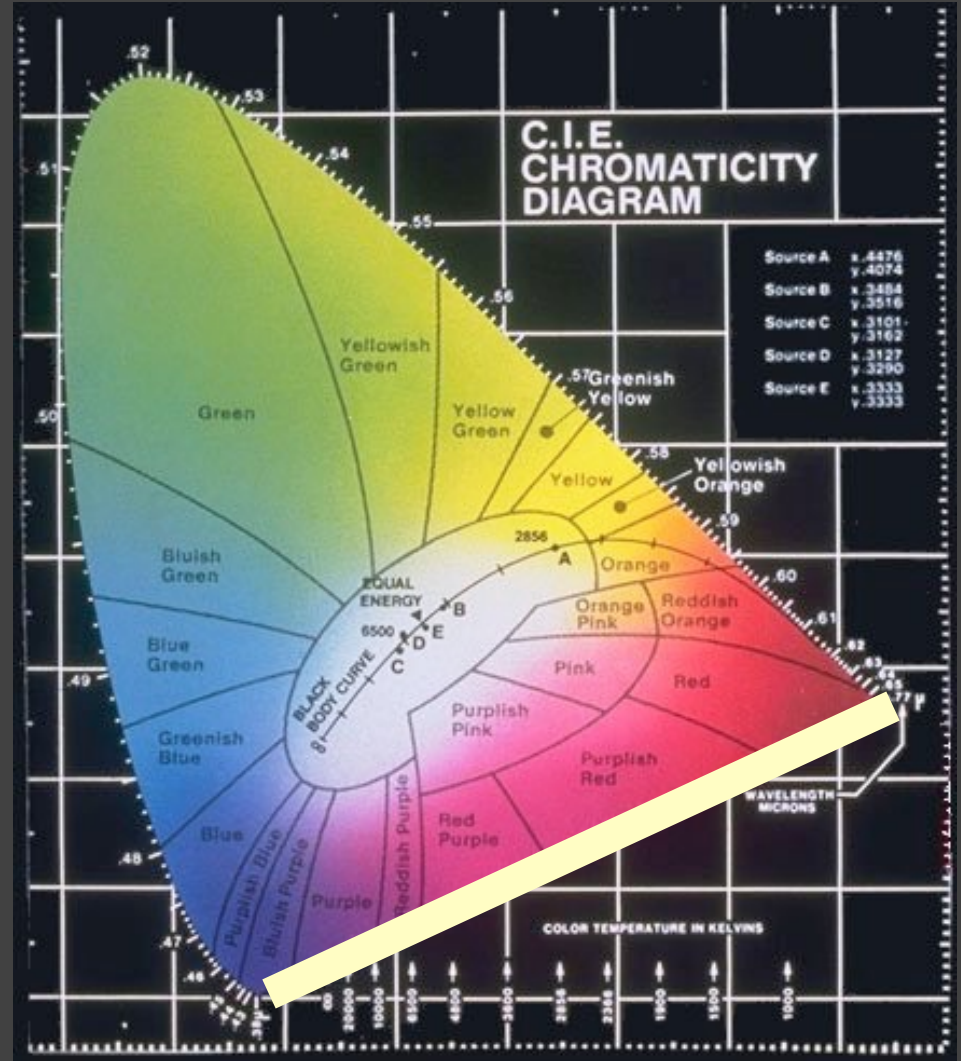


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

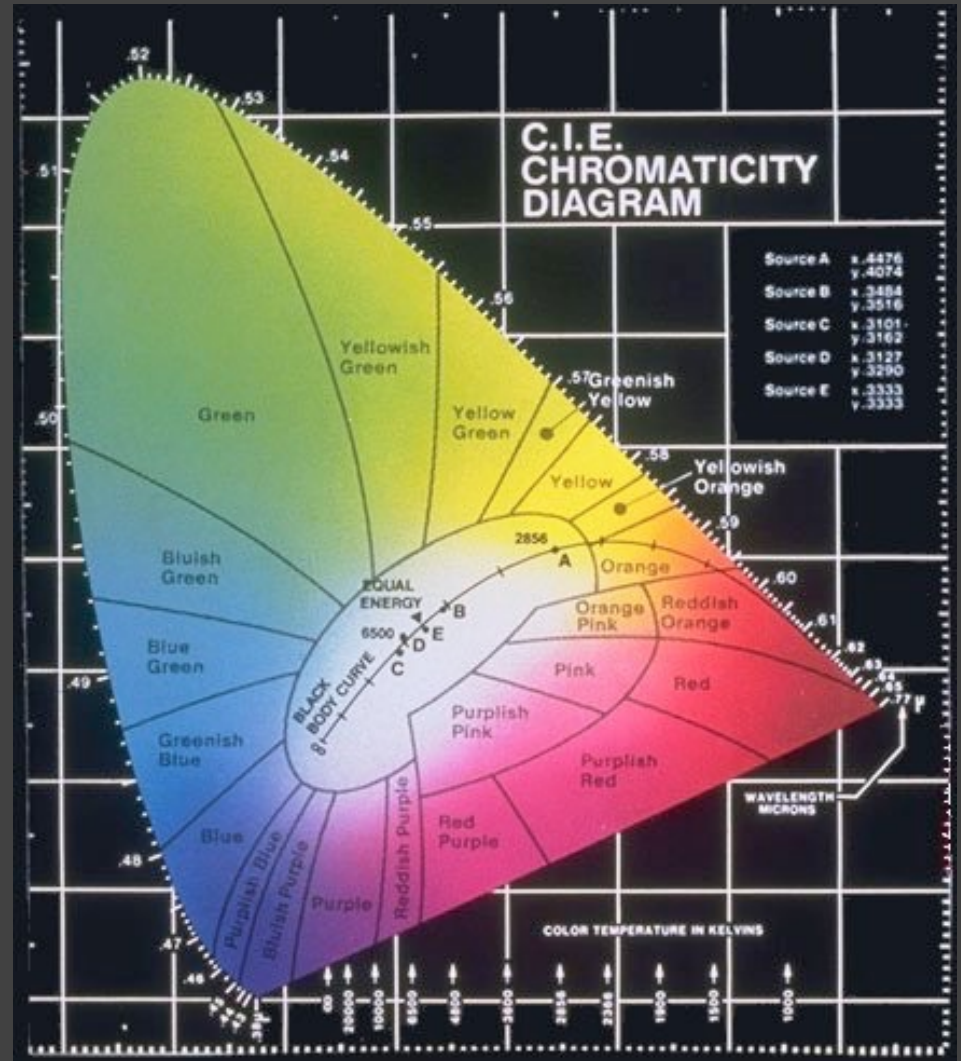


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

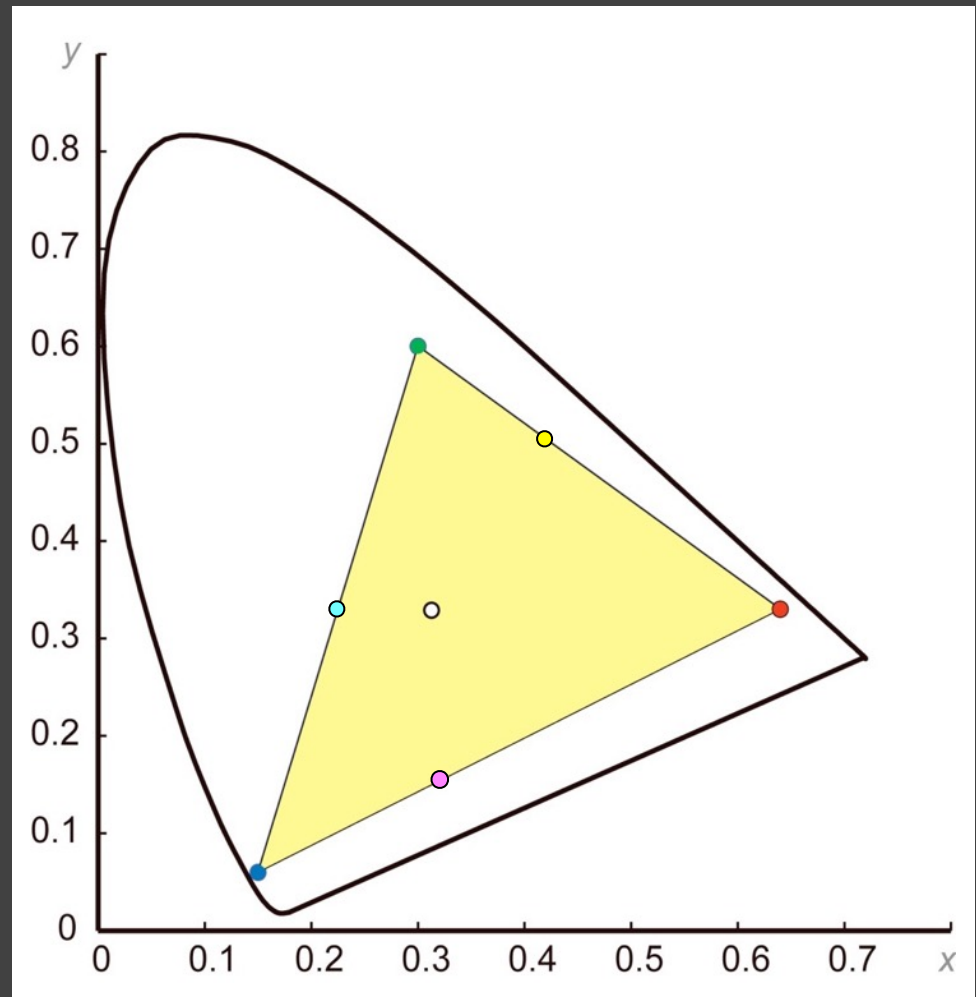


Display Gamuts

Typically defined by:

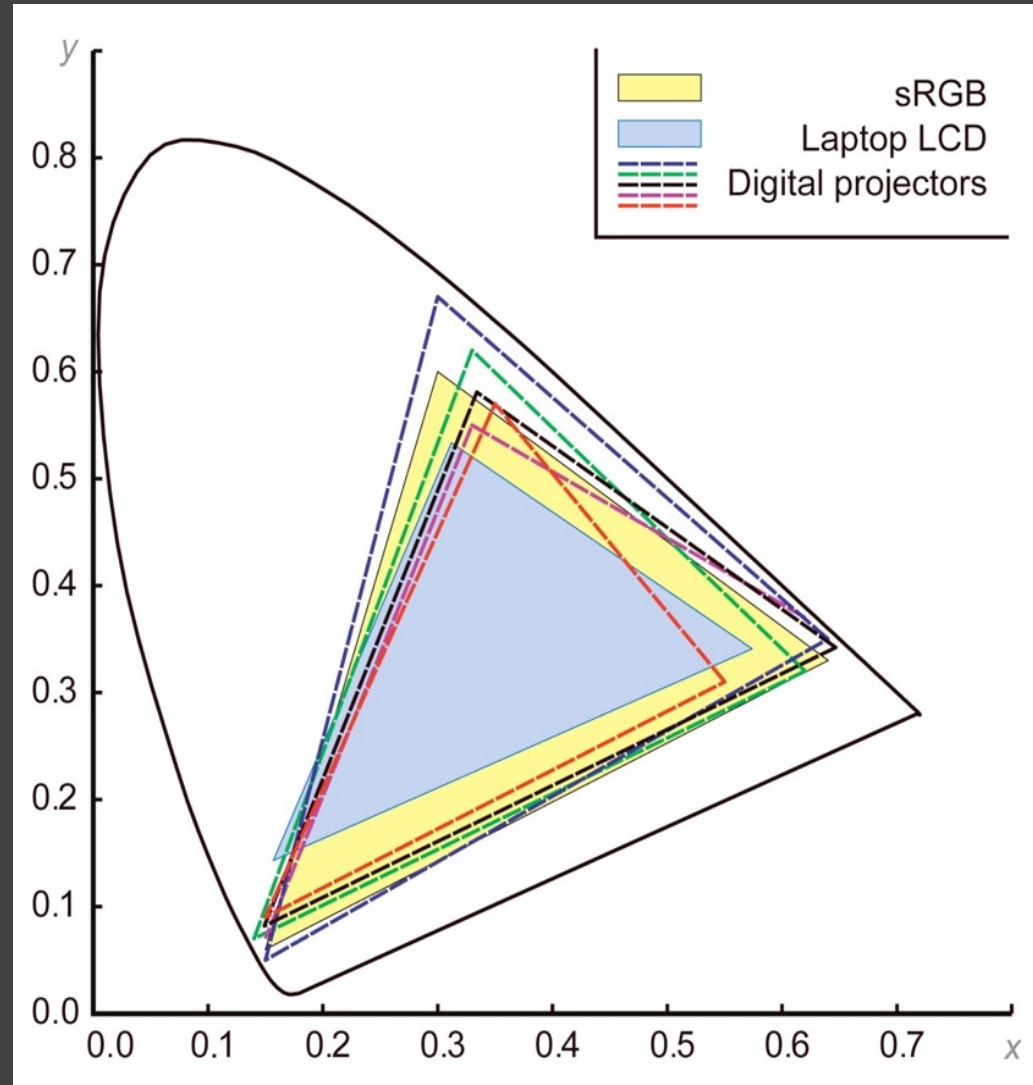
3 Colorants

Convex region



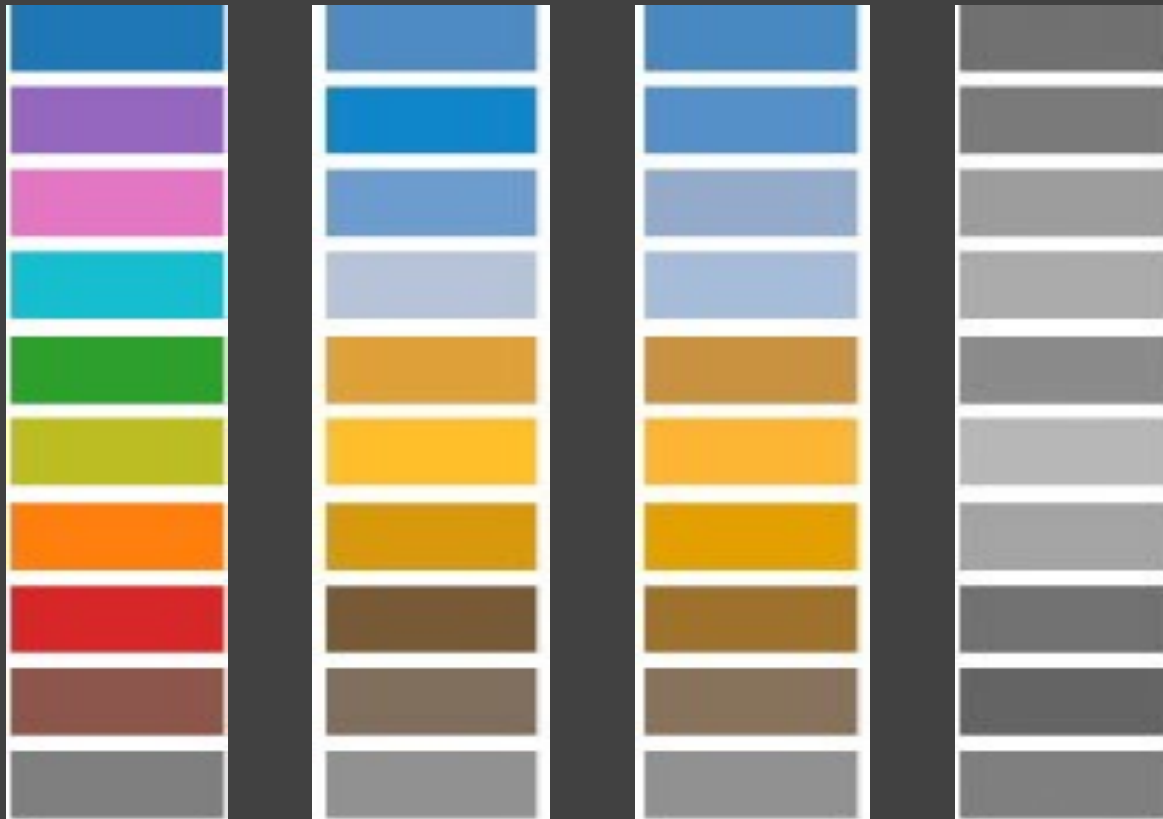
Display Gamuts

Deviations from
sRGB specification



Color Blindness

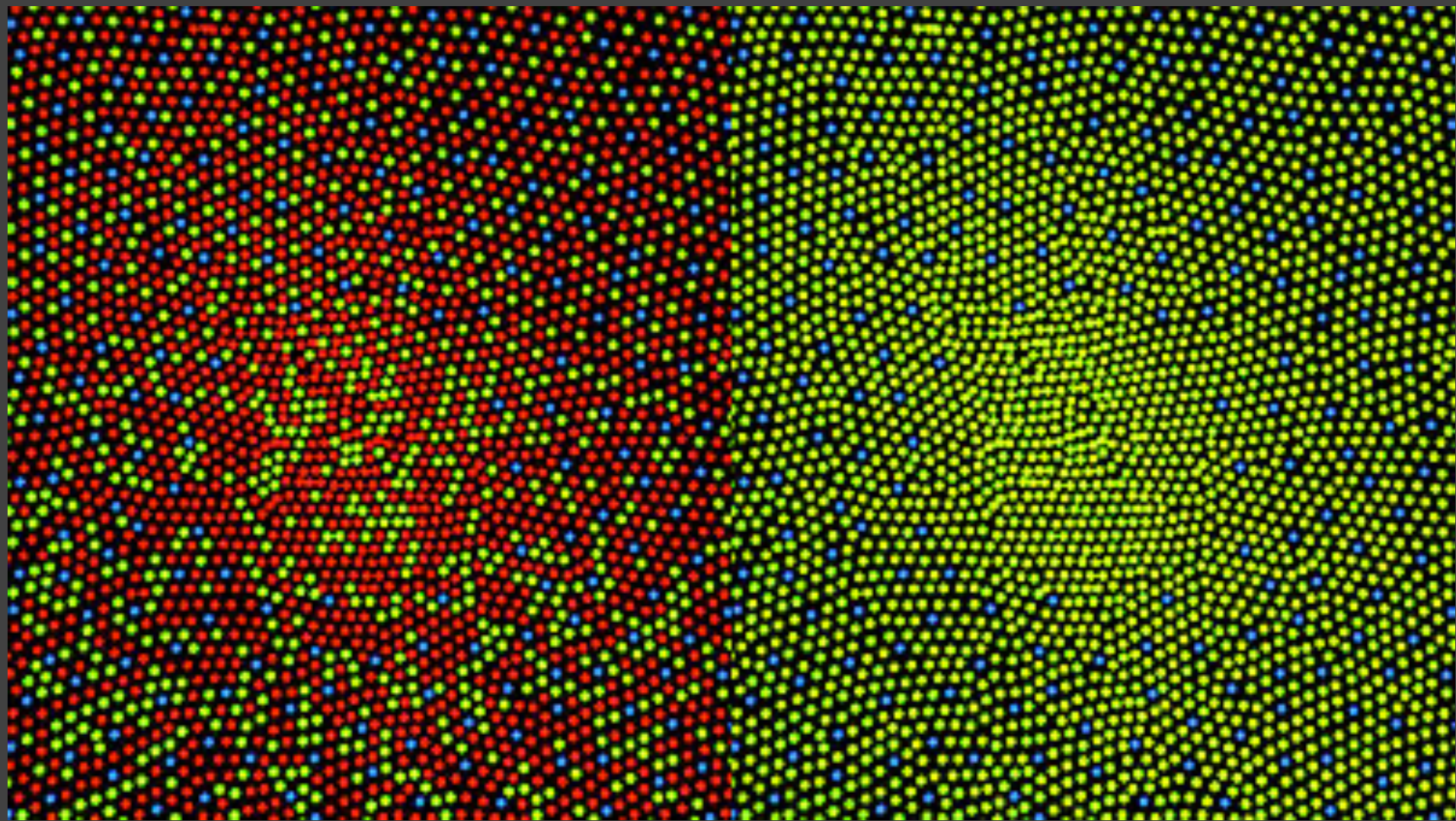
Missing one or more cones or rods in retina.



Protanope

Deuteranope

Luminance



Normal Retina

Protanopia

Color Blindness Simulators

Simulate color vision deficiencies

Browser plug-ins (NoCoffee, SEE, ...)

Photoshop plug-ins, etc...



Deuteranope

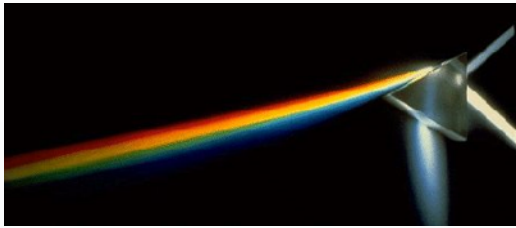


Protanope

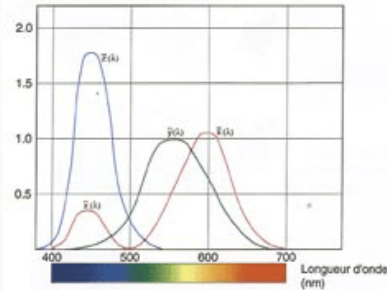


Tritanope

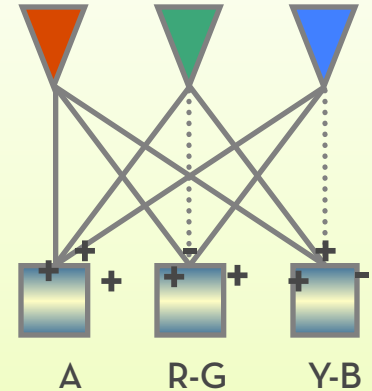
Perception of Color



Light



Cone Response



Opponent Signals

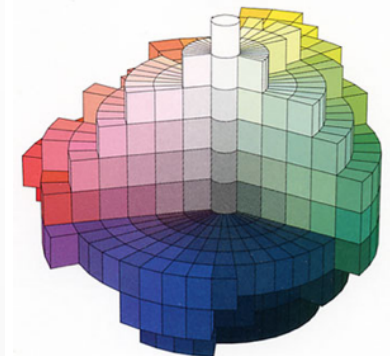
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE
MODELS

Color Appearance



Color Perception

Primary Colors

To paint "all colors":

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

Yellow

Blue

Green

Red

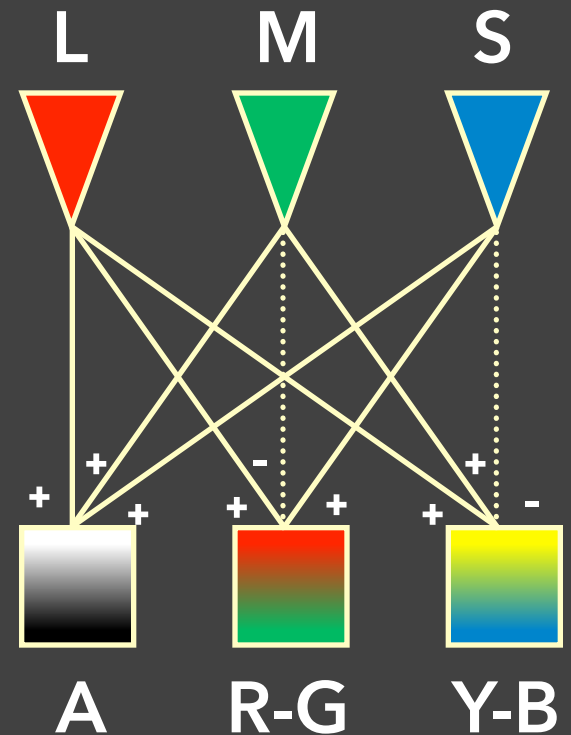
Opponent Processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Fairchild

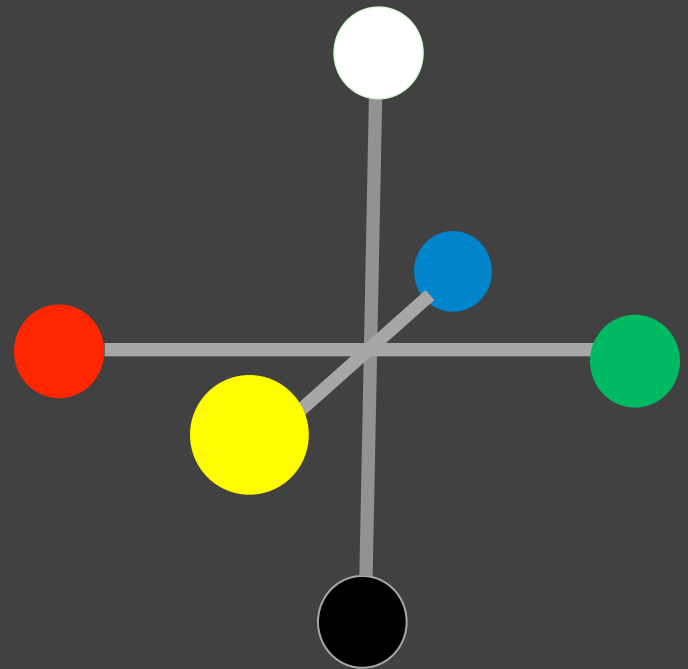
Opponent Processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Opponent Processing

LMS are combined to create:

Lightness

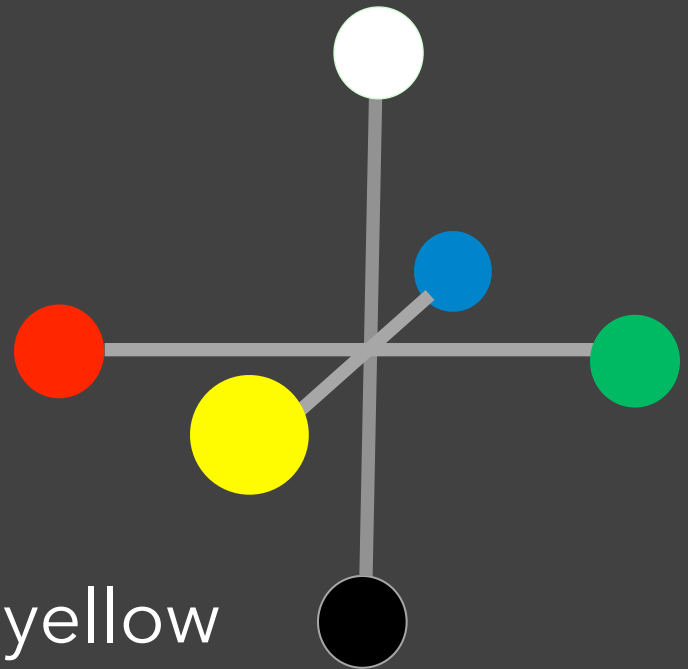
Red-green contrast

Yellow-blue contrast

Experiments:

No reddish-green, no blueish-yellow

Color after images



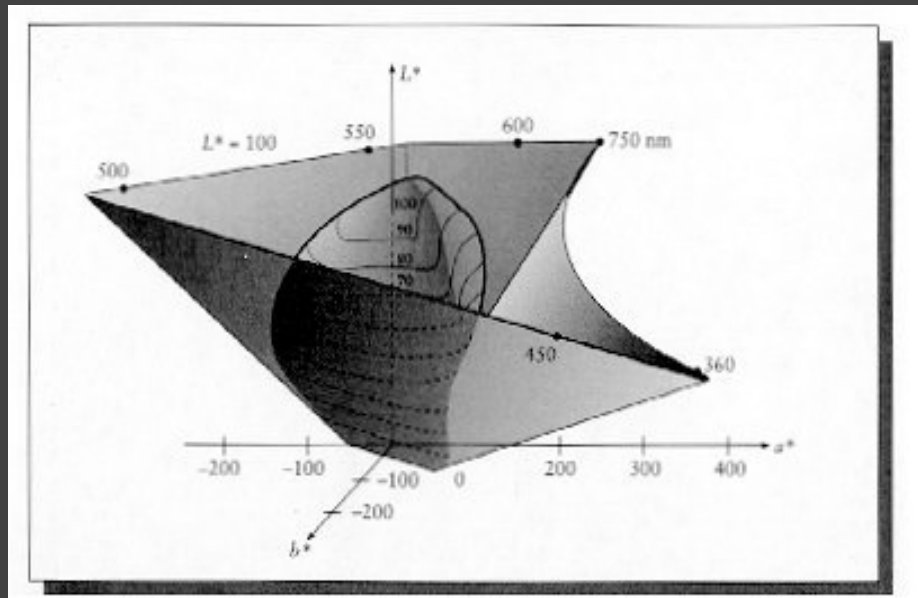
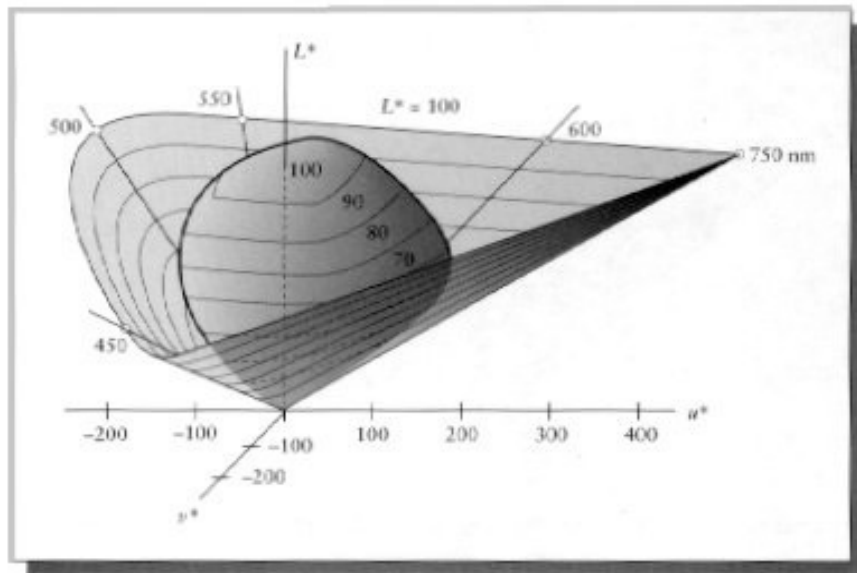




CIE LAB and LUV Color Spaces

Standardized in 1976 to mathematically represent opponent processing theory.

Non-linear transformation of CIE XYZ



CIE LAB Color Space

Axes correspond to opponent signals

L^* = Luminance

a^* = Red-green contrast

b^* = Yellow-blue contrast

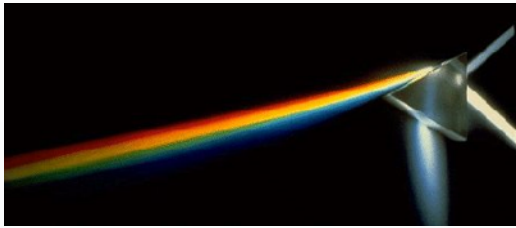
Much more perceptually uniform than sRGB!

Scaling of axes to represent "color distance"

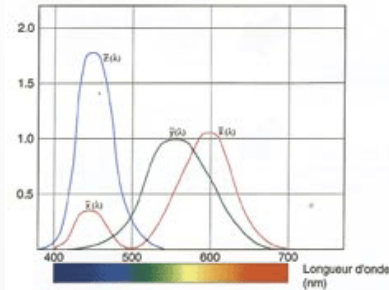
JND = Just noticeable difference (~2.3 units)

D3 includes LAB color space support!

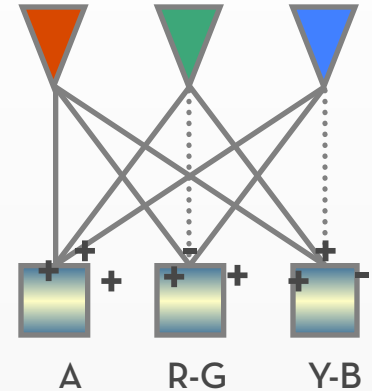
Perception of Color



Light



Cone Response



Opponent Signals

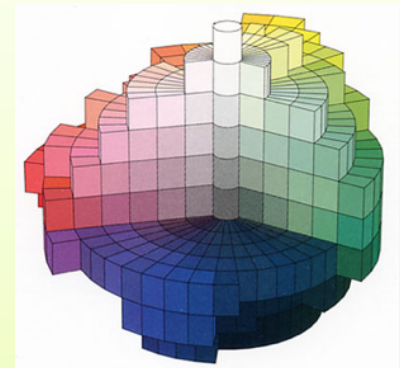
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE
MODELS

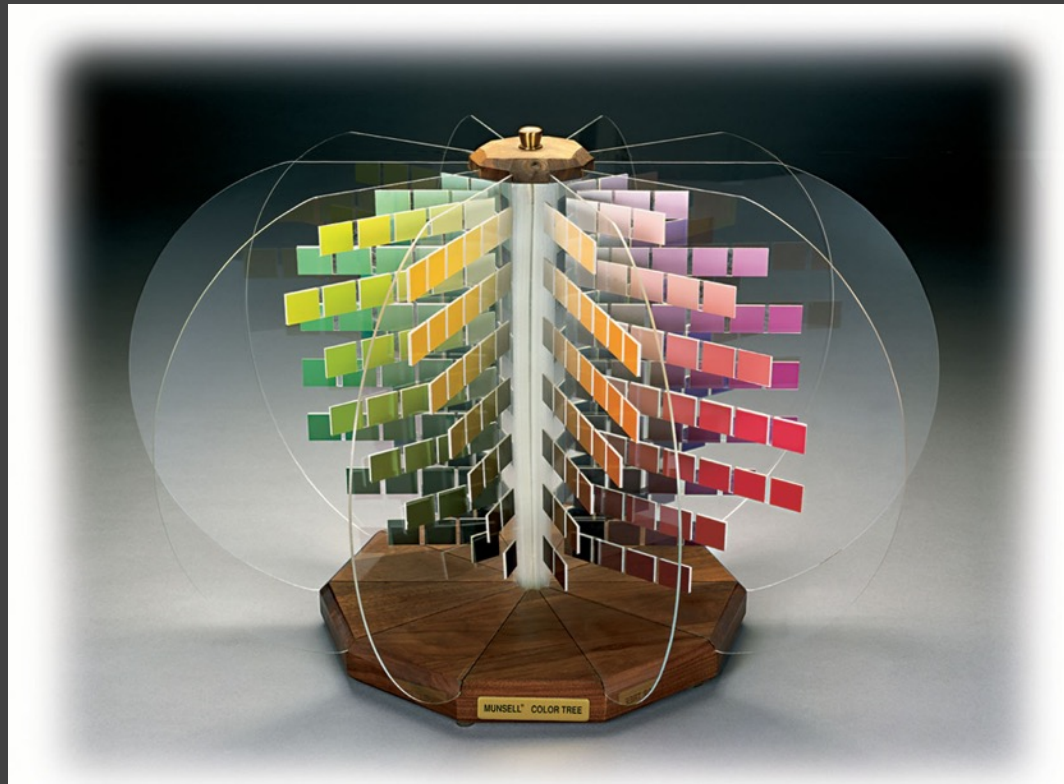
Color Appearance



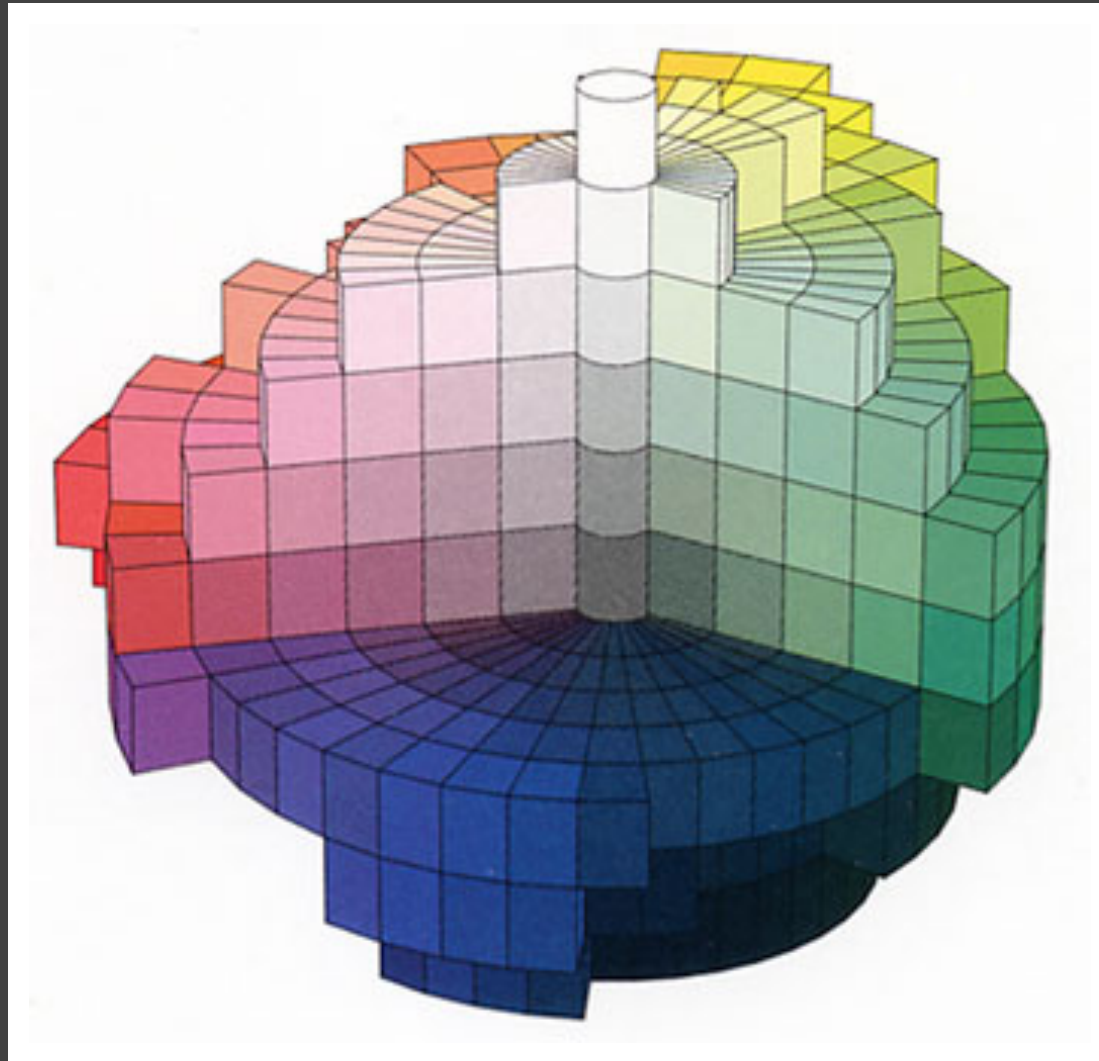
Color Perception

Albert Munsell

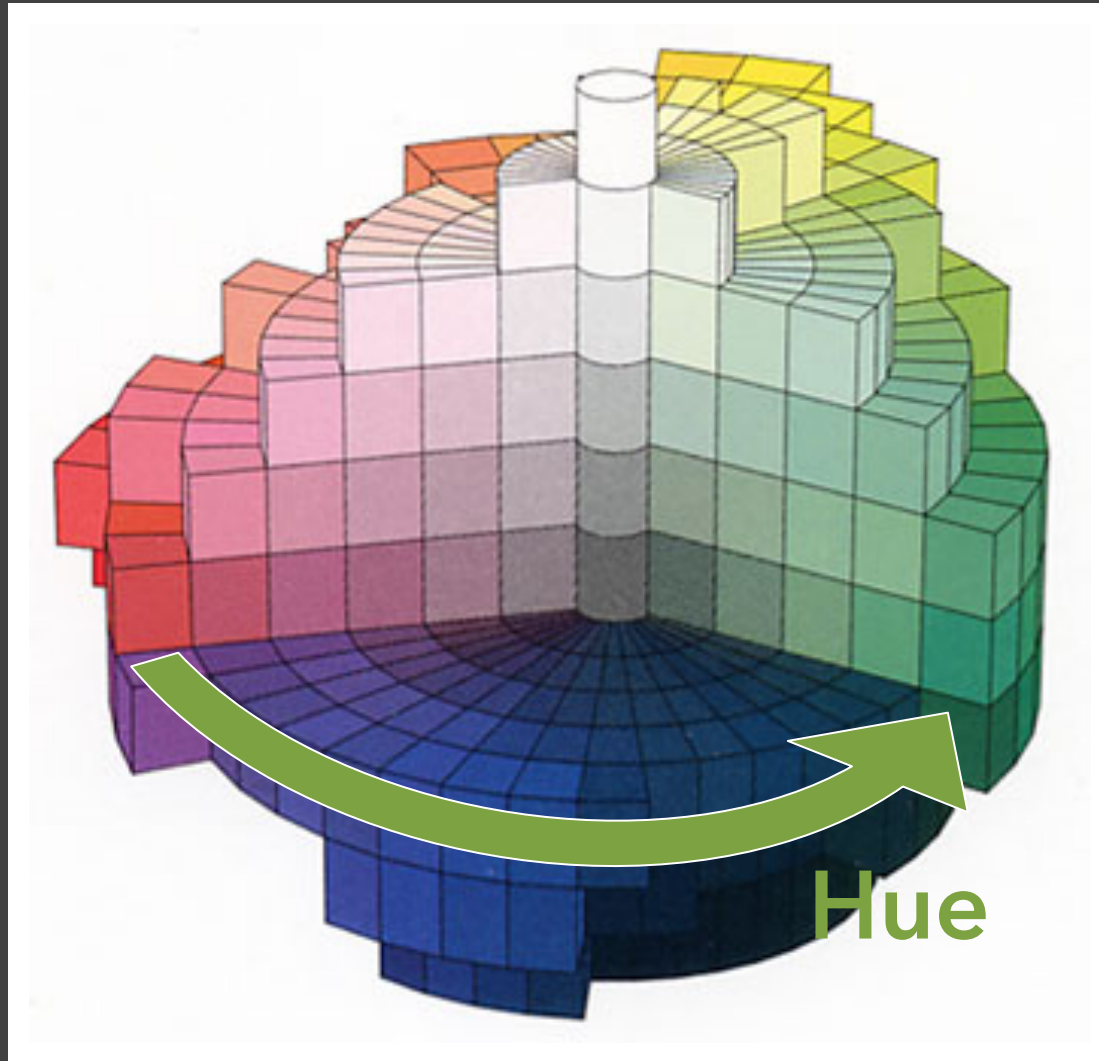
Developed the first perceptual color system based on his experience as an artist (1905).



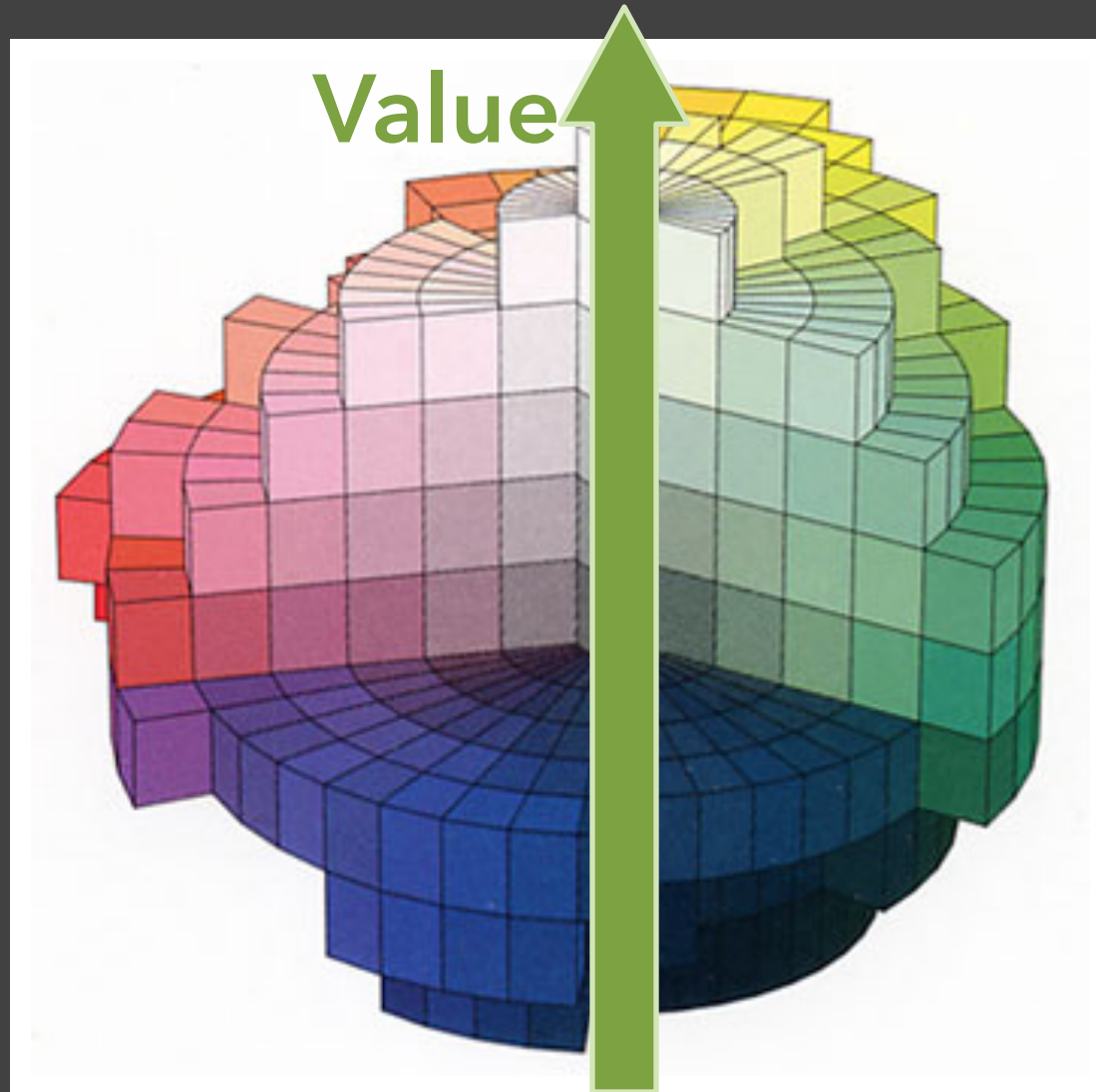
Hue, Value and Chroma



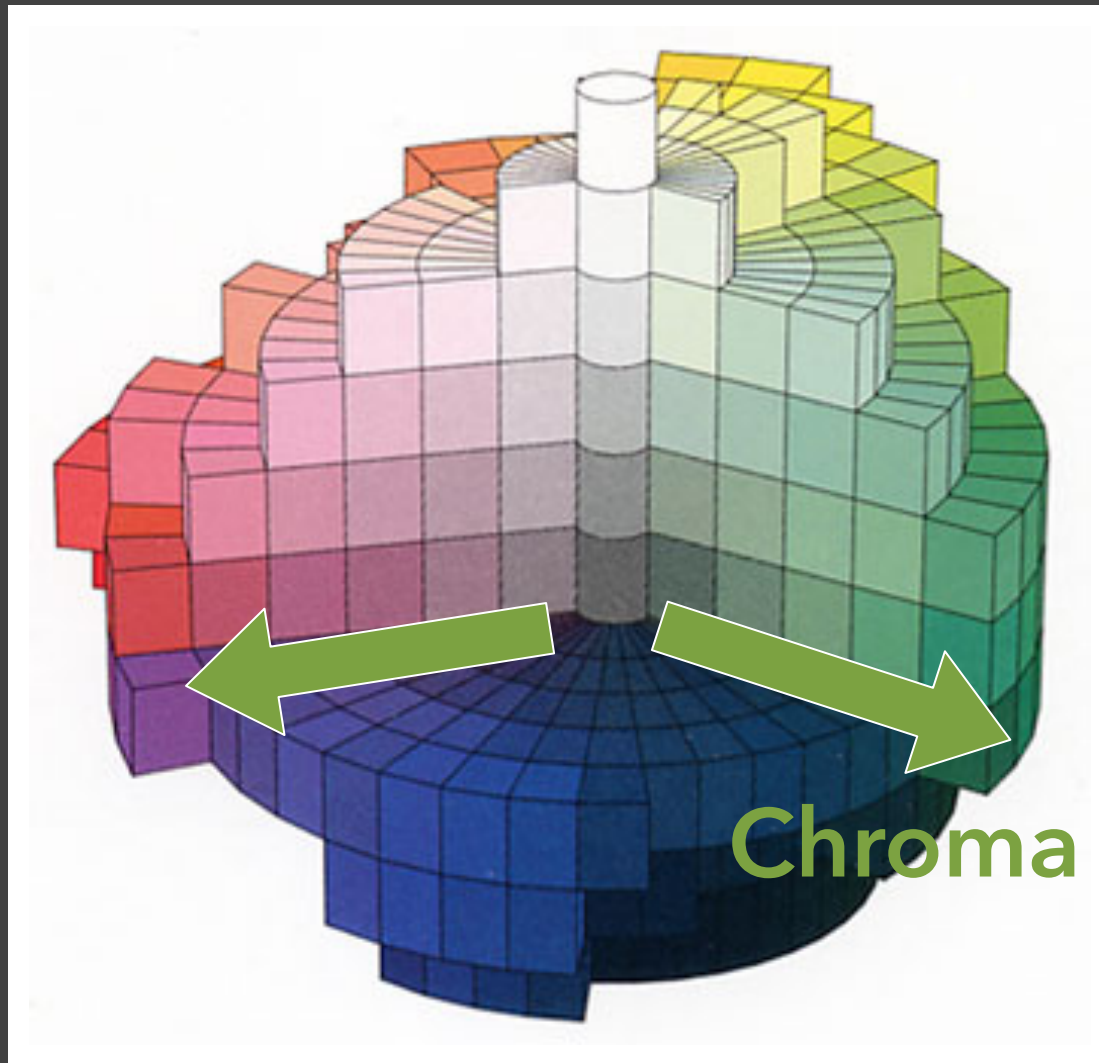
Hue, Value and Chroma



Hue, Value and Chroma



Hue, Value and Chroma



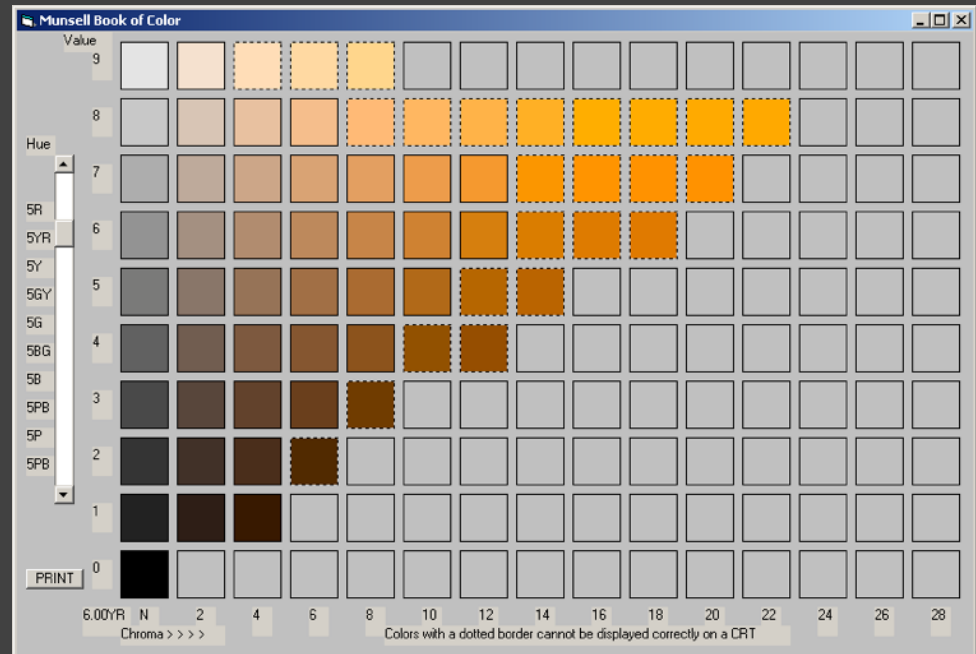
Munsell Color System

Perceptually-based

Precisely reference a color

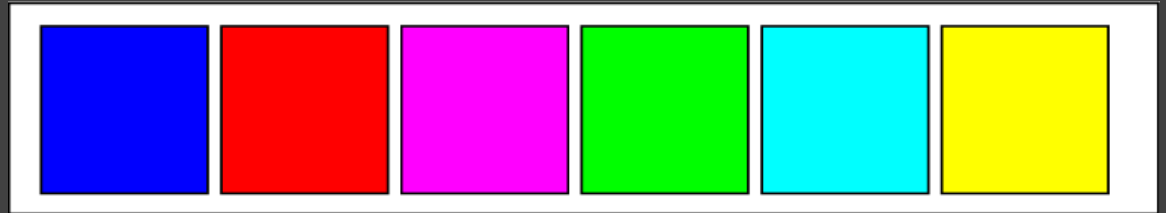
Intuitive dimensions

Look-up table (LUT)



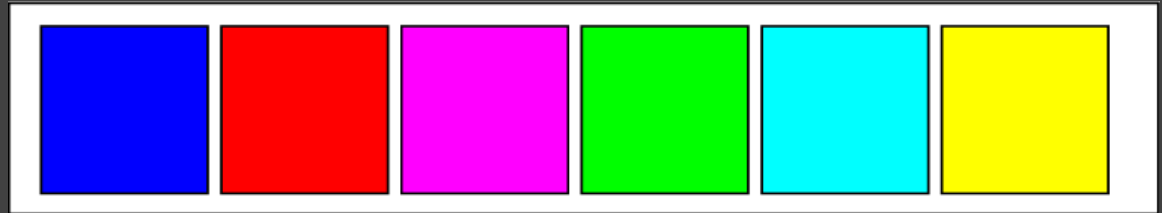
Perceptual Brightness

Color palette



Perceptual Brightness

Color palette

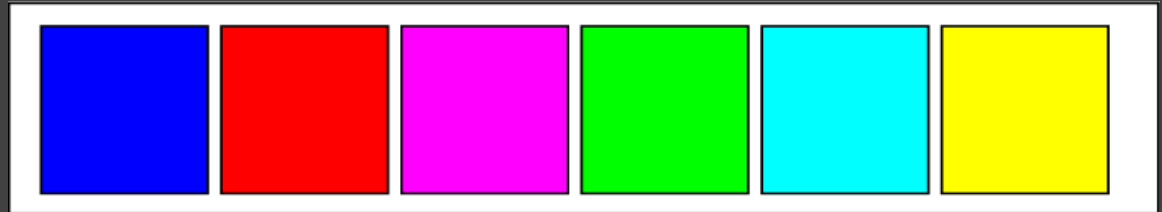


HSL Lightness
(*Photoshop*)



Perceptual Brightness

Color palette

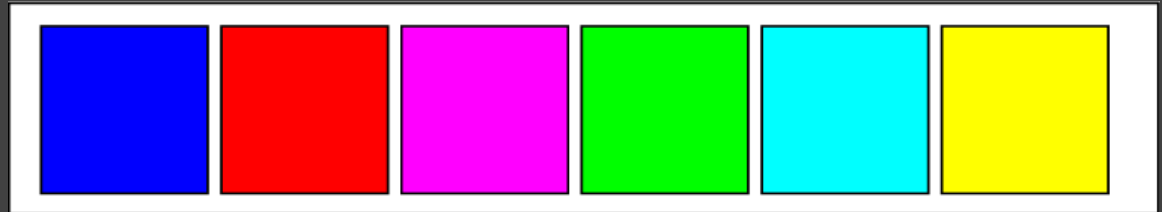


Luminance Y
(*CIE XYZ*)



Perceptual Brightness

Color palette

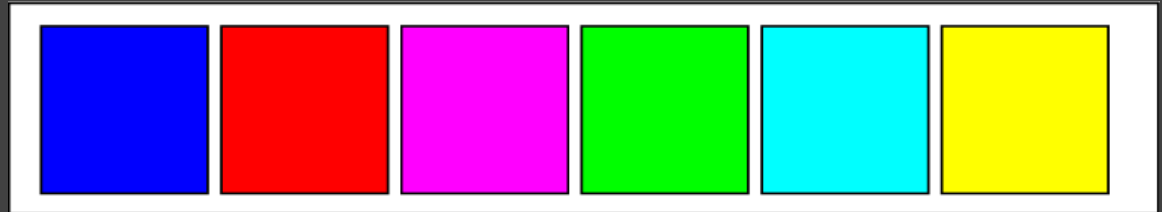


Munsell Value



Perceptual Brightness

Color palette

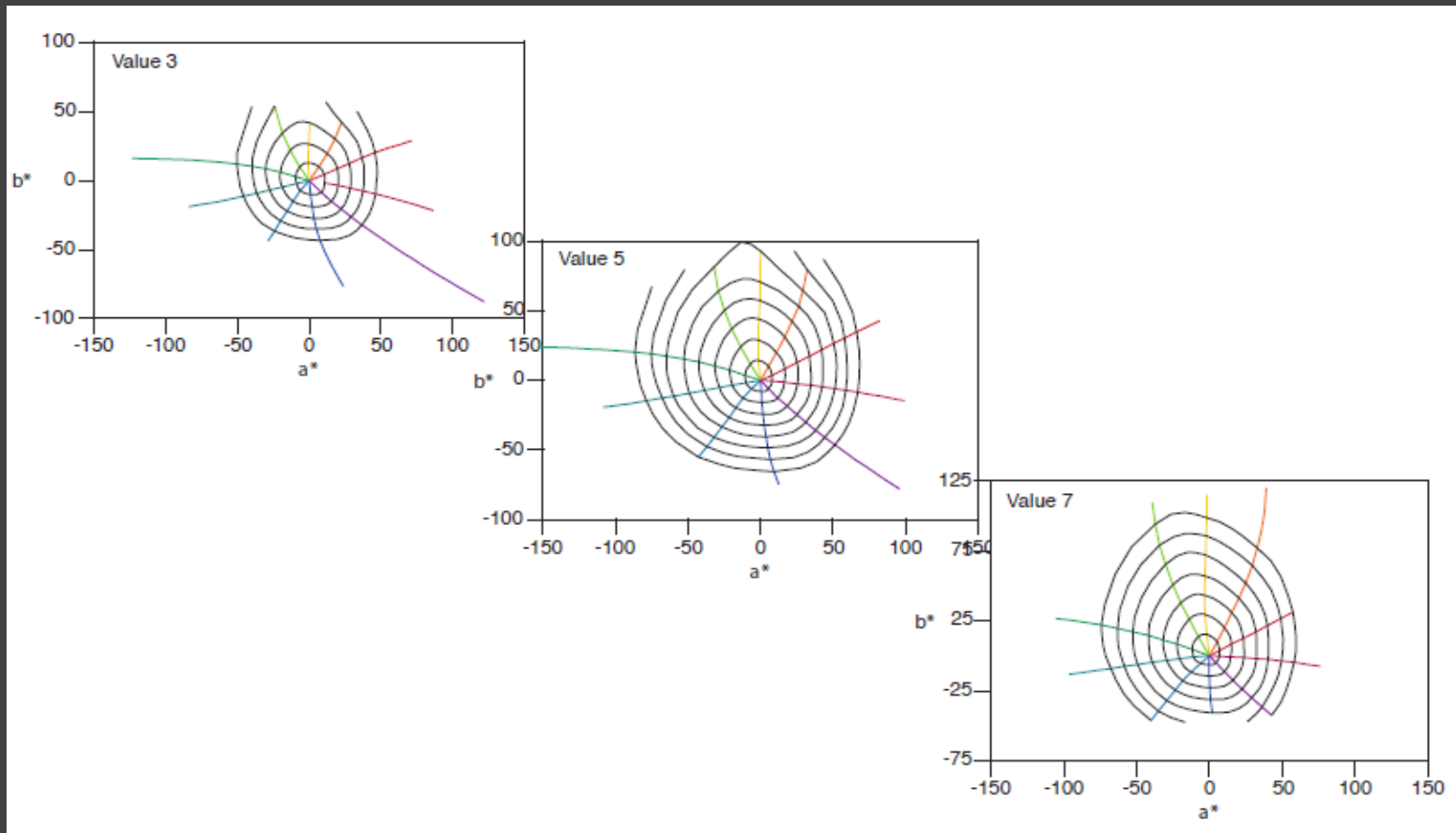


Munsell Value
L* (CIE LAB)



Perceptually-Uniform Color Space

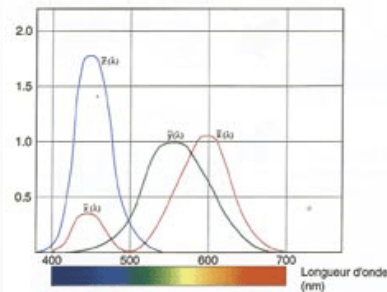
Munsell colors in CIE LAB coordinates



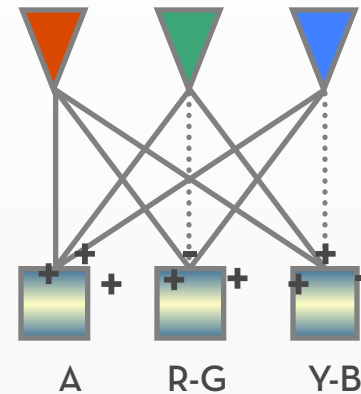
Perception of Color



Light



Cone Response



Opponent Signals

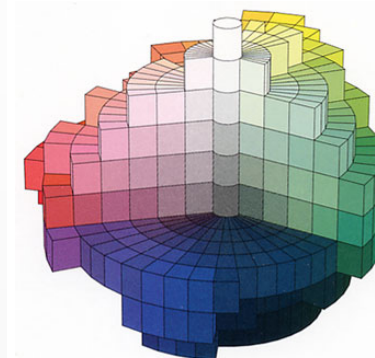
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE
MODELS

Color Appearance



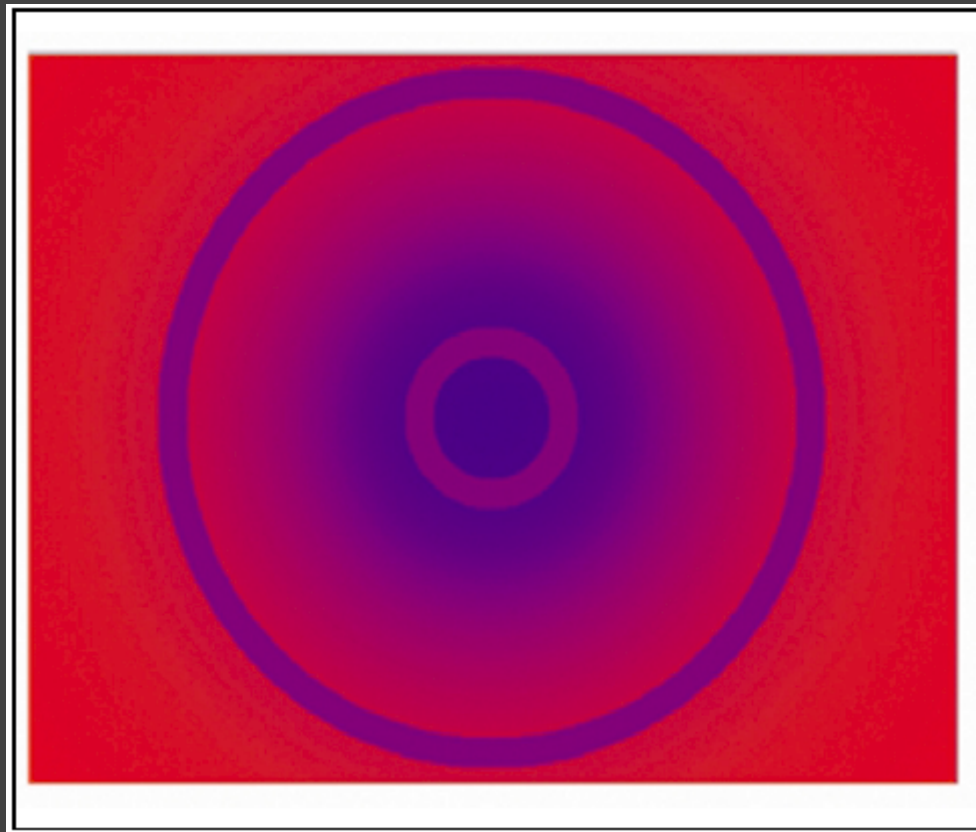
Color Perception

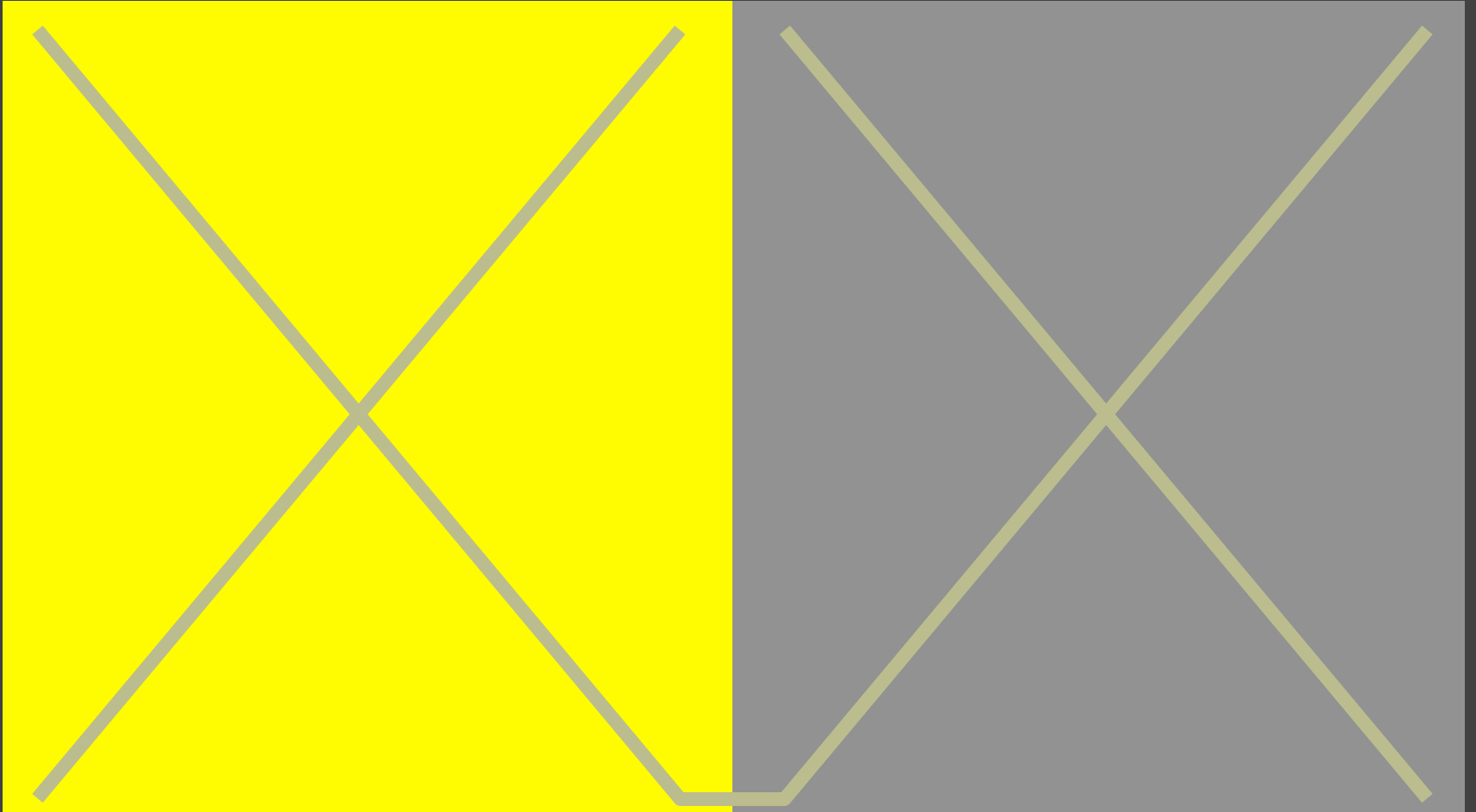
Color Appearance

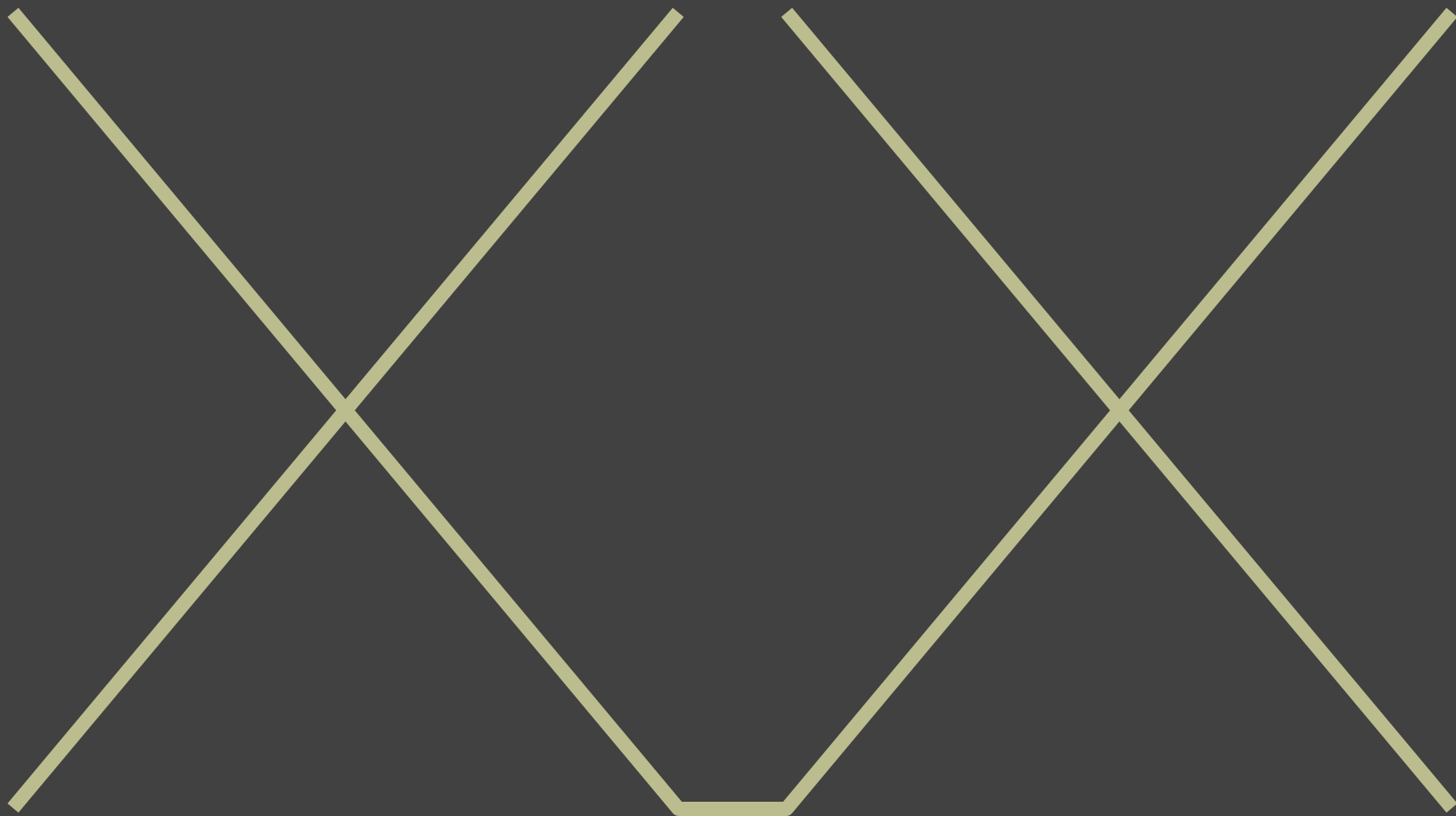
If we had a perceptually-uniform color space, can we predict how we perceive colors?

Simultaneous Contrast

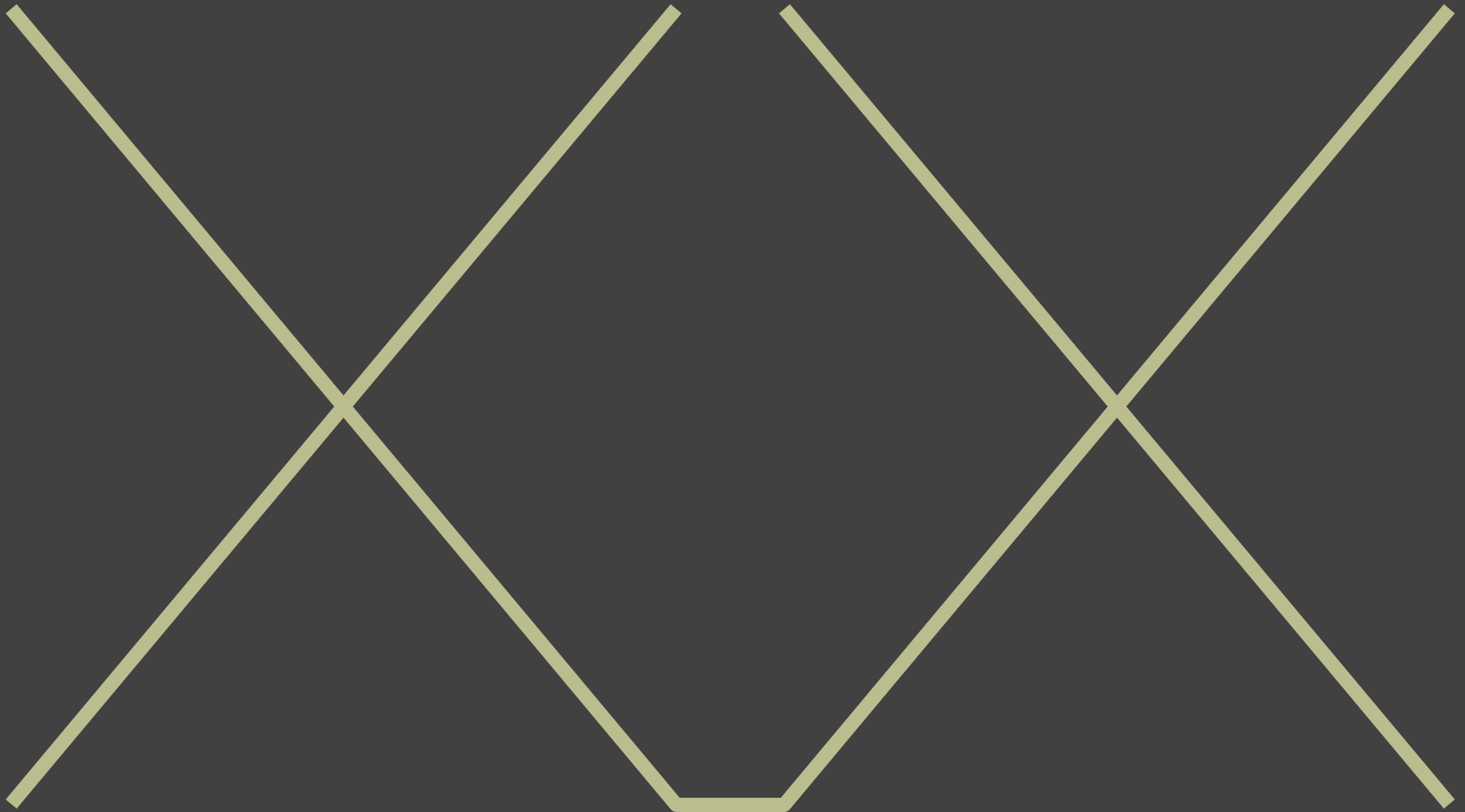
The inner and outer thin rings are in fact the same physical purple.





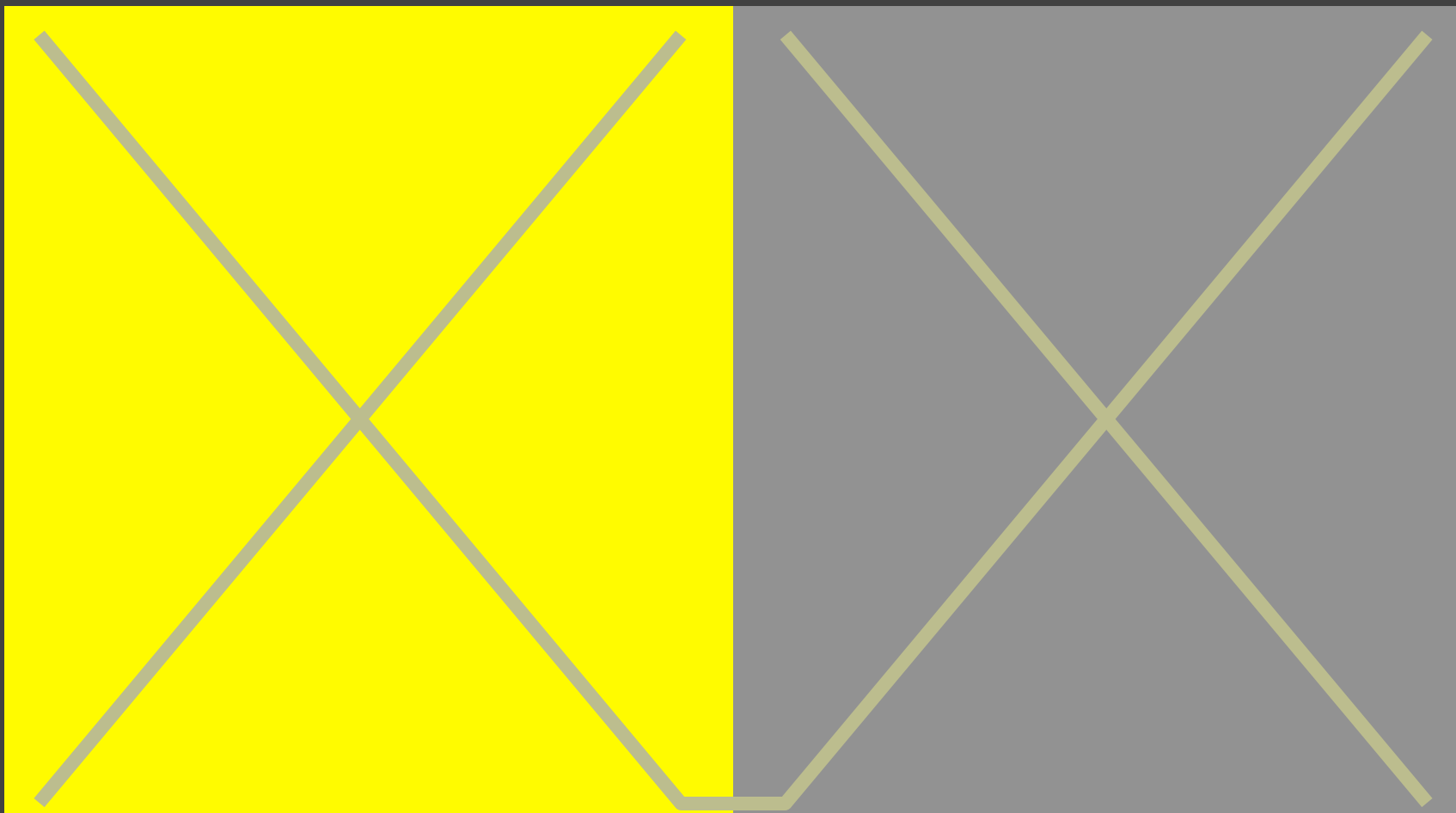


Simultaneous Contrast



Josef Albers

Simultaneous Contrast



Josef Albers

Chromatic Adaptation

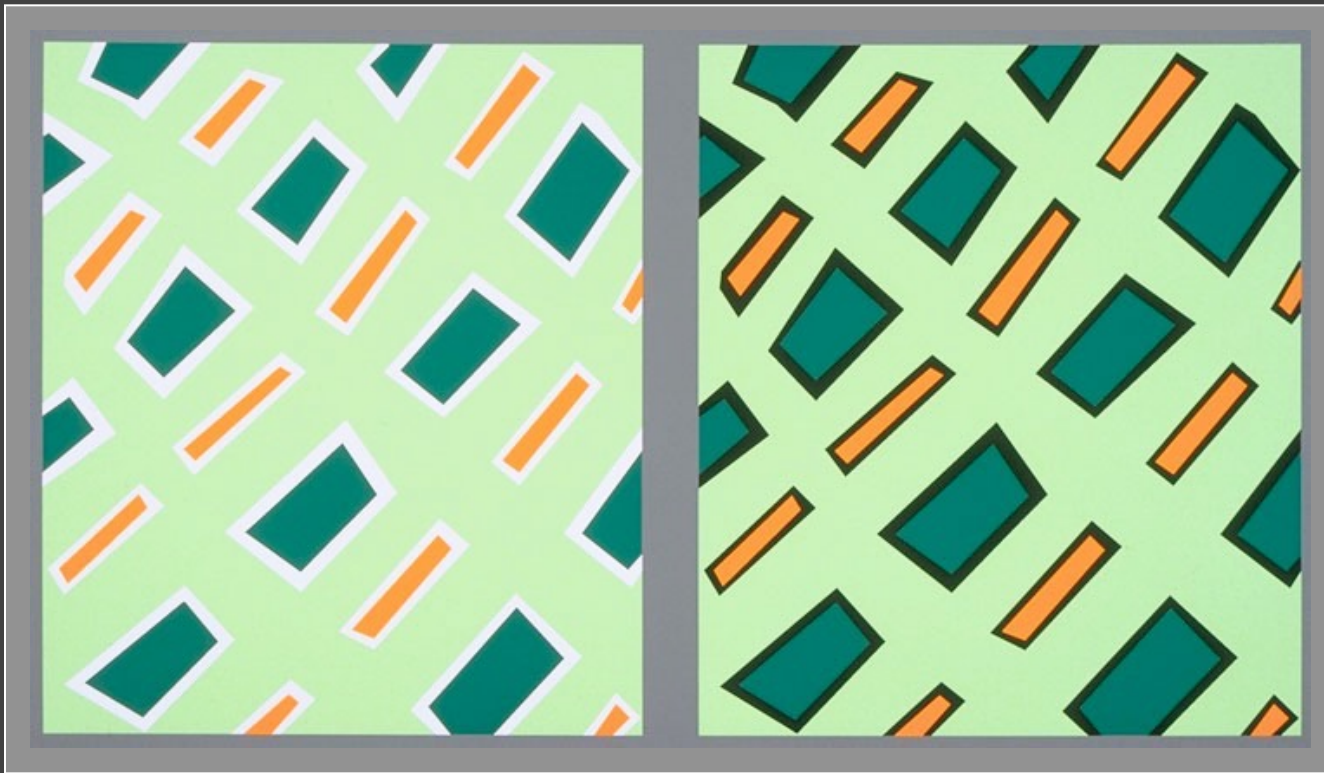


Chromatic Adaptation



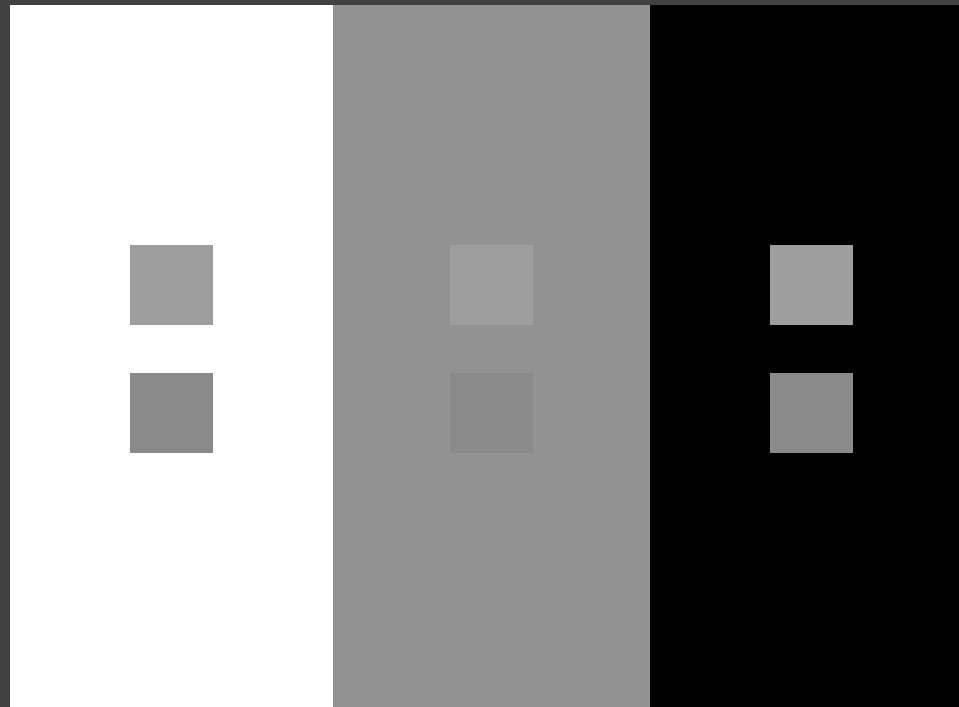
Bezold Effect

Color appearance depends adjacent colors



Crispening

Perceived difference depends on background



Color Appearance Models, Fairchild

Spreading

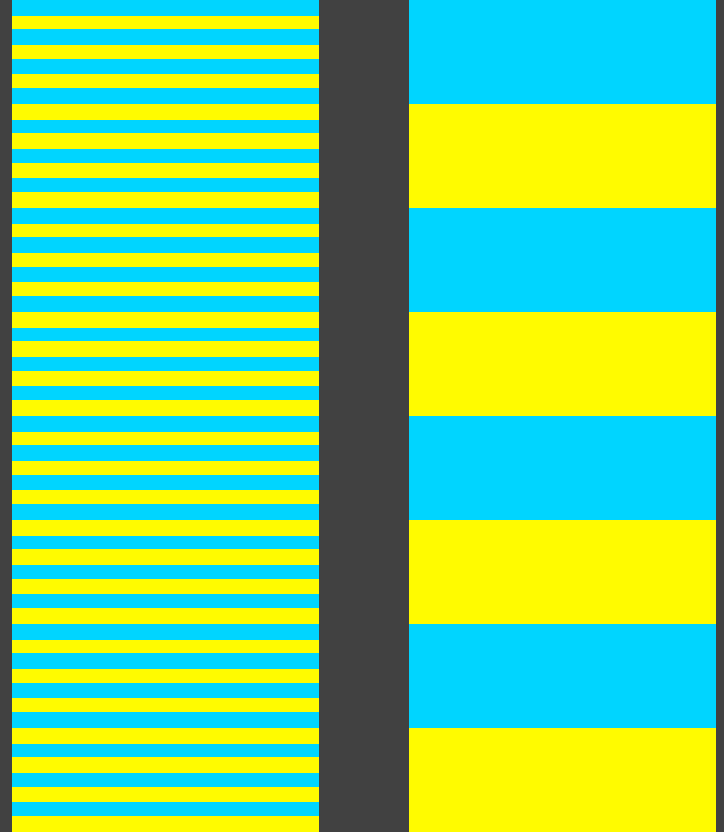
Spatial frequency

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

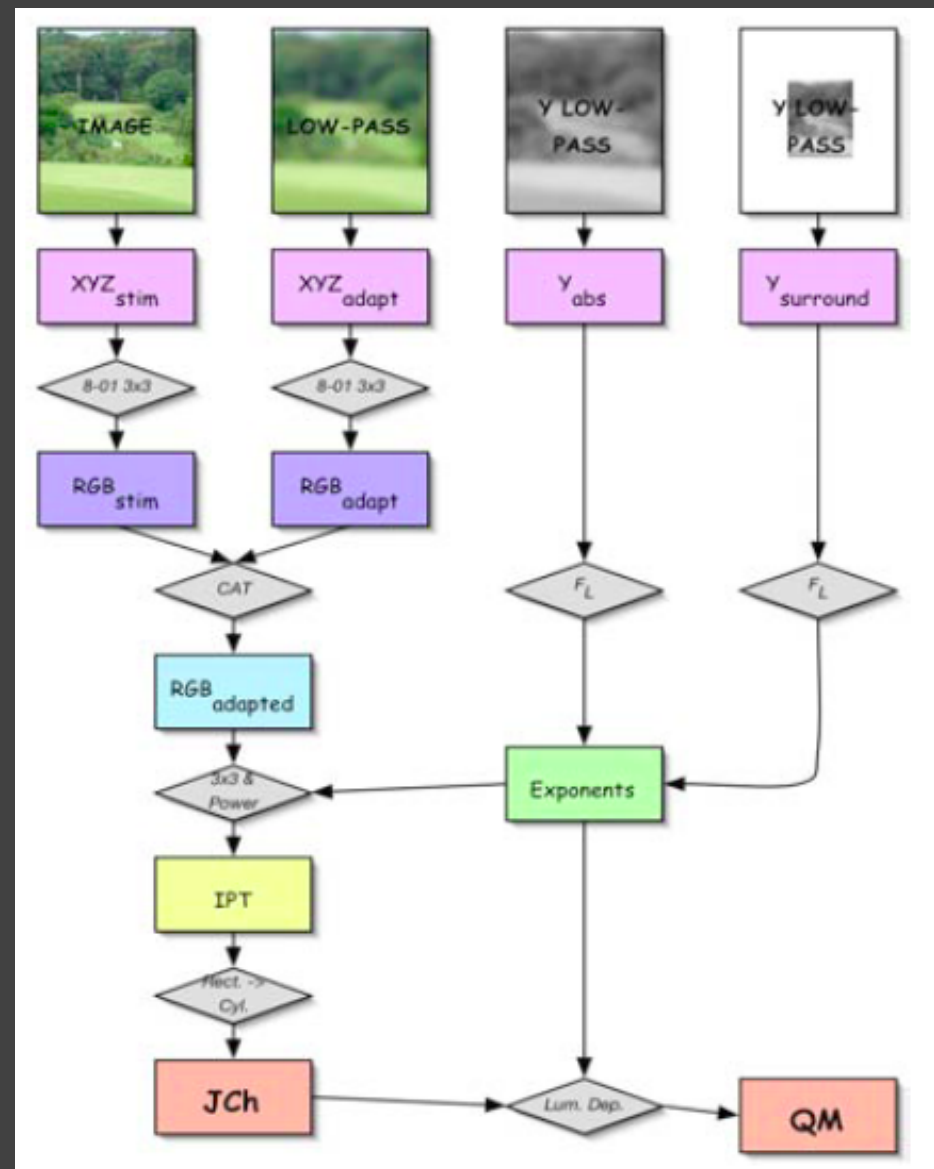
Spatial effects

Viewing angle

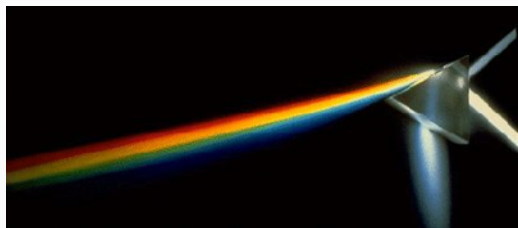
iCAM

iCAM (2002) models:
Chromatic adaptation
Appearance scales
Color difference
Crispensing
Spreading
HDR tone mapping
(see also **CIECAM02**)

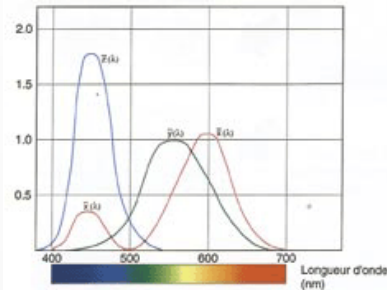
Mark Fairchild



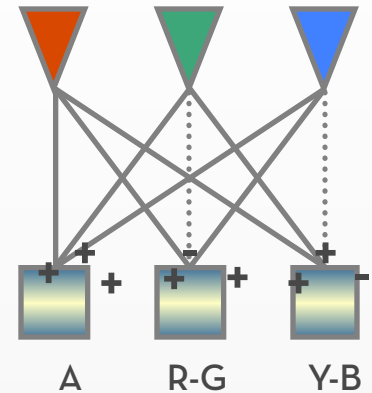
Perception of Color



Light



Cone Response



Opponent Signals

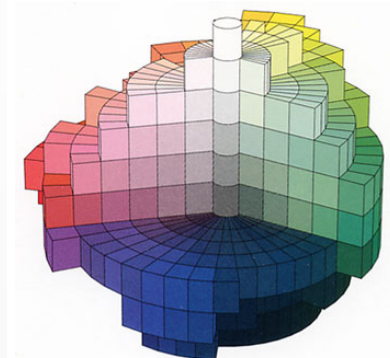
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE
MODELS

Color Appearance












Color Perception

Colors according to XKCD...

Color names if
you're a girl...

Color names if
you're a guy...

Maraschino		Red
Cayenne		Purple
Maroon		
Plum		
Eggplant		
Grape		
Orchid		Pink
Lavender		
Carnation		
Strawberry		
Bubblegum		
Magenta		Orange
Salmon		
Tangerine		Yellow
Cantaloupe		
Banana		
Lemon		Green
Honeydew		
Lime		
Spring		
Clover		
Fern		
Moss		
Flora		
Sea Foam		
Spindrift		
Teal		Blue
Sky		
Turquoise		

Doghouse Diaries
"We take no as an answer."

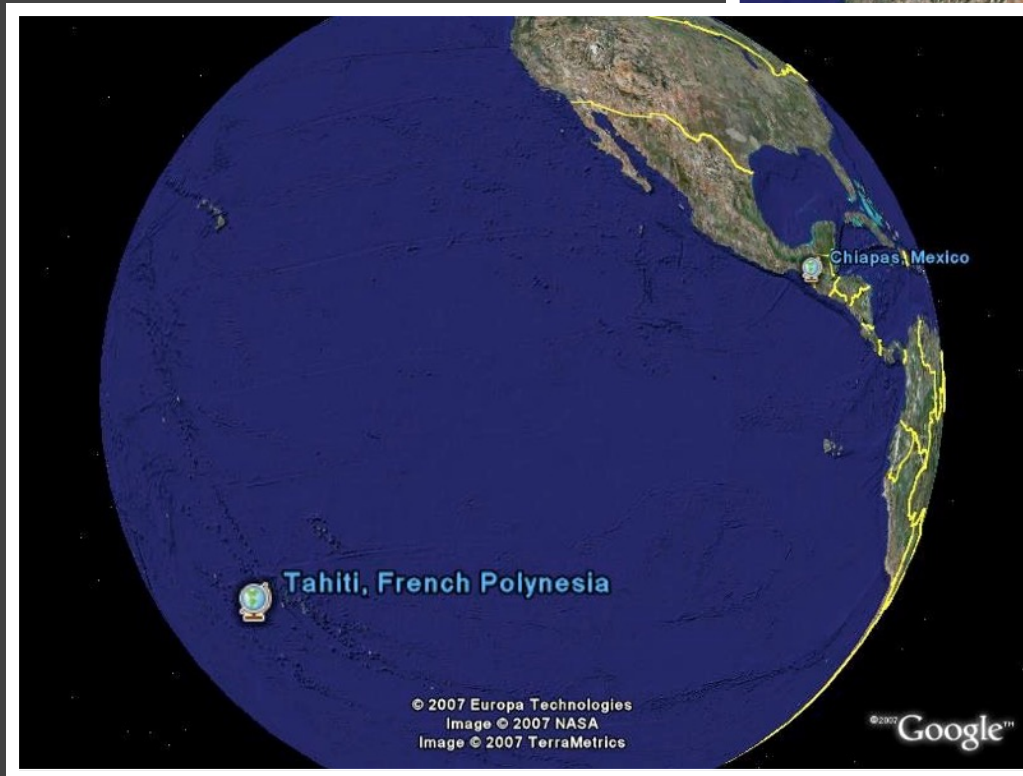
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.



Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.



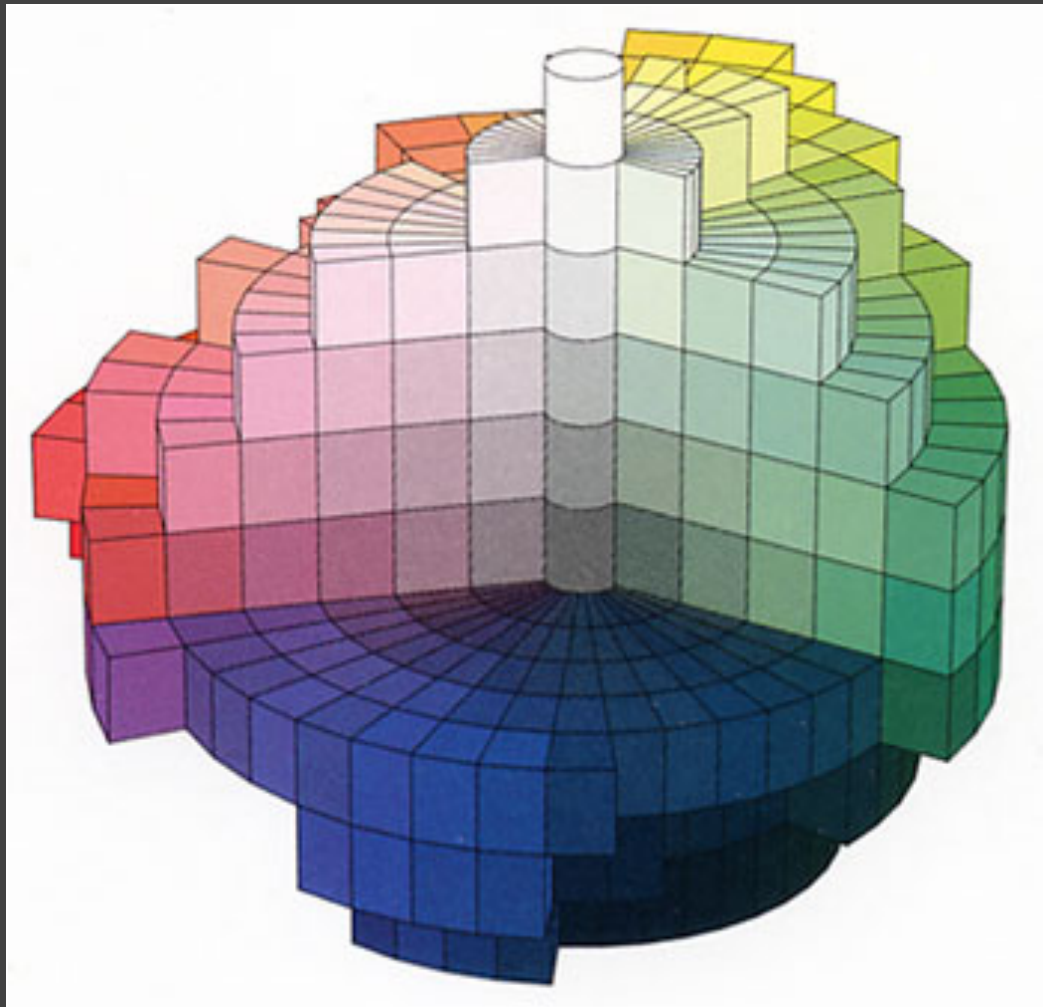
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.

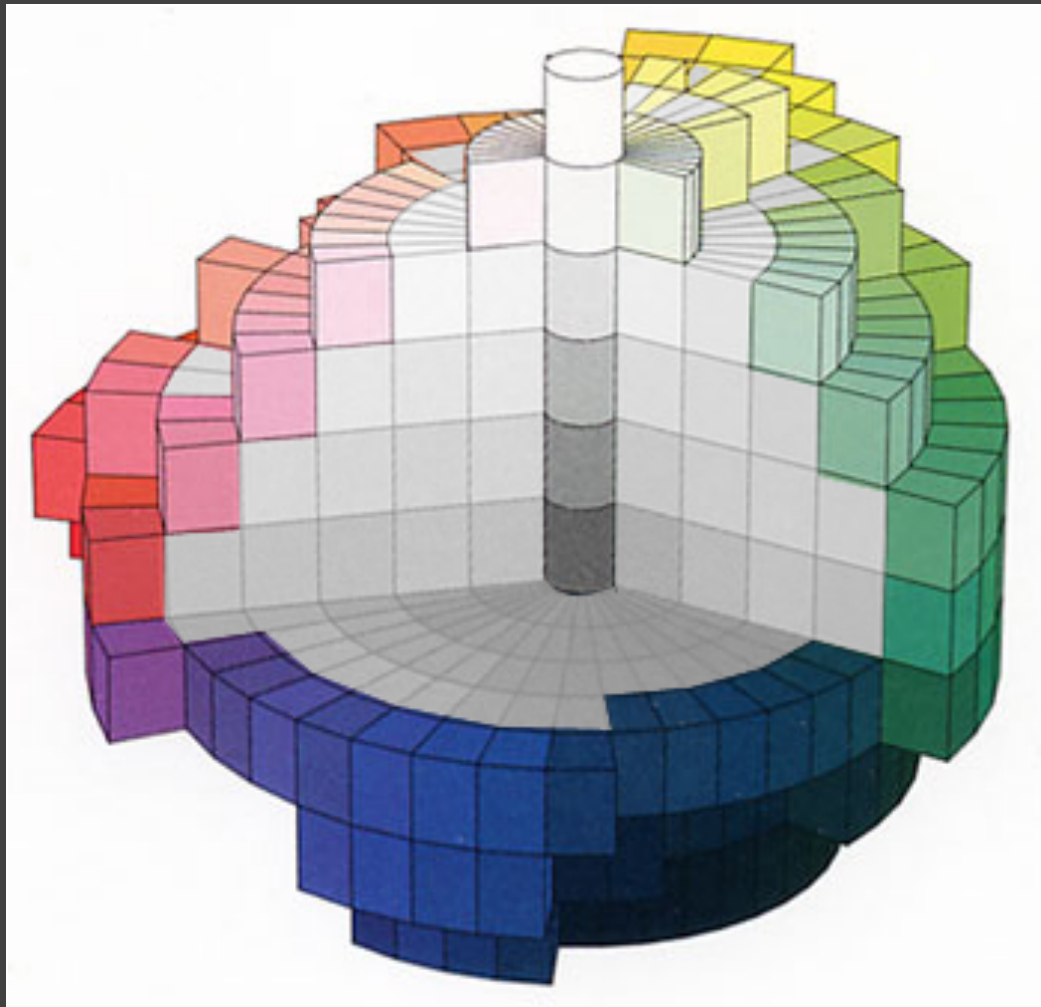
Initial study in 1969

- Surveyed speakers from 20 languages
- Literature from 69 languages

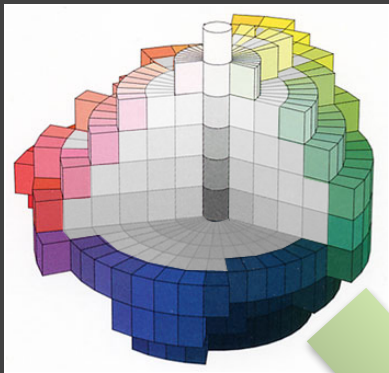
World Color Survey



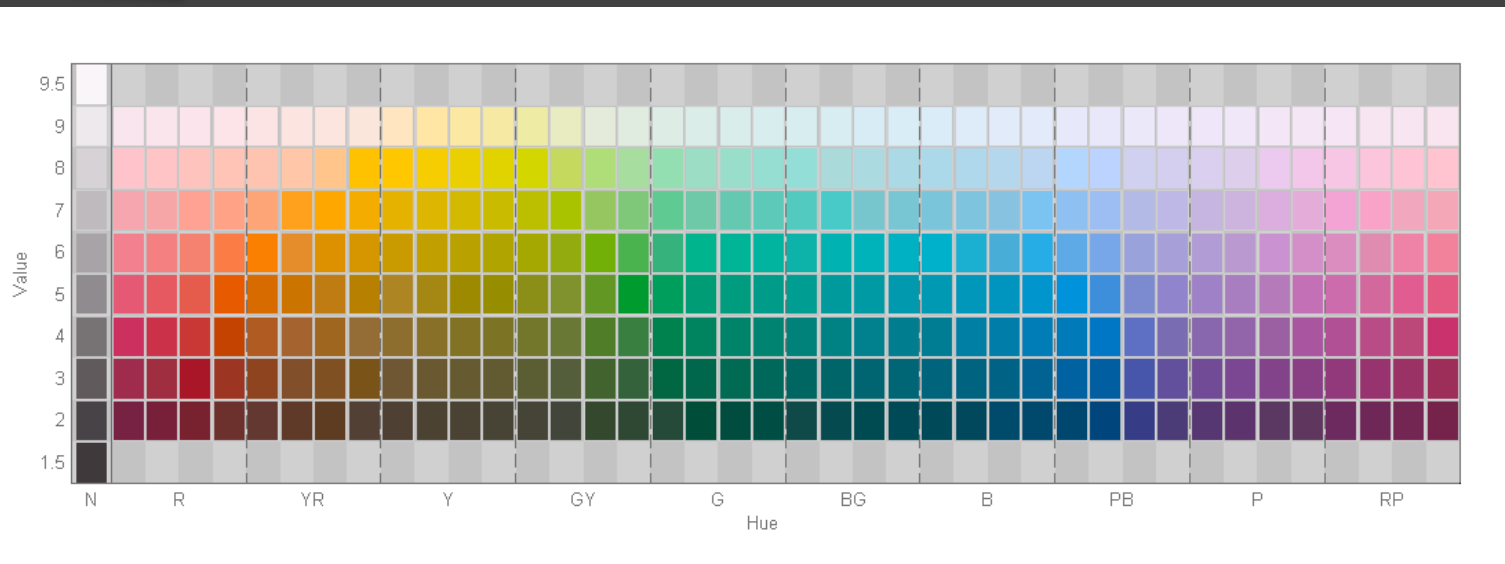
World Color Survey



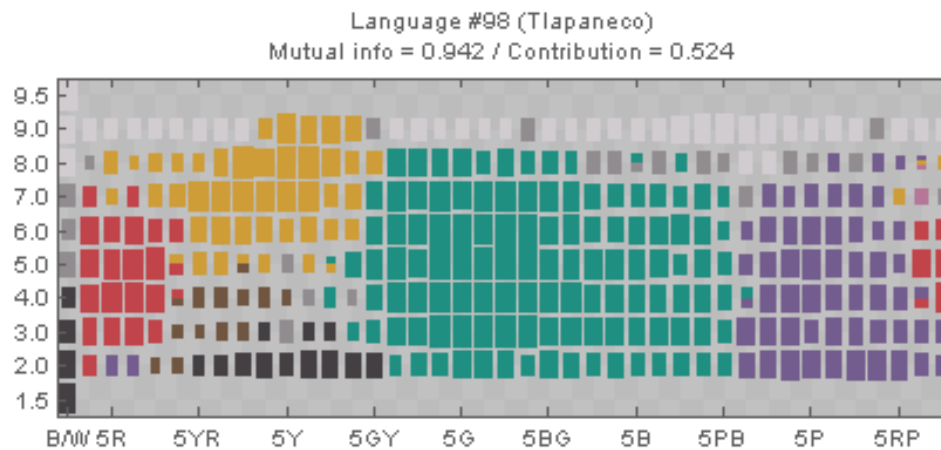
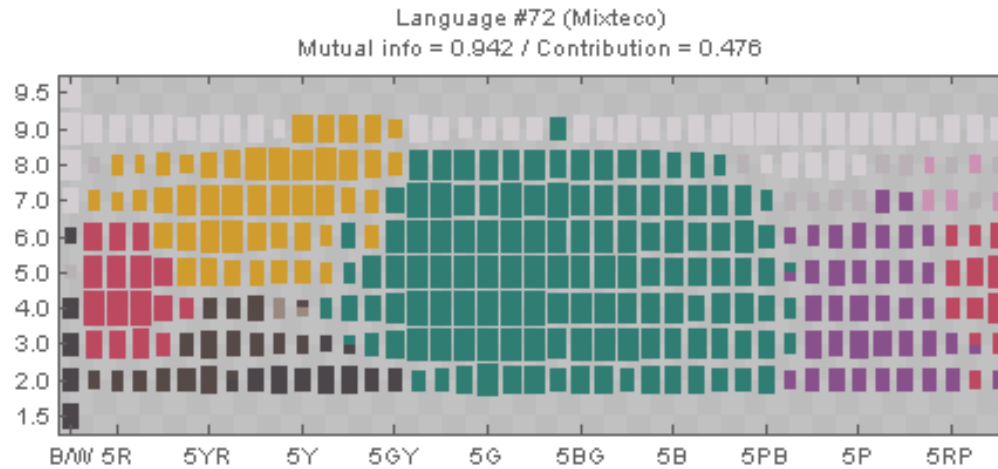
World Color Survey



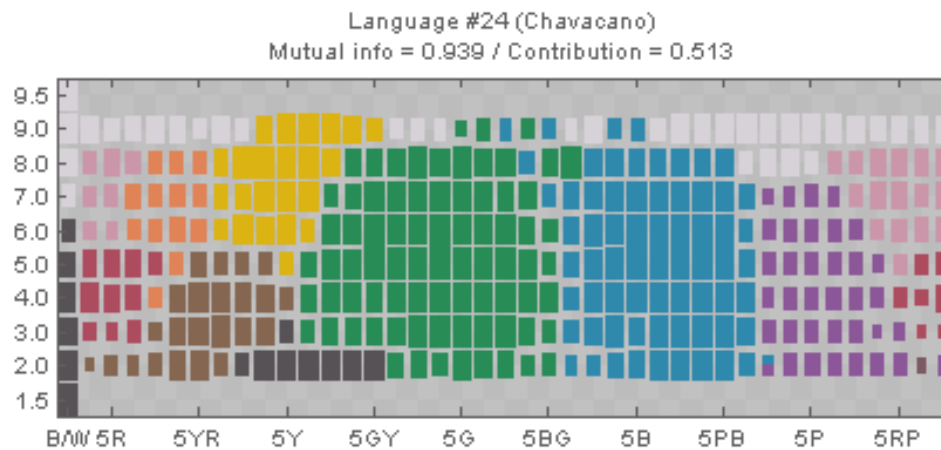
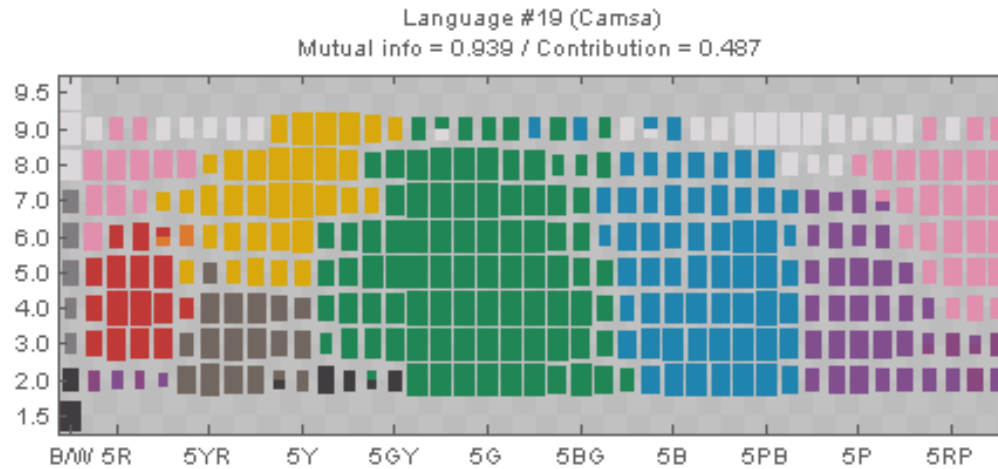
Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



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



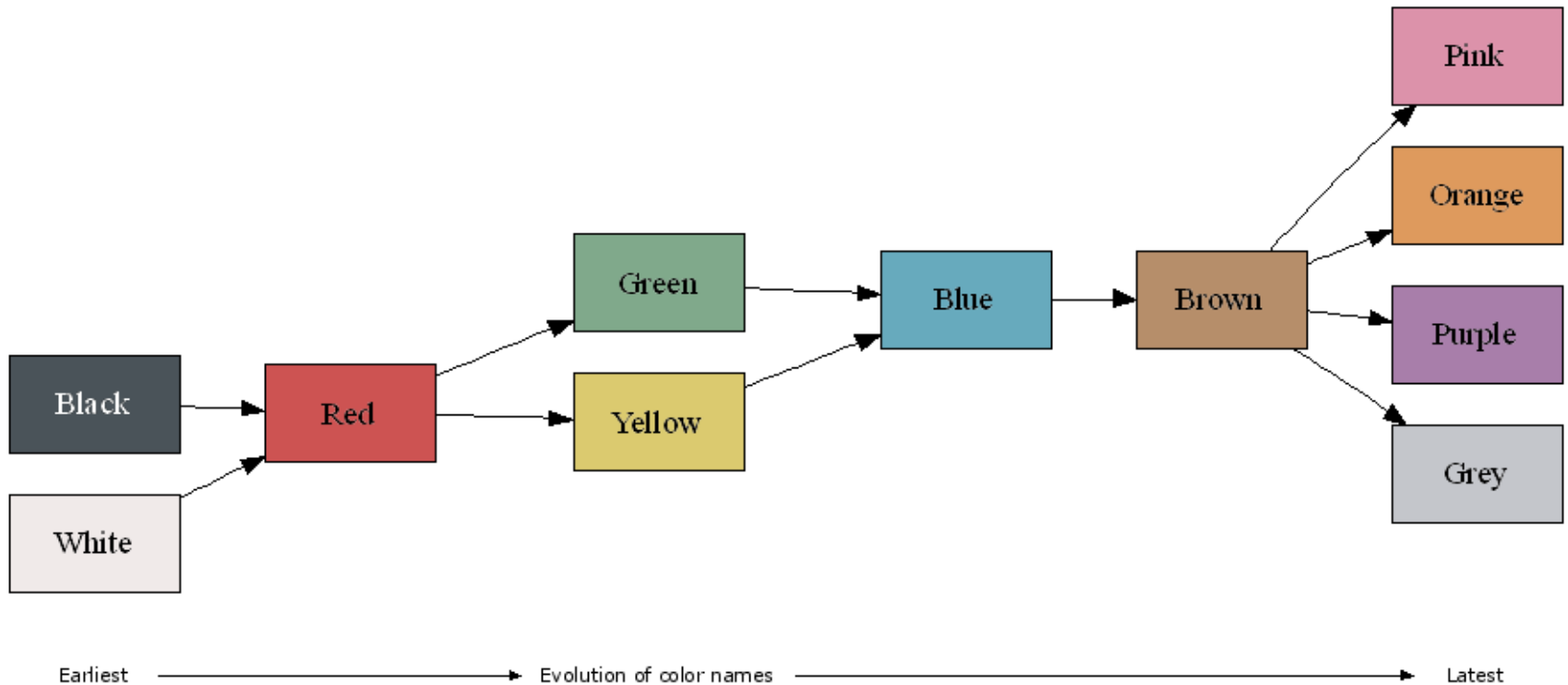
Blue



Purple

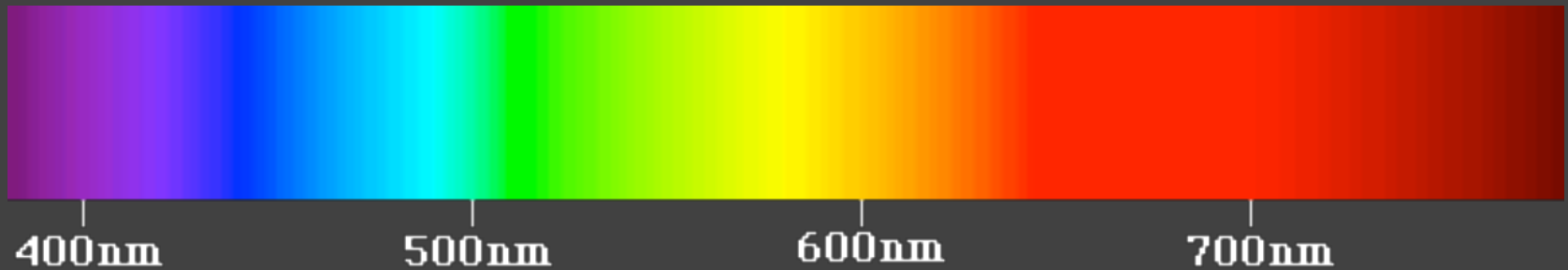
Evolution of Basic Color Terms

Proposed universal evolution across languages.



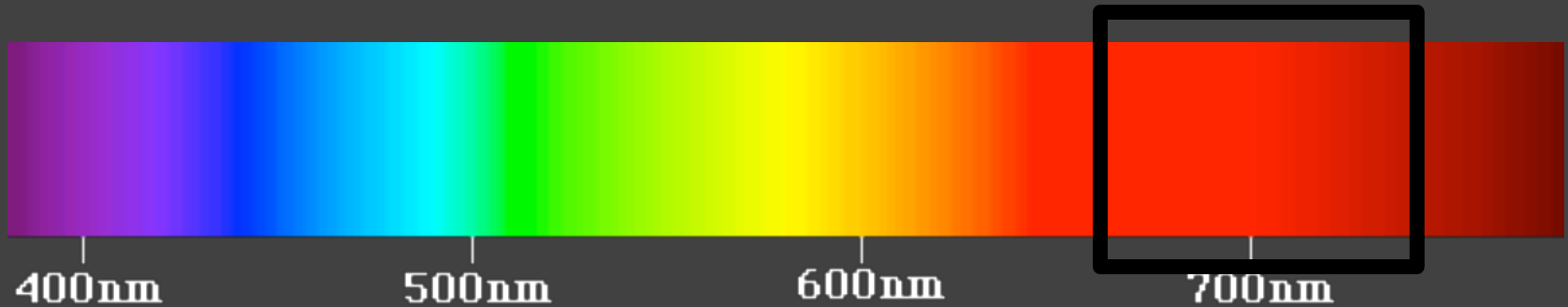
Rainbow Color Map

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



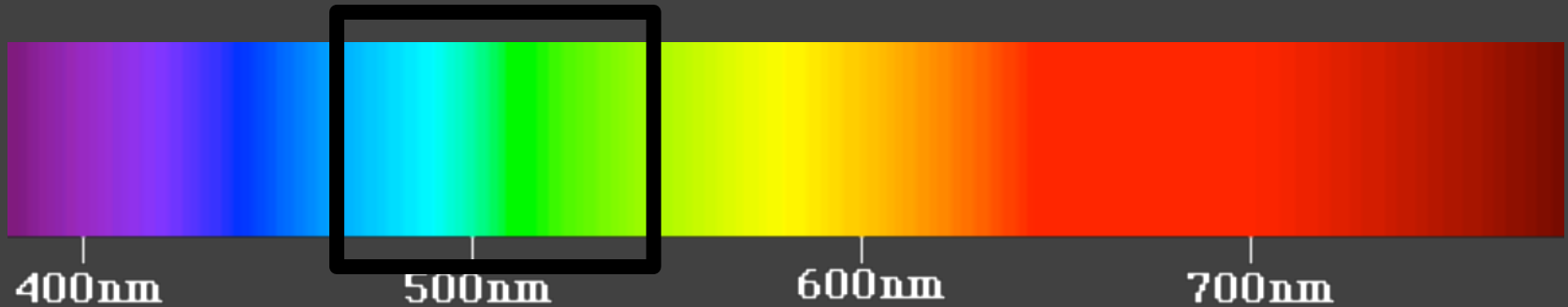
Rainbow Color Map

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



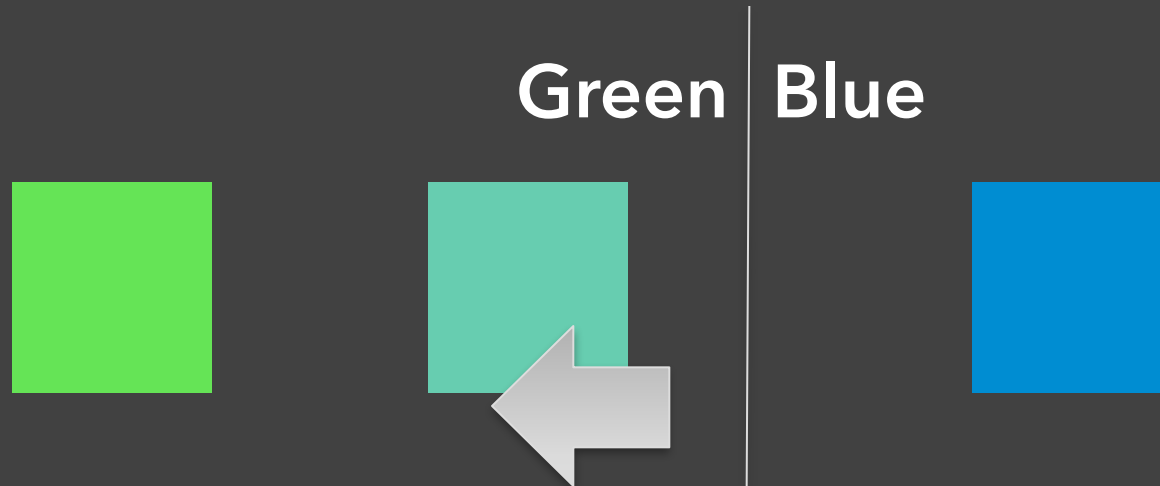
Rainbow Color Map

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



Naming Effects Color Perception

Color name boundaries



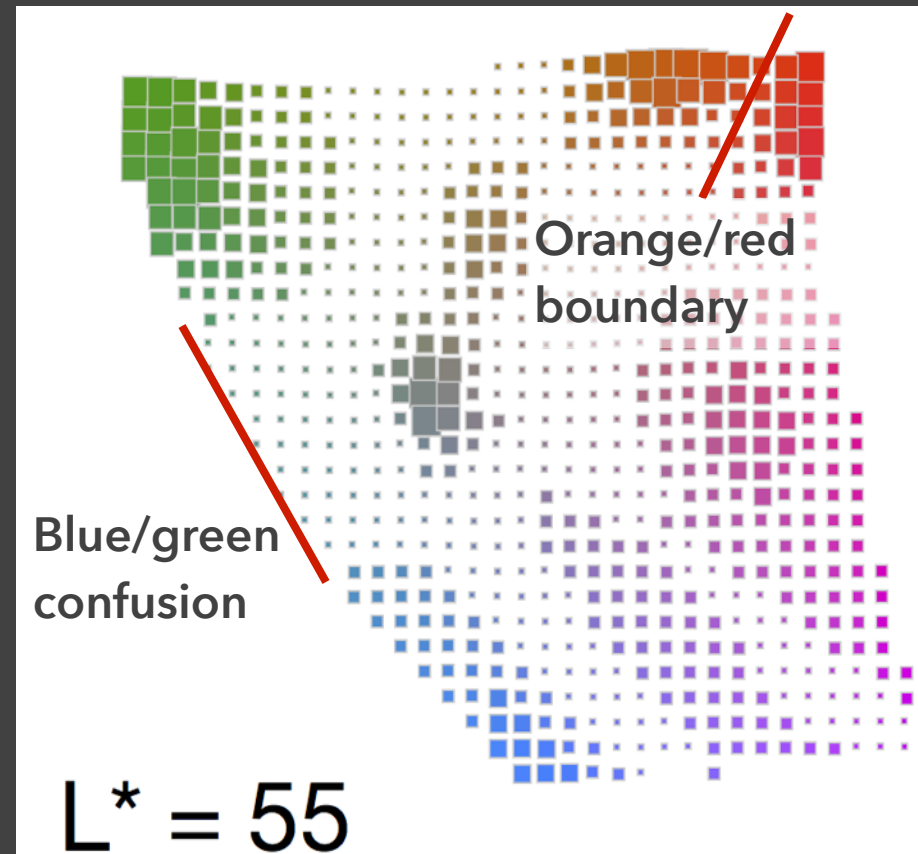
Color Naming Models [Heer & Stone '12]

Model 3 million responses from XKCD survey

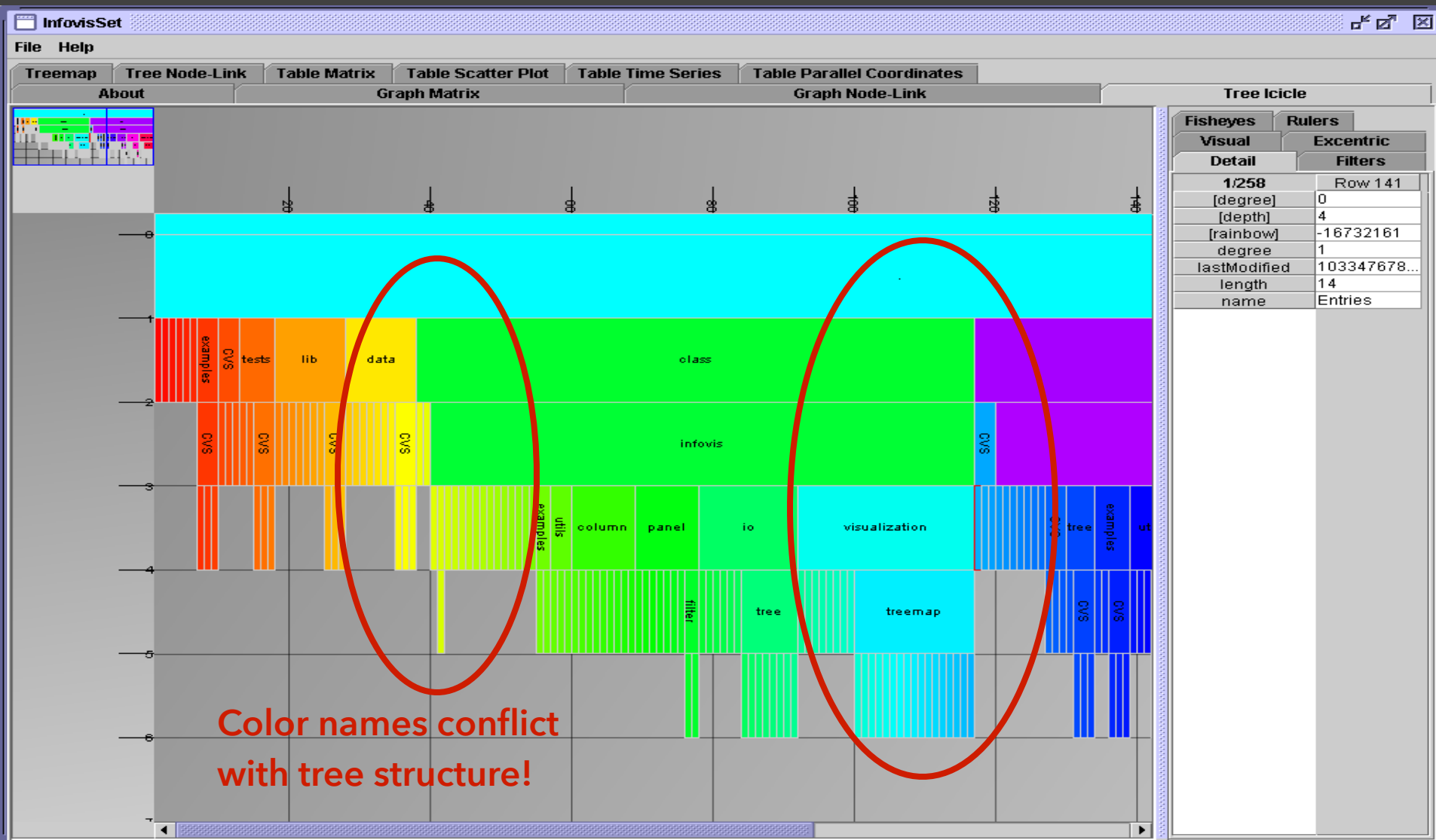
Bins in LAB space
sized by *saliency*:

How much do people
agree on color name?

Modeled by entropy
of $p(\text{name} \mid \text{color})$



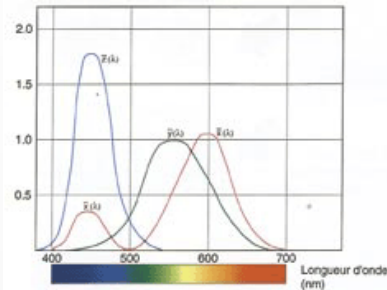
Icicle Tree with Rainbow Coloring



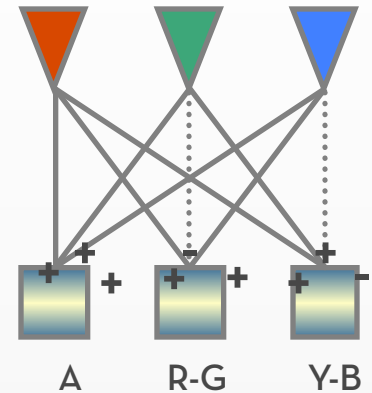
Perception of Color



Light



Cone Response



Opponent Signals

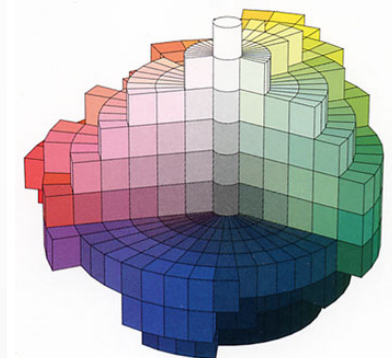
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE
MODELS

Color Appearance



Color Perception

Color Encodings

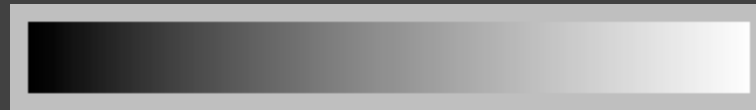
Encoding Data with Color

Value is perceived as ordered

∴ Encode ordinal variables (O)



∴ Encode continuous variables (Q) [not as well]



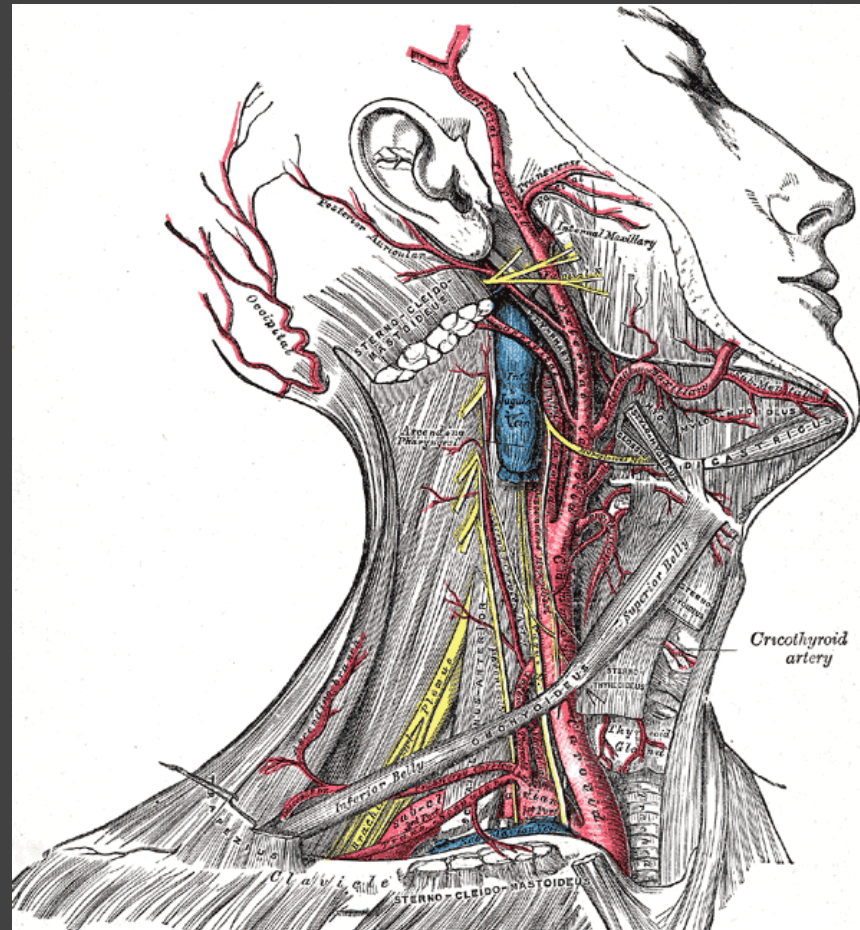
Hue is normally perceived as unordered

∴ Encode nominal variables (N) using color



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

UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM

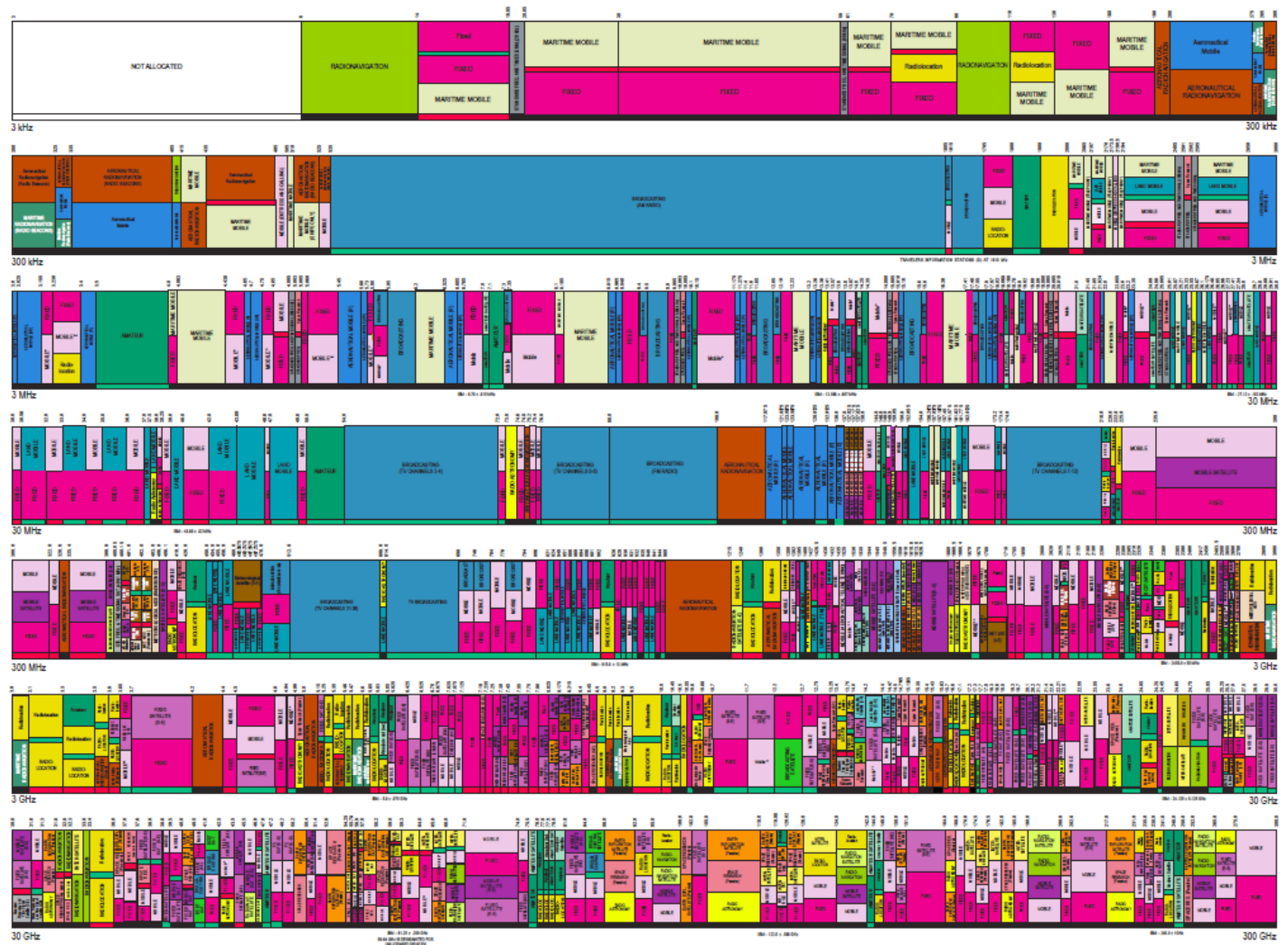
RADIO SERVICES COLOR LEGEND

- | | | |
|-------------------------------|--------------------------------------|--|
| AERONAUTICAL MOBILE | AEROMOBILE | ASTRONOMY |
| AERONAUTICAL MOBILE SATELLITE | LAND MOBILE | BROADCASTING TERRESTRIAL SATELLITE |
| AERONAUTICAL RADIATION | LAND MOBILE SATELLITE | RADIATION |
| AMATEUR | MARITIME MOBILE | RADIATION SATELLITE |
| AMATEUR SATELLITE | MARITIME MOBILE SATELLITE | NAVIGATION |
| BROADCASTING | MARITIME RADIATION | NAVIGATION SATELLITE |
| BROADCASTING FIXED | METEOROLOGICAL AERONAUTICS | SPACE OPERATION |
| EARTH STATION SATELLITE | METEOROLOGICAL AERONAUTICS SATELLITE | SPACE RESEARCH |
| FIXED | MOBILE | STANDARD FREQUENCY AND TIME SIGNAL |
| FIXED SATELLITE | MOBILE SATELLITE | STANDARD FREQUENCY AND TIME SIGNAL SATELLITE |

- ### ACTIVITY CODE
- | | |
|--------------------------|----------------------------------|
| GOVERNMENT EXCLUSIVE | GOVERNMENT/NON-GOVERNMENT SHARED |
| NON-GOVERNMENT EXCLUSIVE | |

ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	F1E2D	Capital Letters
Co-primary	F1E2D	Capital Letters



Allocation

UNITED STATES FREQUENCY ALLOCATION THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

ACTIVITY CODE

ALLOCATION USAGE DESIGNATION

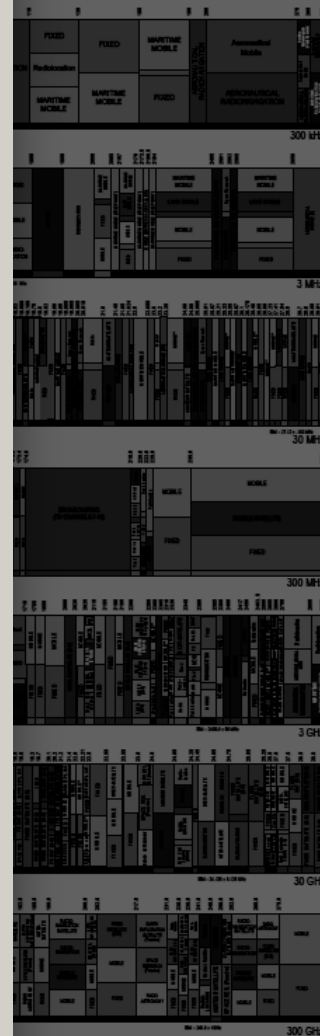
SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	MOBILE	Capital Letters, Numbers, Punctuation

RADIO SERVICES COLOR LEGEND

	AERONAUTICAL MOBILE		INTER-SATELLITE		RADIO ASTRONOMY
	AERONAUTICAL MOBILE SATELLITE		LAND MOBILE		RADIODETERMINATION SATELLITE
	AERONAUTICAL RADIOLOCATION		LAND MOBILE SATELLITE		RADIOLOCATION
	AMATEUR		MARITIME MOBILE		RADIOLOCATION SATELLITE
	AMATEUR SATELLITE		MARITIME MOBILE SATELLITE		RADIONAVIGATION
	BROADCASTING		MARITIME RADIOLOCATION		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

rum




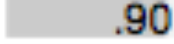
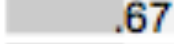





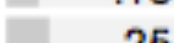

Palette Design & Color Names

Minimize overlap and ambiguity of colors.

Color Name Distance

0.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.20
1.00	0.00	1.00	0.97	1.00	1.00	1.00	1.00	0.96	1.00
1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.90	0.99
1.00	0.97	1.00	0.00	1.00	0.95	0.99	1.00	1.00	1.00
0.98	1.00	1.00	1.00	0.00	0.96	0.91	0.97	1.00	0.99
1.00	1.00	1.00	0.95	0.96	0.00	0.97	0.93	0.98	1.00
1.00	1.00	1.00	0.99	0.91	0.97	0.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	0.97	0.93	1.00	0.00	1.00	1.00
1.00	0.96	0.90	1.00	1.00	0.98	1.00	1.00	0.00	1.00
0.20	1.00	0.99	1.00	0.99	1.00	1.00	1.00	1.00	0.00

Saliency

	.47
	.90
	.67
	.66
	.47
	.37
	.58
	.67
	.18
	.25

Name

blue	62.9%
orange	93.9%
green	79.8%
red	80.4%
purple	51.4%
brown	54.0%
pink	71.7%
grey	79.4%
yellow	31.2%
blue	25.4%

Tableau-10

Average 0.97

.52

Palette Design & Color Names

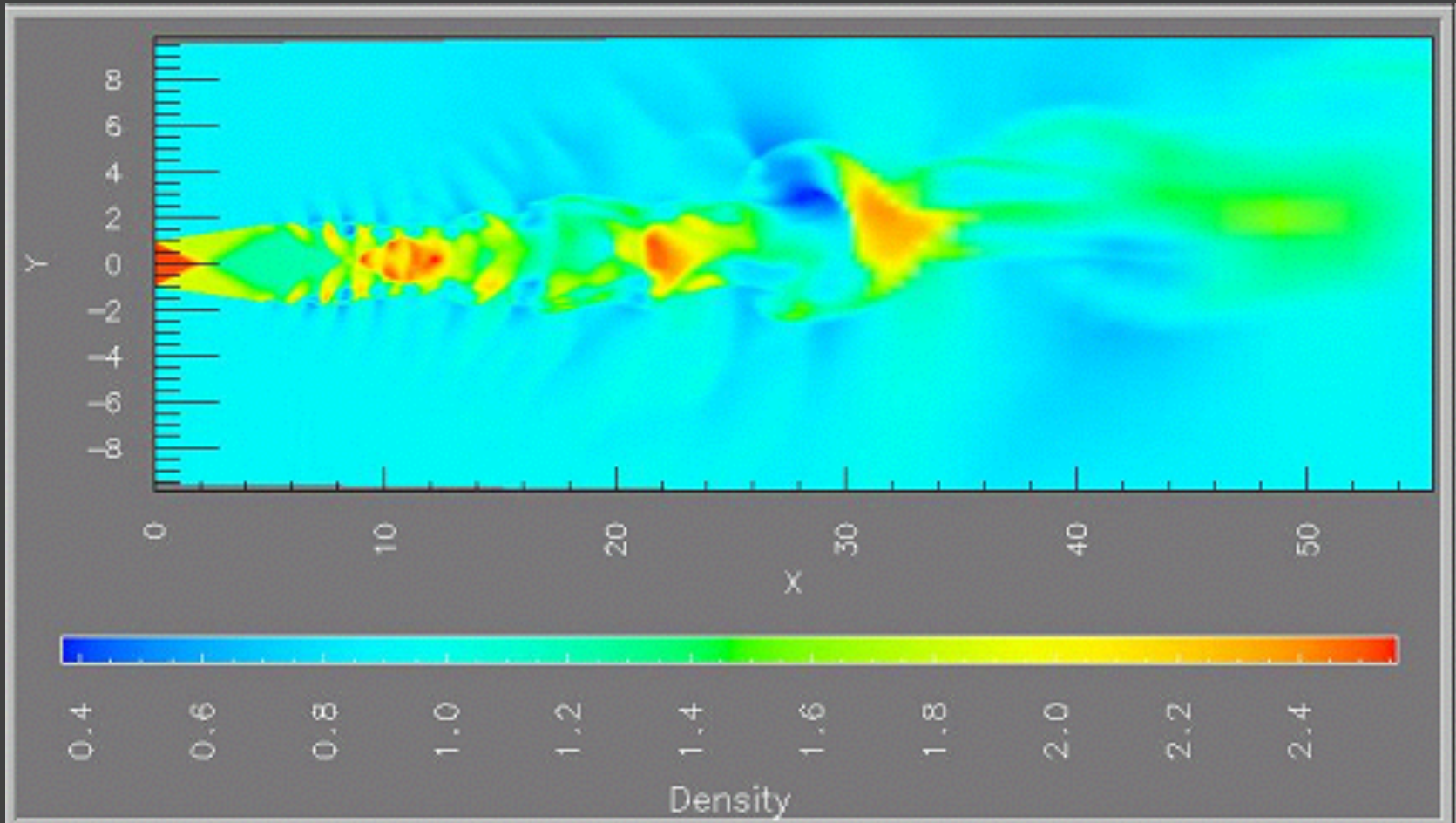
Minimize overlap and ambiguity of colors.

Color Name Distance

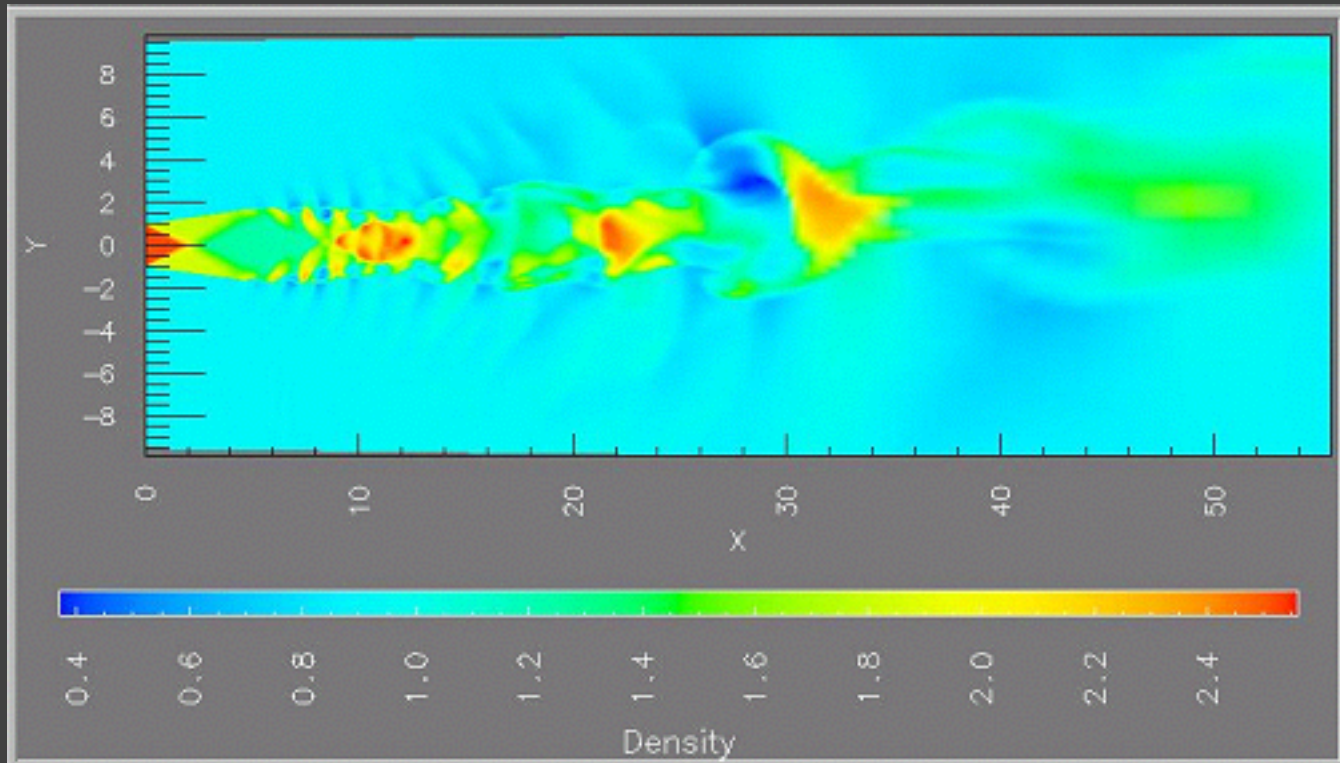
	0.00	1.00	1.00	0.89	0.07	1.00	0.35	0.99	1.00	0.89	Saliency	Name
0.00	1.00	1.00	0.89	0.07	1.00	0.35	0.99	1.00	0.89	.30	blue 50.5%	
1.00	0.00	0.99	1.00	1.00	0.92	1.00	0.84	0.98	0.99	.21	red 27.8%	
1.00	0.99	0.00	1.00	0.98	1.00	1.00	1.00	0.17	1.00	.34	green 36.8%	
0.89	1.00	1.00	0.00	0.98	1.00	0.71	0.93	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	<i>Average</i>									0.87	.27	

Quantitative Color

Rainbow Color Maps



Be Wary of Rainbows!



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

Color Brewer: Palettes for Maps

number of data classes on your map

3 [learn more >](#)

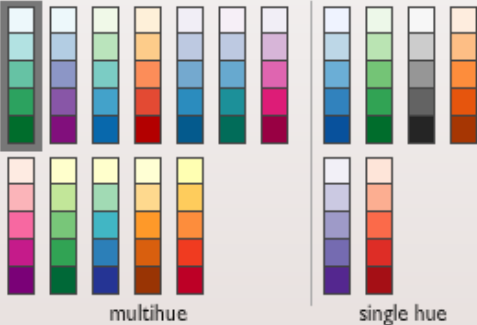
[how to use](#) | [updates](#) | [credits](#)

COLORBREWER 2.0
color advice for cartography

the nature of your data

sequential [learn more >](#)

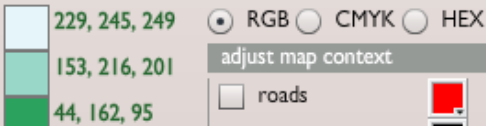
pick a color scheme: BuGn



(optional) only show schemes that are:

- colorblind safe
- print friendly
- photocopy-able [learn more >](#)

pick a color system

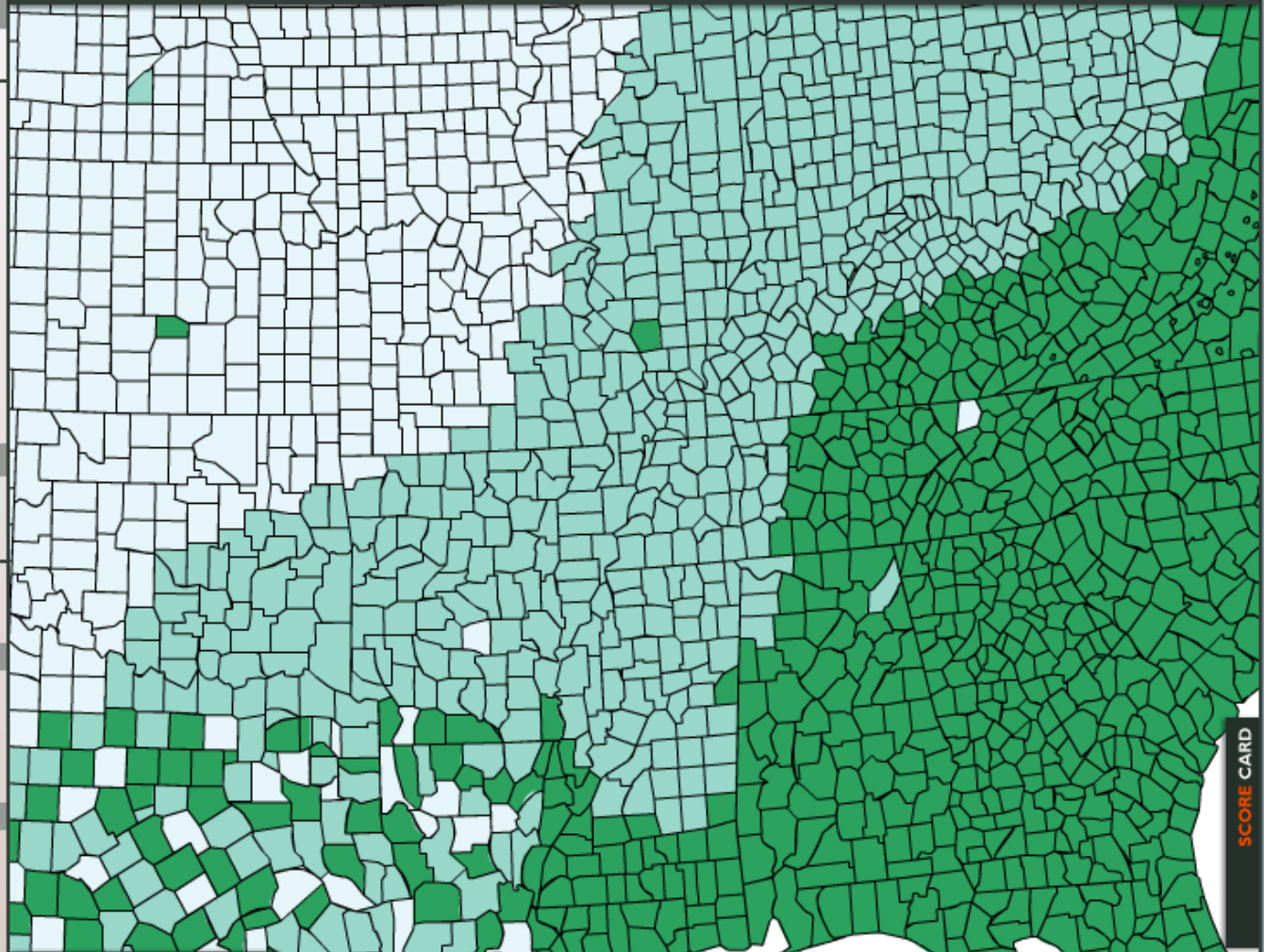


adjust map context

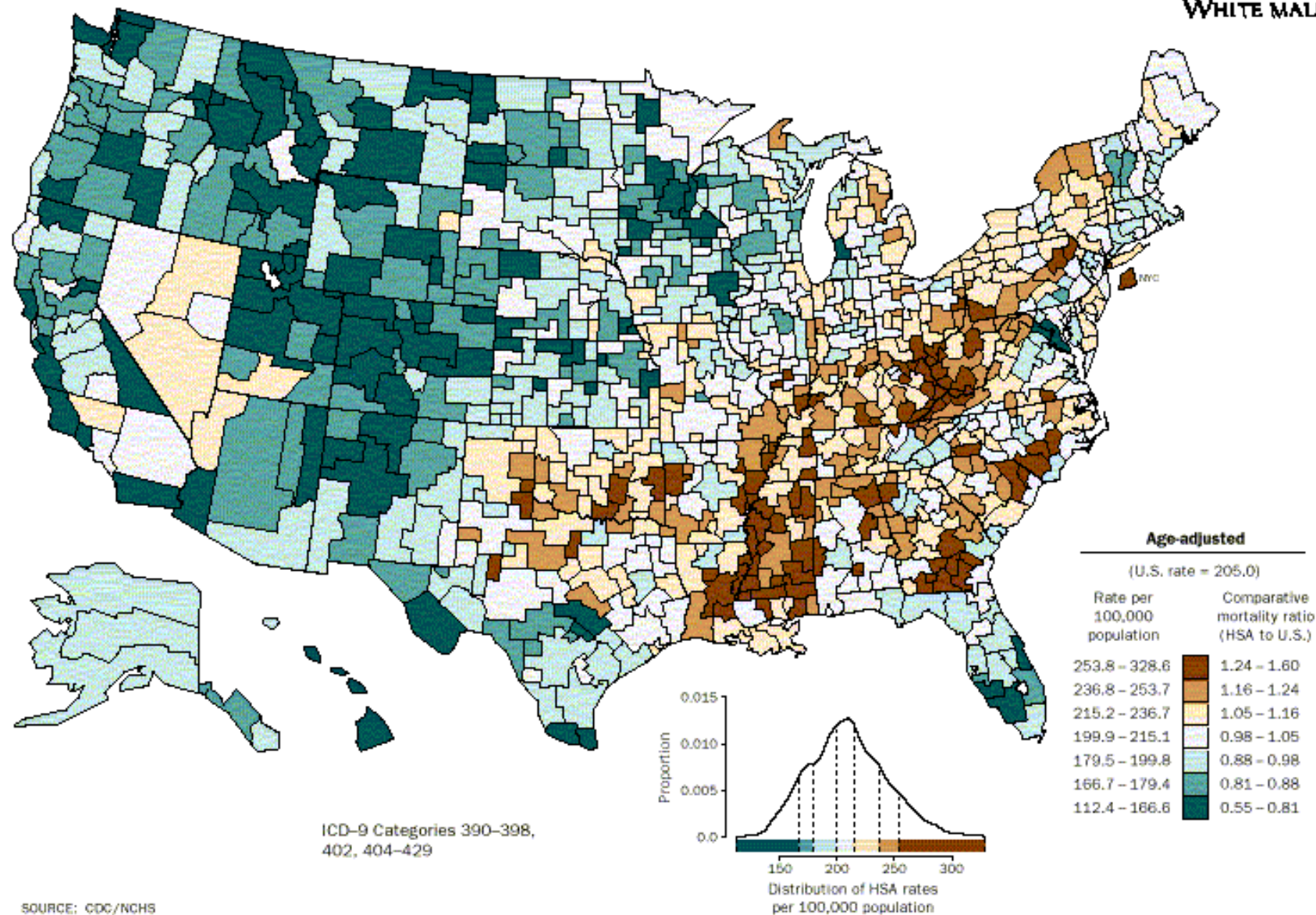
- roads
- cities
- borders

select a background

- solid color
- terrain

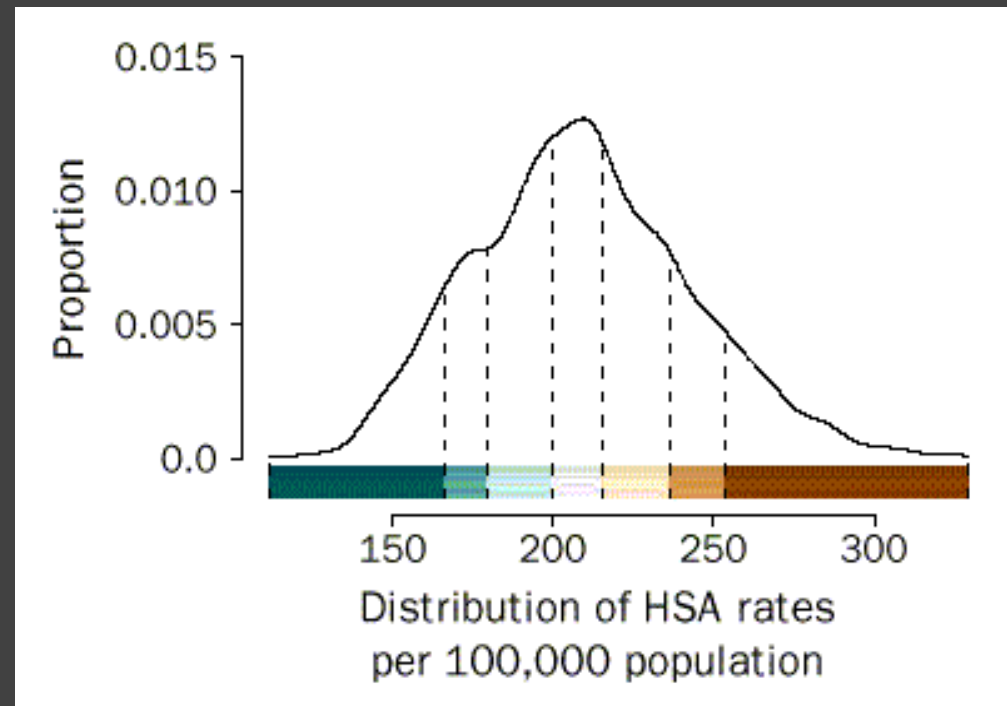
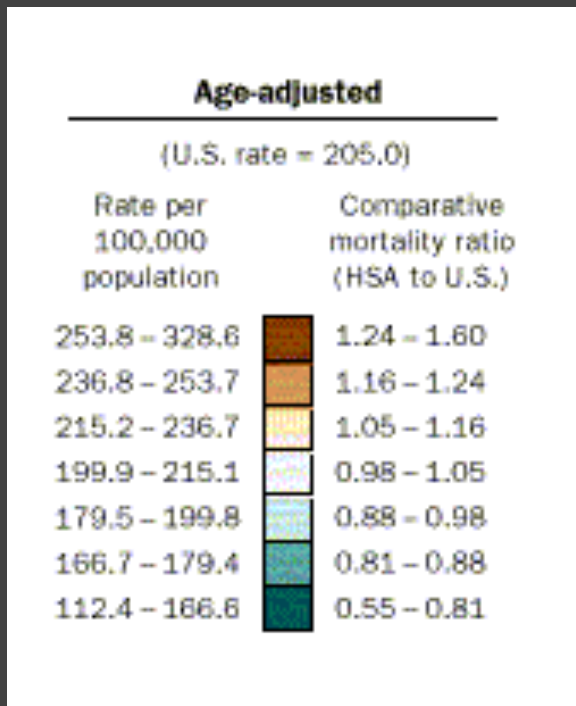


AGE-ADJUSTED DEATH RATES BY HSA, 1988-92

HEART DISEASE
WHITE MALE

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

Constrain hue, vary luminance/saturation

Map higher values to darker colors



Quantitative Color Encoding

Sequential color scale

Constrain hue, vary luminance/saturation

Map higher values to darker colors

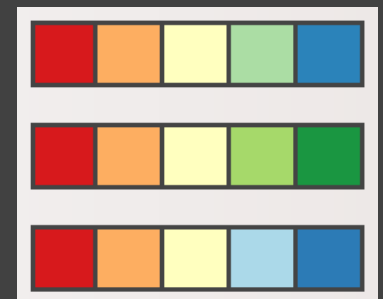


Diverging color scale

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

Constrain hue, vary luminance/saturation
Map higher values to darker colors



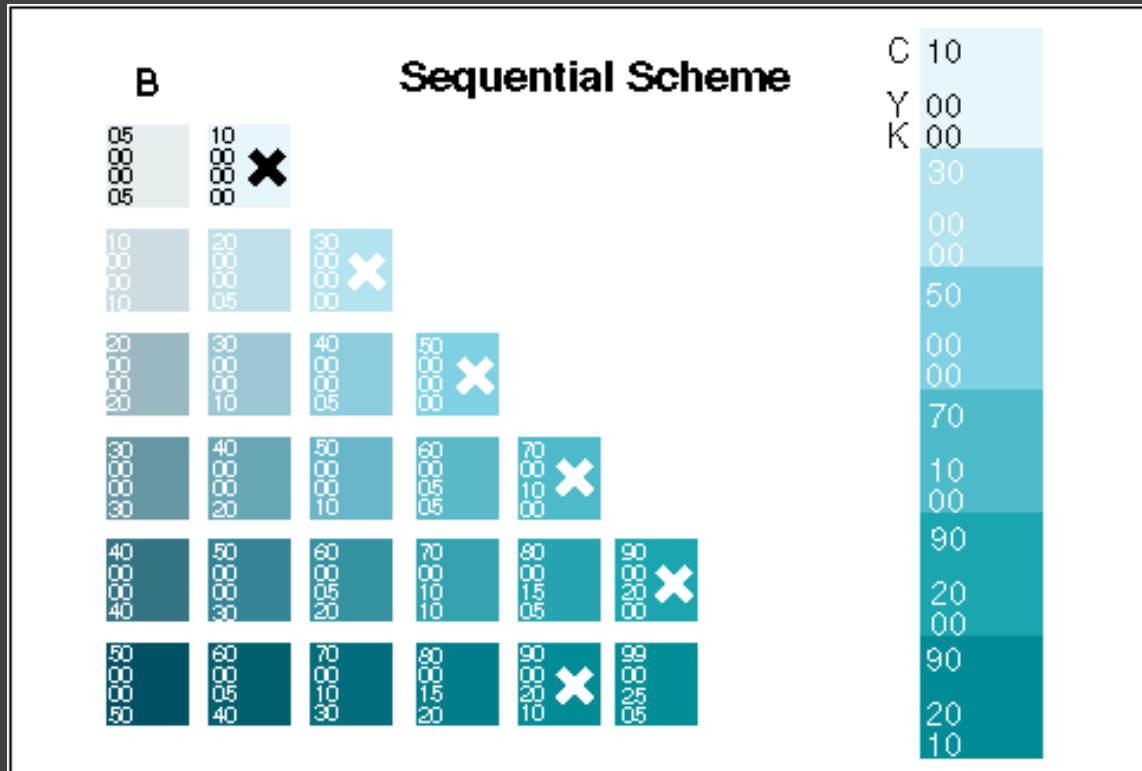
Diverging color scale

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

Designing Sequential Scales



Designing Sequential Scales

Hue-Lightness (*Recommended*)

Higher values mapped to darker colors

ColorBrewer schemes have 3-9 steps

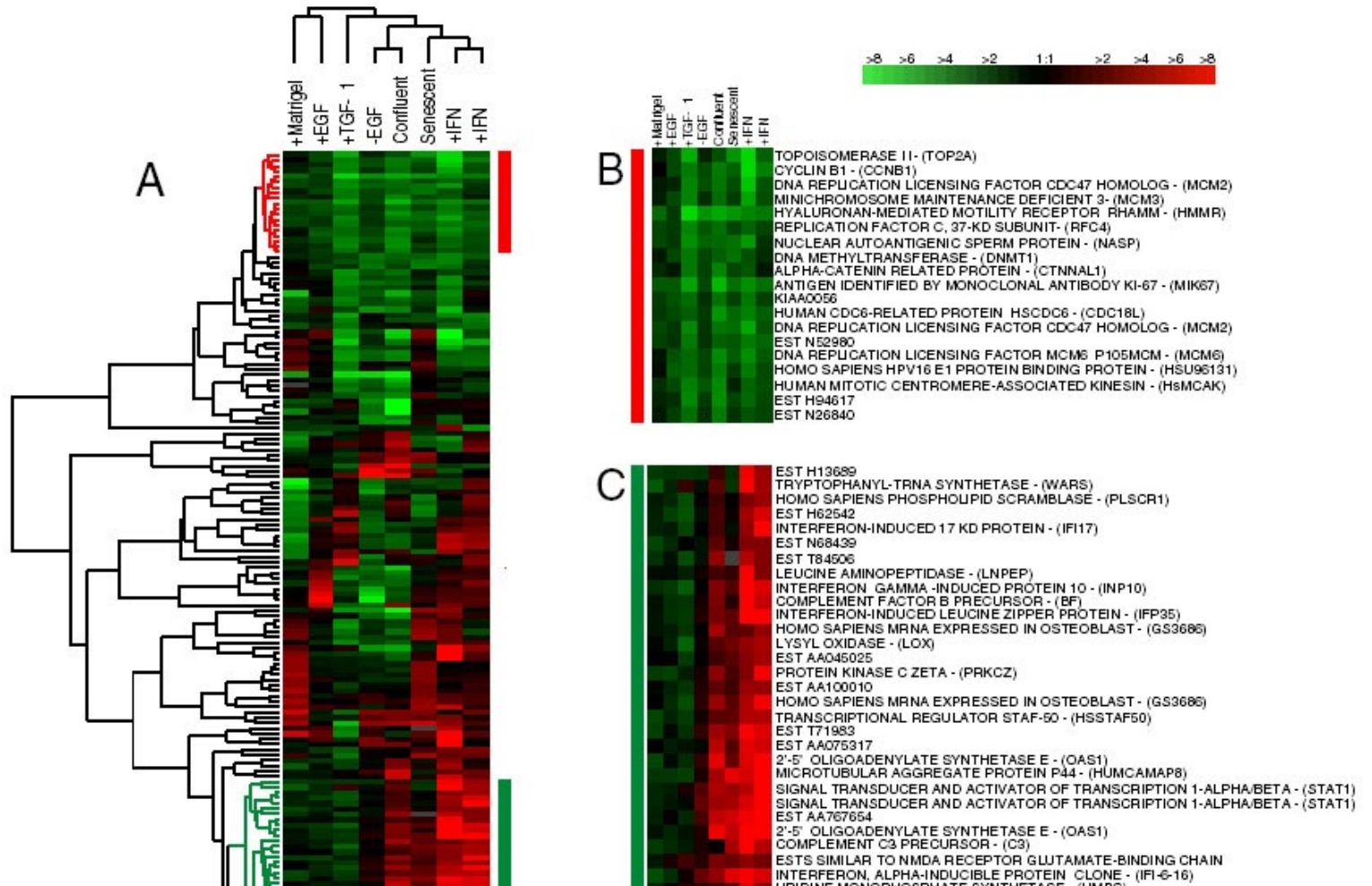
Hue Transition

Two hues

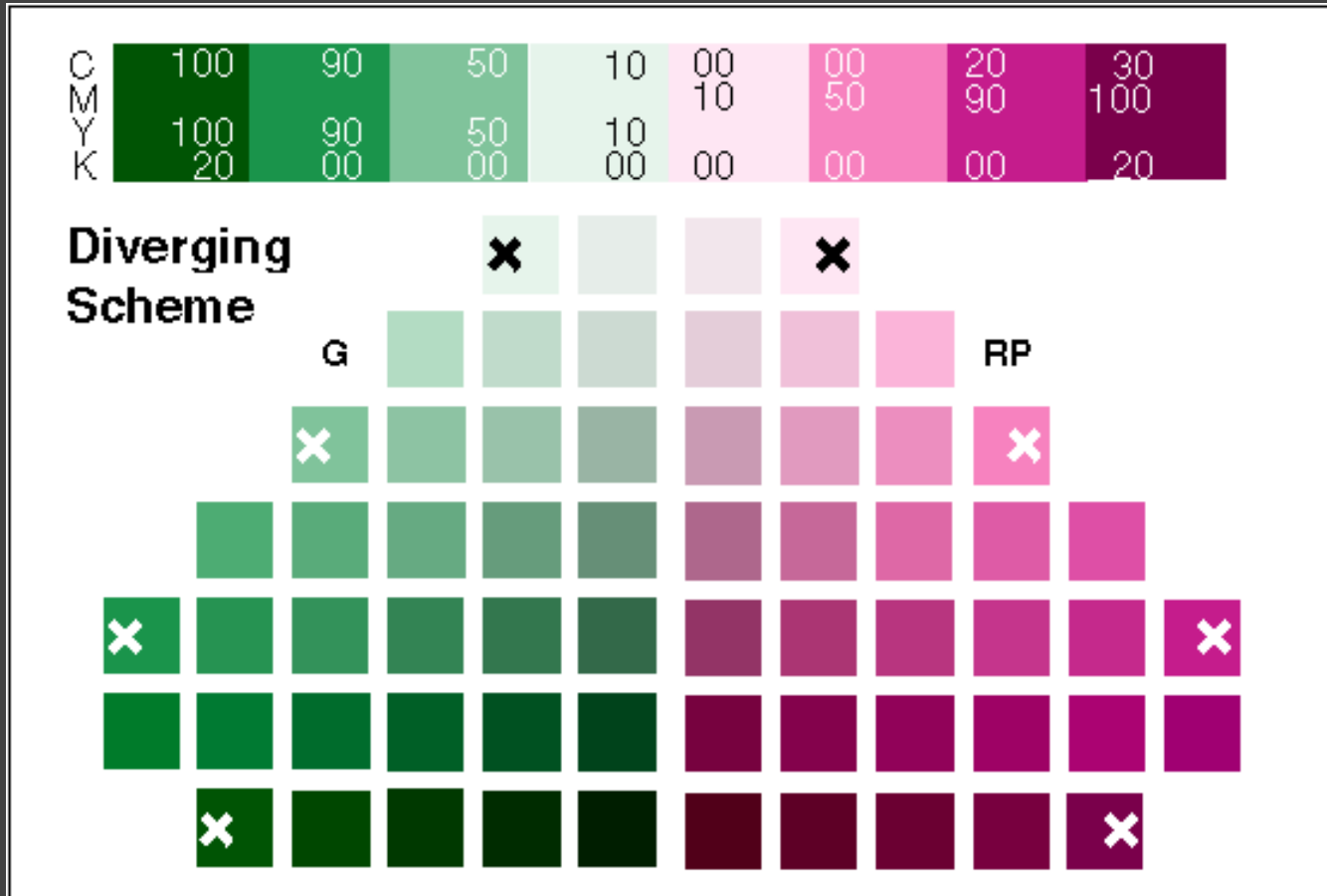
Neighboring hues interpolate better

Couple with change in lightness

Diverging Color Scheme



Designing Diverging Scales



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

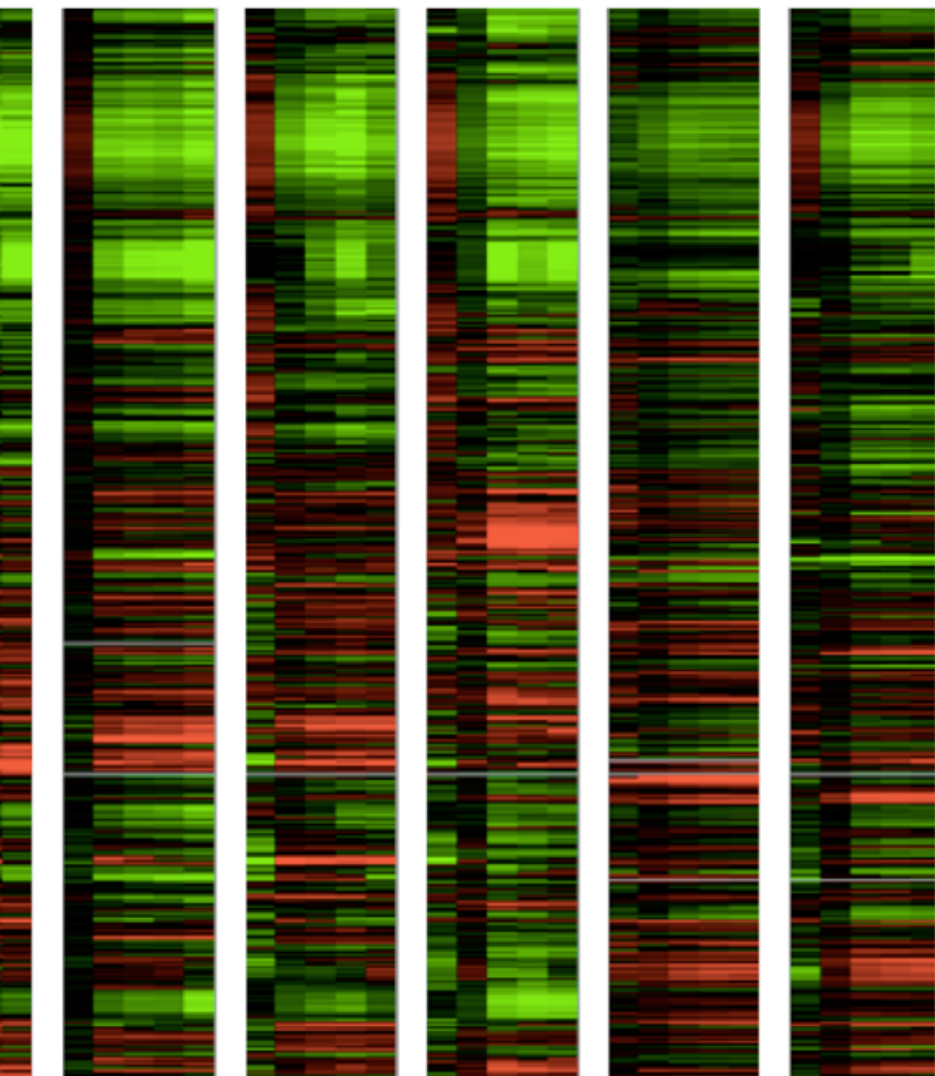
Positive & negative should use different hues

Extremes saturated, middle desaturated

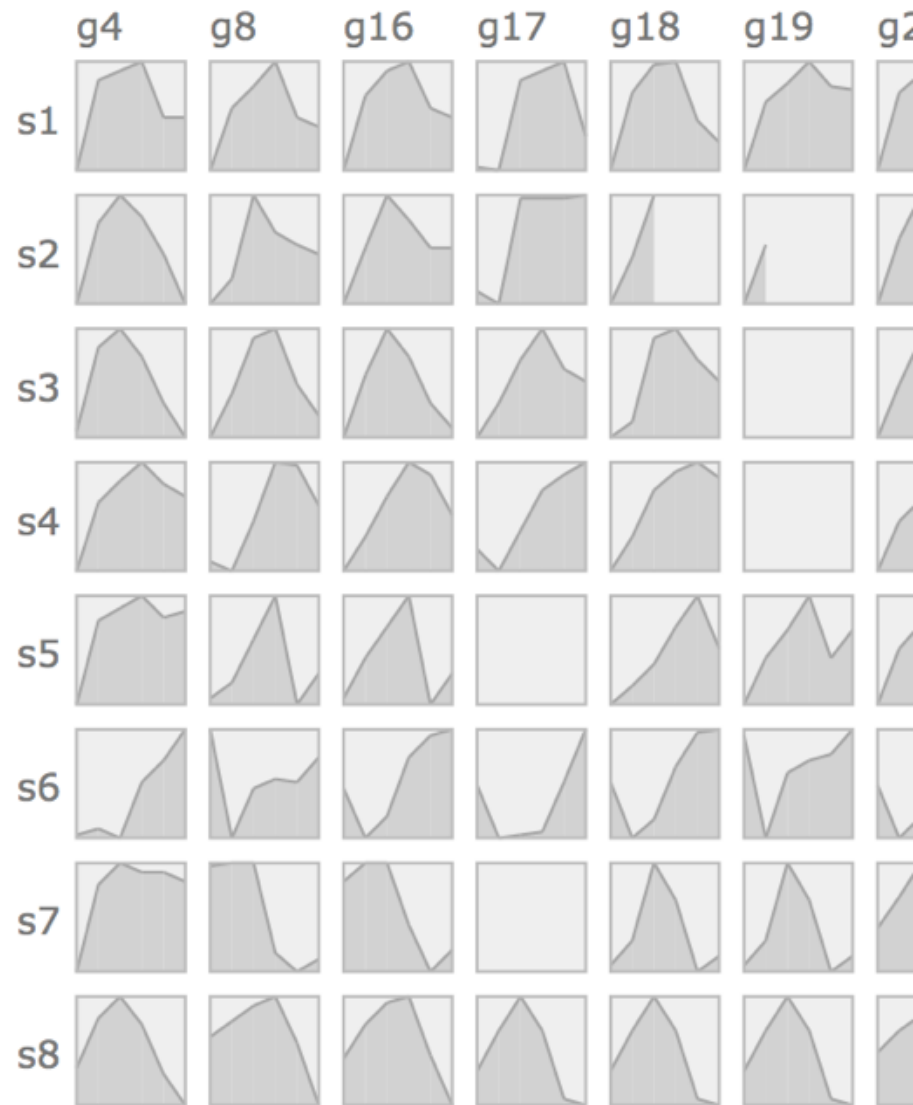
Perceptual Re-designs

Gene Expression Time-Series [Meyer et al 11]

Color Encoding



Position Encoding



Artery Visualization [Borkin et al 11]

Rainbow Palette

2D



3D



Artery Visualization [Borkin et al 11]

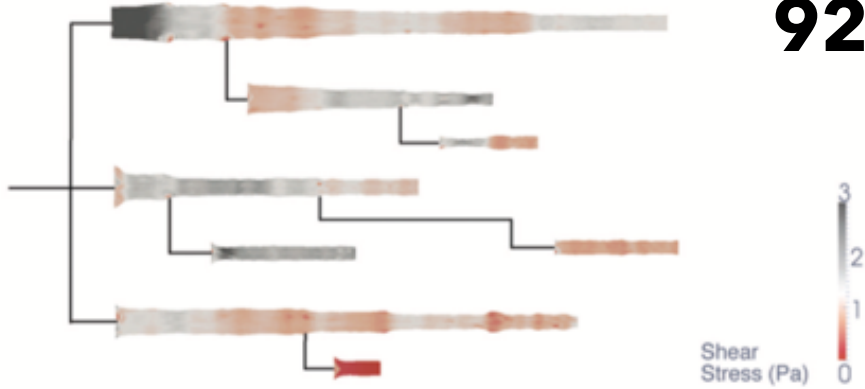
Rainbow Palette

Diverging Palette

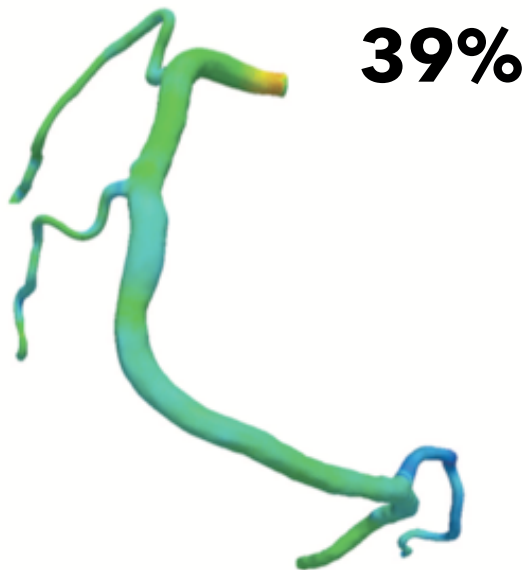
Accuracy: **62%**

92%

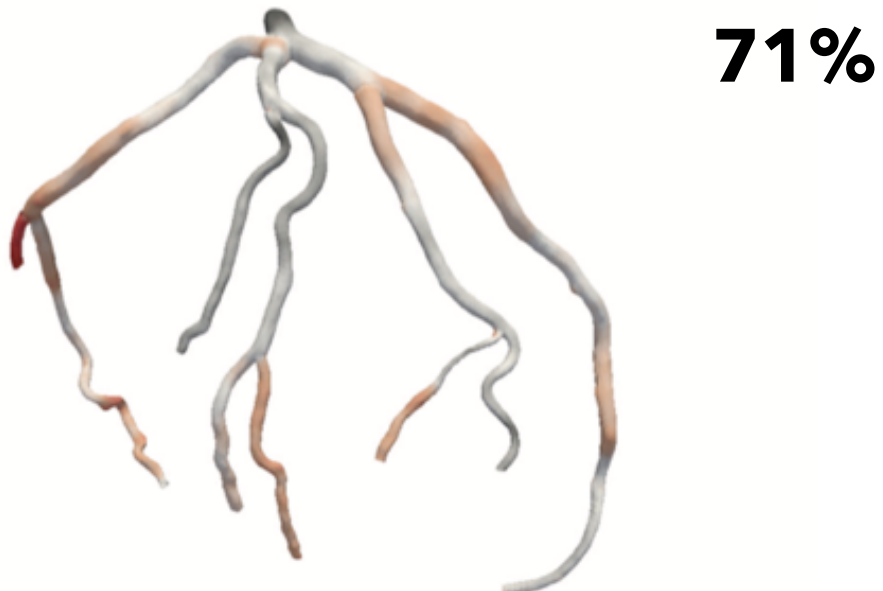
2D



3D



39%



71%

Hints for the Colorist

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

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Colors should be **distinctive** and **named**

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Get it right in **black and white**

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Get it right in **black and white**

Respect the **color blind**

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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**