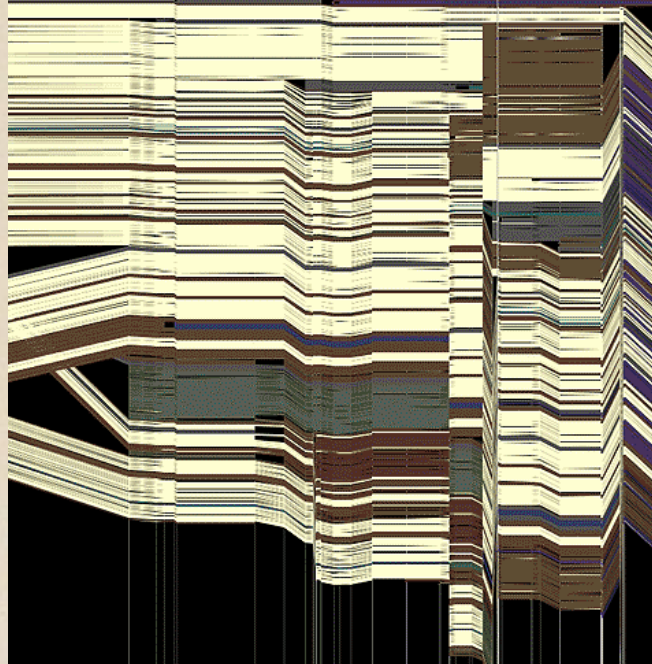
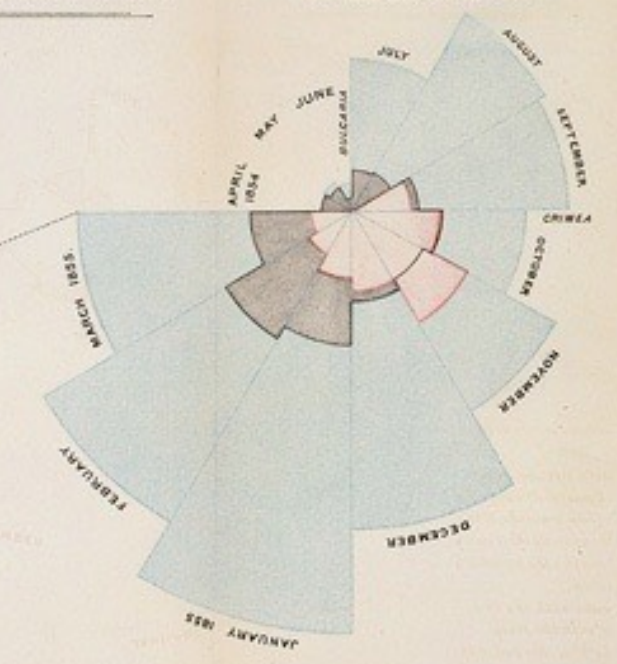


# CSE 412 - Data Visualization

# Color



Jeffrey Heer University of Washington

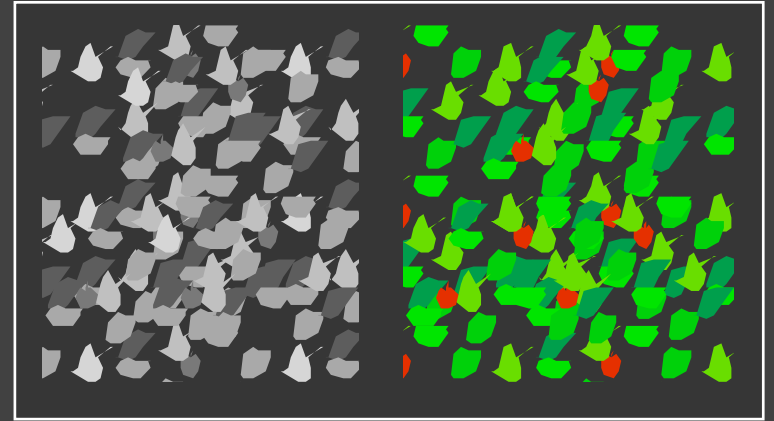
# Purpose of Color

To label

To measure

To represent and imitate

To enliven and decorate



*"Above all, do no harm."*

- Edward Tufte

# Topics

## **Perception of Color**

Light, Visual system, Mental models

## **Color in Information Visualization**

Categorical & Quantitative encoding

Guidelines for color palette design

# Perception of Color

What color is this?

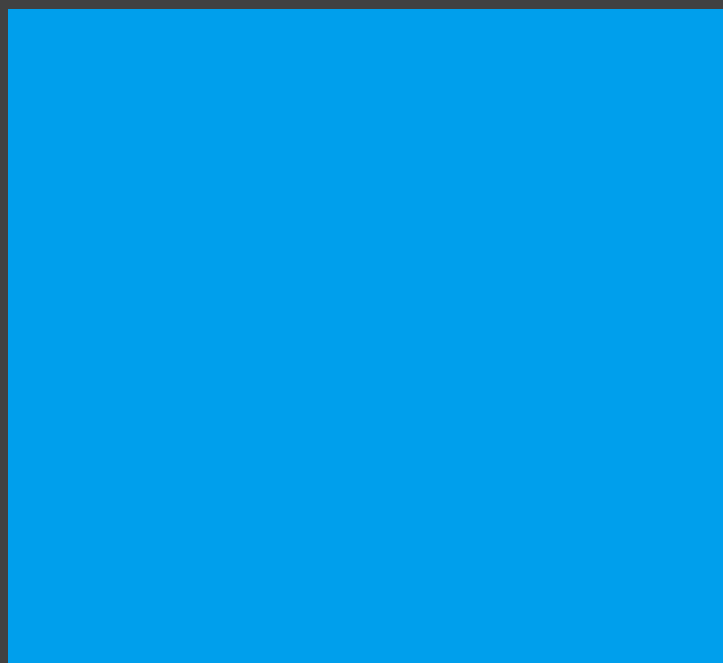


What color is this?

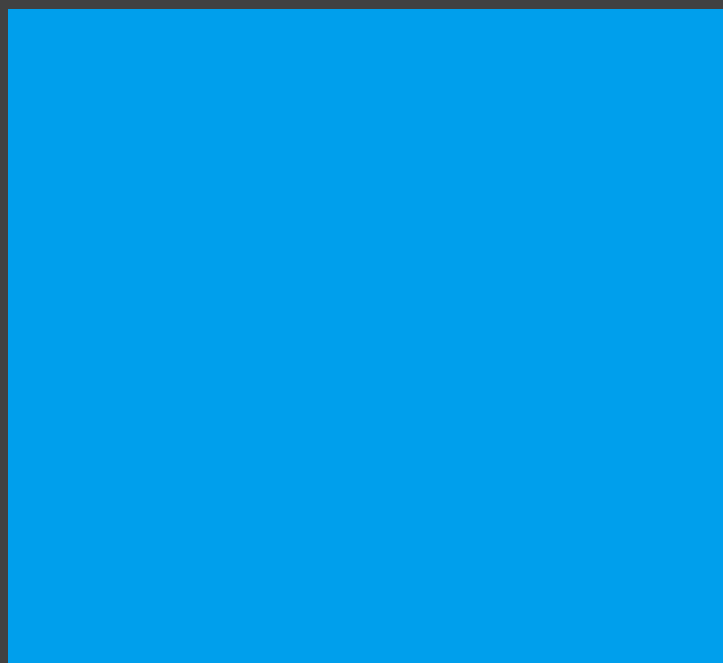


"Yellow"

What color is this?



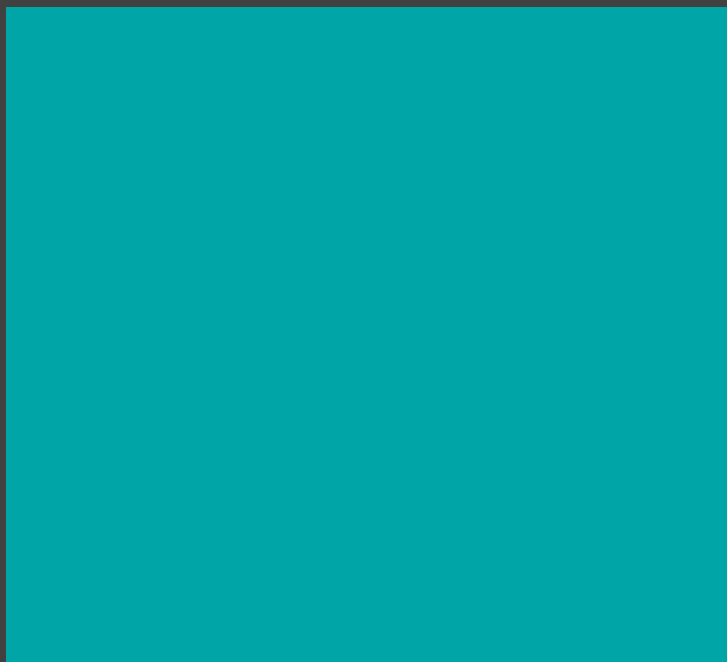
What color is this?



"Blue"



What color is this?

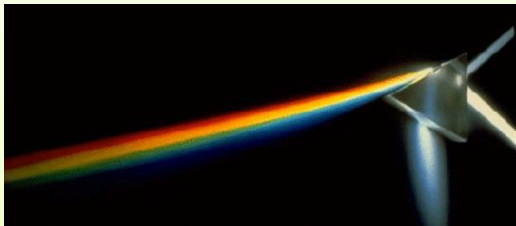


What color is this?

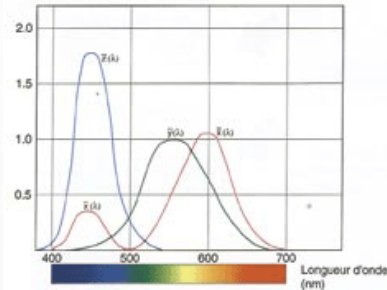


"Teal" ?

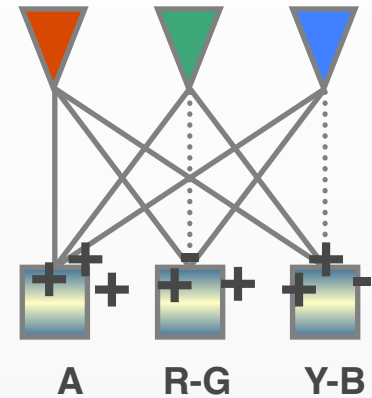
# Perception of Color



Light



Cone Response



Opponent Signals

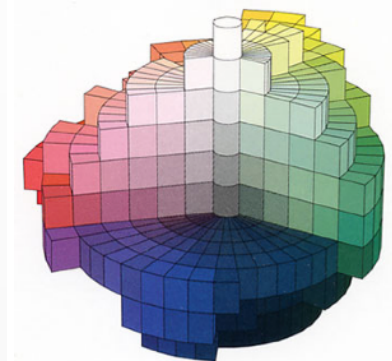
**“Yellow”**

Color Cognition



Mark D. Fairchild  
**COLOR APPEARANCE  
MODELS**

Color Appearance



Color Perception

# Physicist's View

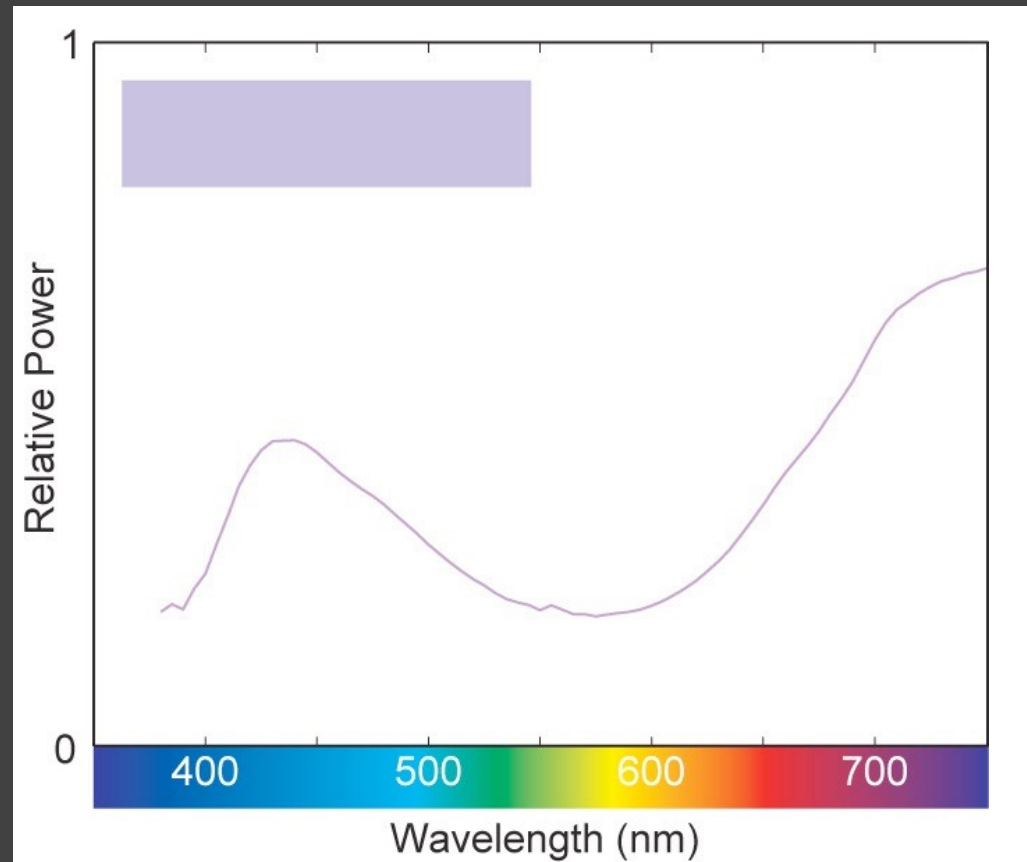
Light as electromagnetic waves

## Wavelength

Visible spectrum is  
370-730 nm

## Power or

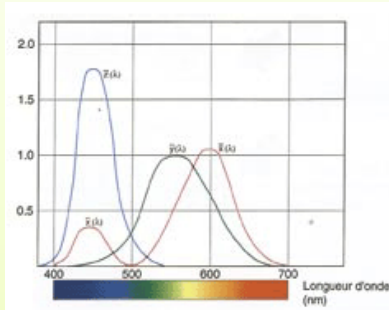
"Relative luminance"



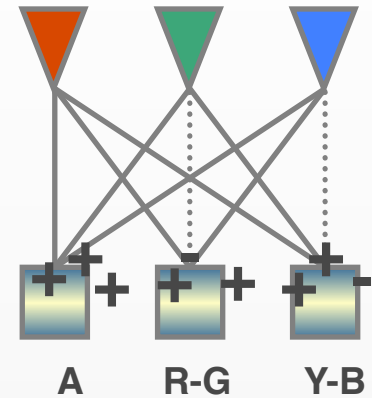
# Perception of Color



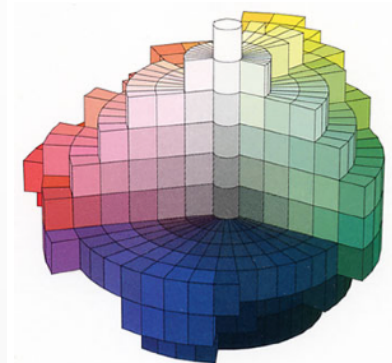
Light



Cone Response



Opponent Signals



Color Perception

“Yellow”

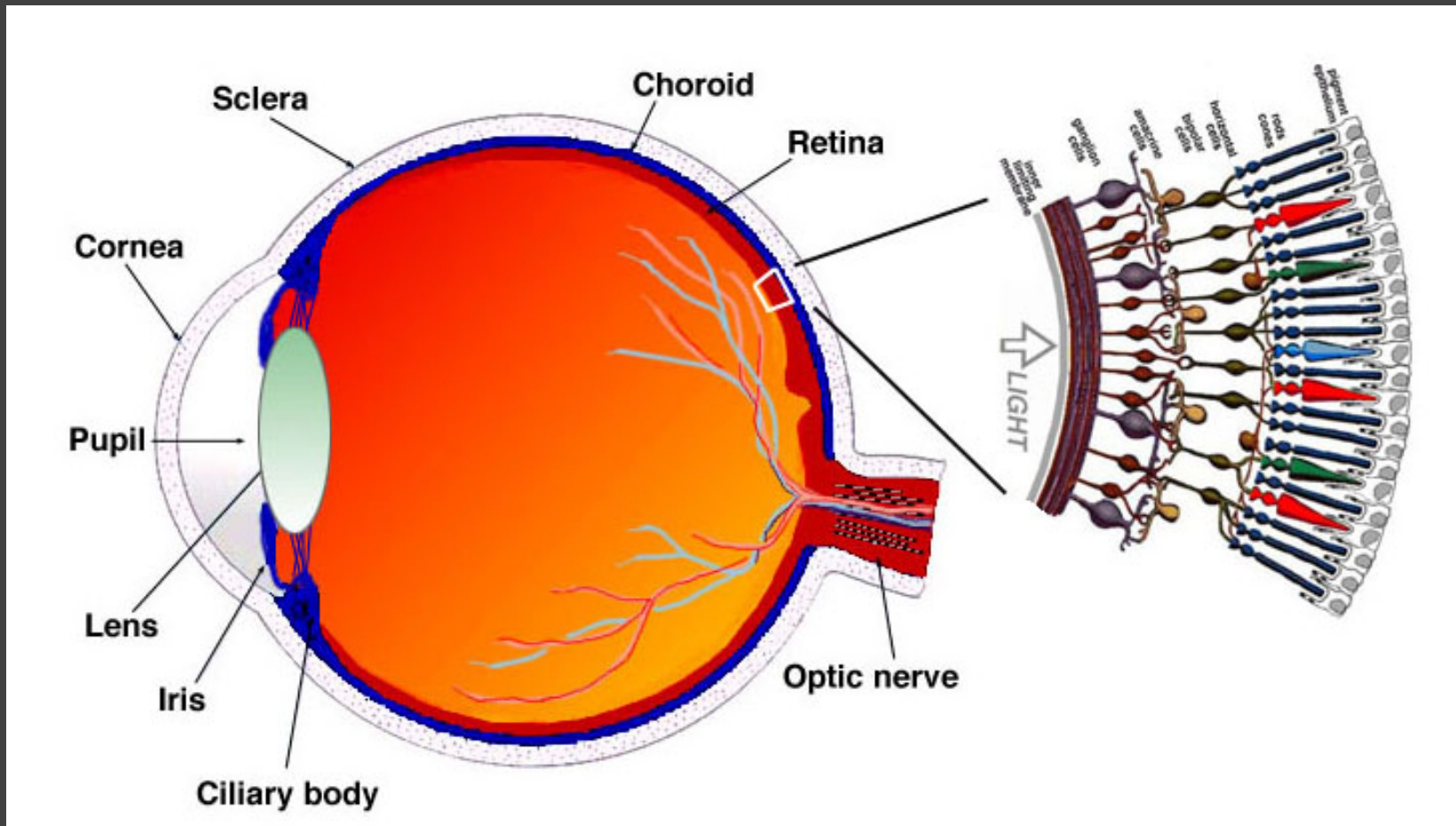
Color Cognition



Mark D. Fairchild  
COLOR APPEARANCE  
MODELS

Color Appearance

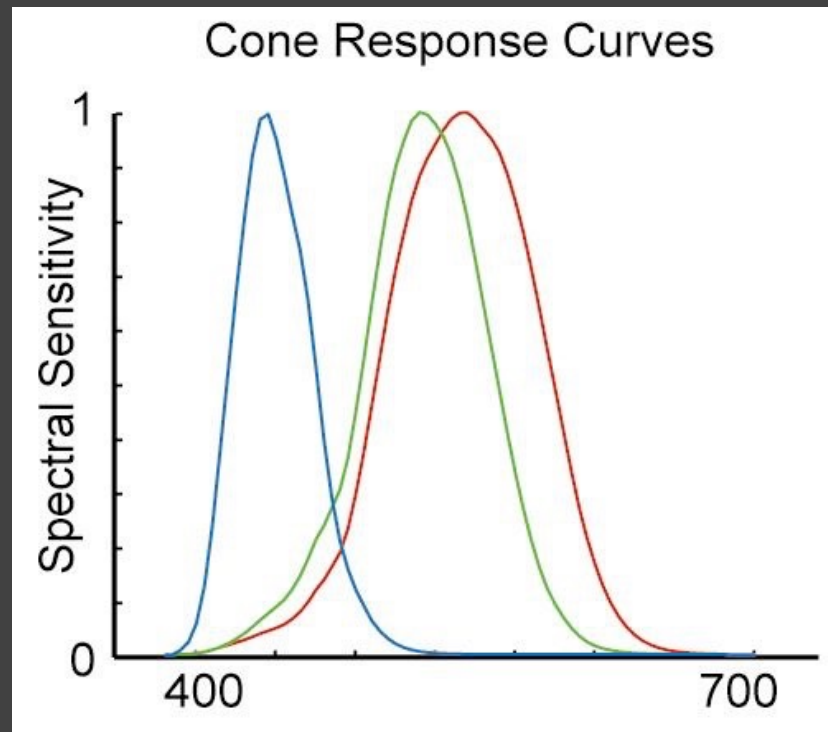
# Retina



*Simple Anatomy of the Retina, Helga Kolb*

# As light enters our retina...

LMS (Long, Middle, Short) Cones  
Sensitive to different wavelengths



# Effects of Retina Encoding

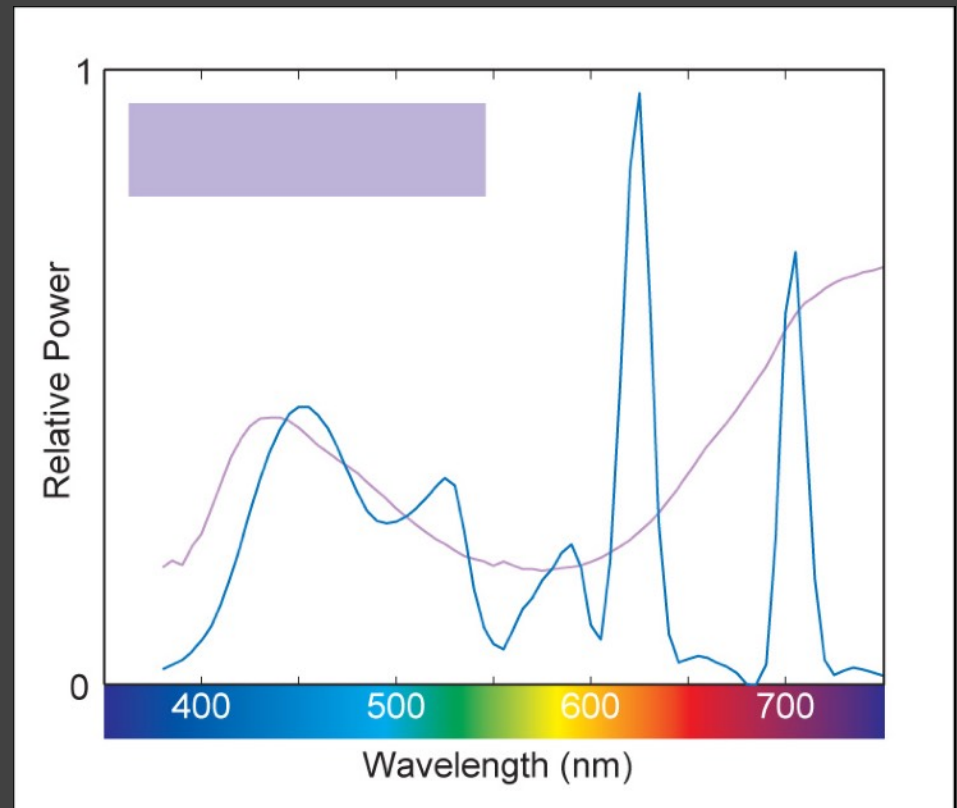
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

## "Tri-stimulus"

Computer displays

Digital scanners

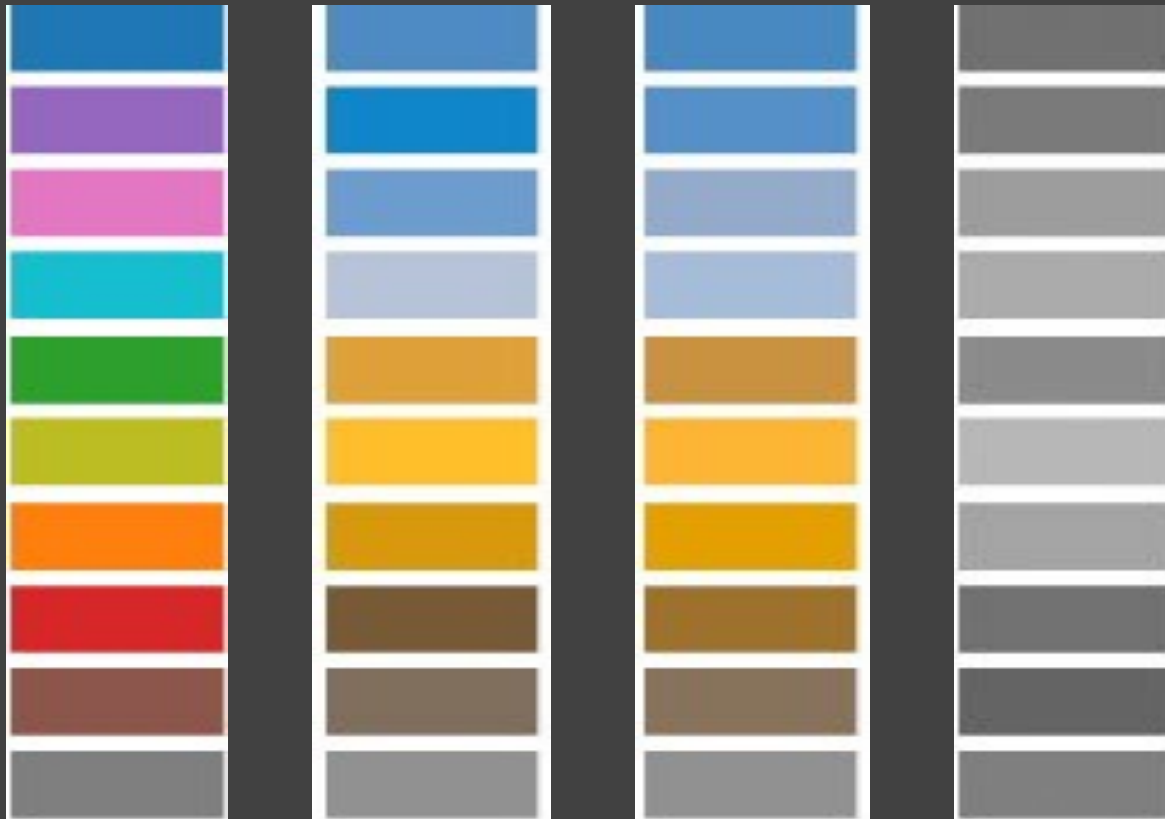
Digital cameras





# Color Vision Deficiency (CVD)

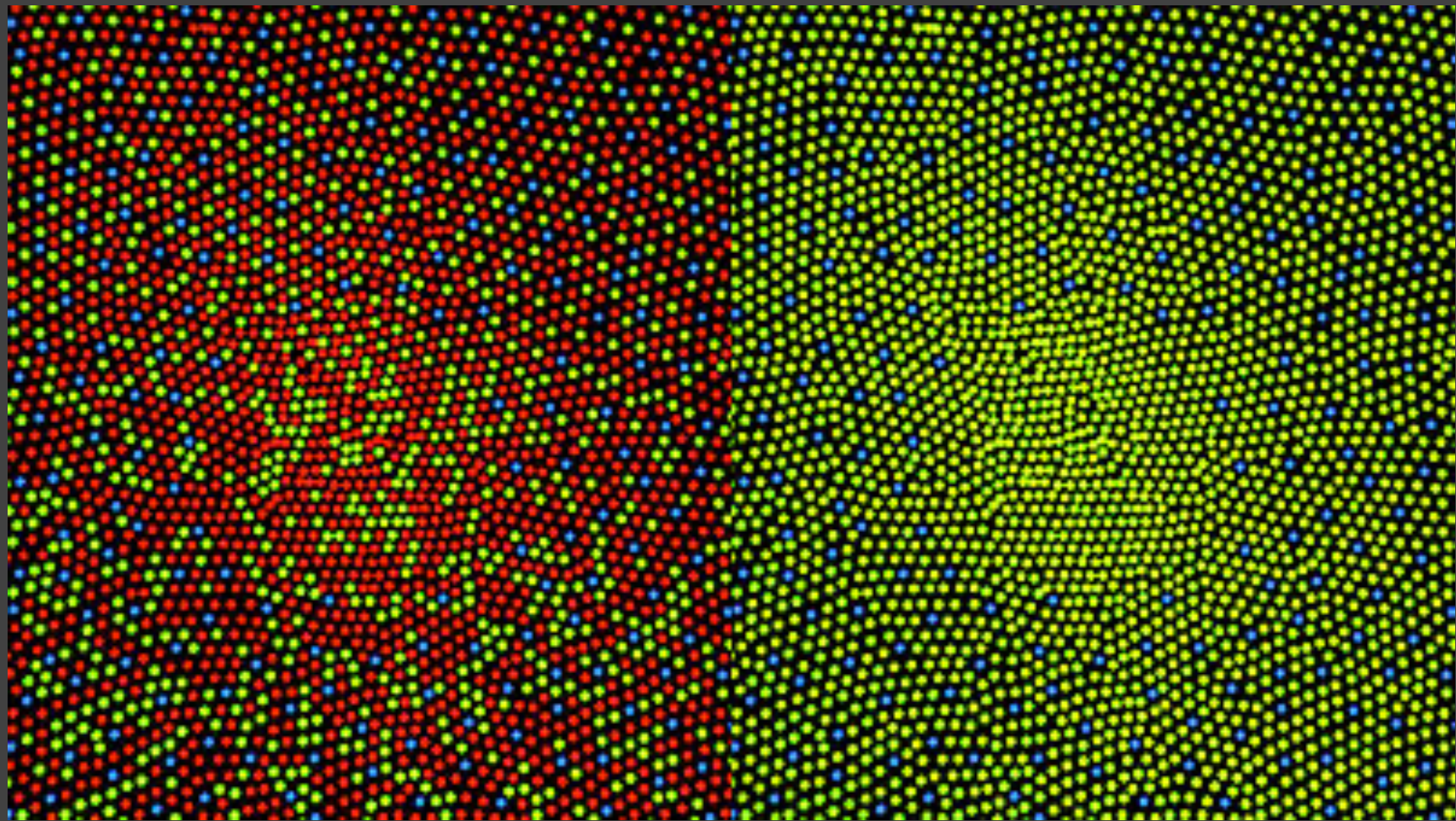
Missing one or more cones or rods in retina.



Protanope

Deuteranope

Luminance



Normal Retina

Protanopia



# Color Vision Simulators

Simulate color vision deficiencies

Browser plug-ins

Photoshop plug-ins, etc.



Deuteranope

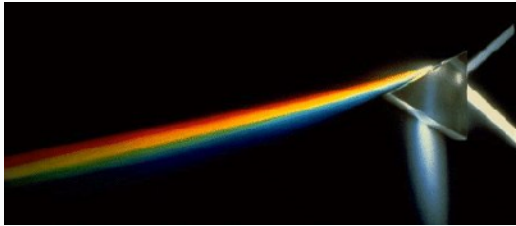


Protanope

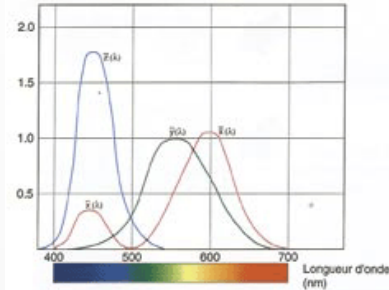


Tritanope

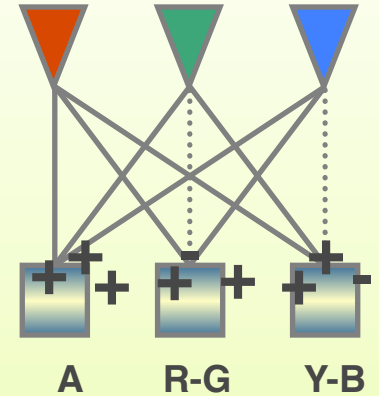
# Perception of Color



Light



Cone Response



Opponent Signals

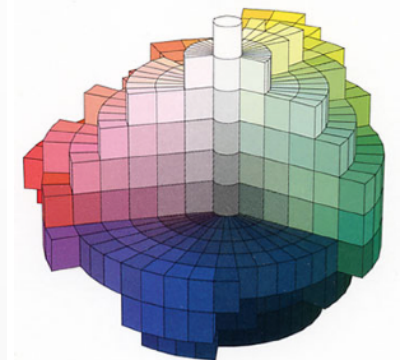
“Yellow”

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**

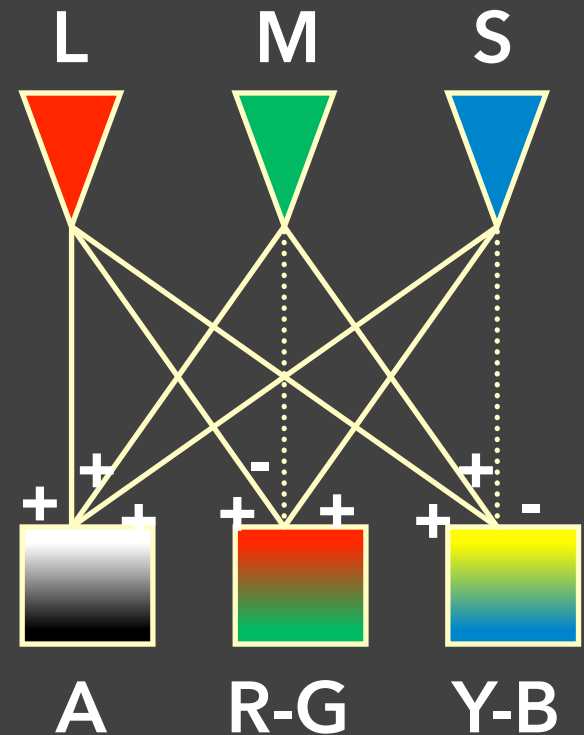
# Opponent Processing

**LMS are combined to create:**

Lightness

Red-green contrast

Yellow-blue contrast



[Fairchild]

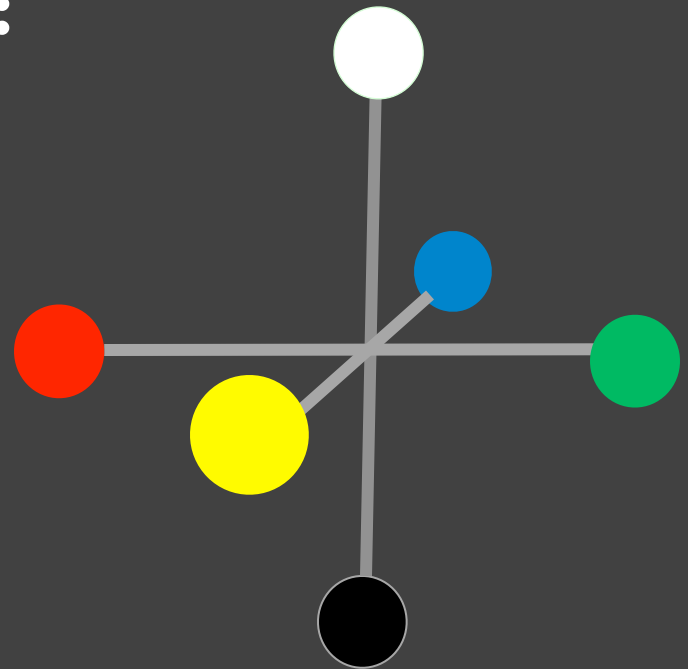
# Opponent Processing

**LMS are combined to create:**

Lightness

Red-green contrast

Yellow-blue contrast



# Opponent Processing

**LMS are combined to create:**

Lightness

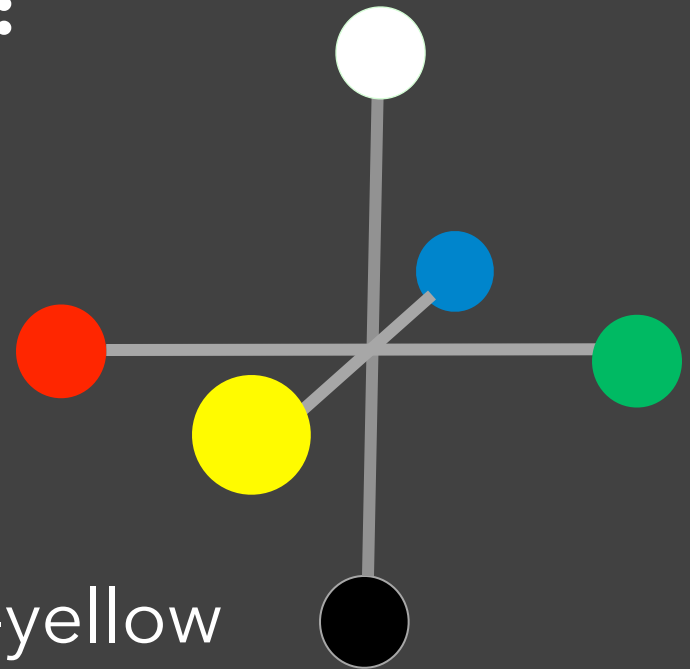
Red-green contrast

Yellow-blue contrast

**Experiments:**

No reddish-green, no blueish-yellow

Color after images









# CIE LAB Color Space

Axes correspond to opponent signals

**L\*** = Luminance

**a\*** = Red-green contrast

**b\*** = Yellow-blue contrast

Much more perceptually uniform than RGB!

Scaling of axes to represent "color distance"

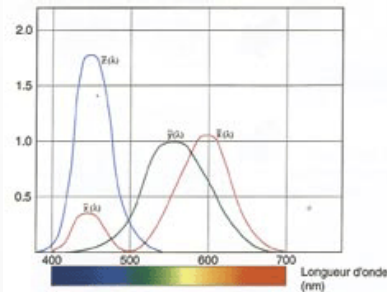
JND = Just noticeable difference (~2.3 units)

D3 + Vega include LAB color space support

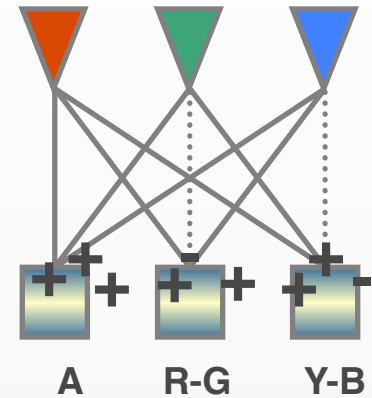
# Perception of Color



Light



Cone Response



Opponent Signals

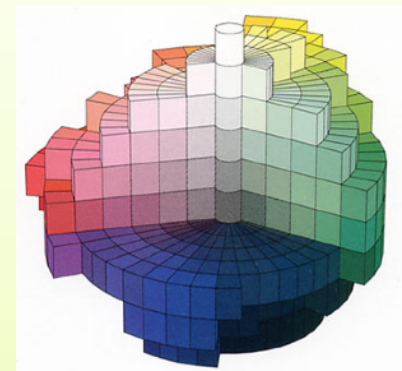
“Yellow”

Color Cognition



Mark D. Fairchild  
COLOR APPEARANCE  
MODELS

Color Appearance



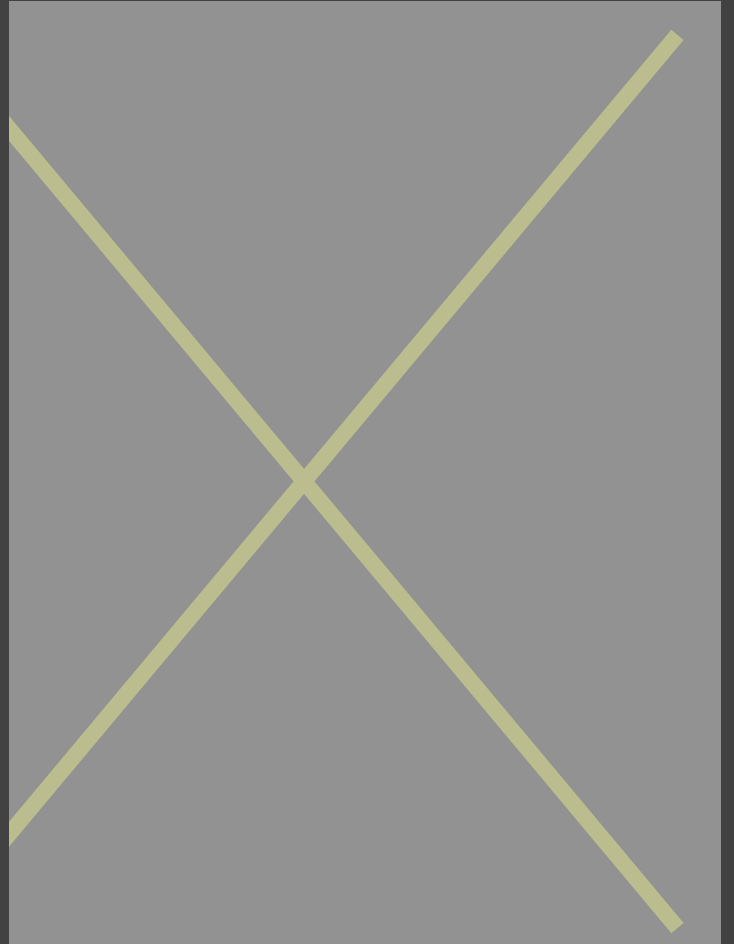
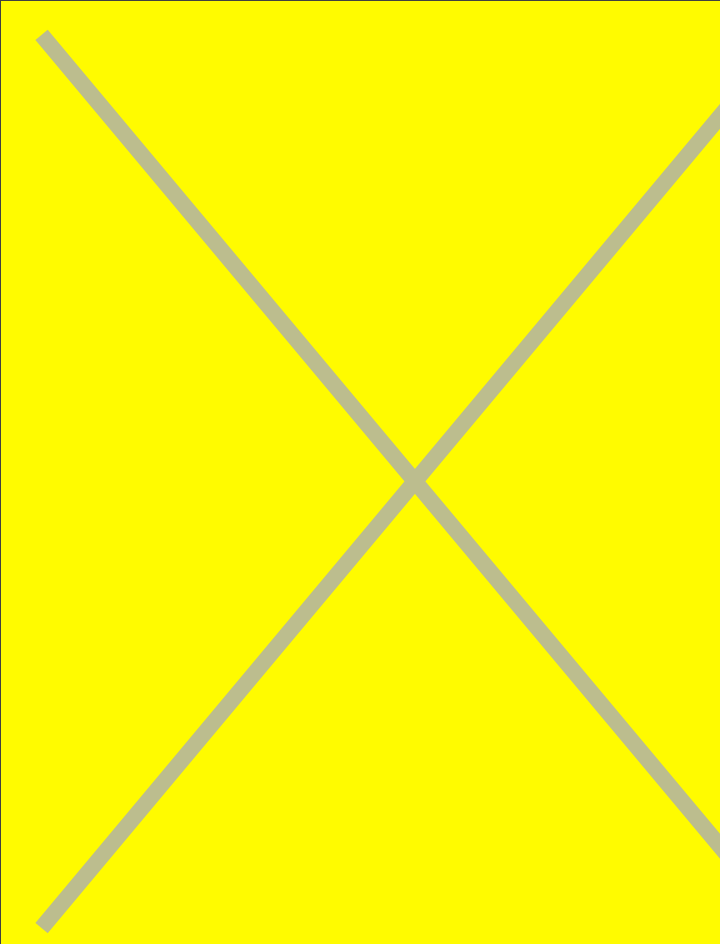
Color Perception

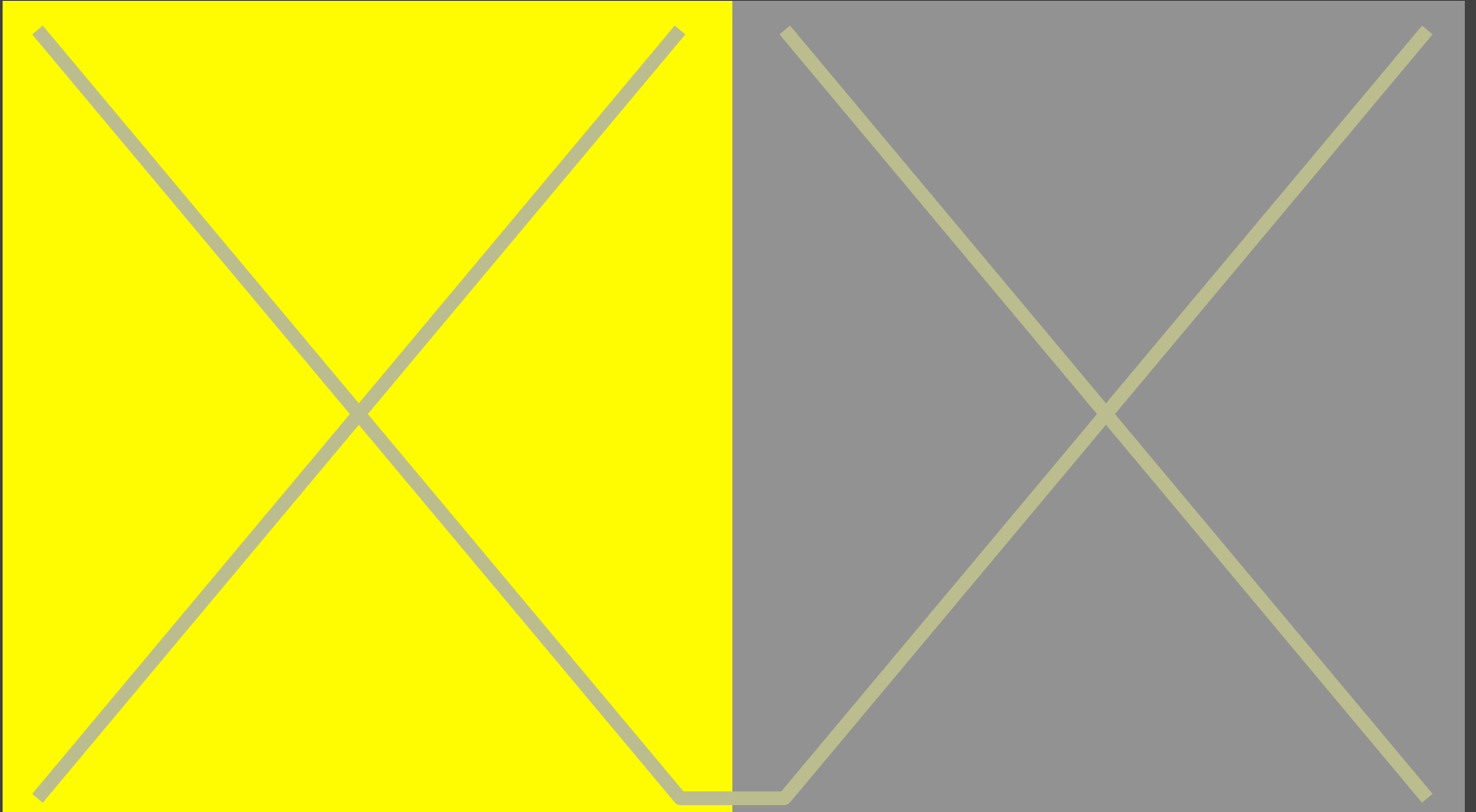
# Color Appearance

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

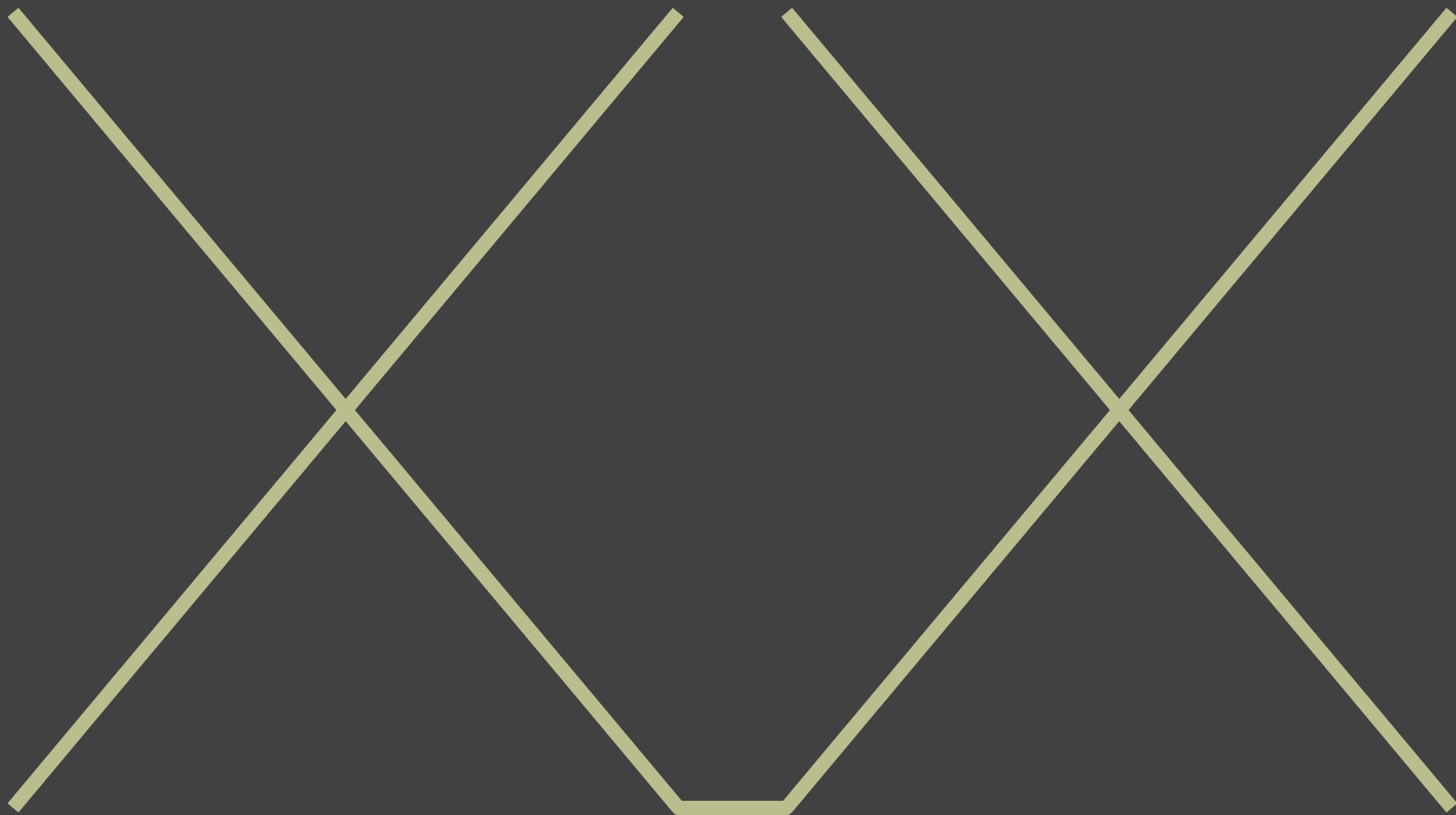
**“In order to use color effectively it is necessary to recognize that it deceives continually.”**

- Josef Albers, *Interaction of Color*

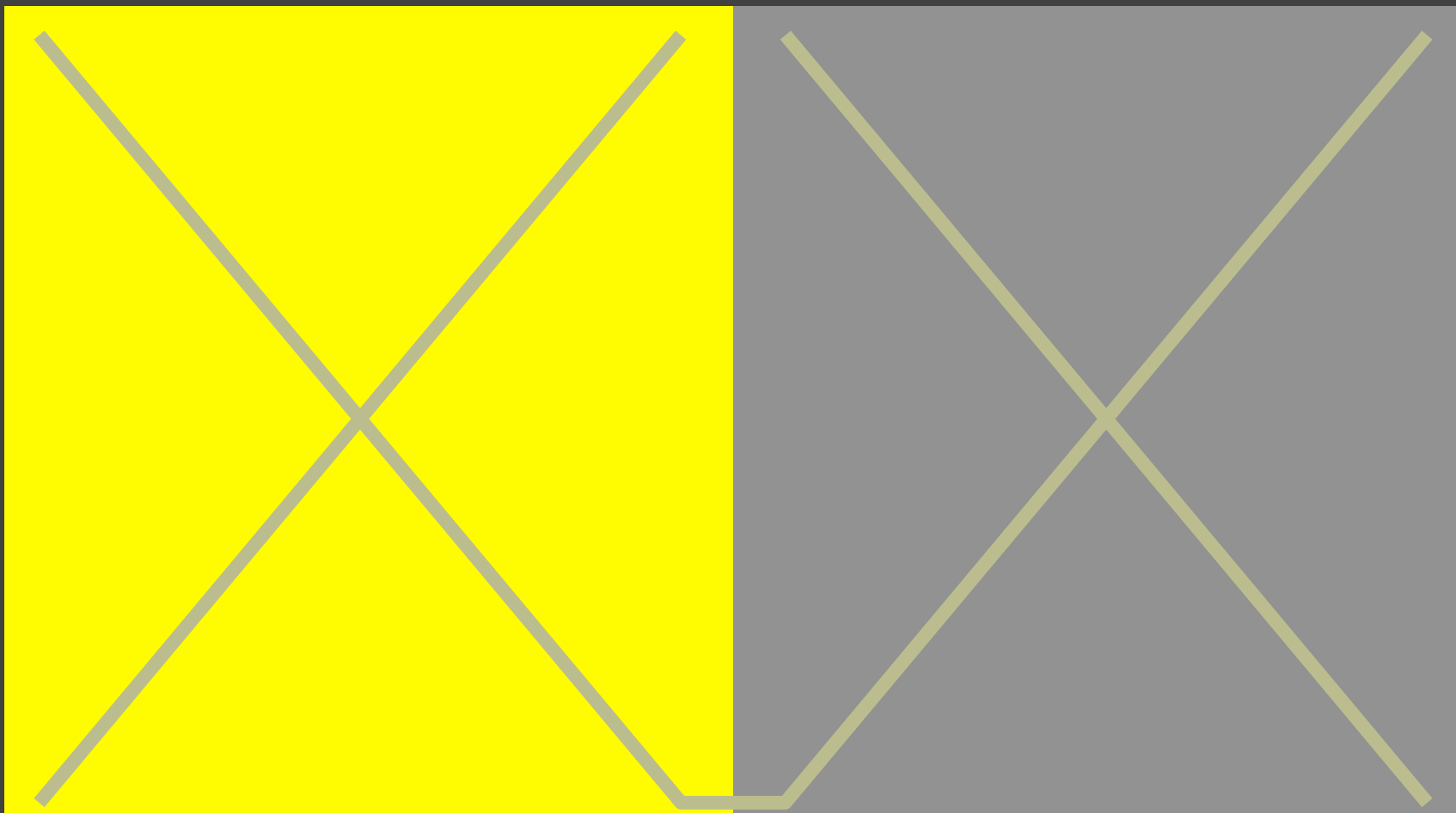








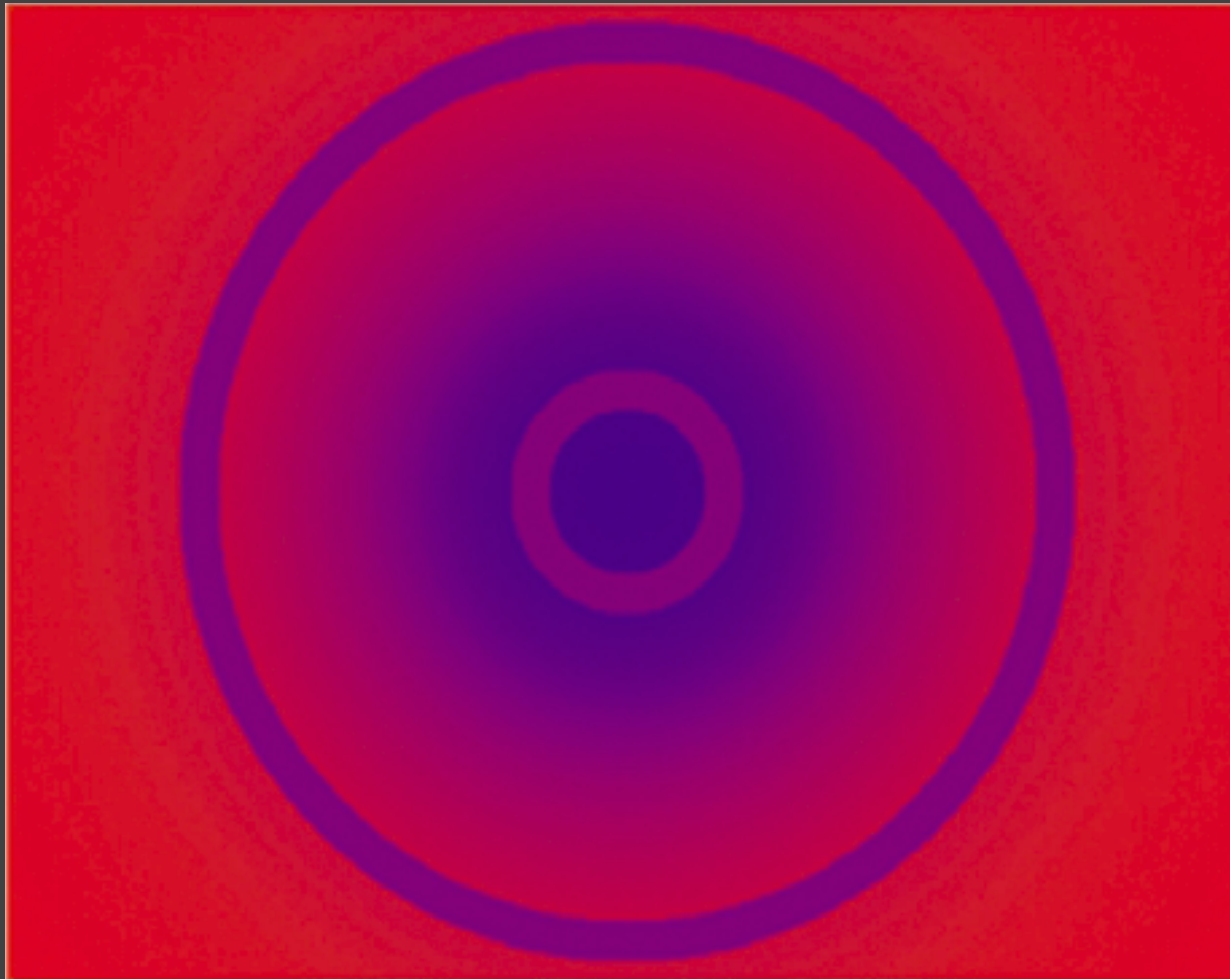
# Simultaneous Contrast



Josef Albers

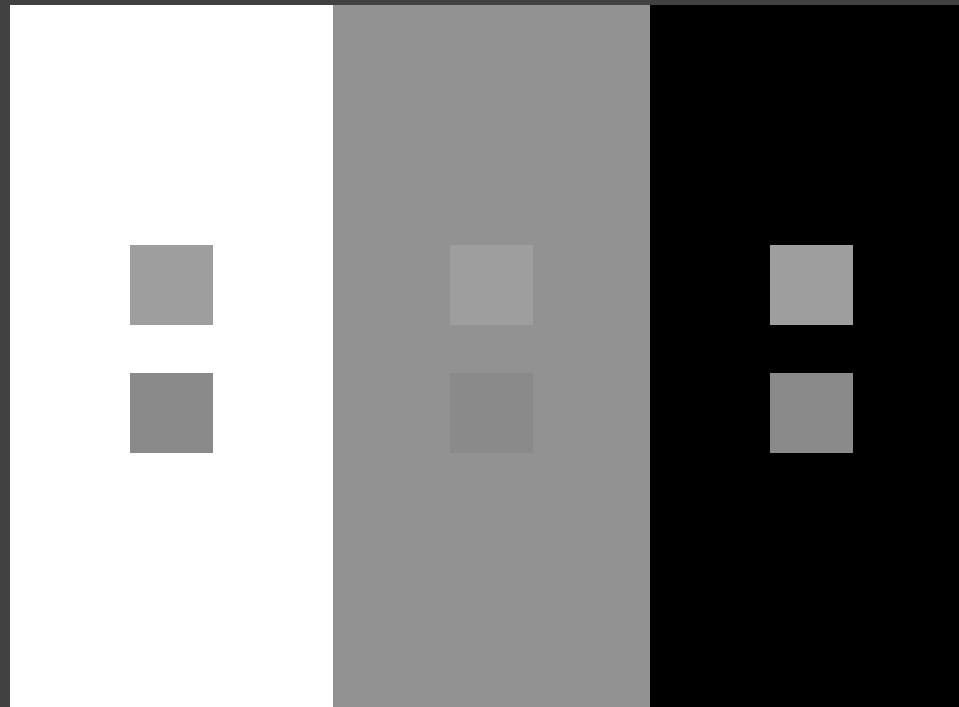
# Simultaneous Contrast

Inner & outer rings are the same physical purple.



# Crispening

Perceived difference depends on background

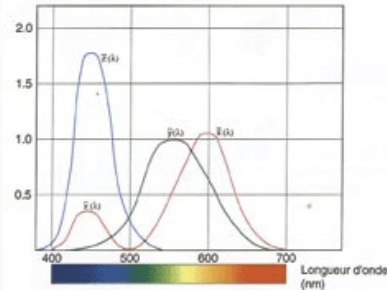


*Color Appearance Models, Fairchild*

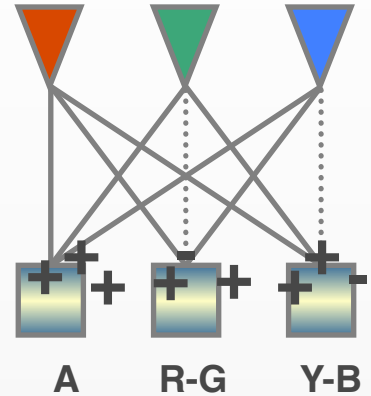
# Perception of Color



Light



Cone Response



Opponent Signals

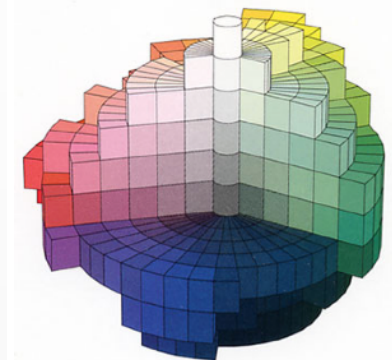
“Yellow”

Color Cognition



Mark D. Fairchild  
COLOR APPEARANCE  
MODELS

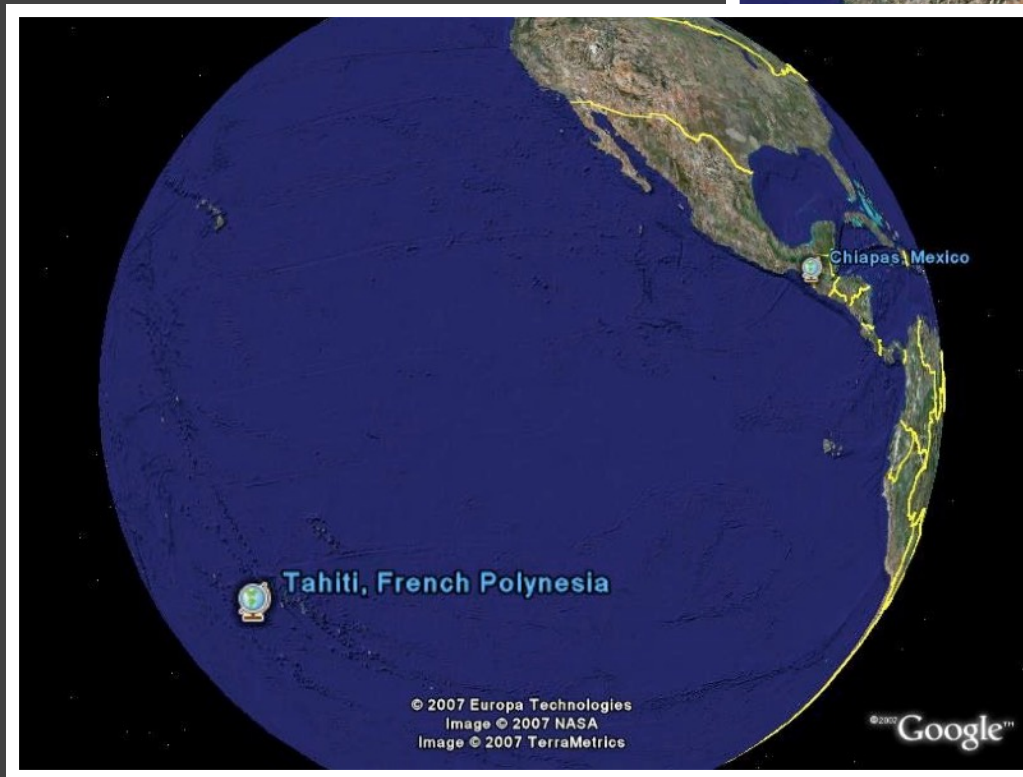
Color Appearance



Color Perception

# Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.



# Basic Color Terms

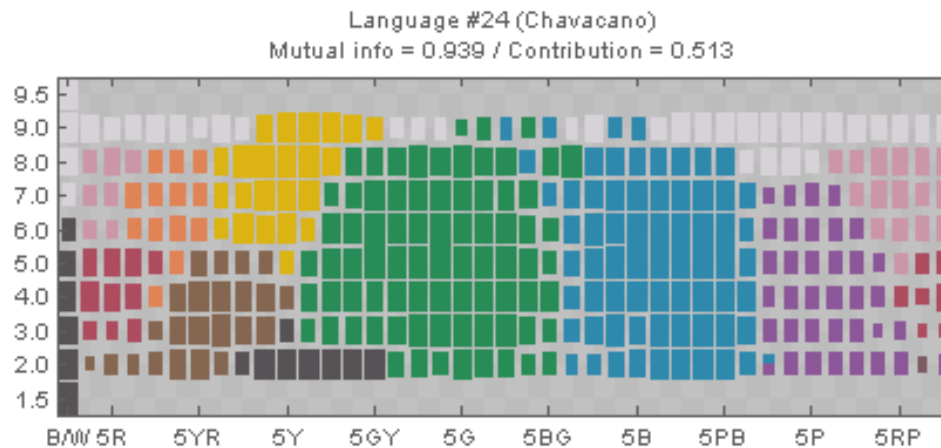
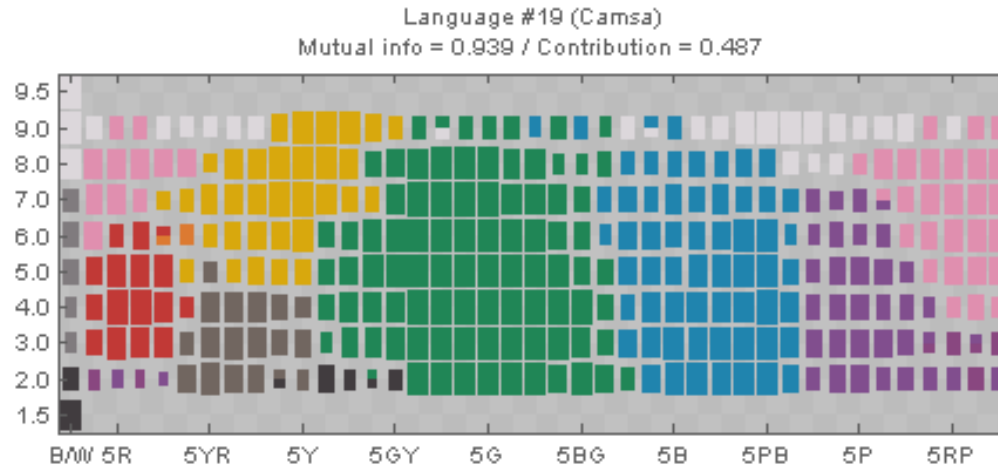
Chance discovery by Brent Berlin and Paul Kay.

Initial study in 1969

Surveyed speakers from 20 languages

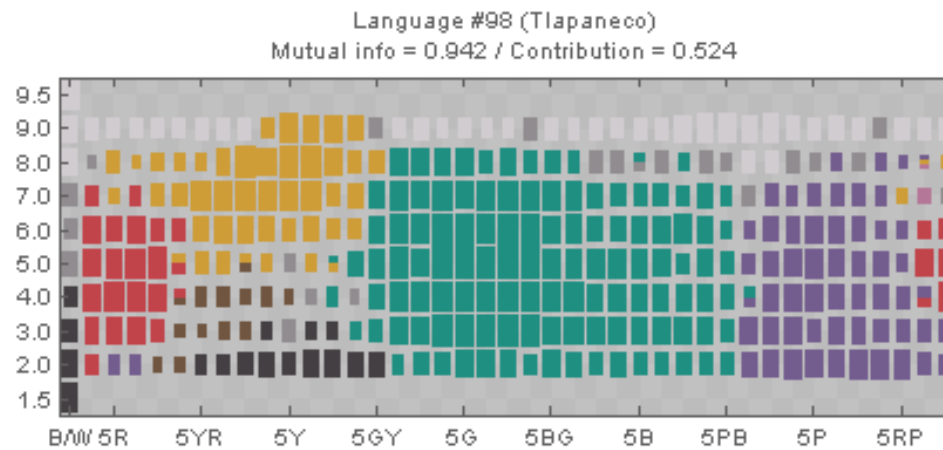
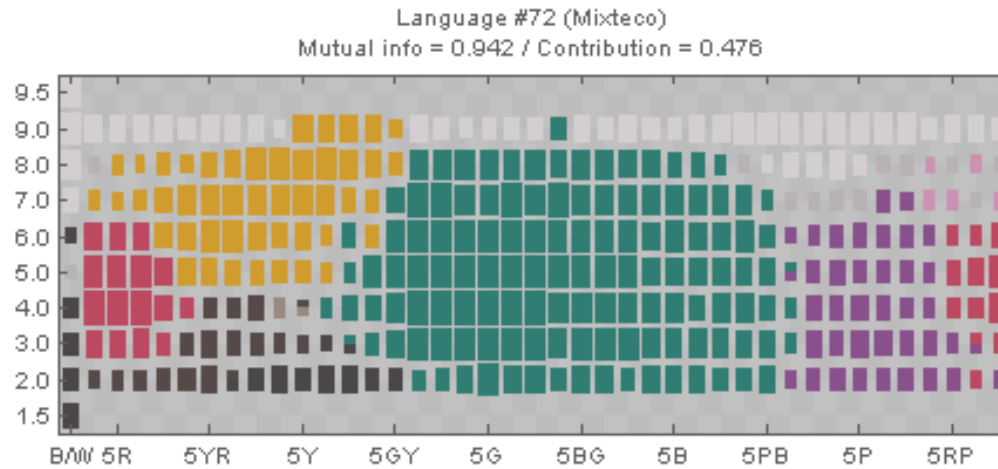
Literature from 69 languages

# Results from WCS





# Results from WCS



# Universal (?) Basic Color Terms

Basic color terms recur across languages.



White



Red



Pink



Grey



Yellow



Brown



Black



Green



Orange



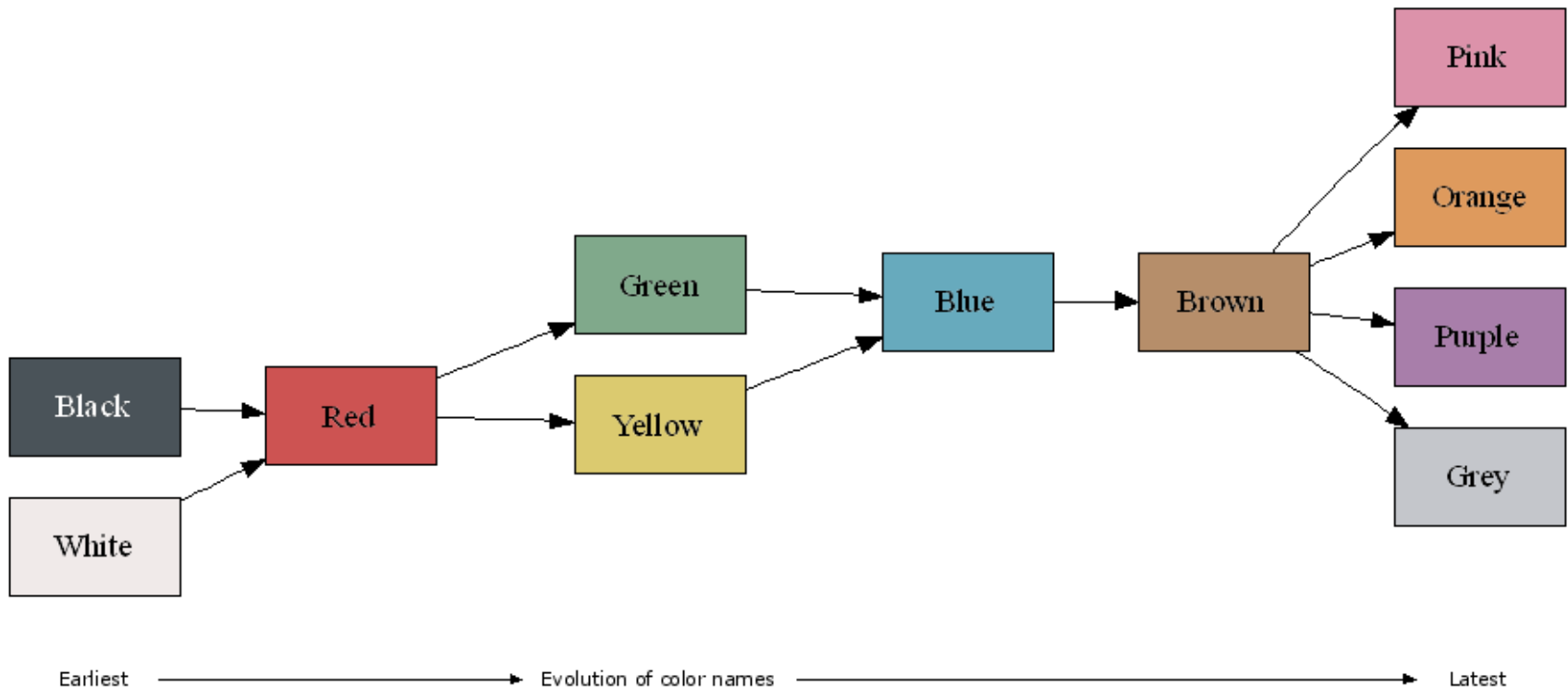
Blue



Purple

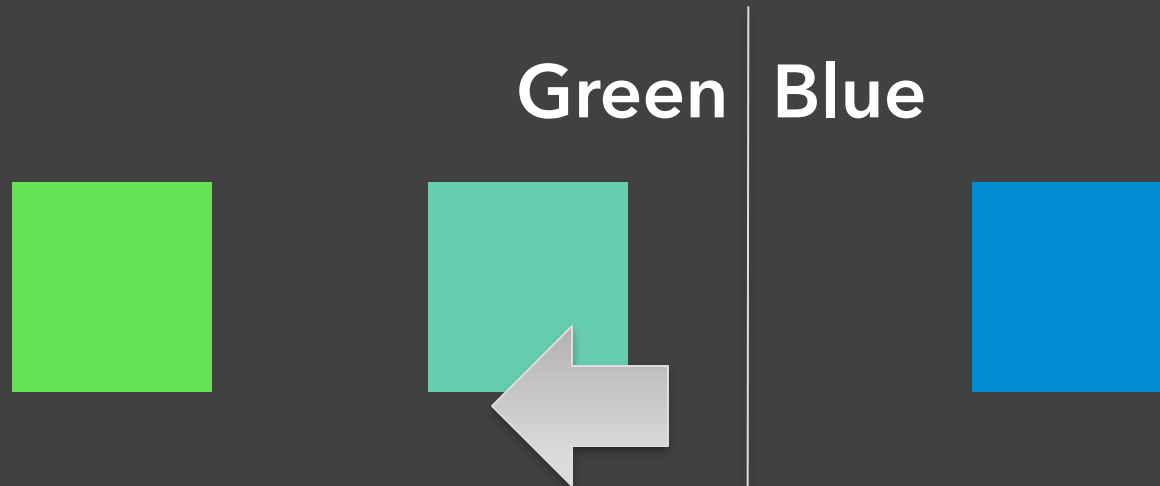
# Evolution of Basic Color Terms

Proposed term evolution across languages.



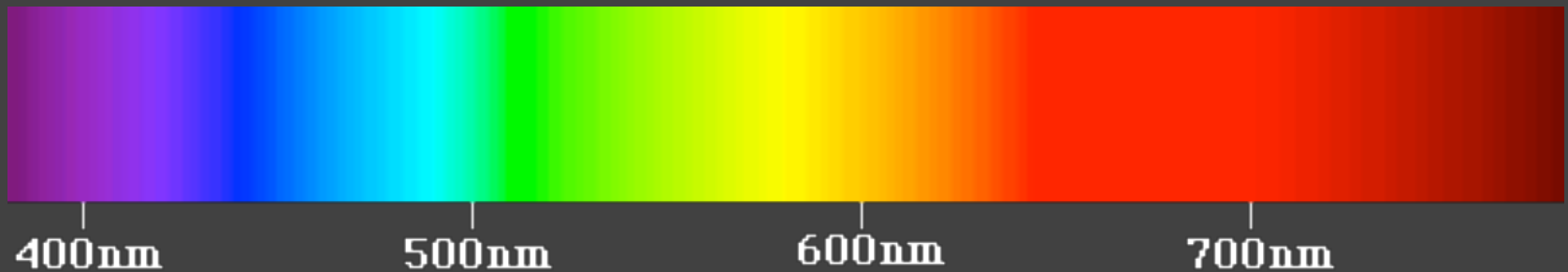
# Naming Effects Color Perception

Color name boundaries



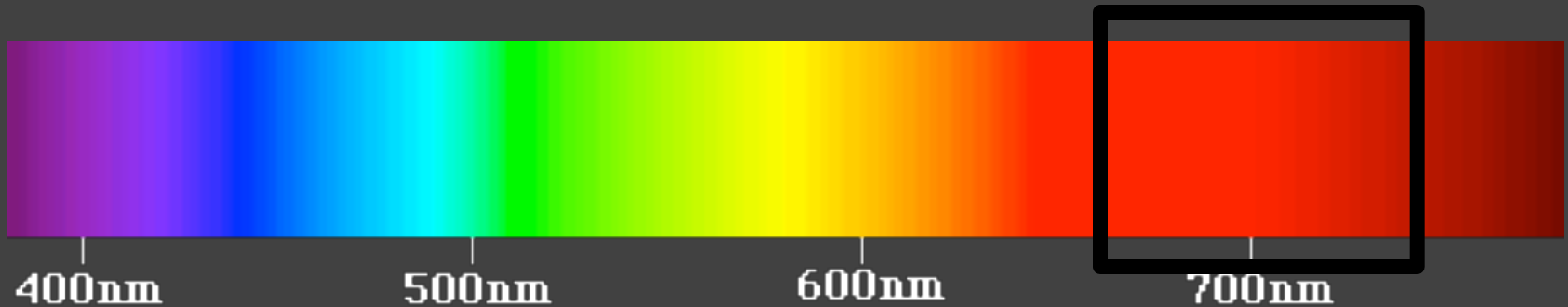
# Rainbow Color Map

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



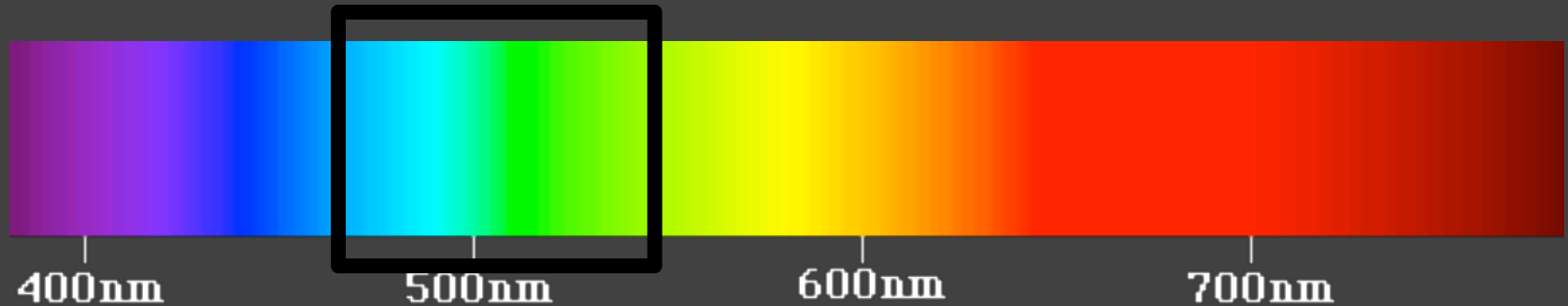
# Rainbow Color Map

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

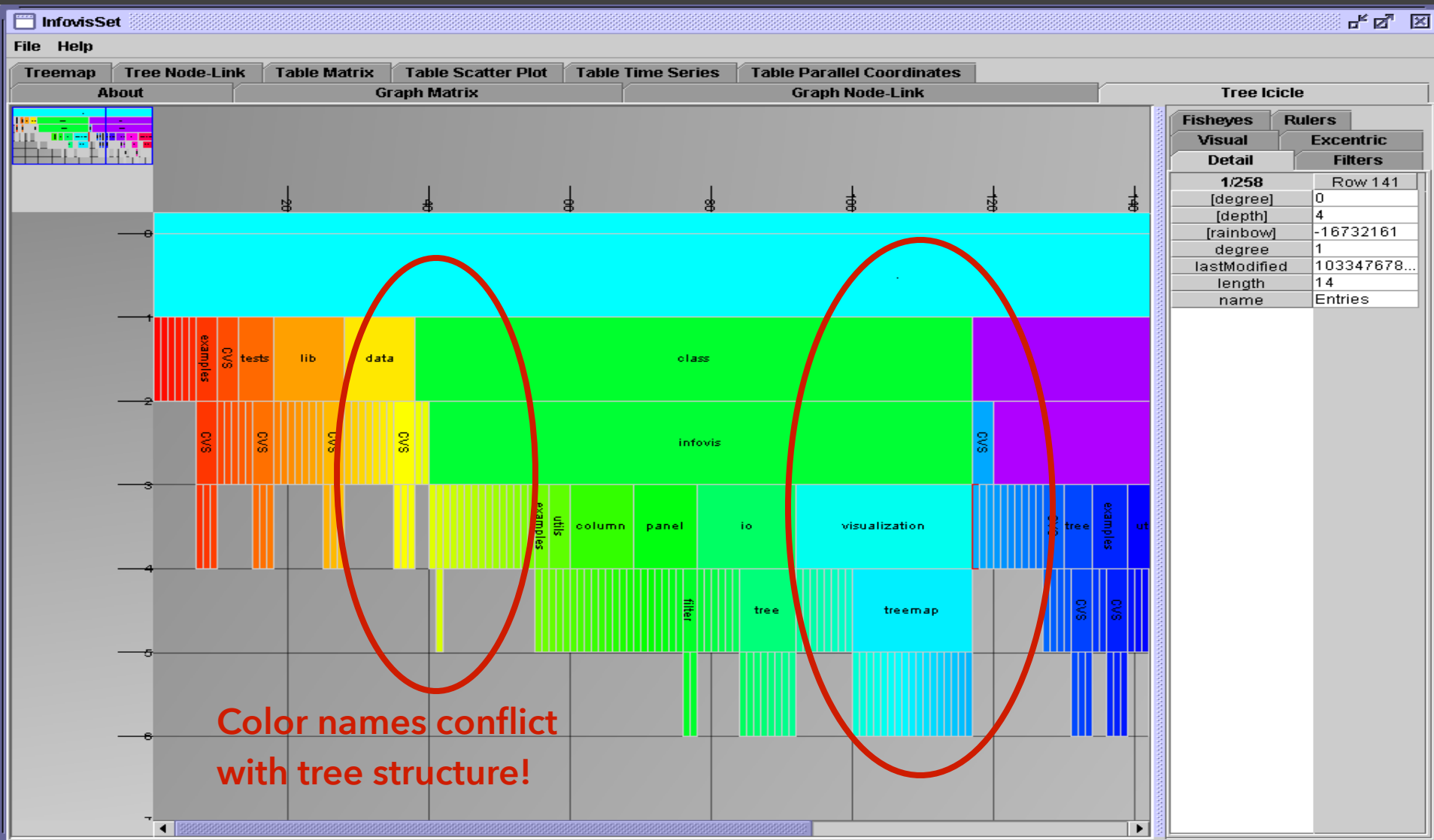


# Rainbow Color Map

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



# Icicle Tree with Rainbow Coloring





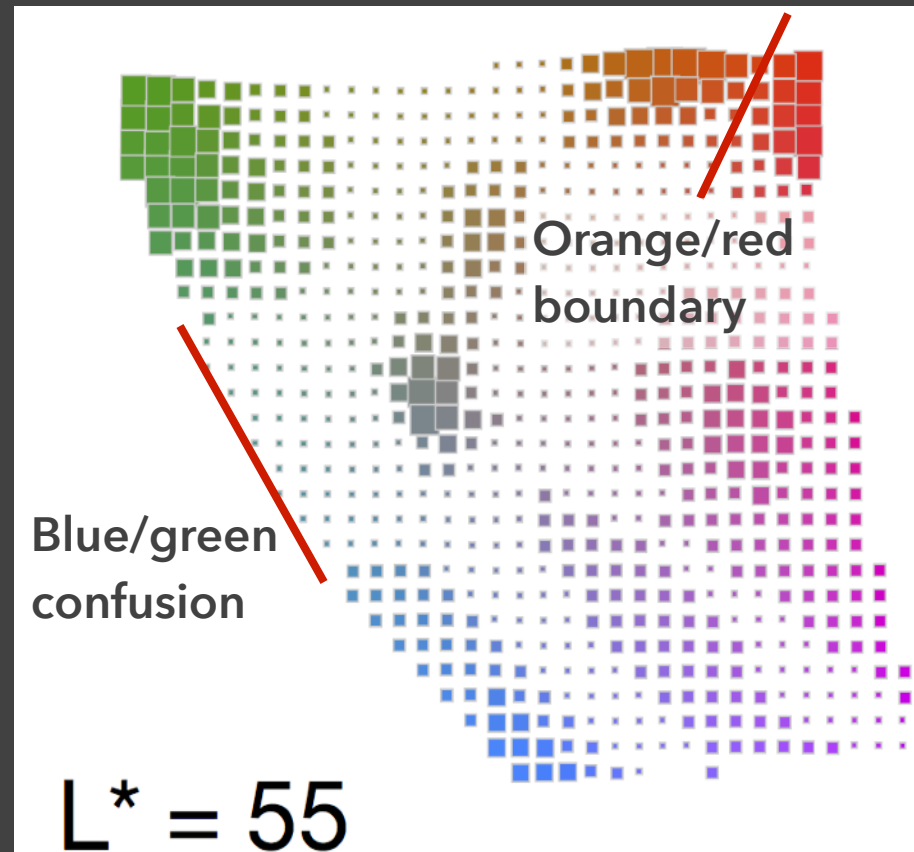
# Color Naming Models [Heer & Stone '12]

Model 3 million responses from XKCD survey

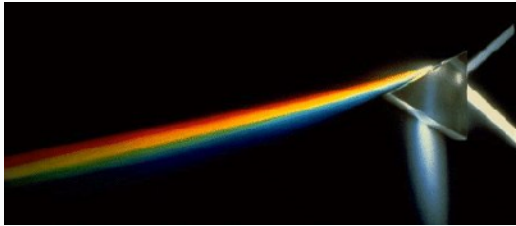
Bins in LAB space  
sized by *saliency*:

How much do people  
agree on color name?

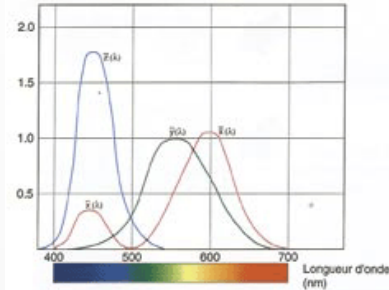
Modeled by entropy  
of  $p(\text{name} \mid \text{color})$



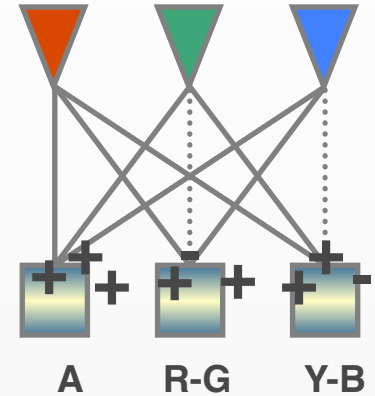
# Perception of Color



Light



Cone Response



Opponent Signals

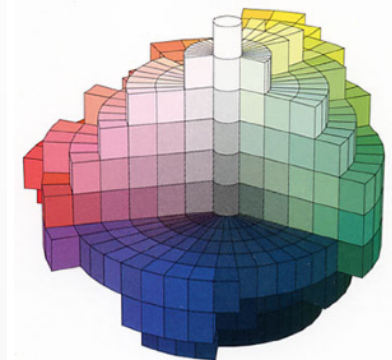
“Yellow”

Color Cognition



Mark D. Fairchild  
COLOR APPEARANCE  
MODELS

Color Appearance



Color Perception

# Designing Colormaps

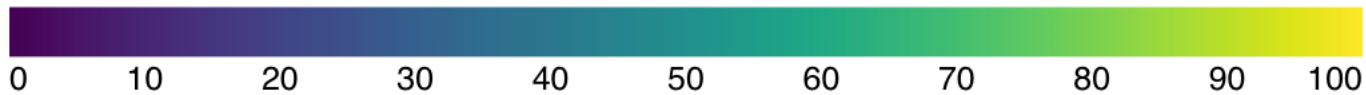
# Discrete (Binary, Categorical)

## Symbol Legend



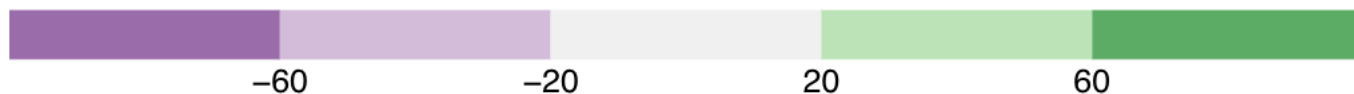
# Continuous (Sequential, Diverging, Cyclic)

## Gradient Legend



# Discretized Continuous

## Discrete Gradient



# Colormap Design Considerations

Perceptually distinguishable colors

Value distance matches perceptual distance

Colors and concepts properly align

Aesthetically pleasing, intriguing

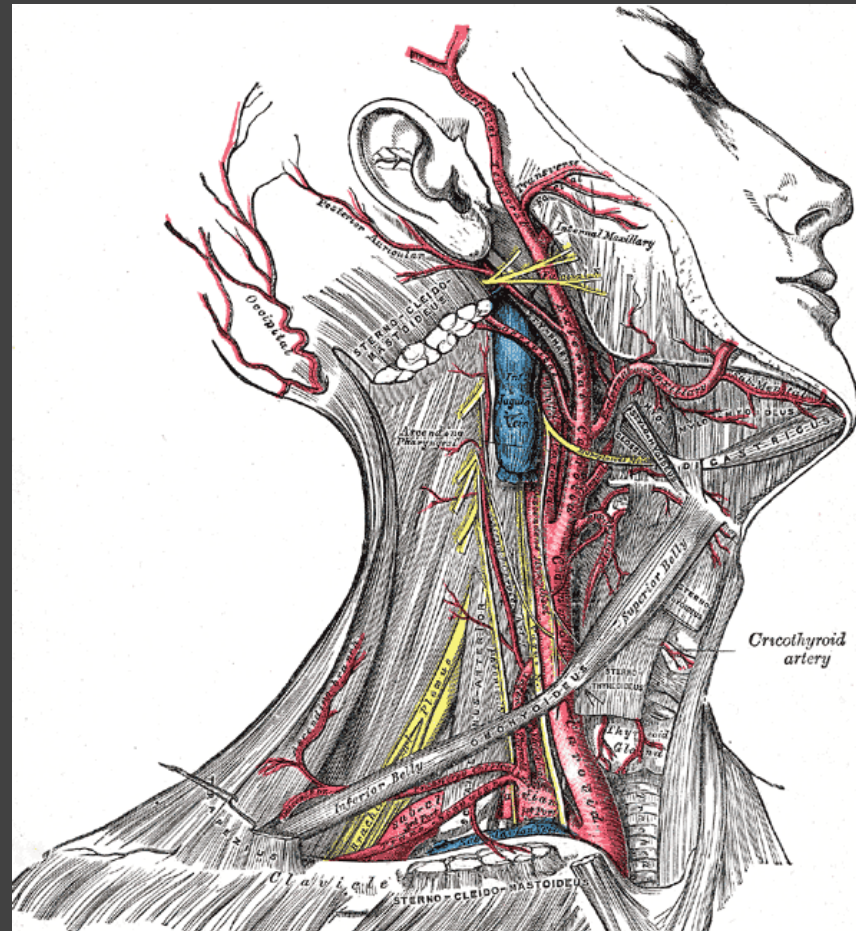
Respect color vision deficiencies

Should survive printing to black & white

Don't overwhelm people's capability!

# Categorical Color

# Gray's Anatomy



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

# Allocation of the Radio Spectrum

## UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM

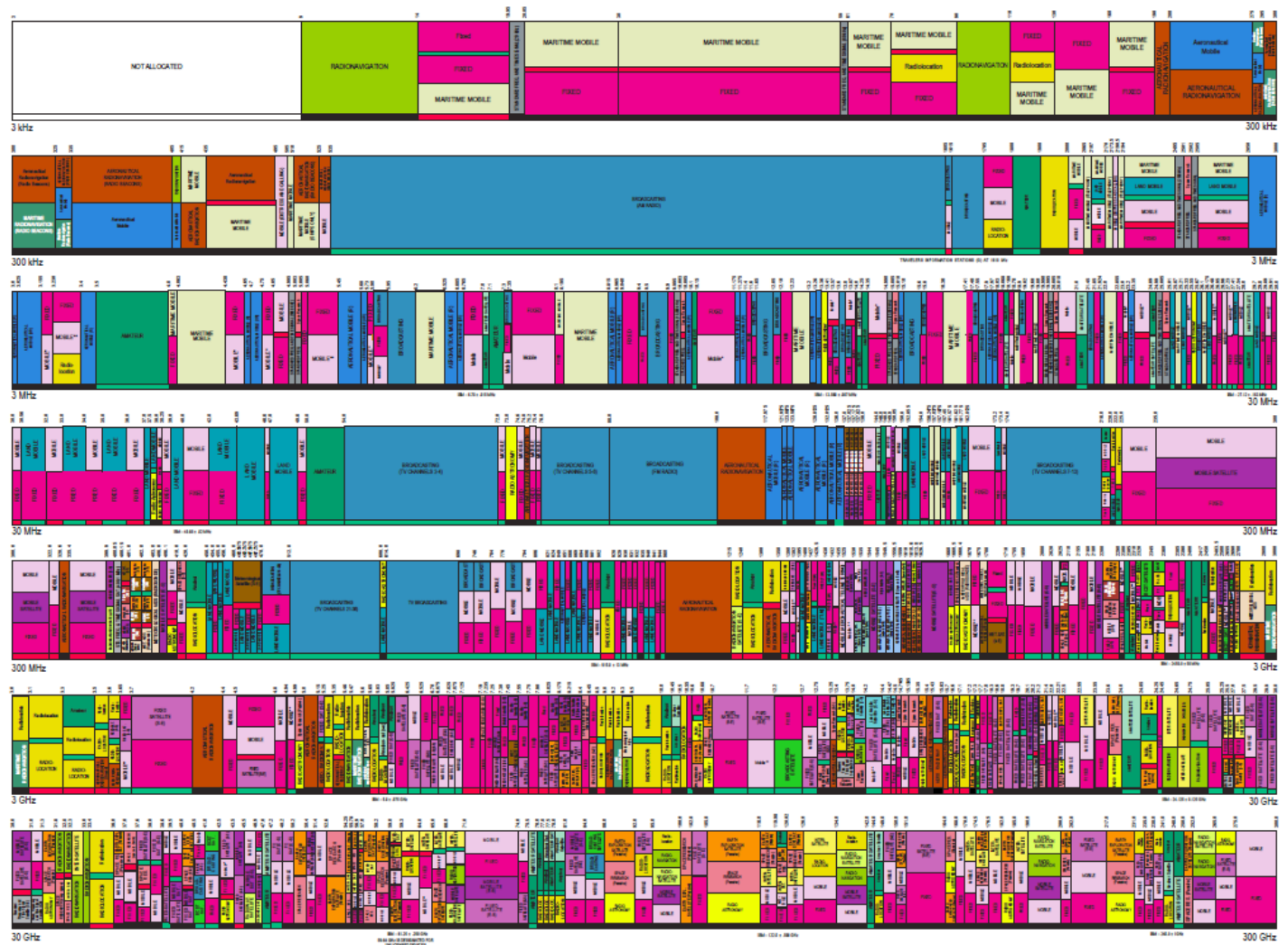
### RADIO SERVICES COLOR LEGEND

- |                               |                           |  |
|-------------------------------|---------------------------|--|
| AERONAUTICAL MOBILE           | HYPER-SATELLITE           | RADIO ASTRONOMY                              |
| AERONAUTICAL MOBILE SATELLITE | LAND MOBILE               | RADIO DETERMINATION SATELLITE                |
| AERONAUTICAL RADIO NAVIGATION | LAND MOBILE SATELLITE     | RADIO LOCATION                               |
| AMATEUR                       | MARITIME MOBILE           | RADIO LOCATION SATELLITE                     |
| AMATEUR SATELLITE             | MARITIME MOBILE SATELLITE | RADIO NAVIGATION                             |
| BROADCASTING                  | MARITIME RADIO NAVIGATION | RADIO NAVIGATION SATELLITE                   |
| BROADCASTING SATELLITE        | METEOROLOGICAL AID        | SPACE OPERATION                              |
| EARTH DEPLOYMENT 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 USE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	F1E2	Capital Letters
Secondary	F1E2	Capital Letters





# Alloc

# 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

## ACTIVITY CODE

### RADIO SERVICES COLOR LEGEND

<input type="checkbox"/> AERONAUTICAL MOBILE	<input type="checkbox"/> INTER-SATELLITE	<input type="checkbox"/> RADIO ASTRONOMY
<input type="checkbox"/> AERONAUTICAL MOBILE SATELLITE	<input type="checkbox"/> LAND MOBILE	<input type="checkbox"/> RADIODETERMINATION SATELLITE
<input type="checkbox"/> AERONAUTICAL RADIONAVIGATION	<input type="checkbox"/> LAND MOBILE SATELLITE	<input type="checkbox"/> RADIOLOCATION
<input type="checkbox"/> AMATEUR	<input type="checkbox"/> MARITIME MOBILE	<input type="checkbox"/> RADIOLOCATION SATELLITE
<input type="checkbox"/> AMATEUR SATELLITE	<input type="checkbox"/> MARITIME MOBILE SATELLITE	<input type="checkbox"/> RADIONAVIGATION
<input type="checkbox"/> BROADCASTING	<input type="checkbox"/> MARITIME RADIONAVIGATION	<input type="checkbox"/> RADIONAVIGATION SATELLITE
<input type="checkbox"/> BROADCASTING SATELLITE	<input type="checkbox"/> METEOROLOGICAL AIDS	<input type="checkbox"/> SPACE OPERATION
<input type="checkbox"/> EARTH EXPLORATION SATELLITE	<input type="checkbox"/> METEOROLOGICAL SATELLITE	<input type="checkbox"/> SPACE RESEARCH
<input type="checkbox"/> FIXED	<input type="checkbox"/> MOBILE	<input type="checkbox"/> STANDARD FREQUENCY AND TIME SIGNAL
<input type="checkbox"/> FIXED SATELLITE	<input type="checkbox"/> MOBILE SATELLITE	<input type="checkbox"/> STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

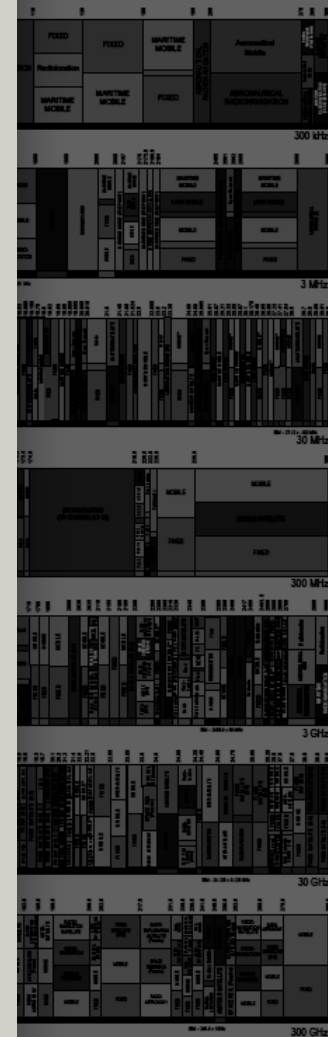
### ACTIVITY CODE

<input type="checkbox"/> GOVERNMENT EXCLUSIVE	<input type="checkbox"/> GOVERNMENT-GOVERNMENT SHARED
<input type="checkbox"/> NON-GOVERNMENT EXCLUSIVE	

### ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	Alphabetical

# rum



# Allocation of the Radio Spectrum

## UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM

### RADIO SERVICES COLOR LEGEND

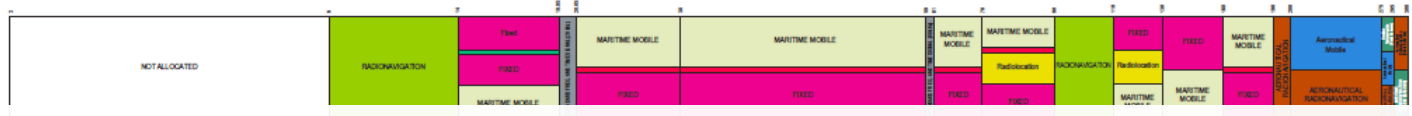
AERONAUTICAL MOBILE	INTERSATELLITE	RADIO ASTRONOMY
AERONAUTICAL MOBILE SATELLITE	LAND MOBILE	RADIO DETERMINATION SATELLITE
AERONAUTICAL RADIOLOCATION	LAND MOBILE SATELLITE	RADIO LOCATION
AMATEUR	MARITIME MOBILE	RADIO LOCATION SATELLITE
AMATEUR SATELLITE	MARITIME MOBILE SATELLITE	RADIO NAVIGATION
BROADCASTING	MARITIME RADIOLOCATION	RADIO NAVIGATION 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

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

### ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	Capital Letters



## Issues:

Too many colors

Hard to remember mapping

Colors not distinctive, some are very similar

Poor grouping: similar colors, different values

Labels cause clutter

Color surround effects

Colors interactions may not look good together



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

Saliency

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

Name

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

Tableau-10

Average 0.97

.52

# Palette Design & Color Names

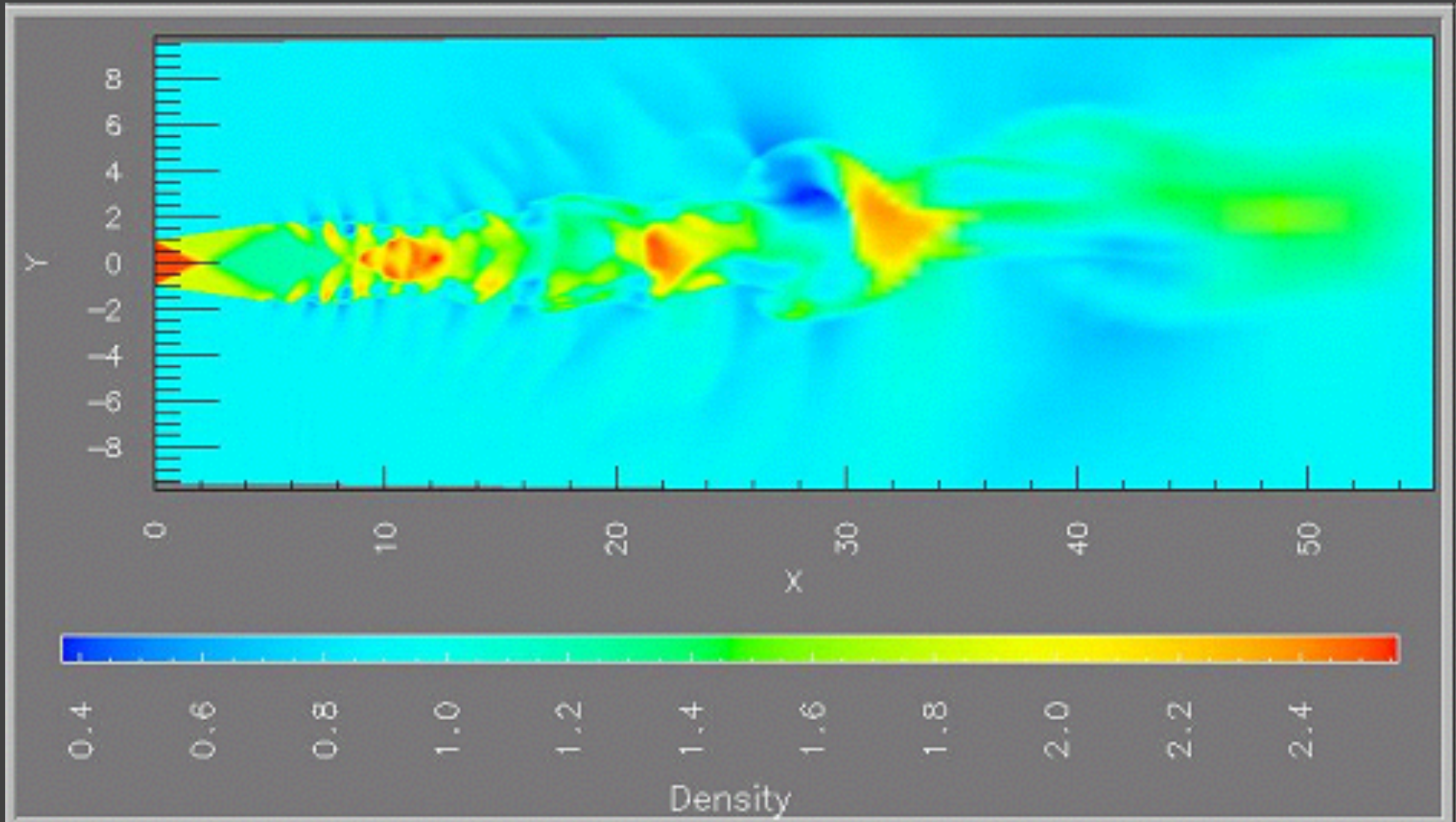
Minimize overlap and ambiguity of colors.

Color Name Distance

	1	2	3	4	5	6	7	8	9	10	Saliency	Name
<b>0.00</b>	1.00	1.00	0.89	<b>0.07</b>	1.00	<b>0.35</b>	0.99	1.00	0.89		.30	<b>blue</b> 50.5%
1.00	<b>0.00</b>	0.99	1.00	1.00	0.92	1.00	<b>0.84</b>	0.98	0.99		.21	<b>red</b> 27.8%
1.00	0.99	<b>0.00</b>	1.00	0.98	1.00	1.00	1.00	<b>0.17</b>	1.00		.34	<b>green</b> 36.8%
0.89	1.00	1.00	<b>0.00</b>	0.98	1.00	<b>0.71</b>	0.93	1.00	<b>0.32</b>		.55	<b>purple</b> 67.3%
<b>0.07</b>	1.00	0.98	0.98	<b>0.00</b>	1.00	<b>0.36</b>	1.00	0.97	0.95		.20	<b>blue</b> 36.6%
1.00	0.92	1.00	1.00	1.00	<b>0.00</b>	1.00	0.97	0.99	1.00		.39	<b>orange</b> 51.9%
<b>0.35</b>	1.00	1.00	<b>0.71</b>	<b>0.36</b>	1.00	<b>0.00</b>	0.95	0.92	<b>0.42</b>		.13	<b>blue</b> 15.7%
0.99	<b>0.84</b>	1.00	0.93	1.00	0.97	0.95	<b>0.00</b>	0.98	<b>0.85</b>		.16	<b>pink</b> 29.4%
1.00	0.98	<b>0.17</b>	1.00	0.97	0.99	0.92	0.98	<b>0.00</b>	0.97		.12	<b>green</b> 21.7%
0.89	0.99	1.00	<b>0.32</b>	0.95	1.00	<b>0.42</b>	0.85	0.97	<b>0.00</b>		.30	<b>purple</b> 23.9%
<b>Excel-10</b>	<i>Average</i>									<b>0.87</b>	<b>.27</b>	

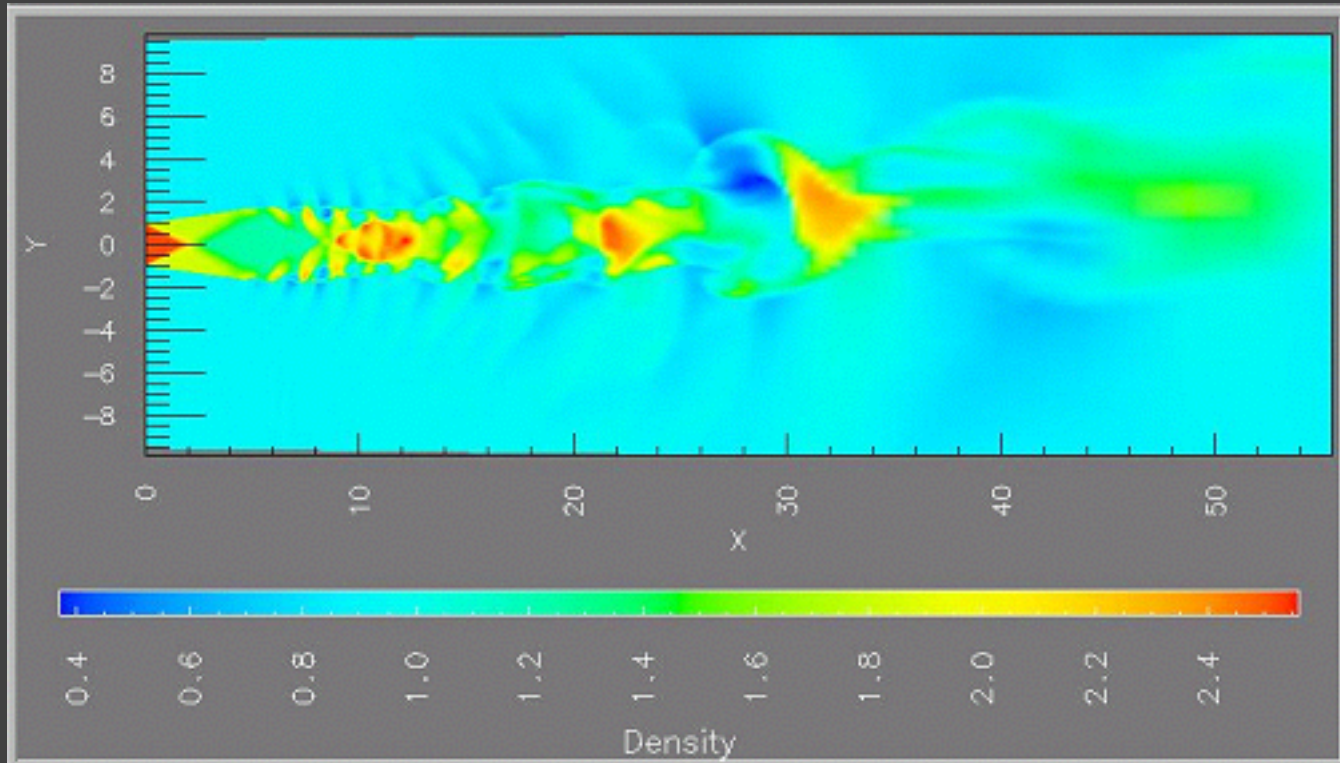
# Quantitative Color

# Rainbow Color Maps





# Be Wary of Naïve Rainbows!



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

# Steps, rather than Gradients?

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  
153, 216, 201  
44, 162, 95

adjust map context  
 roads  cities  borders

select a background  
 solid color  terrain

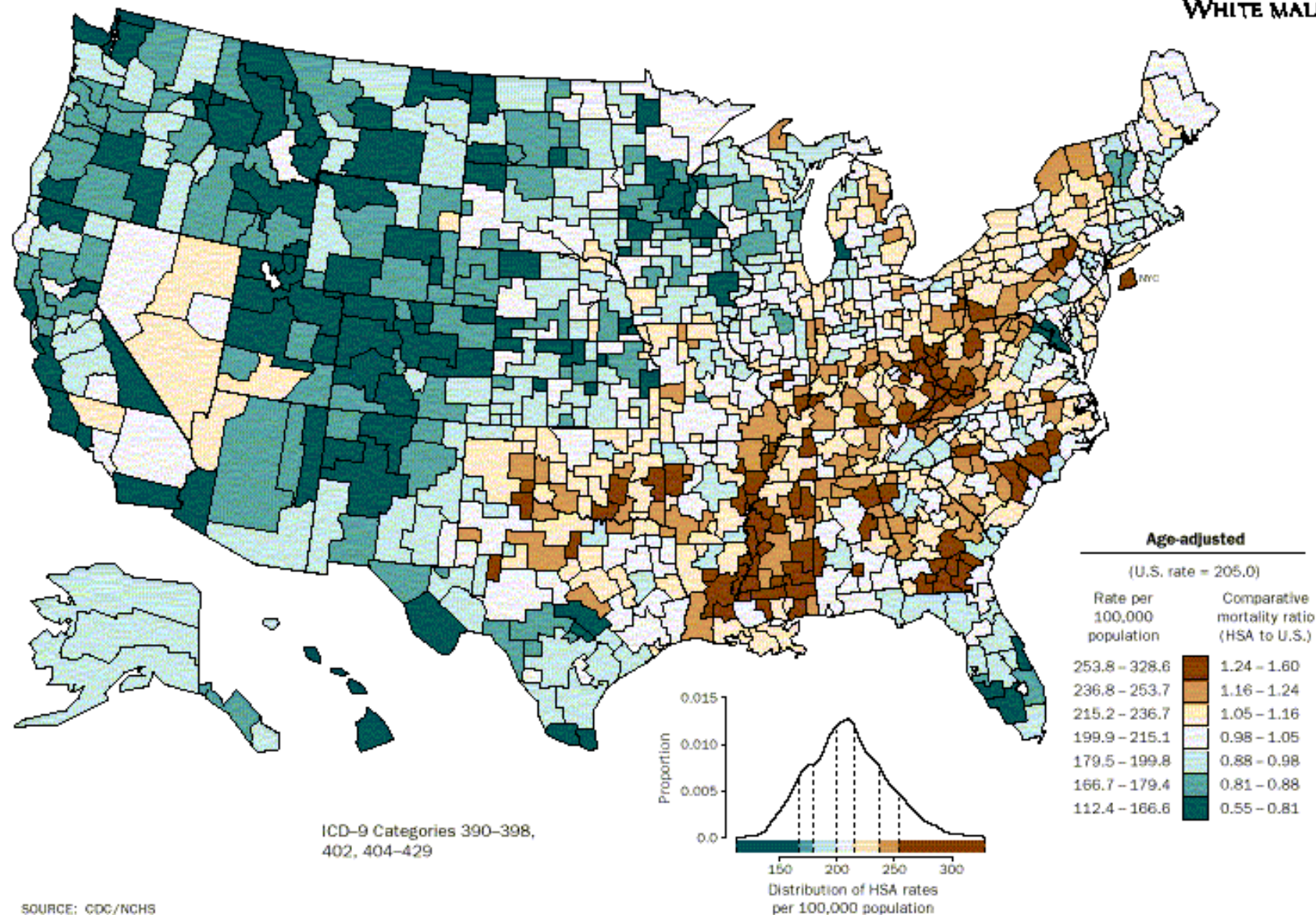
how to use | updates | credits

**COLORBREWER 2.0**  
color advice for cartography

SCORE CARD

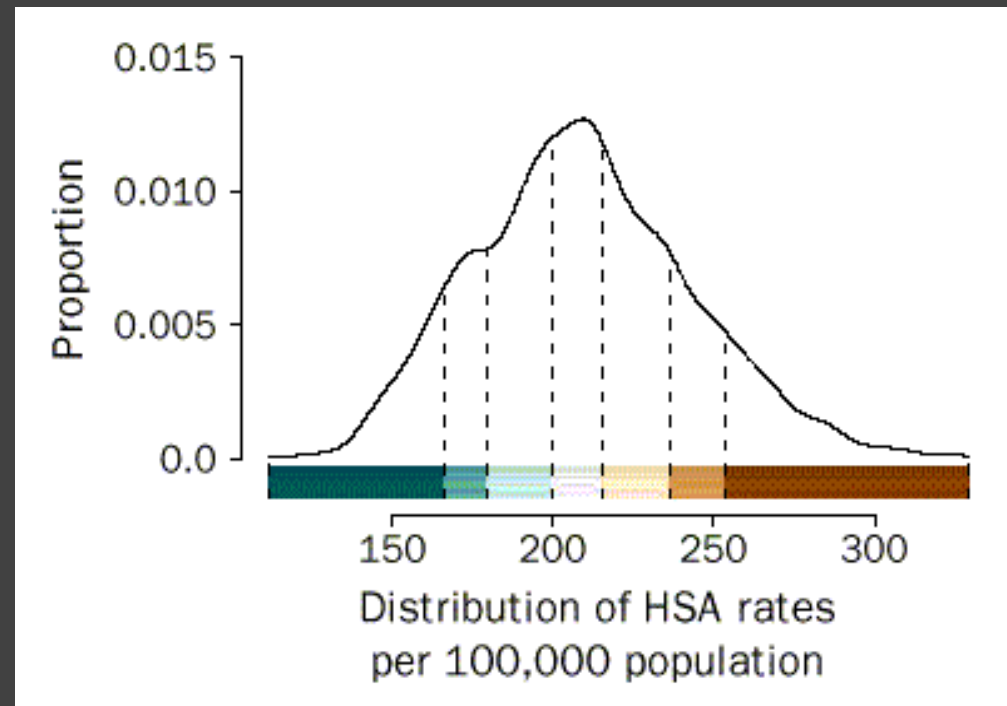
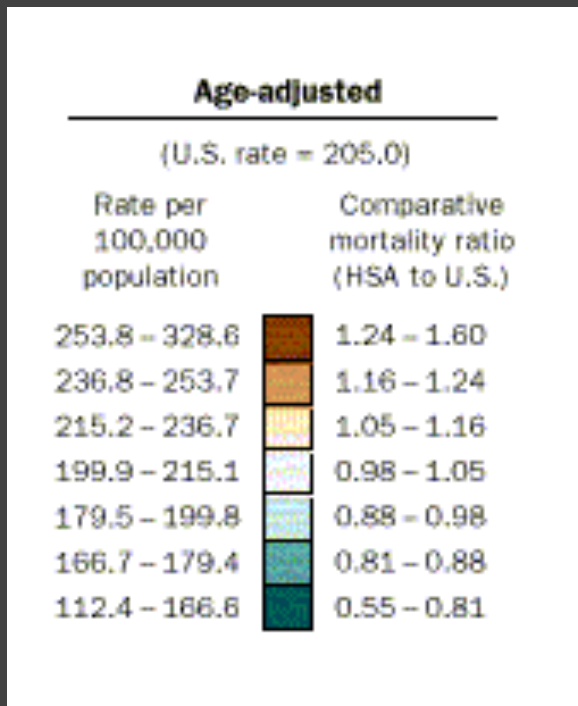


## AGE-ADJUSTED DEATH RATES BY HSA, 1988-92

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

Ramp in luminance, possibly also hue

Higher value -> darker color (or vice versa)



# Quantitative Color Encoding

## Sequential color scale

Ramp in luminance, possibly also hue

Higher value -> darker color (or vice versa)

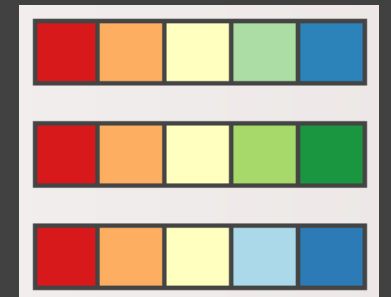


## Diverging color scale

Useful when data has meaningful "midpoint"

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

Use saturated colors for endpoints



# Quantitative Color Encoding

## Sequential color scale

Ramp in luminance, possibly also hue

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## Limit number of steps in color to 3-9

*Why?*

# Quantitative Color Encoding

## Sequential color scale

Ramp in luminance, possibly also hue

Higher value -> darker color (or vice versa)



## Diverging color scale

Useful when data has meaningful "midpoint"

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

Use saturated colors for endpoints

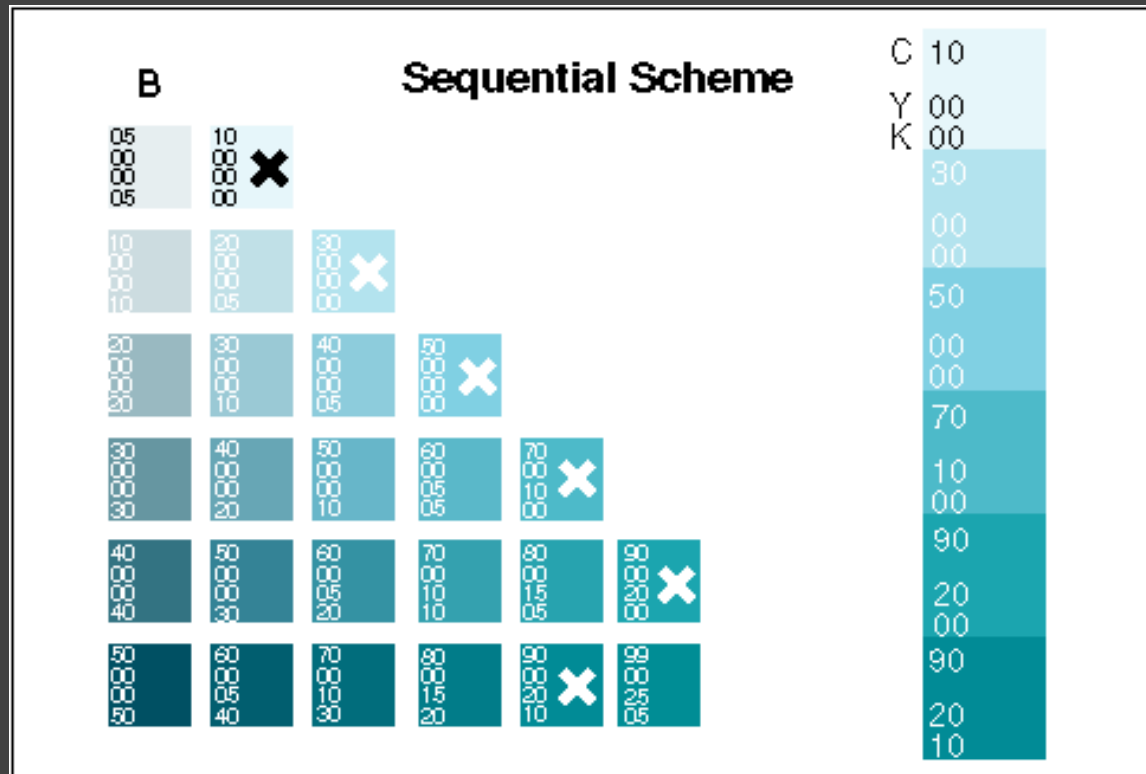


## Limit number of steps in color to 3-9

Avoid simultaneous contrast, hold mappings in memory

# Sequential Scales: Single-Hue

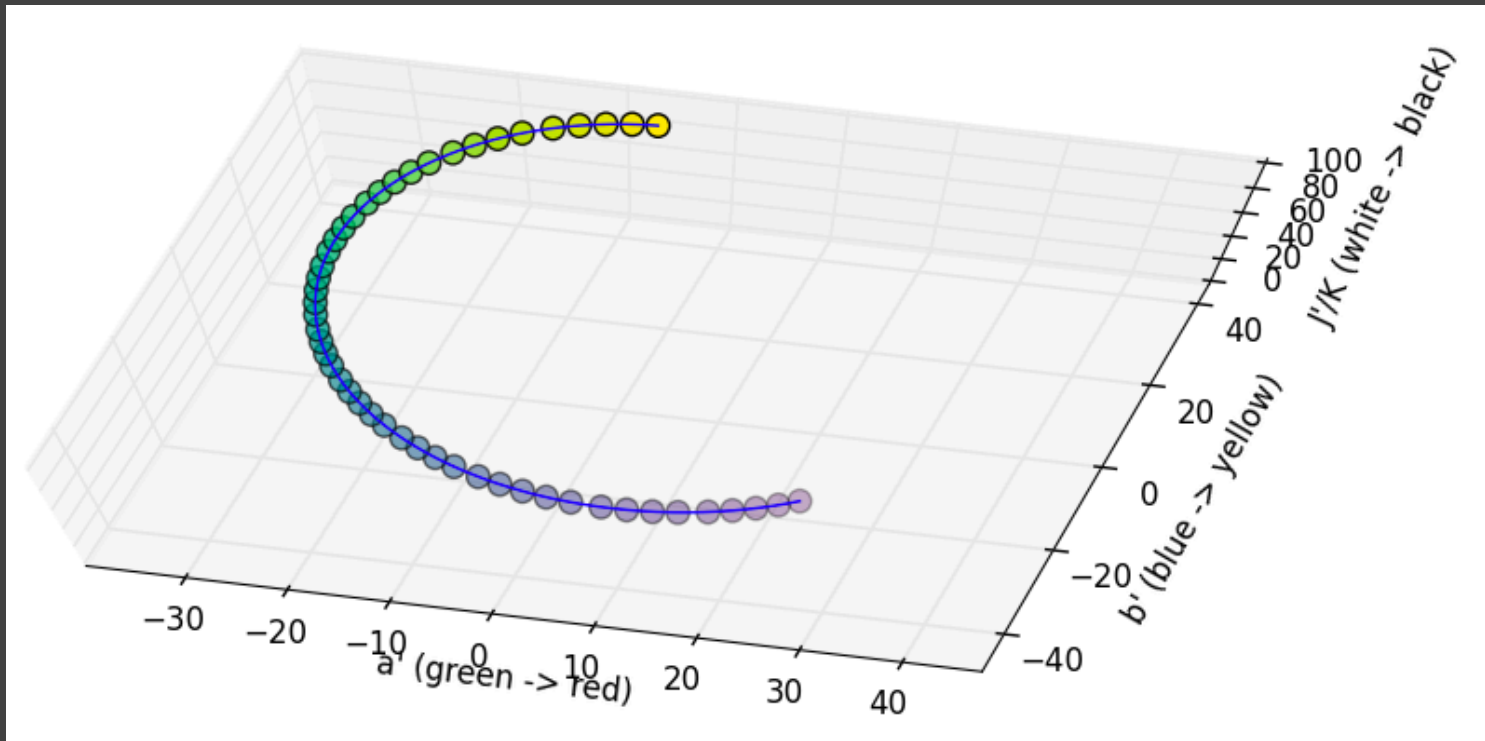
Ramp primarily in luminance, subtle hue difference



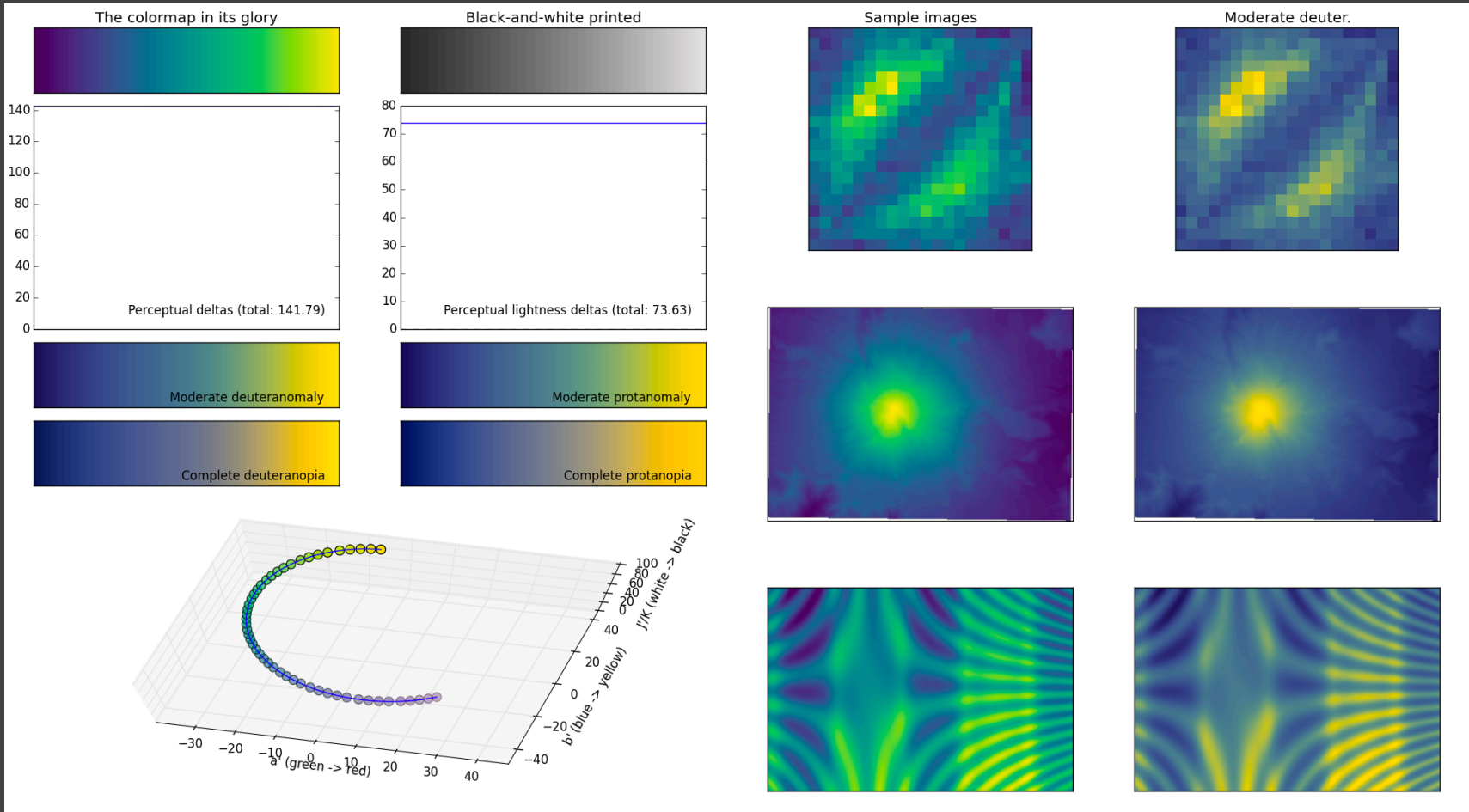


# Sequential Scales: Multi-Hue

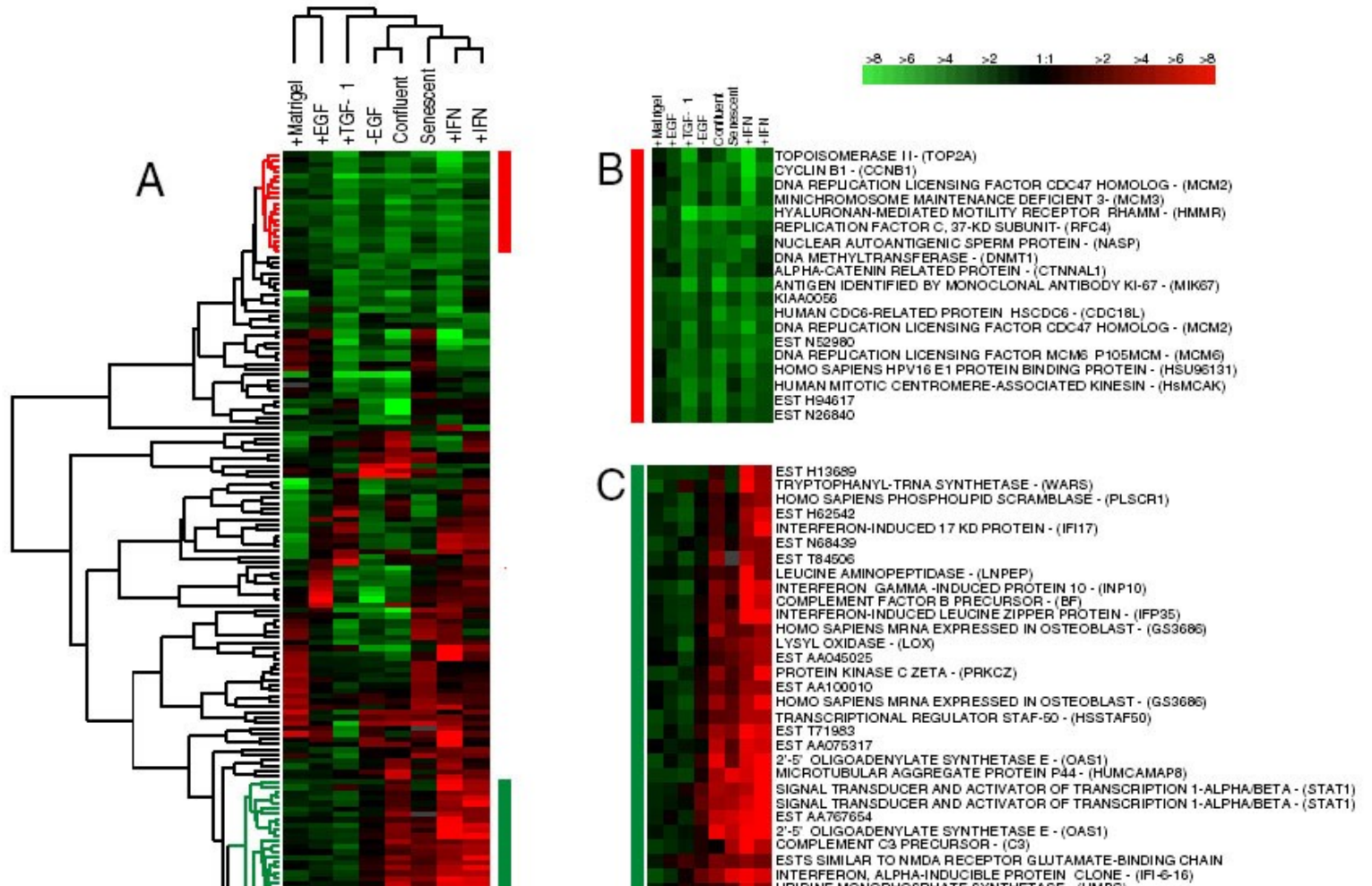
Ramp luminance & hue in perceptual color space  
Avoid contrasts subject to color blindness!



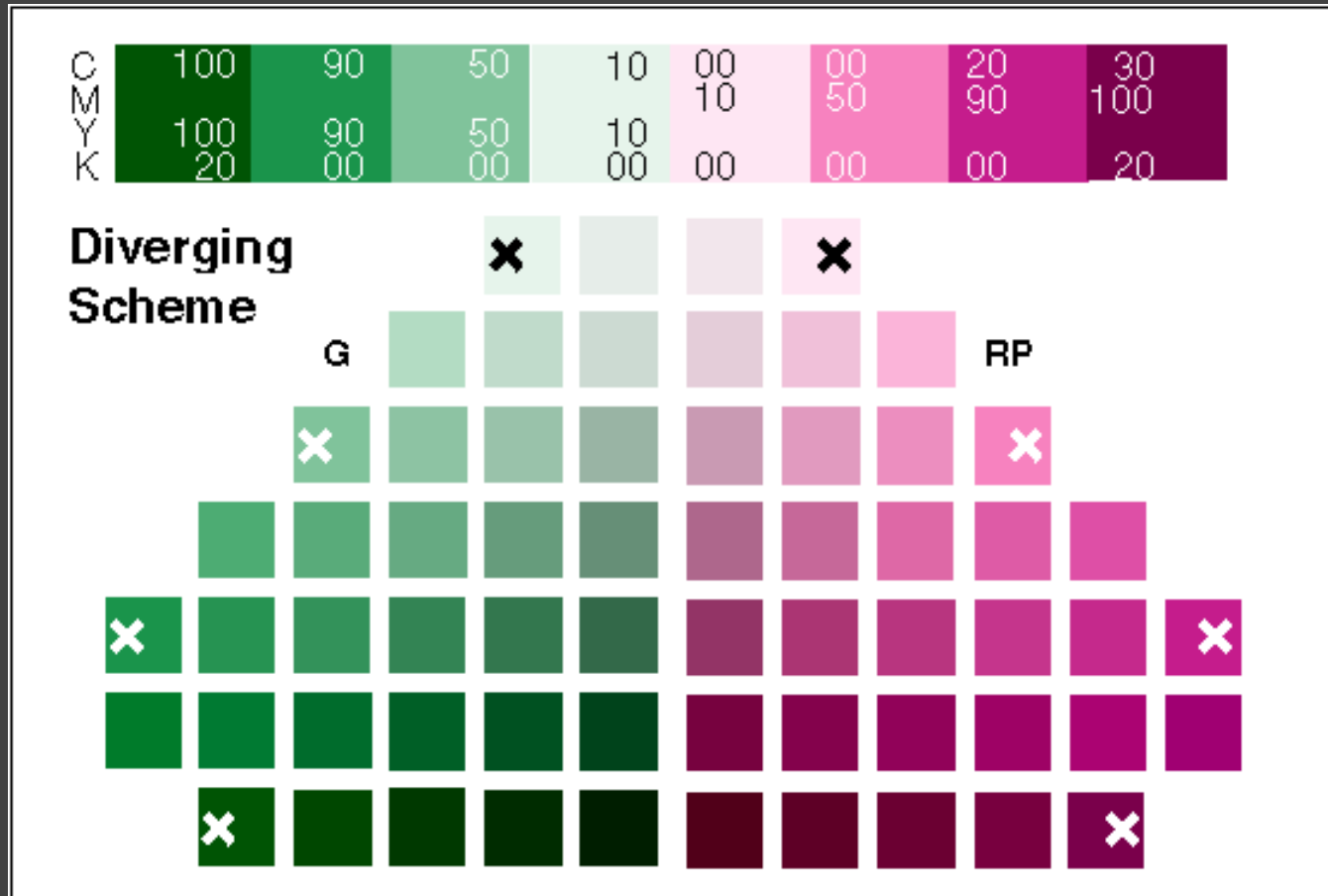
# Sequential Scales: Multi-Hue



# 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**

# Hints for the Colorist

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

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

Strive for color **harmony** (natural colors?)

Use **cultural conventions**; appreciate symbolism

Get it right in **black and white**

Respect the **color blind**

Take advantage of **perceptual color spaces**

**Color is cultural and a matter of taste!**