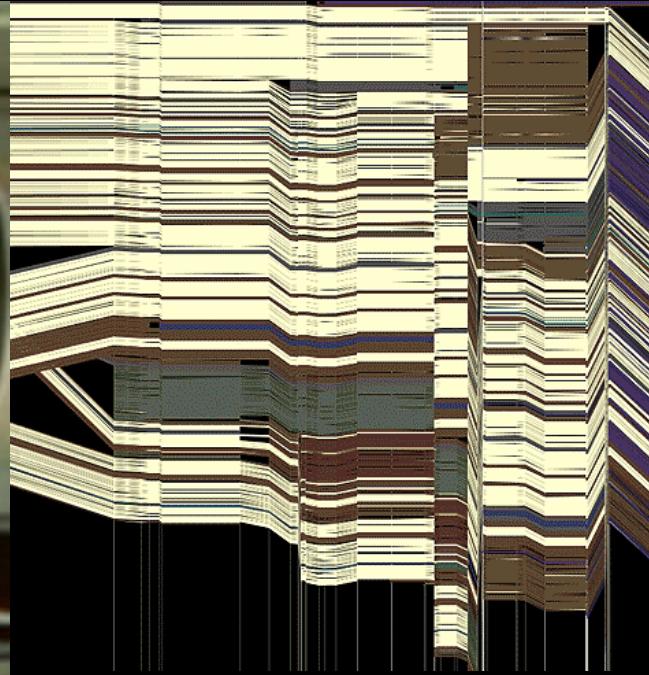
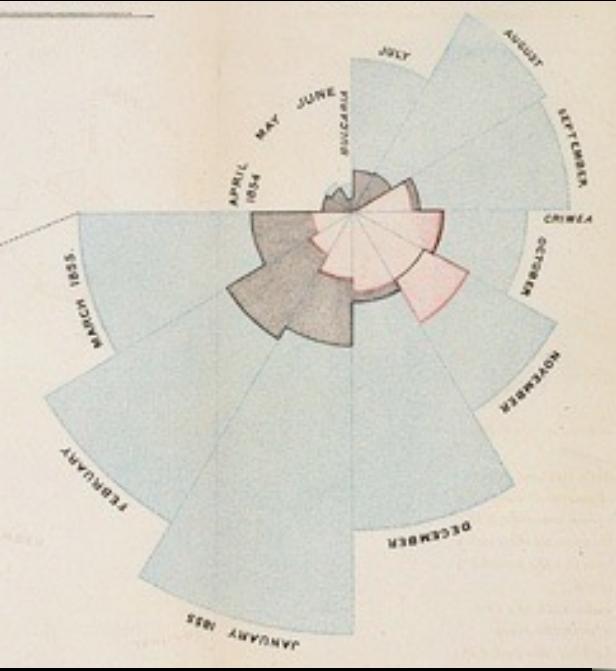


CSE 512 - Data Visualization

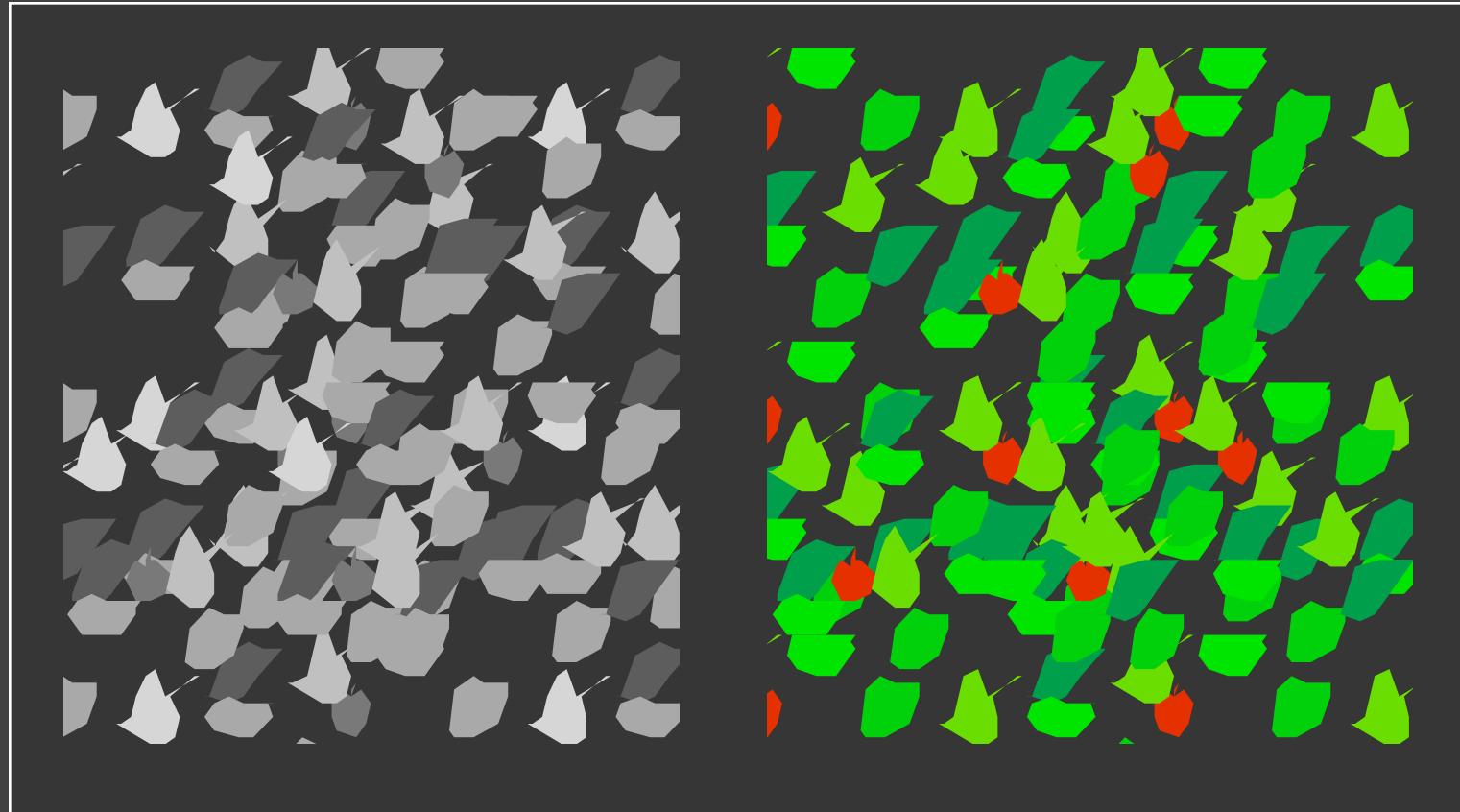
Color



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

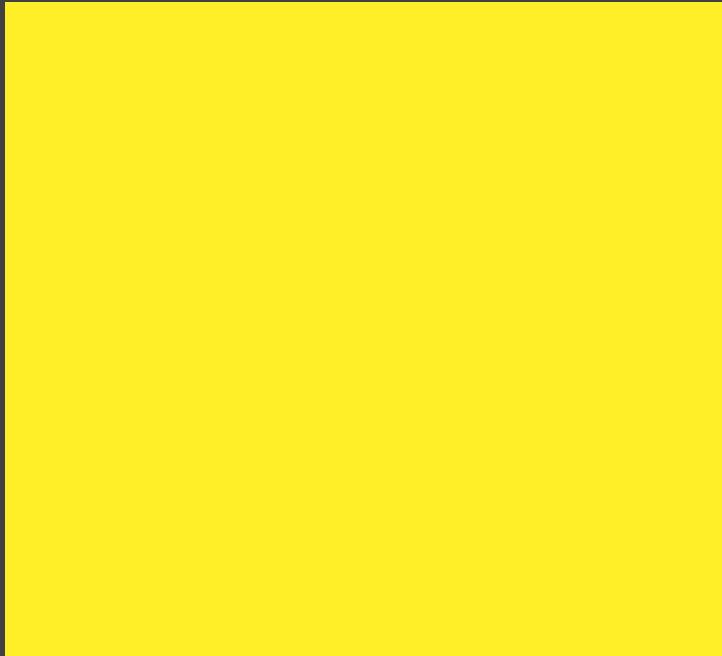
Color in Information Visualization

Nominal, Ordinal & Quantitative encoding

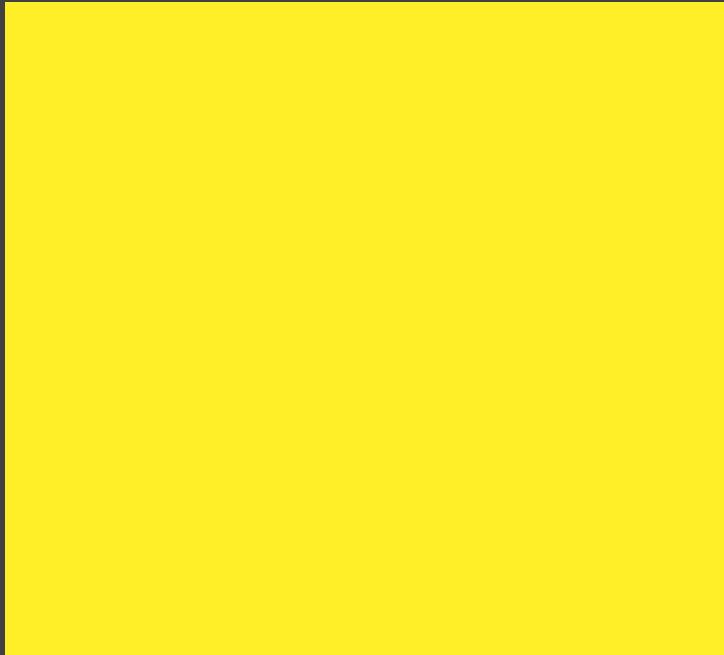
Guidelines for color palette design

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?

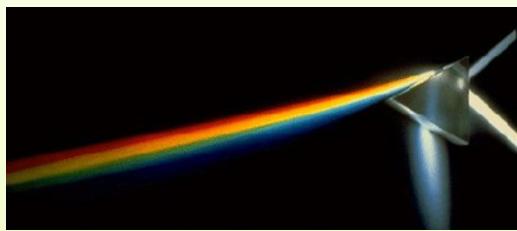


What color is this?

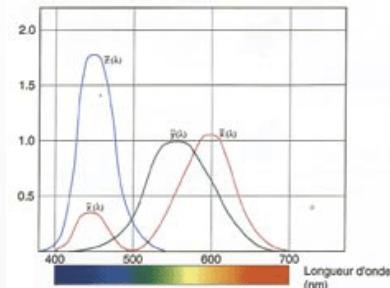


“Teal” ?

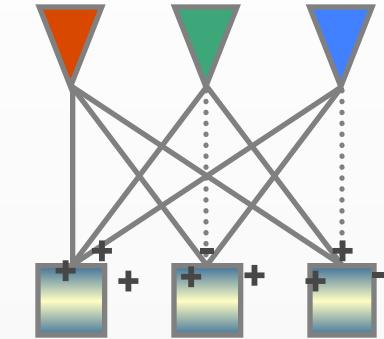
Perception of Color



Light



Cone Response



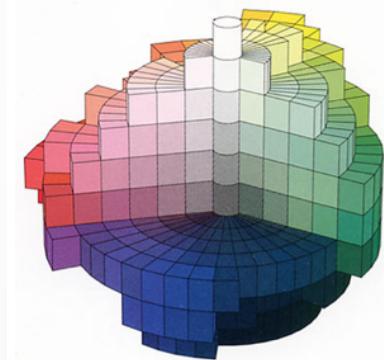
Opponent Signals

“Yellow”



Mark D. Fairchild
COLOR APPEARANCE MODELS

Color Cognition



Color Perception

Color Appearance

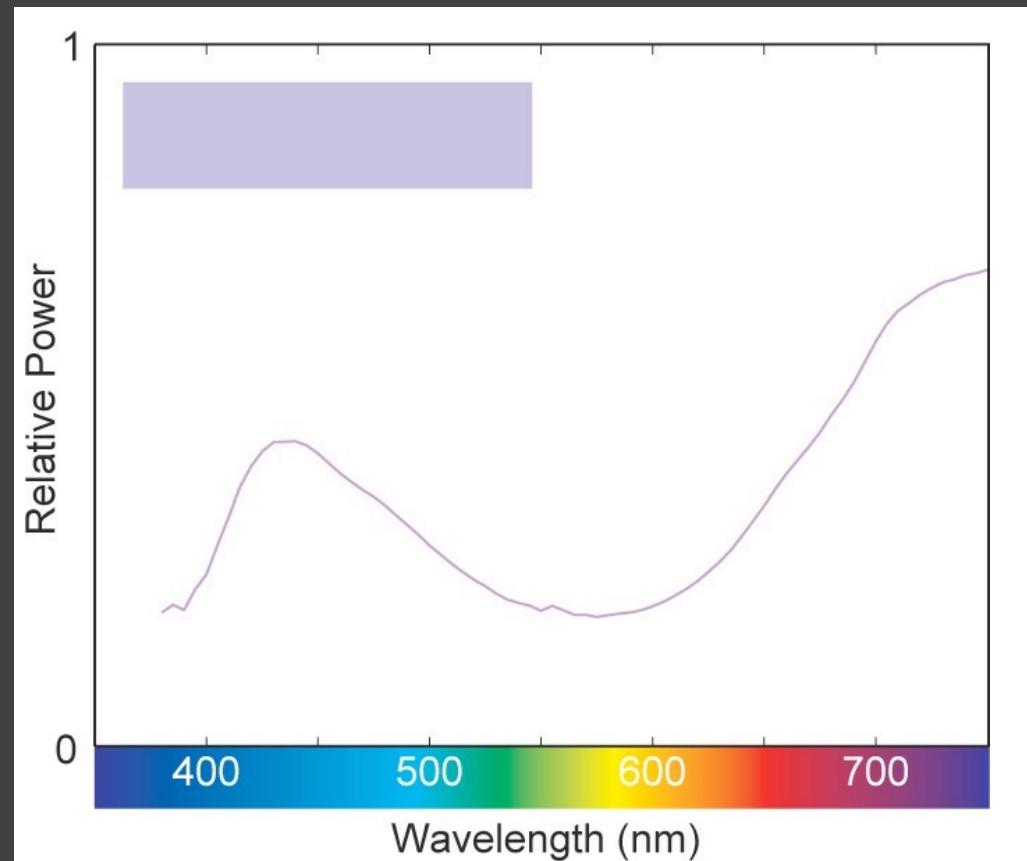
Physicist's View

Light as electromagnetic wave

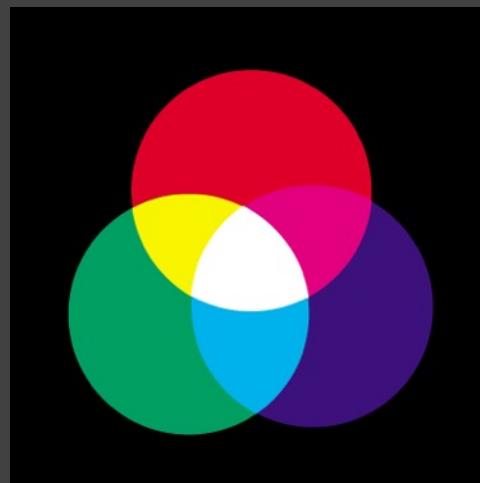
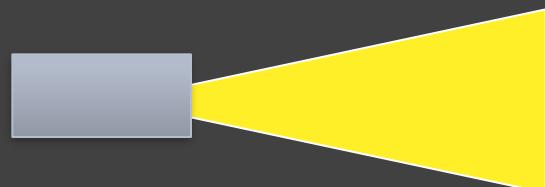
Wavelength

Energy or

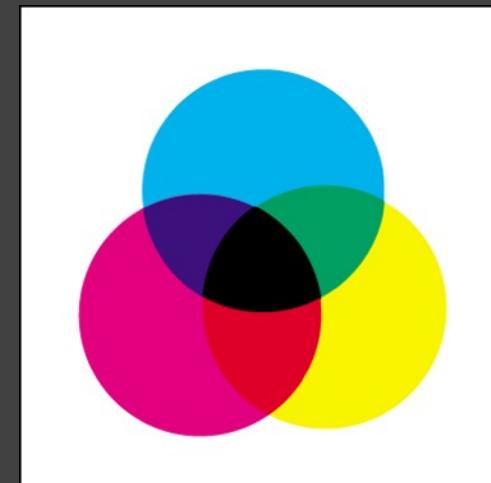
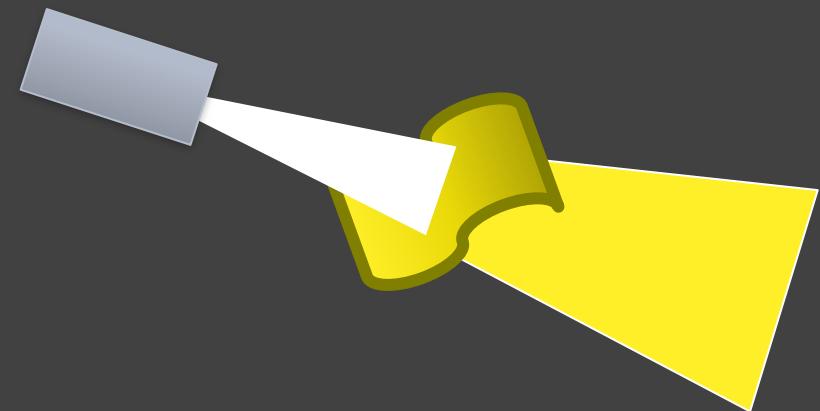
"Relative luminance"



Emissive vs. Reflective Light

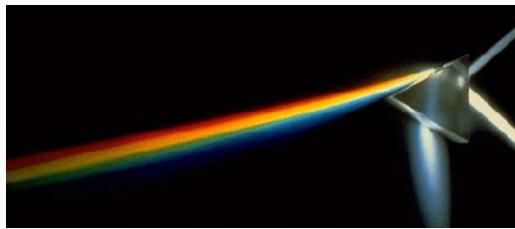


Additive
(digital displays)

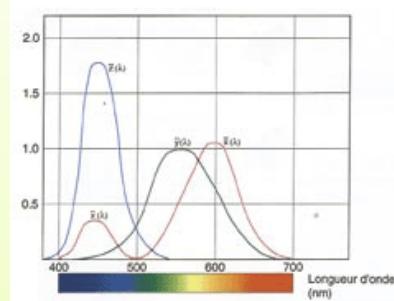


Subtractive
(print, e-paper)

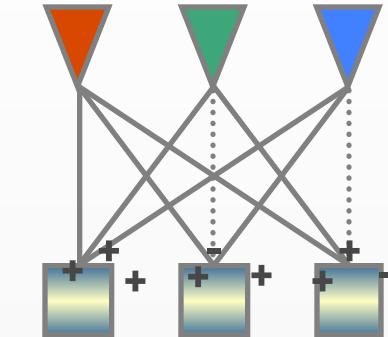
Perception of Color



Light

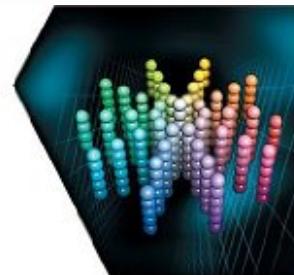


Cone Response



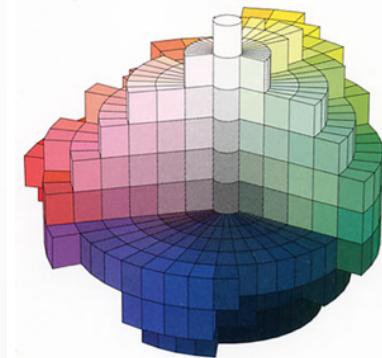
Opponent Signals

“Yellow”



Mark D. Fairchild
COLOR APPEARANCE MODELS

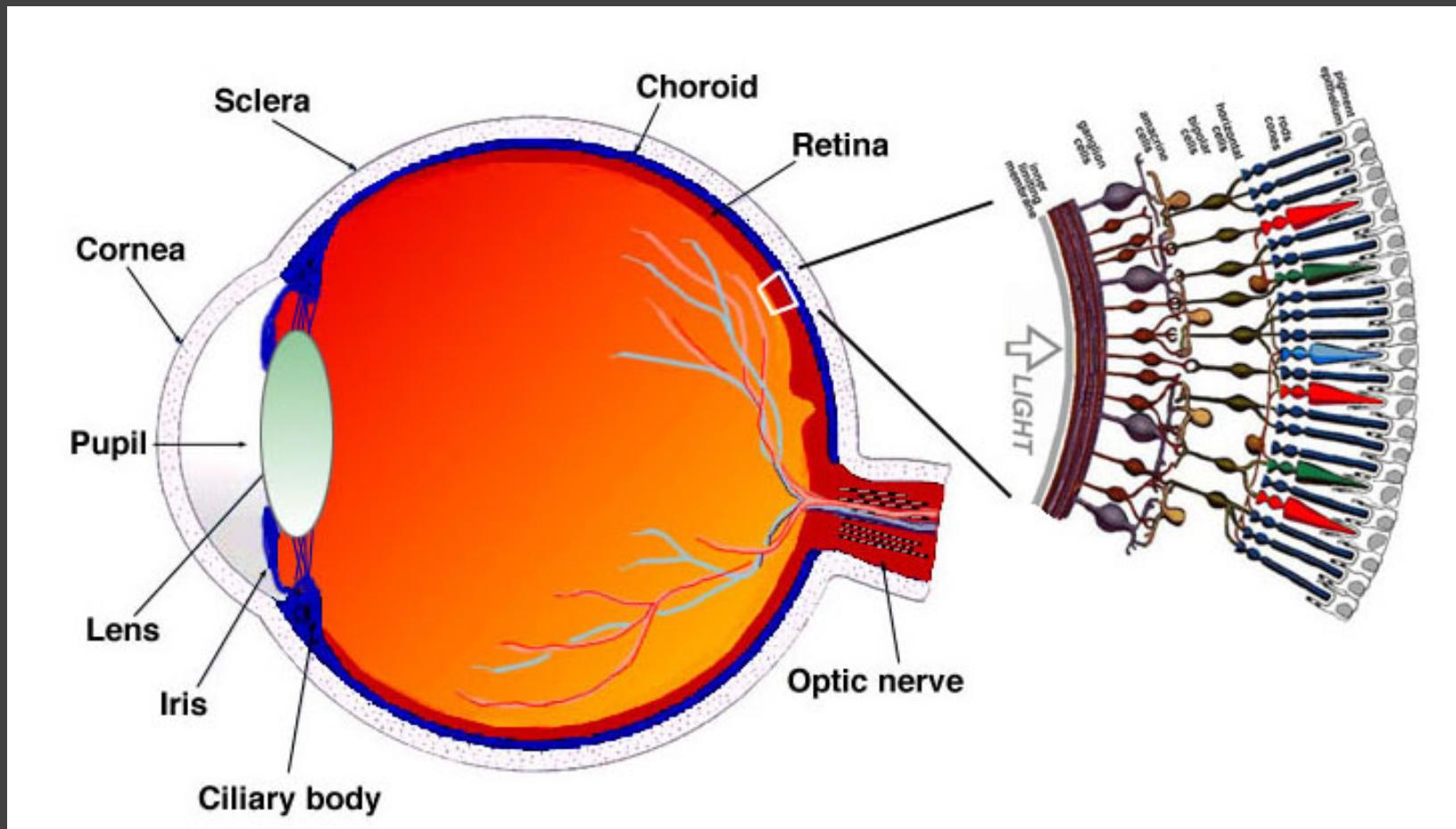
Color Cognition



Color Perception

Color Appearance

Retina

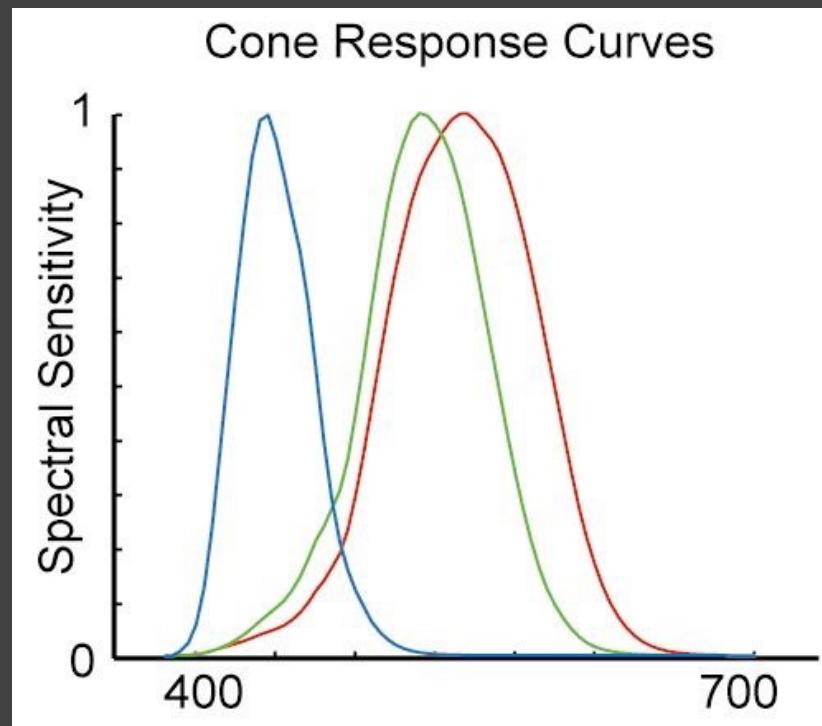


Simple Anatomy of the Retina, Helga Kolb

As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength

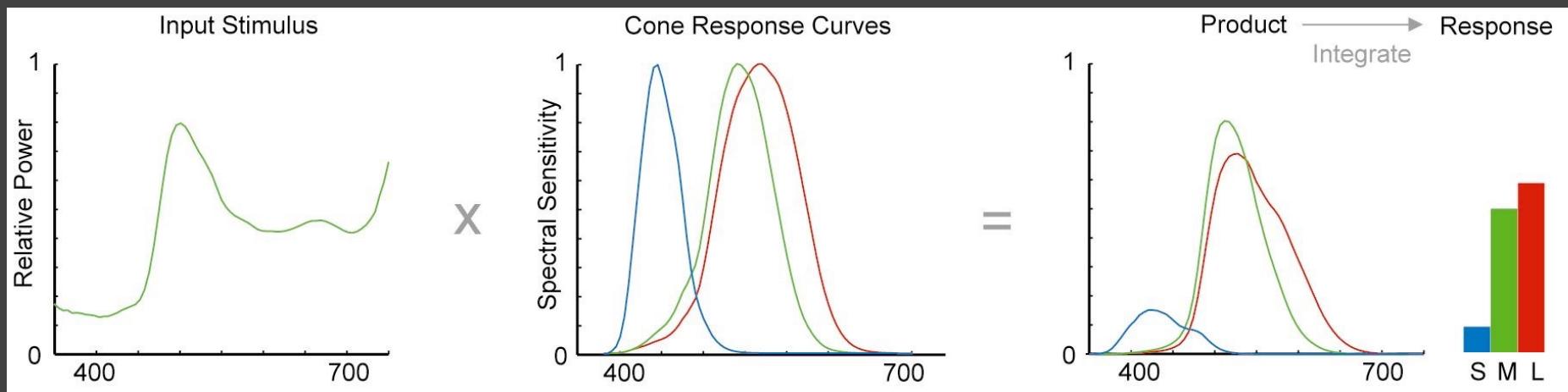


As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength

Integration with input stimulus



Effects of Retina Encoding

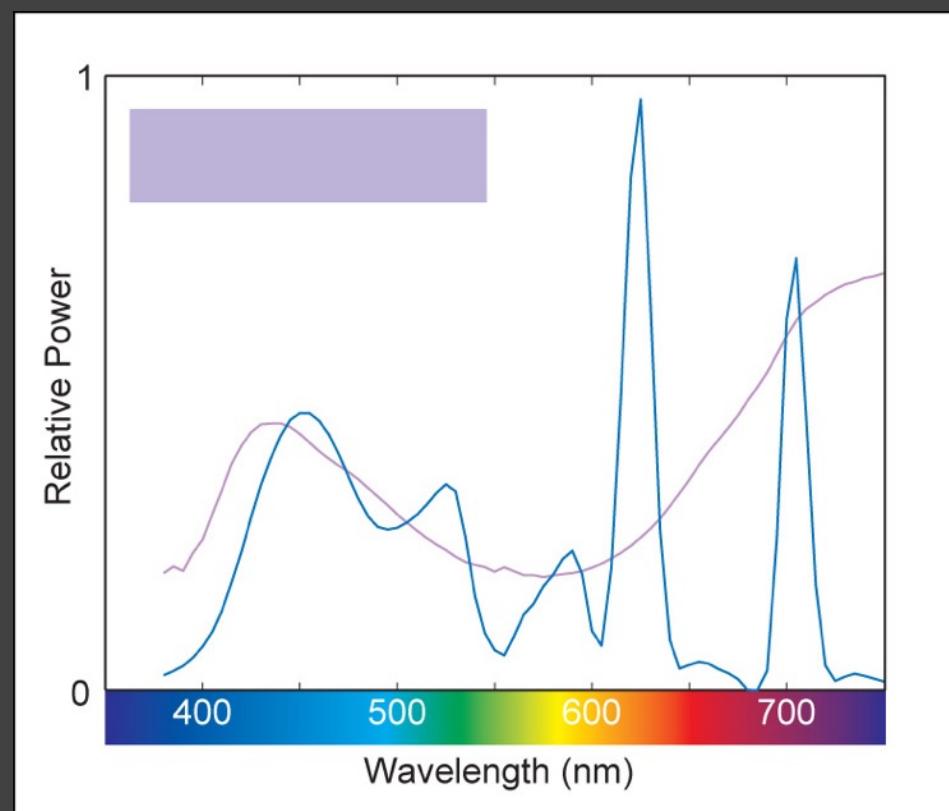
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. “metamers”).

“Tri-stimulus”

Computer displays

Digital scanners

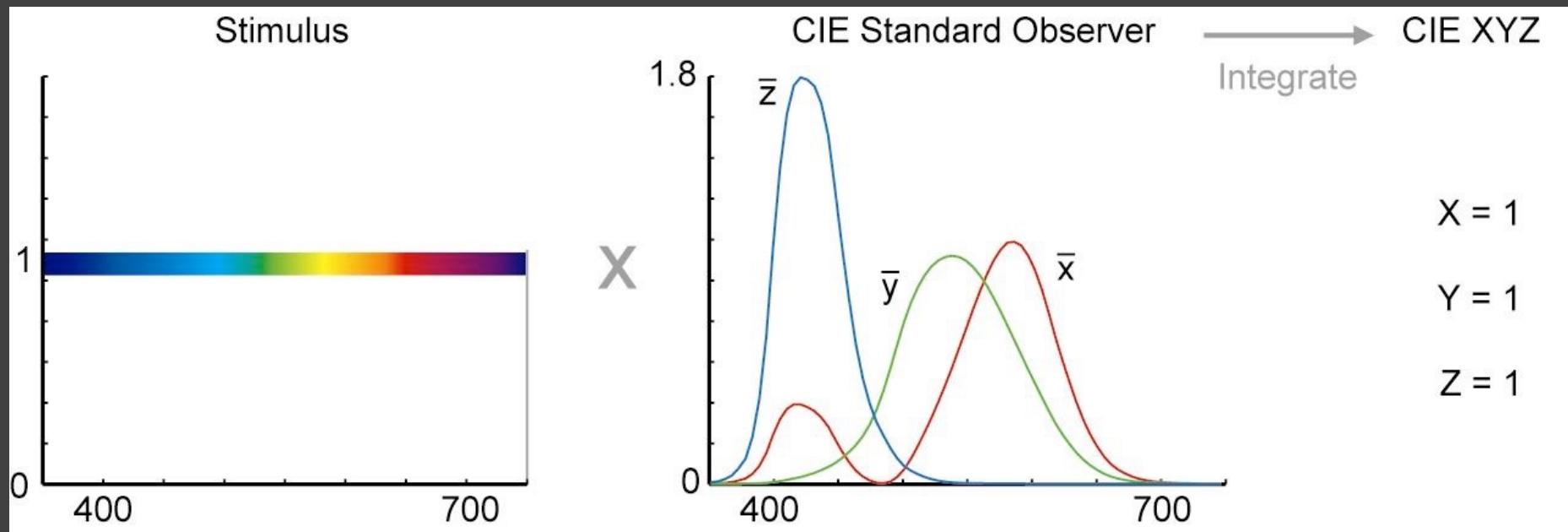
Digital cameras



CIE XYZ Color Space

Standardized in 1931 to mathematically represent tri-stimulus response.

"Standard observer" response curves

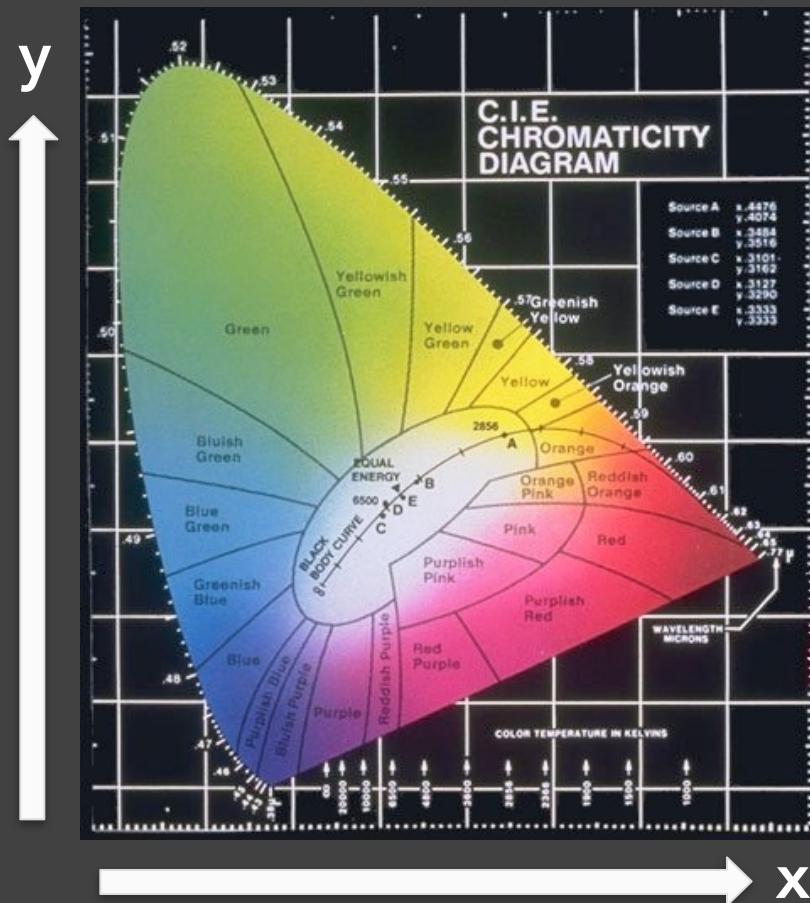


CIE Chromaticity Diagram

Colorfulness vs. Brightness

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

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

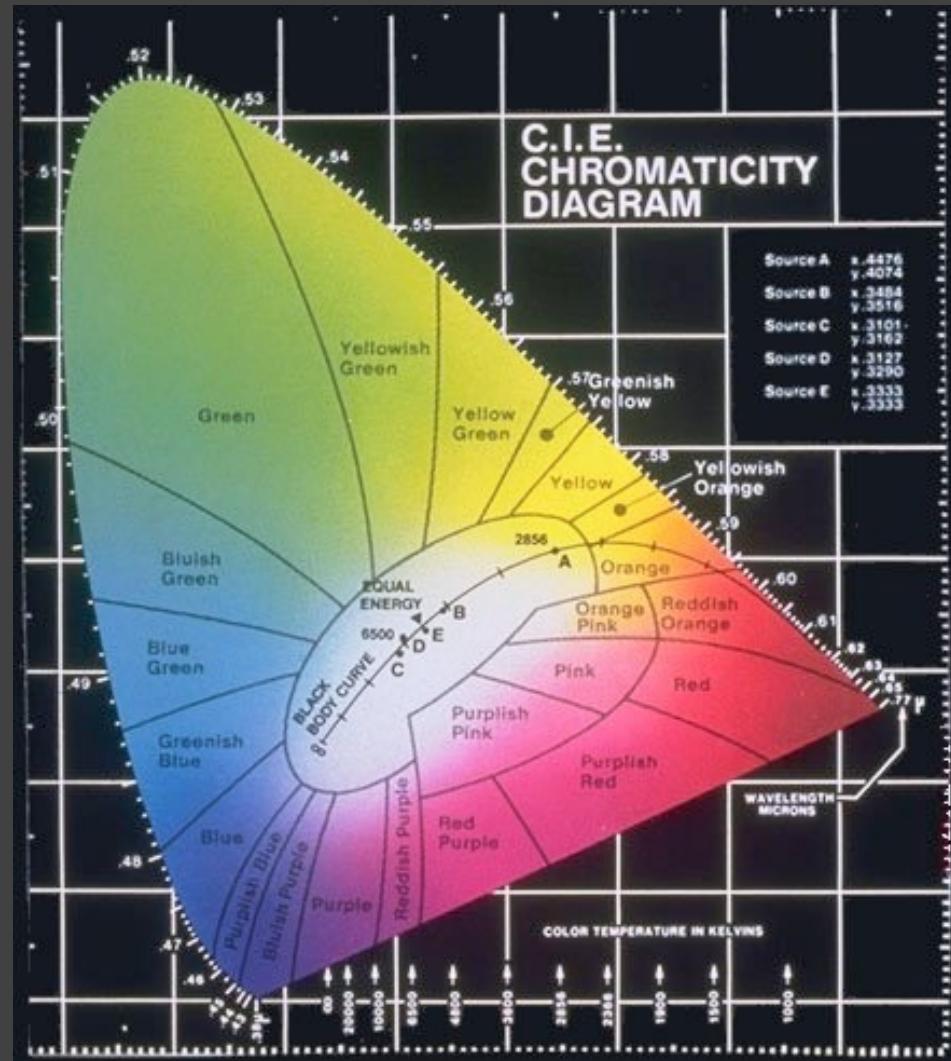


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

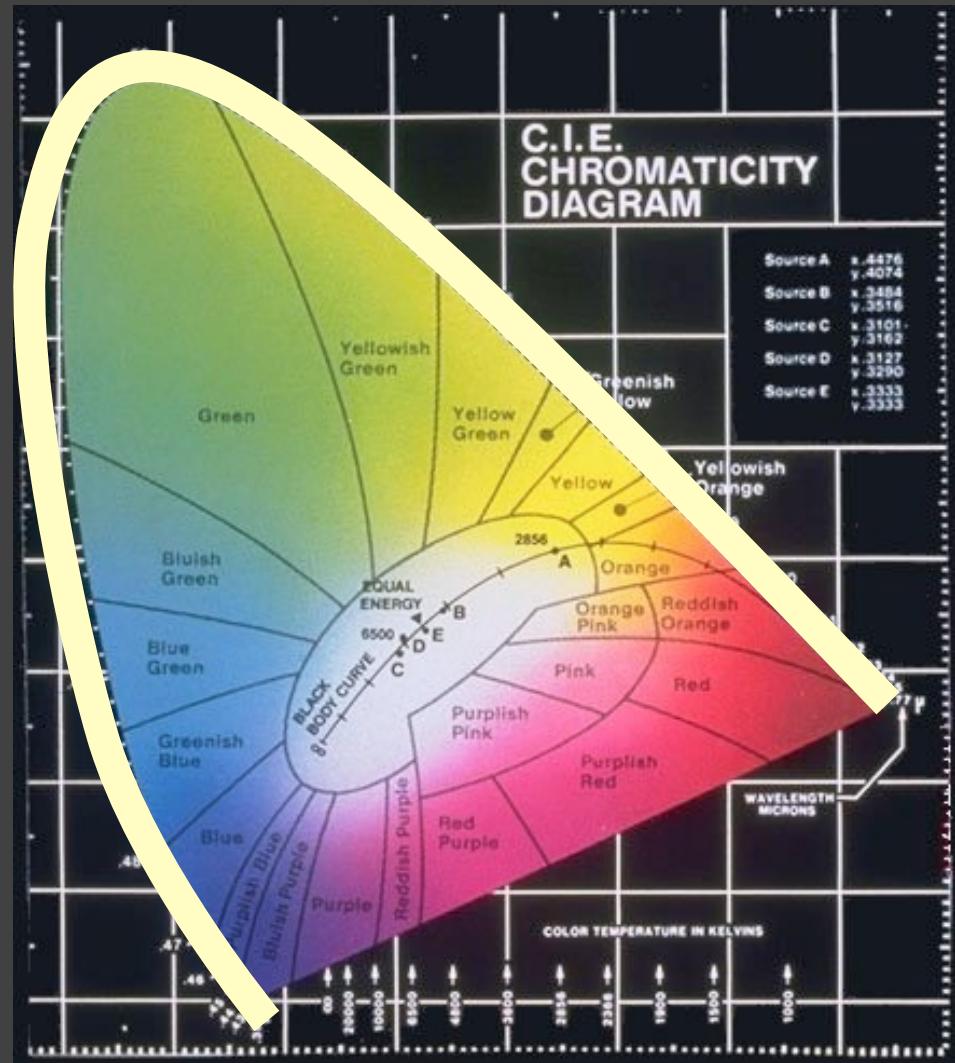


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

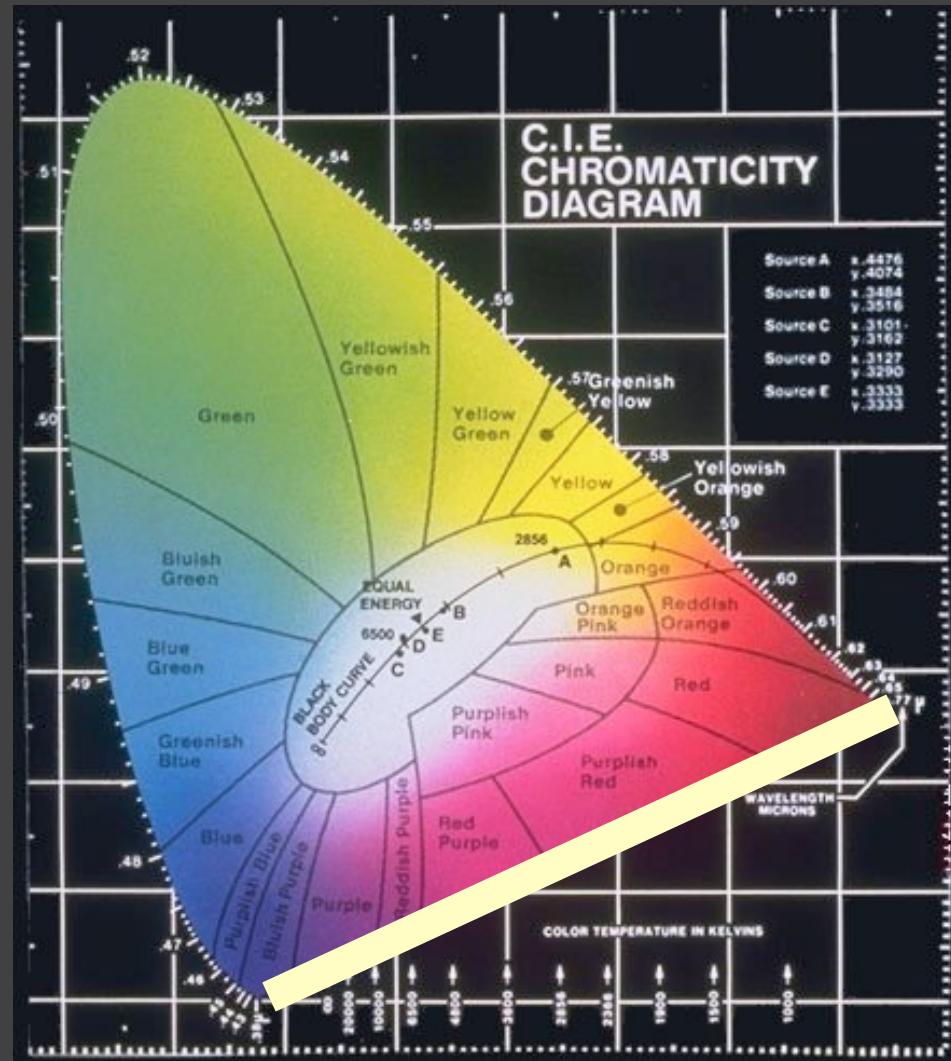


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

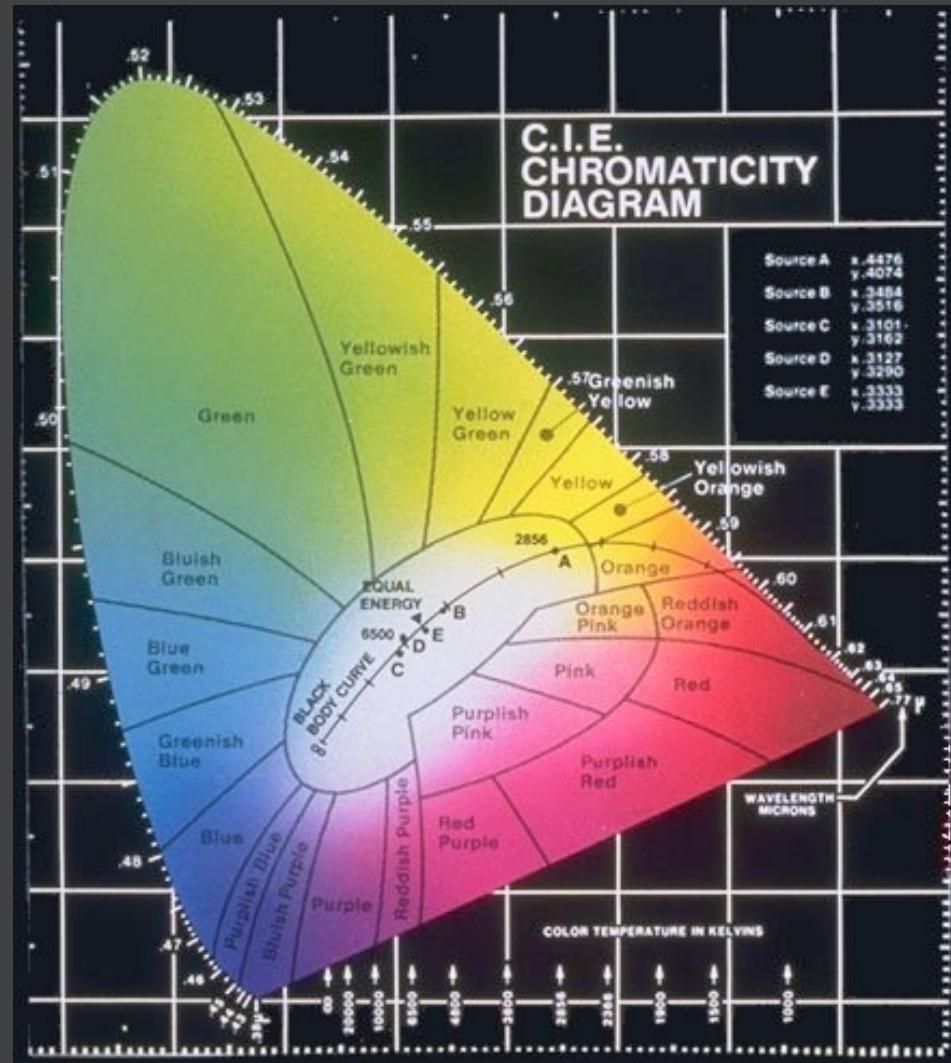


CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

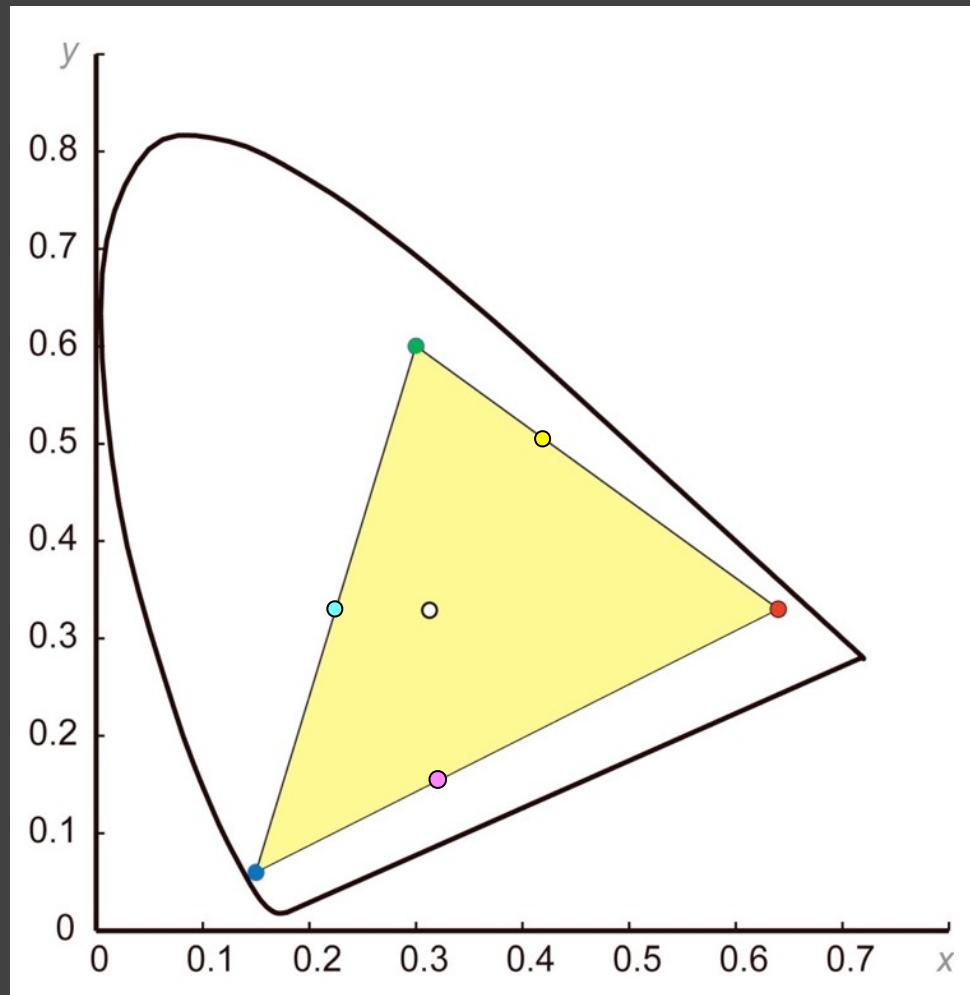


Display Gamuts

Typically defined by:

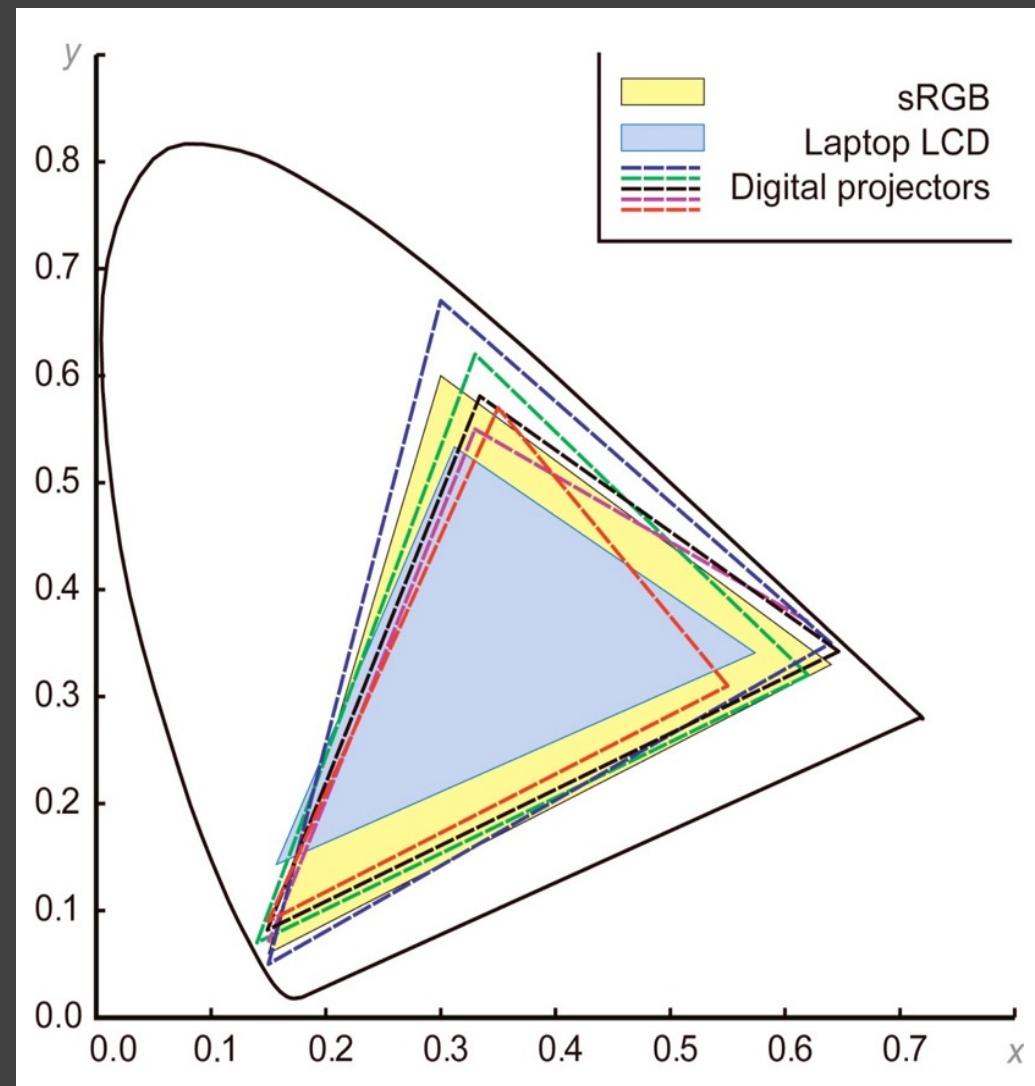
3 Colorants

Convex region



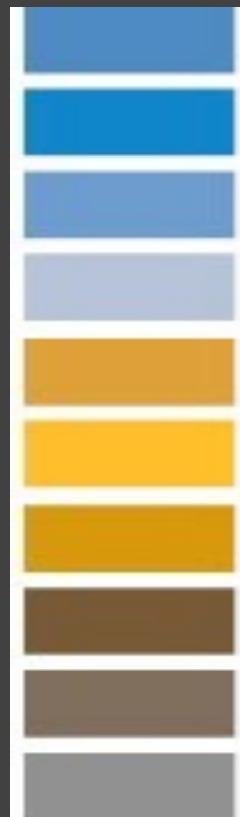
Display Gamuts

Deviations from
sRGB specification



Color Blindness

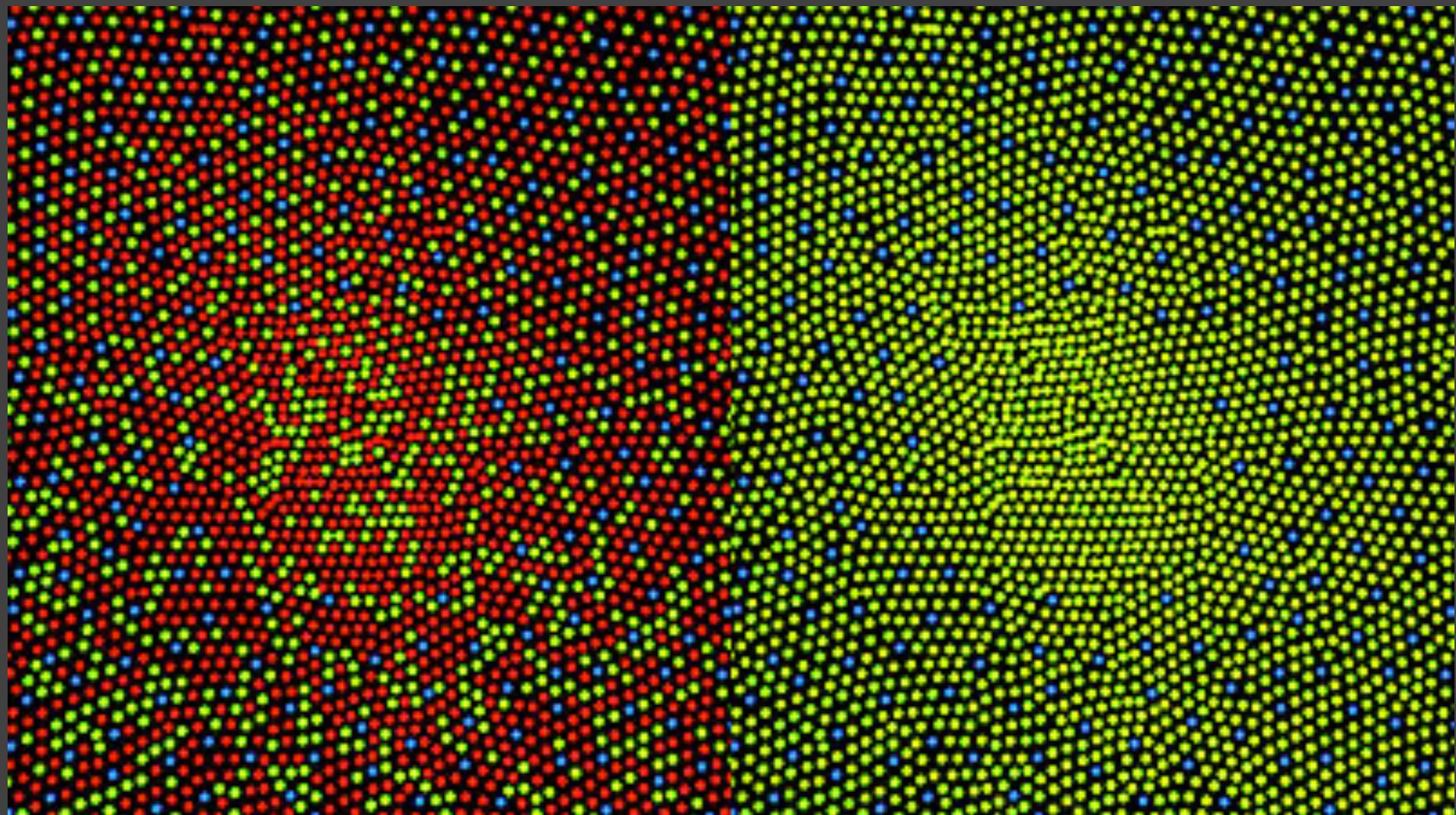
Missing one or more cones or rods in retina.



Protanope

Deuteranope

Luminance



Normal Retina

Protanopia

Color Blindness Simulators

Simulate color vision deficiencies

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

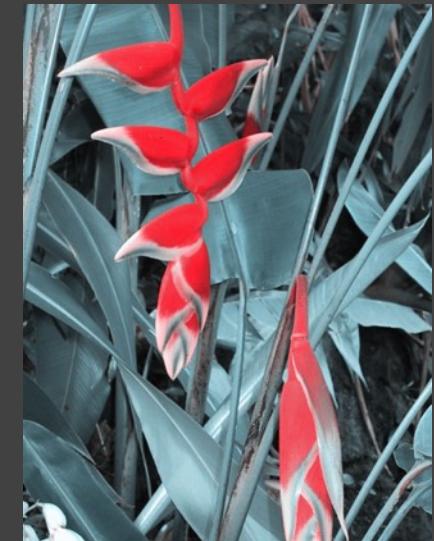
Photoshop plug-ins, etc...



Deuteranope

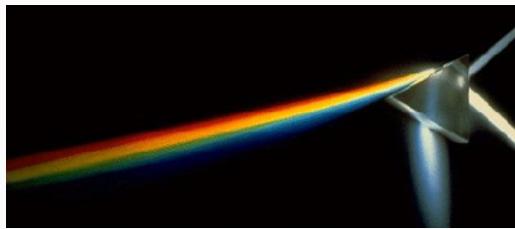


Protanope

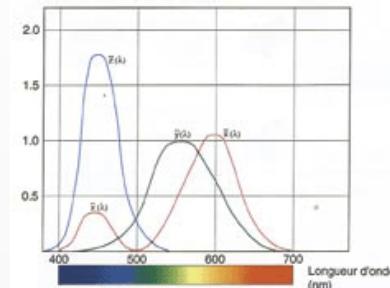


Tritanope

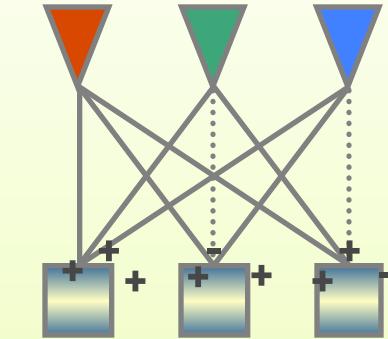
Perception of Color



Light



Cone Response



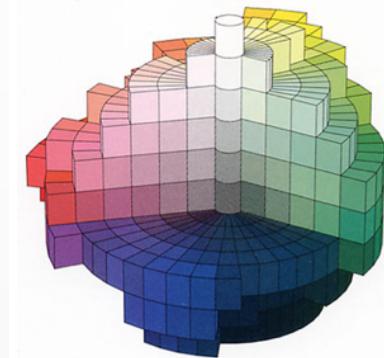
Opponent Signals

“Yellow”



Mark D. Fairchild
COLOR APPEARANCE MODELS

Color Cognition



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

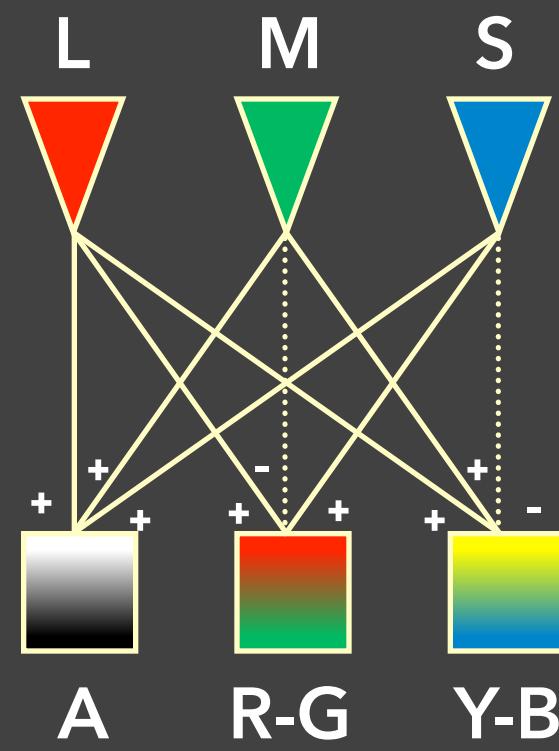
Opponent Processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Fairchild

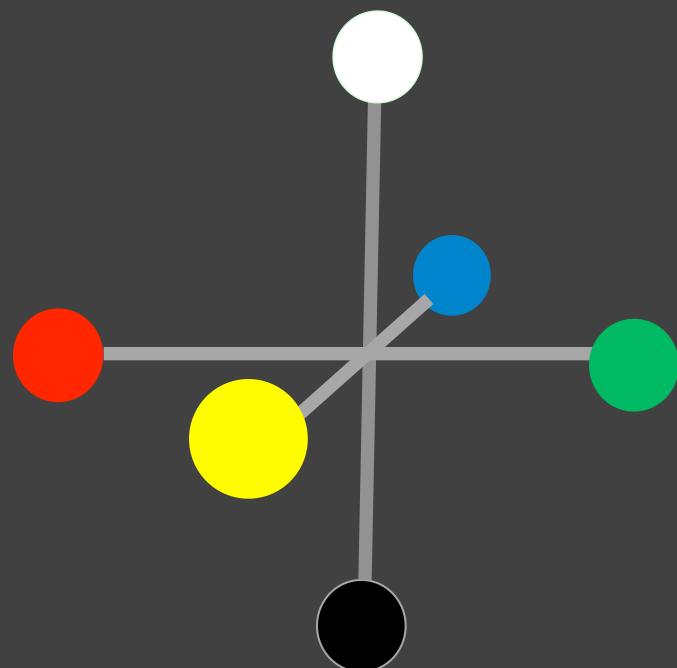
Opponent Processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



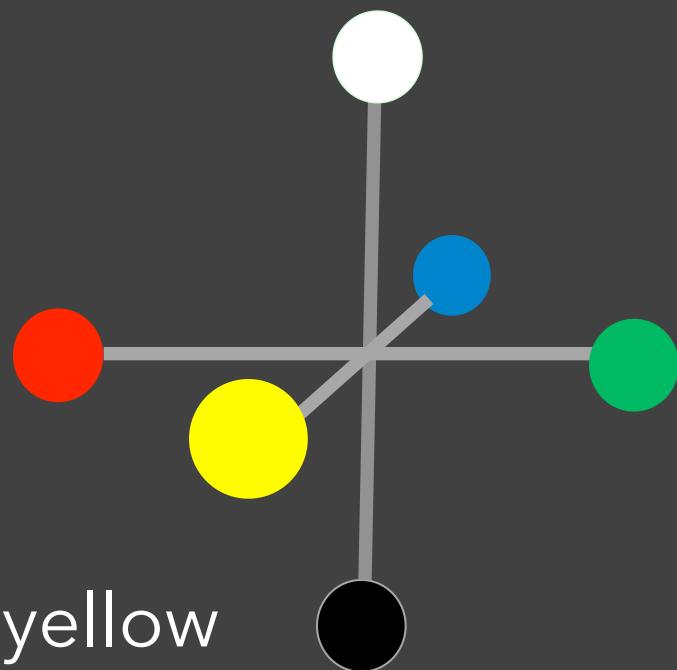
Opponent Processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Experiments:

No reddish-green, no blueish-yellow

Color after images

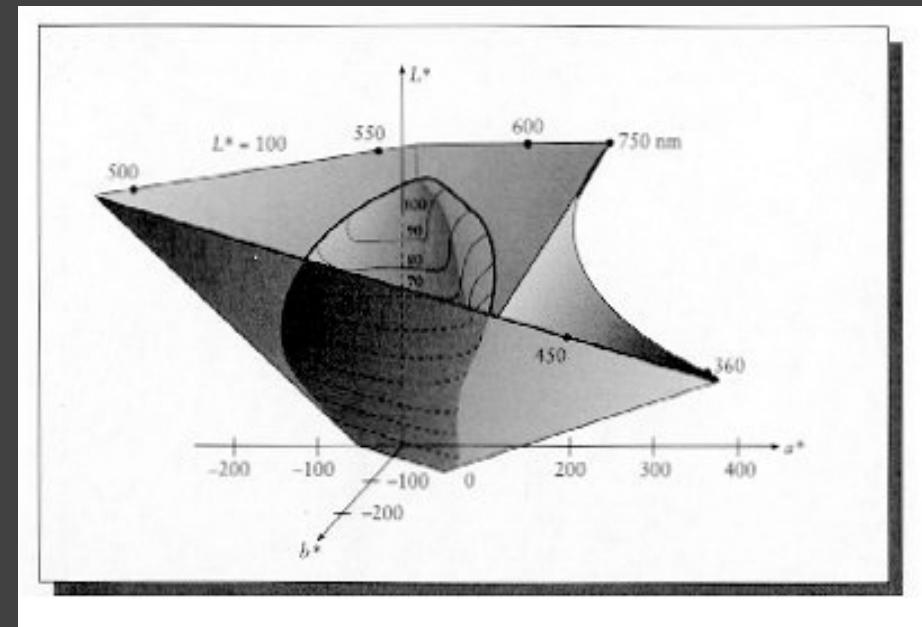
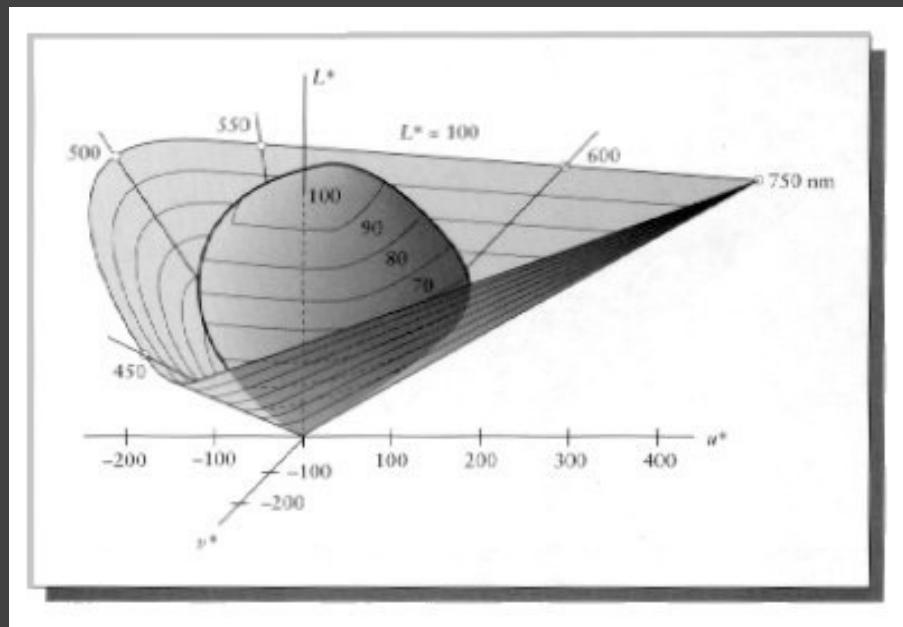




CIE LAB and LUV Color Spaces

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

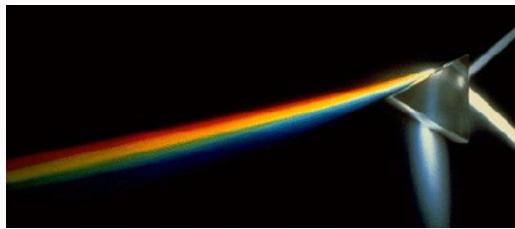
Much more perceptually uniform than sRGB!

Scaling of axes to represent “color distance”

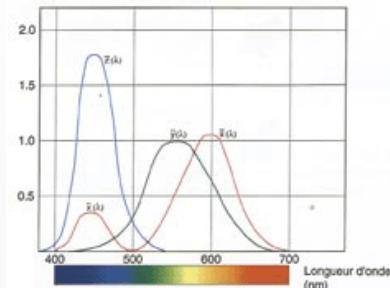
JND = Just noticeable difference (~2.3 units)

D3 includes LAB color space support!

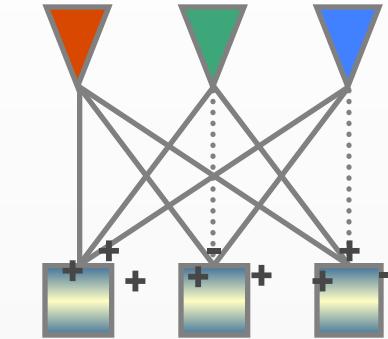
Perception of Color



Light



Cone Response



Opponent Signals

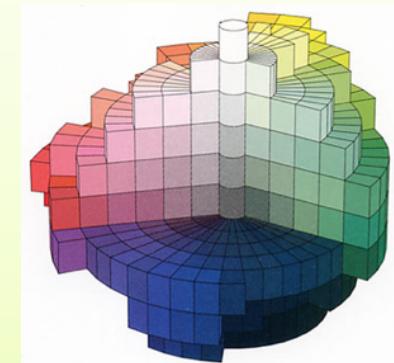
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE MODELS

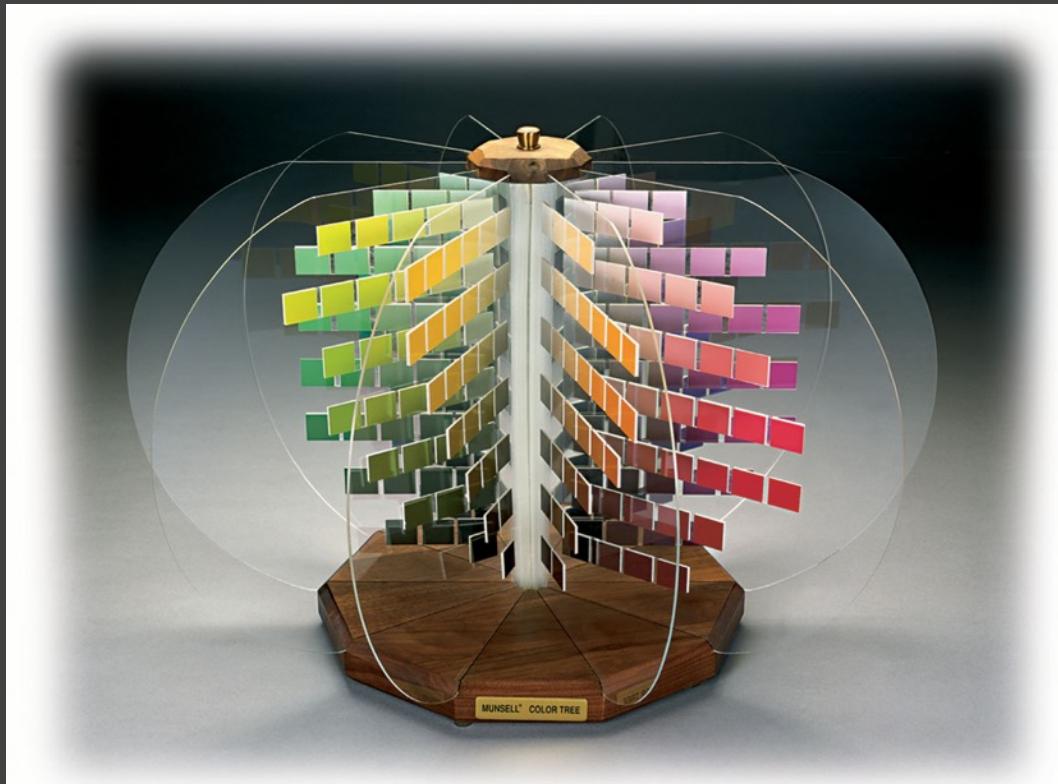
Color Appearance



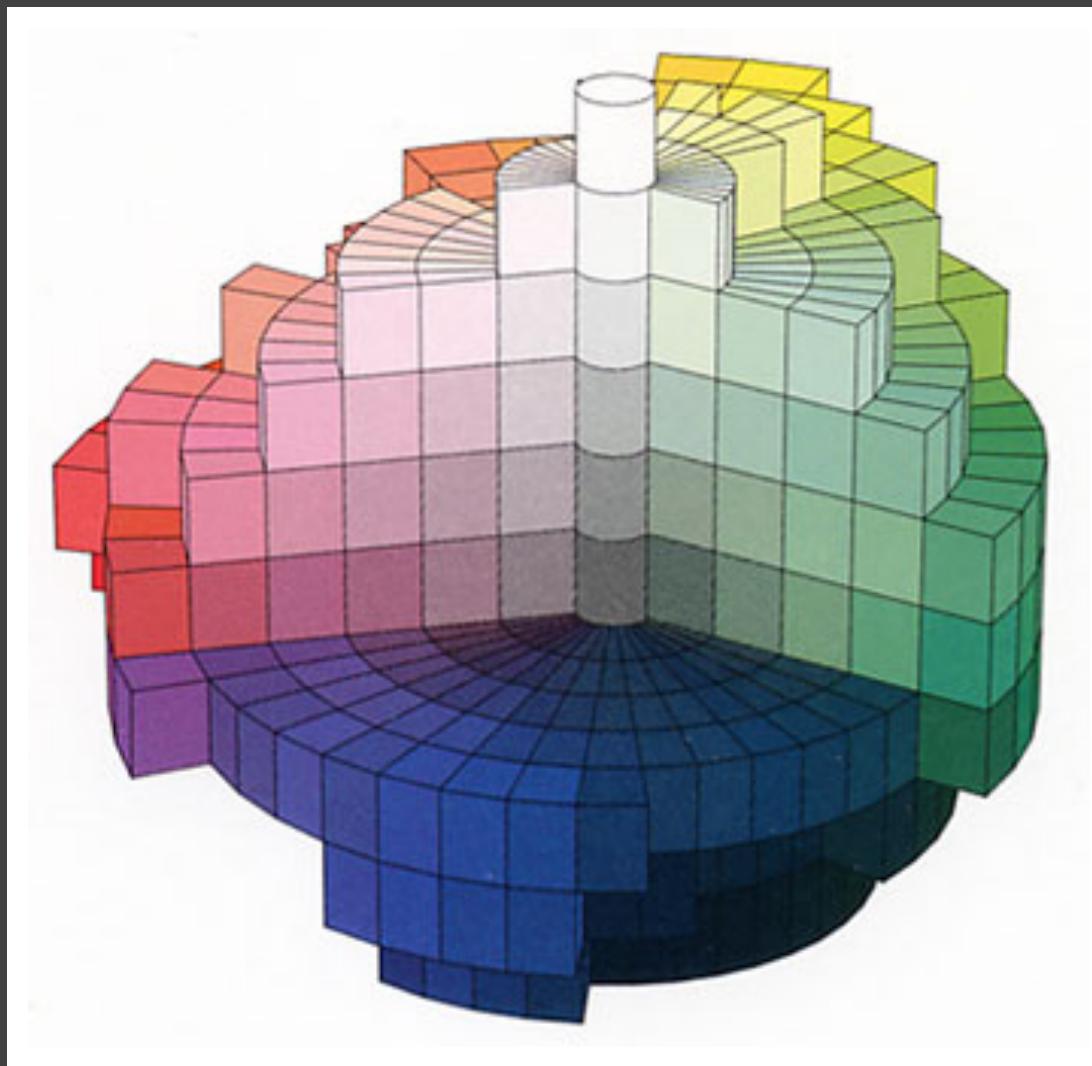
Color Perception

Albert Munsell

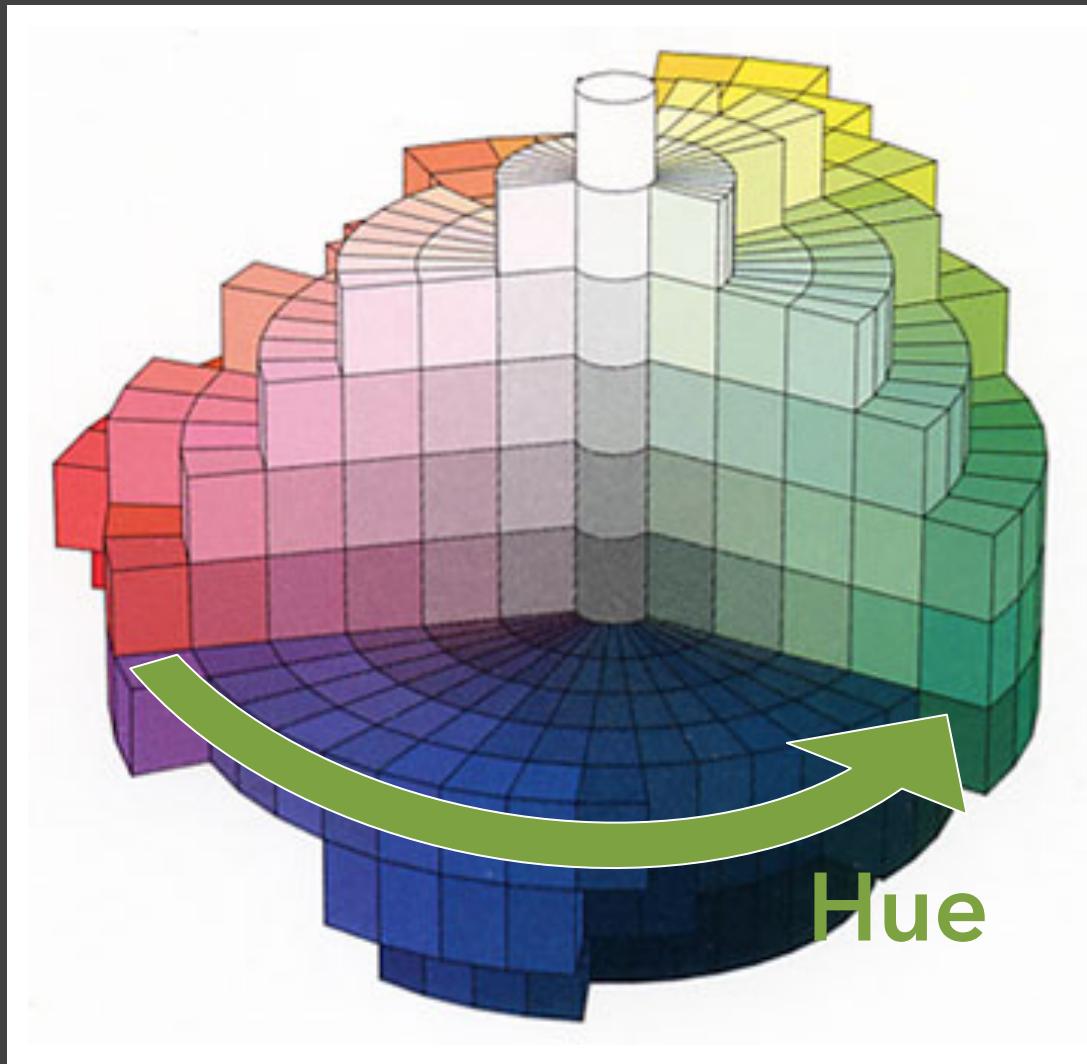
Developed the first perceptual color system based on his experience as an artist (1905).



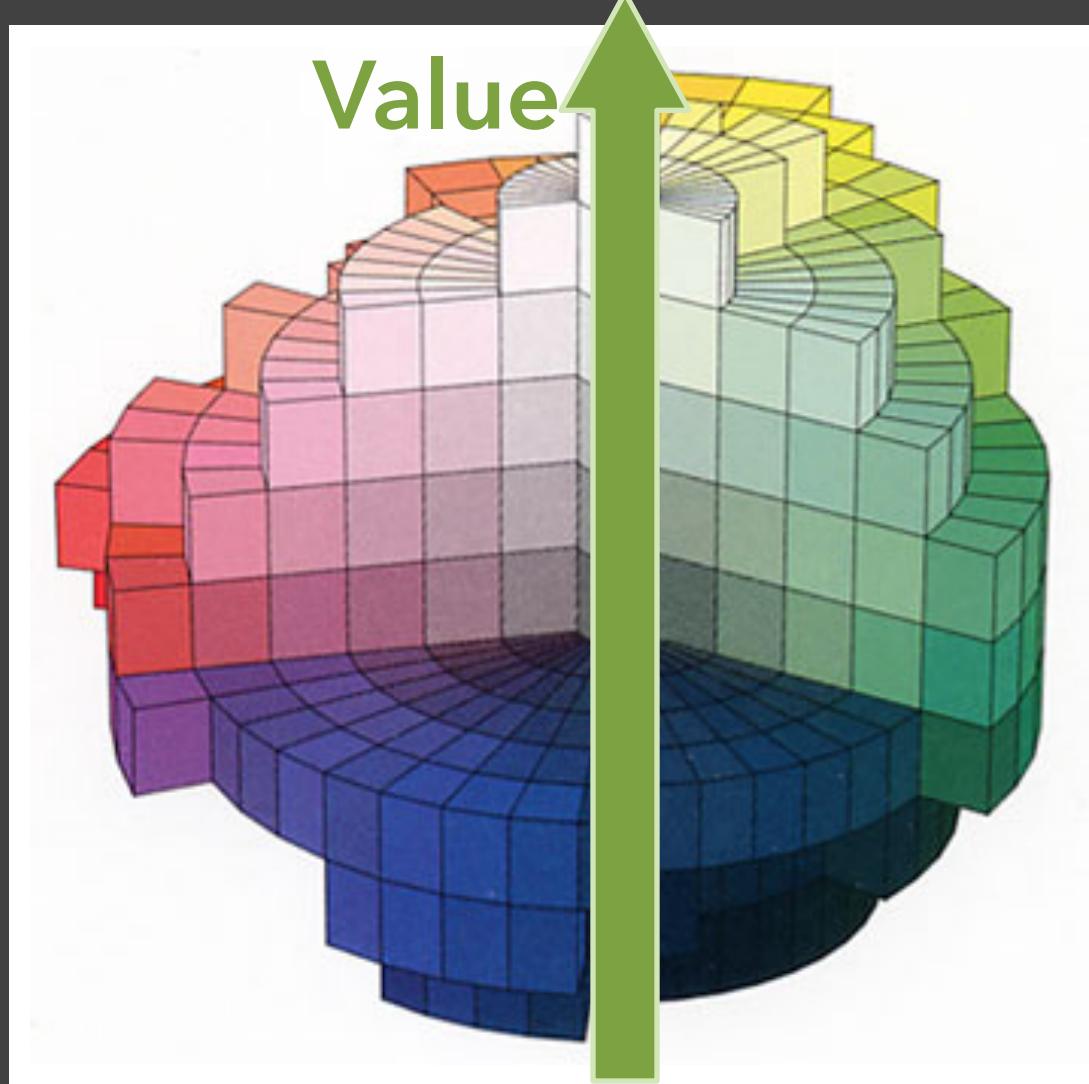
Hue, Value and Chroma



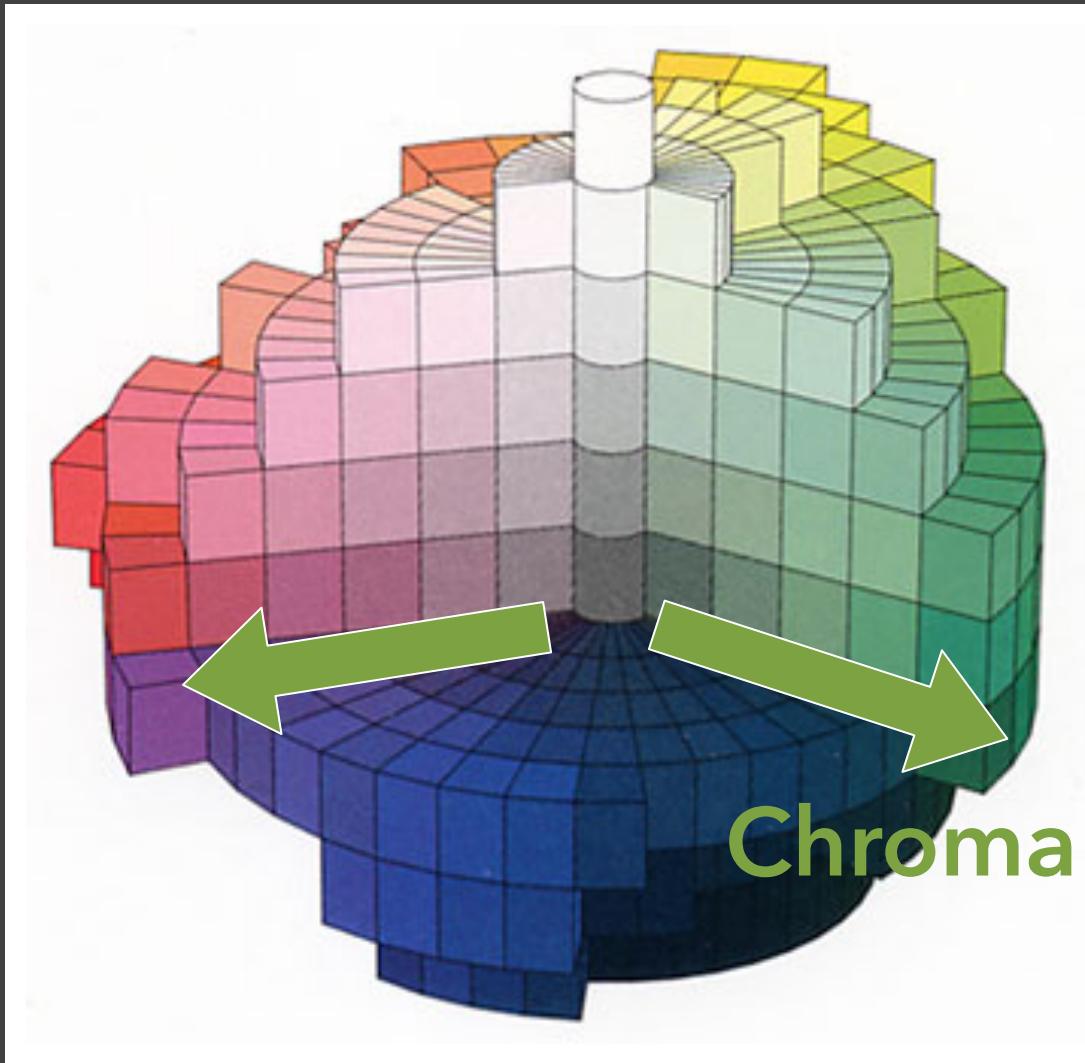
Hue, Value and Chroma



Hue, Value and Chroma



Hue, Value and Chroma



Munsell Color System

Perceptually-based

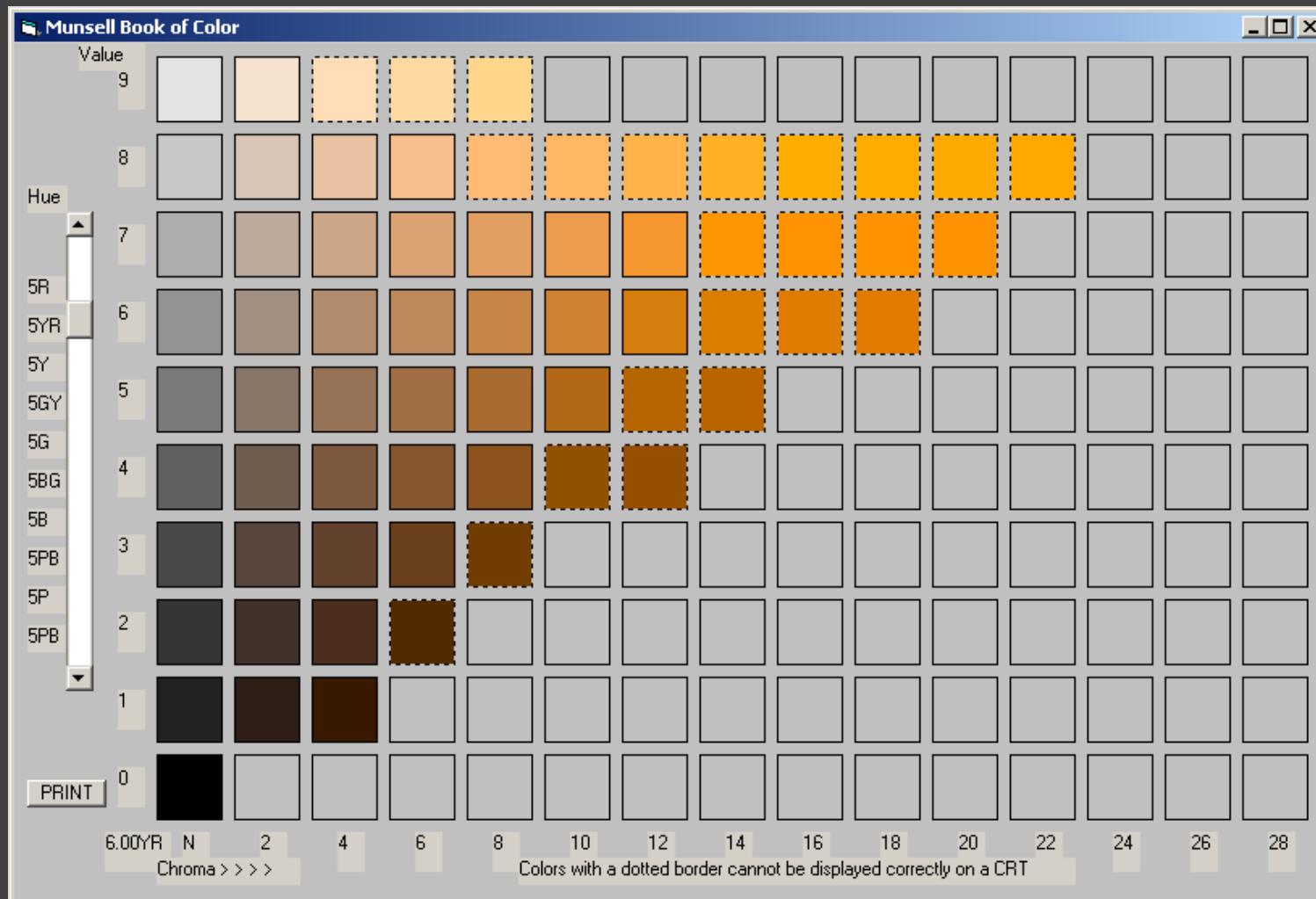
Precisely reference a color

Intuitive dimensions

Look-up table (LUT)

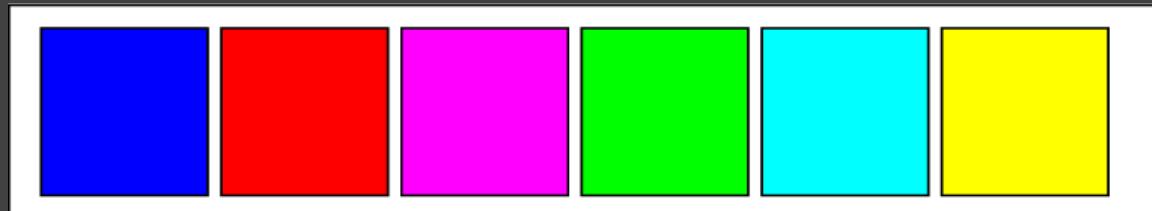


Munsell Color System



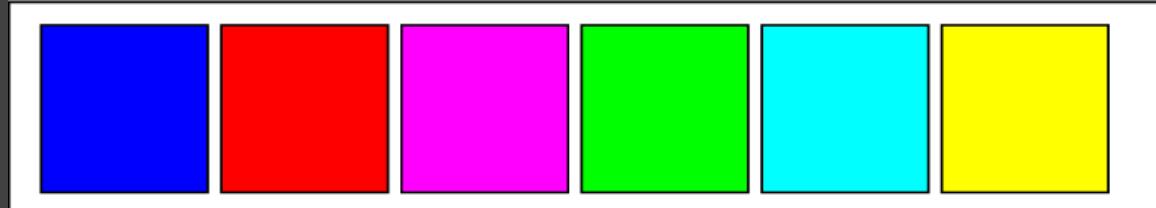
Perceptual Brightness

Color palette



Perceptual Brightness

Color palette

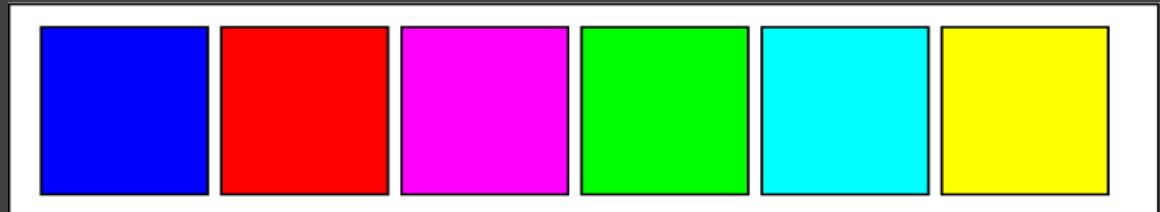


HSL Lightness
(Photoshop)



Perceptual Brightness

Color palette

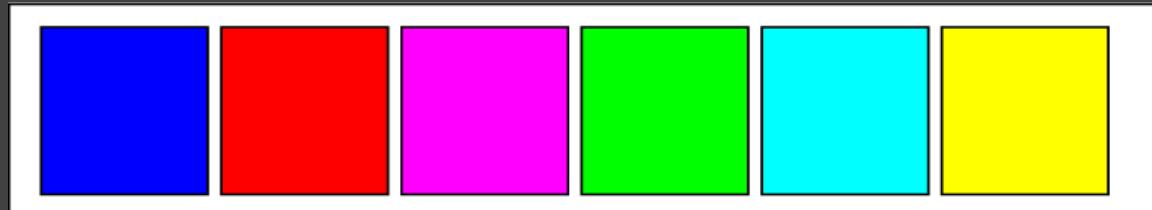


Luminance Y
(*CIE XYZ*)



Perceptual Brightness

Color palette

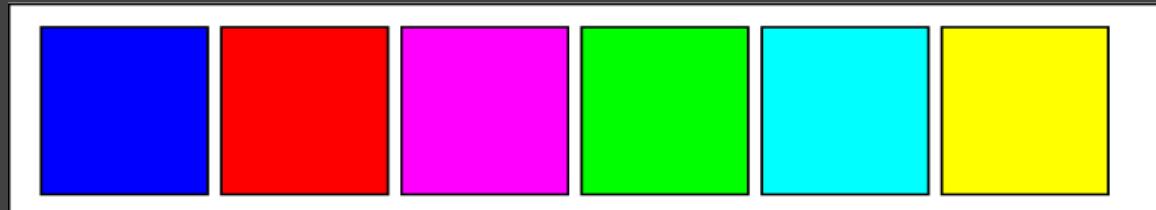


Munsell Value



Perceptual Brightness

Color palette

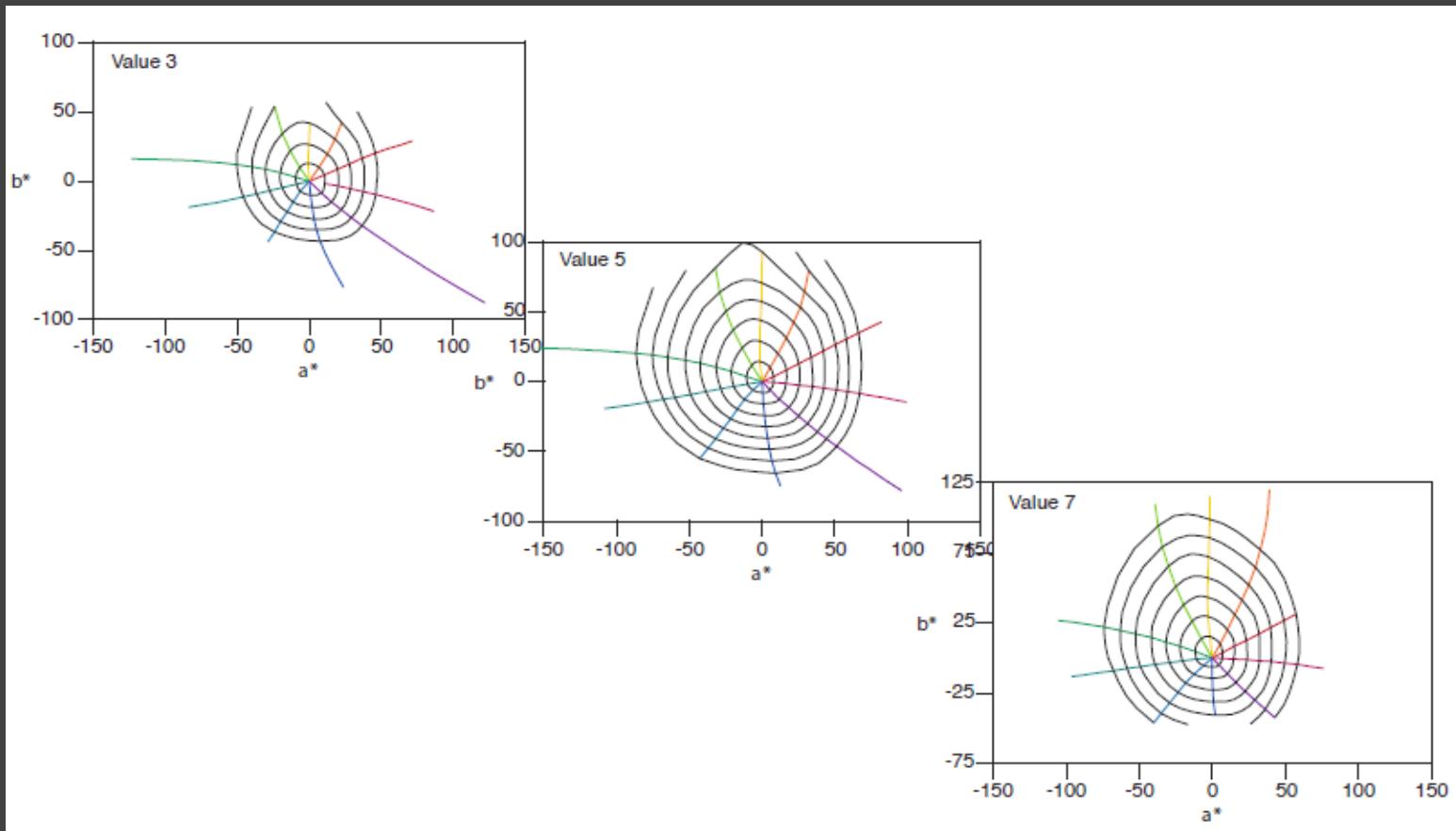


Munsell Value
 L^* (CIE LAB)

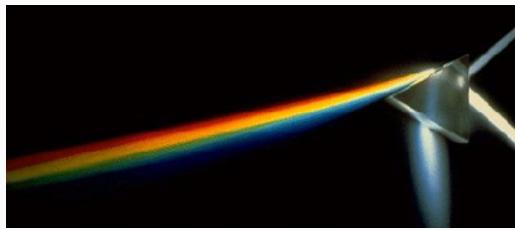


Perceptually-Uniform Color Space

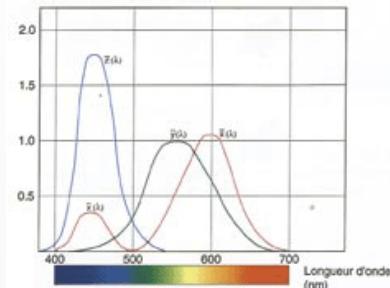
Munsell colors in CIE LAB coordinates



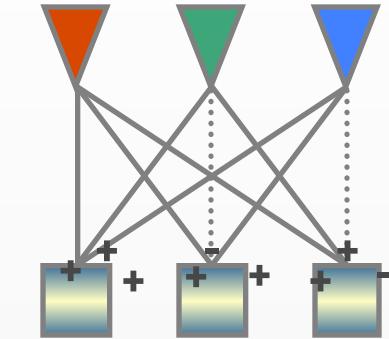
Perception of Color



Light



Cone Response



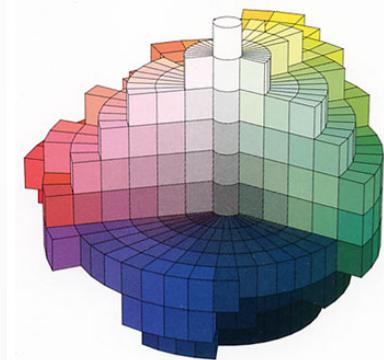
Opponent Signals

“Yellow”



Mark D. Fairchild
COLOR APPEARANCE MODELS

Color Cognition



Color Perception

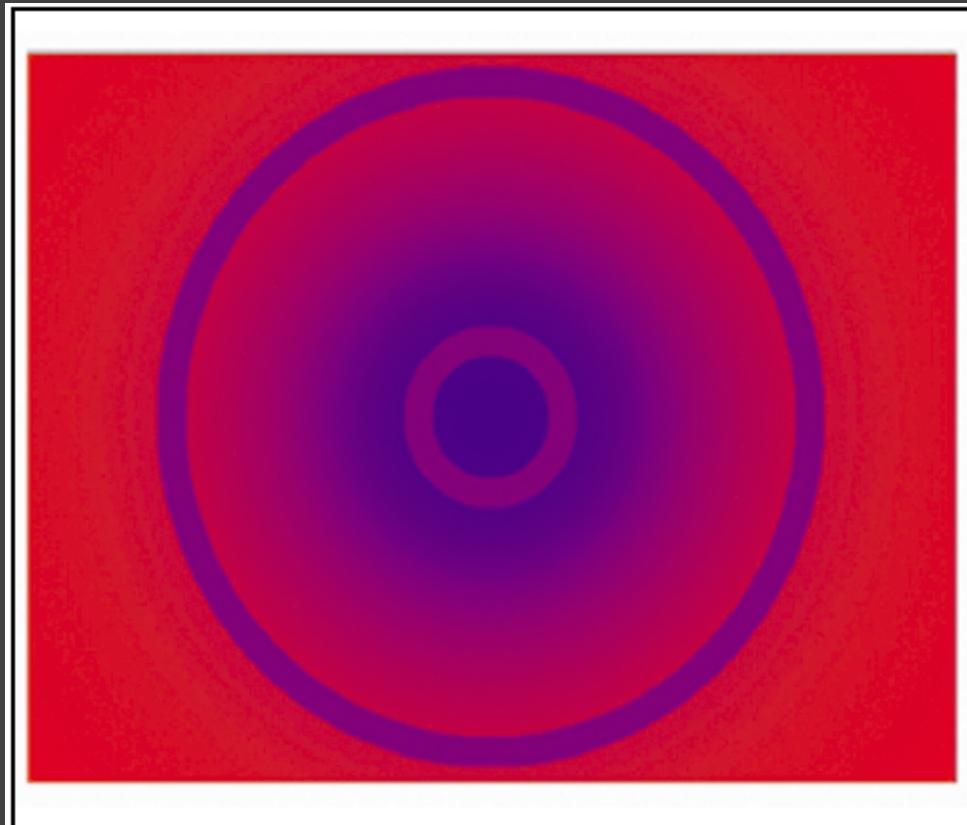
Color Appearance

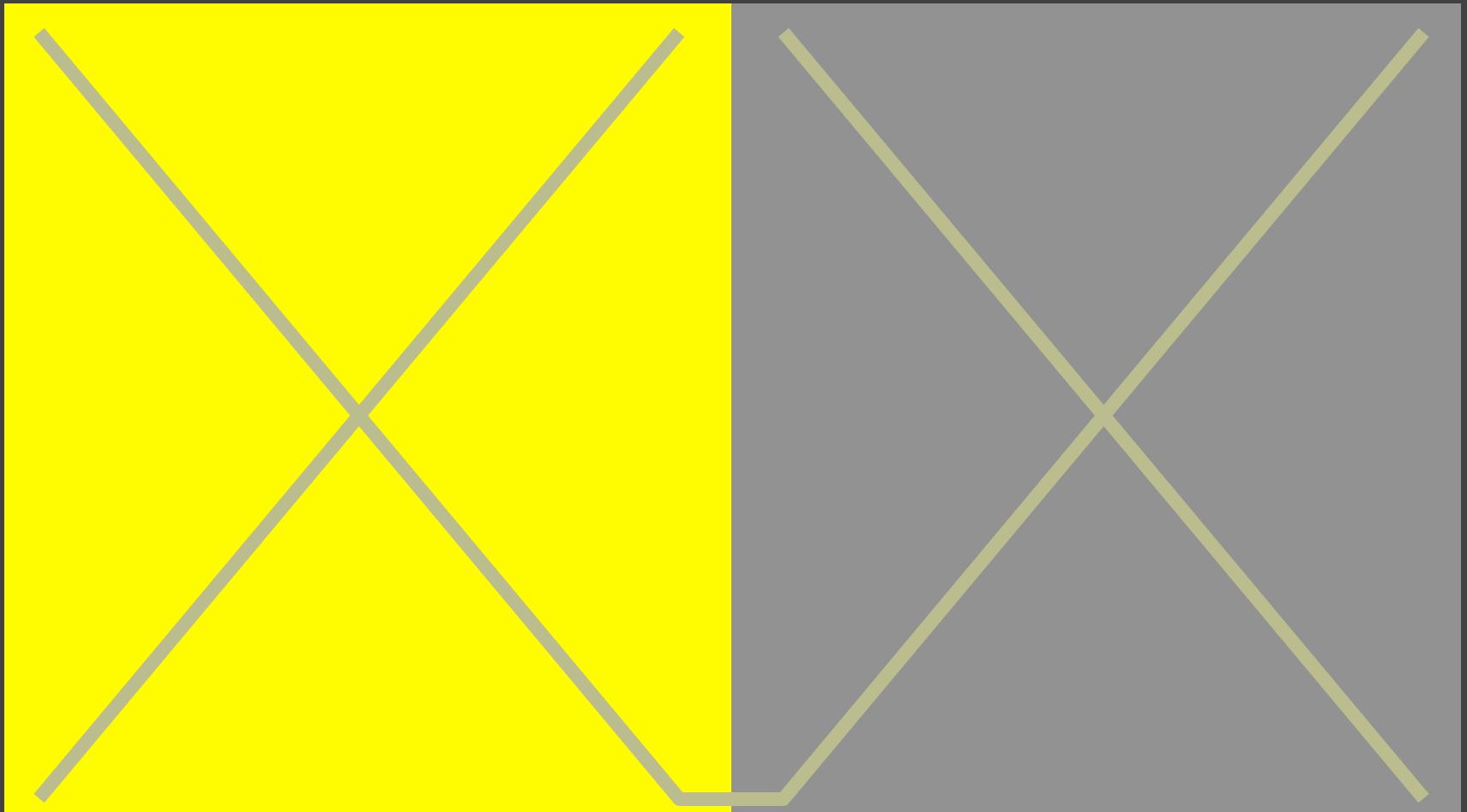
Color Appearance

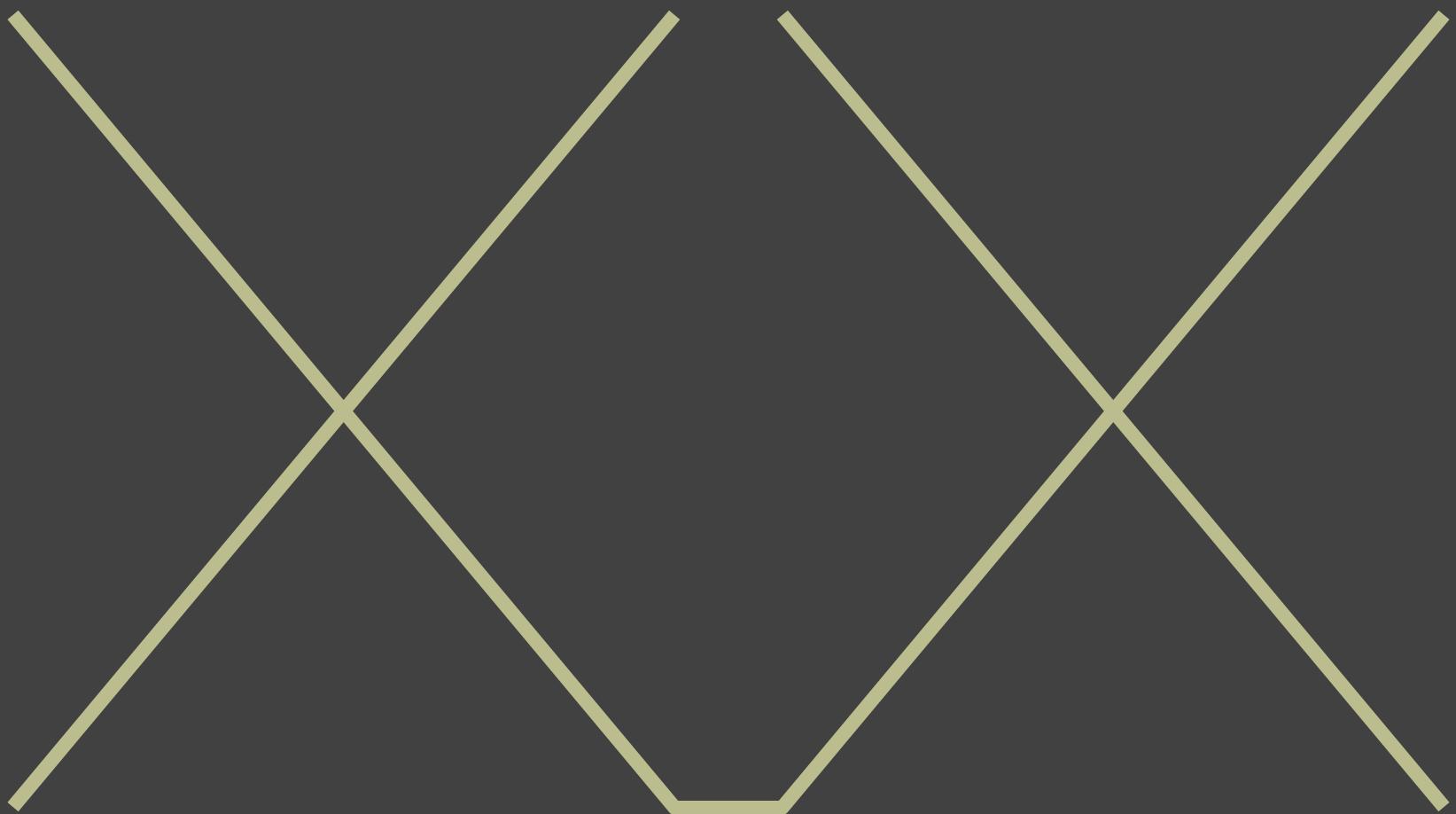
If we had a perceptually-uniform color space, can we predict how we perceive colors?

Simultaneous Contrast

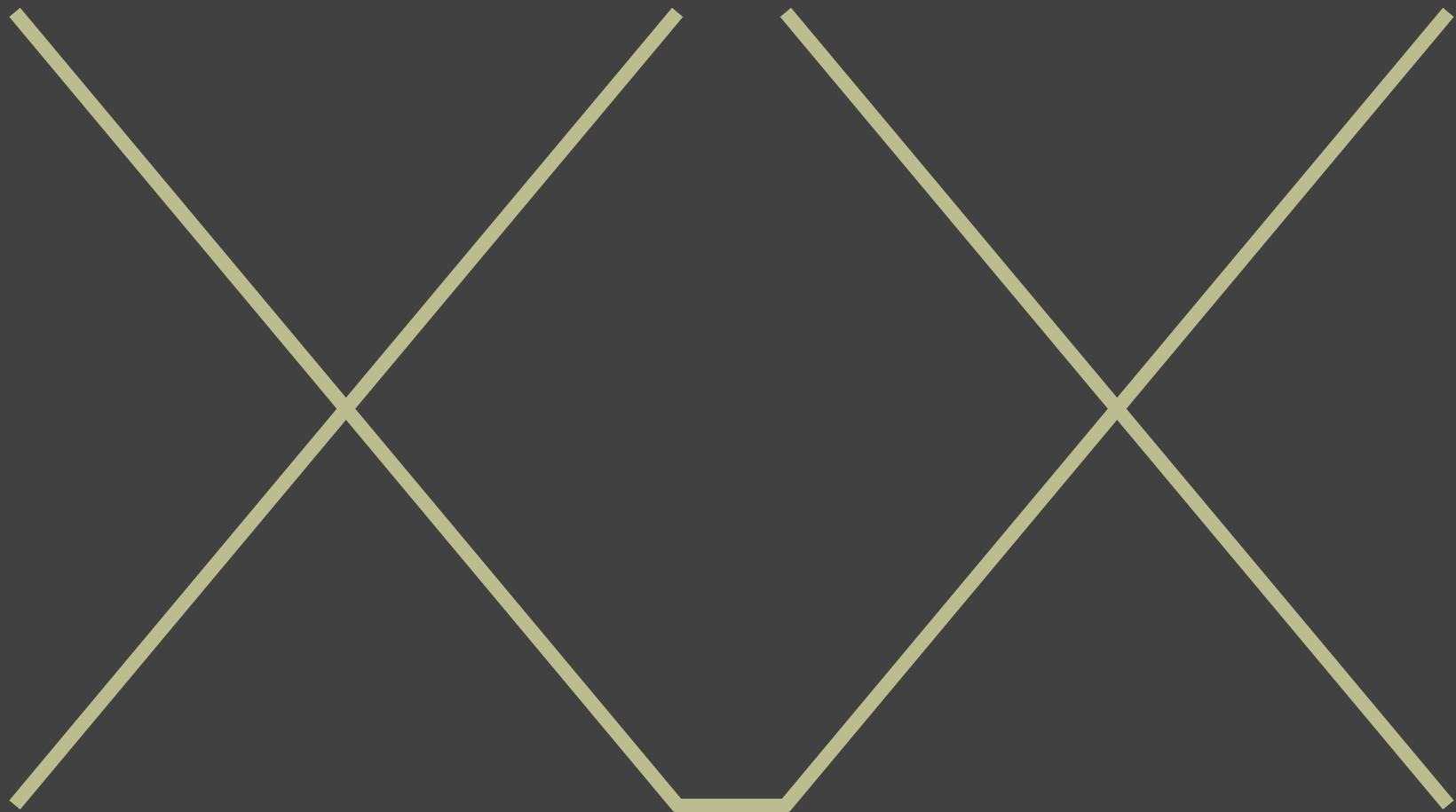
The inner and outer thin rings are in fact the same physical purple.





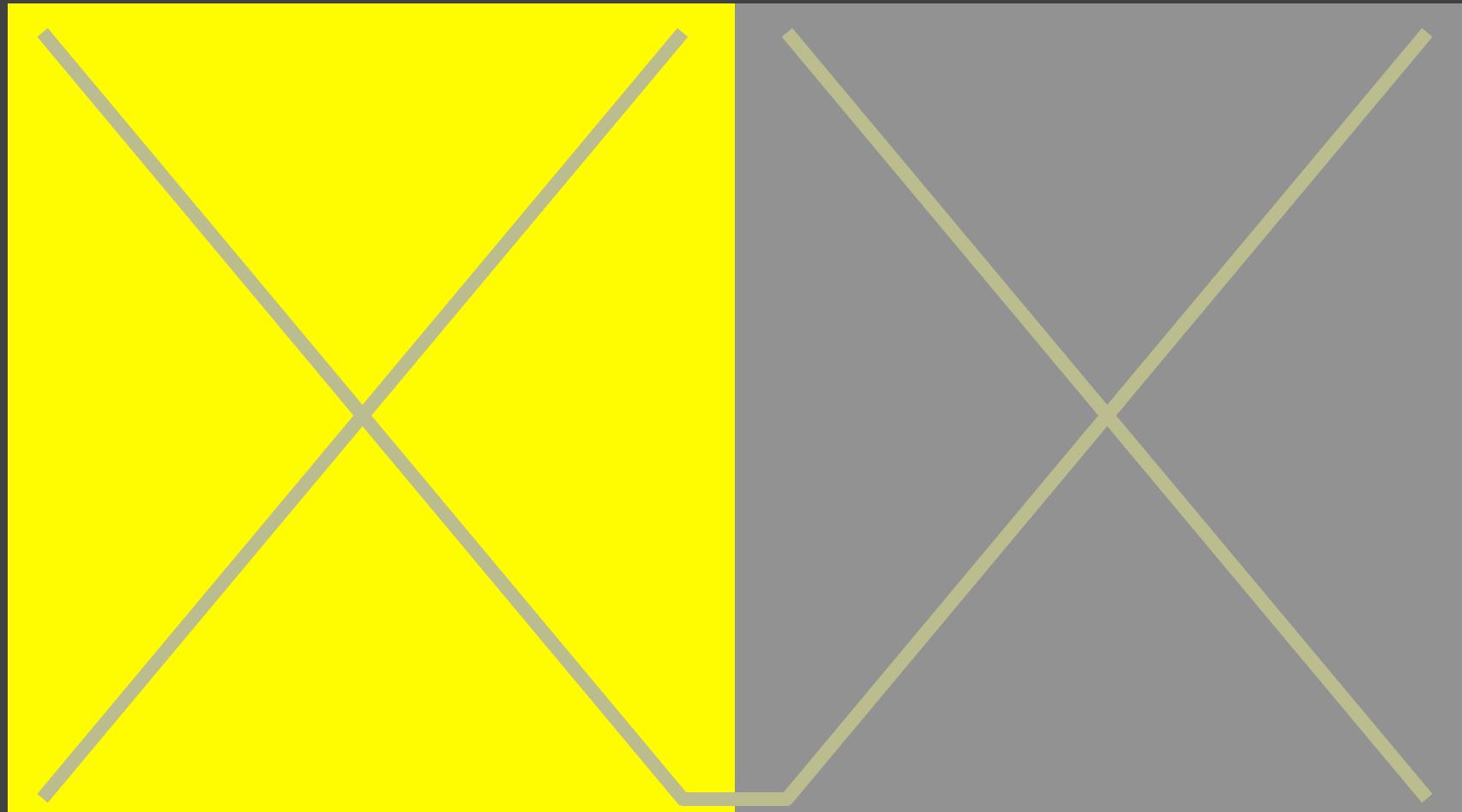


Simultaneous Contrast



Josef Albers

Simultaneous Contrast



Josef Albers

Chromatic Adaptation



Chromatic Adaptation



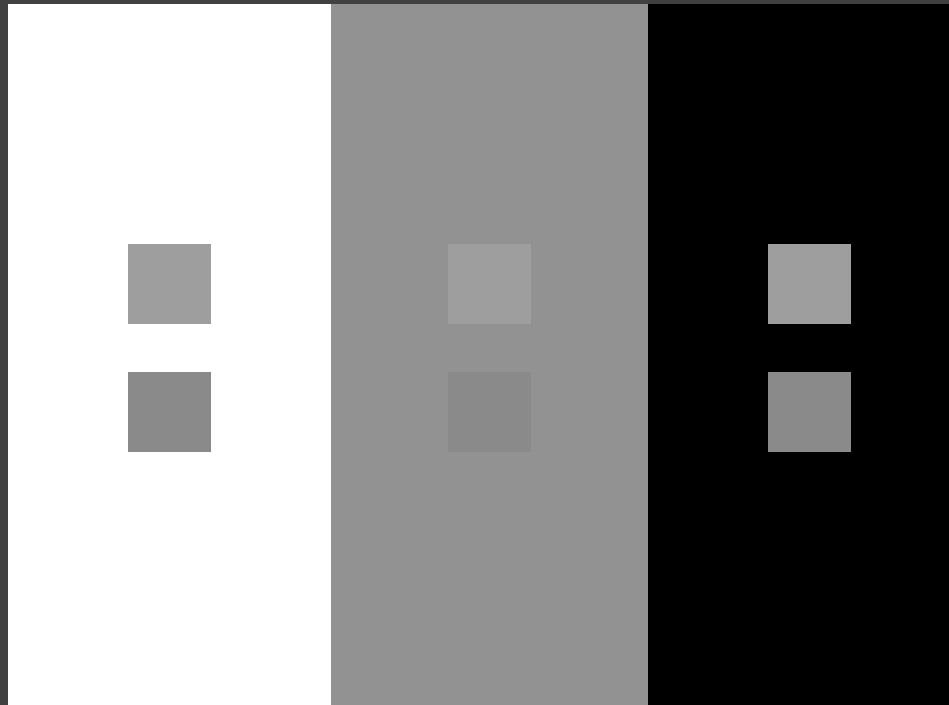
Bezold Effect

Color appearance depends adjacent colors



Crispening

Perceived difference depends on background



Color Appearance Models, Fairchild

Spreading

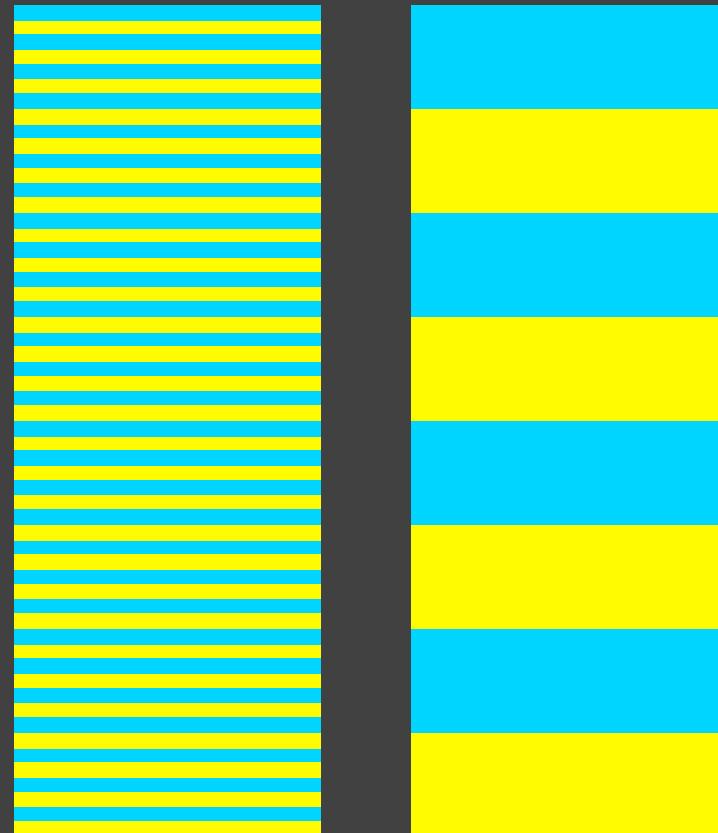
Spatial frequency

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

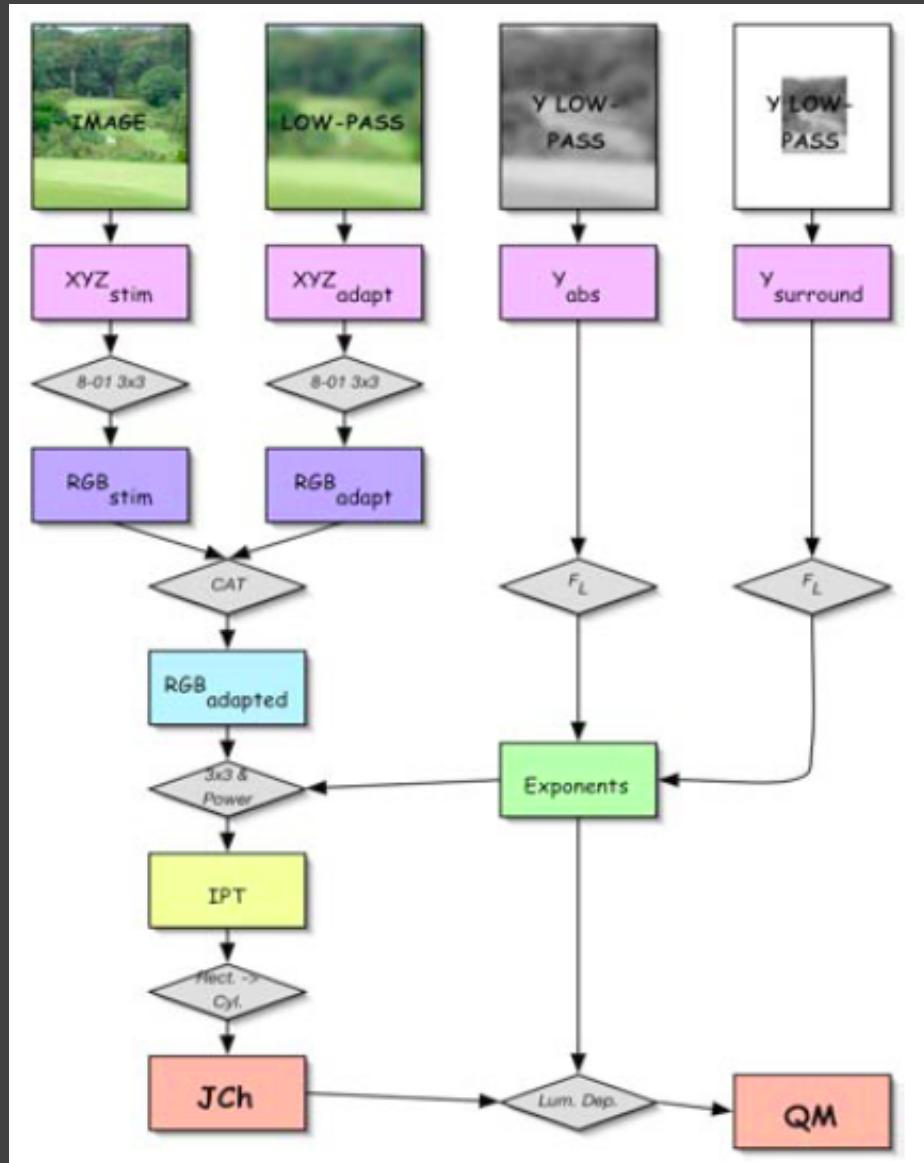
Spatial effects

Viewing angle

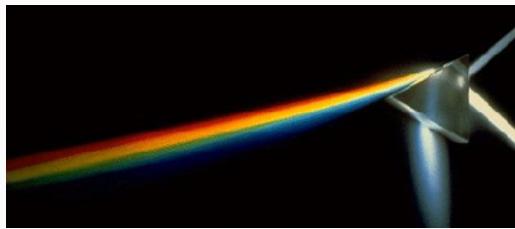
iCAM

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

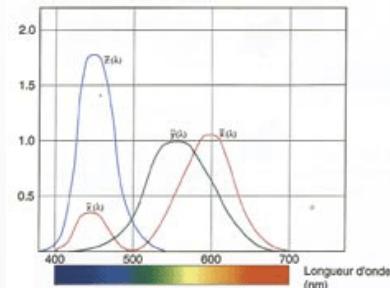
Mark Fairchild



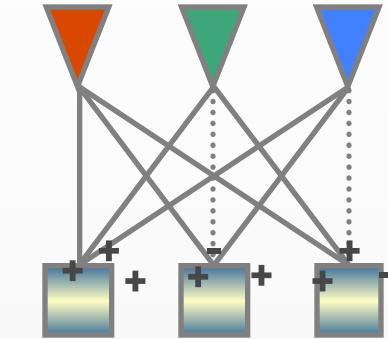
Perception of Color



Light



Cone Response



Opponent Signals

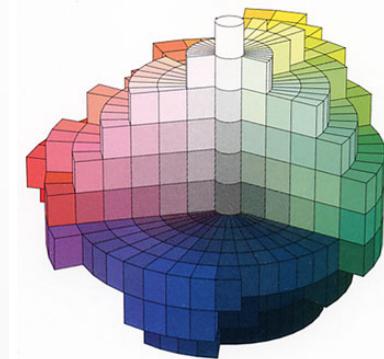
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE MODELS

Color Appearance



Color Perception

Colors according to XKCD...



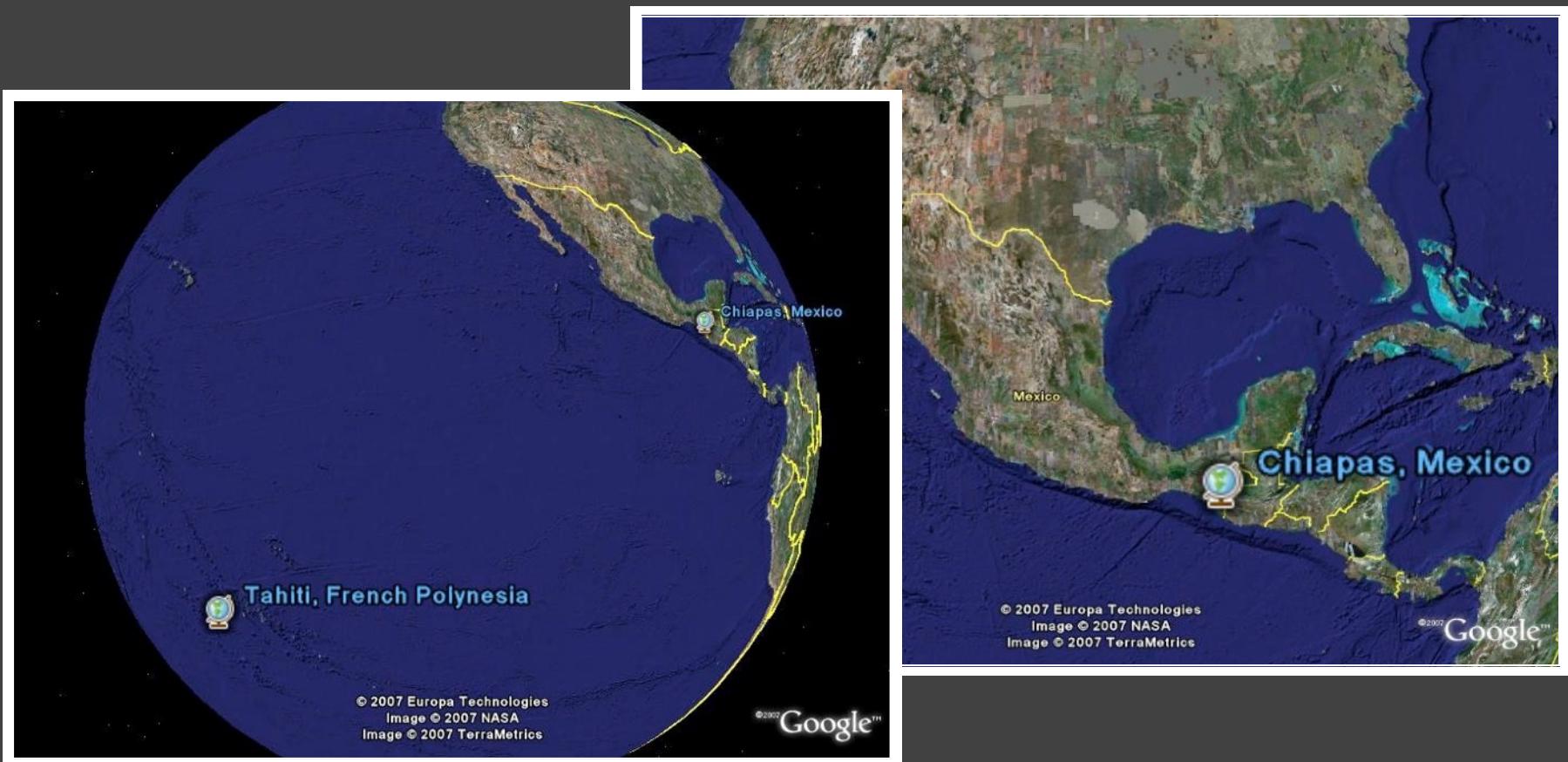
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.



Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.



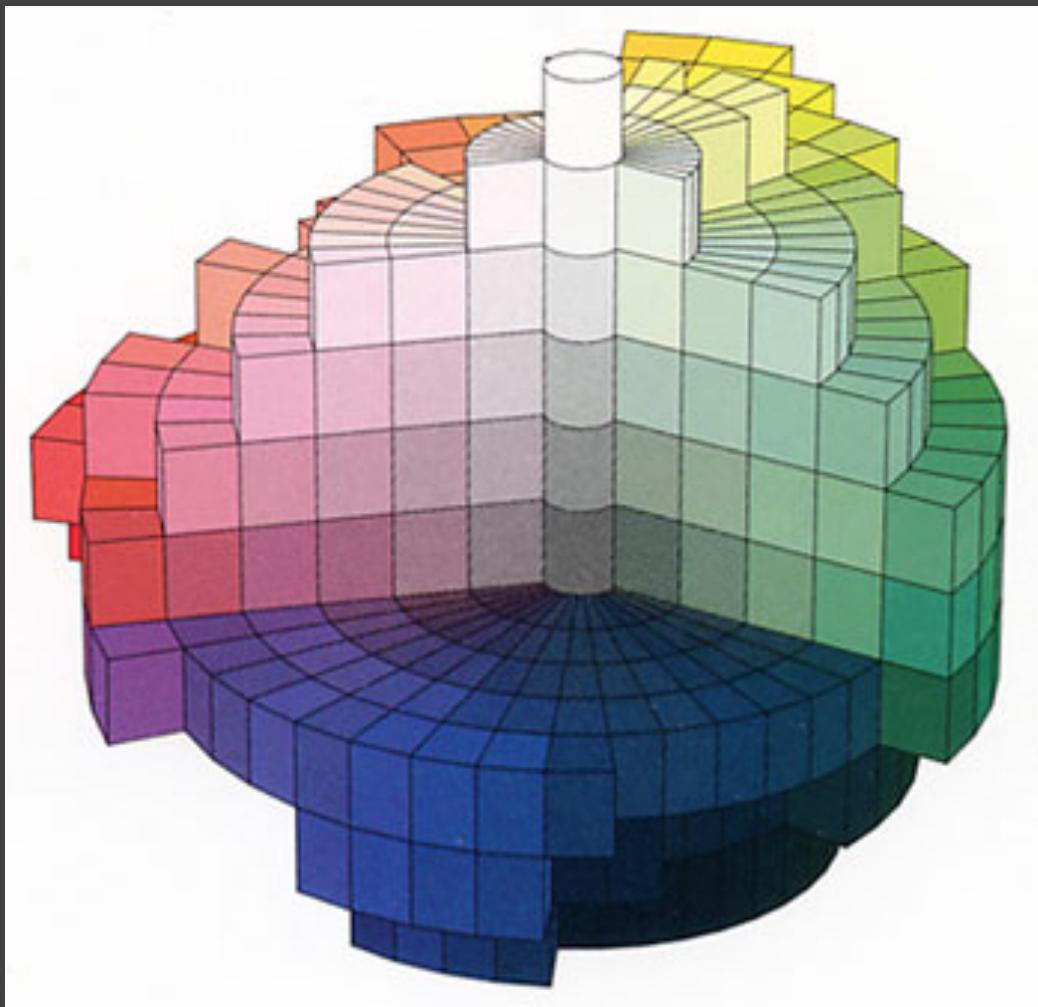
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.

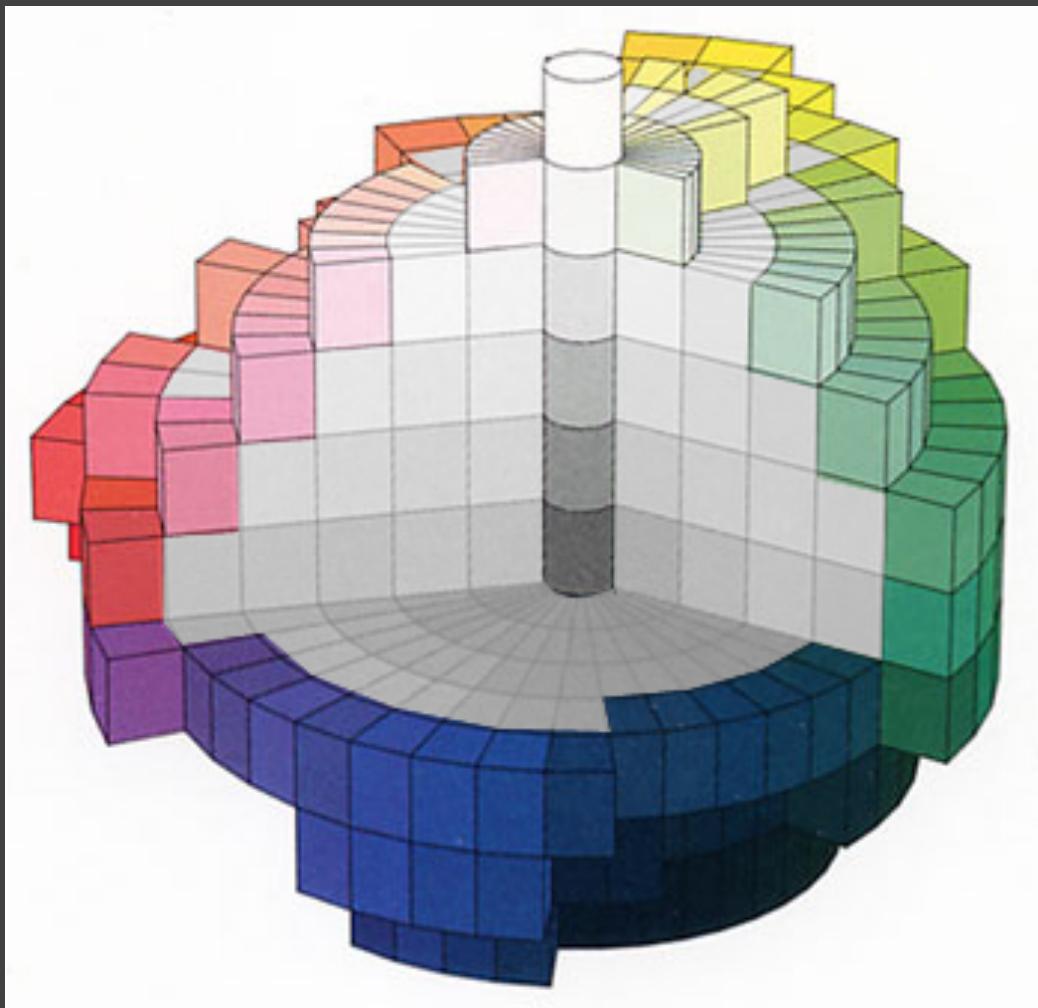
Initial study in 1969

- Surveyed speakers from 20 languages
- Literature from 69 languages

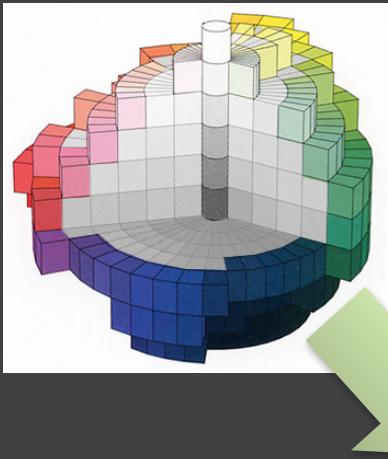
World Color Survey



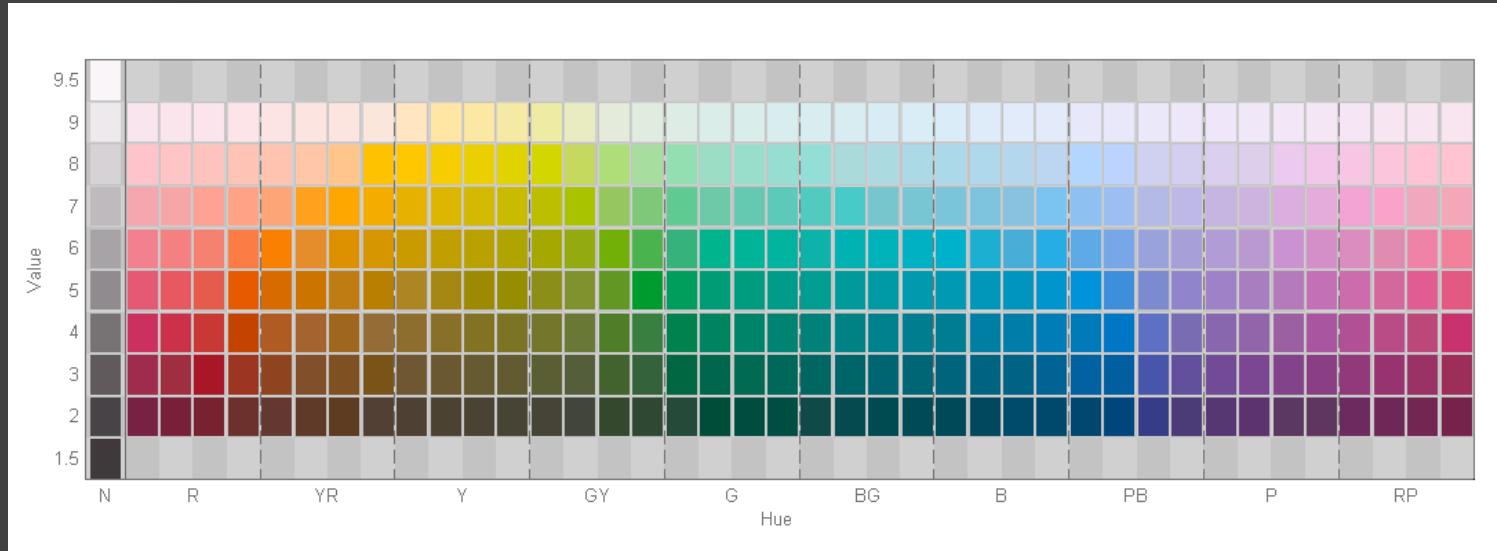
World Color Survey



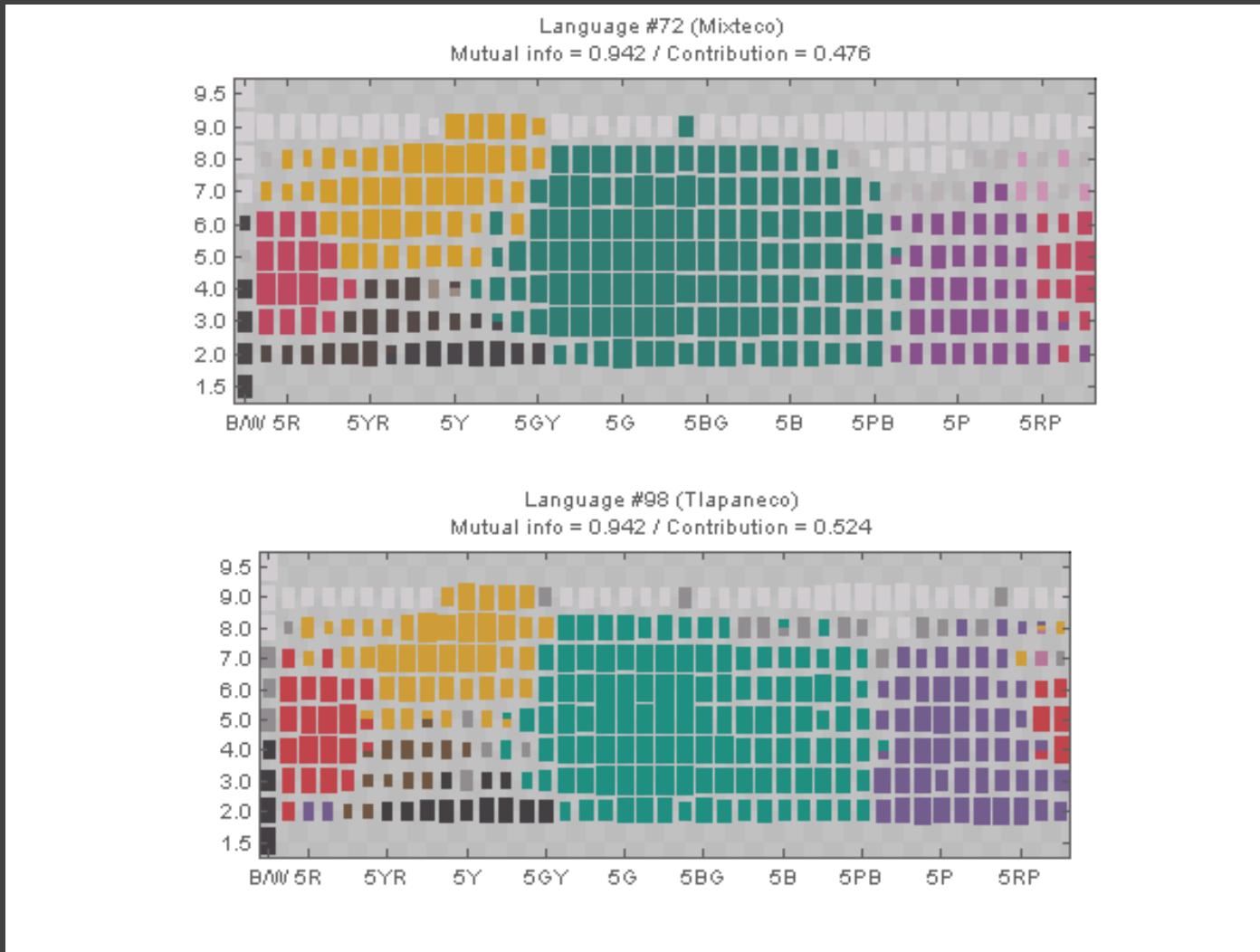
World Color Survey



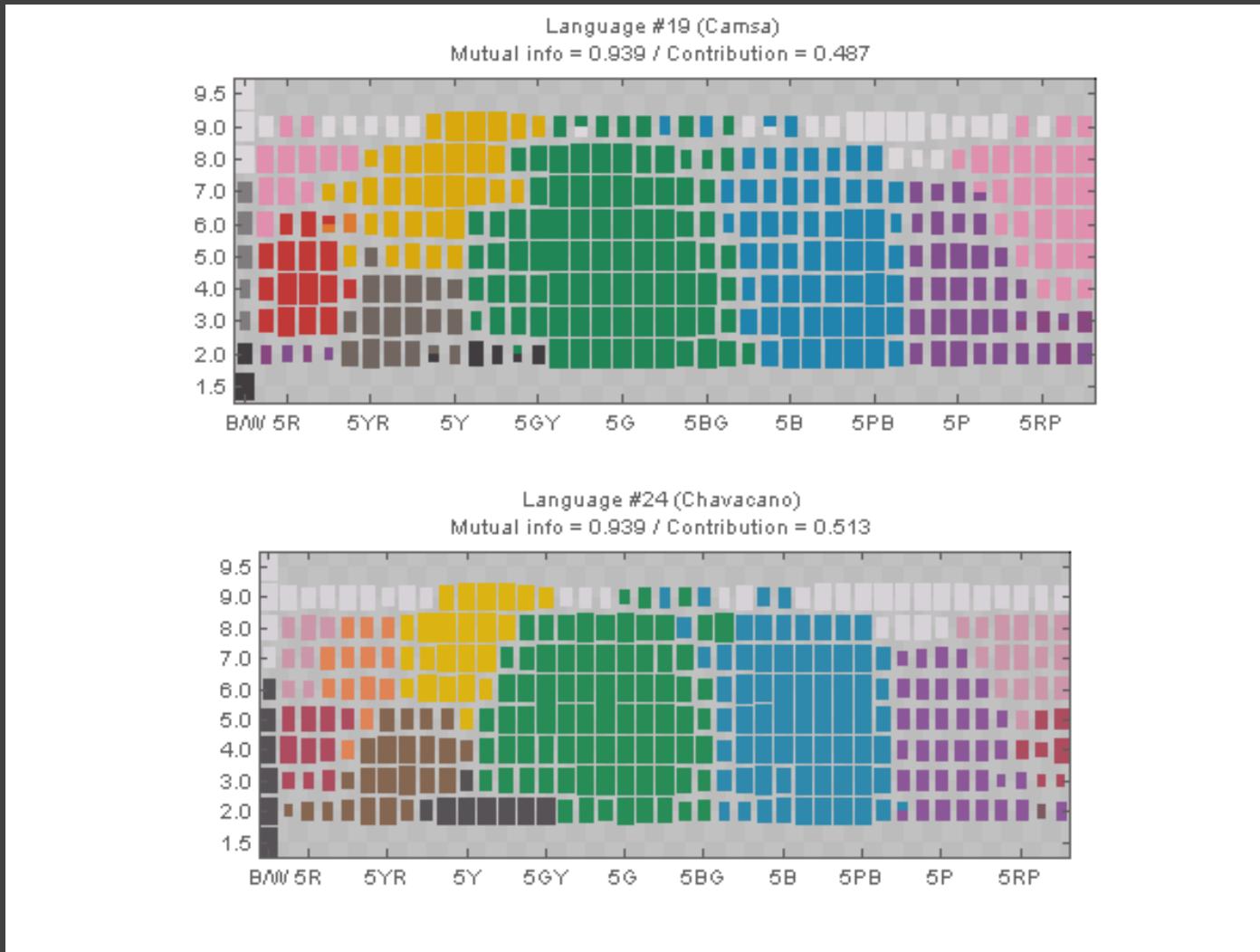
Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



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



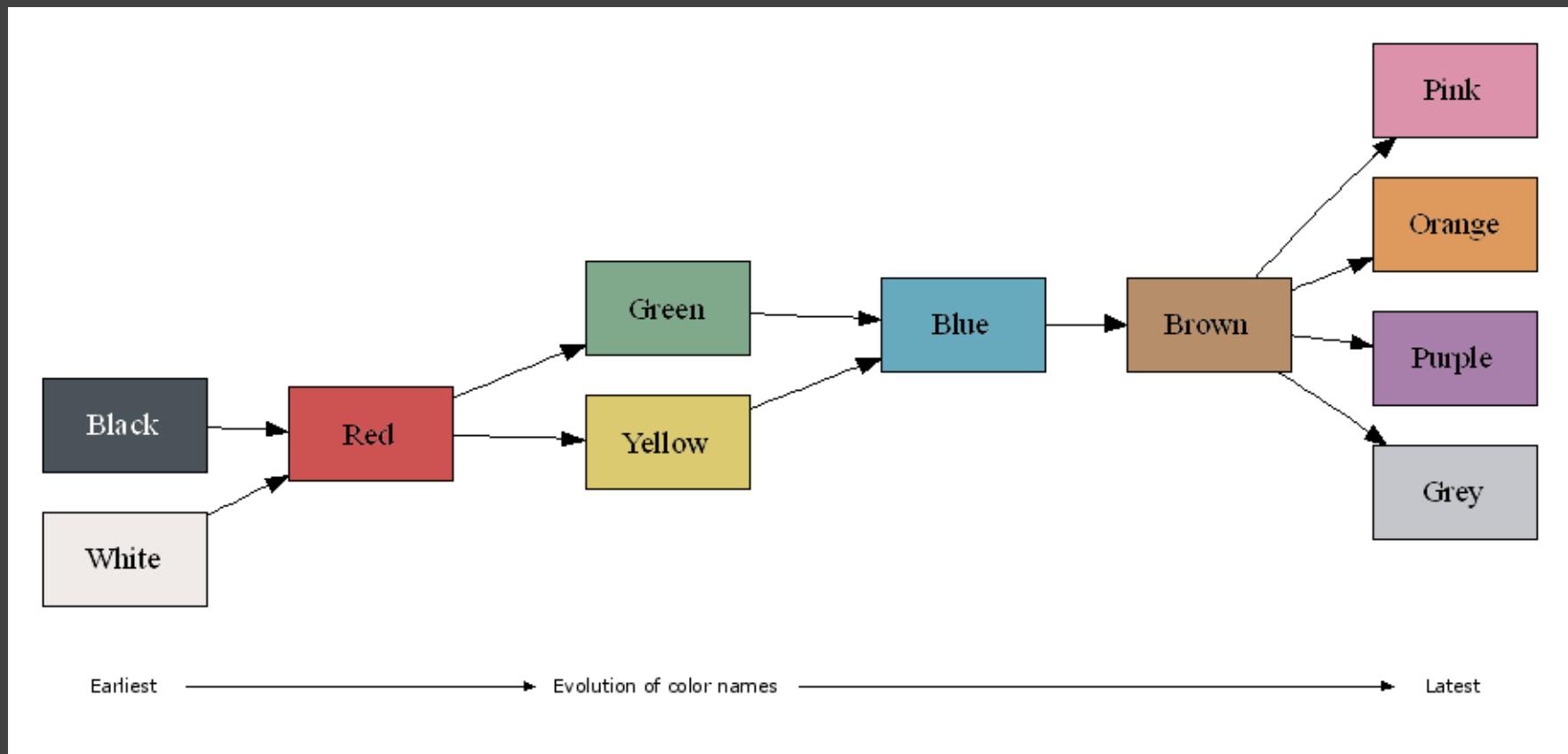
Blue



Purple

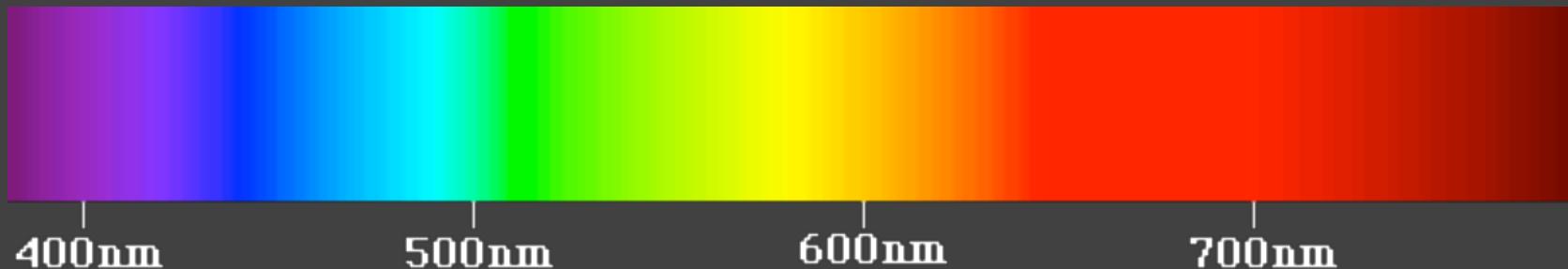
Evolution of Basic Color Terms

Proposed universal evolution across languages.



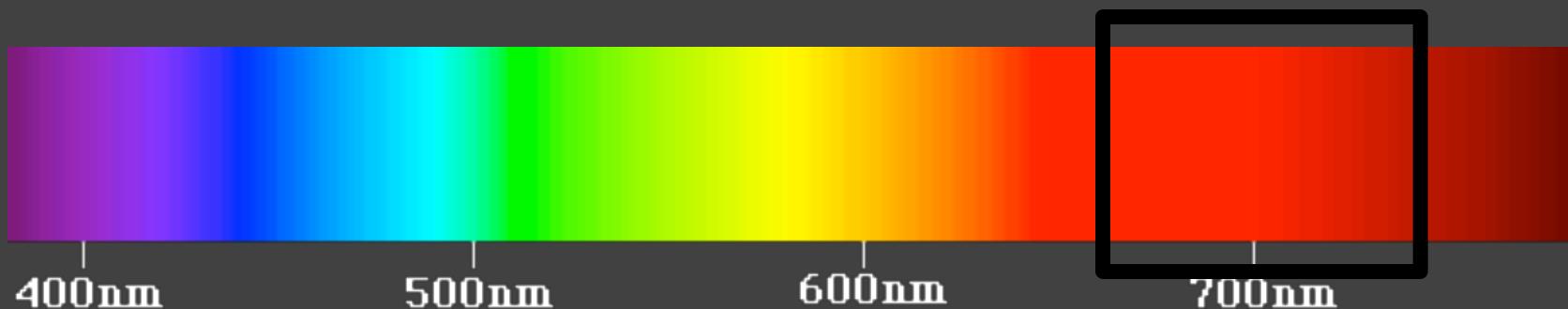
Rainbow Color Map

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



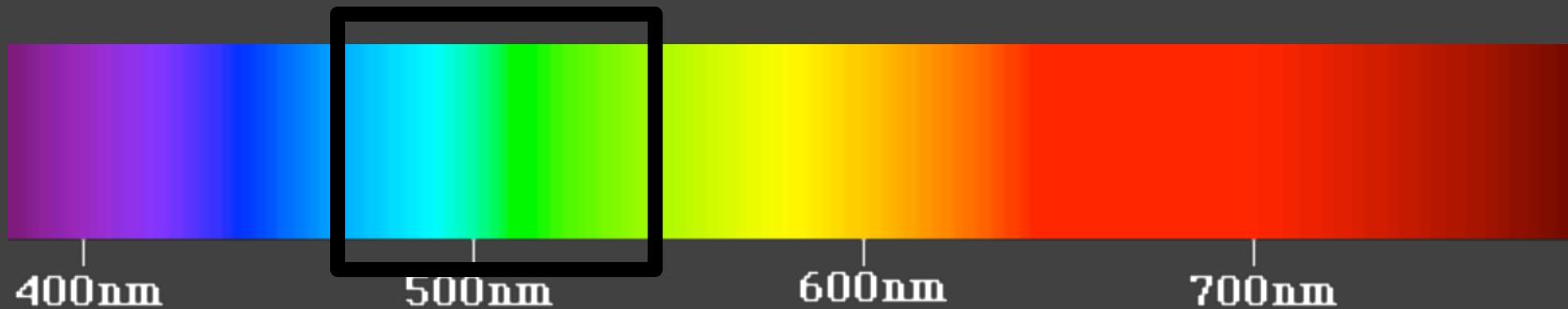
Rainbow Color Map

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



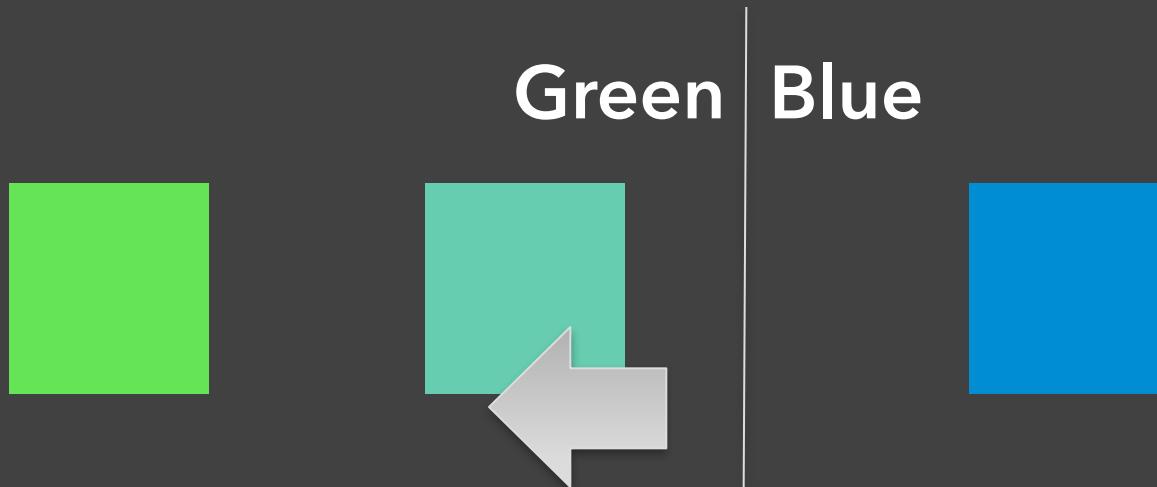
Rainbow Color Map

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

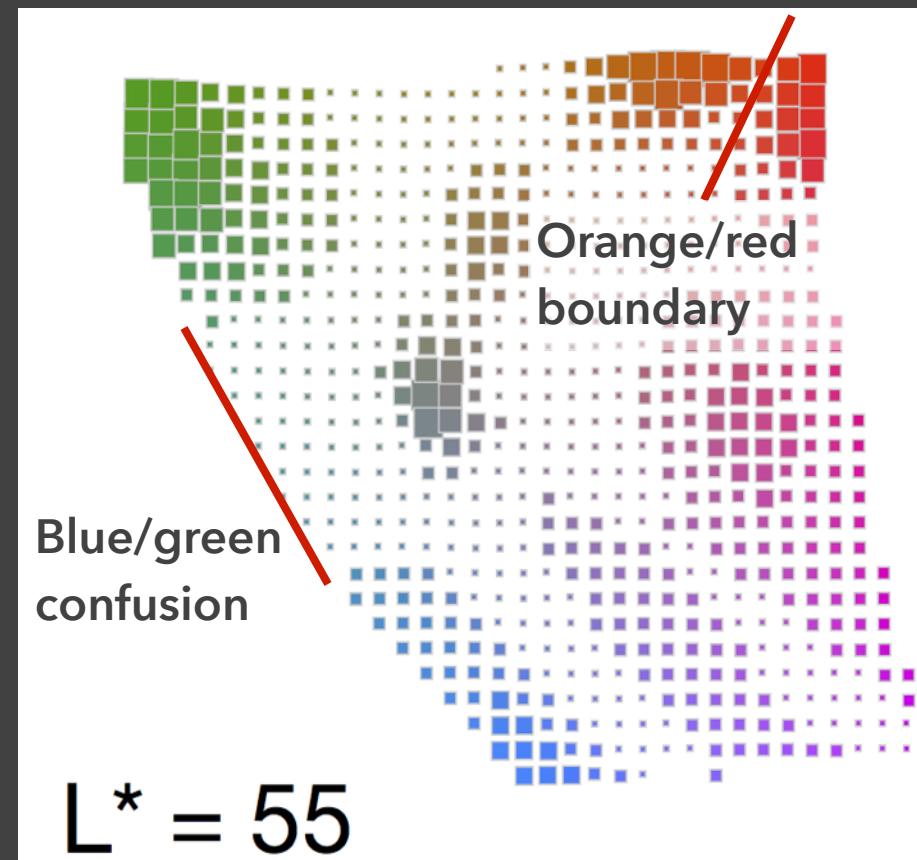
[Heer & Stone '12]

Model 3 million responses from XKCD survey

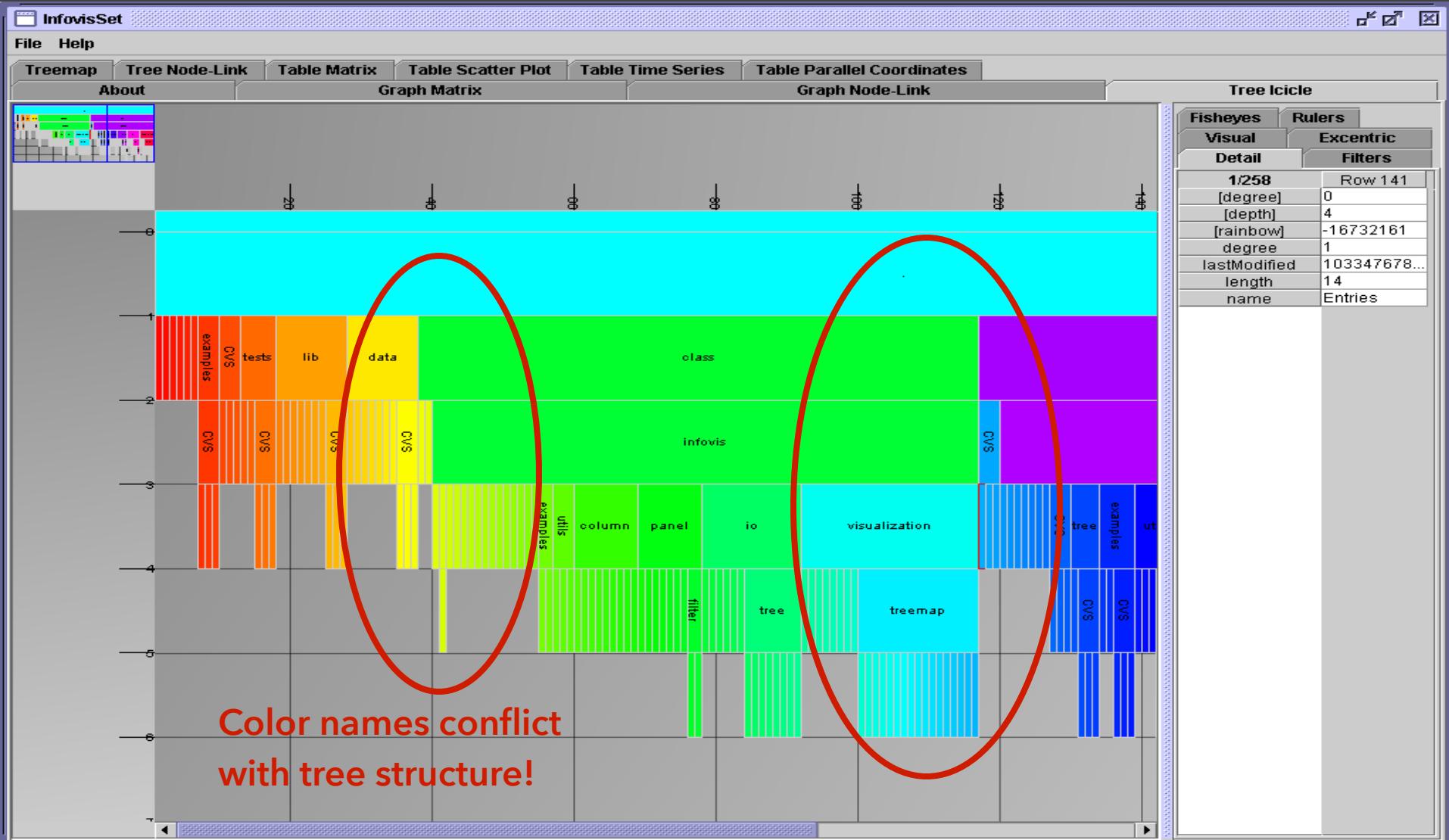
Bins in LAB space
sized by *saliency*:

How much do people
agree on color name?

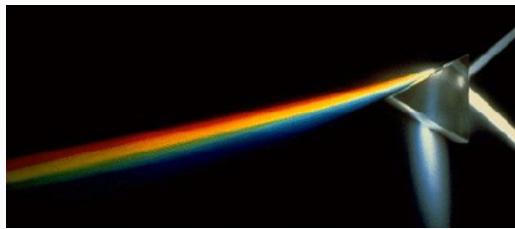
Modeled by entropy
of $p(\text{name} \mid \text{color})$



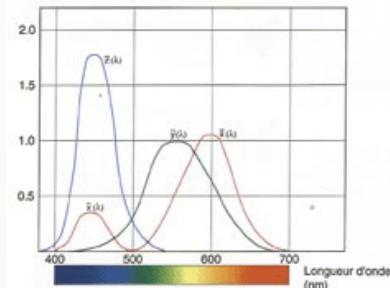
Icicle Tree with Rainbow Coloring



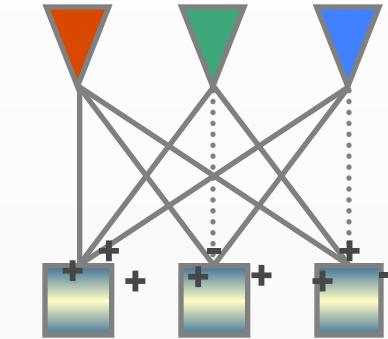
Perception of Color



Light



Cone Response



Opponent Signals

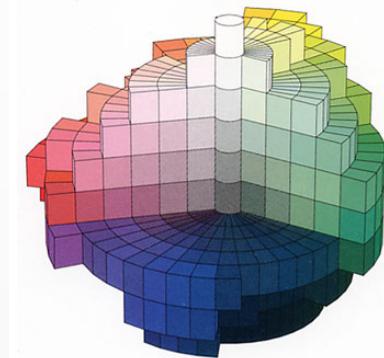
“Yellow”

Color Cognition



Mark D. Fairchild
COLOR APPEARANCE MODELS

Color Appearance

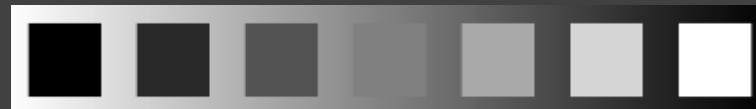


Color Perception

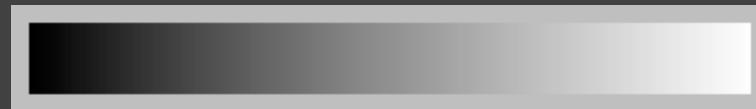
Color Encodings

Encoding Data with Color

Value is perceived as ordered
∴ Encode ordinal variables (O)



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

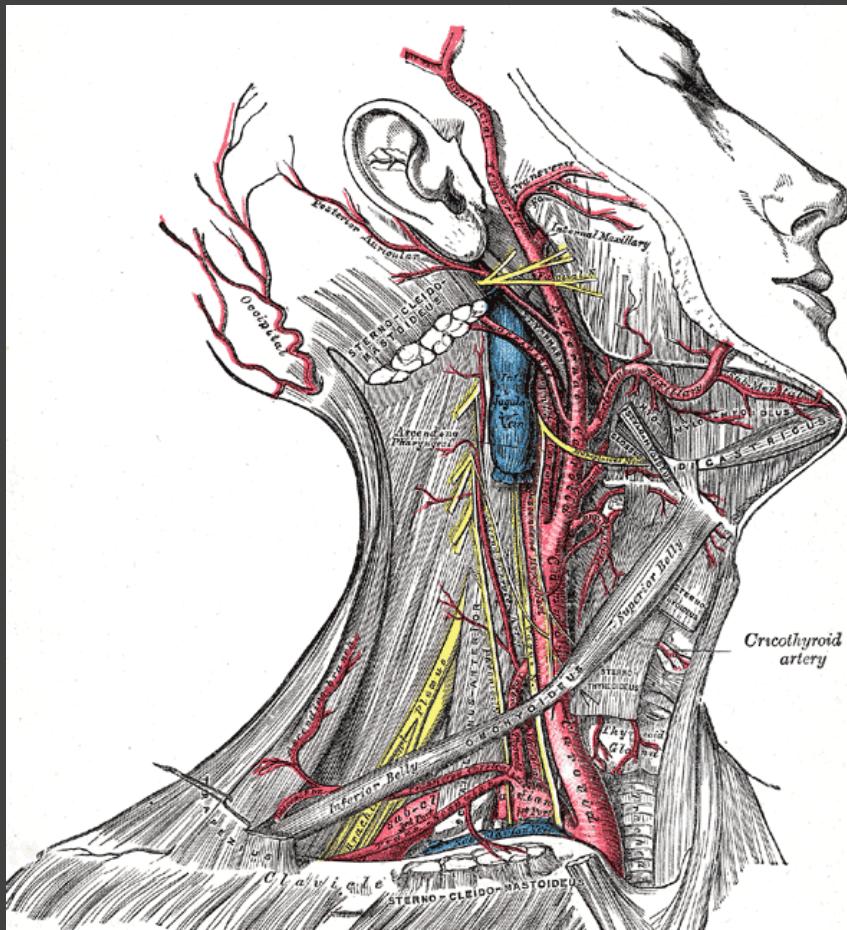


Hue is normally perceived as unordered
∴ Encode nominal variables (N) using color



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

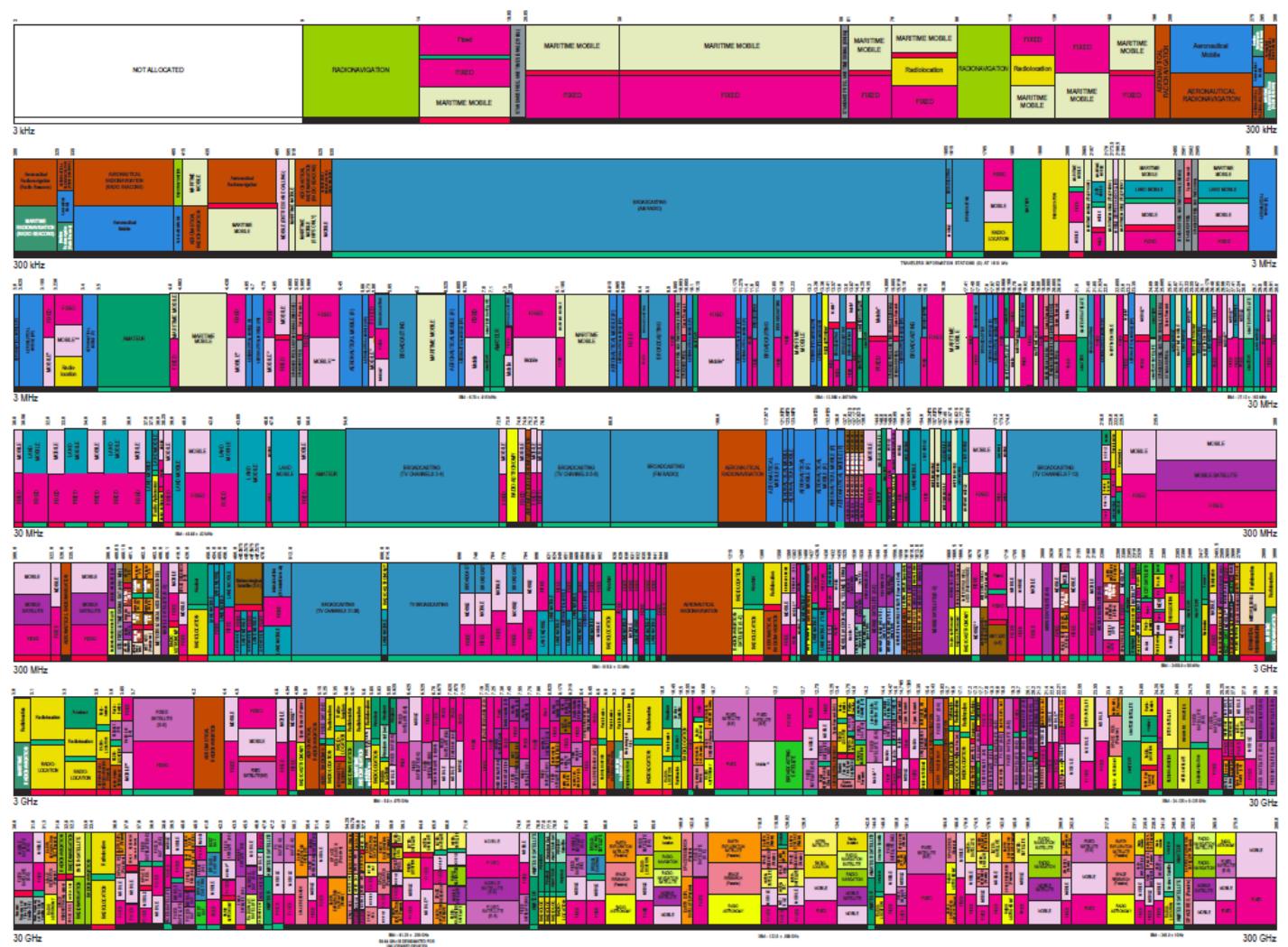
AERONAUTICAL	INTER-SATELLITE	RADIOTELM
AERONAUTICAL MOBILE	LAND MOBILE	RADIOTELM SATELLITE
AERONAUTICAL NAVIGATION	LAND MOBILE SATELLITE	RADLOCATE
AMATEUR	MARITIME MOBILE	RADLOCATE SATELLITE
AMATEUR SATELLITE	MARITIME SATELLITE	RADIOPATH
BROADCASTING	MARITIME NAVIGATION	RADIOPATH SATELLITE
BROADCASTING SATELLITE	METEOROLOGICAL	SPACE OPERATION
EARTH EXPLORATION SATELLITE	METEOROLOGICAL SATELLITE	SPACE RESEARCH
FIXED	MOBILE	STANDARD FREQUENCY AND TIME SIGNAL
FIXED SATELLITE	MOBILE SATELLITE	STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

GOVERNMENT EXCLUSIVE	GOVERNMENT-NON-GOVERNMENT SHARED
NON-GOVERNMENT EXCLUSIVE	

ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters for Commercial Services



Allocation

UNITED STATES FREQUENCY ALLOCATION

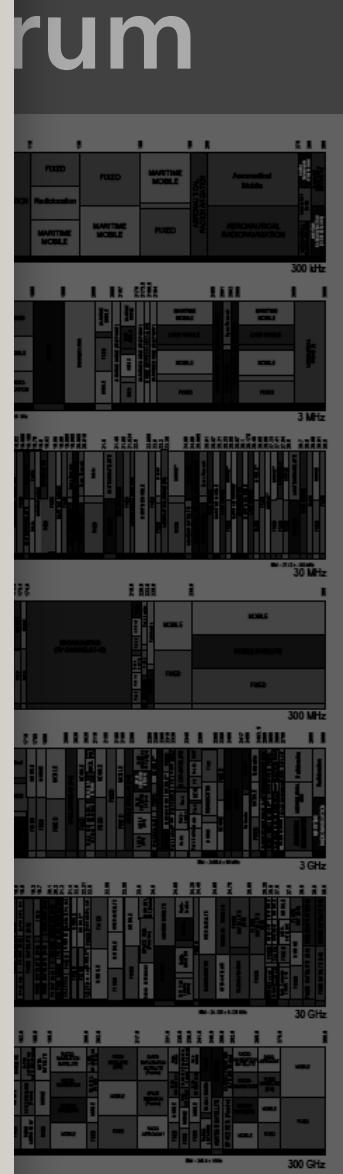
THE RADIO SPECTRUM

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
GOVERNMENT EXCLUSIVE	GOVERNMENT-GOVERNMENT SHARED	
NON-GOVERNMENT EXCLUSIVE		
ACTIVITY CODE		
GOVERNMENT EXCLUSIVE	GOVERNMENT-GOVERNMENT SHARED	
NON-GOVERNMENT EXCLUSIVE		
ALLOCATION USAGE DESIGNATION		
SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters

RADIO SERVICES COLOR LEGEND

AERONAUTICAL MOBILE	INTER-SATELLITE	RADIO ASTRONOMY
AERONAUTICAL MOBILE SATELLITE	LAND MOBILE	RADIODETERMINATION SATELLITE
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AMATEUR SATELLITE	MARITIME MOBILE SATELLITE	RADIONAVIGATION
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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 colors.

Color Name Distance											Salience	Name
0.00	1.00	1.00	1.00	0.98	1.00	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	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	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	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	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	1.00	0.00	.25	blue 25.4%
Tableau-10											Average 0.97	.52

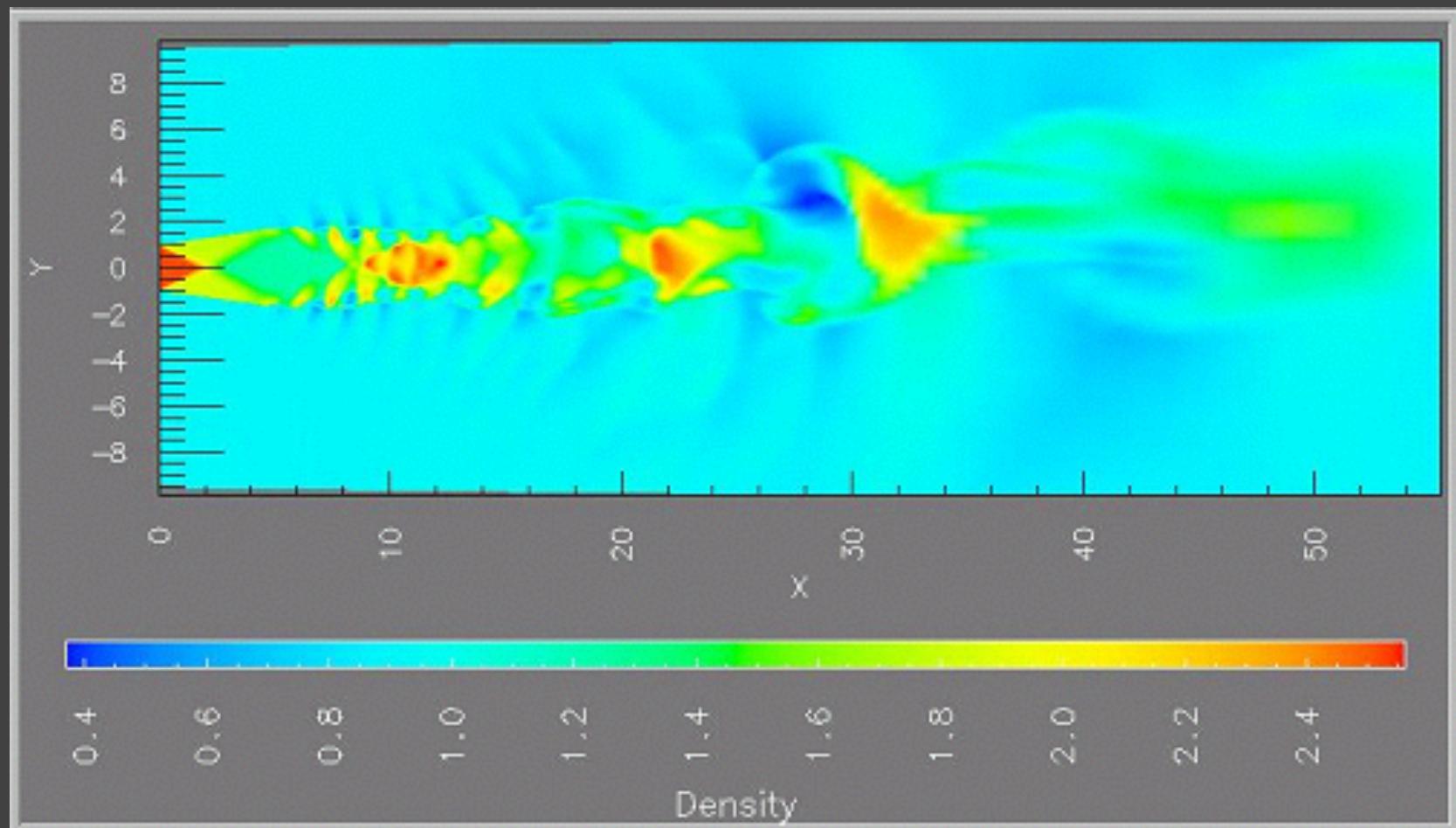
Palette Design & Color Names

Minimize overlap and ambiguity of colors.

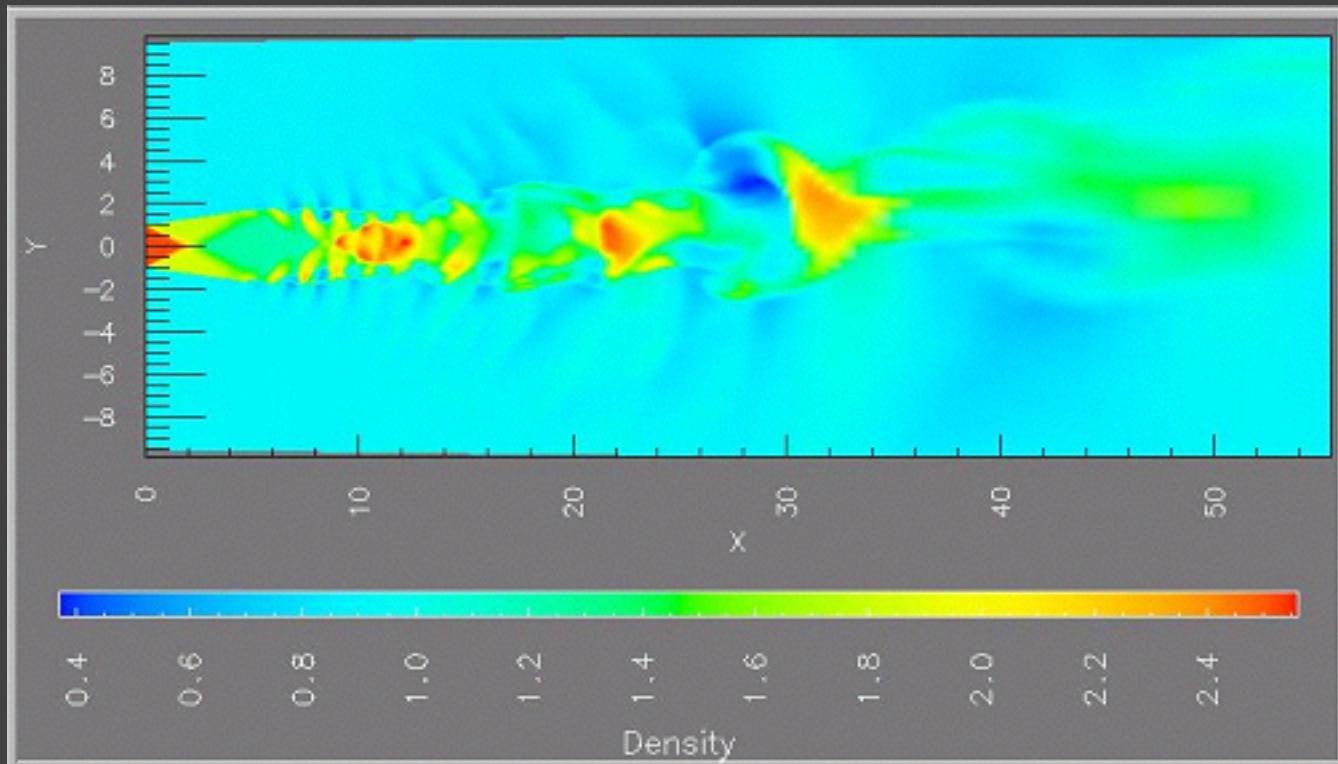
Color Name Distance											Salience	Name
0.00	1.00	1.00	0.89	0.07	1.00	0.35	0.99	1.00	0.89		.30	blue 50.5%
1.00	0.00	0.99	1.00	1.00	0.92	1.00	0.84	0.98	0.99		.21	red 27.8%
1.00	0.99	0.00	1.00	0.98	1.00	1.00	1.00	0.17	1.00		.34	green 36.8%
0.89	1.00	1.00	0.00	0.98	1.00	0.71	0.93	1.00	0.32		.55	purple 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

Quantitative Color

Rainbow Color Maps



Be Wary of Rainbows!



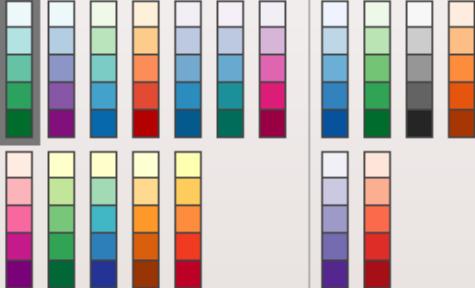
1. People segment colors into classes
2. Hues are not naturally ordered
3. Different lightness emphasizes certain scalar values
4. Low luminance colors (blue) hide high frequencies

Color Brewer: Palettes for Maps

number of data classes on your map
3 | [learn more >](#)

the nature of your data
sequential | [learn more >](#)

pick a color scheme: BuGn



multihue single hue

(optional) only show schemes that are:

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

pick a color system

229, 245, 249	<input checked="" type="radio"/> RGB	<input type="radio"/> CMYK	<input type="radio"/> HEX
153, 216, 201			
44, 162, 95			

adjust map context

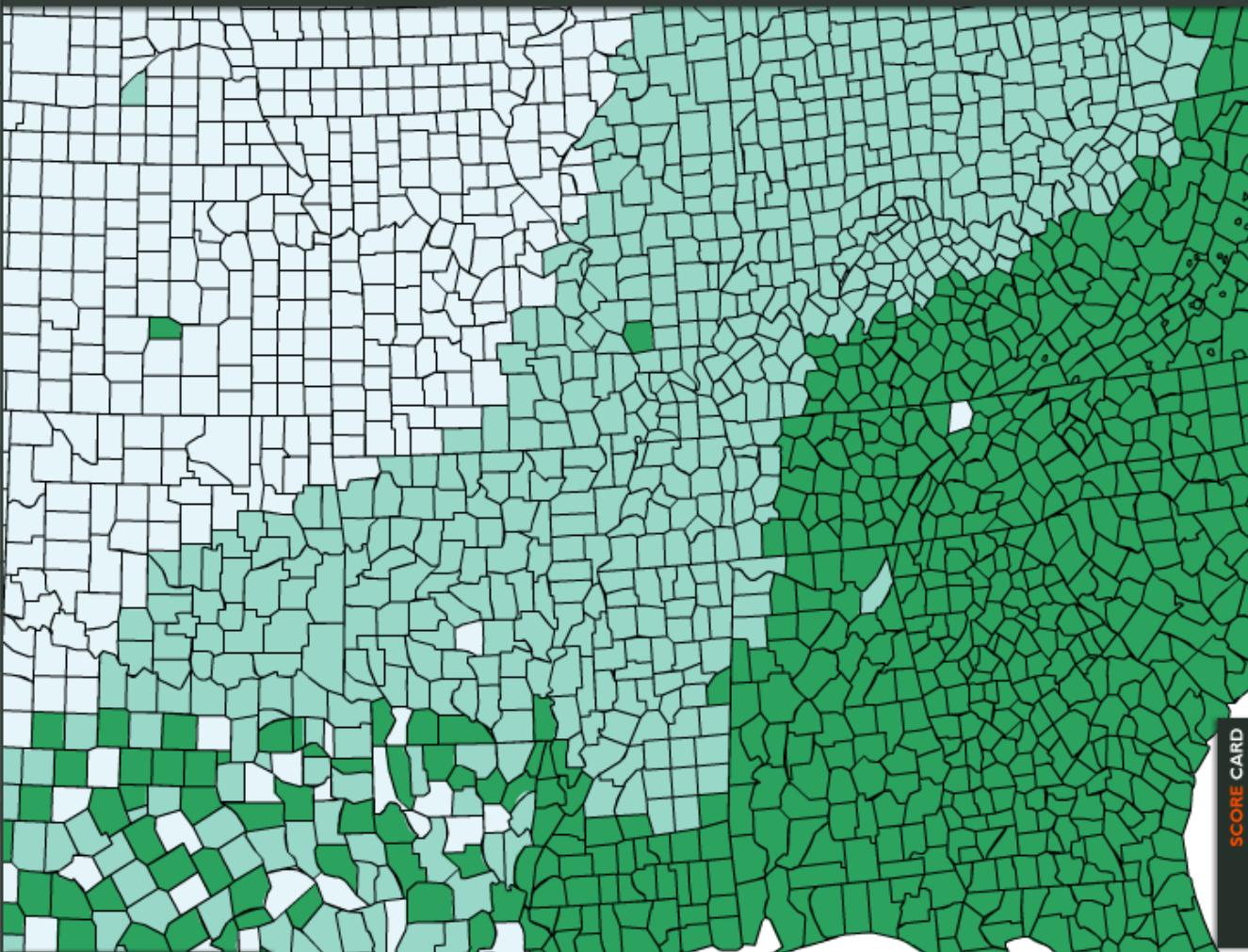
roads 
 cities 
 borders

select a background

solid color 
 terrain

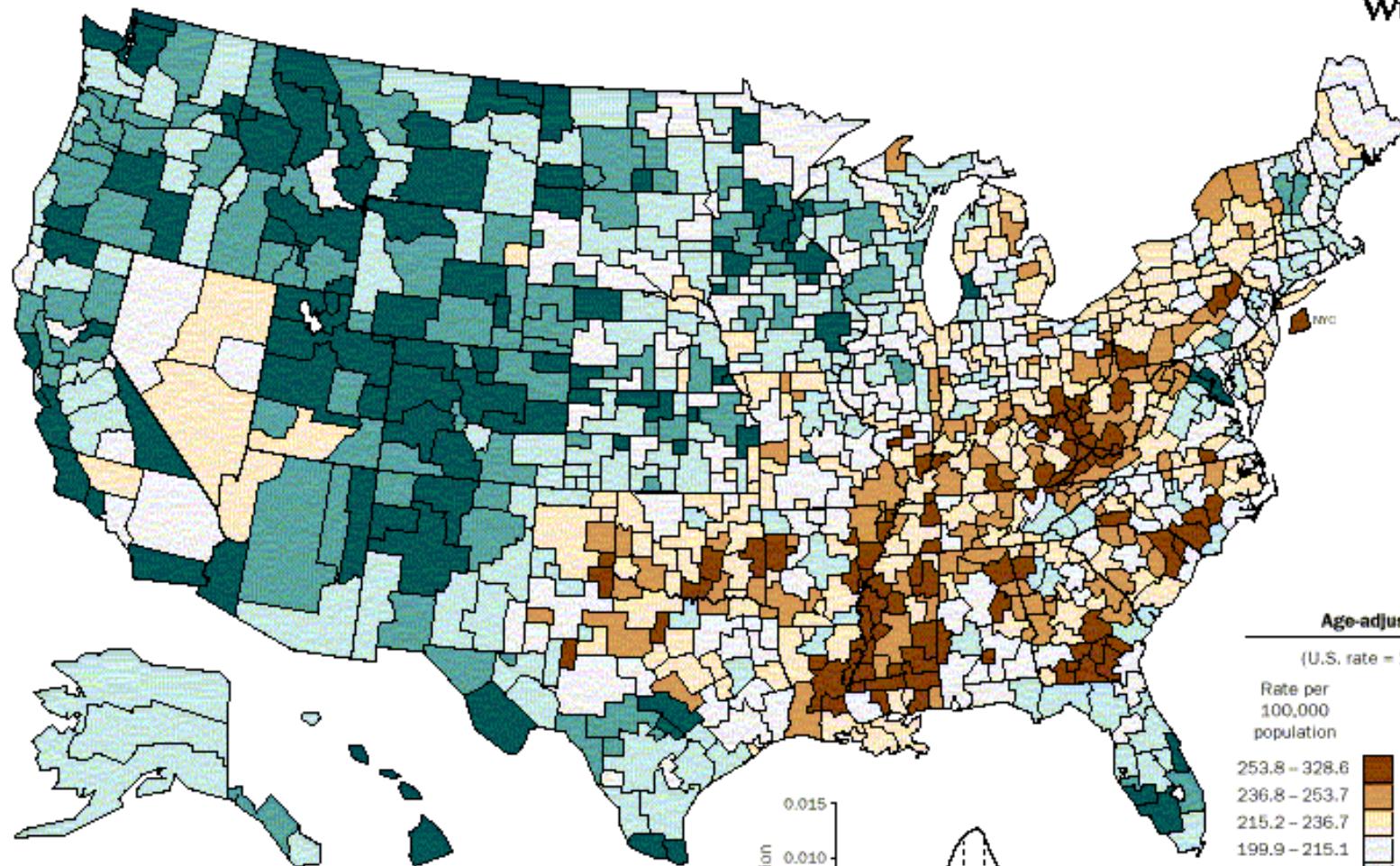
how to use | updates | credits

COLORBREWER 2.0
color advice for cartography



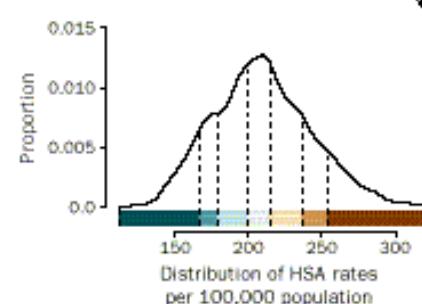
AGE-ADJUSTED DEATH RATES BY HSA, 1988-92

HEART DISEASE
WHITE MALE



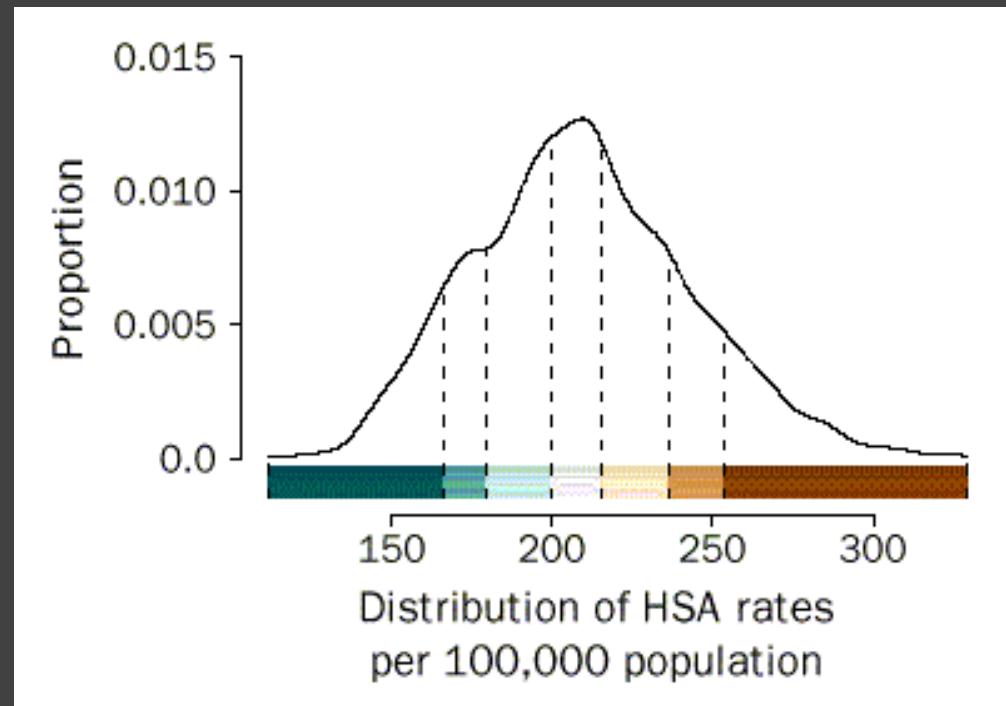
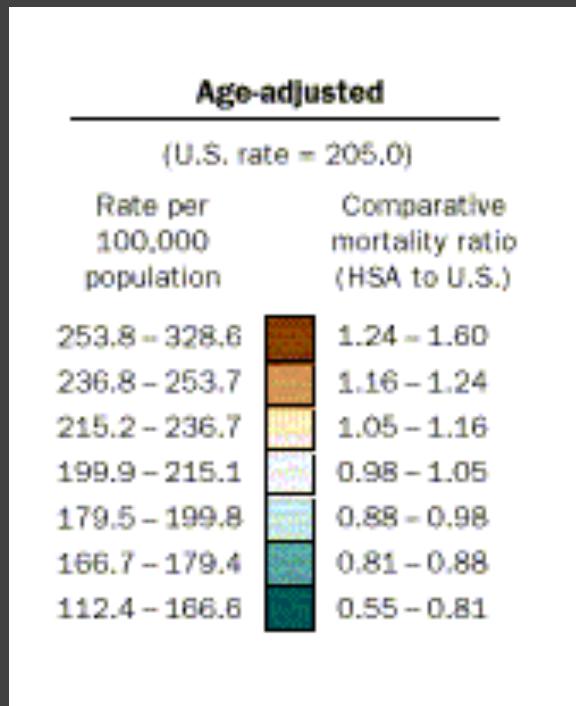
ICD-9 Categories 390-398,
402, 404-429

SOURCE: CDC/NCHS



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

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

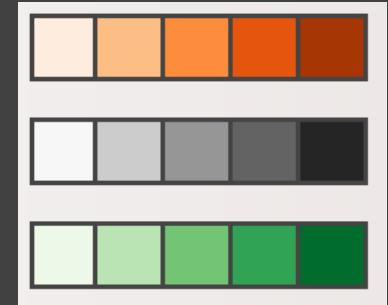
Maximize between group variance

Quantitative Color Encoding

Sequential color scale

Constrain hue, vary luminance/saturation

Map higher values to darker colors

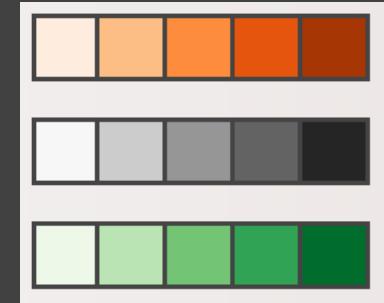


Quantitative Color Encoding

Sequential color scale

Constrain hue, vary luminance/saturation

Map higher values to darker colors

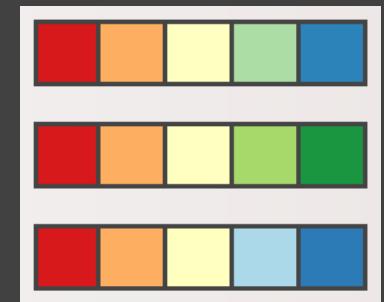


Diverging color scale

Useful when data has meaningful “midpoint”

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

Use saturated colors for endpoints

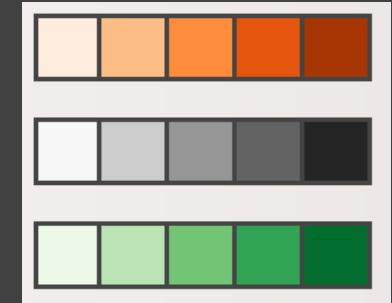


Quantitative Color Encoding

Sequential color scale

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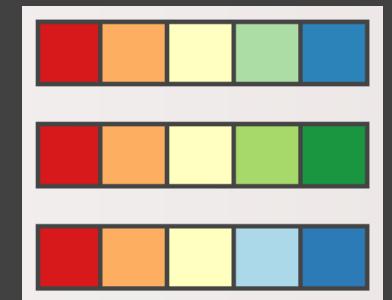


Diverging color scale

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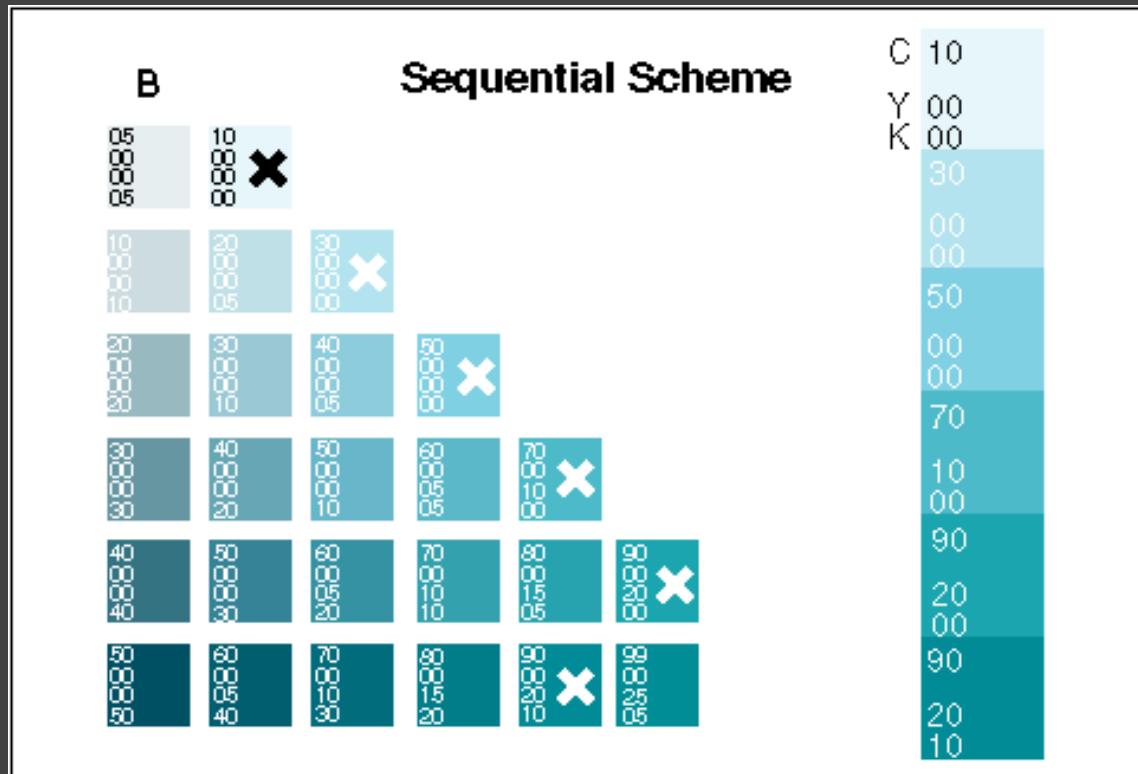
Use neutral color (e.g., grey) for midpoint

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

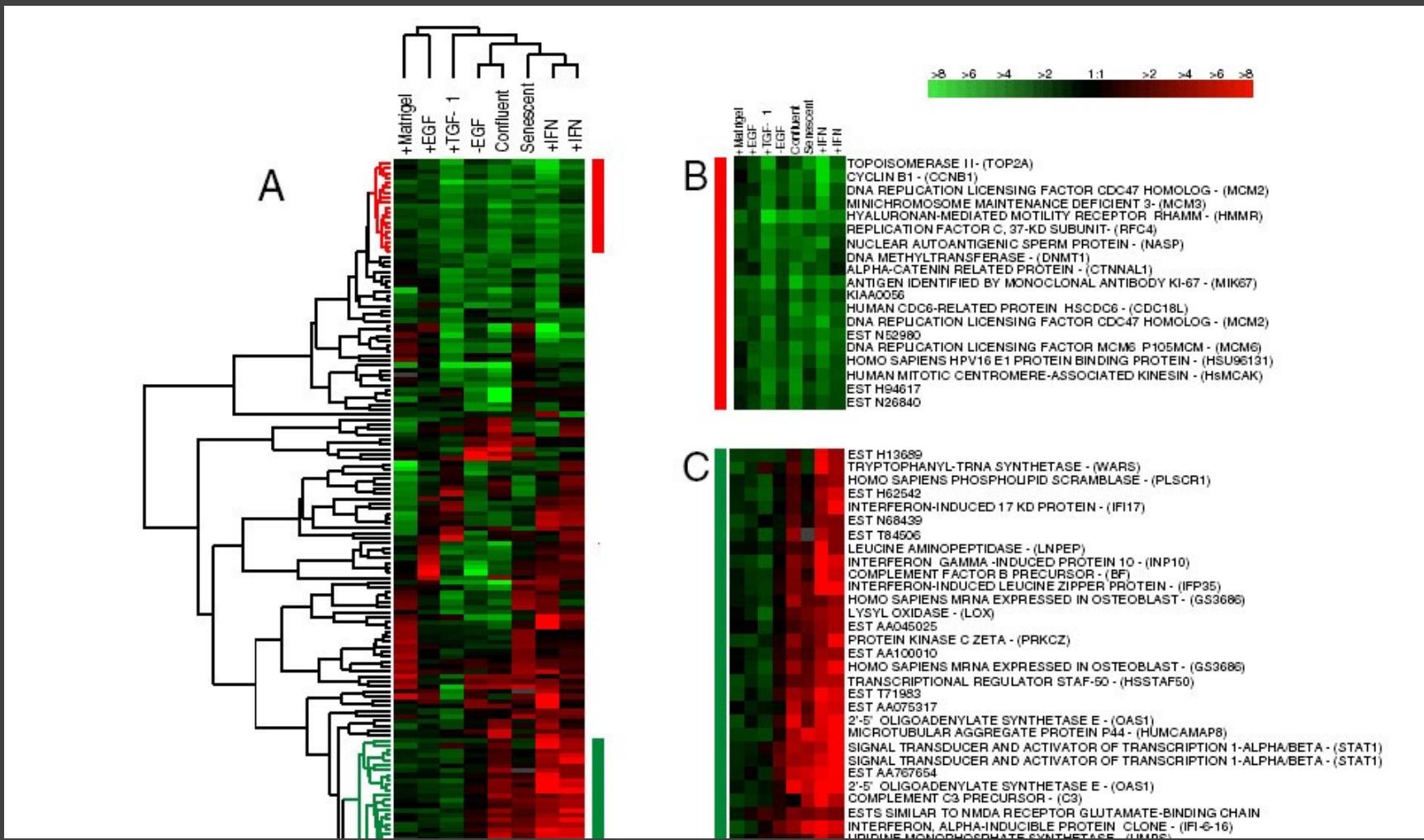
Hue Transition

Two hues

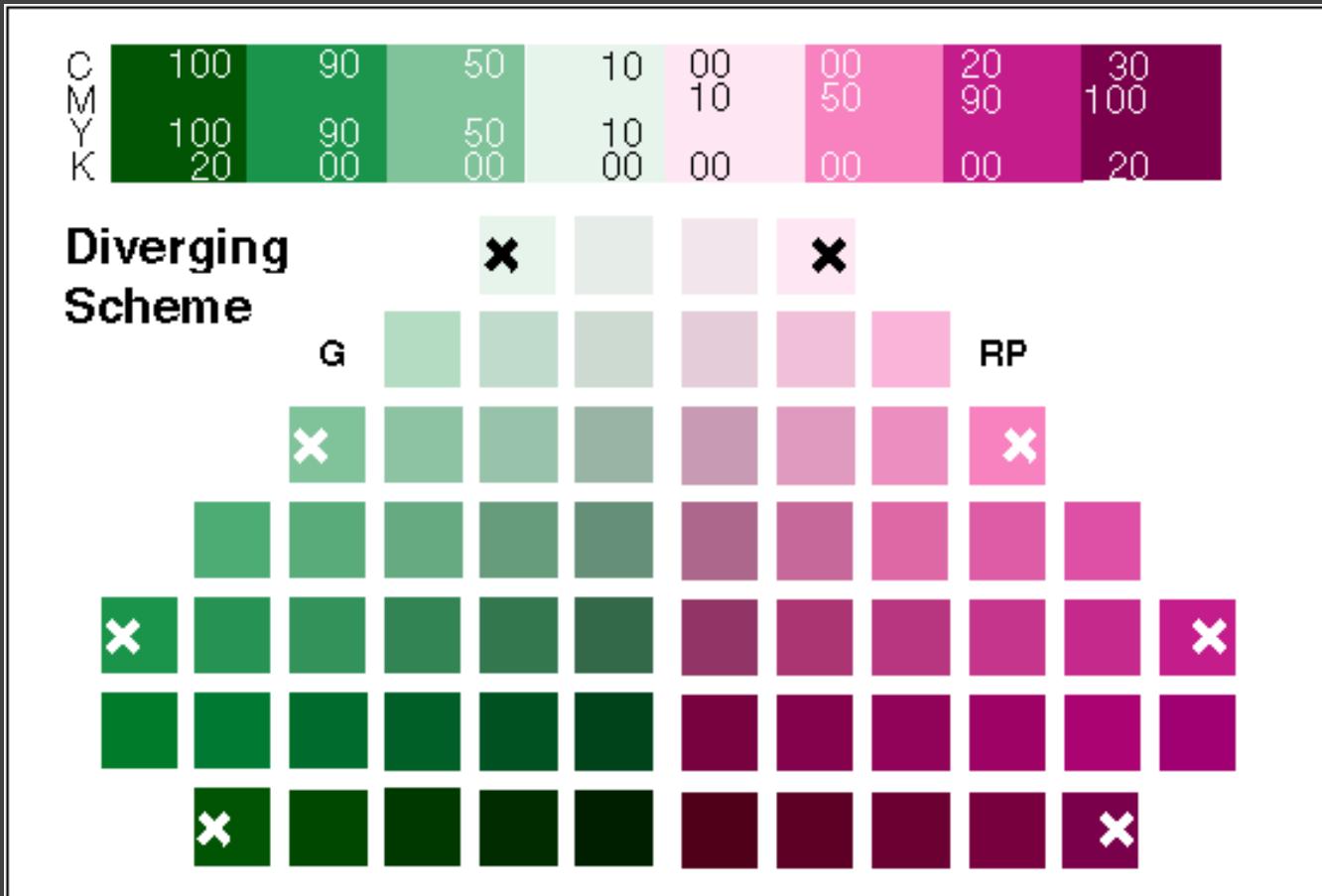
Neighboring hues interpolate better

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

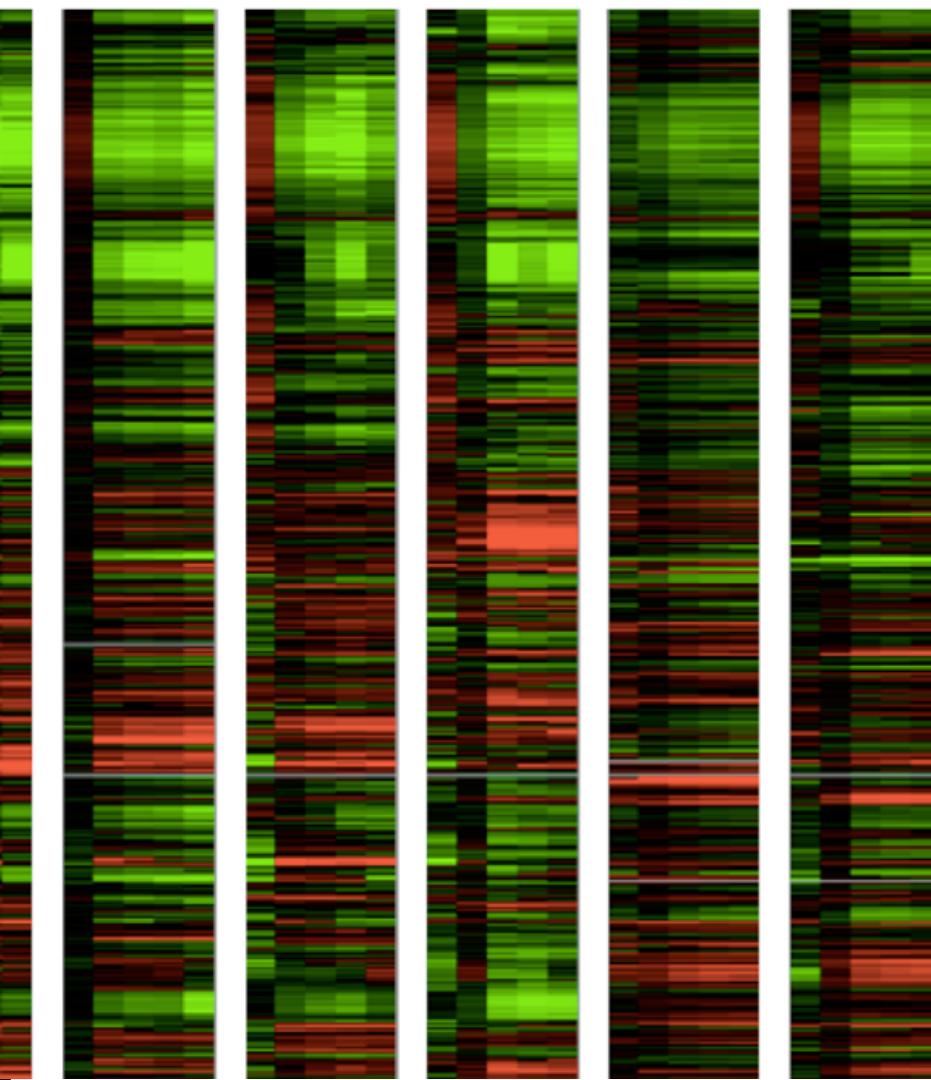
Positive & negative should use different hues

Extremes saturated, middle desaturated

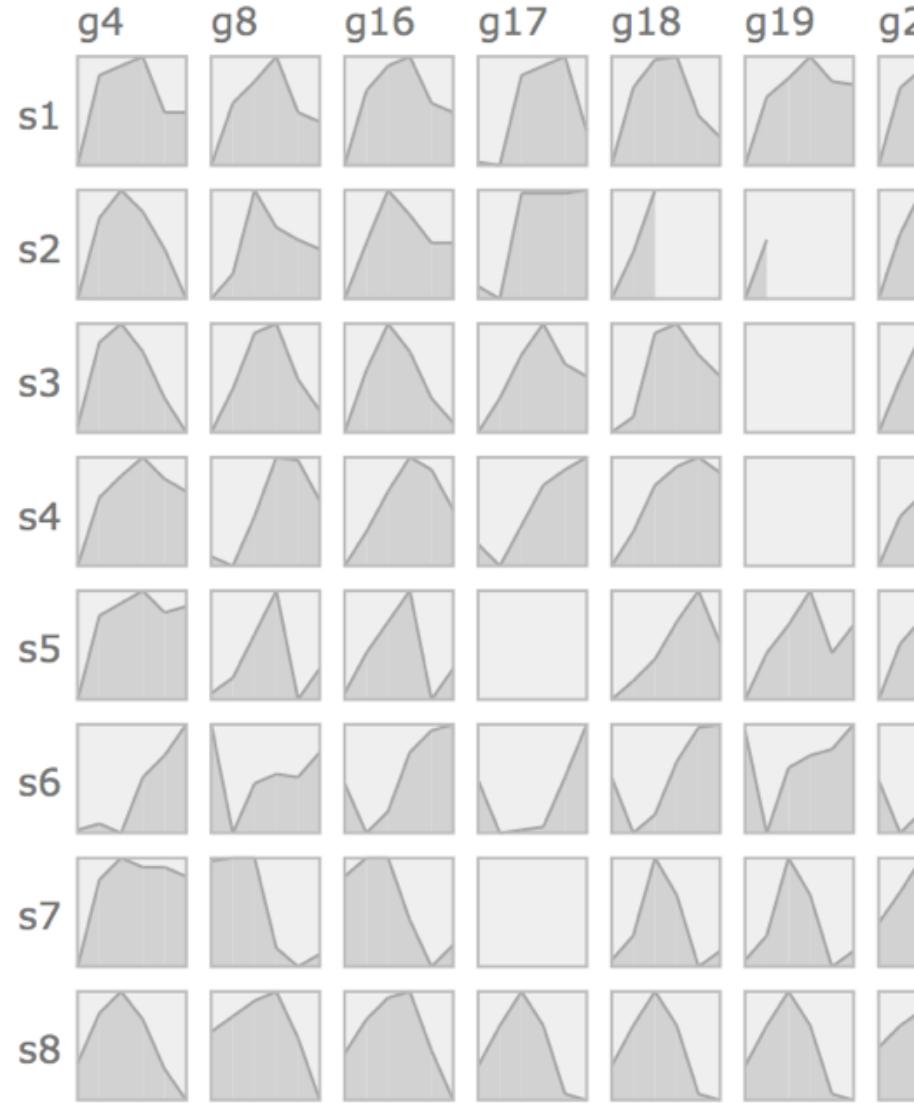
Perceptual Re-designs

Gene Expression Time-Series [Meyer et al 11]

Color Encoding



Position Encoding



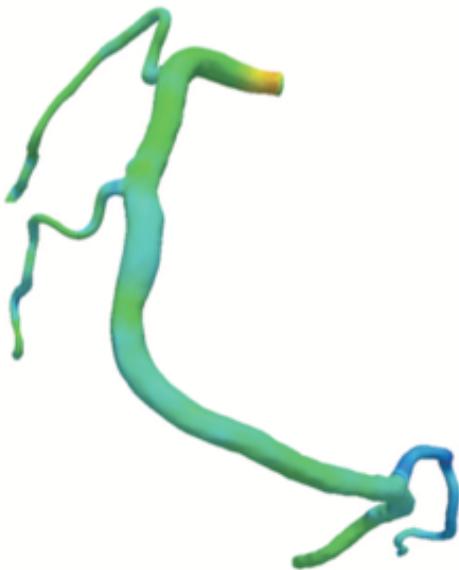
Artery Visualization [Borkin et al 11]

Rainbow Palette

2D



3D



Artery Visualization

[Borkin et al 11]

Rainbow Palette

Accuracy: **62%**

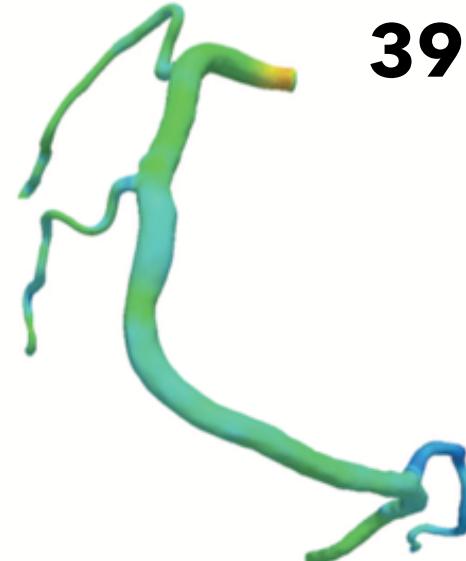
2D



Shear
Stress (Pa)



3D



39%

Diverging Palette

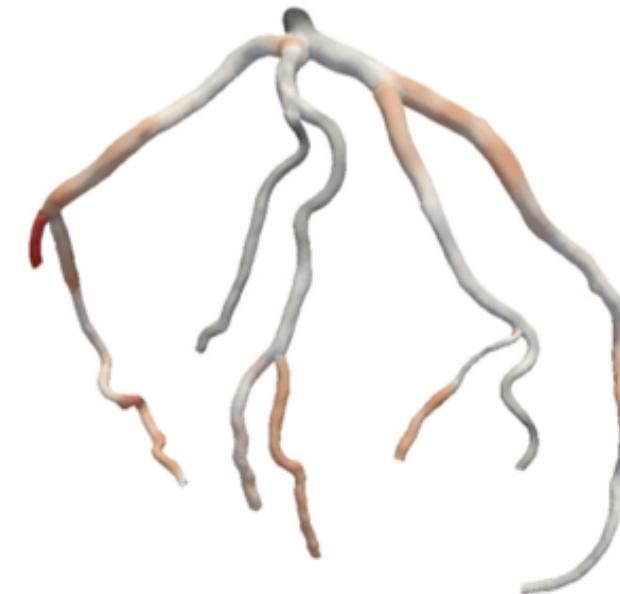
92%



Shear
Stress (Pa)



71%



Hints for the Colorist

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

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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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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**