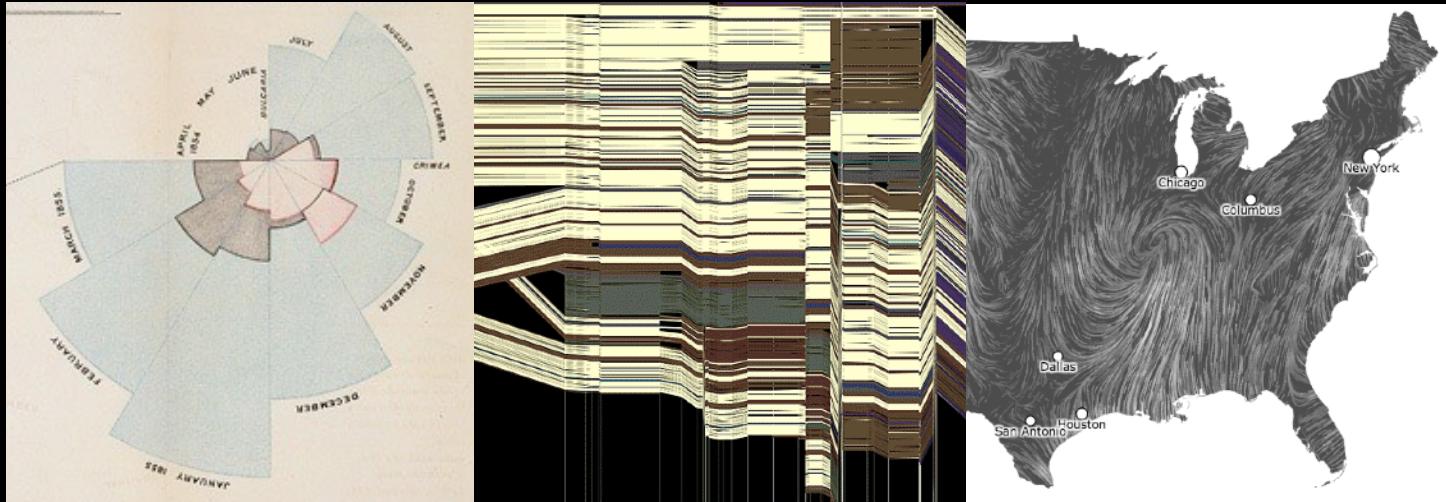


# CSE 442 - Data Visualization

# Color



Jeffrey Heer University of Washington

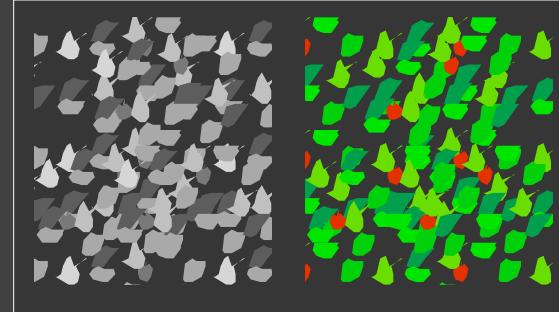
# Purpose of Color

To label

To measure

To represent and imitate

To enliven and decorate



*“Above all, do no harm.”*

- Edward Tufte

# Color Topics

## Perception of Color

Light, Visual system, Mental models

## Color in Information Visualization

Categorical & Quantitative encoding

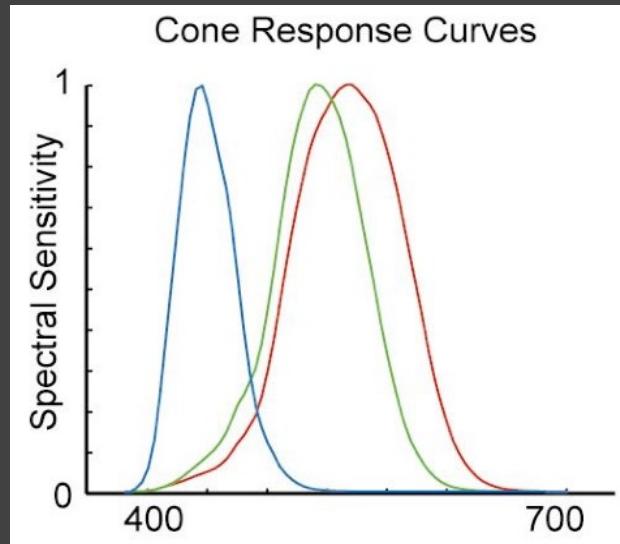
Guidelines for color palette design

# Perception of Color

# As light enters our retina...

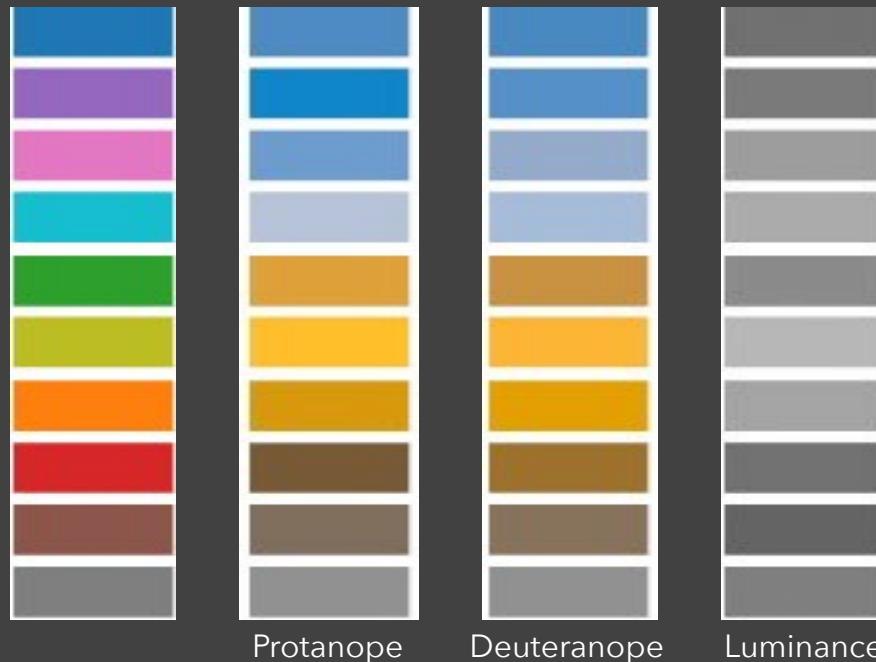
LMS (Long, Middle, Short) Cones

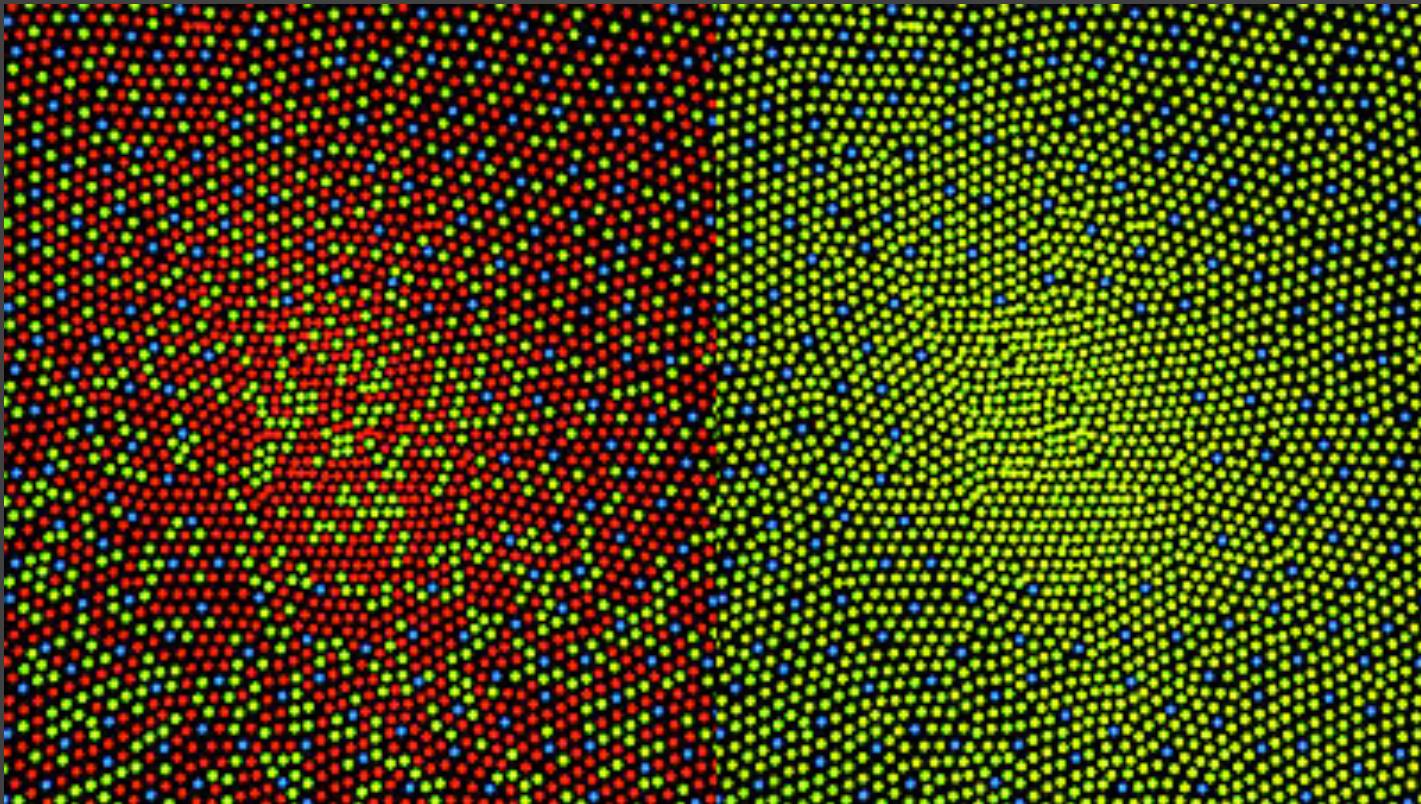
Sensitive to different wavelengths



# Color Vision Deficiency (CVD)

Missing one or more cones or rods in retina.





Normal Retina

Protanopia

# Color Vision Simulators

**Simulate color vision deficiencies**

Browser plug-ins

Photoshop plug-ins, etc.



Deutanope



Protanope



Tritanope

# Primary Colors

To paint “all colors”:

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

**Yellow**

**Blue**

**Green**

**Red**

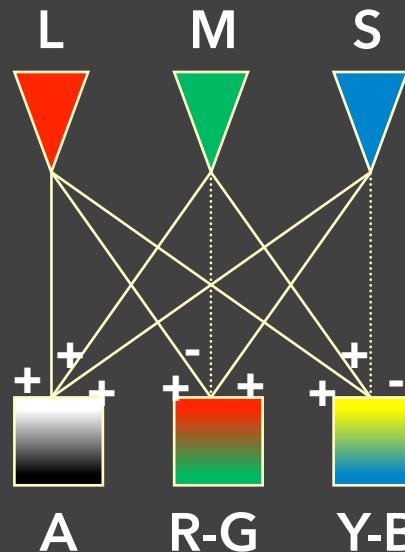
# Opponent Processing

**LMS are combined to create:**

Lightness

Red-green contrast

Yellow-blue contrast



[Fairchild]

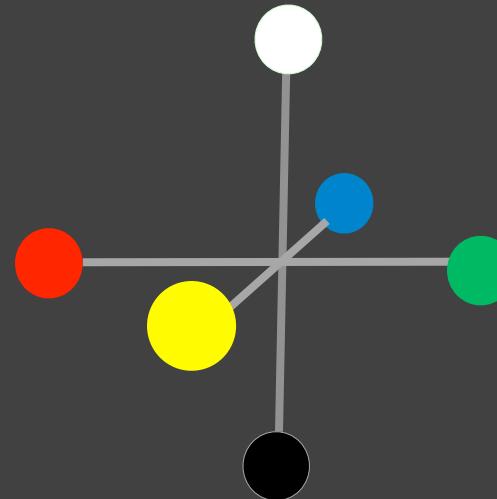
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# Opponent Processing

**LMS are combined to create:**

Lightness

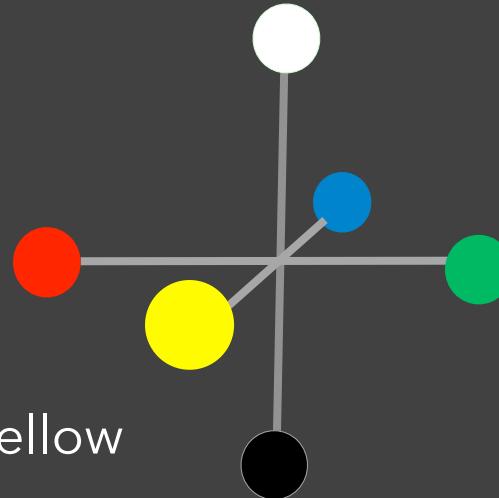
Red-green contrast

Yellow-blue contrast

**Experiments:**

No reddish-green, no blueish-yellow

Color after images







# CIE LAB Color Space

Axes correspond to opponent signals

**L**\* = Luminance

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

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

Much more perceptually uniform than sRGB!

Scaling of axes to represent “color distance”

JND = Just noticeable difference (~2.3 units)

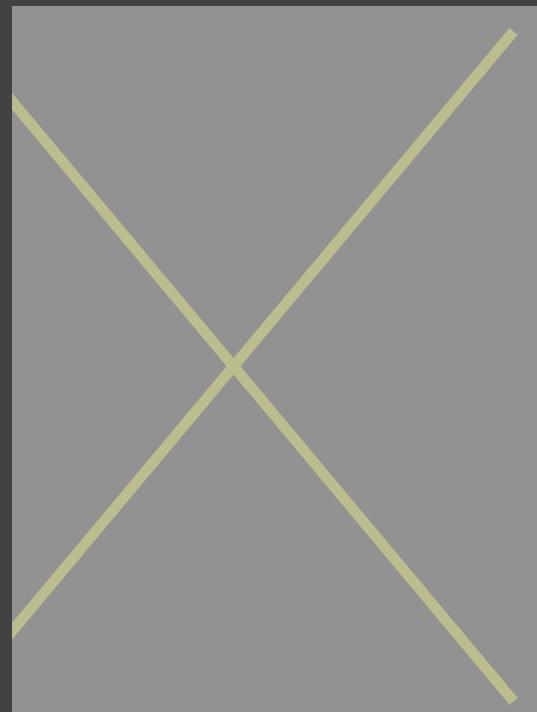
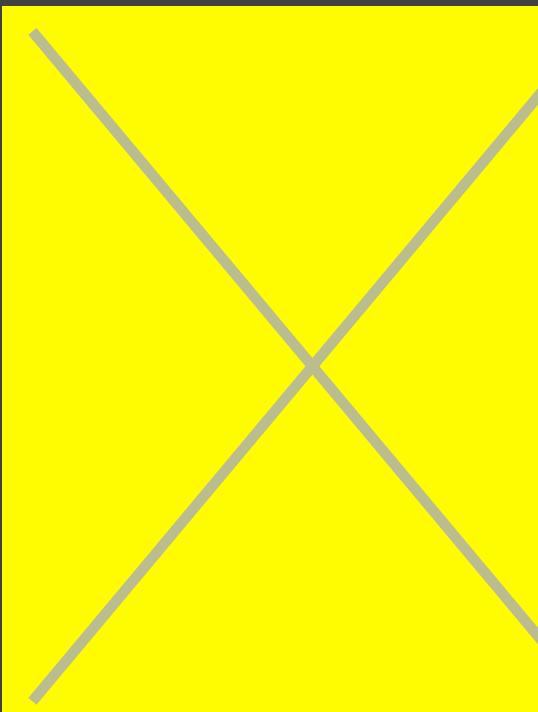
D3 + Vega include LAB color space support!

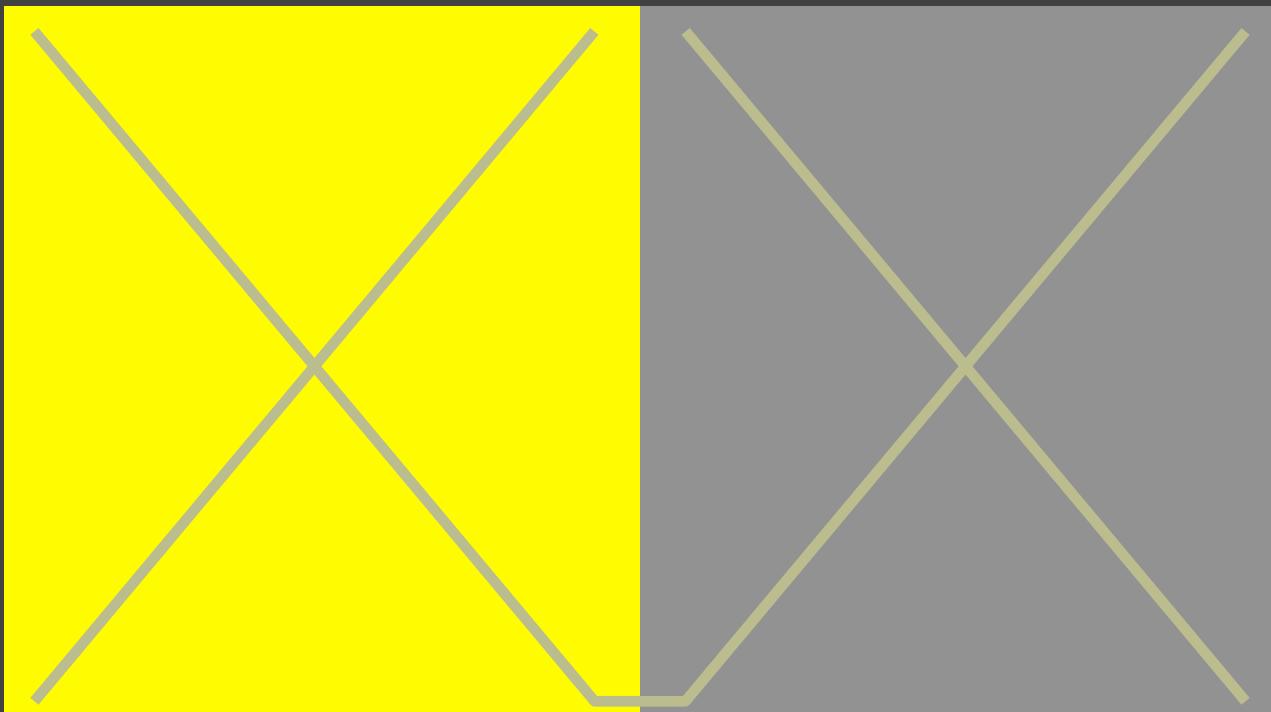
# Color Appearance

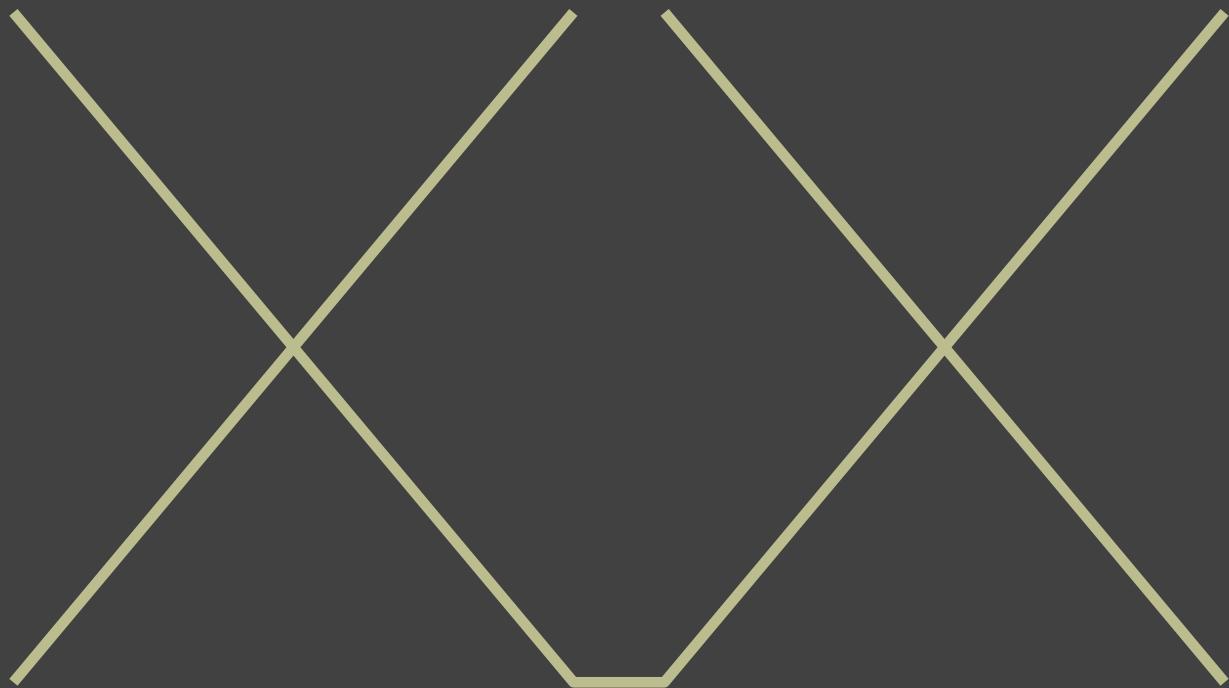
If we have a perceptually-uniform color space, can we predict how we perceive colors?

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

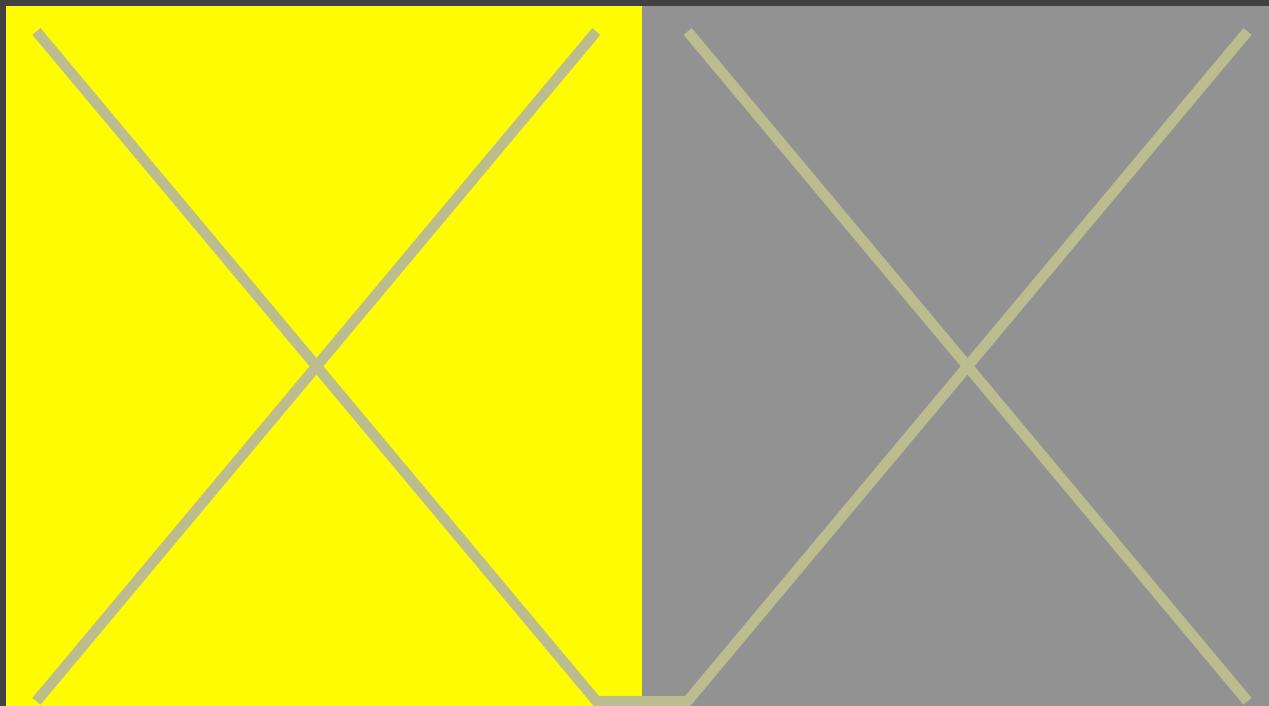
- Josef Albers, *Interaction of Color*







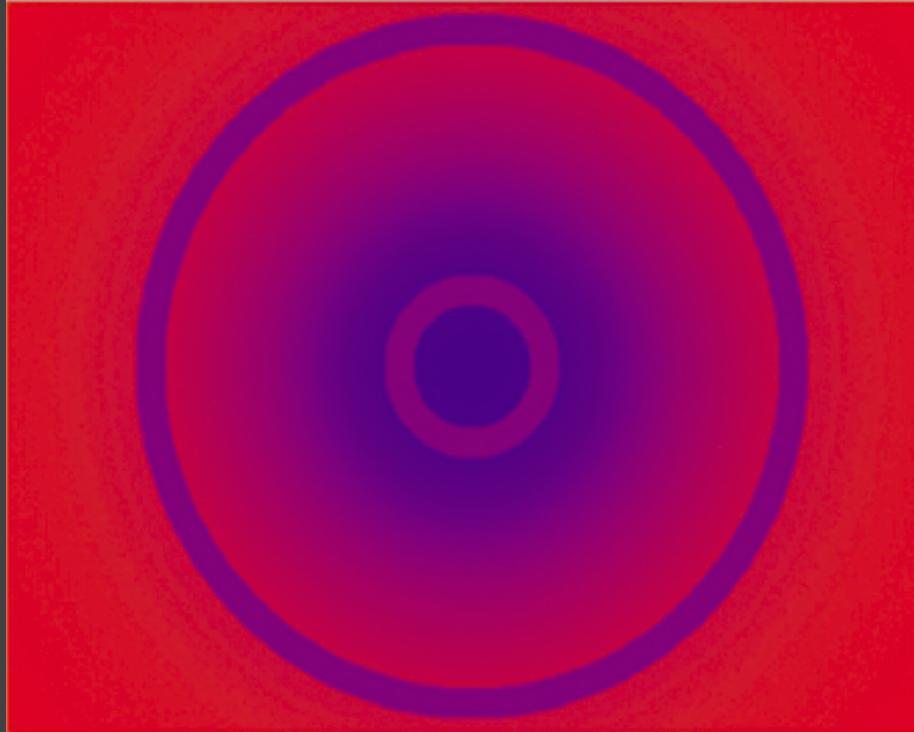
# Simultaneous Contrast



Josef Albers

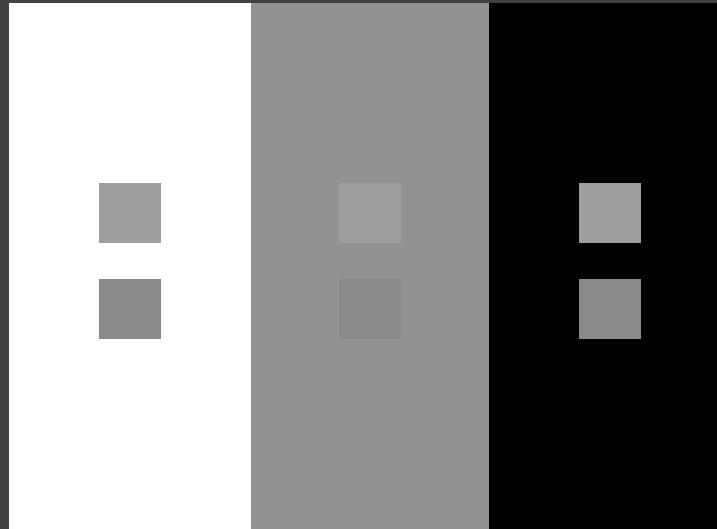
# Simultaneous Contrast

Inner & outer rings are the same physical purple.



# Crispening

Perceived difference depends on background



*Color Appearance Models, Fairchild*

# Designing Colormaps

# 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!

# Discrete (Binary, Categorical)

## Symbol Legend



Alpha



Beta



Gamma



Delta



Epsilon



Zeta

# Continuous (Sequential, Diverging, Cyclic)

## Gradient Legend



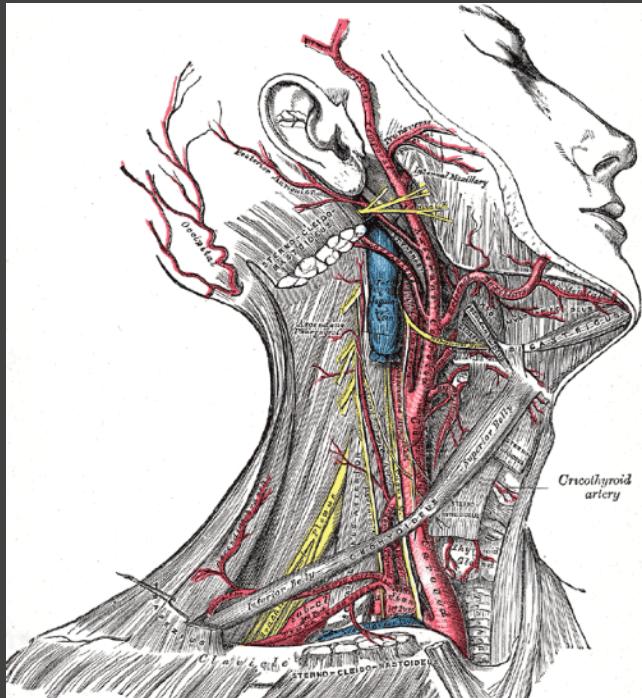
# Discretized Continuous

## Discrete Gradient



# Categorical Color

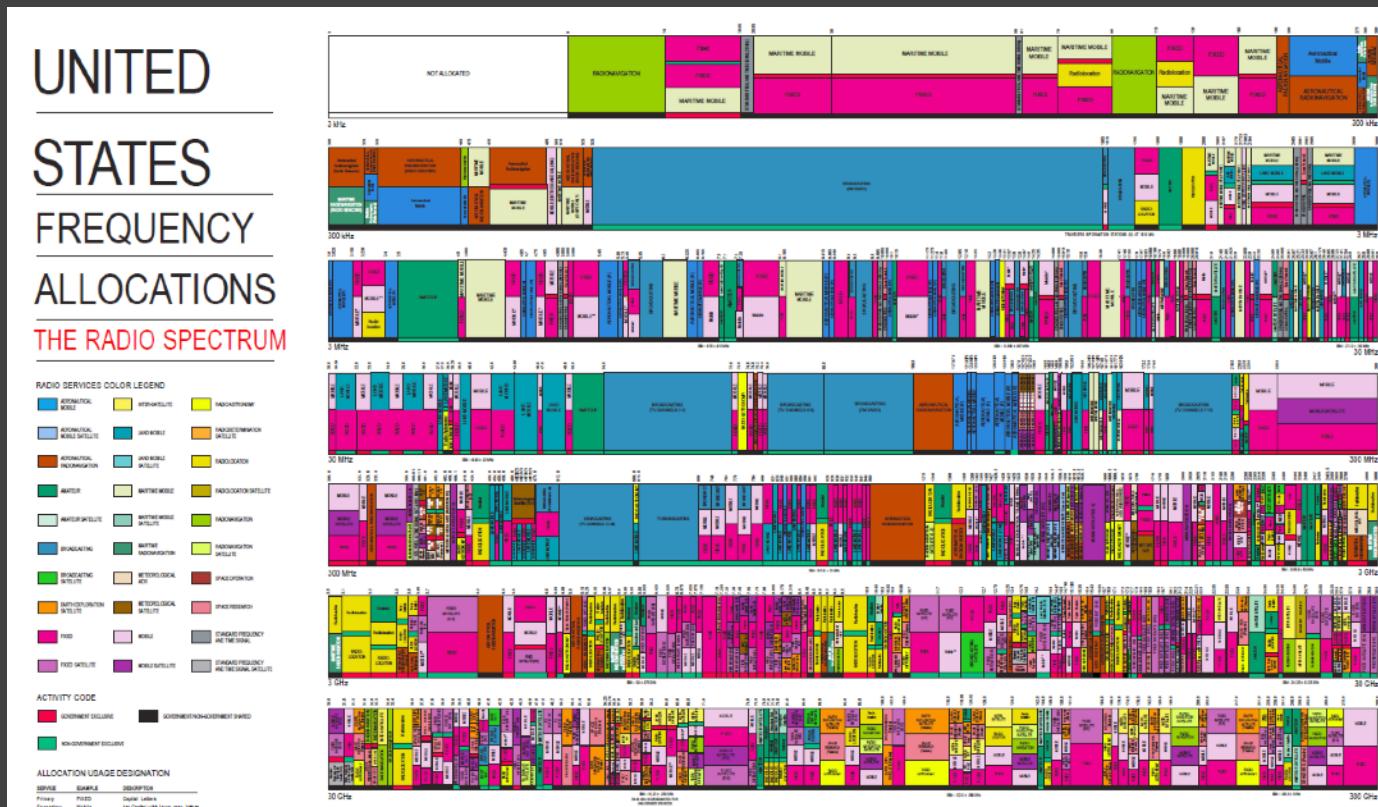
# Gray's Anatomy



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

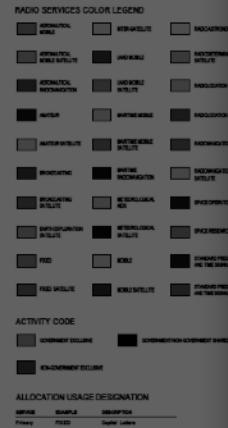
# UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM



# Allocation

## UNITED STATES FREQUENCY ALLOCATION

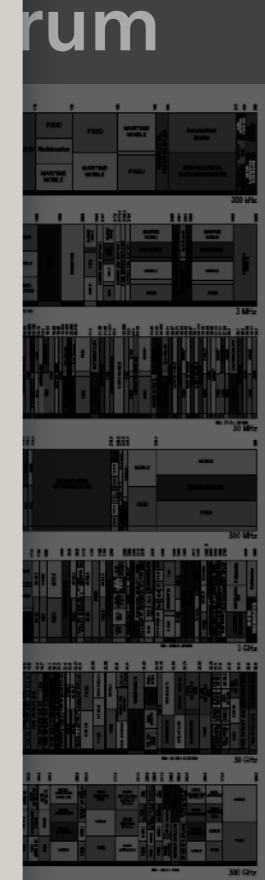
### THE RADIO SPECTRUM



## 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 |

## ACTIVITY CODE



# Allocation of the Radio Spectrum

## Issues:

Too many colors

Hard to remember mapping

Colors not distinctive, some are very similar

Poor grouping: similar colors, different values

Labels cause clutter

Color surround effects

Colors interactions may not look good together

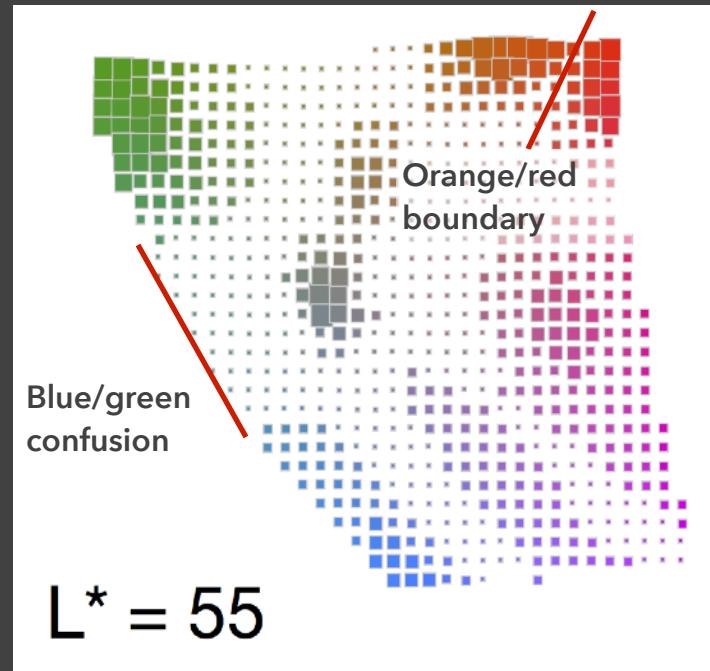
# Color Naming Models [Heer & Stone '12]

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  $p(\text{name} \mid \text{color})$



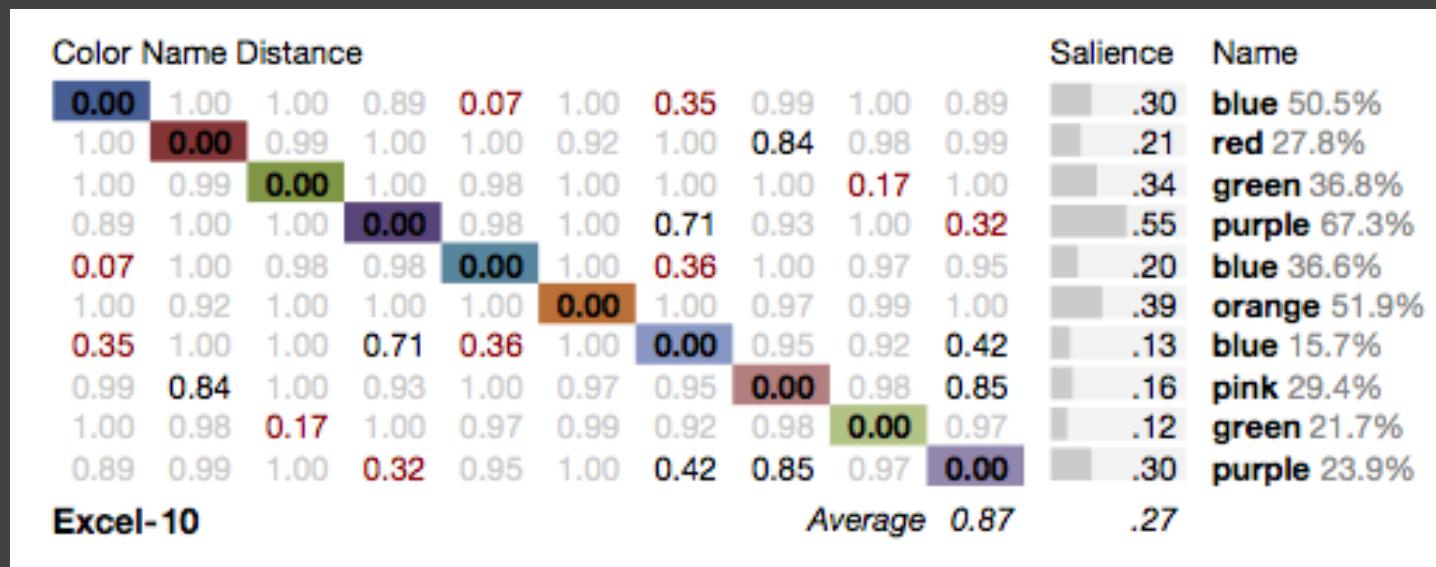
# Palette Design & Color Names

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 | 0.96 | 1.00 | .90  | orange 93.9% |            |
| 1.00                | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.90 | 0.99 | .67  | green 79.8%  |            |
| 1.00                | 0.97 | 1.00 | 0.00 | 1.00 | 0.95 | 0.99 | 1.00 | 1.00 | 1.00 | .66  | red 80.4%    |            |
| 0.98                | 1.00 | 1.00 | 1.00 | 0.00 | 0.96 | 0.91 | 0.97 | 1.00 | 0.99 | .47  | purple 51.4% |            |
| 1.00                | 1.00 | 1.00 | 0.95 | 0.96 | 0.00 | 0.97 | 0.93 | 0.98 | 1.00 | .37  | brown 54.0%  |            |
| 1.00                | 1.00 | 1.00 | 0.99 | 0.91 | 0.97 | 0.00 | 1.00 | 1.00 | 1.00 | .58  | pink 71.7%   |            |
| 1.00                | 1.00 | 1.00 | 1.00 | 0.97 | 0.93 | 1.00 | 0.00 | 1.00 | 1.00 | .67  | grey 79.4%   |            |
| 1.00                | 0.96 | 0.90 | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 0.00 | 1.00 | .18  | yellow 31.2% |            |
| 0.20                | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | .25  | blue 25.4%   |            |
| Tableau-10          |      |      |      |      |      |      |      |      |      |      | Average 0.97 | .52        |

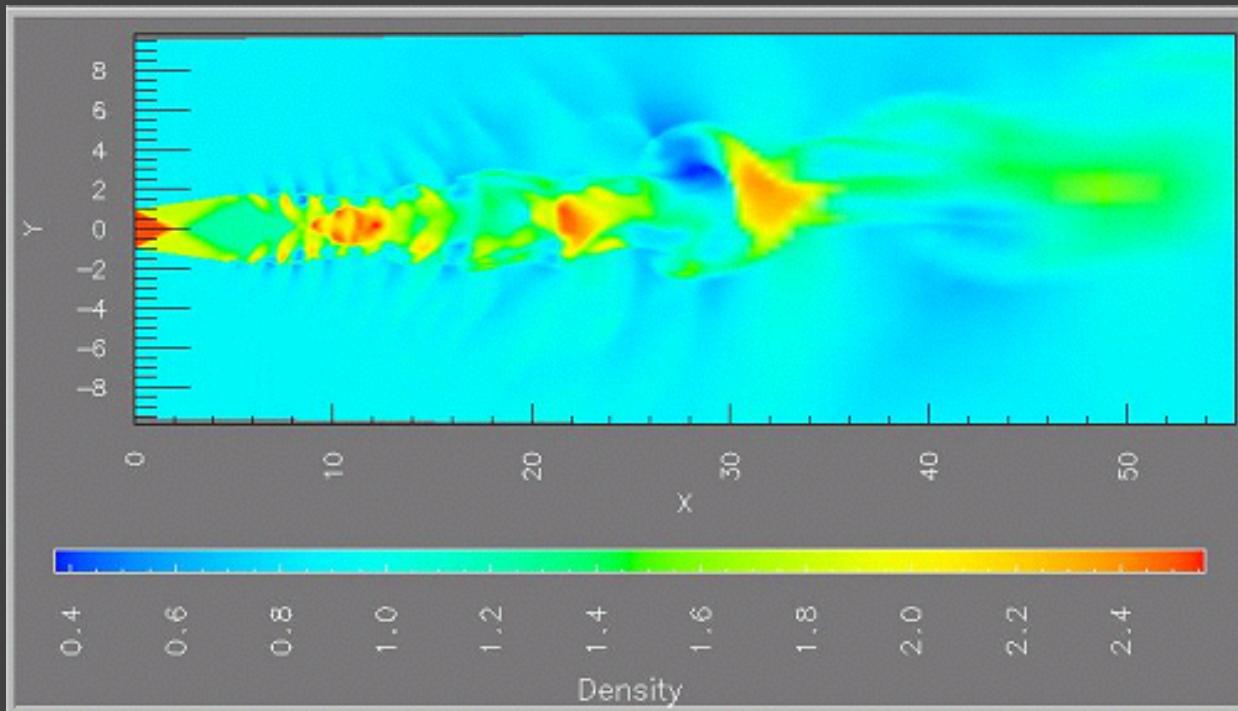
# Palette Design & Color Names

Minimize overlap and ambiguity of colors.

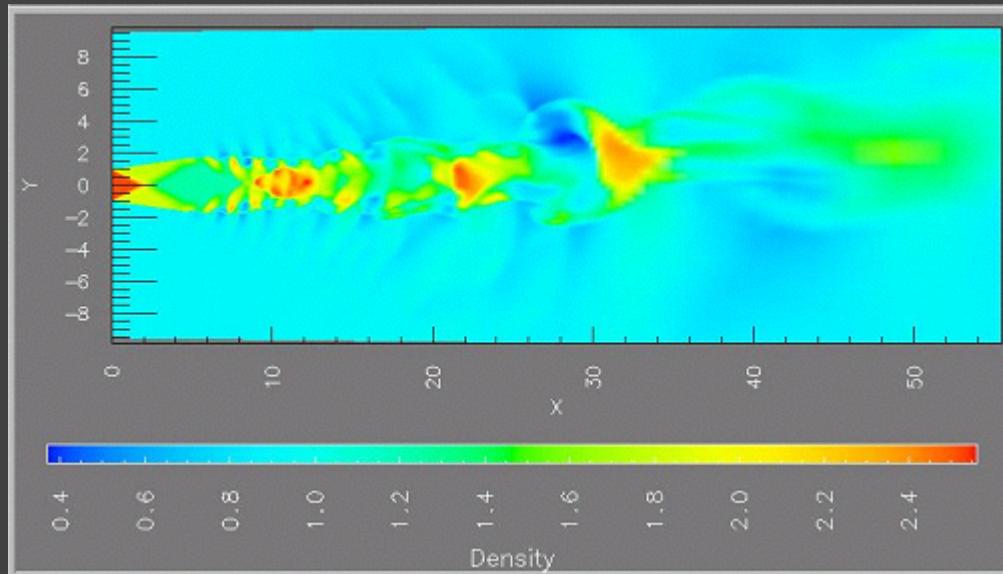


# Quantitative Color

# Rainbow Color Maps

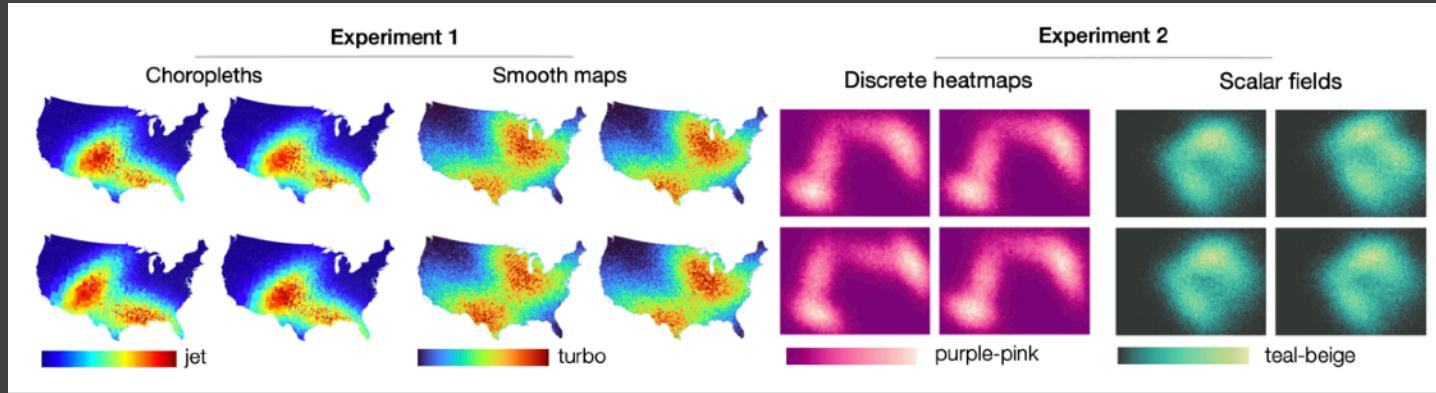


# Be wary of naïve rainbows?



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

# But rainbow helpful for inference?



Reda et al. '21: Color Nameability Predicts Inference Accuracy in Spatial Visualizations

Rainbow found ineffective for *value comparison* [Liu '18]...

...but color name salience found to improve performance on *inference task* of distinguishing distributions [Reda '21]

**Task matters!**

# 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 >](#)

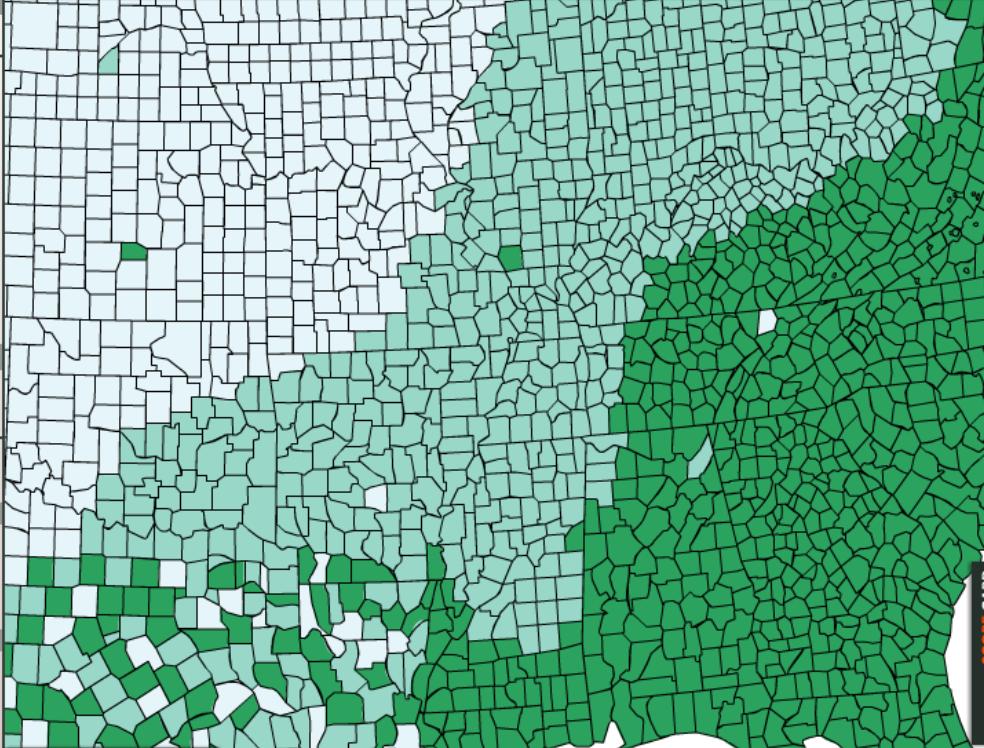
pick a color system

229, 245, 249  RGB  CMYK  HEX  
153, 216, 201  
44, 162, 95

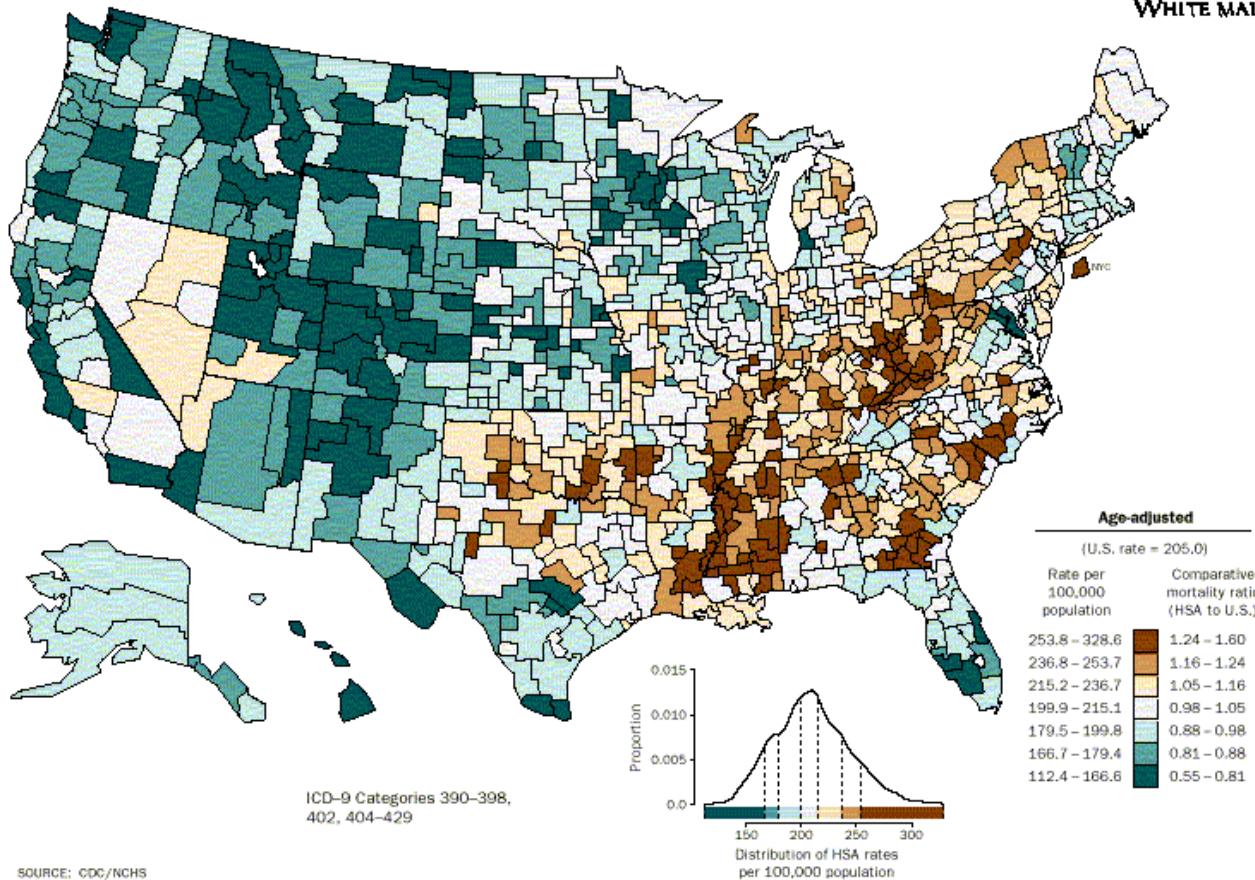
adjust map context  
 roads  
 cities  
 borders

select a background  
 solid color  
 terrain

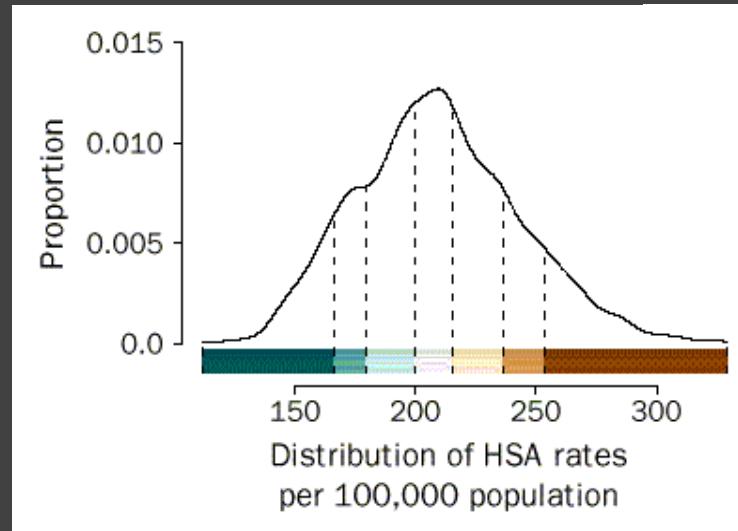
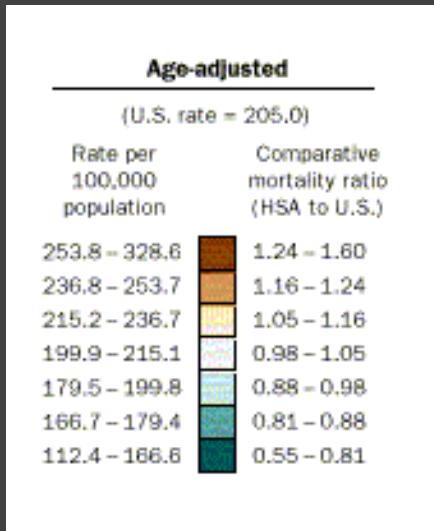
SCORE CARD



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

HEART DISEASE  
WHITE MALE

# 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

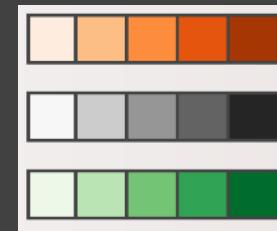
Maximize between group variance

# Quantitative Color Encoding

## Sequential color scale

Ramp in luminance, possibly also hue

Higher value -> darker color (or vice versa)

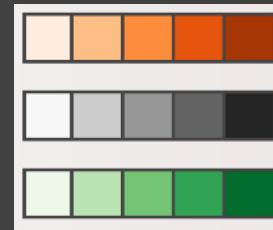


# Quantitative Color Encoding

## Sequential color scale

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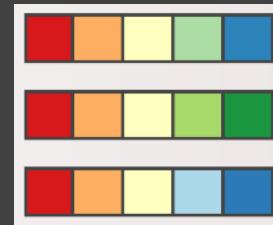


## Diverging color scale

Useful when data has meaningful “midpoint”

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

Use saturated colors for endpoints

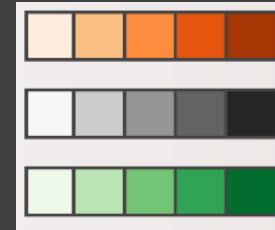


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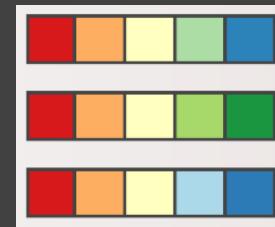


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**Limit number of steps in color to 3-9**

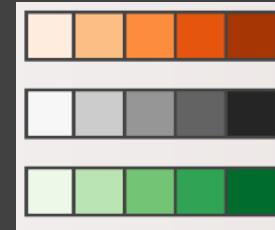
*Why?*

# Quantitative Color Encoding

## Sequential color scale

Ramp in luminance, possibly also hue

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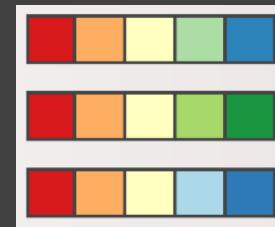


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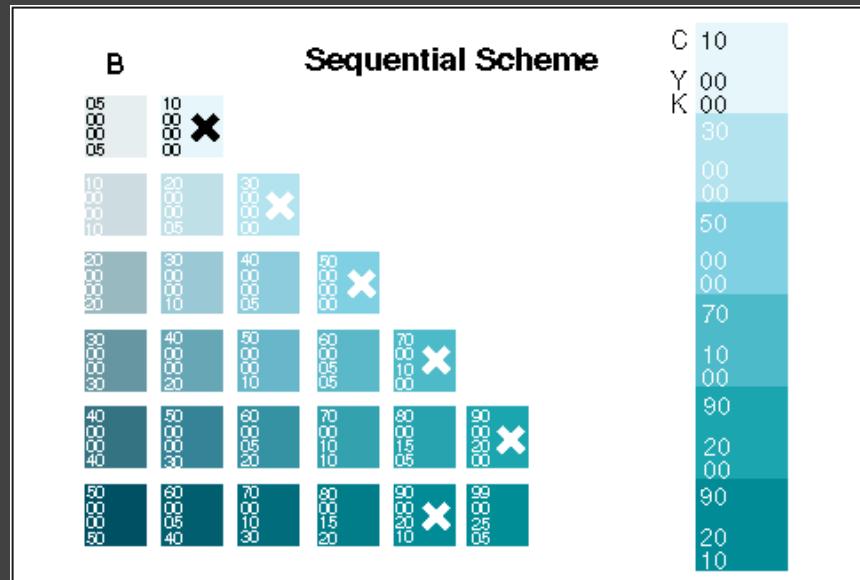


## Limit number of steps in color to 3-9

Avoid simultaneous contrast, hold mappings in memory

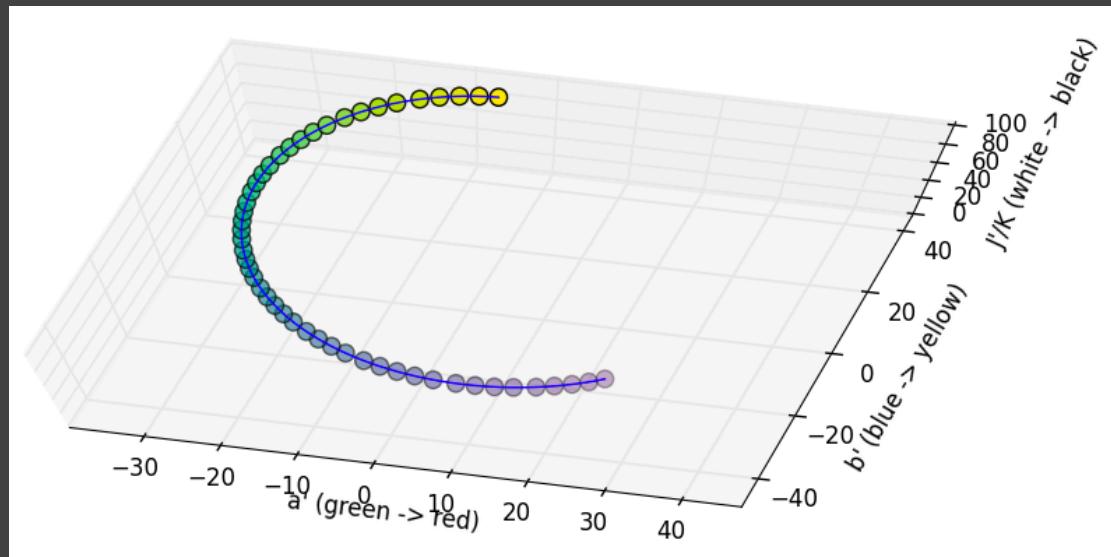
# Sequential Scales: Single-Hue

Ramp primarily in luminance, subtle hue difference

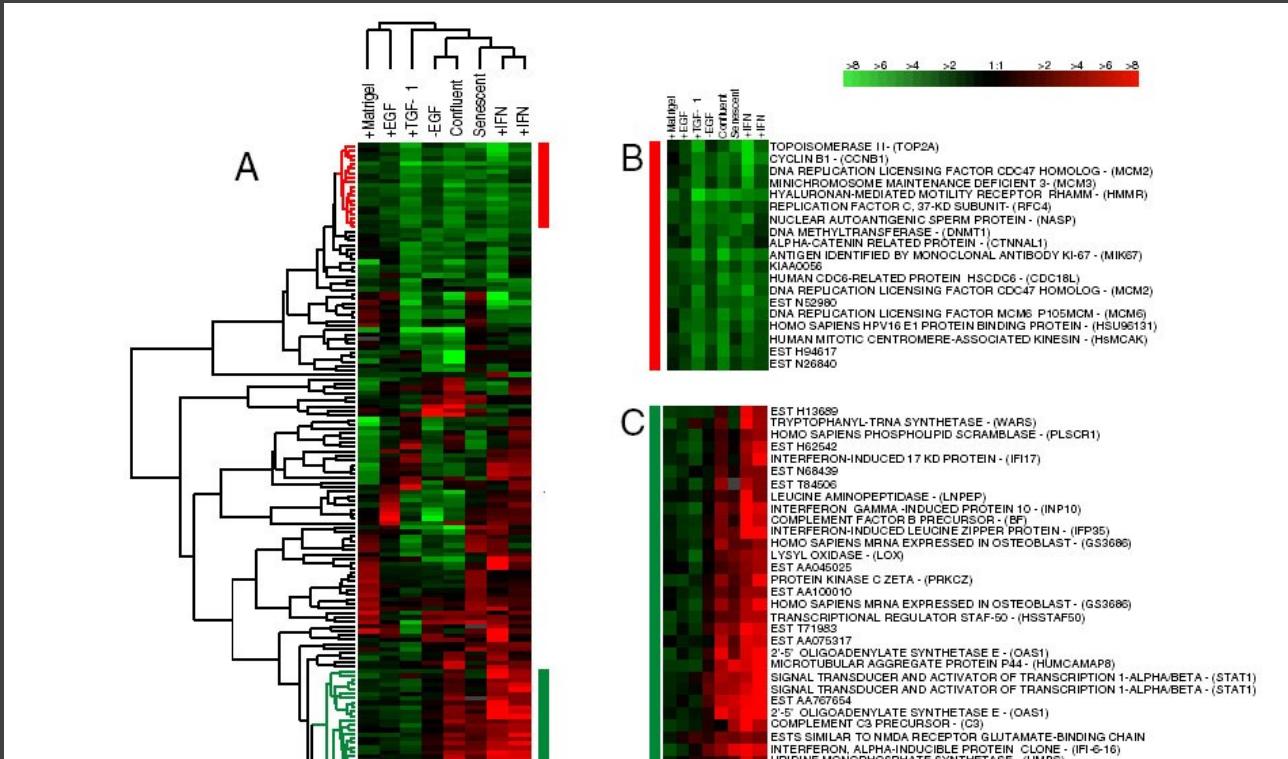


# Sequential Scales: Multi-Hue

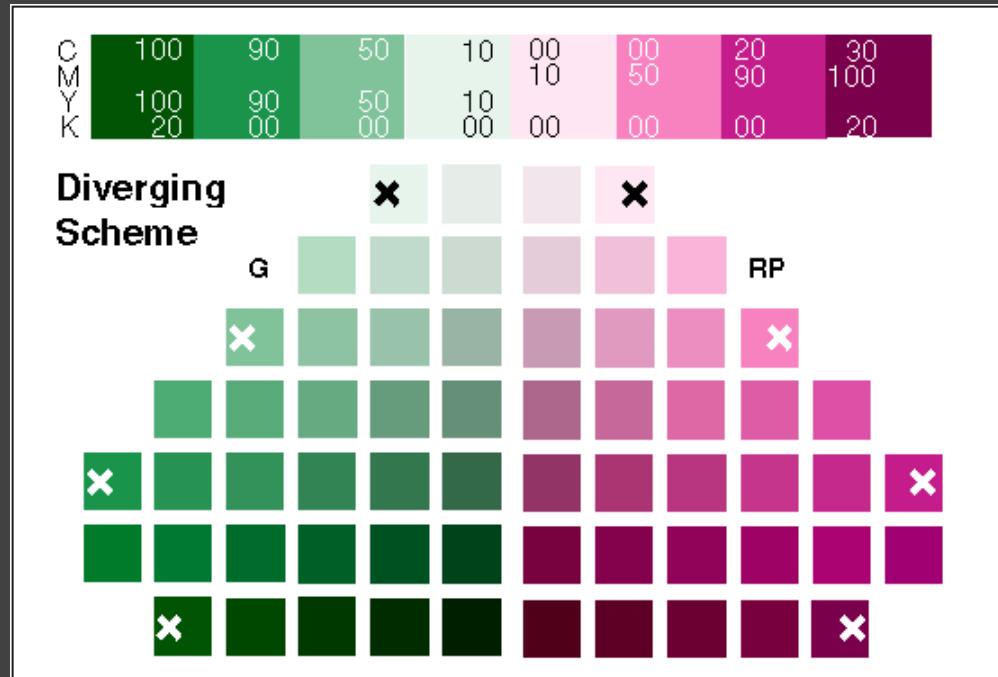
Ramp luminance & hue in perceptual color space  
Avoid contrasts subject to color blindness!



# 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!**