# Information Visualization
# PERCEPTION and COLOR

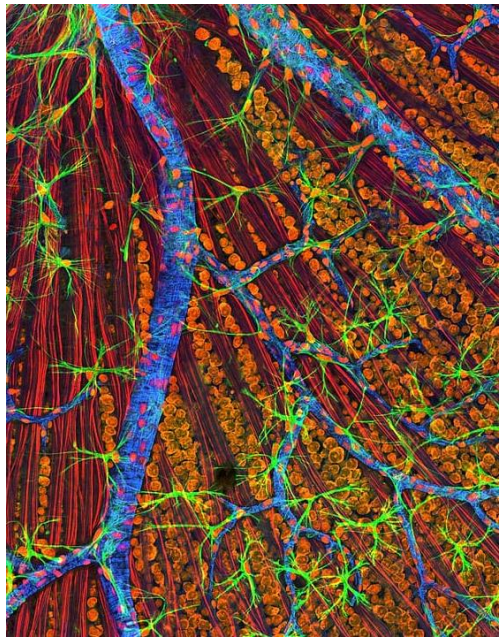
Petra Isenberg

Let’s do
an experiment …

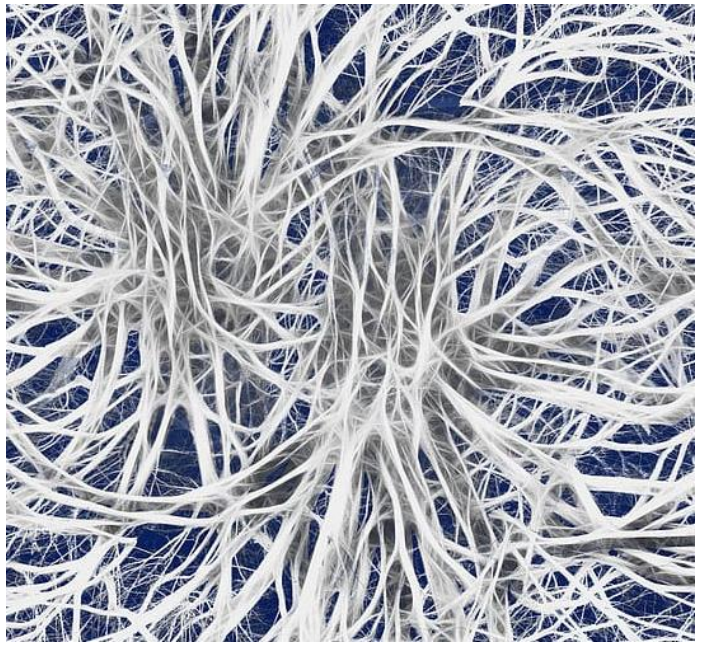
# What is Color?

= the set of **perceptions** elicited by the spectral distribution of light

Through the eye…



…onto sensors (retina)

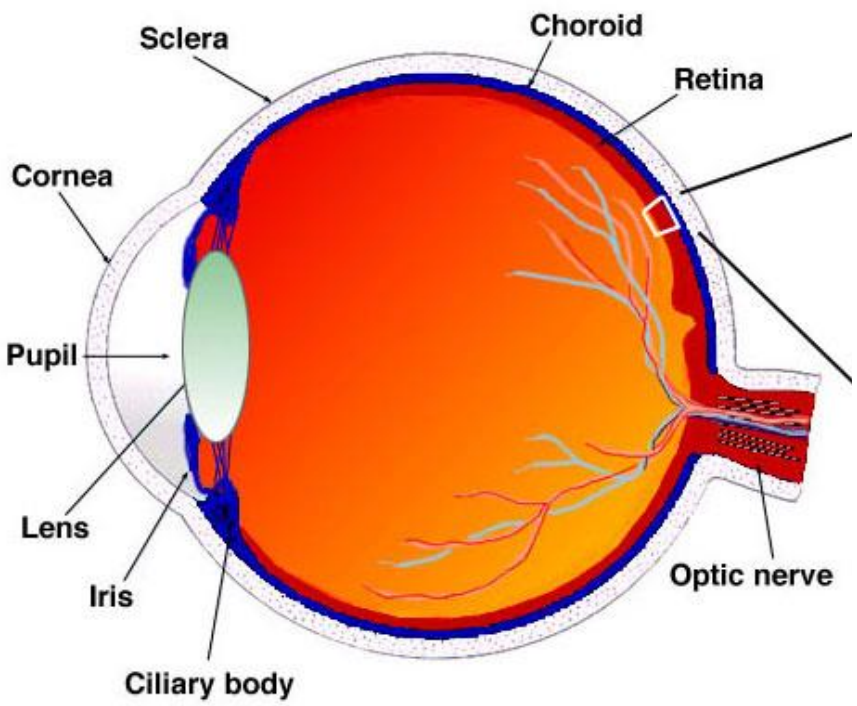


…to processing by the visual system

# Color Vision - Remember

- What we call color is generated by the visual brain
- There is no one to one relationship between the colors seen and wavelengths

# Physical World ➡ Visual System

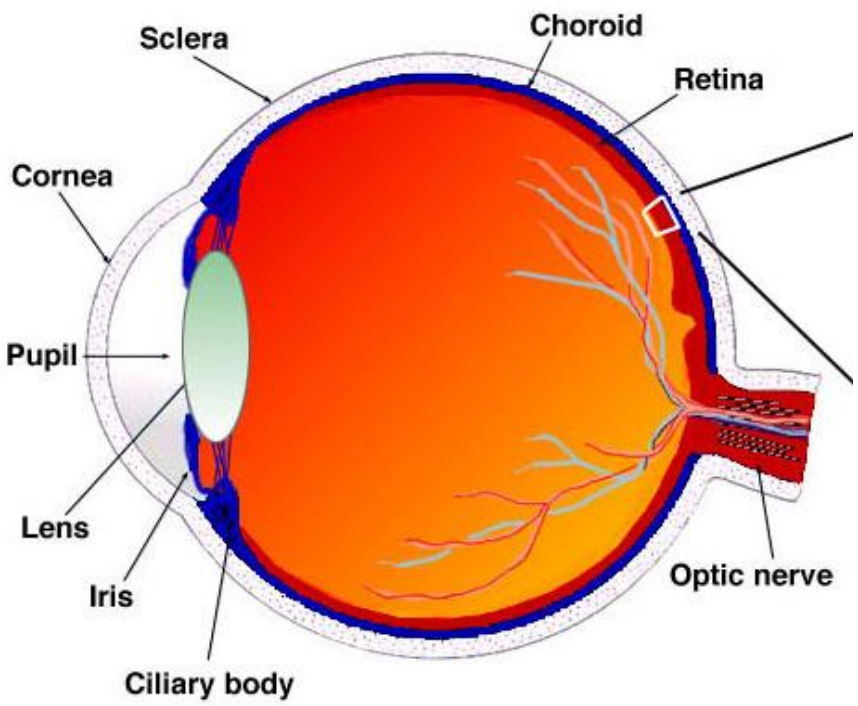



Retina is stimulated by three factors:

- illumination (light source)
- reflectance (from object)
- transmittance (atmosphere)

*Simple Anatomy of the Retina, Helga Kolb*

# Physical World ➡ **Visual System**




- The eye gets **a** retinal stimulus
- It cannot be reverse engineered

→ To behave in the world the brain needs to step in and interpret

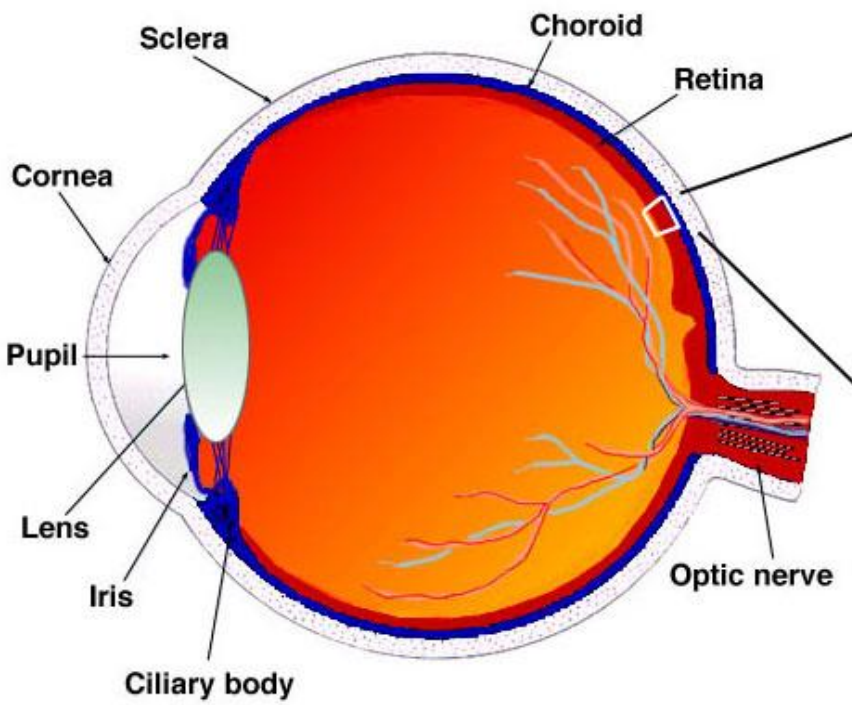
*Simple Anatomy of the Retina, Helga Kolb*

# The Inverse Problem

- What the retina receives as input (stimulus) is a combination of photons/light waves
  - From illumination sources
  - From reflectance of objects
  - From transmittance through objects
- How do we know who contributed what?

→ To solve this problem we have learned what the relationships are between the physical world and our perceived information

# Physical World ➡ Visual System




The visual system often relies on experience to interpret

*Simple Anatomy of the Retina, Helga Kolb*

# Example: Lightness vs. Luminance

- LUMINANCE: an objective measurement of light intensity per unit area (e.g. cd/m2; physical)

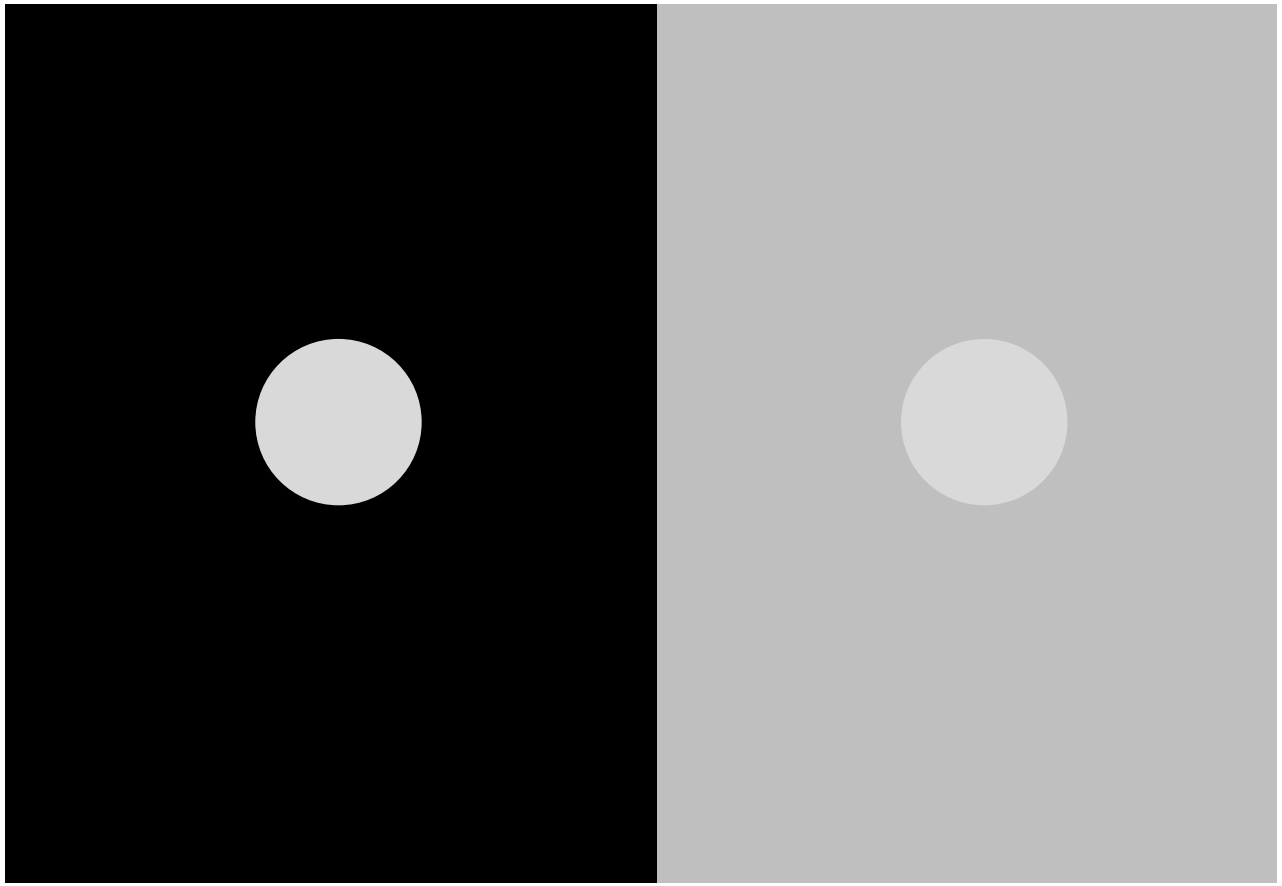

- LIGHTNESS: a **subjective impression** of the intensity of light reflected from on object surface
(no units; psychophysical)

# Lightness experiment



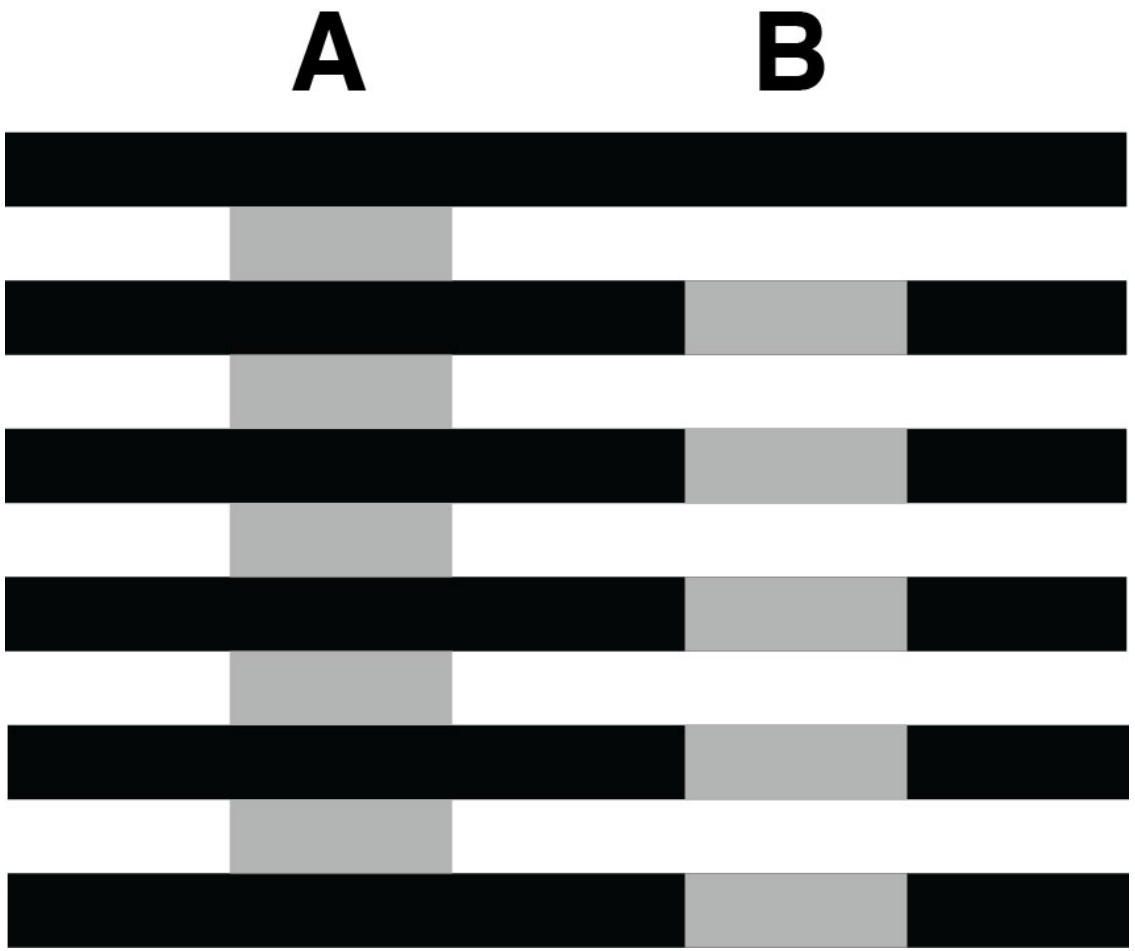
The two circles are physically the same

# Lightness experiment



The two circles are still physically the same, but the lightness you perceive is not

# White’s illusion: the opposite effect




A is surrounded by more black but seems darker than B, which is surrounded by more white

# The Cornsweet Edge

As a result of two gradients, but why does this happen?

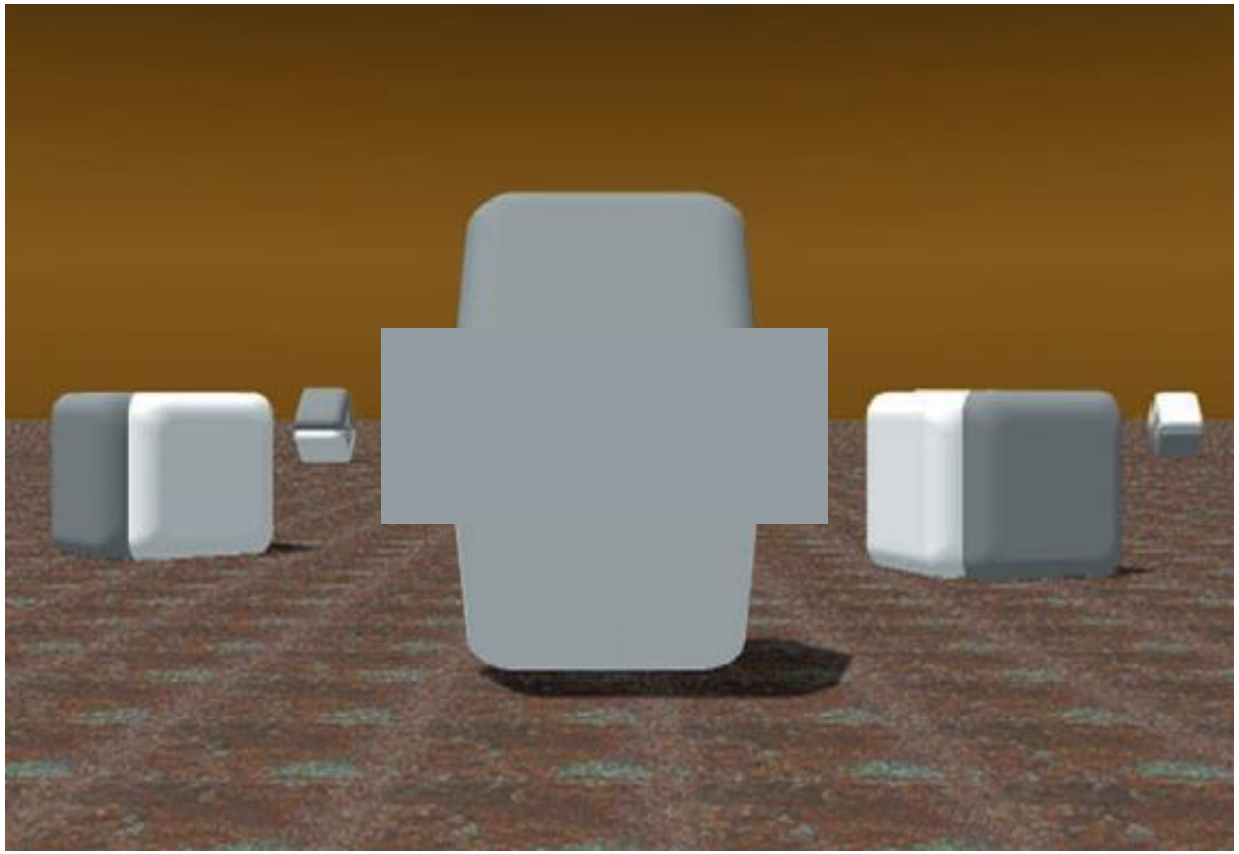


*Image source: The Journal of Neuroscience, October 1, 1999, 19(19):8542–8551* [*An Empirical Explanation of the Cornsweet Effect.*]

Back to….

# WHAT IS COLOR?

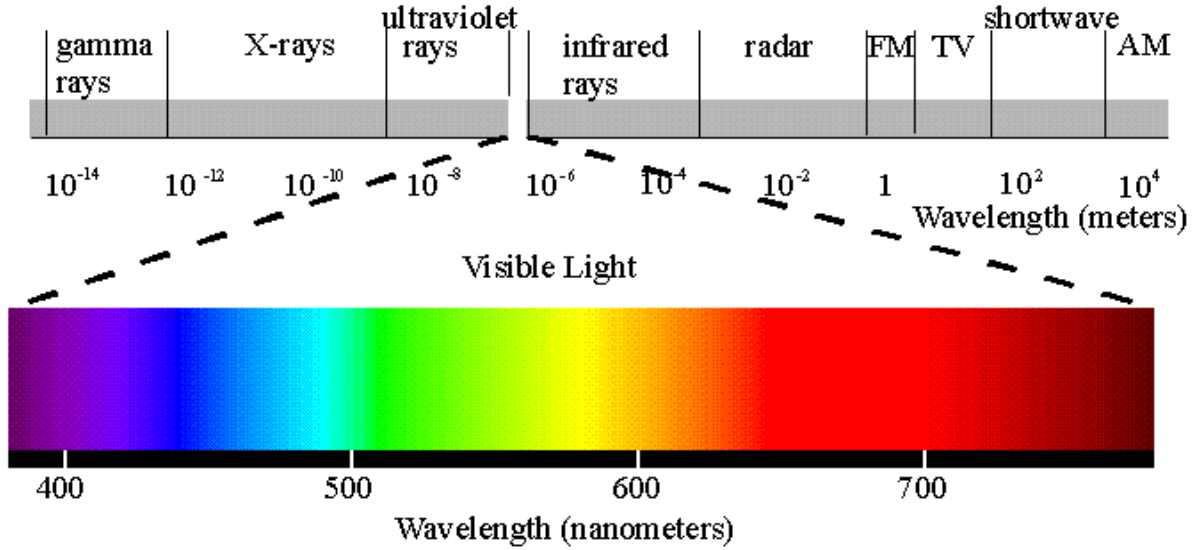
# Some definitions

**Physical measurement**:
the relative intensities of wavelengths in light measured with a spectrophotometer

**Psychophysical measurement**:
report of the color seen by a normal subject, typically made by comparison

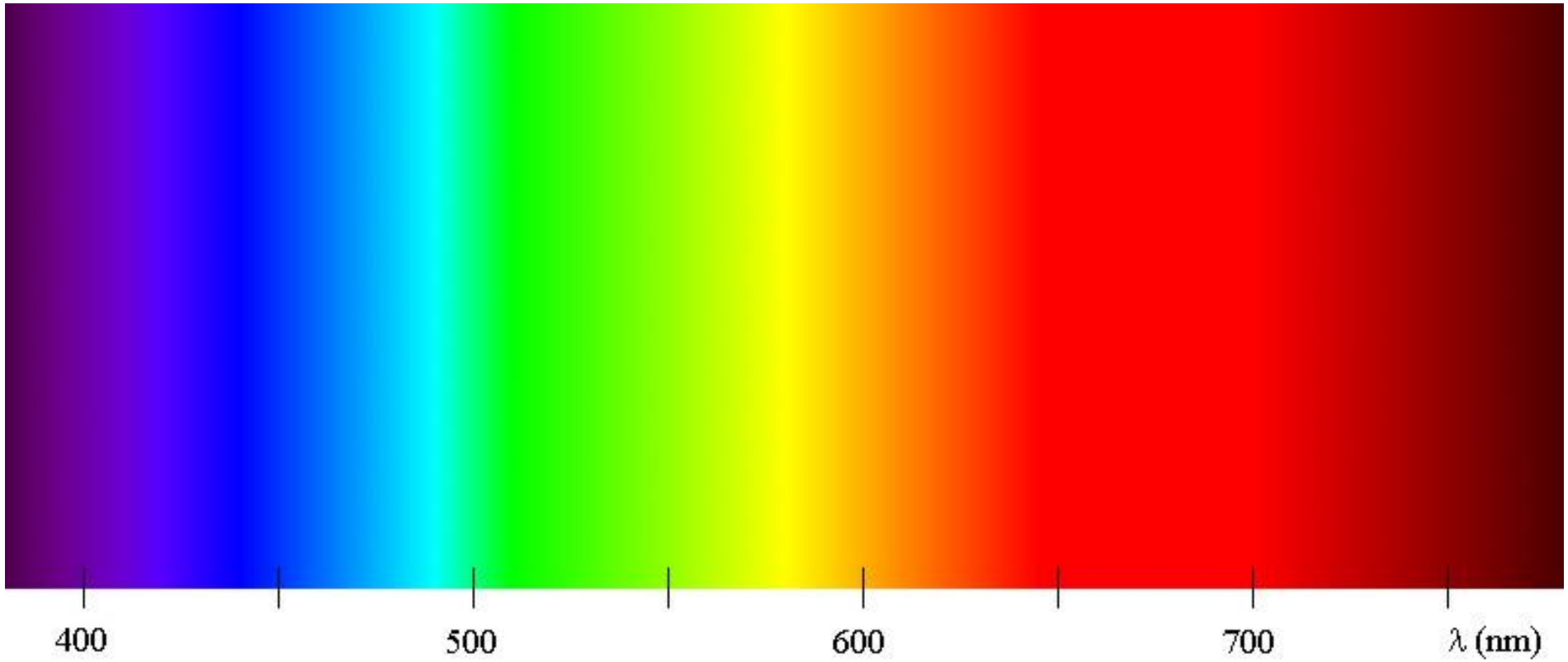
# Physical World – The Nature of Light

We have evolved to see a range of wavelengths: ~400 - 700nm

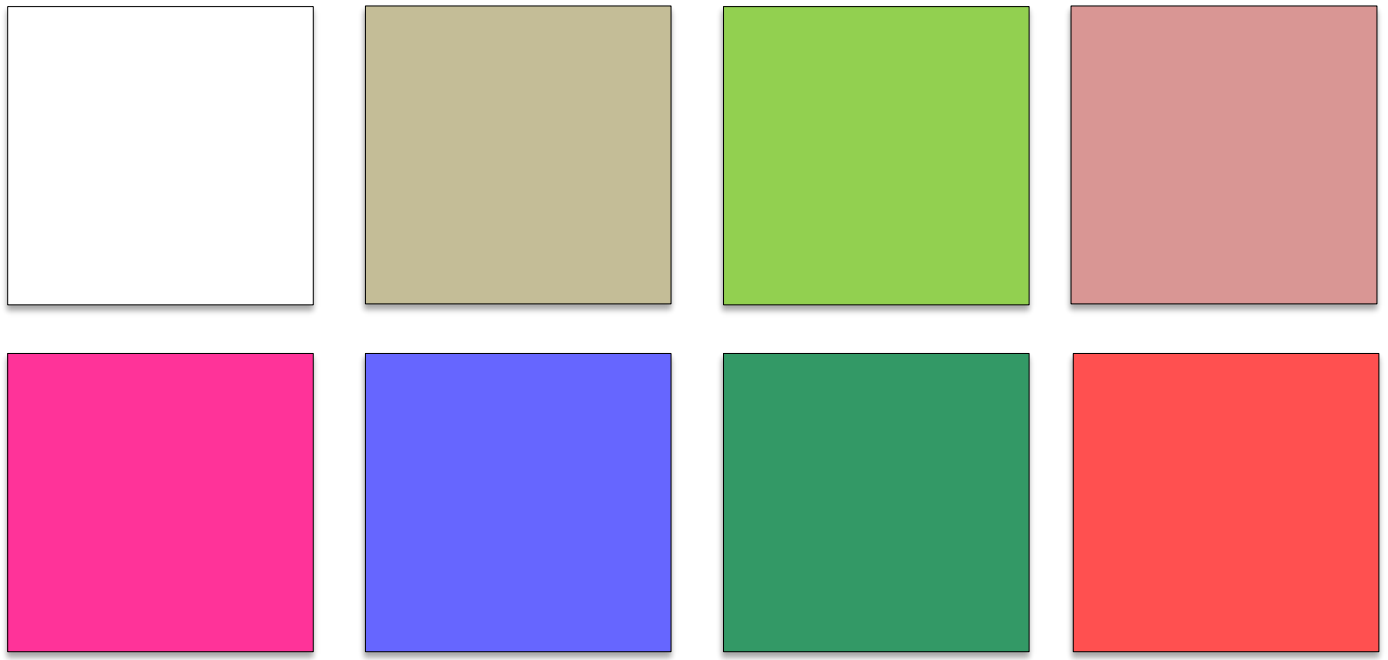



Light of a single wavelength is *monochromatic*

# Look around you and then at this image - what do you notice?

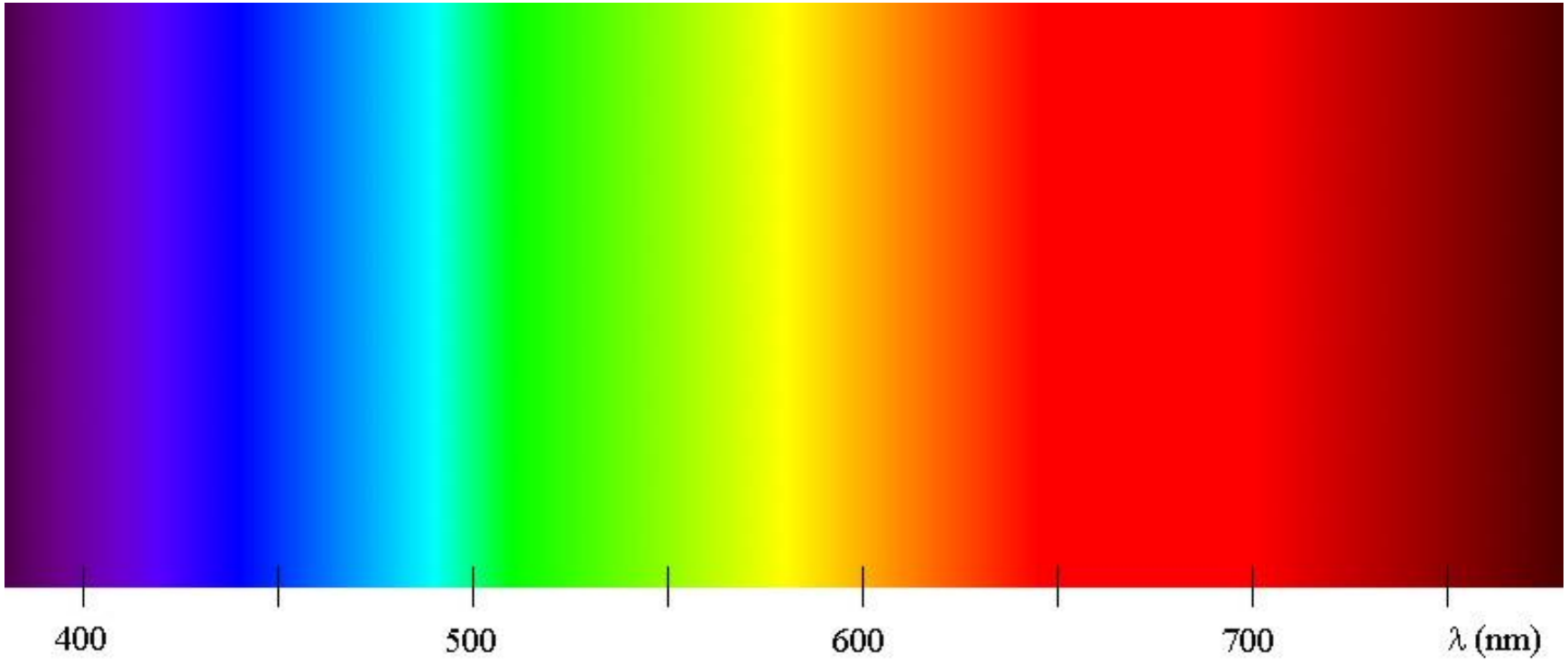



http://www.science4all.org/article/colors/



Many colors are not monochromatic

# Monochromatic colors

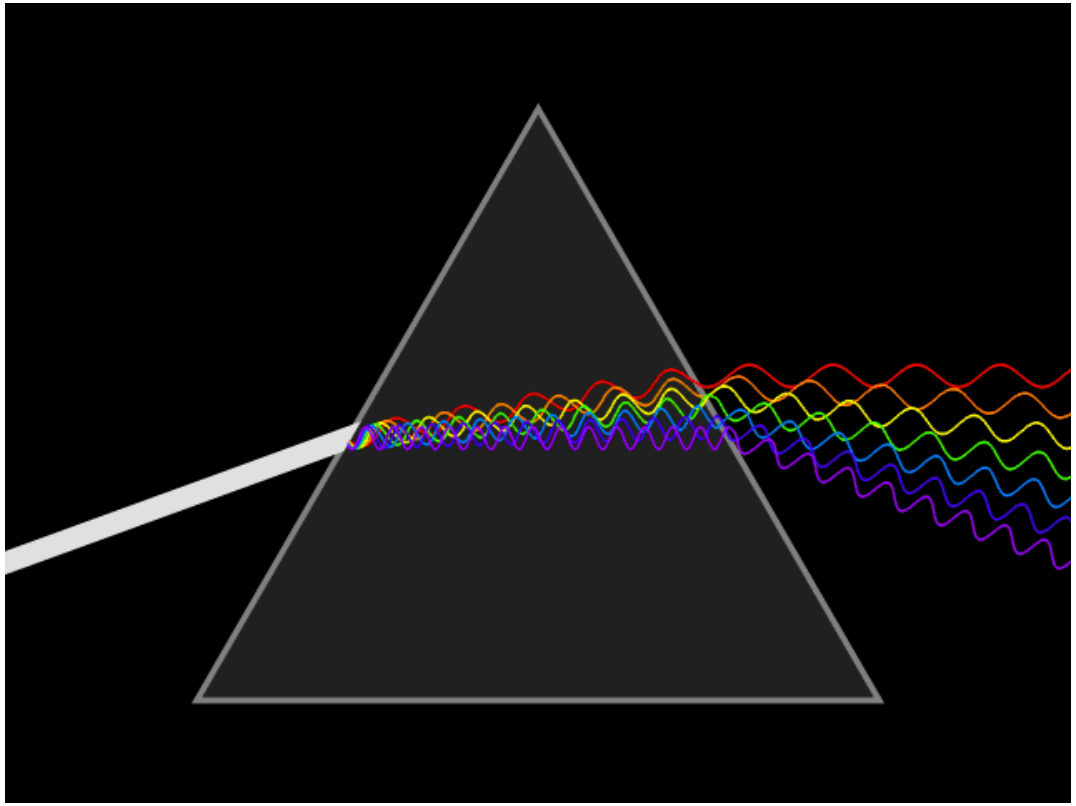



Can be obtained with one or more rays of light with a single wavelength

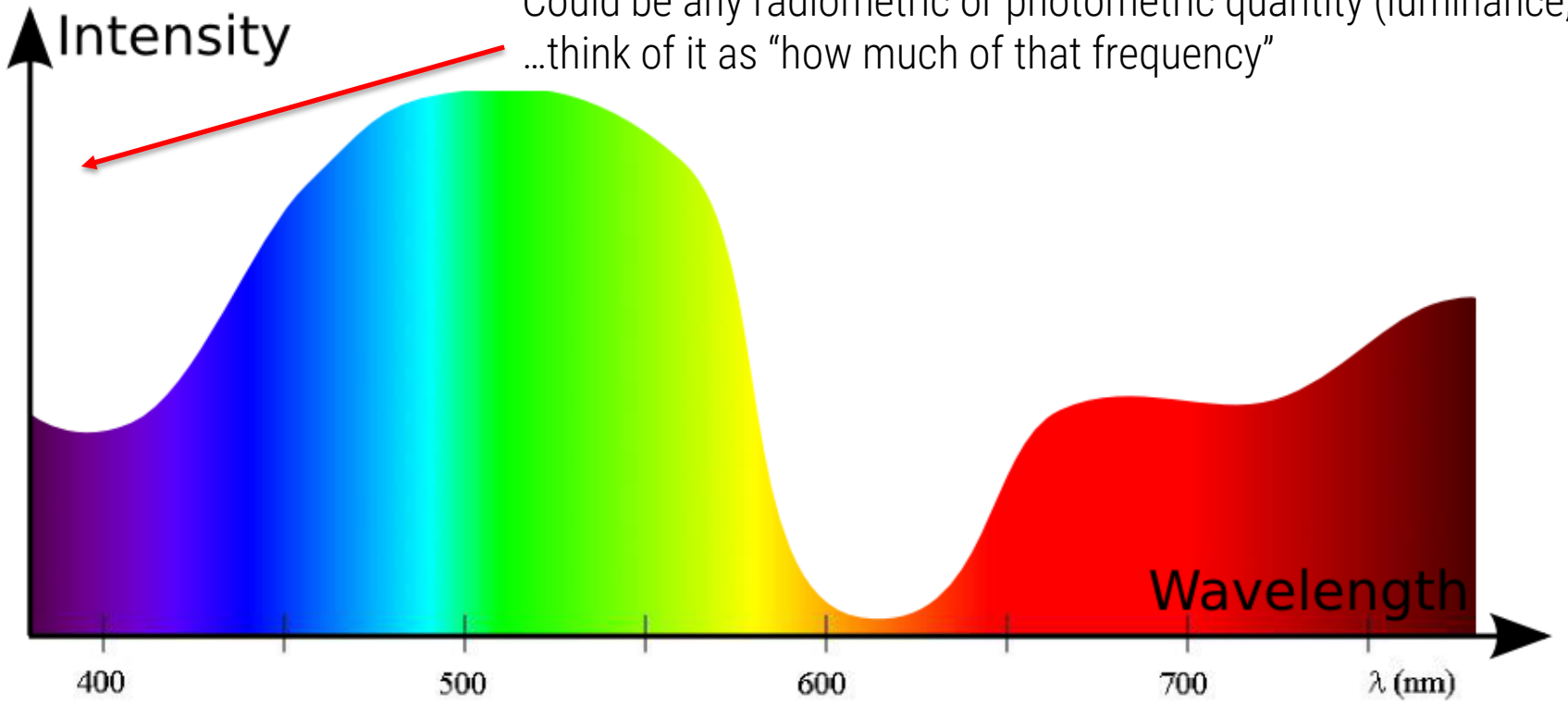
http://www.science4all.org/article/colors/

# BUT…

Light rays are typically composed of multiple wavelengths



# How do we describe a beam of light?

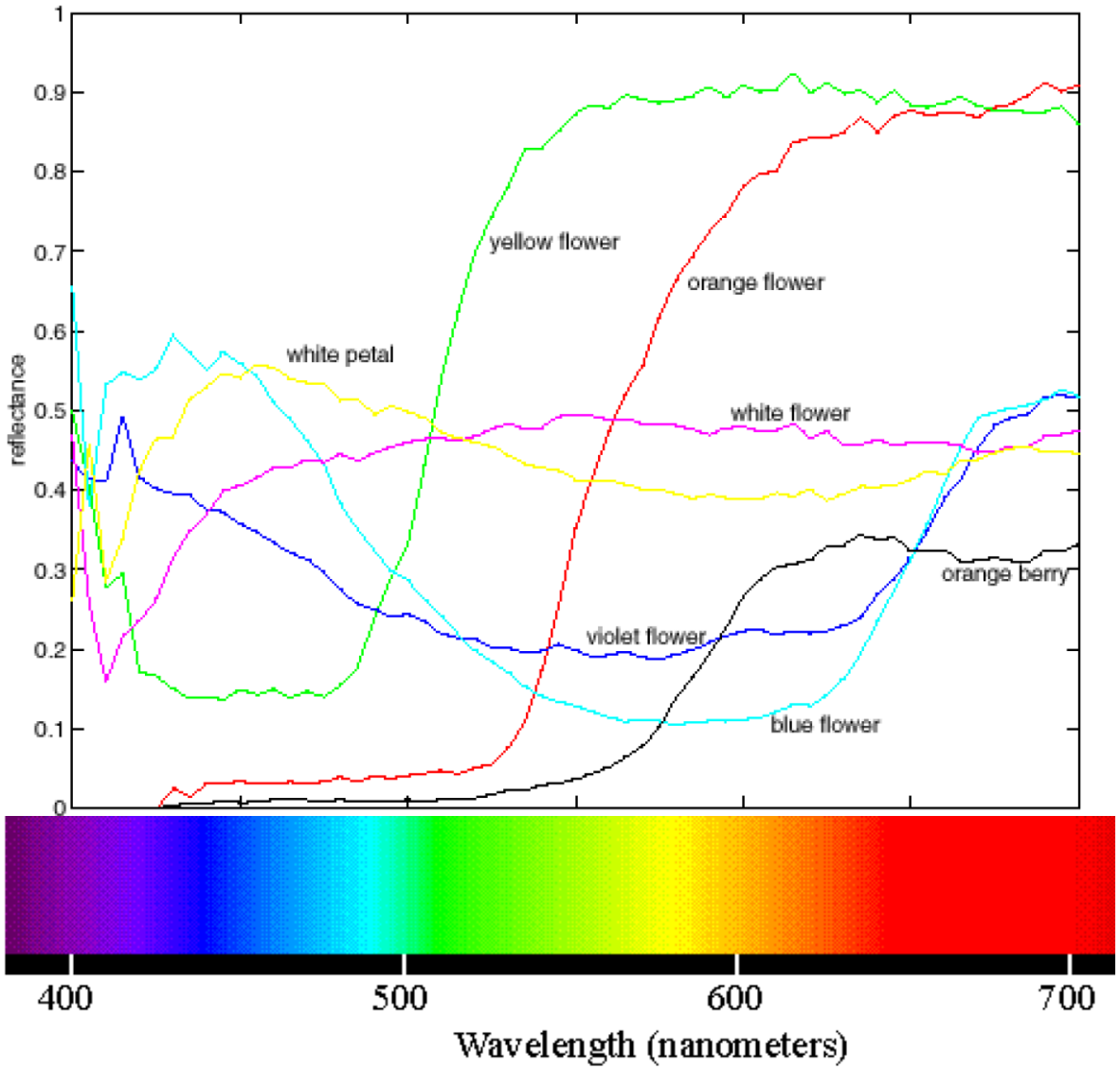



Could be any radiometric or photometric quantity (luminance, radiance, …)
…think of it as “how much of that frequency”

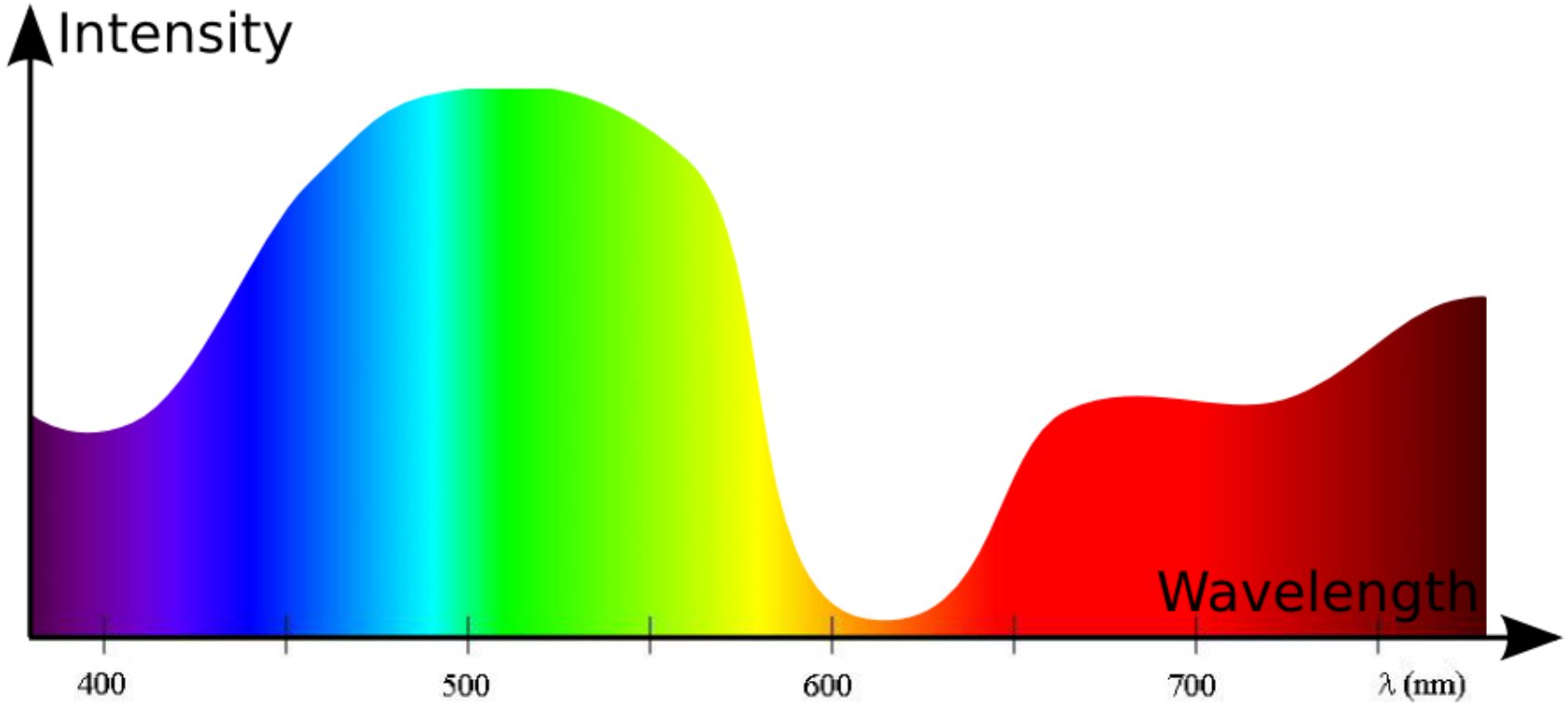
spectral power distribution (SPD)

http://www.science4all.org/article/colors/

# Non-monochromatic color spectra



# How do we know which color this would be?




http://www.science4all.org/article/colors/

# Physically speaking

If you want to see different wavelengths at different energies across the spectrum

→ you need to have multiple photo receptors that can be compared

# Thomas Young & Hermann von Helmholtz

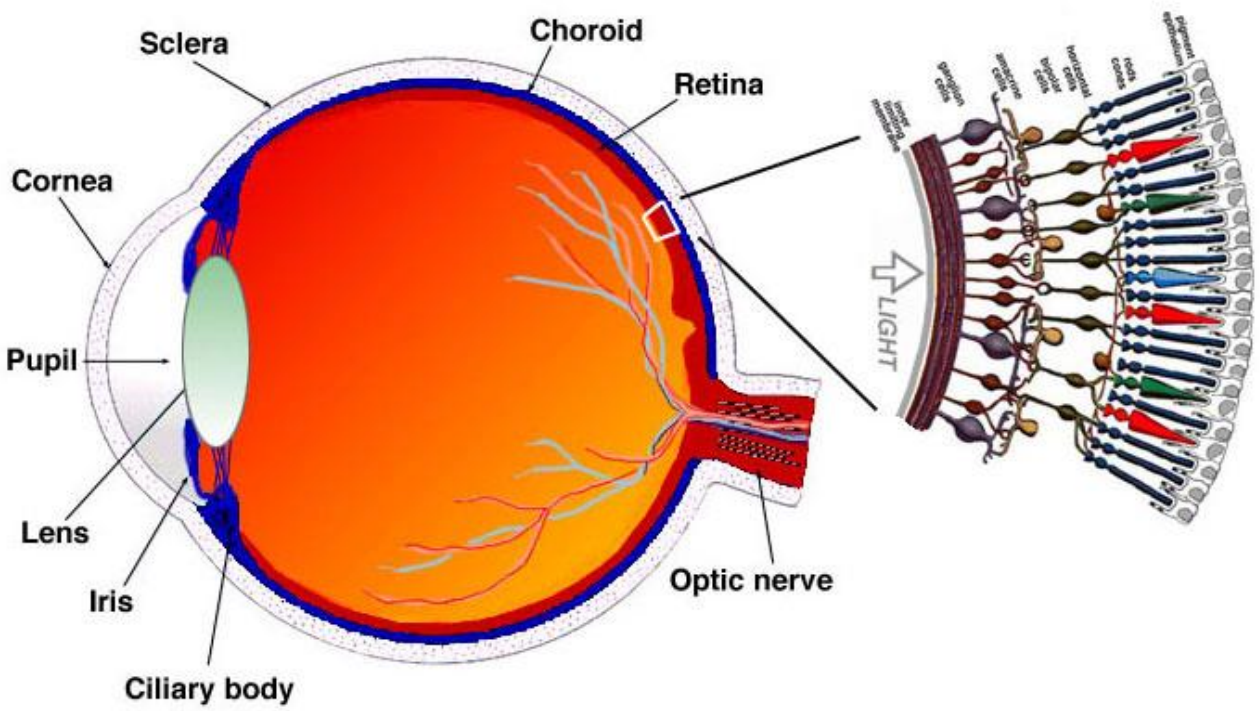
**Young (1802):**
we should have 3 different photoreceptors with different but overlapping response to different wavelengths of light

**Helmholtz (1850) & James Clerk Maxwell (1855):** run experiments & confirm Young

According to the Young-Helmholtz theory of color vision, there are three perceiving elements in the retina: red, green, and violet (now: blue).

https://vision.psychol.cam.ac.uk/jdmollon/papers/Mollon%202003%20_Thomas%20Young%20and%20the%20Chromatic%20Theory%20of%20Colour%20Vision.pdf

# Physical World ➡ **Visual System**




## Rods

No color (sort of)

All over the retina

More sensitive

## Cones

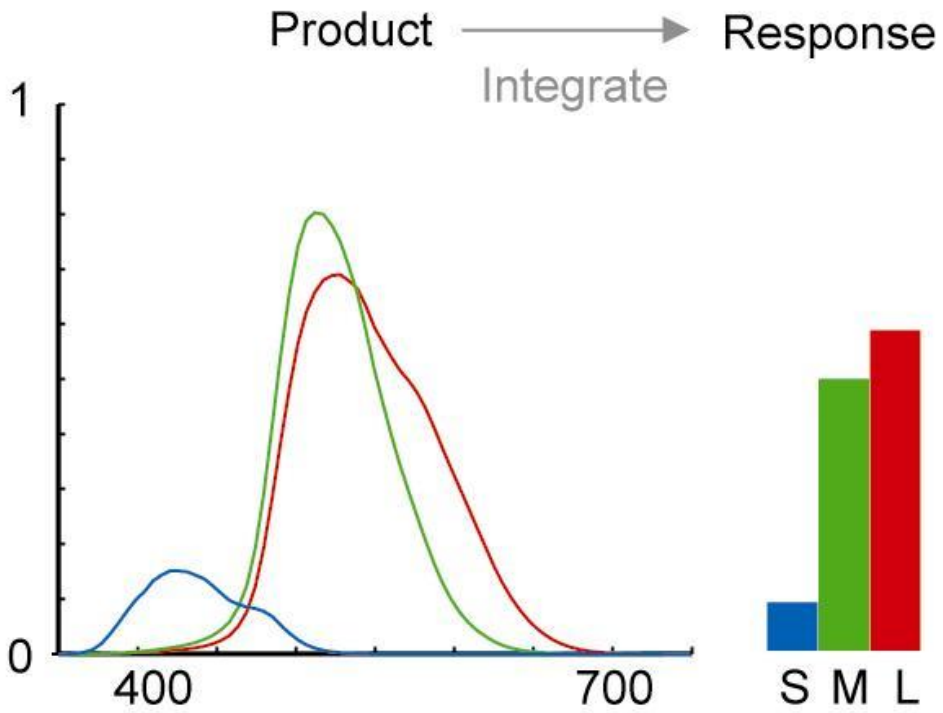
**Three** different kinds of “color receptors”

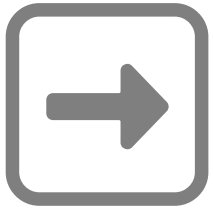
Mostly in the center

Less Sensitive

*Simple Anatomy of the Retina, Helga Kolb*

# Visual System → **Color Models**





This is the color the eye sees
This is not necessarily the color the brain sees!

# HOW TO DESCRIBE COLOR PERCEPTION

# How can we find a standard way to describe color?

Especially if color is wholly defined in terms of human perception?

Can we predict how a human will see different combinations of wavelengths?

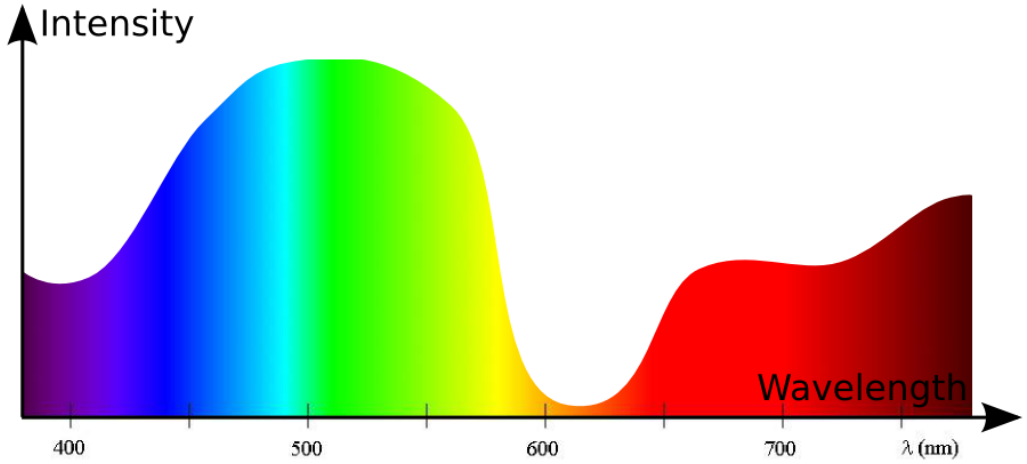
# Usually a viewer recognizes…

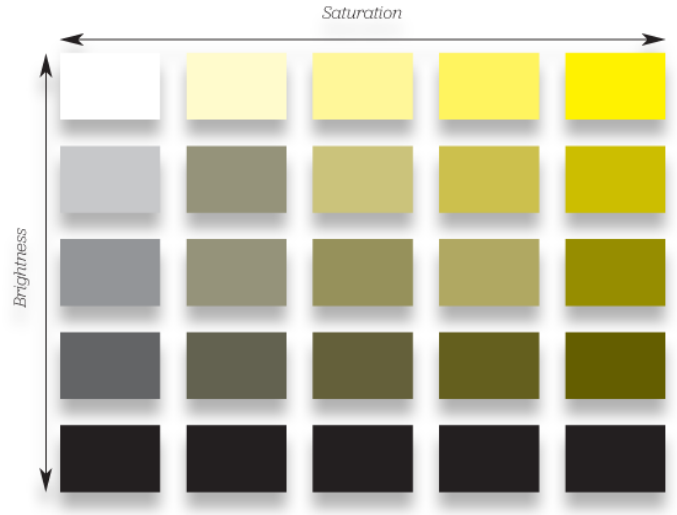
## LUMINANCE - think of it as the brightness of the light

## CHROMATICITY – the property that distinguishes red from blue, …

consists of HUE and COLORFULNESS (saturation, chroma, intensity, …)

(most people think of this as color, but formally the concept includes luminance)



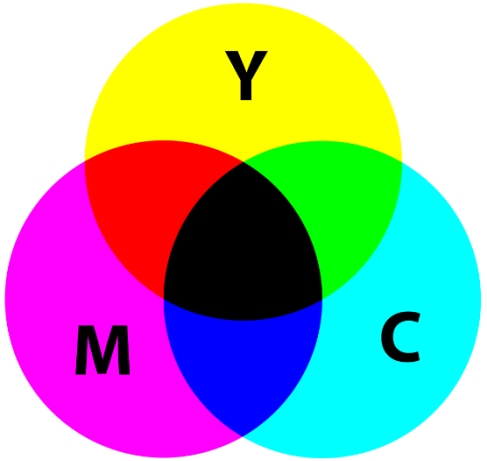
# What do we know so far?

We can describe any color of light with 3 numerical values

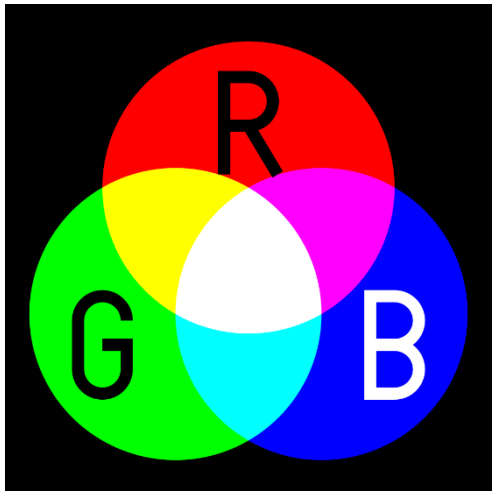
→Color is “3D” (mathematically)

But how do we combine these 3 values?

→ The color spaces set the rules!




Subtractive (CMYK)




Additive (RGB)

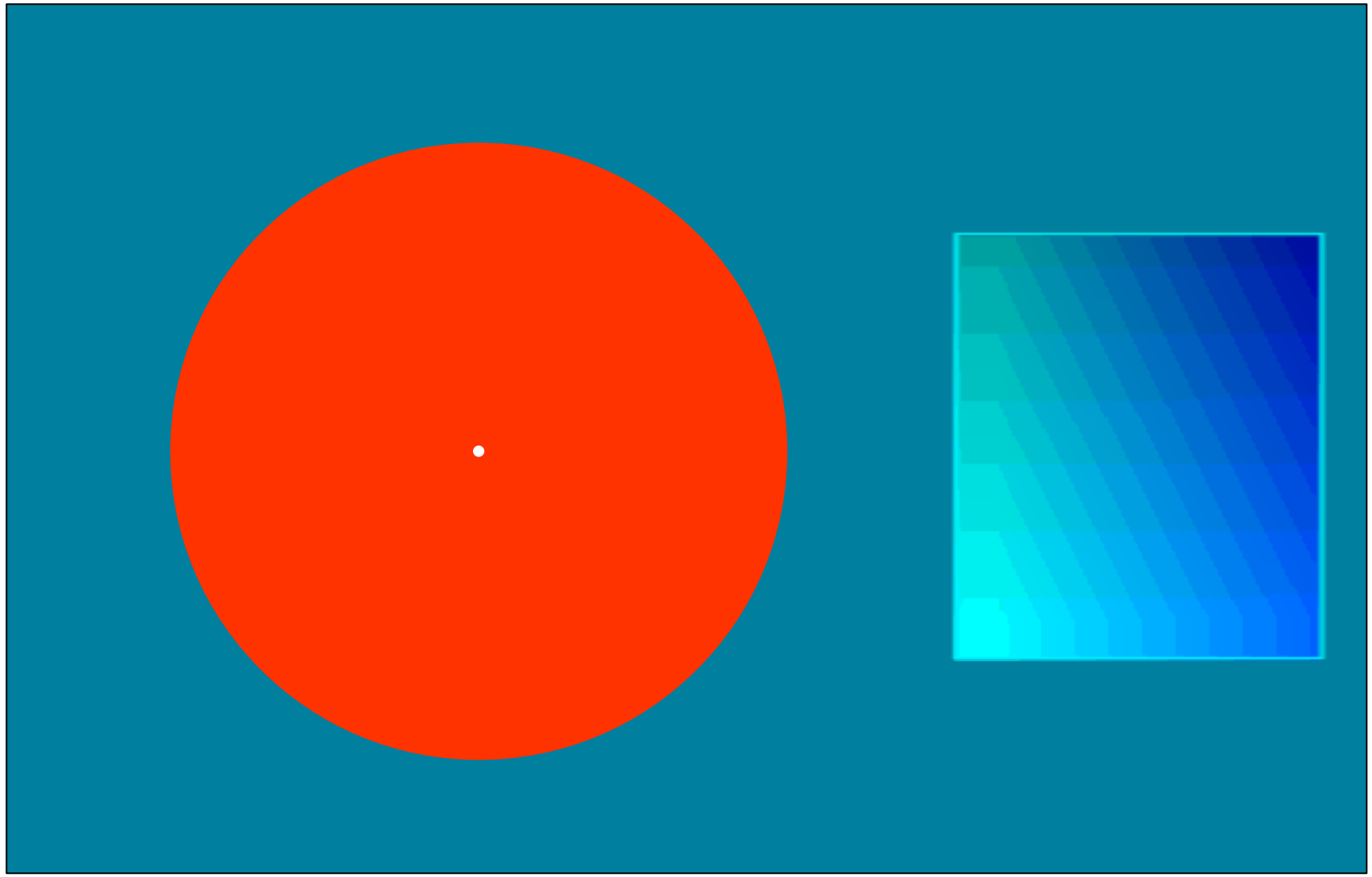
$$Q_\lambda = aR + bG + cB$$

# Most relevant for us: RGB

- Additive
- Chromaticity Coordinates: red, green, blue
  which specific red, green, and blue is usually described using another color space that we won't cover today

- Used in TVs, LCDs, phones, …
- BUT is device-dependent
  (without color management colors don't look the same on every screen)
- Cannot display all visible colors

# Let’s see REAL cyan …



# THE OTHER STRANGE WAYS WE EXPERIENCE COLOR…

# Color Perception → **Color Naming**



What color is this?

"Yellow"

# Color Perception → **Color Naming**

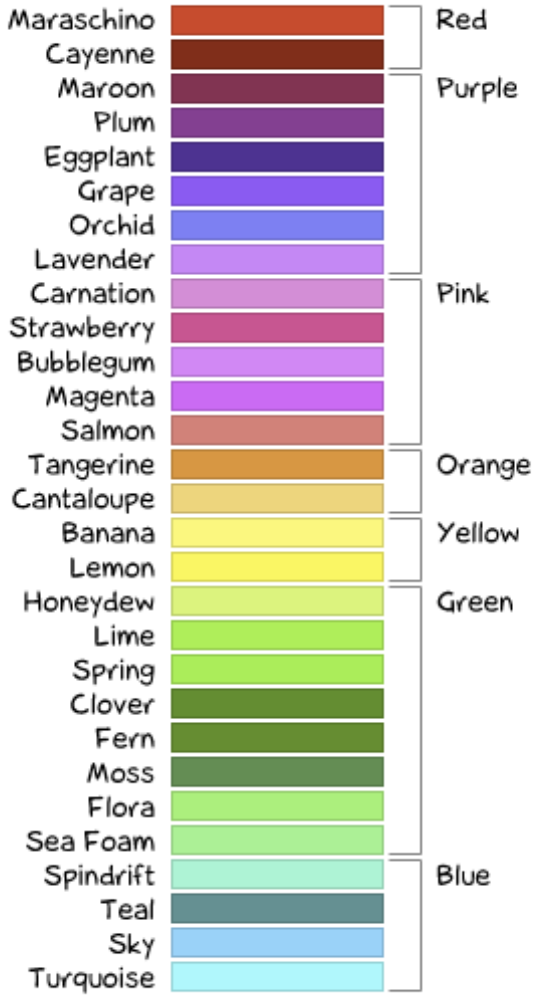
What color is this?

“Teal ?”

*“Turquoise ?”* *“Blue-Green ?”* *“Sarcelle ?”*

# Color according to gender?

Color names if you're a girl...




Color names if you're a guy...

Doghouse Diaries
"We take no as an answer."

# Color according to XKCD

A crowdsourced color-labeling game

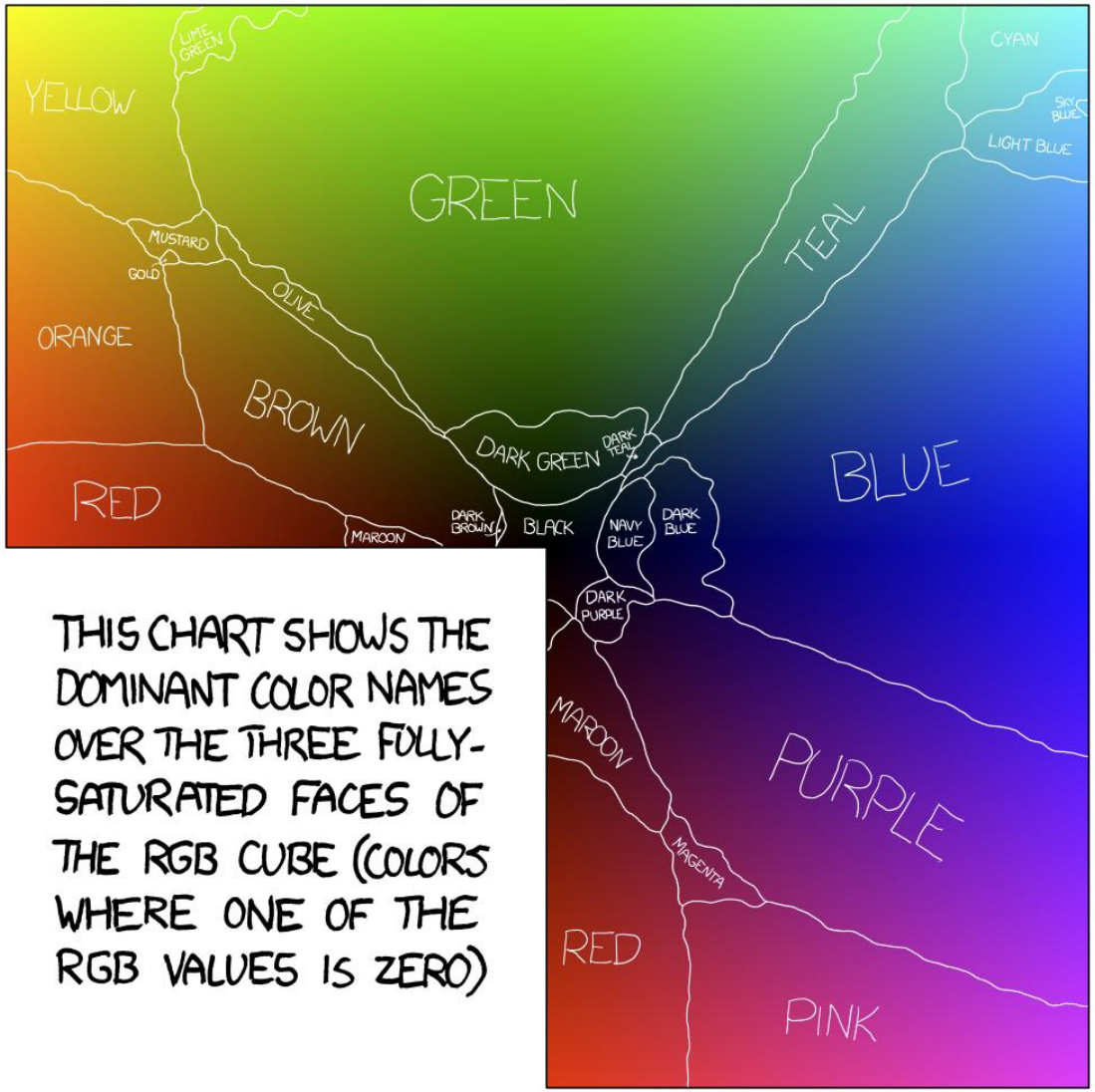
~5 million colors

~222,500 user sessions

http://blog.xkcd.com/2010/05/03/color-survey-results/

# Color according to XKCD

# Are there natural boundaries?

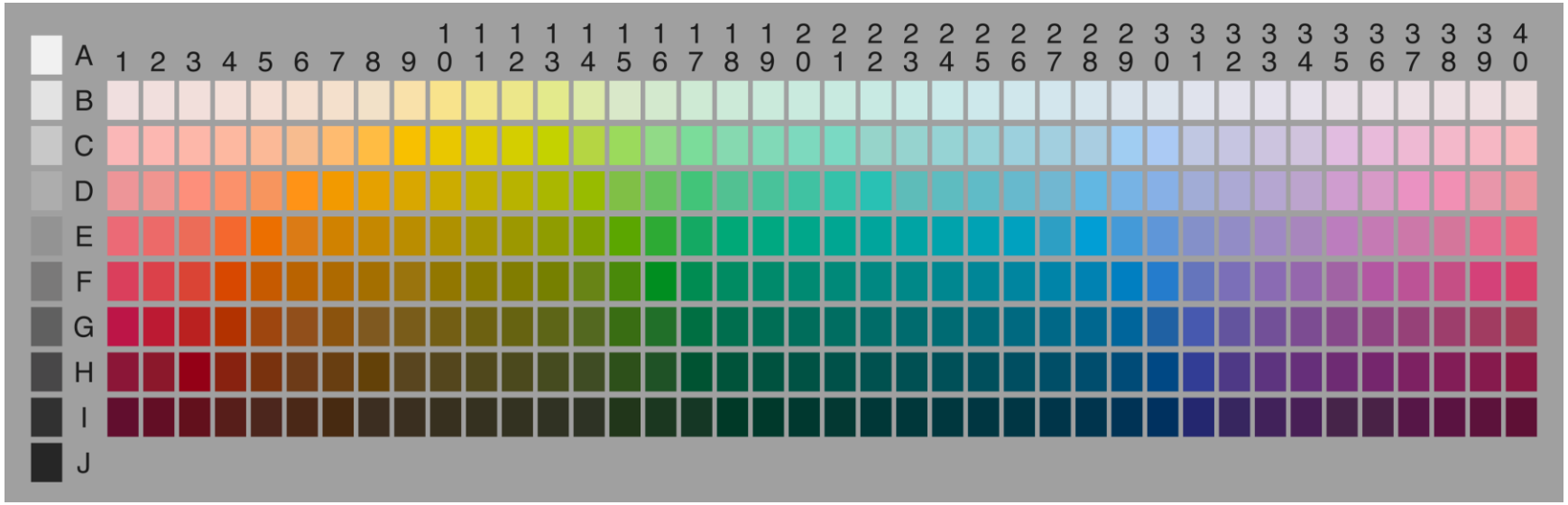



xkcd

# World Color Survey

Brent Berlin & Paul Kay 1969

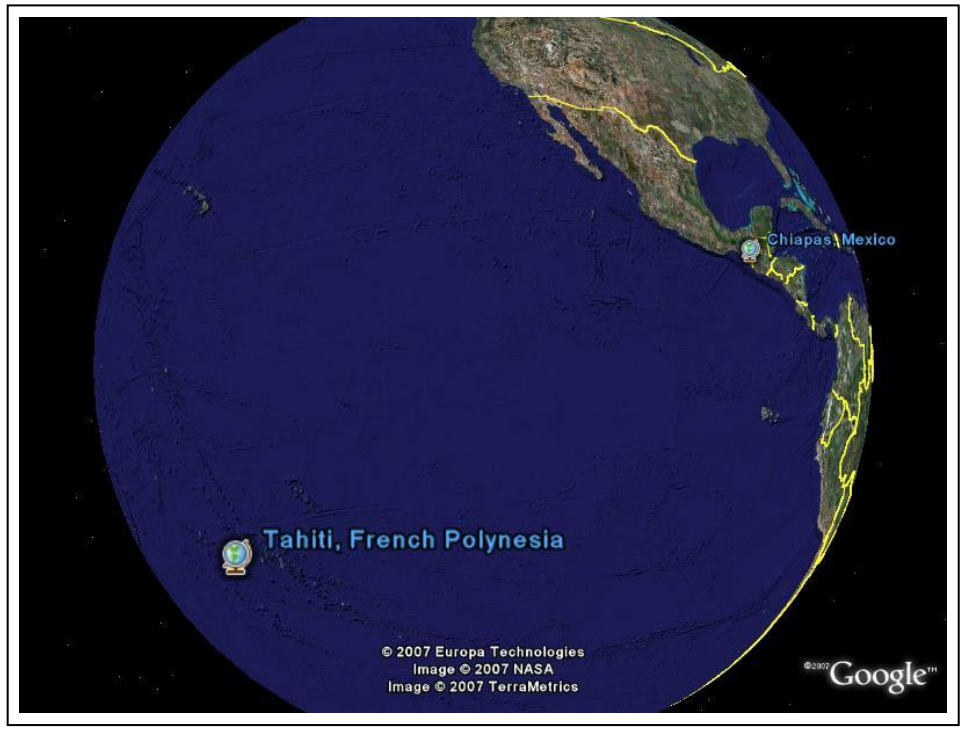
## Surveyed 2616 speakers of 110 languages using 330 different color chips



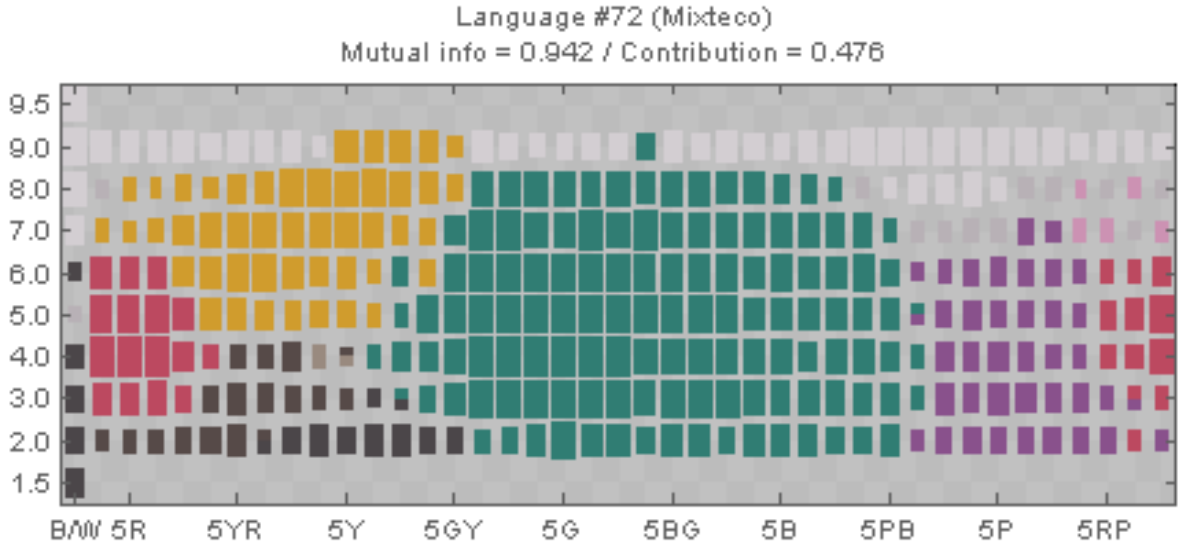

see also: http://wals.info/feature/132A?tg_format=map#2/32.5/153.5

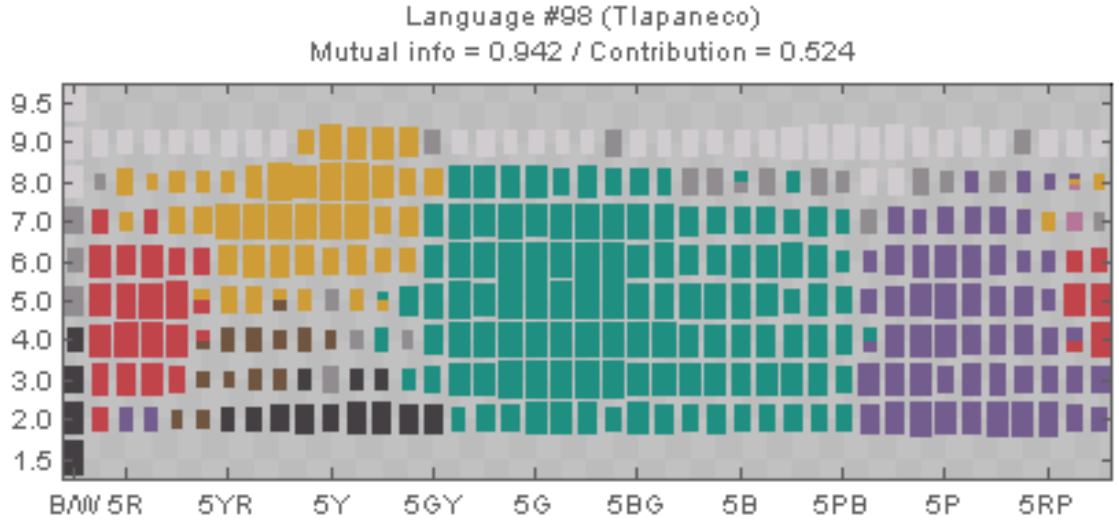
# Basic Color Terms

let’s look at two specific places

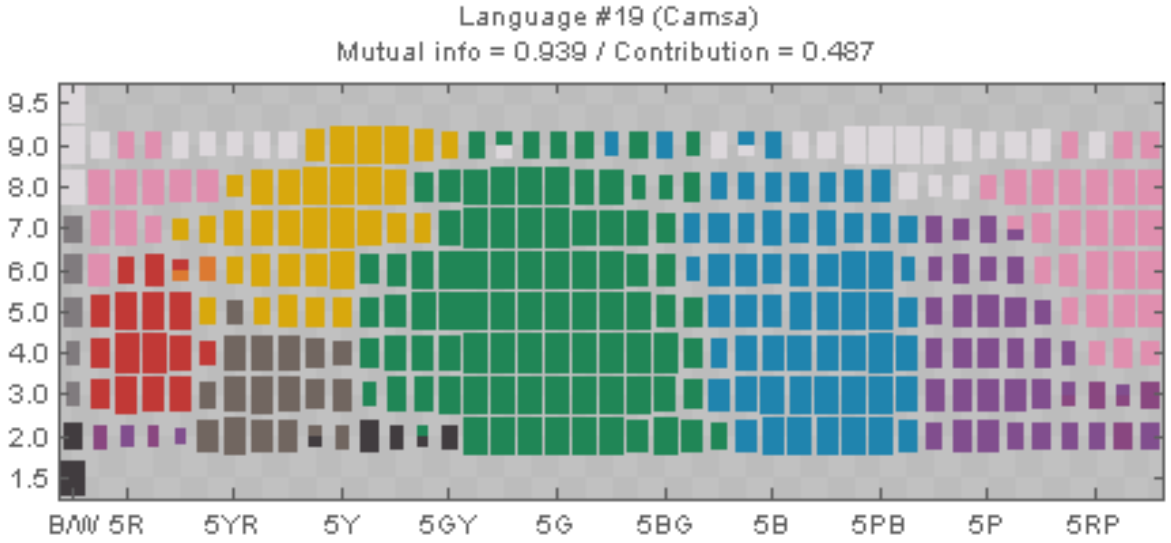


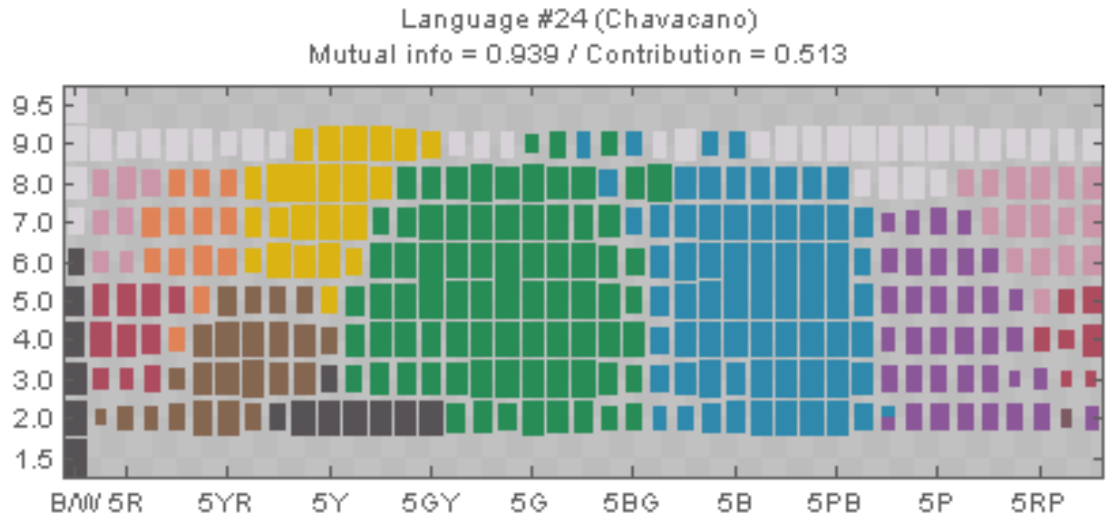

# Results from WCS (Mexico)



# Results from WCS  (South Pacific)



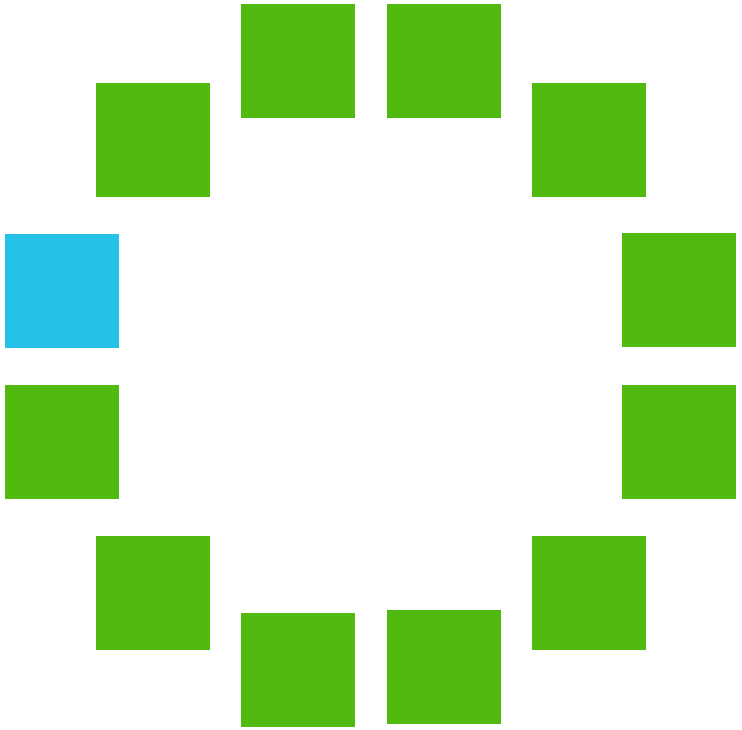



# Language-color interaction

- Himba tribe in Namibia – only few color words:
  - **zoozu**: most dark colors (red, blue, green, violet)
  - **vapa**: white, also some yellow
  - **borou**: some green and blue colors
  - **dumbu**: many green but also red colors

# But language-color interaction

- experiment: how long to find a differing color?

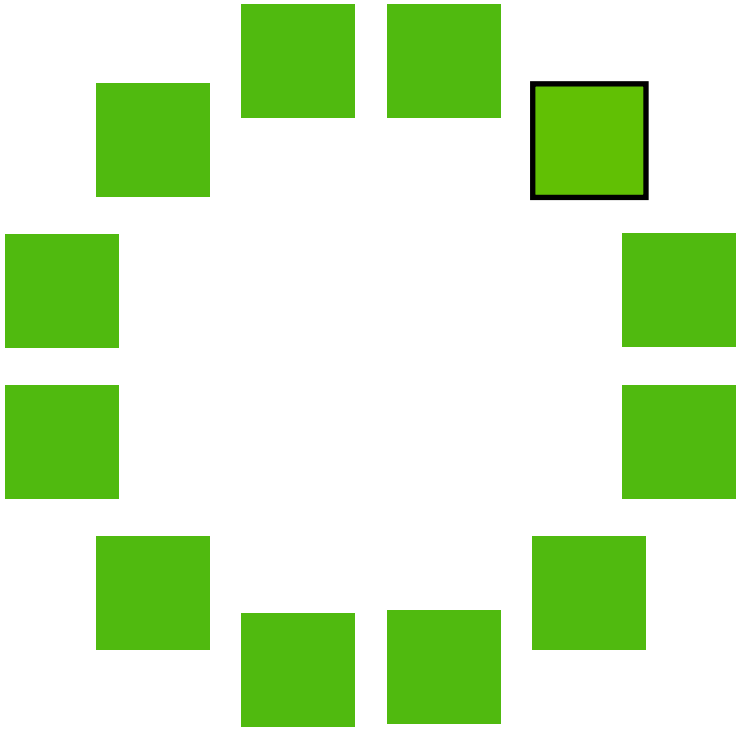


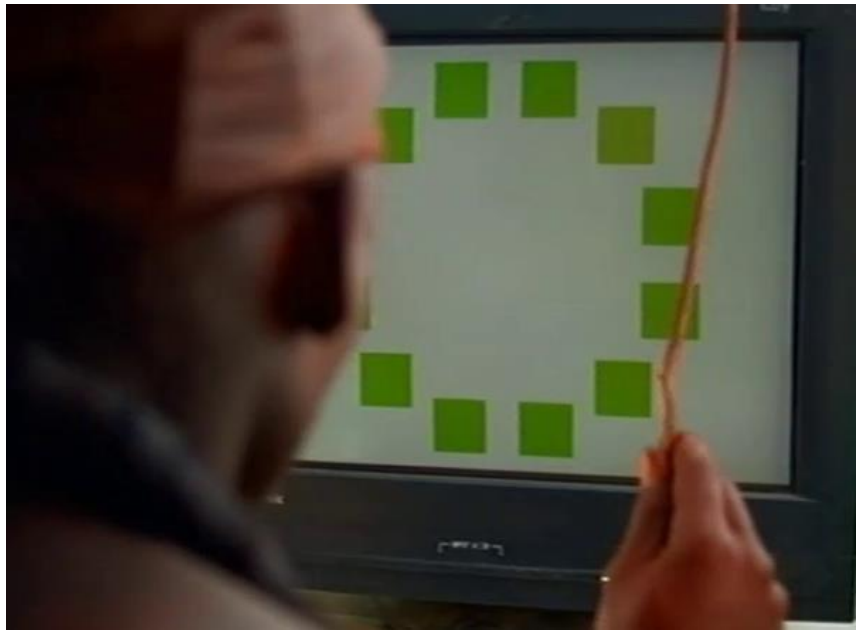


difficult to impossible for Himba people

# But language-color interaction

- experiment: how long to find a differing color?



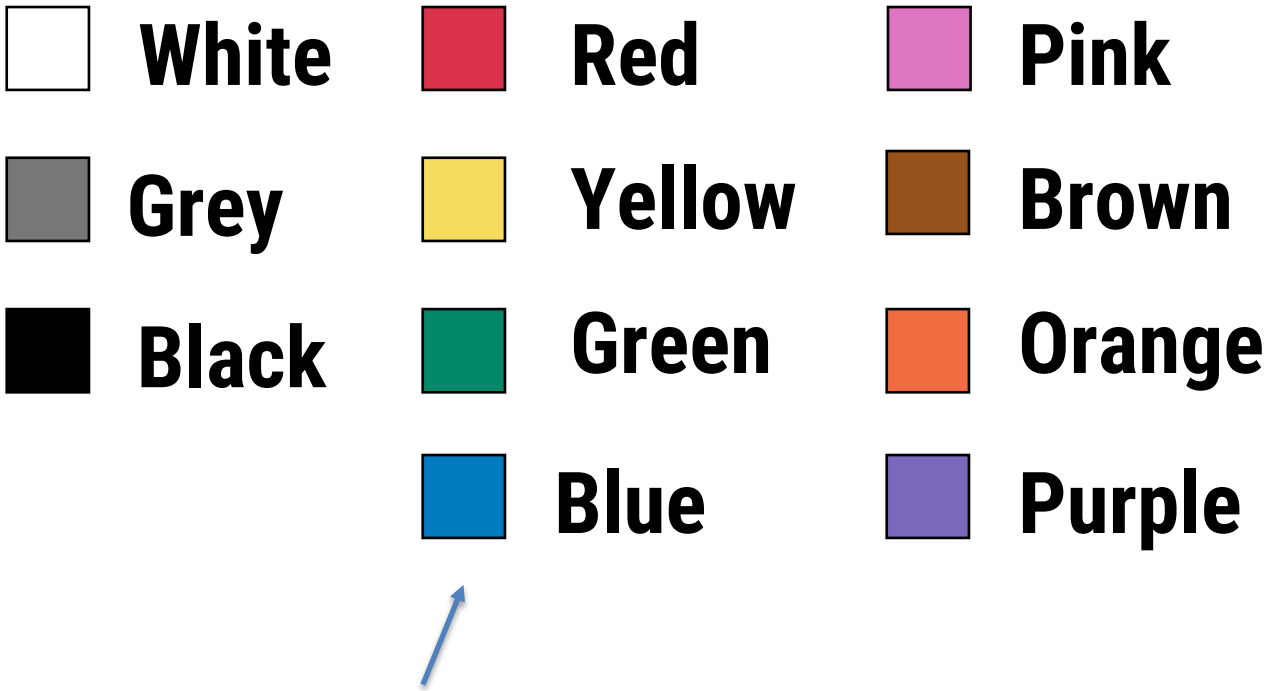




easy for Himba people: different words for both types of green

# Universal (?) Basic Color Terms

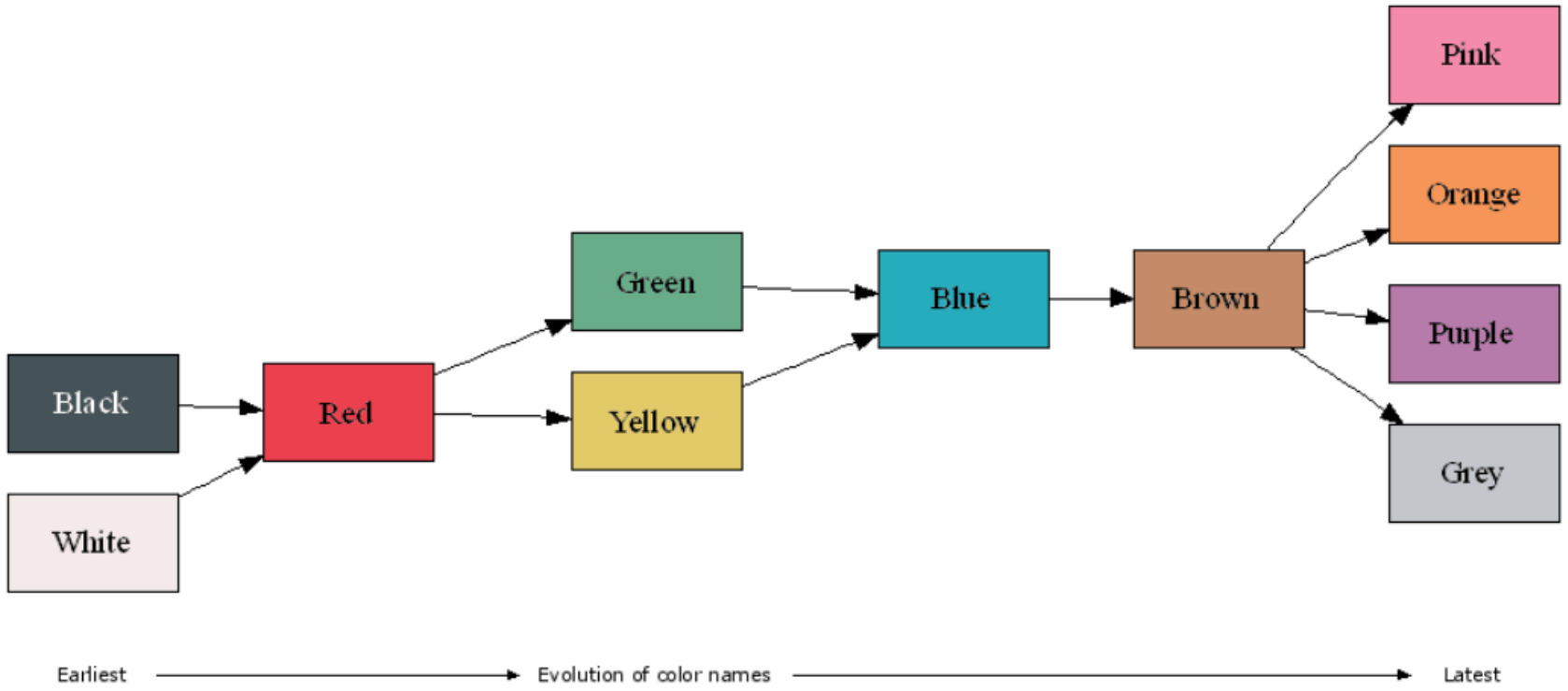
Basic color terms recur across languages




Interesting factoid: Cartographers found out that they need 4 unique hues to unambiguously distinguish all areas on an arbitrarily complex map

# Evolution of Basic Color Terms

Proposed universal evolution of color names across languages.



# CONCLUSION

- Color vision (just like brightness) does not correspond to physical measurements

- Be mindful in how you apply color in your computer-generated scenes!

# COLOR FOR VISUALIZATION

# COLOR SCALES

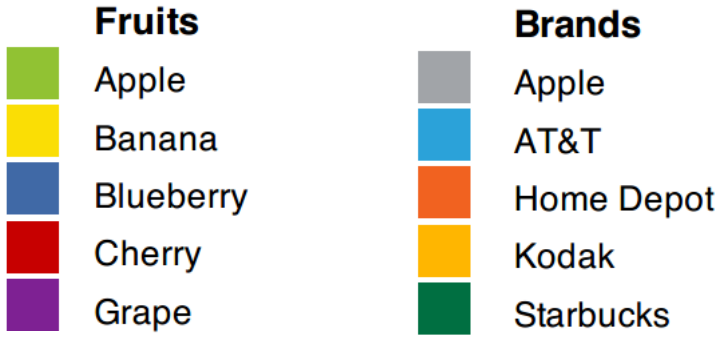
# Using Color to Label

**(For groups, categories, highlights, etc.)**

## Colors should be distinctive and named

"Blue" "Blue-er?" "Other Blue???"

## Use cultural conventions & appreciate symbolism




Lin et al. (2013) Selecting Semantically-Resonant Colors for Data Visualization

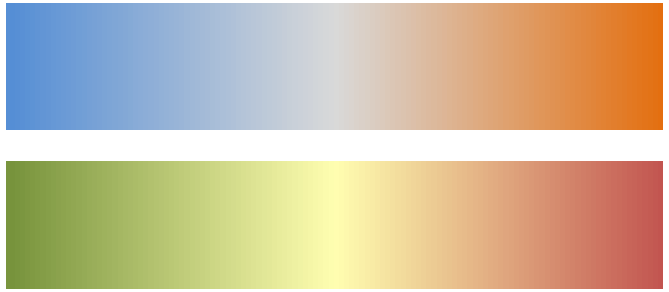
## Beware of bad interactions

# Using color for ordinal or quantitative data

Use a scale that varies **lightness** in addition to color

Shades of **gray** or shades of **a single color** are easiest

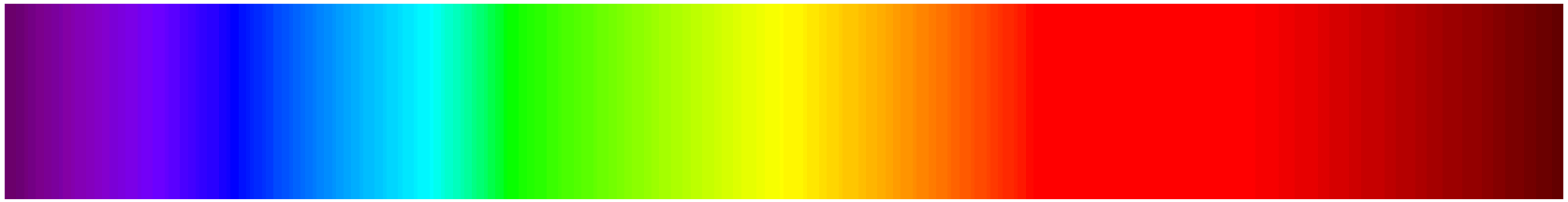
For **diverging scales**, use a lighter, desaturated value for the critical mid-point and darker hues for the ends



# Why are color choices important?

## Example: The Rainbow Color Scale

- Represent data by varying hue across (approximately) the full range of visible wavelengths
- One of the most common color scales in use today



# Very contested choice

2007

Visualization Viewpoints

Editor:
Theresa-Marie Rhyne

## Rainbow Color Map (Still) Considered Harmful

David Borland and Russell M. Taylor II
*University of North Carolina at Chapel Hill*

Research has shown that the rainbow color map is rarely the optimal choice when displaying data with a pseudocolor map. The rainbow color map confuses viewers through its lack of perceptual ordering, obscures data through its uncontrolled luminance variation, and actively misleads interpretation through the introduction of non-data-dependent gradients.

Despite much published research on its deficiencies, the rainbow color map is prevalent in the visualization community. We present survey results showing that the rainbow color map continues to appear in more than half of the relevant papers in IEEE Visualization Conference proceedings; for example, it appeared on 61 pages in 2005. Its use is encouraged by its selection as the default color map used in most visualization toolkits that we inspected. The visualization community must do better.

In this article, we reiterate the characteristics that make the rainbow color map a poor choice, provide examples that clearly illustrate these deficiencies even on simple data sets, and recommend better color maps for several categories of display.

The goal is to make the rainbow color map as rare in visualization as the `goto` statement is in programming—which complicates the task of analyzing and verifying program correctness (see the classic "Go To Statement Considered Harmful" paper by Dijkstra at http://www.acm.org/classics/oct95/).

### Problems with the rainbow color map

mercials, weather forecasts, and even the IEEE Visualization Conference 2006 call for papers, just to name a few. The problem with this wide use of the rainbow color map is that research shows that it is rarely, if ever, the optimal color map for a given visualization.[1-6] Here we will discuss the rainbow color map's characteristics of confusing the viewer, obscuring data, and actively misleading interpretation.

#### *Confusing*

For all tasks that involve comparing relative values, the color map used should exhibit perceptual ordering. A simple example of a perceptually ordered color map is the gray-scale color map. Increasing luminance from black to white is a strong perceptual cue that indicates values mapped to darker shades of gray are lower in value than values mapped to lighter shades of gray. This mapping is natural and intuitive.

The rainbow color map is certainly ordered—from a shorter to longer wavelength of light (or vice versa)—but it's not perceptually ordered. If people are given a series of gray paint chips and asked to put them in order, they will consistently place them in either a dark-to-light or light-to-dark order. However, if people are given paint chips colored red, green, yellow, and blue and asked to put them in order, the results vary (see Figure 1).[7] Some even put them in alphabetical order. To put them in the so-called correct order, most people must remember Roy G. Biv (red, orange, yellow, green, blue, indigo, violet), or some other mnemonic representation of the order of

2023

EDITOR: Theresa-Marie Rhyne, theresamarierhyne@gmail.com

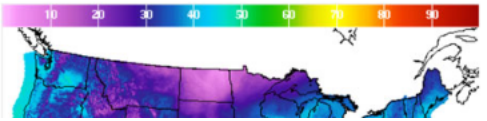
DEPARTMENT: VISUALIZATION VIEWPOINTS

## Rainbow Colormaps Are Not All Bad

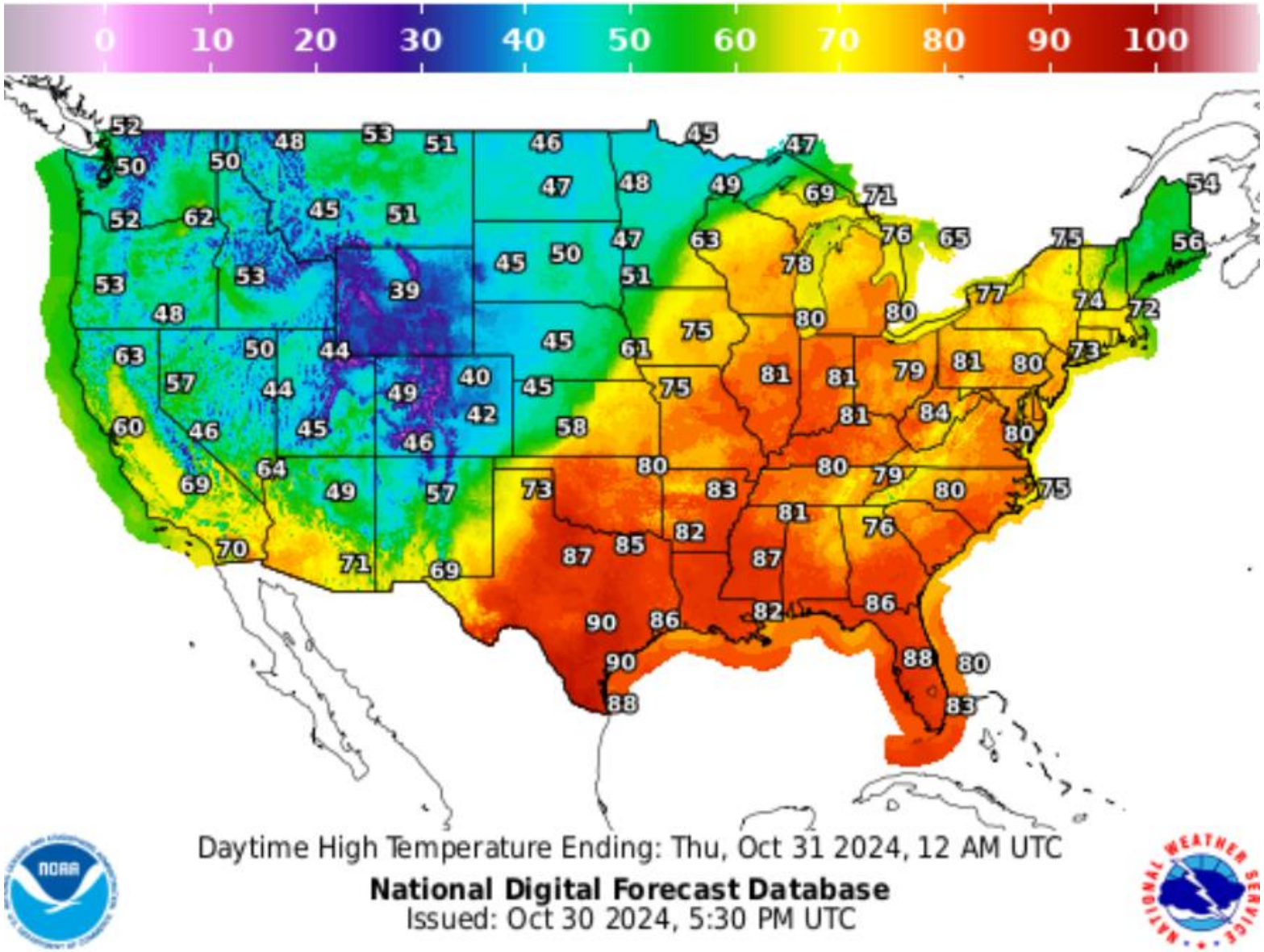
Colin Ware, *University of New Hampshire, Durham, NH, 03824, USA*
Maureen Stone, *Tableau Research, Seattle, WA, 98103, USA*
Danielle Albers Szafir, *University of North Carolina at Chapel Hill, Chapel Hill, NC, 27599, USA*

***Some 15 years ago, Visualization Viewpoints published an influential article titled* Rainbow Color Map (Still) Considered Harmful *(Borland and Taylor, 2007). The paper argued that the "rainbow colormap's characteristics of confusing the viewer, obscuring the data and actively misleading interpretation make it a poor choice for visualization." Subsequent articles often repeat and extend these arguments, so much so that avoiding rainbow colormaps, along with their derivatives, has become dogma in the visualization community. Despite this loud and persistent recommendation, scientists continue to use rainbow colormaps. Have we failed to communicate our message, or do rainbow colormaps offer advantages that have not been fully appreciated? We argue that rainbow colormaps have properties that are underappreciated by existing design conventions. We explore key critiques of the rainbow in the context of recent research to understand where and how rainbows might be misunderstood. Choosing a colormap is a complex task, and rainbow colormaps can be useful for selected applications.***

If you open a newspaper or turn on the local news, you will likely see a weather map using some variant of a *rainbow colormap*—a set of continuous colors traversing the colors of the rainbow—to represent temperature (e.g., Figure 1). However, decades of

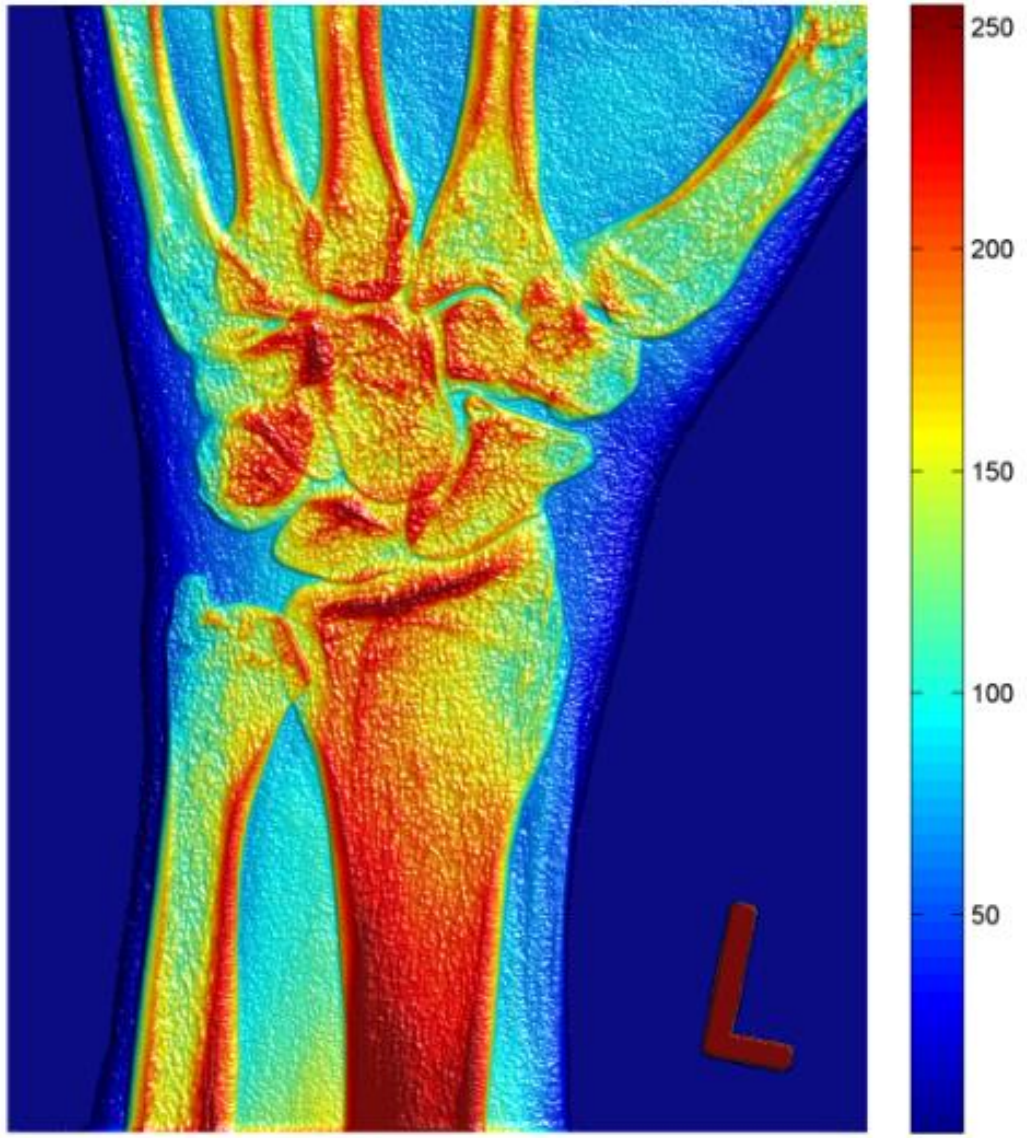


# Rainbow color scales are very common

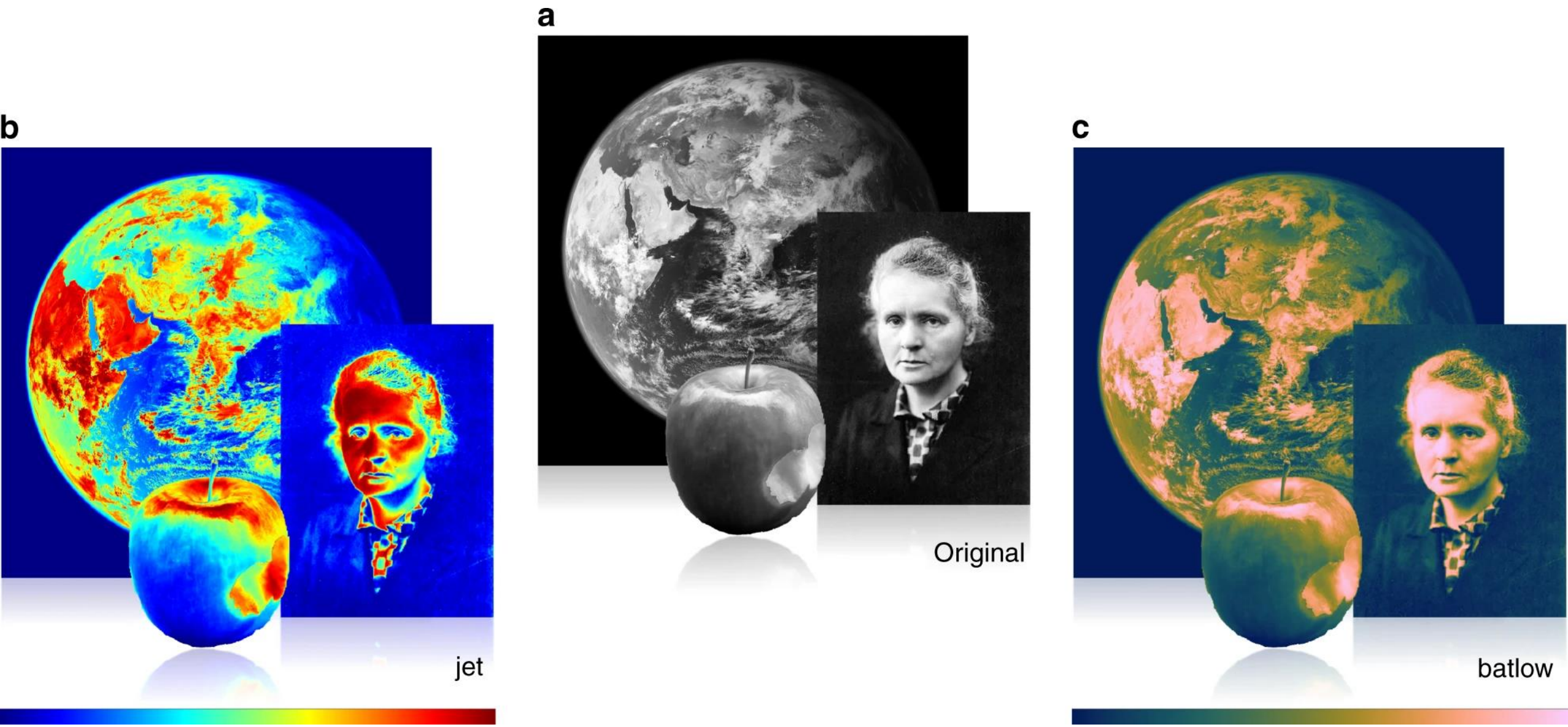


Original X-ray - left wrist


Original X-ray - left wrist - jet (rainbow) colormap

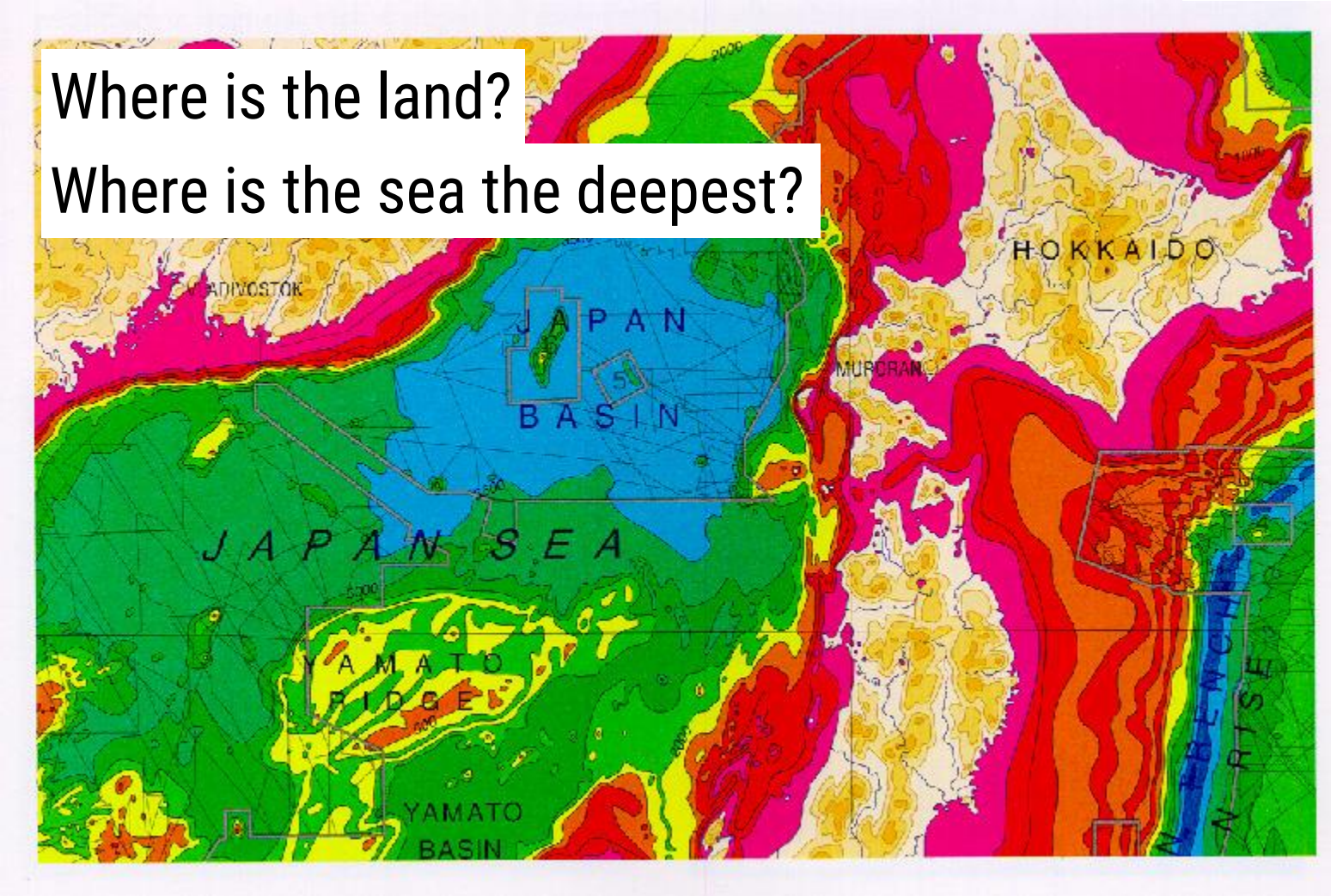



https://pdfs.semanticscholar.org/ee79/2edccb2c88e927c81285344d2d88babfb86f.pdf


a
b
c
Original
jet
batlow

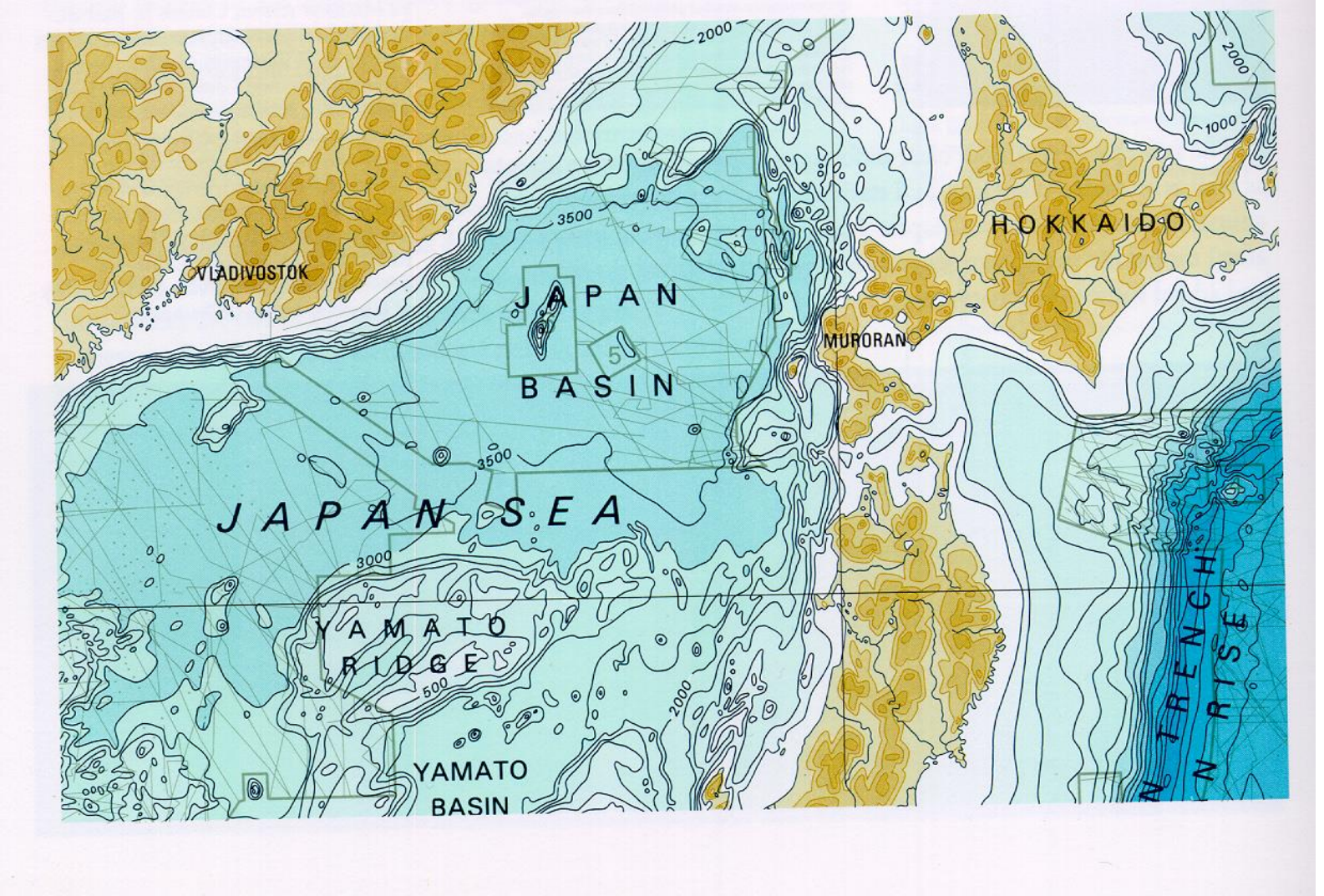
General Bathymetric Chart of the Ocean

Every color mark signals:
longitude, latitude, sea/land, depth/altitude

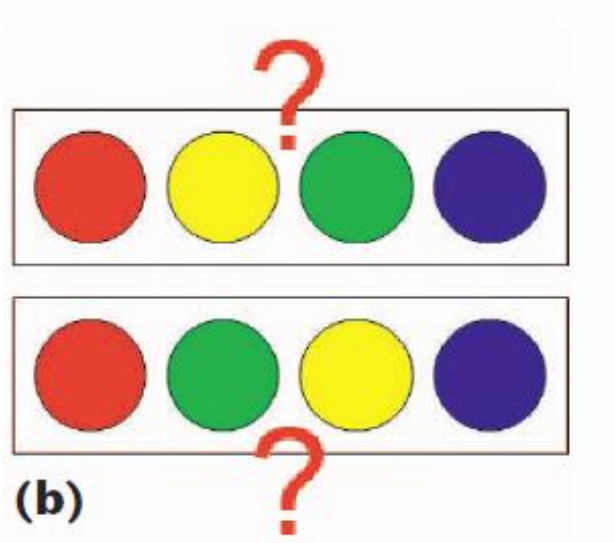


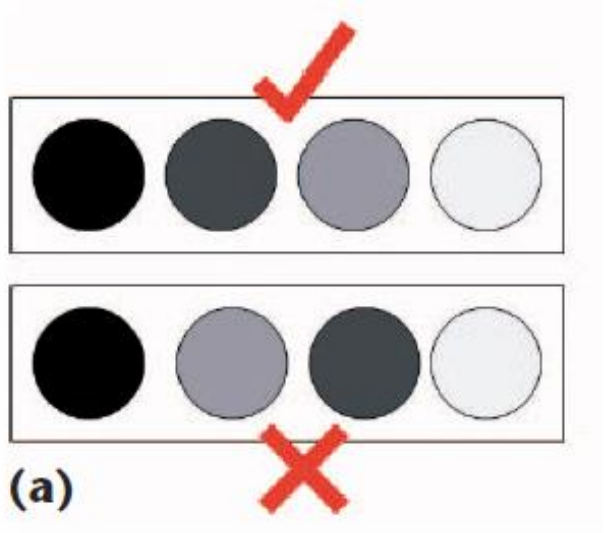
General Bathymetric Chart of the Ocean

# Now describe what kind of color scale was possibly used here



# Perceptual Ordering




## Rainbow Color Scale

- Is ordered by wavelength
- Is **not** perceptually ordered

## Gray Scale

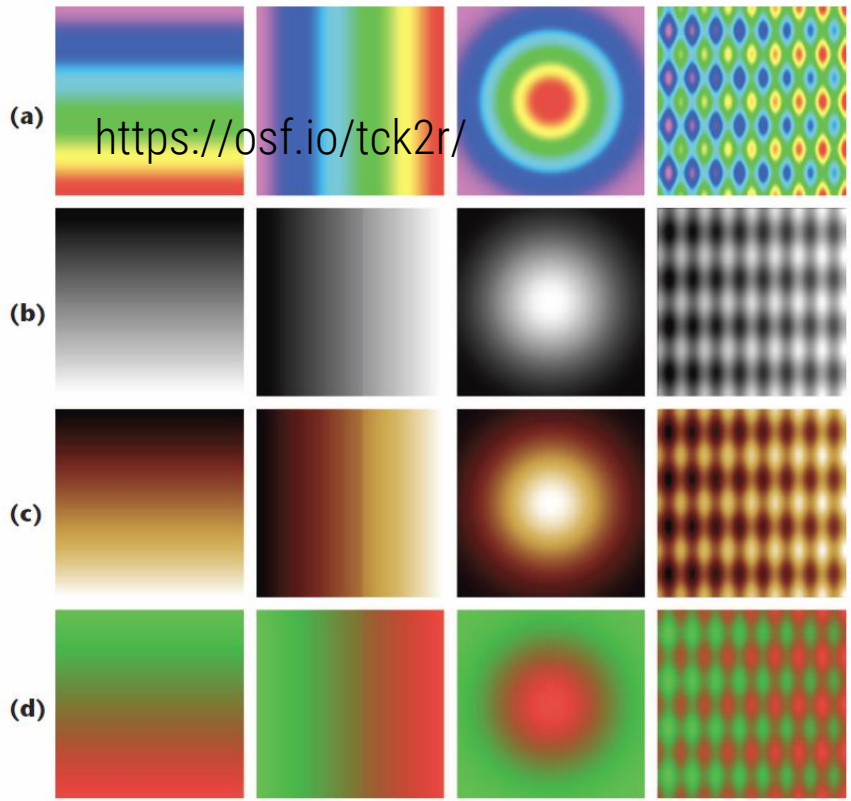
- Increases luminance (value) from dark to light
- Is perceptually ordered

From: Rainbow Color Map (Still) Considered Harmful, CG&A 07

# Color Scale Transitions

## Rainbow color scale

- appears separated into bands of almost constant hue
- sharp transitions can create false divisions within the data




rainbow color scale

gray scale

heated color scale

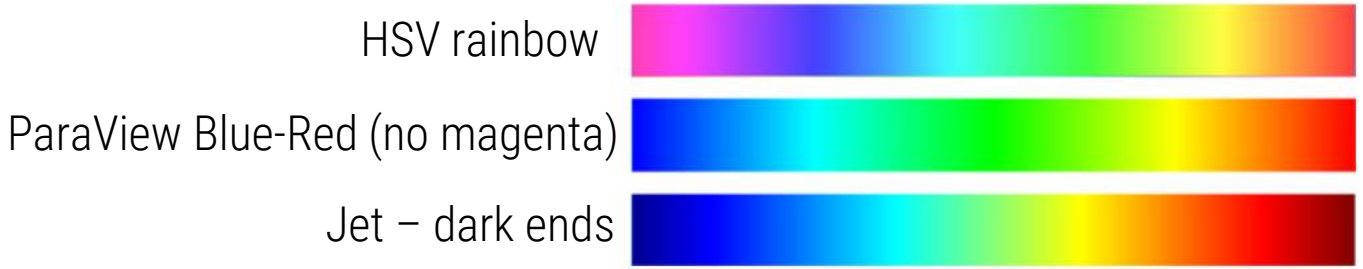
isoluminant green-red scale

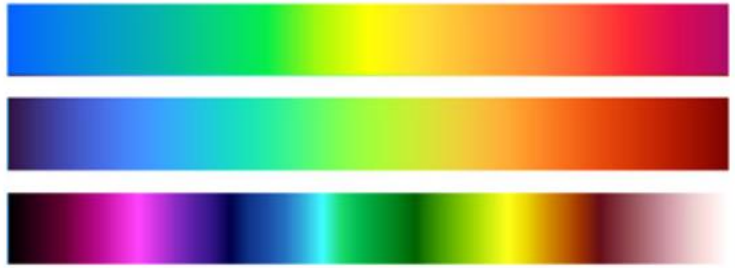
From: Rainbow Color Map (Still) Considered Harmful, CG&A 07

# BUT…

## There are different rainbows

simple interpolations in
RGB (a perceptually nonlinear colorspace), these rain-bows inevitably perform poorly



ParaView Uniform - perceptually uniform with diverging luminance

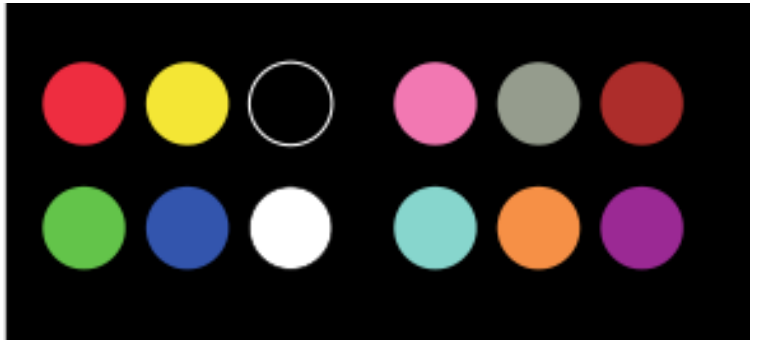
**Turbo** – smoothly rounded luminance to avoid banding

Rainbow crafted for thermal imaging - intentionally leverages the banding effects to highlight relevant regions in imaging data while manipulating local luminance to help peo ple resolve smaller features

# HOW TO PICK COLORS

# A Few General Rules for categorical data

- Always have **high luminance contrast** between foreground and background
- Use **only a few distinct colors**



**> 12 colors will likely not work**
**~5 colors recommended**

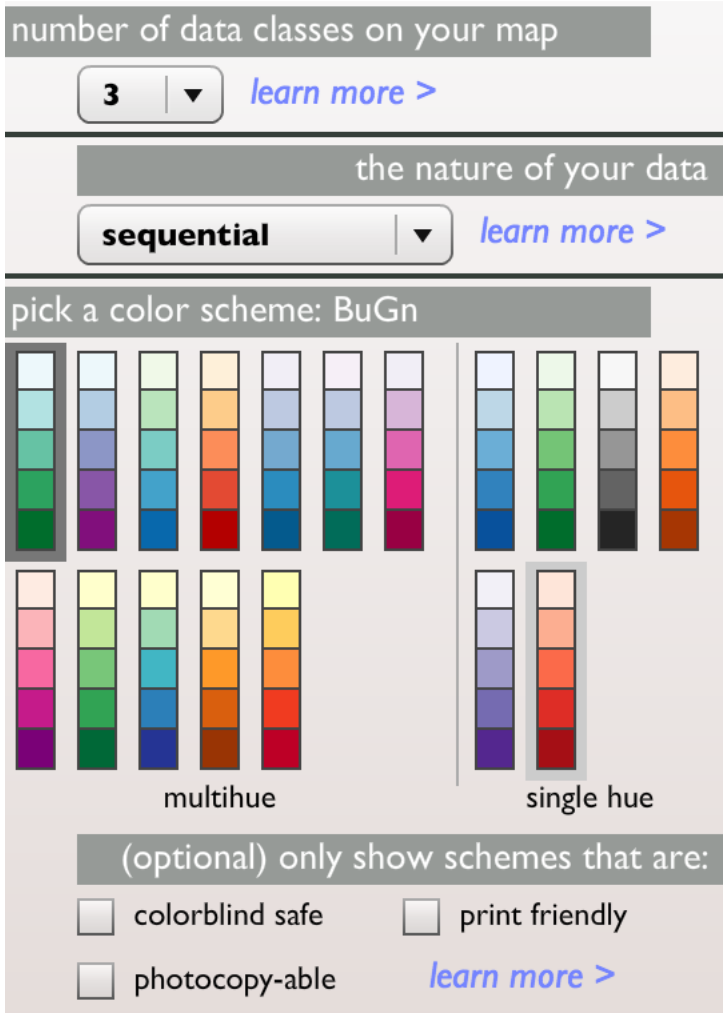
From Ware, Information Visualization

CONTRAST

You can make this work if you consider value

# CONTRAST

# ColorBrewer

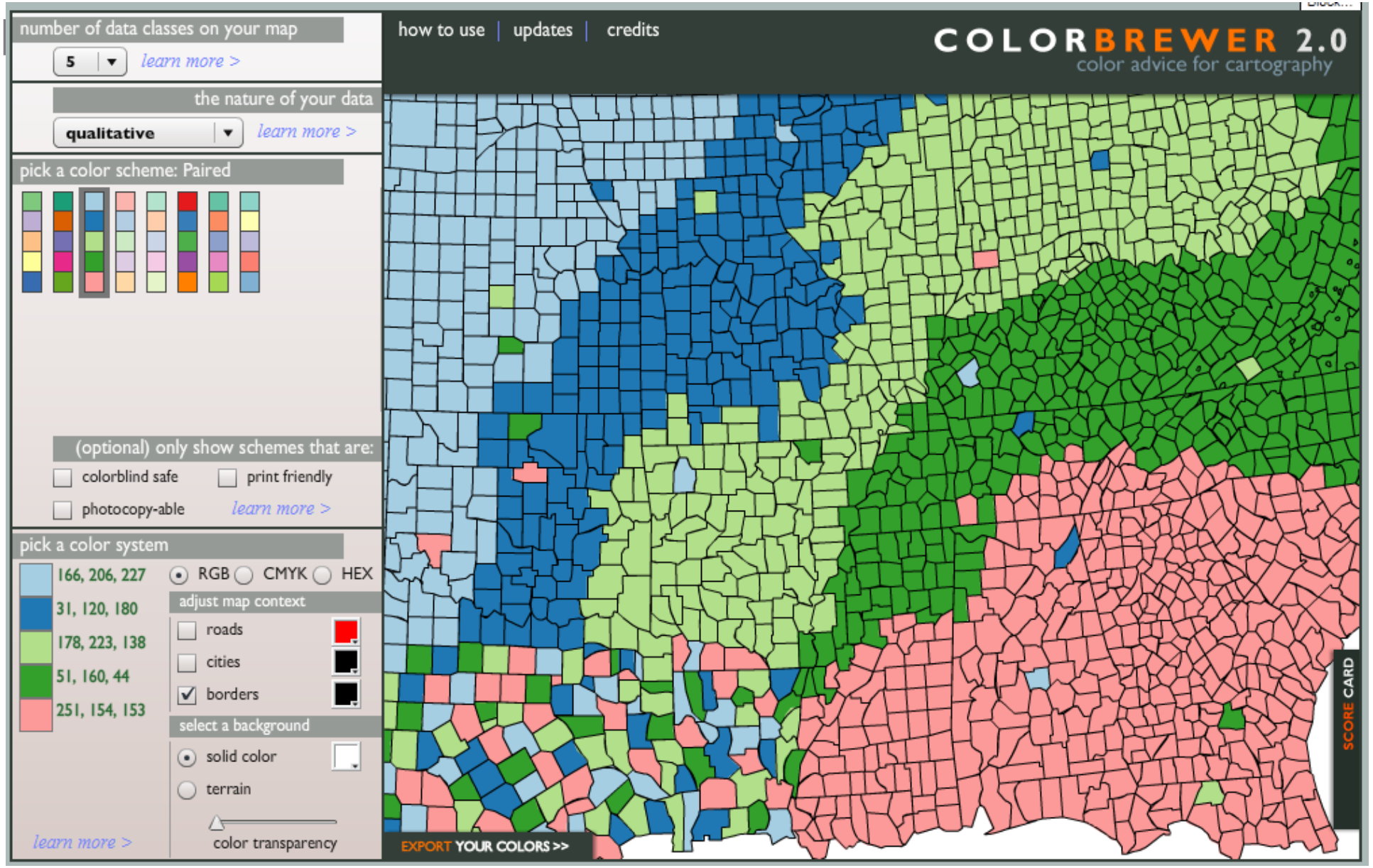



**Highly recommended!**

Designed originally for maps but will also work well for other types of visualizations

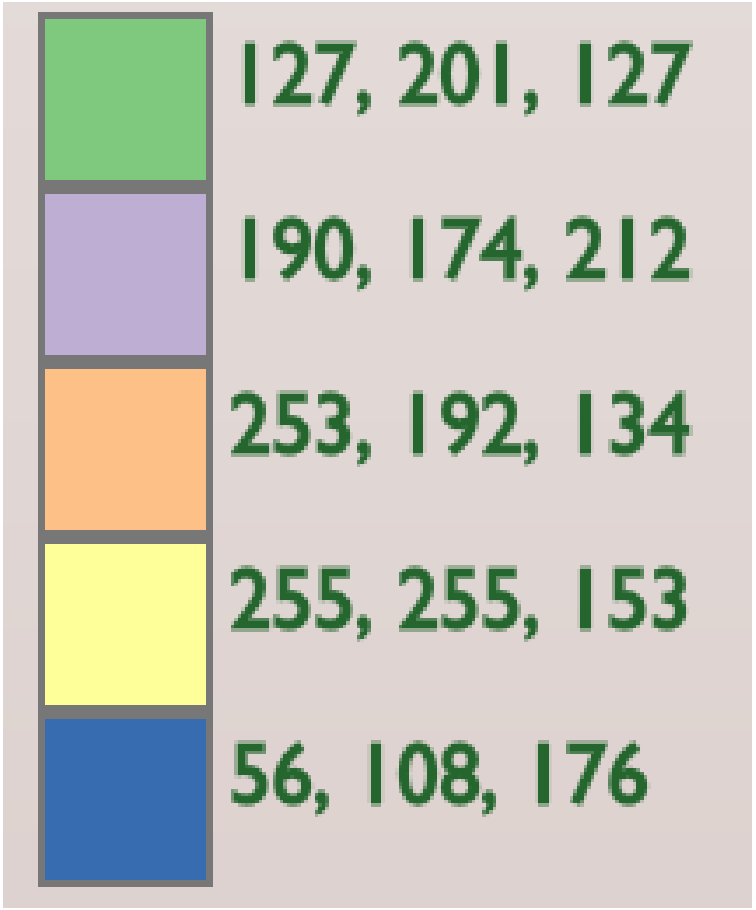
http://colorbrewer2.org/

# Color




http://colorbrewer2.org/

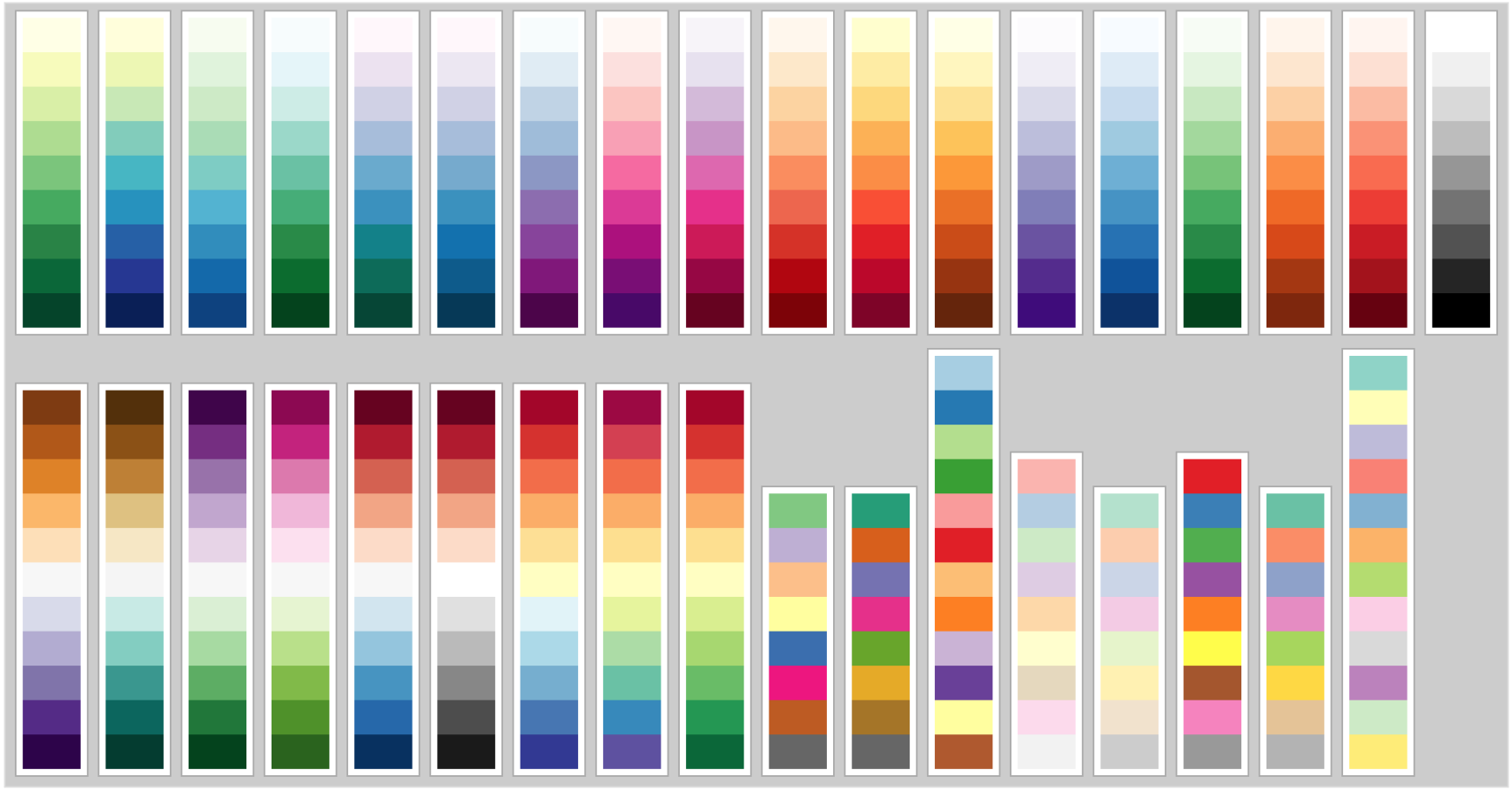
# ColorBrewer




(RGB)


(Hex)

# Every ColorBrewer Scale



For CSS and JavaScript (by Mike Bostock)

http://bl.ocks.org/mbostock/5577023

7% of the viewers may not see anything if you use red-green,

# ONE WARNING ABOUT

# RED-GREEN

The following slides on the topic are adapted from Tobias Isenberg's

# Color Vision Deficiency

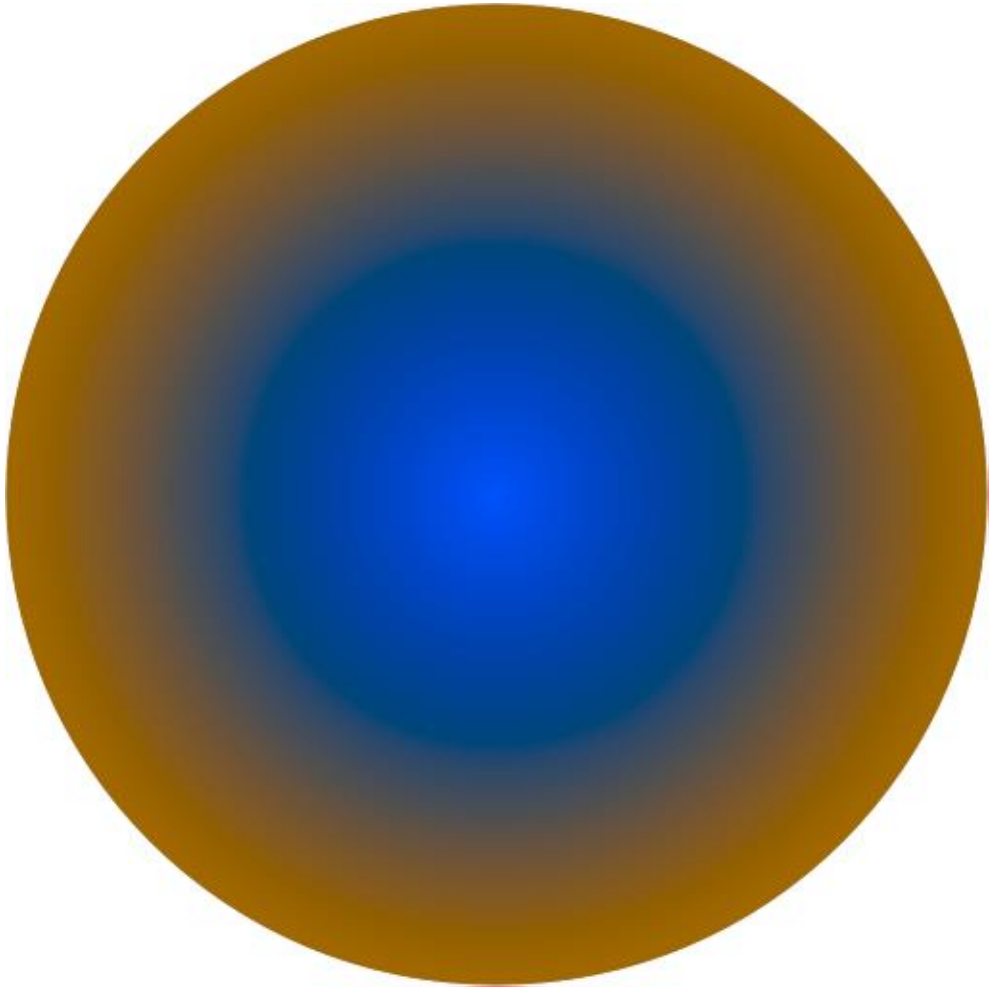
normal color vision

**simulation of color contrast for deuteranopic color vision**
(green receptors absent)

approx. 7% of male population color-deficient

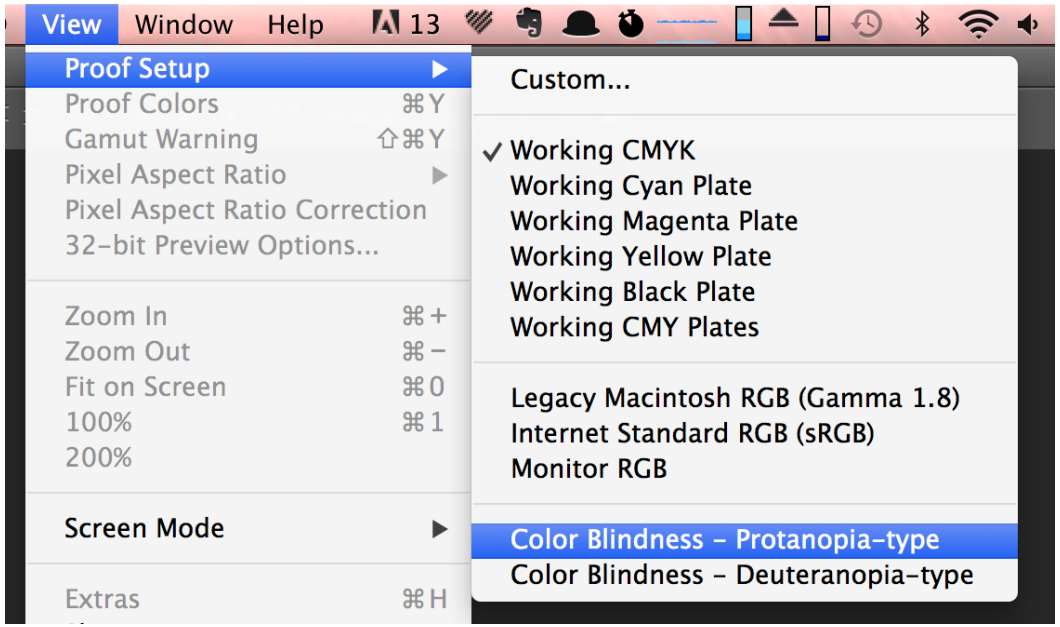
mostly red-green color deficiency (deuteranopia or protanopia) – but other forms exist as well

# Better: Red-Blue Contrast



# Check Your Visualizations!

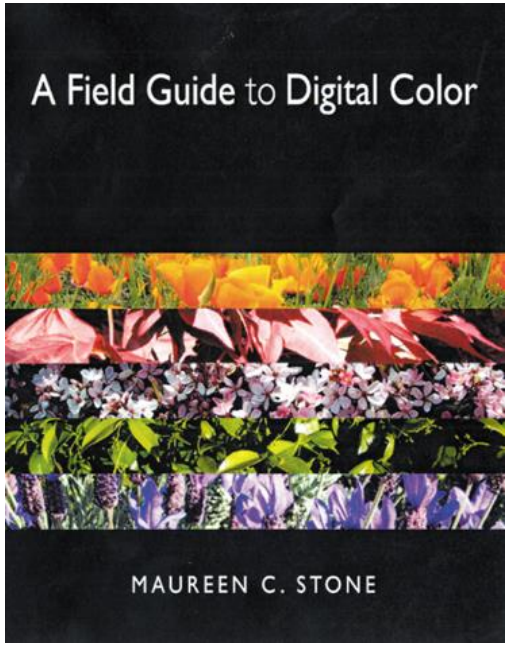
When possible, avoid red-green color contrasts for visualization purposes.




To test your visualizations, use proofing modes in PhotoShop and GIMP, or try VisCheck http://www.vischeck.com/

or http://www.color-blindness.com/coblis-color-blindness-simulator/

# Color Resources




Maureen Stone's Resources
*A Field Guide to Digital Color*
http://www.stonesc.com

Cindy Brewer's *ColorBrewer*
http://colorbrewer2.org
For CSS and JavaScript
http://bl.ocks.org/mbostock/5577023

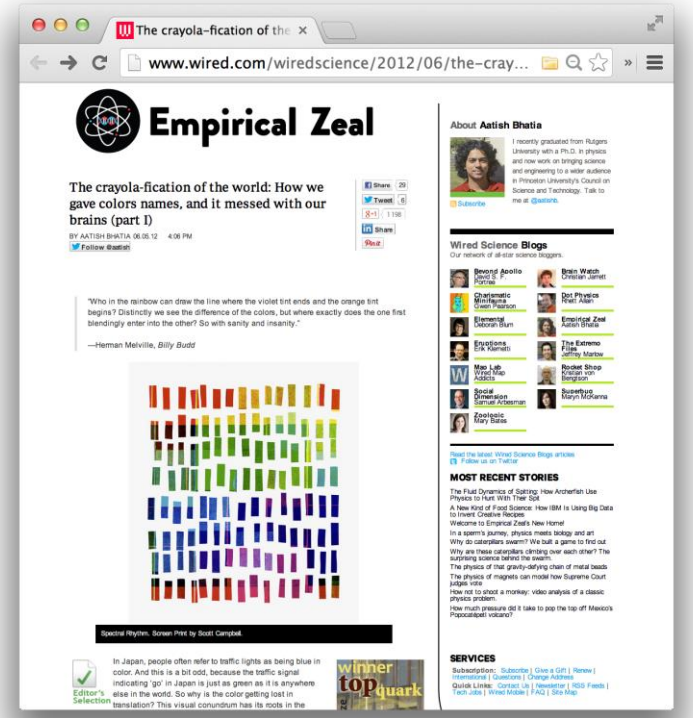
Community Palette Sharing
http://www.colourlovers.com
http://kuler.adobe.com
https://coolors.co/palettes/trending
https://paletton.com

# **(Fun)** Color Resources!

## **Wired** “The Crayola-fication of the World”

by Aatish Bhatia

http://www.wired.com/wiredscience/2012/06/the-crayola-fication-of-the-world-how-we-gave-colors-names-and-it-messed-with-our-brains-part-i/



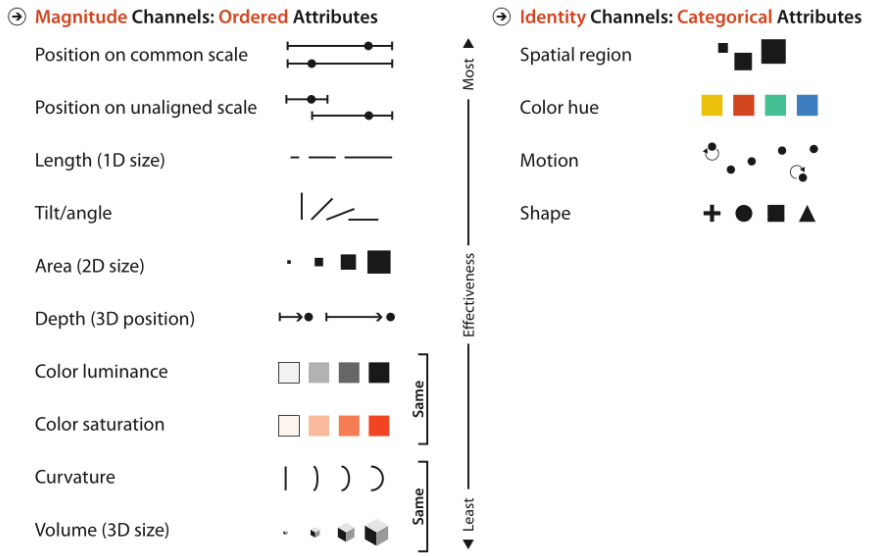

## **RadioLab** “Colors”

### WNYC Podcast

http://www.radiolab.org/story/211119-colors/

# EFFECTIVENESS OF VISUAL ENCODINGS

# Perception of Visual Encodings




There are **lots** of possible visual encodings

Their **effectiveness** is related to how they are handled by our perceptual system

how close is human perceptual judgement to some objective measurement of the stimulus?

# 1) ACCURACY

# Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

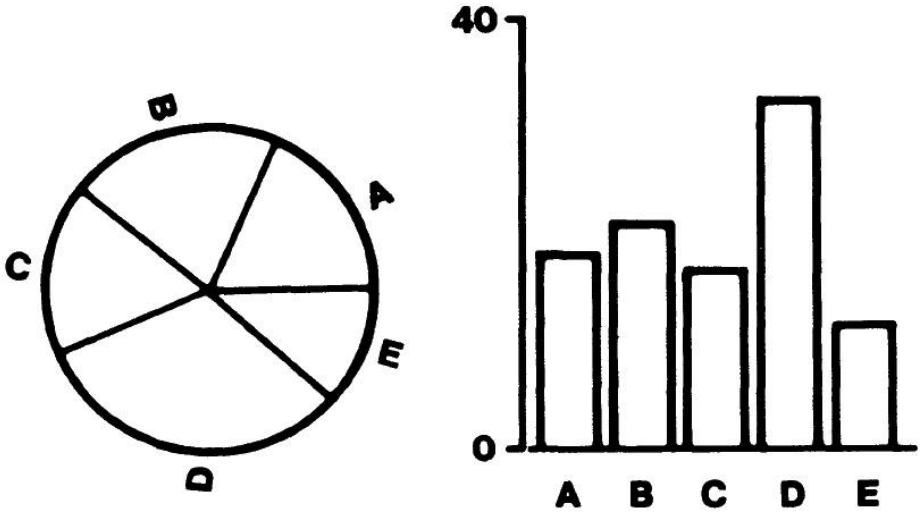



*Figure 3. Graphs from position–angle experiment.*

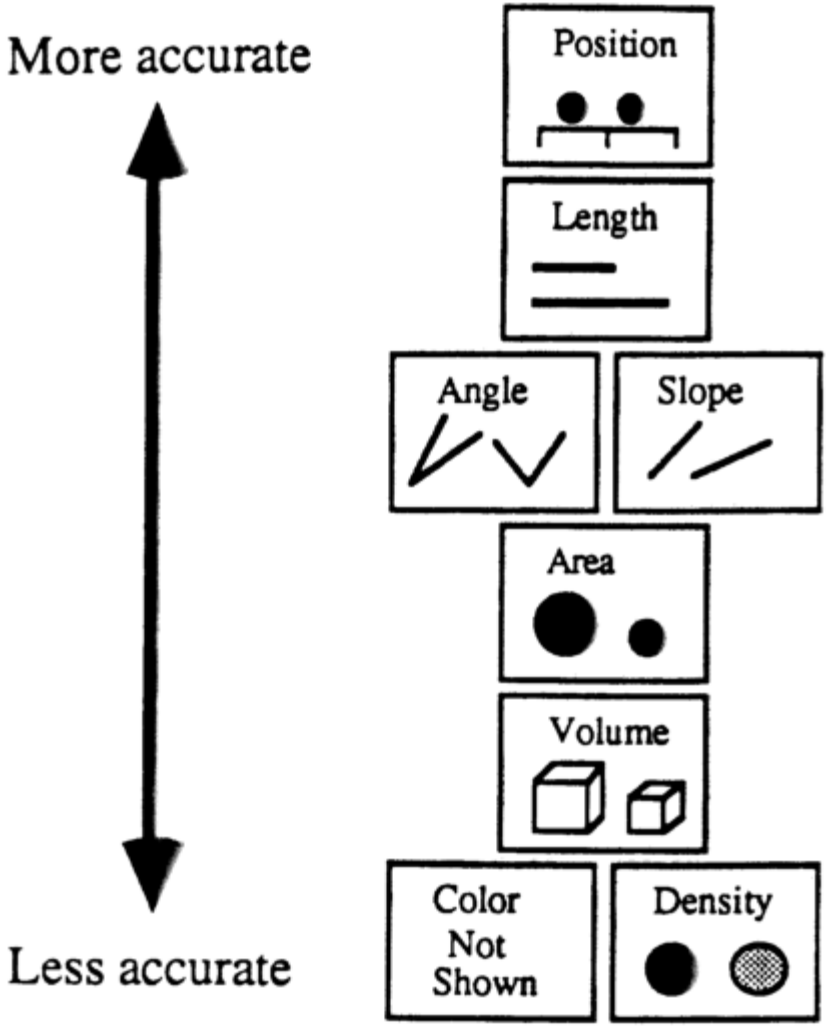
Performed **controlled experiments** to determine how effectively people could judge **changes in visual features**

Focus on **quantitative information**

**Variables used**: angle, area (size), color hue, color saturation, density (value), length, position, slope, volume

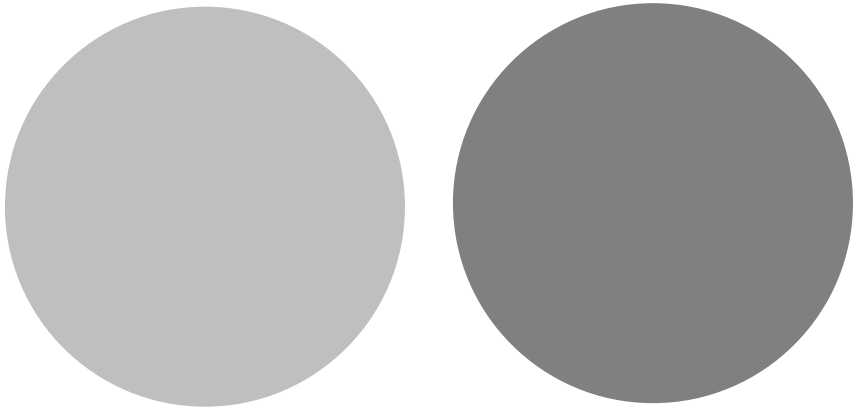
# Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

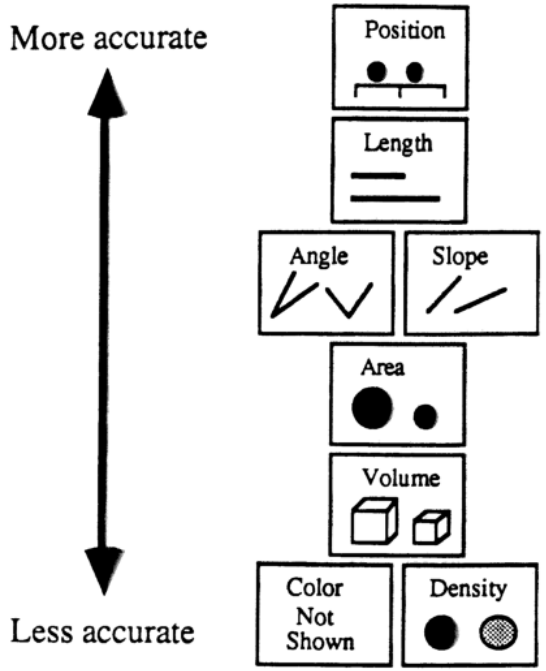


# Color Value

What percentage in
value is the right from the left?

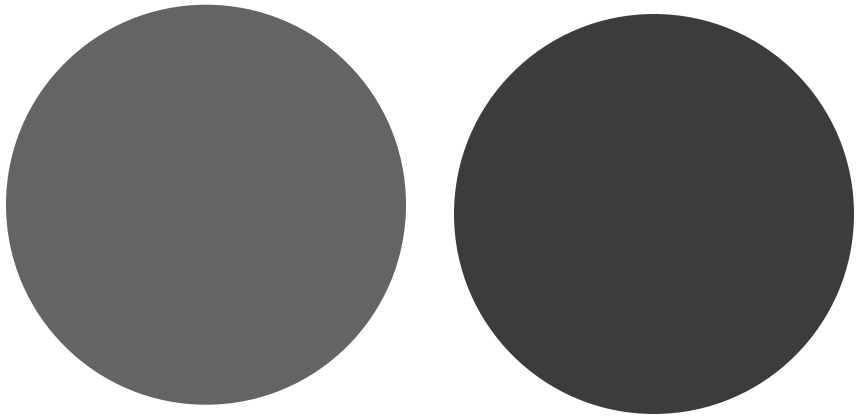


100%  66%

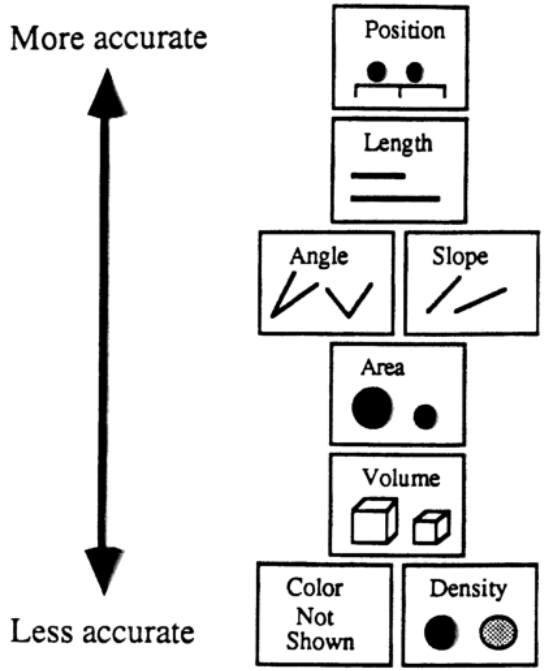


# Color Value

What percentage in
value is the right from the left?

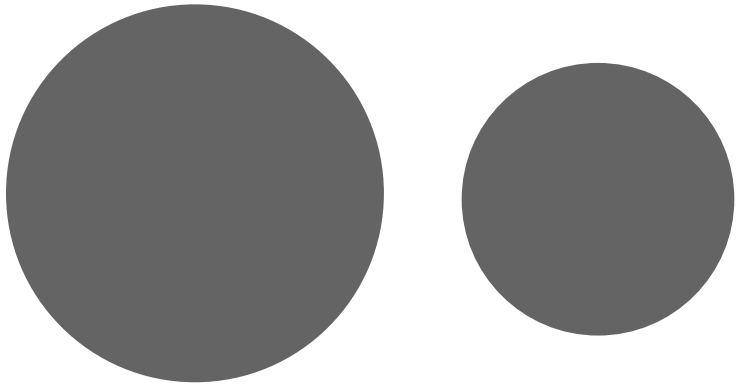


100%  60%

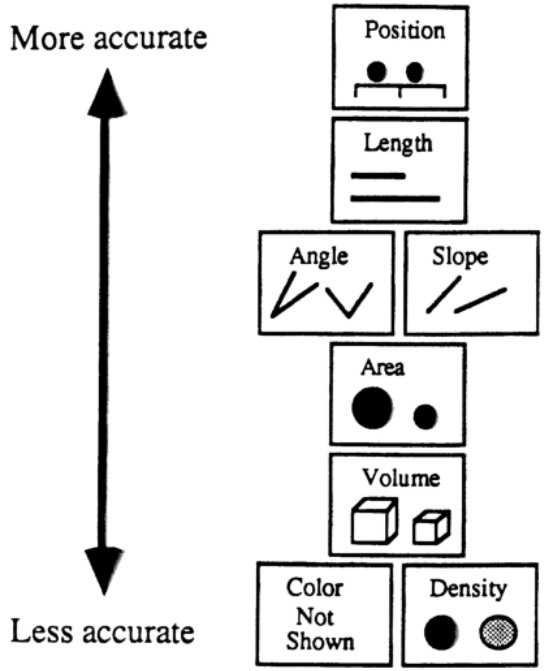


# Area

What percentage in
size is the right from the left?

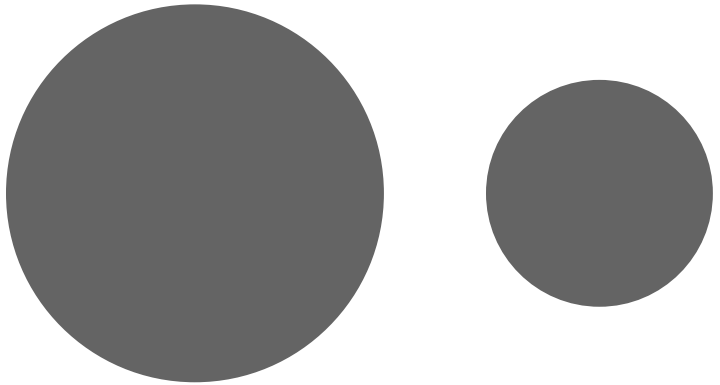


100%  52%

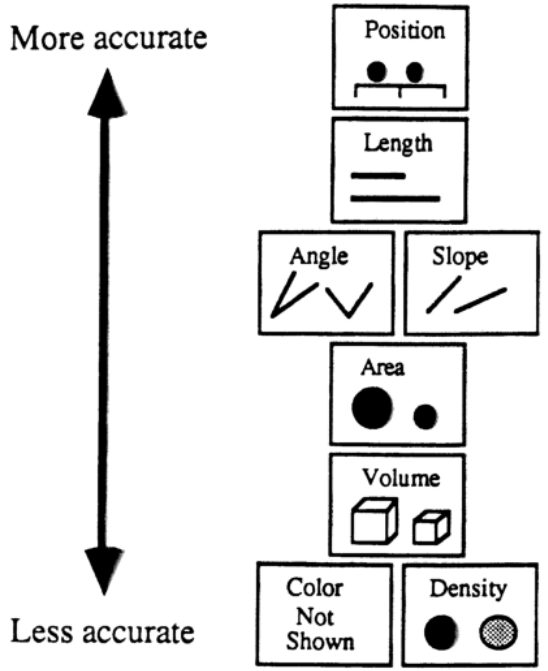


# Area

What percentage in
size is the right from the left?

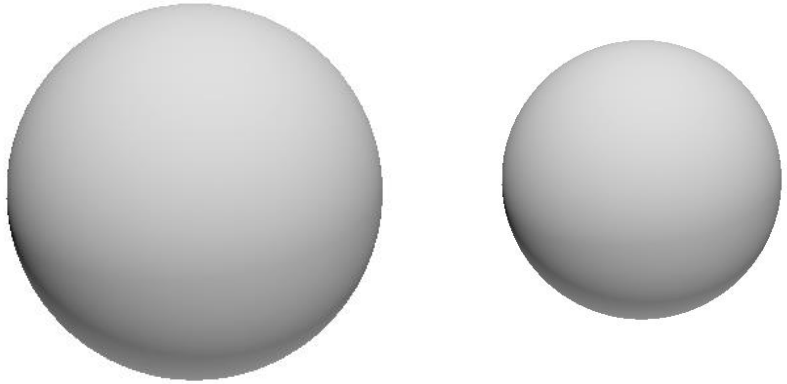


100%  36%



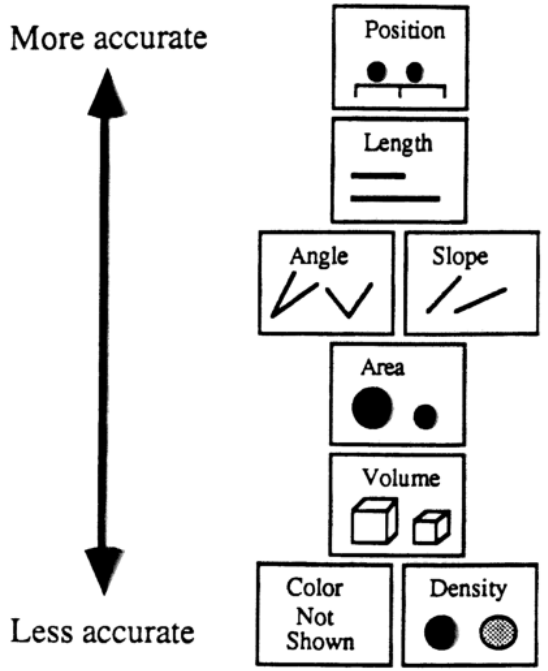
# Volume

What percentage in
size is the right from the left?



100%

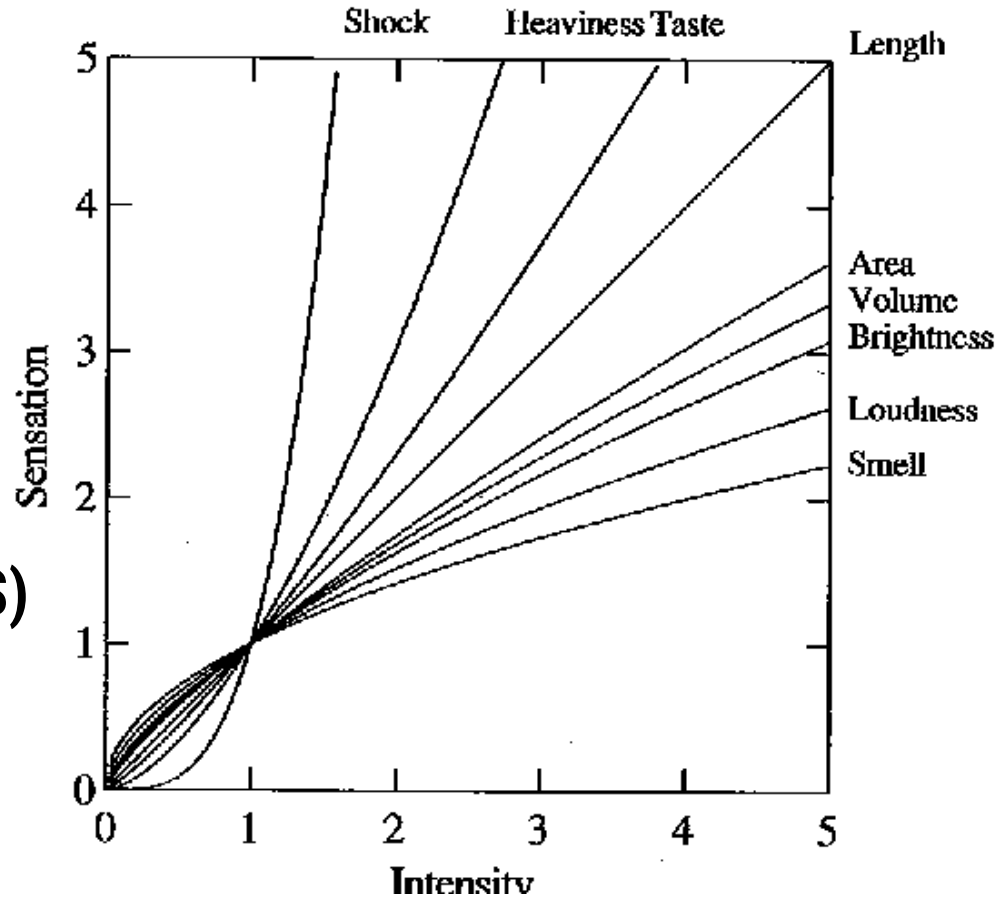
40%



# Why are people so bad at this?

Relationship between stimulus and perception **isn't always linear!**

**Stevens' power law**
**describes a relationship between a physical stimulus (S) and its perceived intensity or strength (P)**

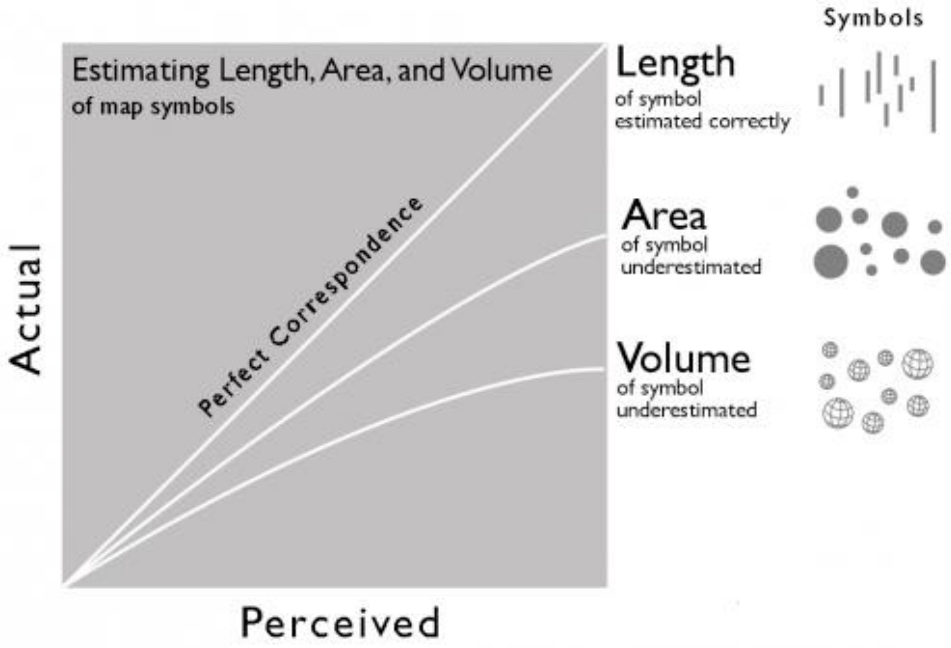


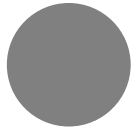

[Graph from Wilkinson 99, based on Stevens 61]

# Perception

People tend to **correctly estimate lengths**

They tend to **underestimate areas and volumes.**



When asked to pick a circle **2 times** the size, people tend to pick a circle **~1.8 times** larger.

This tendency **gets worse** as area grows.

Volume **is even worse**!

http://makingmaps.net/2007/08/28/perceptual-scaling-of-map-symbols/

# Volum

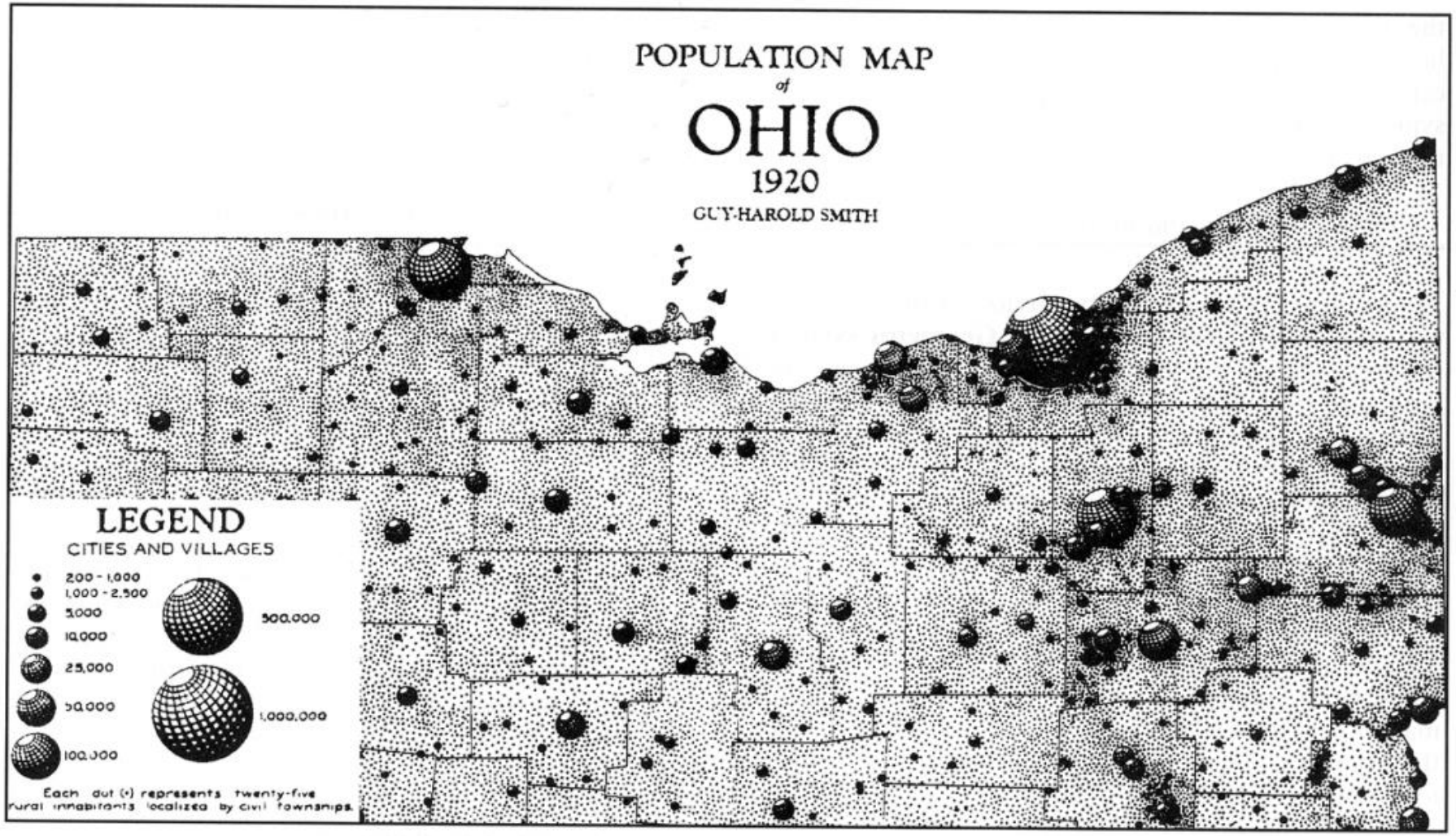
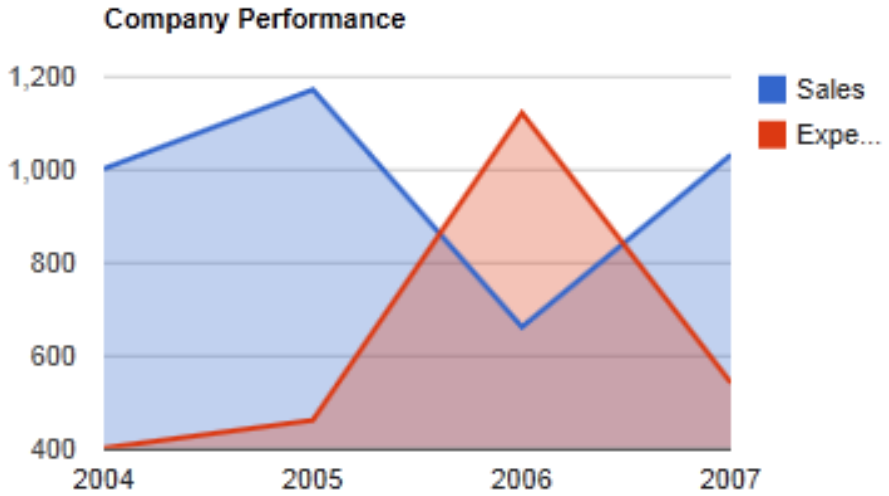
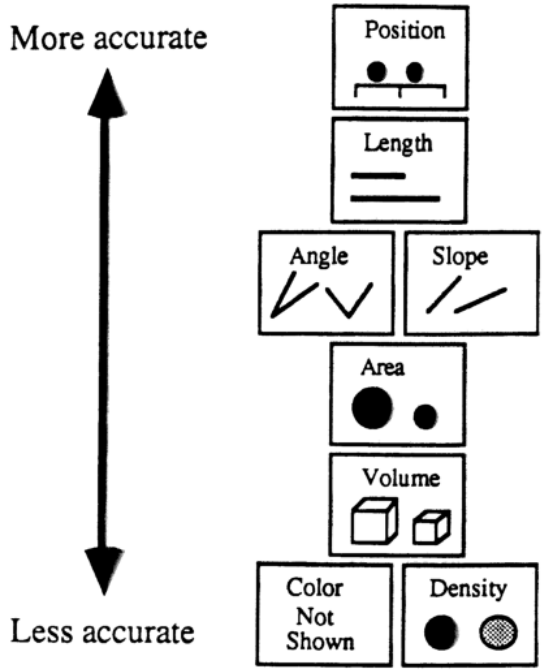



**FIGURE 7.4.** An eye-catching map created using three-dimensional geometric symbols. (After Smith, 1928. First published in *The Geographical Review,* 18(3), plate 4. Reprinted with permission of the American Geographical Society.)

# Area

- What percentage in size is the red from the blue (=100%)?

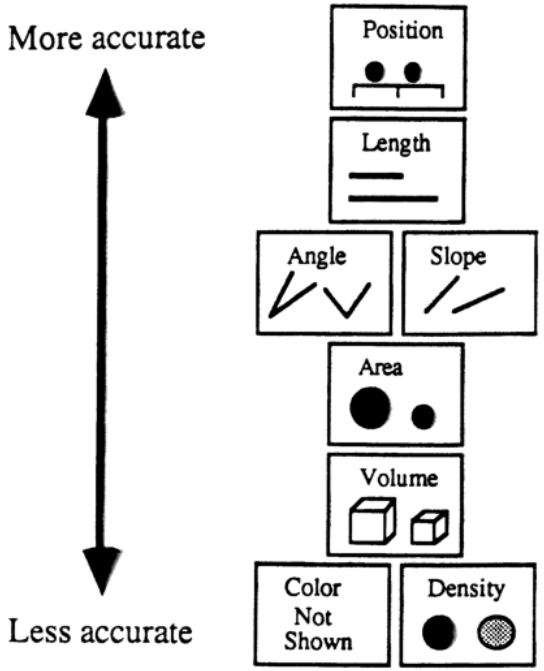



no idea – **this is very difficult**

# Length

What percentage in
length is the right from the left?




100%

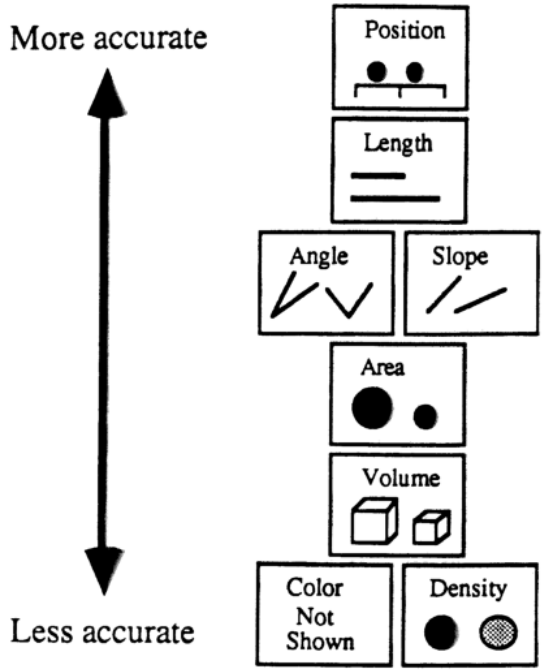
75%

# Length / Position

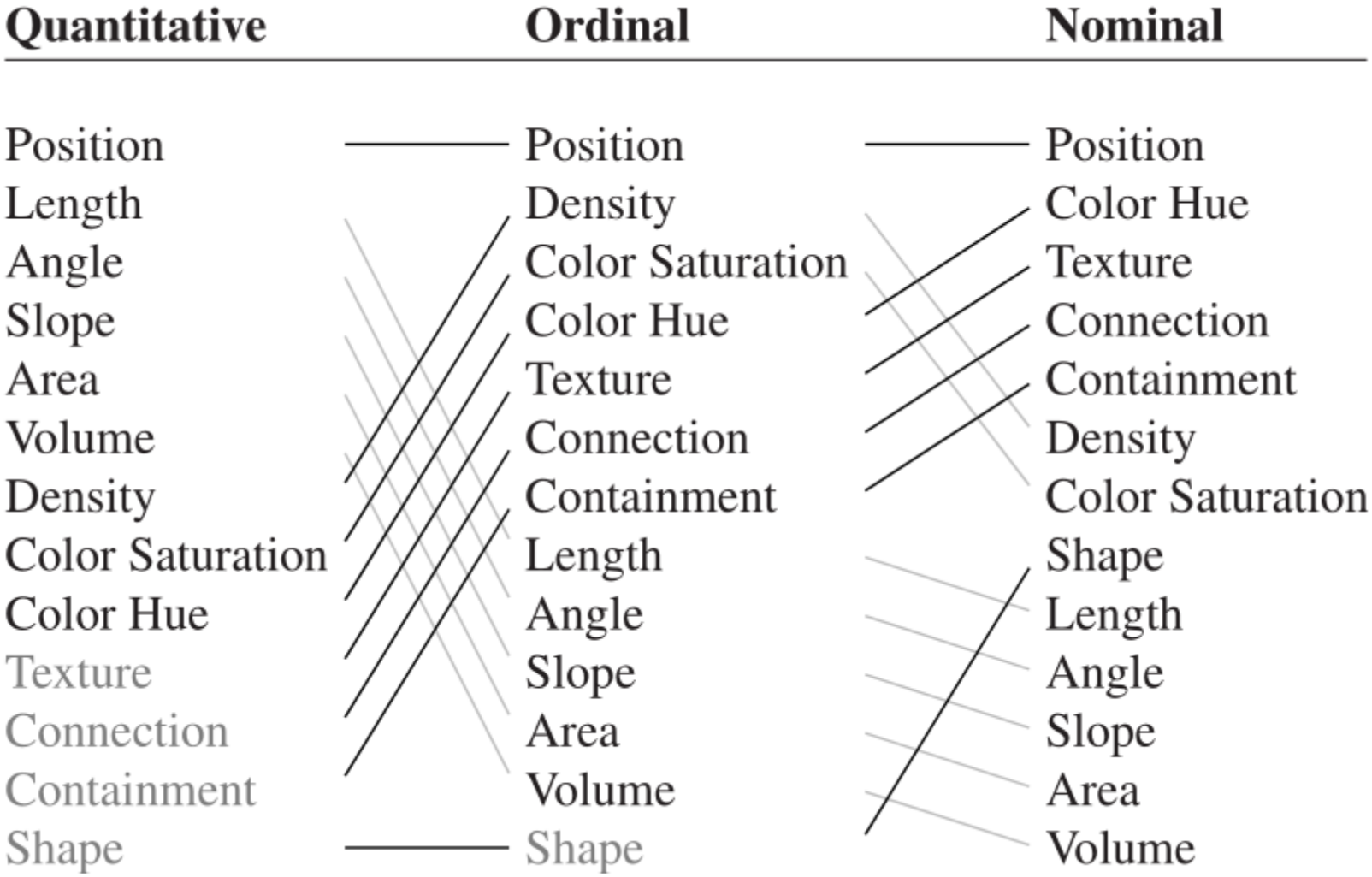
What percentage in
length is the right from the left?

100%

25%



# Effectiveness of Data Encodings (Conjecture)




Mackinlay 1986

## Magnitude Channels: Ordered Attributes

- Position on common scale
- Position on unaligned scale
- Length (1D size)
- Tilt/angle
- Area (2D size)
- Depth (3D position)
- Color luminance
- Color saturation
- Curvature
- Volume (3D size)

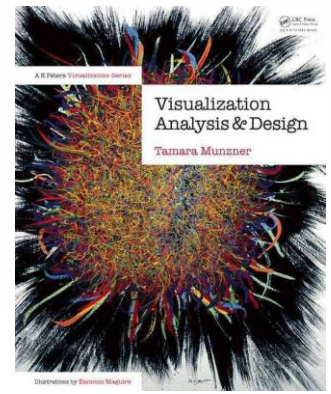
Most ▲ Effectiveness ▼ Least

Same (Color luminance, Color saturation)

Same (Curvature, Volume (3D size))

## Identity Channels: Categorical Attributes

- Spatial region
- Color hue
- Motion
- Shape



a distinct item stands out from many others immediately

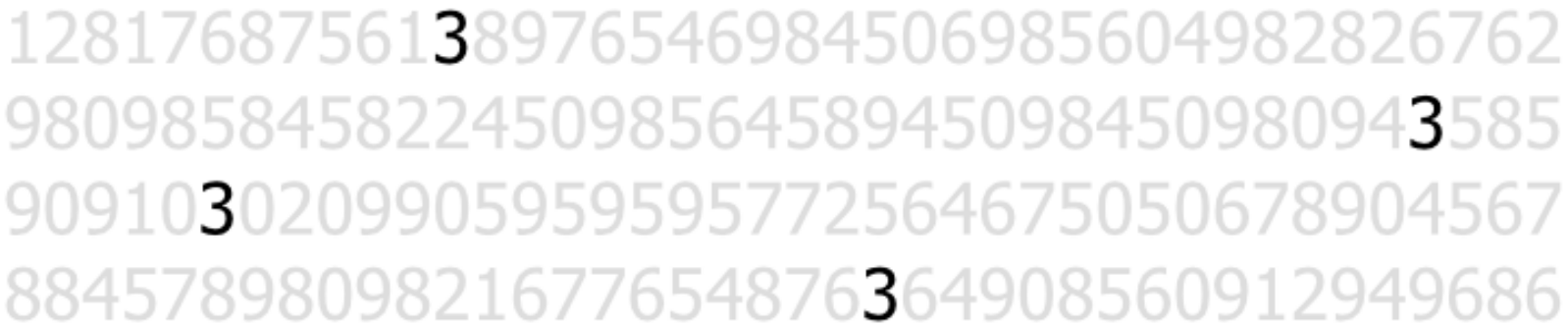
# 2) POPOUT

# How many 3’s do you see?

12817687561389765469845069856049828267629809858458224509856458945098450980943585909103020990595959577256467505067890456788457898098216776548763649085609129496869

From: Ware, Information Visualization using Vision to Think

# How about now?

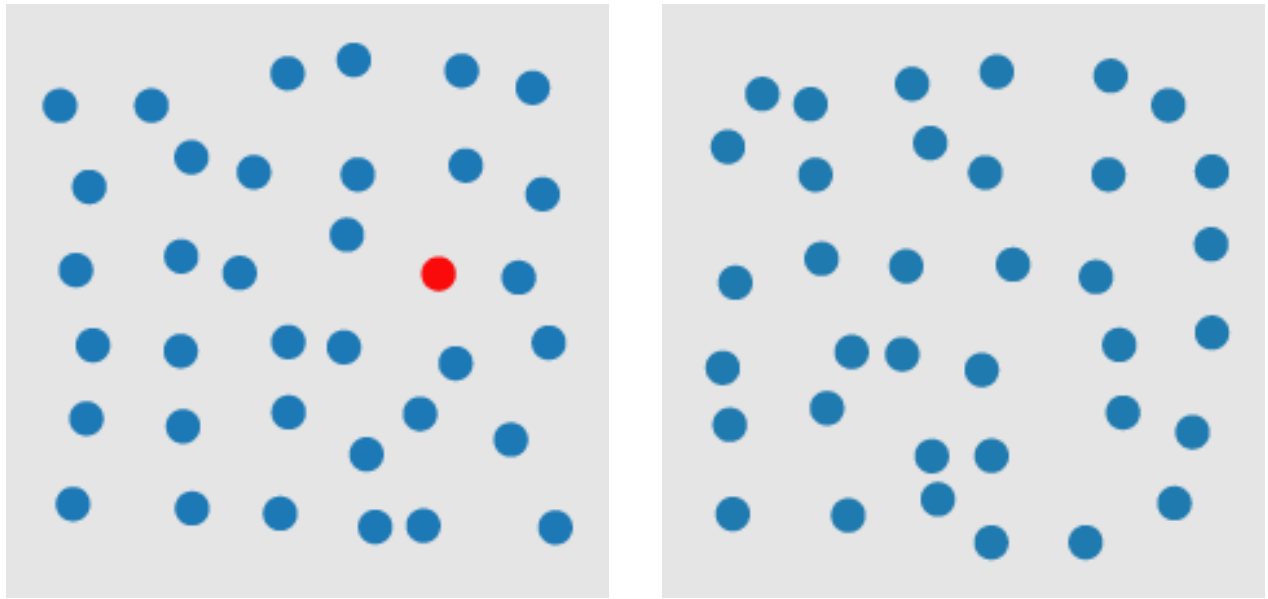



From: Ware, Information Visualization using Vision to Think

Visual encodings influence **popout**

# DETERMINE IF A RED CIRCLE IS PRESENT

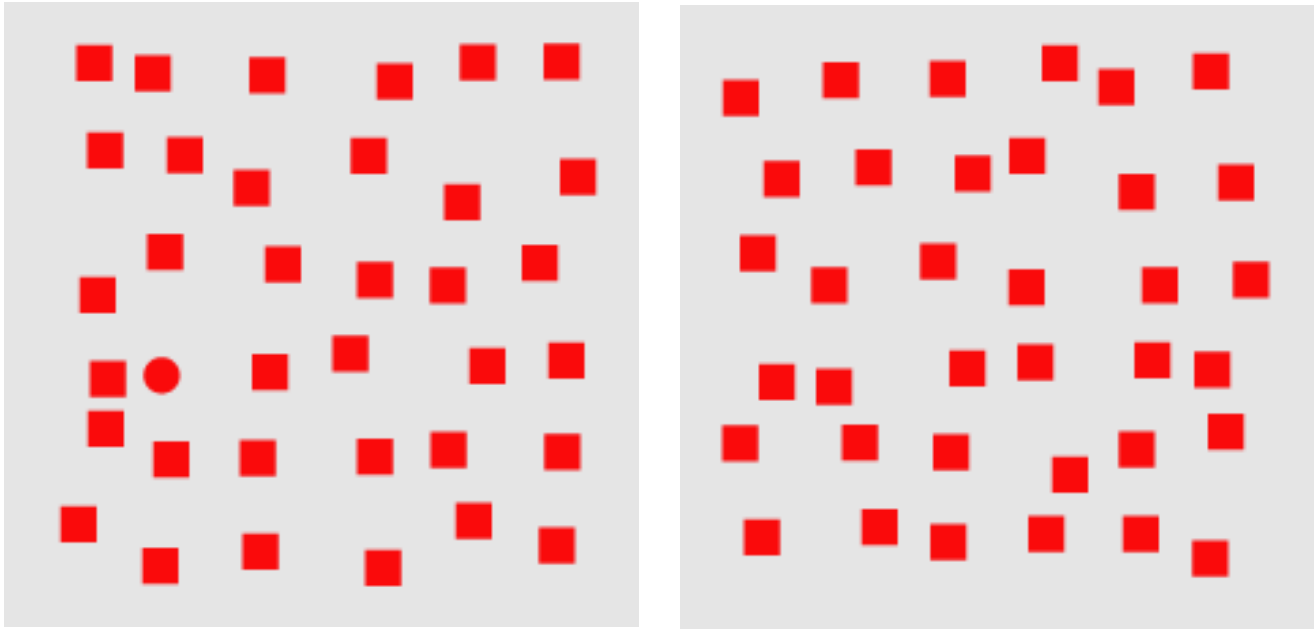
# Hue



Hue pops out, no matter if we have 15 or 50 blue circles

From: Healey, Perception in Visualization

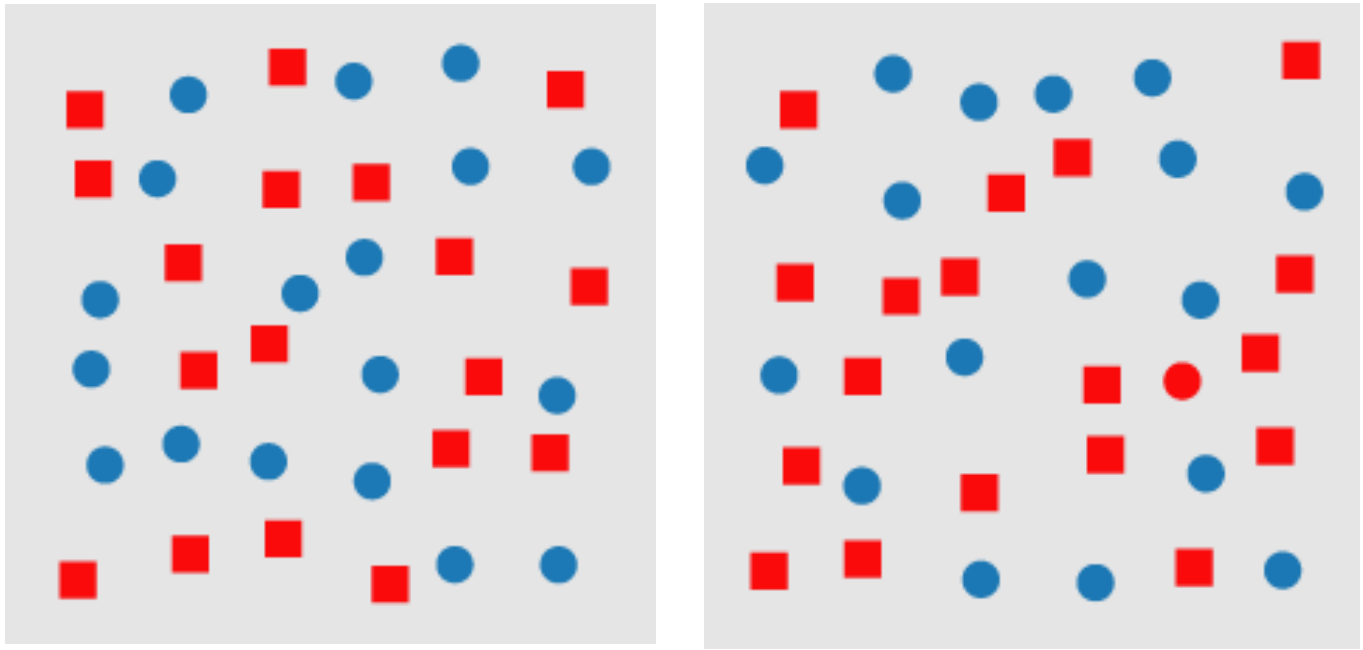
# Shape



Yes, can be done quickly but a bit more slowly than before

From: Healey, Perception in Visualization

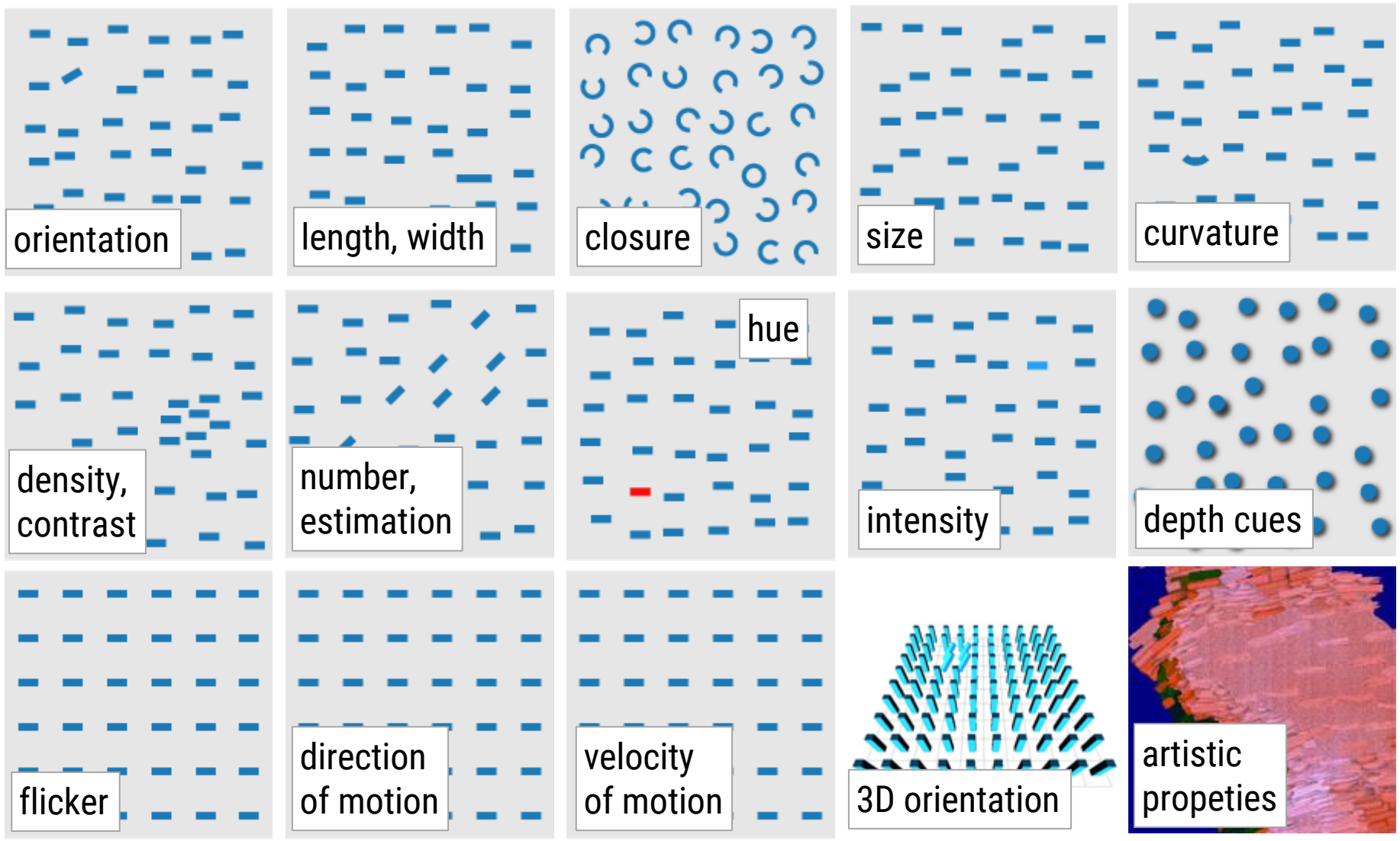
# Hue and Shape



Cannot be done quickly due to the
**conjunction of shape and hue**
→ need to search

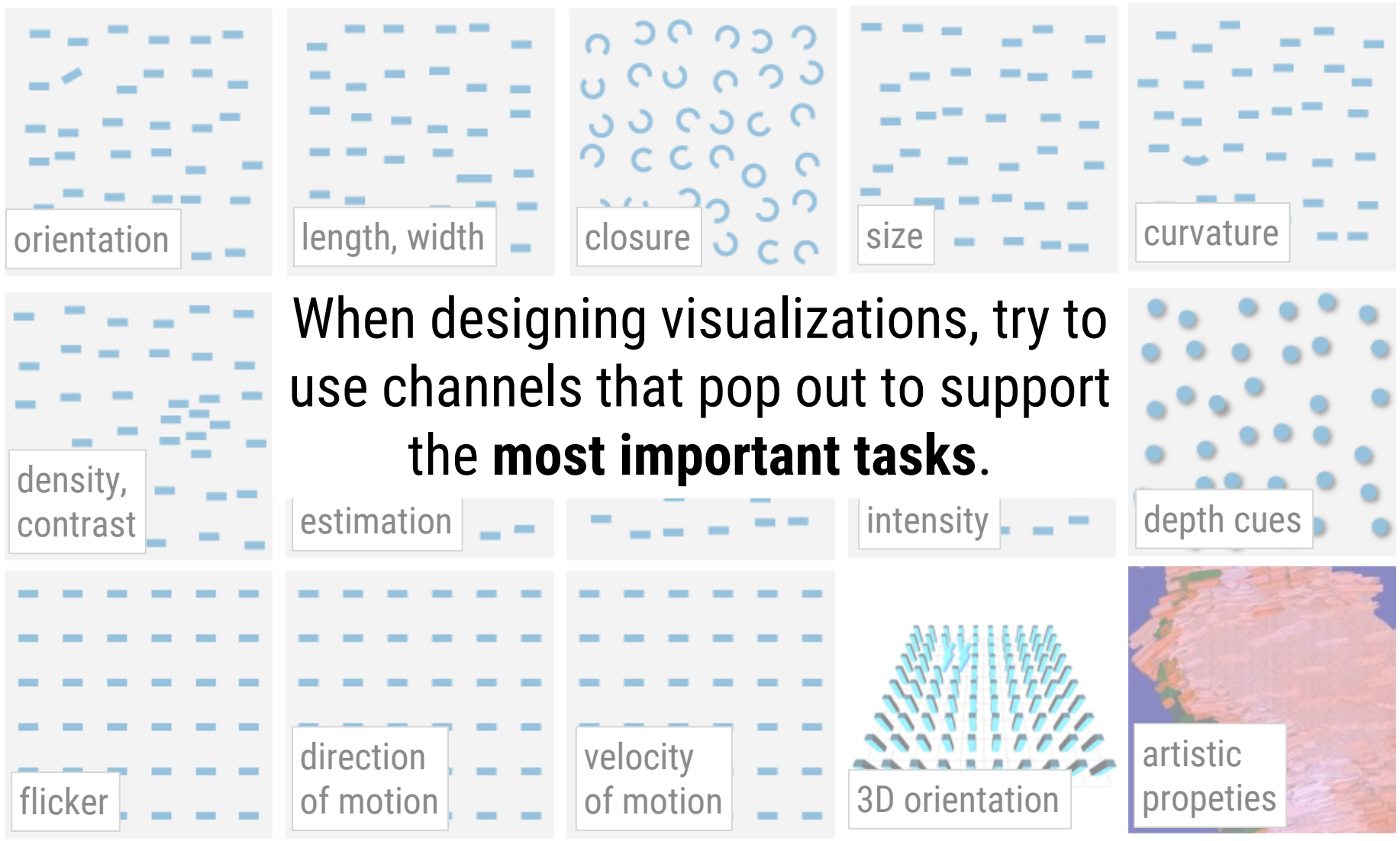
From: Healey, Perception in Visualization

# Channels that support popout (some)




From: Healey, Perception in Visualization

# Channels that support popout (some)

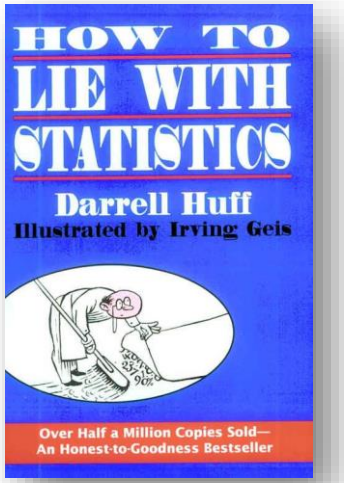


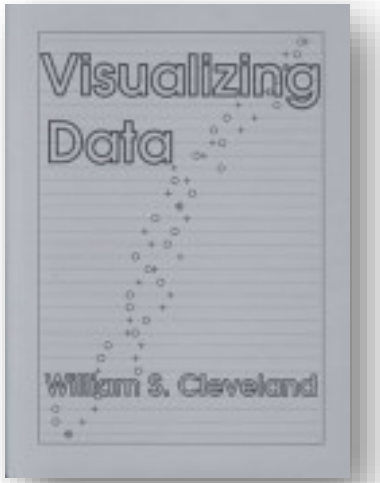

When designing visualizations, try to use channels that pop out to support the **most important tasks**.

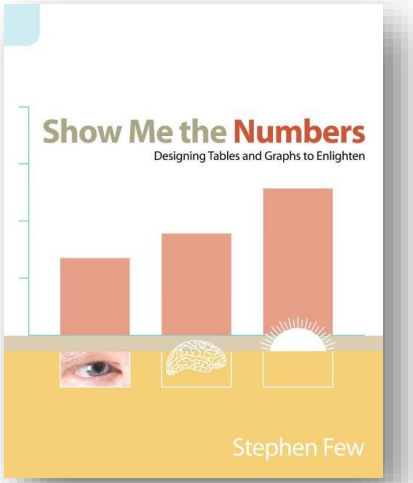
From: Healey, Perception in Visualization

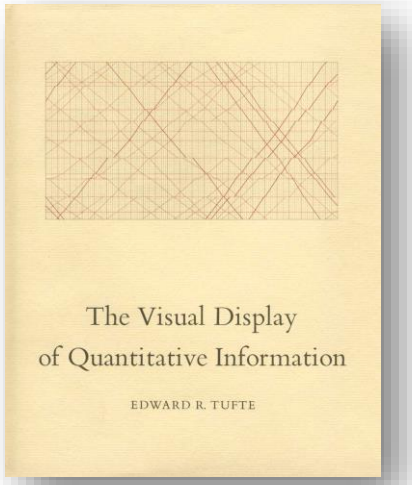
- Most pairs of channels do not support popout
  - A few do: space & color, motion & shape
- No popout possible with 3 or more channels
- Count on using popout for a single channel at a time

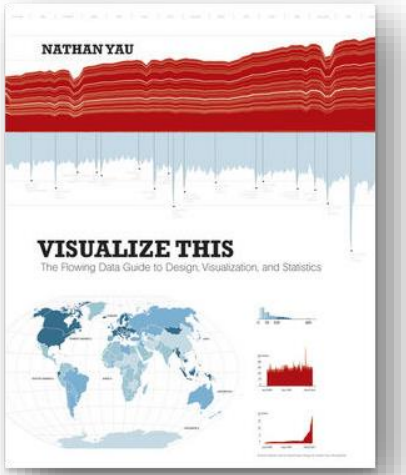
# Many more useful guidelines!



# Summary

## Today you learned

Details about the **perception of color** and
a few **other visual variables**

Saw that the vision system is **quicker and better**
at detecting certain visual variables

# Müller-Lyer Sinusoidal Waves

*New variant by Gianni A. Sarcone*

Though the **blue** and **red** segments seem to oscillate, they are always the **same length**! **Nothing moves except the arrows** at the endpoints of each color segment...