

Information Visualization PERCEPTION and COLOR

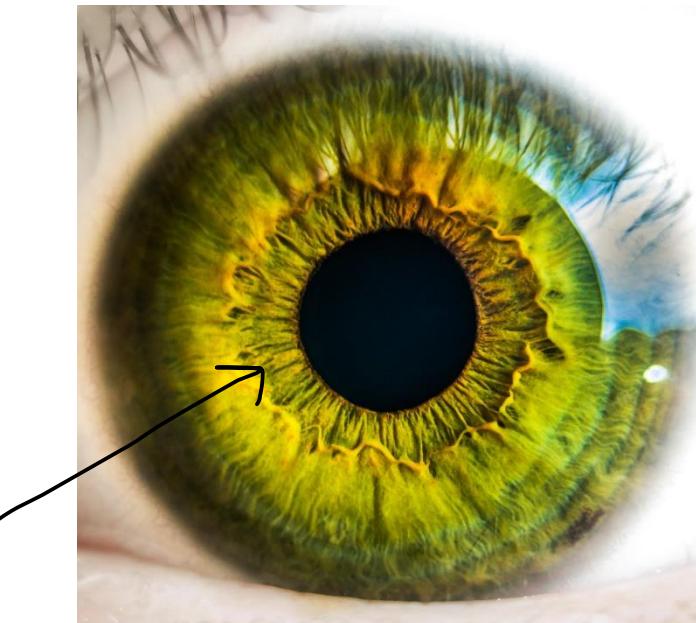
Petra Isenberg

Let's do
an experiment ...

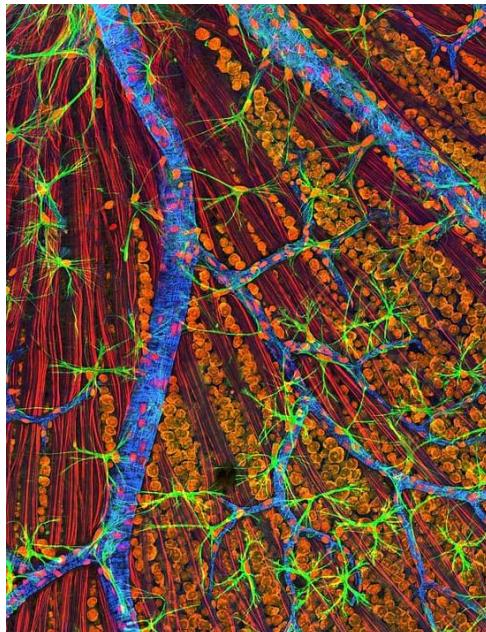


What is Color?

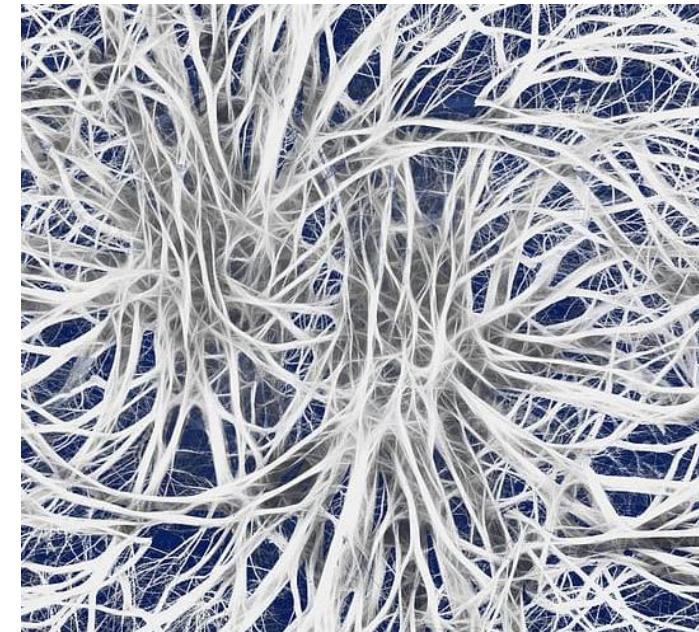
= the set of **perceptions** elicited by the spectral distribution of light



Through the eye...



...onto sensors
(retina)

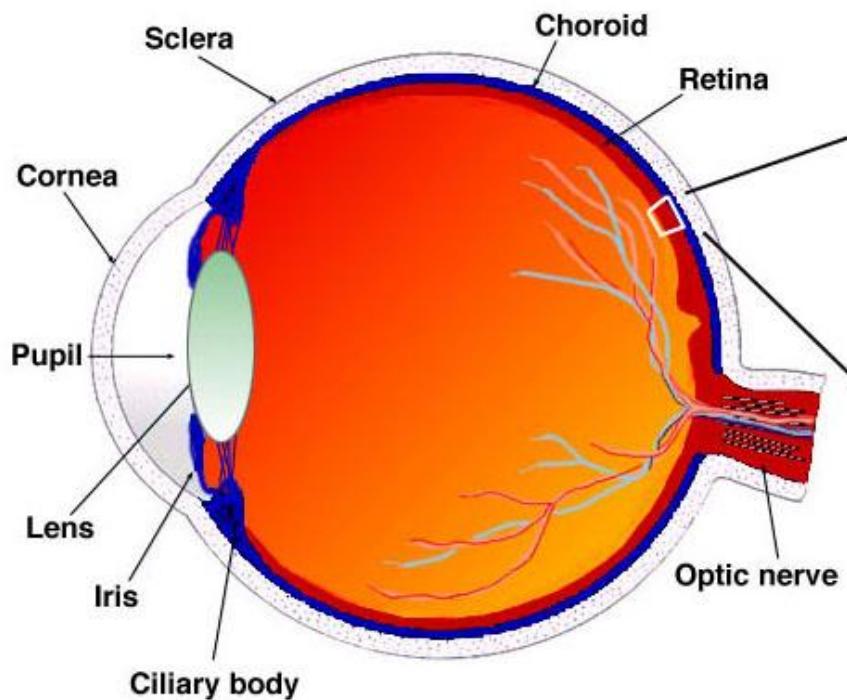


...to processing by the visual system

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

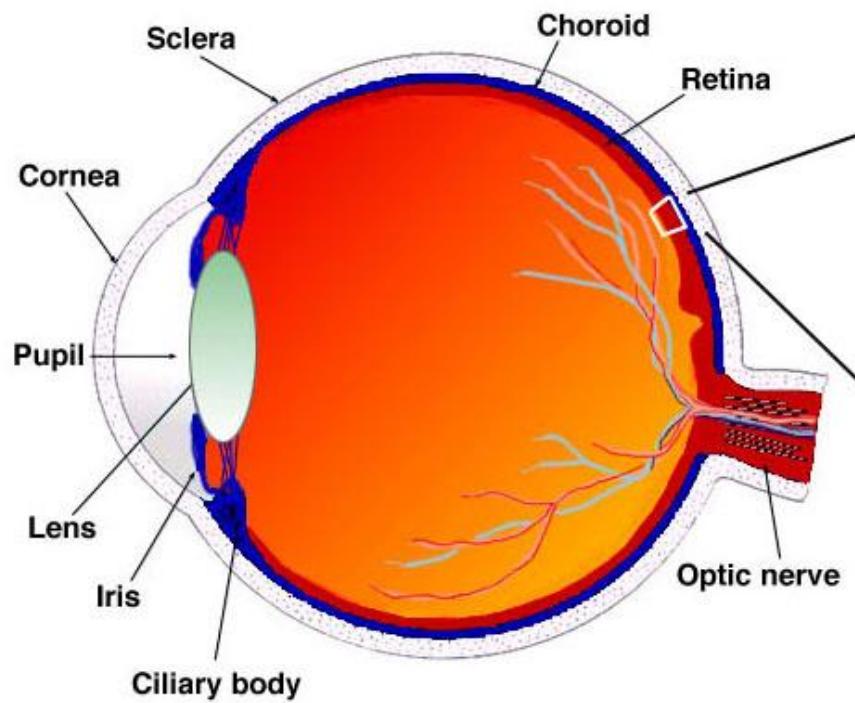
Physical World → Visual System



Retina is stimulated by three factors:

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

Physical World → Visual System

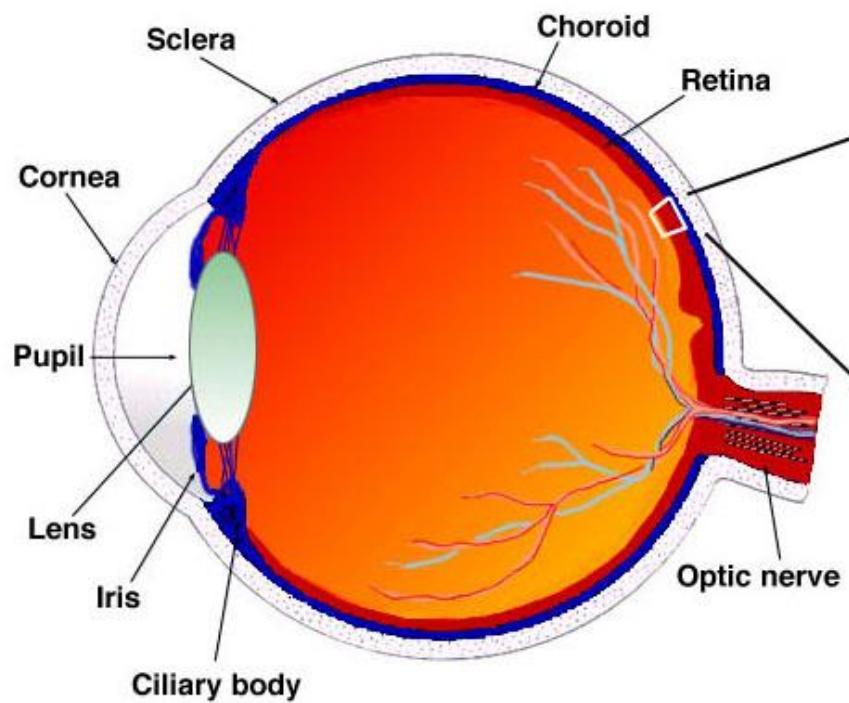


- The eye gets a retinal stimulus
 - It cannot be reverse engineered
- To behave in the world the brain needs to step in and interpret

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

Example: Lightness vs. Luminance

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



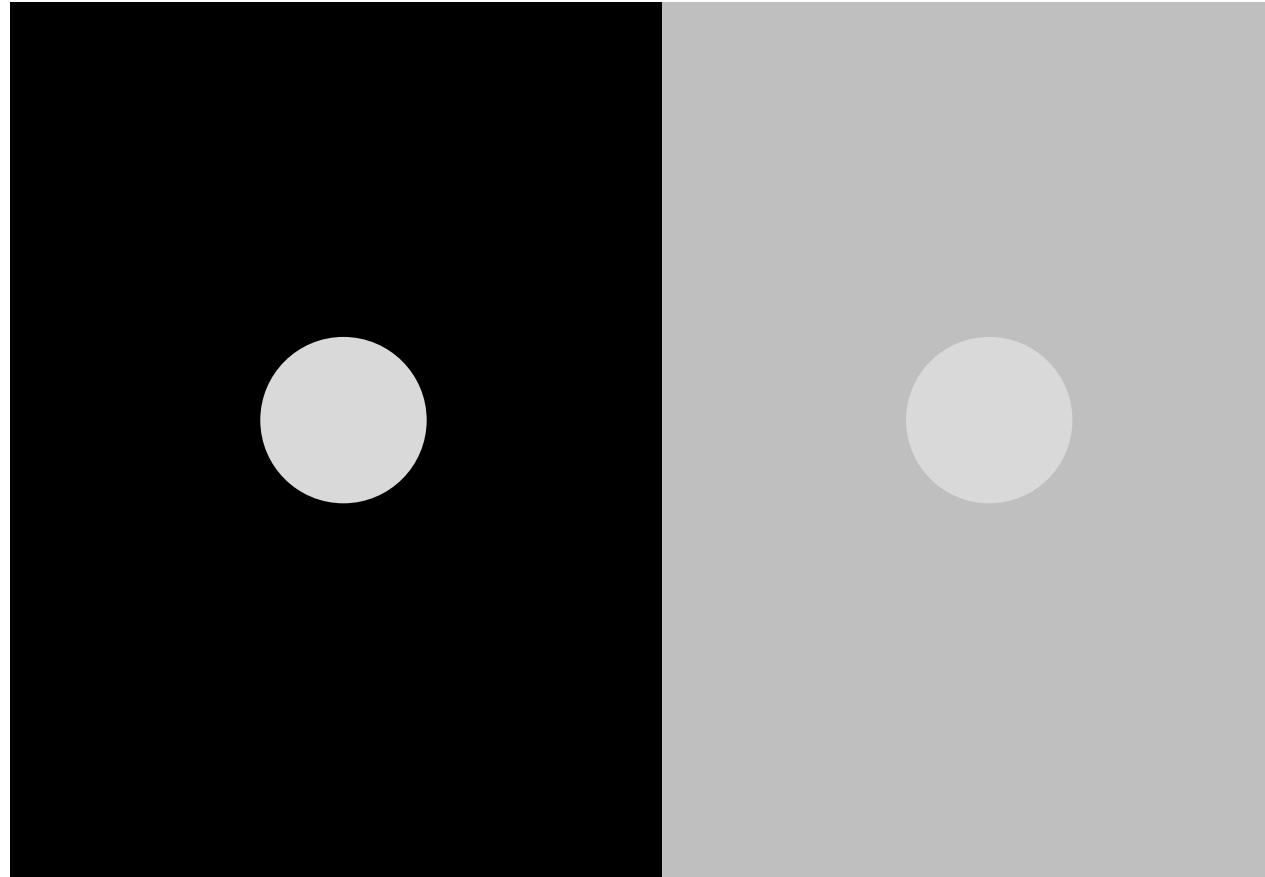
- LIGHTNESS: a **subjective impression** of the intensity of light reflected from on object surface (no units; psychophysical)

Lightness experiment



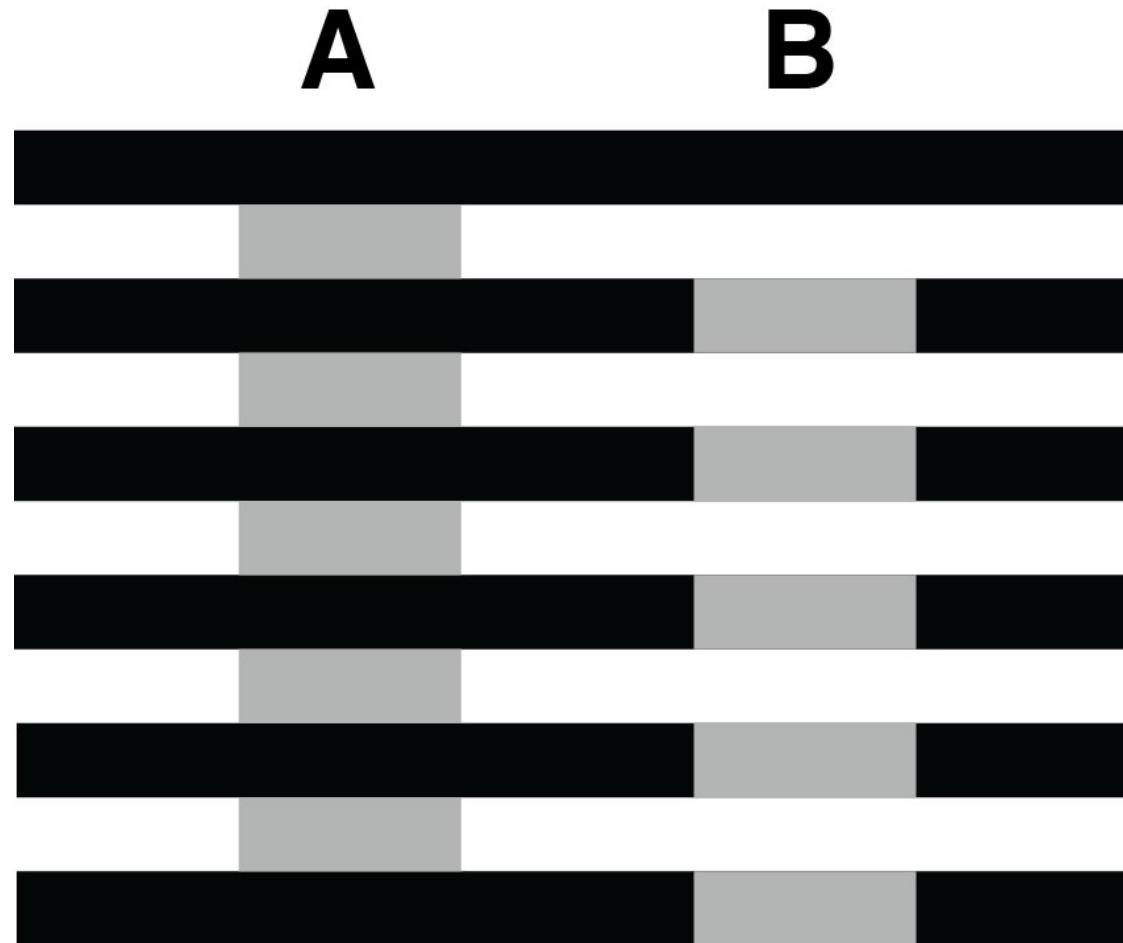
The two circles are physically the same

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?

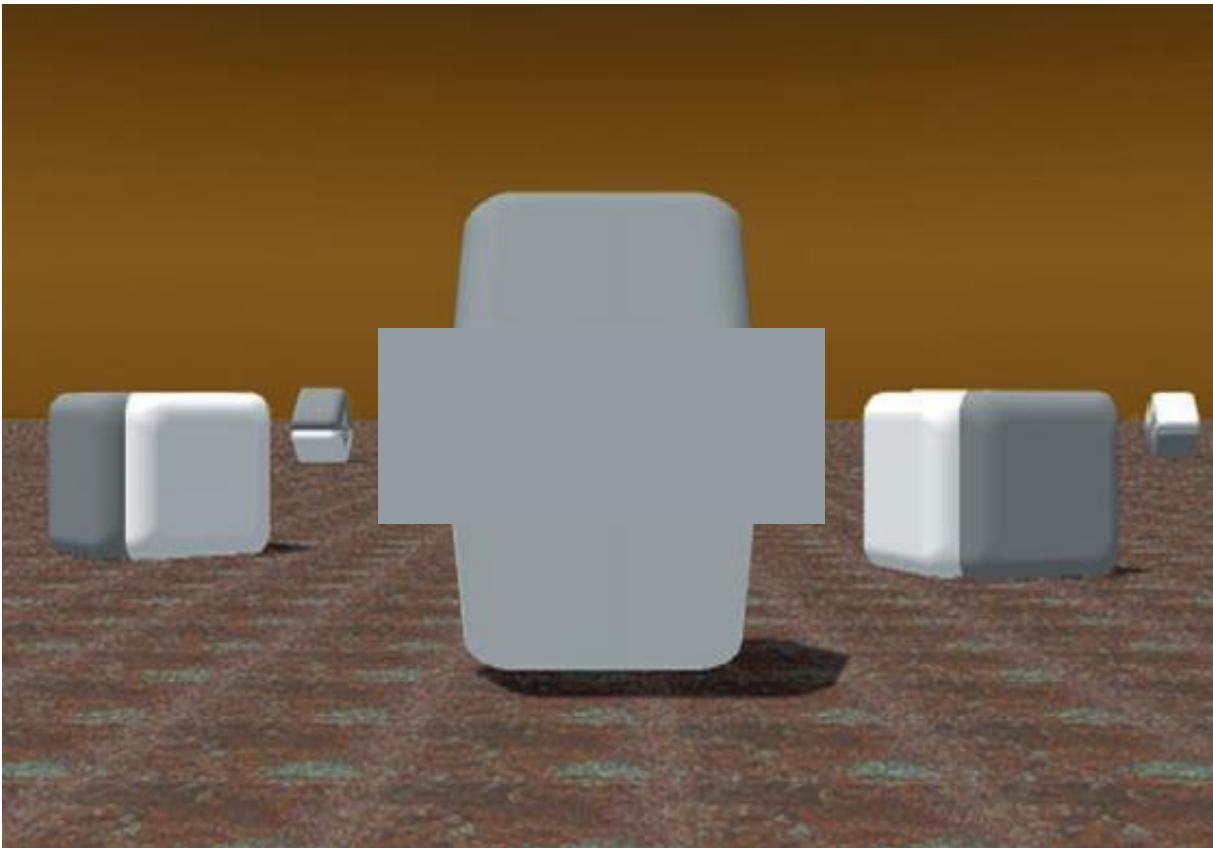


Image source: *The Journal of Neuroscience*, October 1, 1999, 19(19):8542–8551 [An Empirical Explanation of the Cornsweet Effect.](#)

Back to....

WHAT IS COLOR?

Some definitions

Physical measurement:

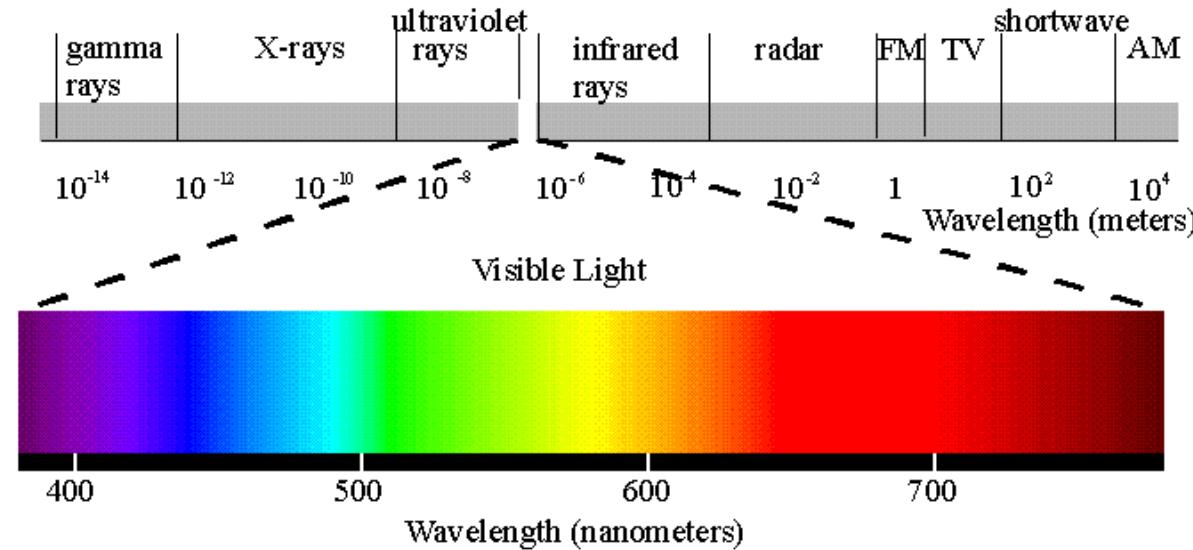
the relative intensities of wavelengths in light measured with a spectrophotometer

Psychophysical measurement:

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

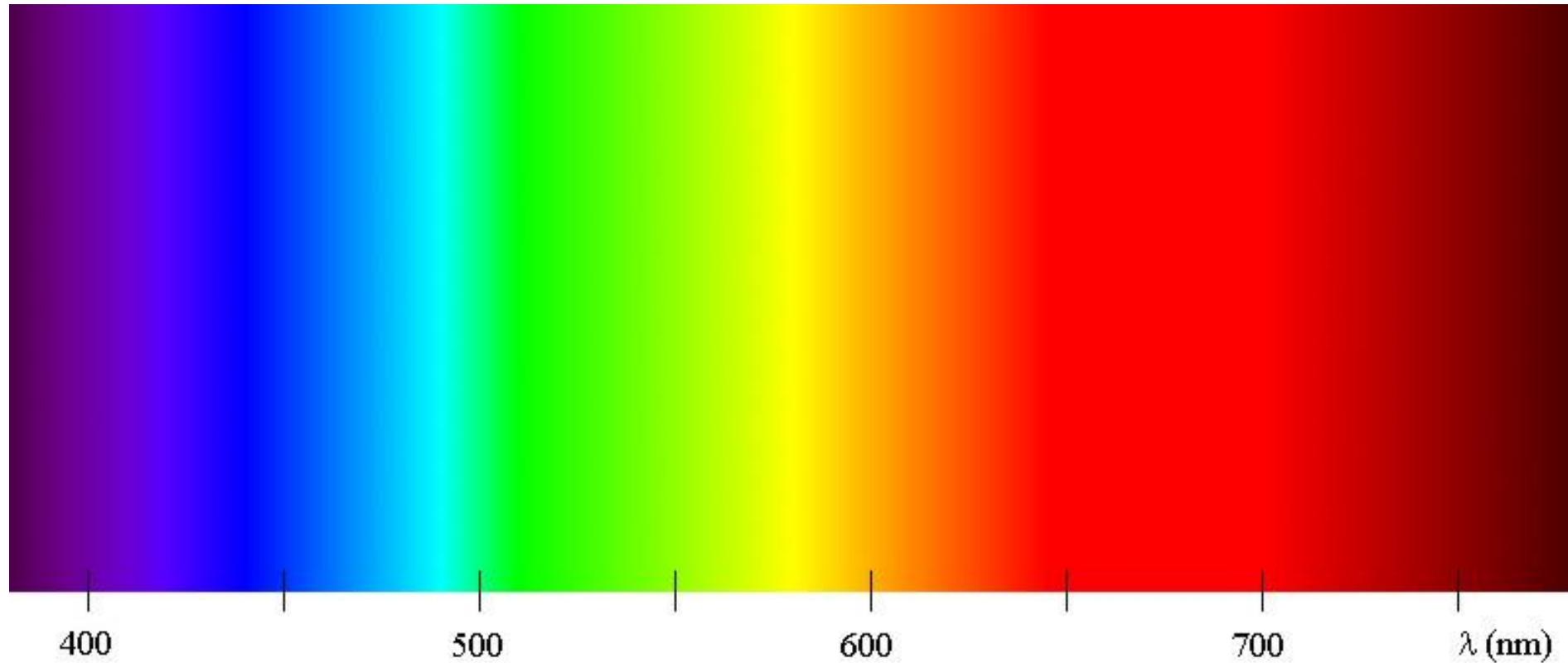
Physical World – The Nature of Light

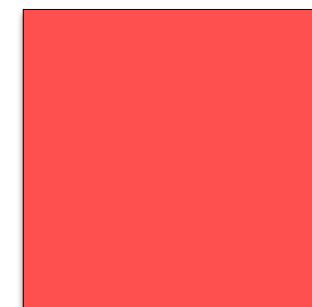
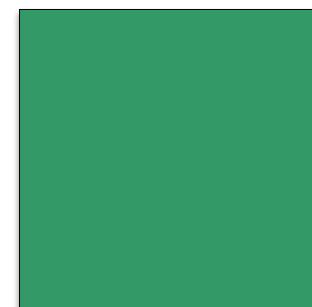
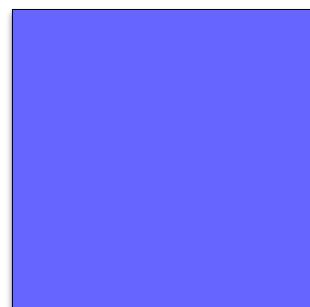
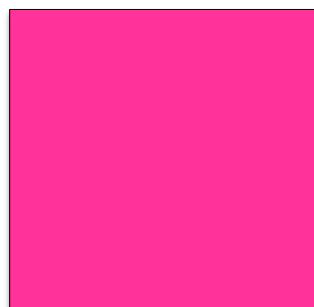
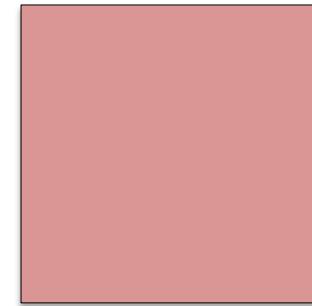
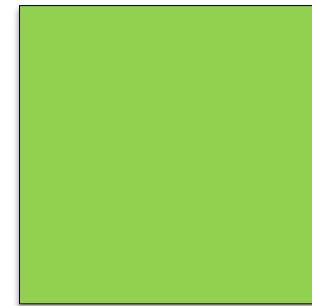
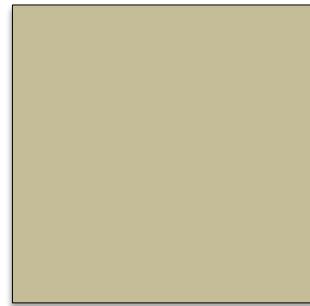
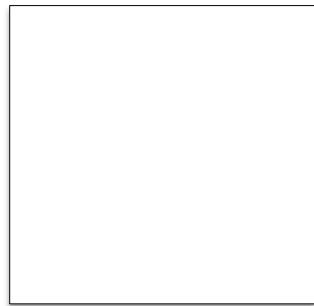
We have evolved to see a range of wavelengths: ~400 - 700nm



Light of a single wavelength is *monochromatic*

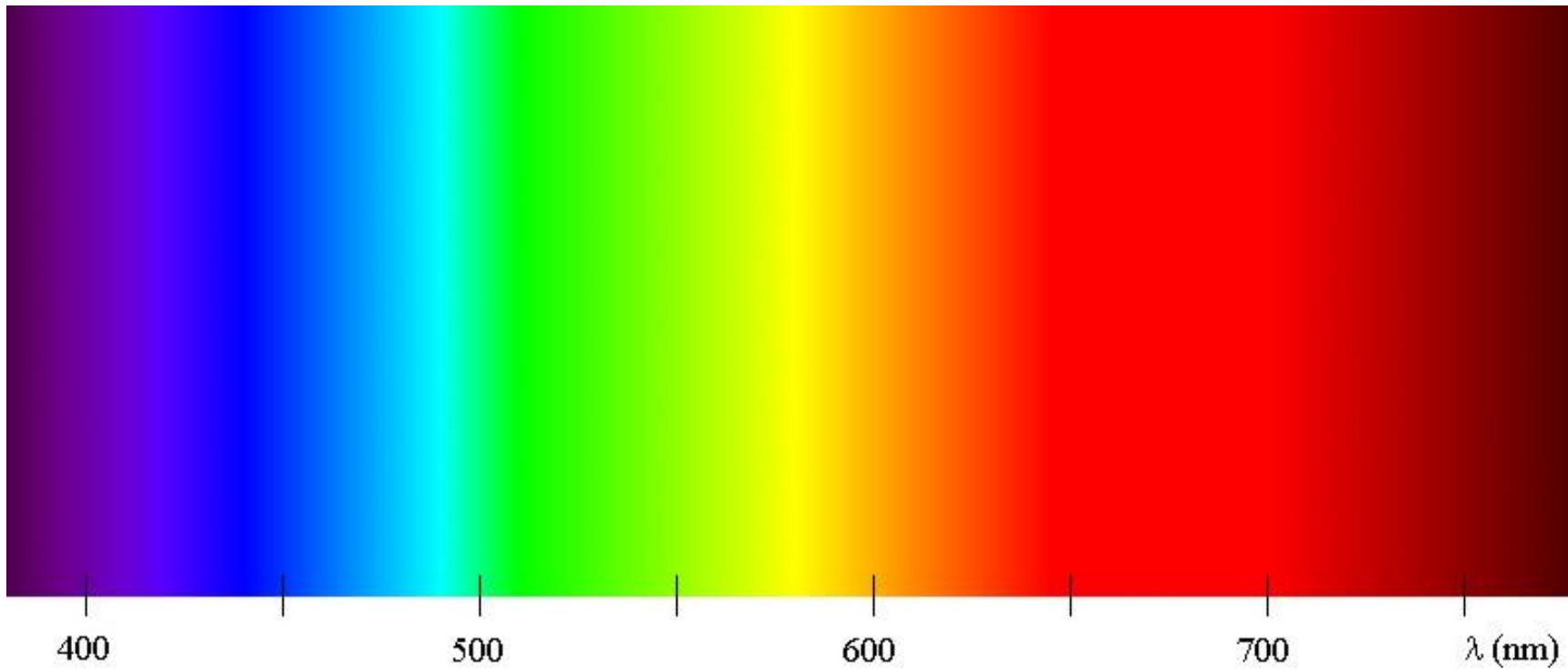
Look around you and then at this image - what do you notice?





Many colors are not monochromatic

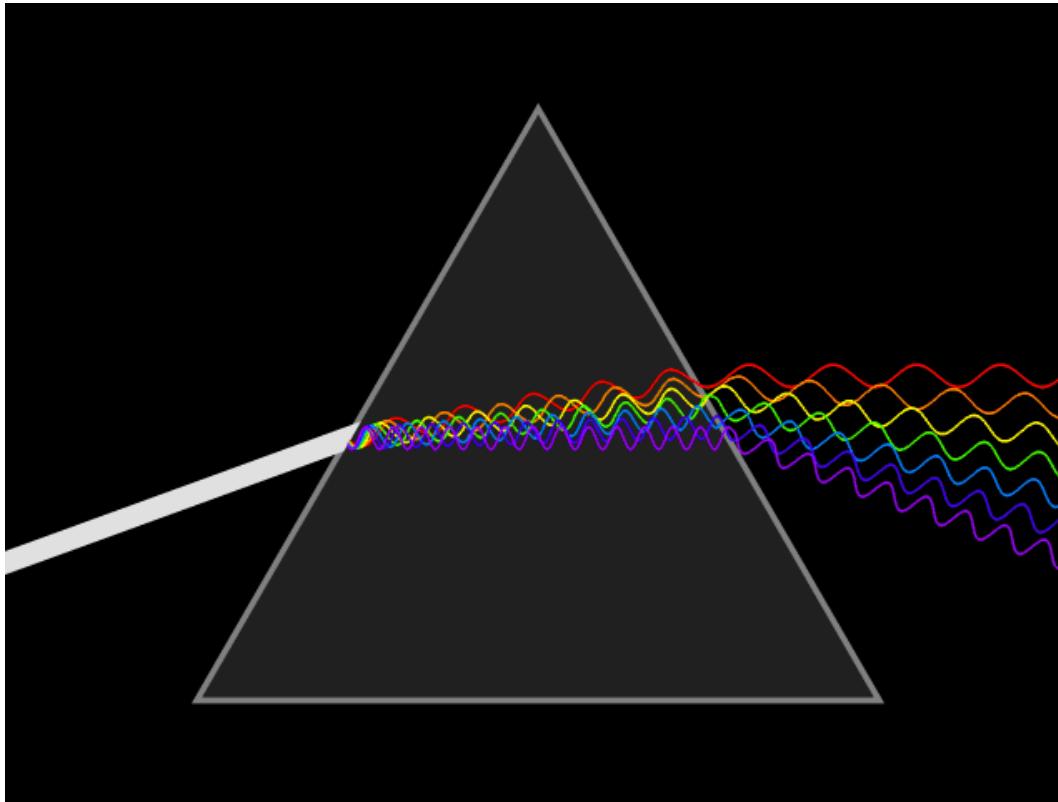
Monochromatic colors



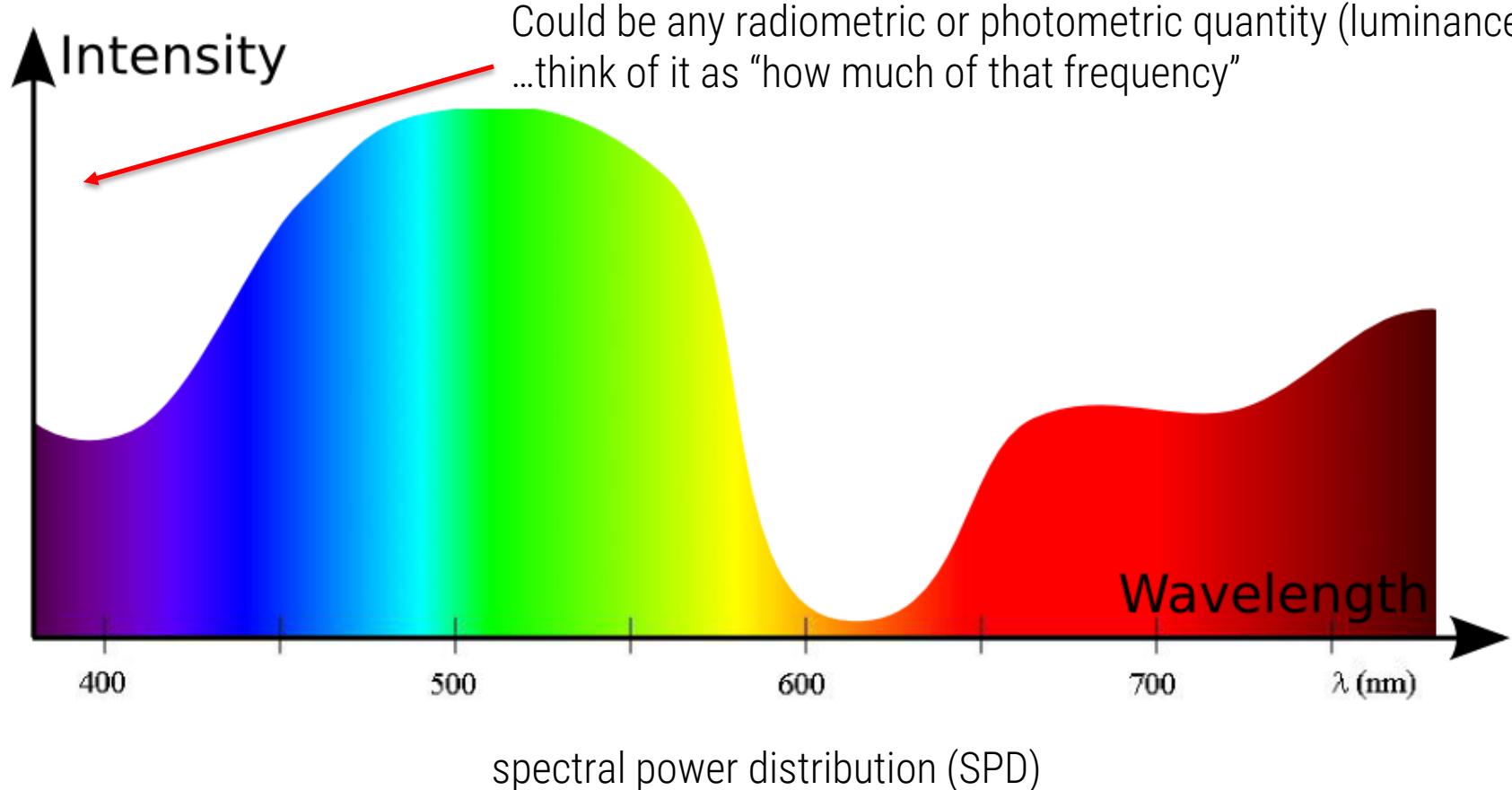
Can be obtained with one or more rays of light with a single wavelength

BUT...

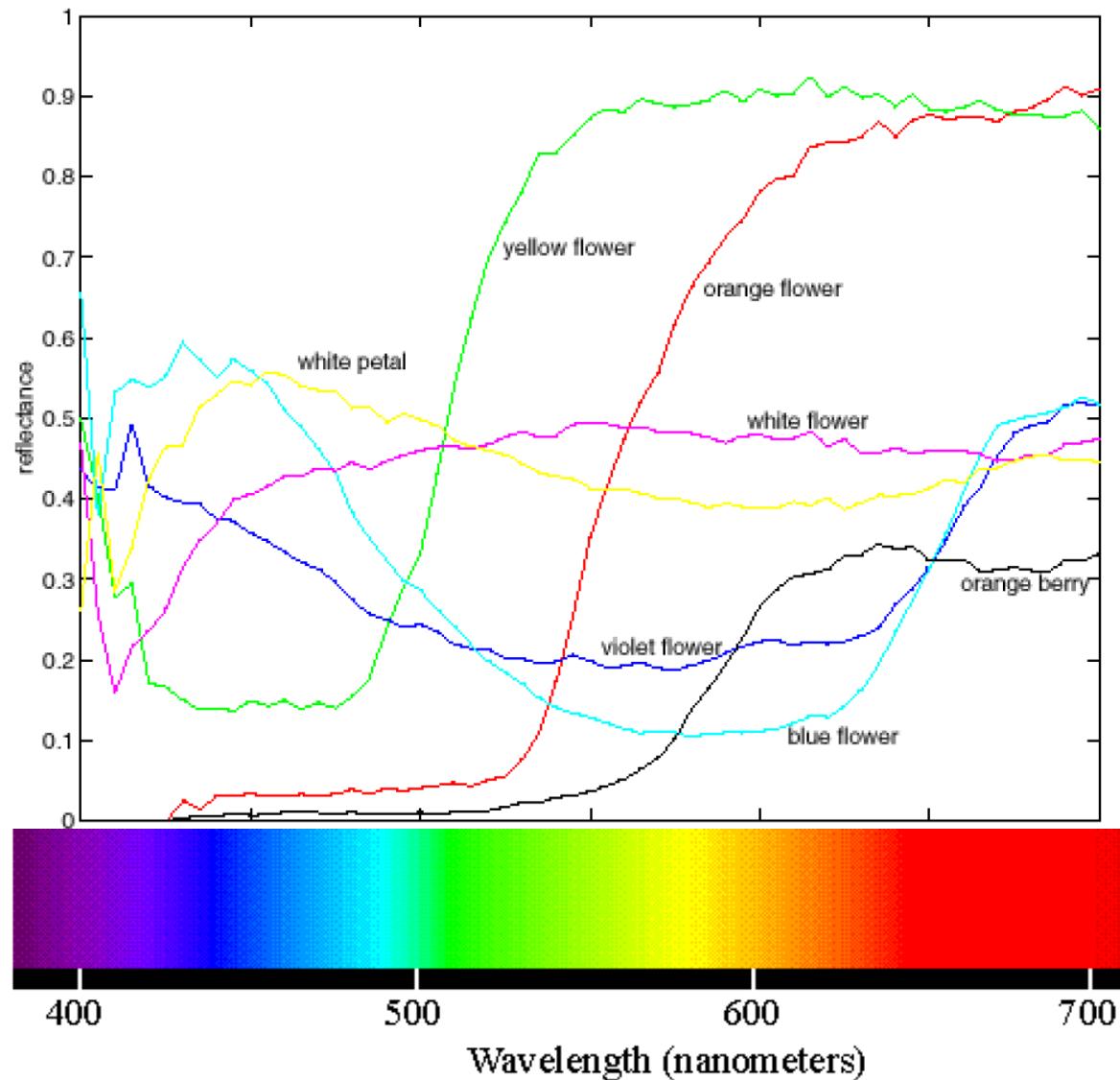
Light rays are typically composed of multiple wavelengths



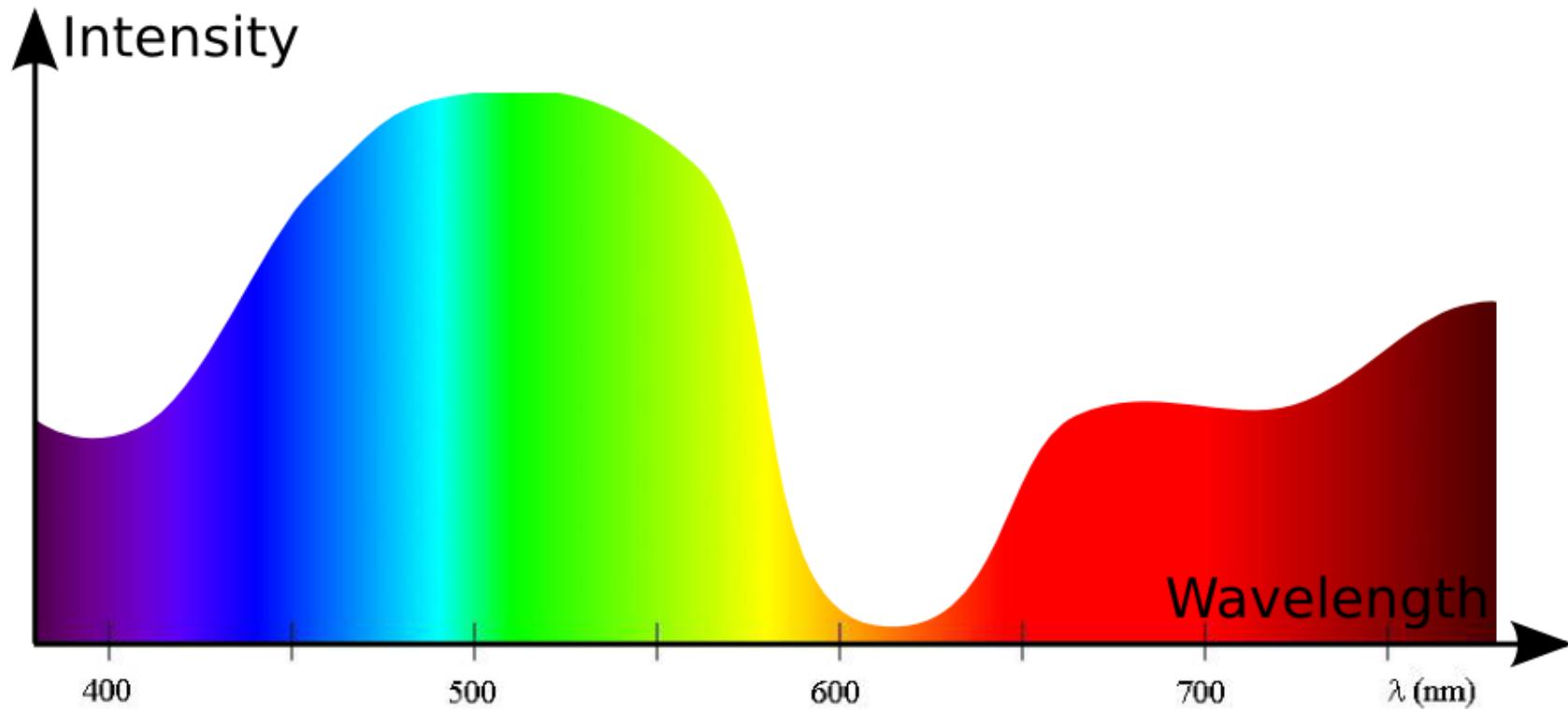
How do we describe a beam of light?



Non-monochromatic color spectra



How do we know which color this would be?



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

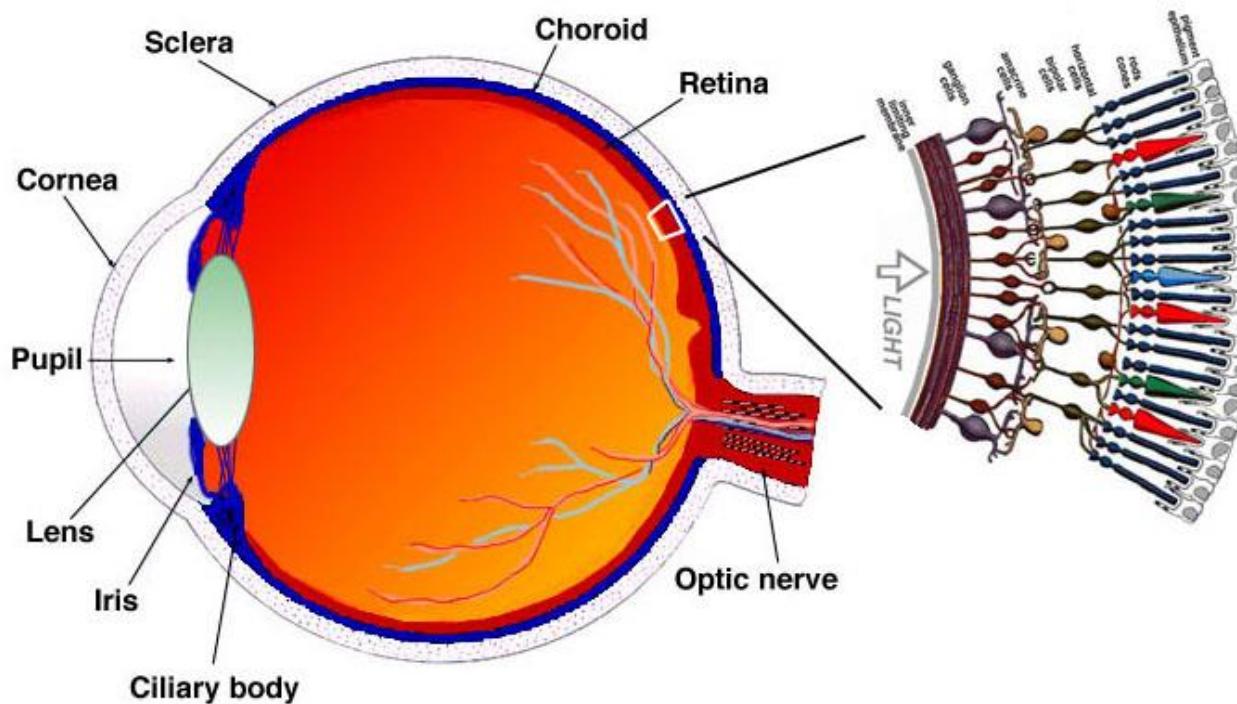


Helmholtz (1850) & James Clerk

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).

Physical World → Visual System



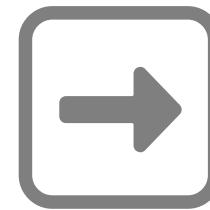
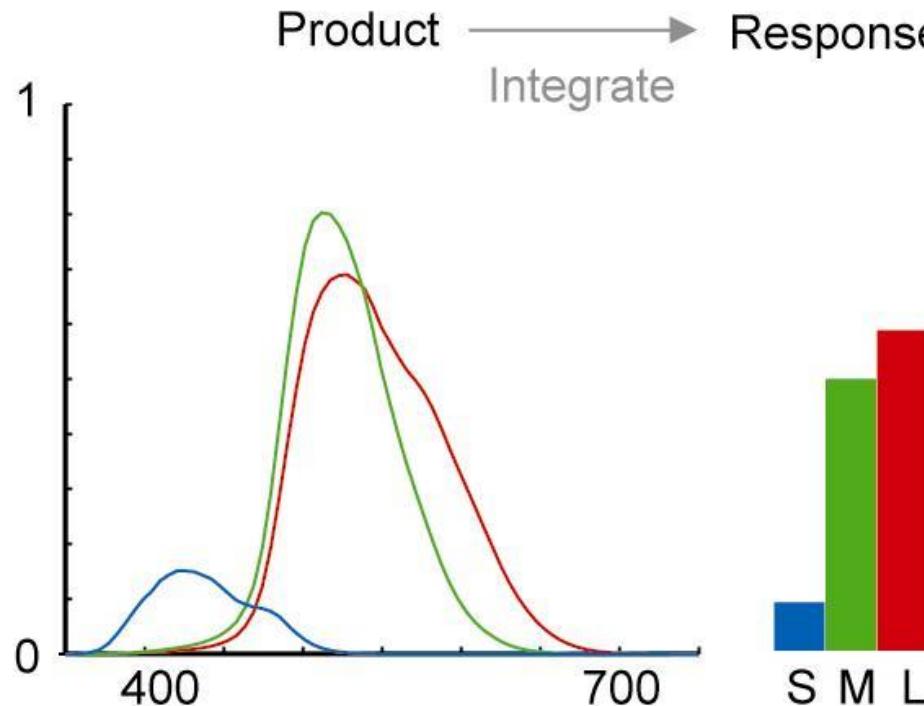
Rods

No color (sort of)
All over the retina
More sensitive

Cones

Three different kinds of
“color receptors”
Mostly in the center
Less Sensitive

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?

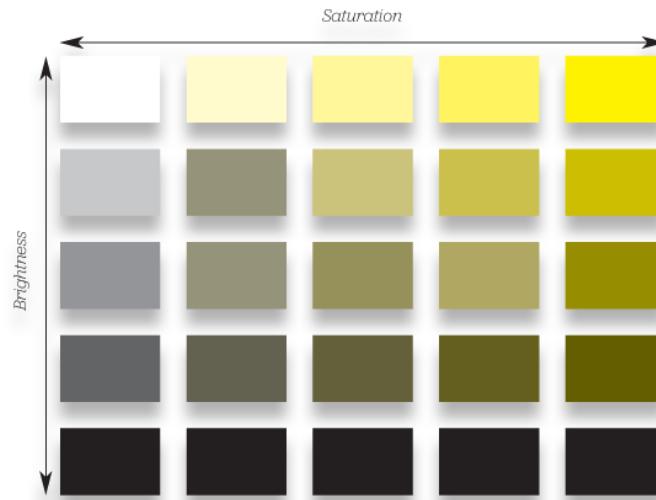
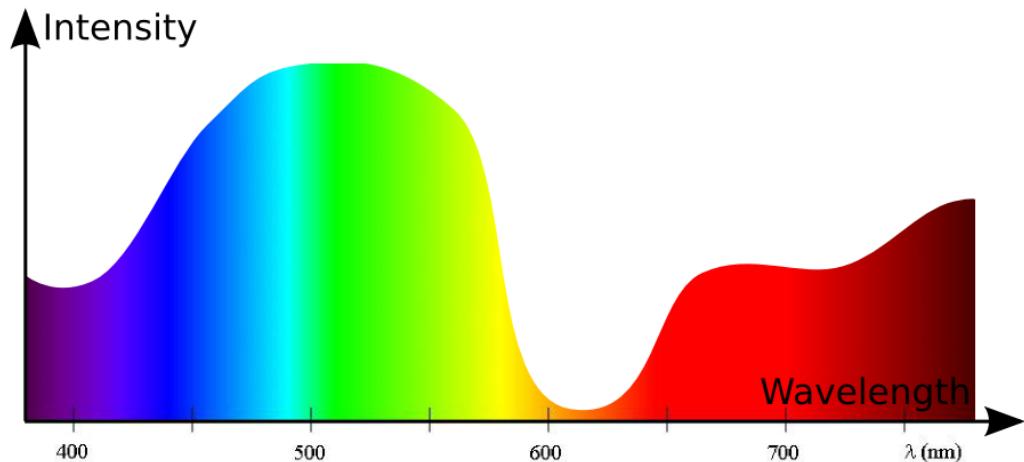
Usually a viewer recognizes...

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)



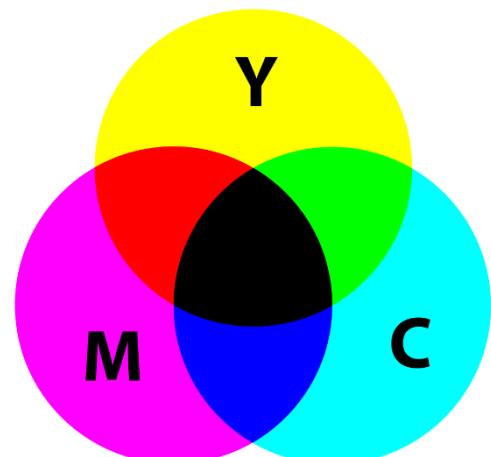
What do we know so far?

We can describe any color of light with 3 numerical values

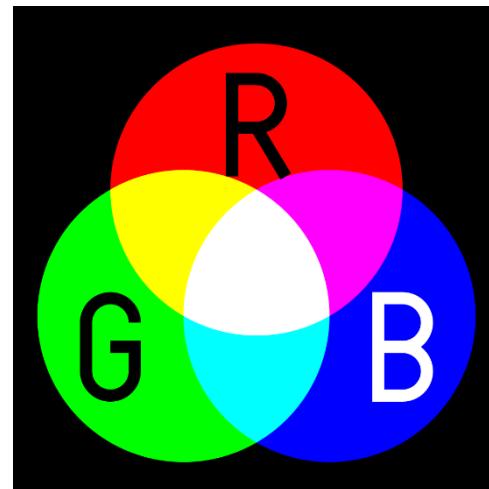
→ Color is “3D” (mathematically)

But how do we combine these 3 values?

→ The color spaces set the rules!



Subtractive (CMYK)



Additive (RGB)

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

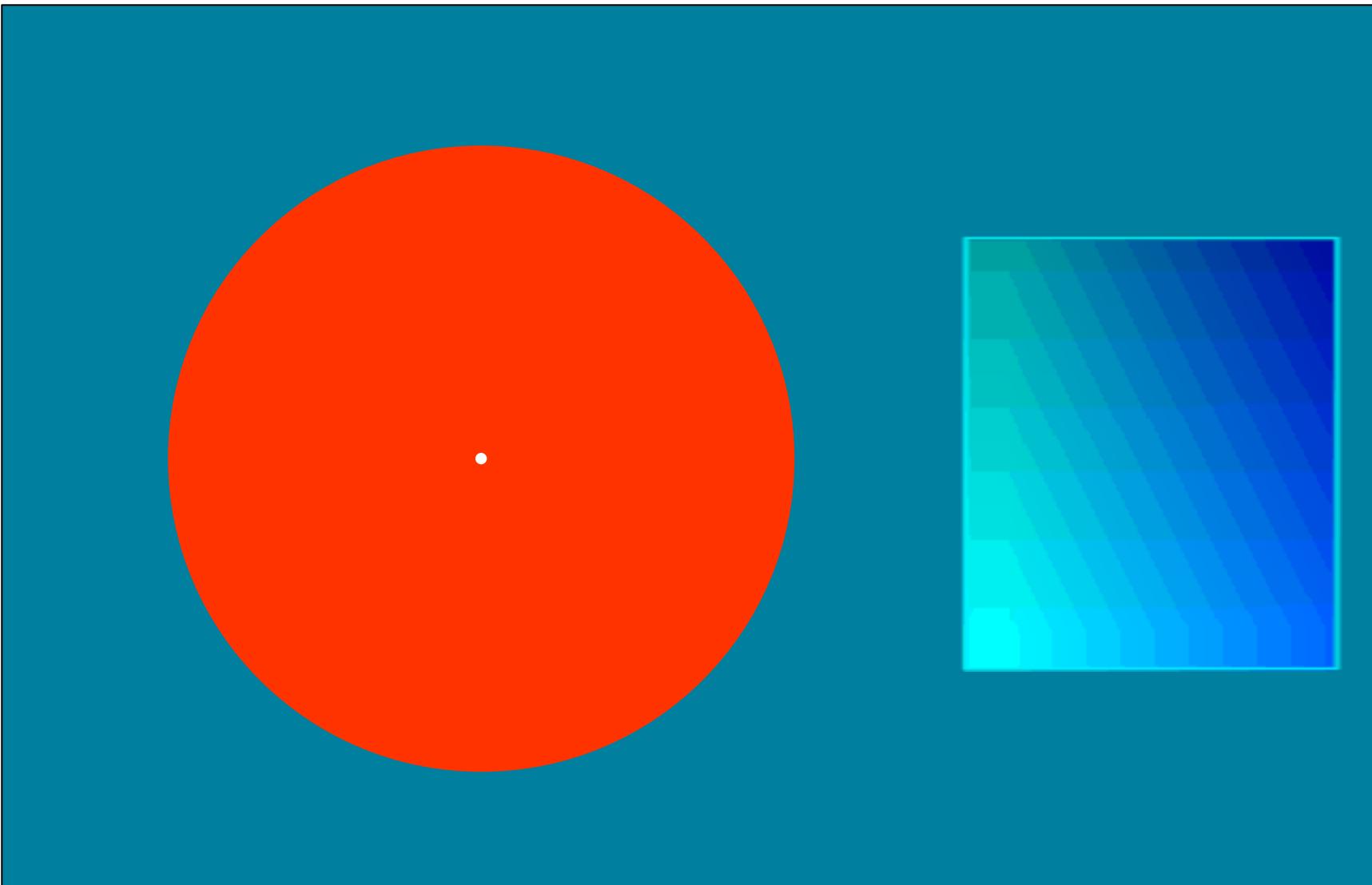
Most relevant for us: RGB

- 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

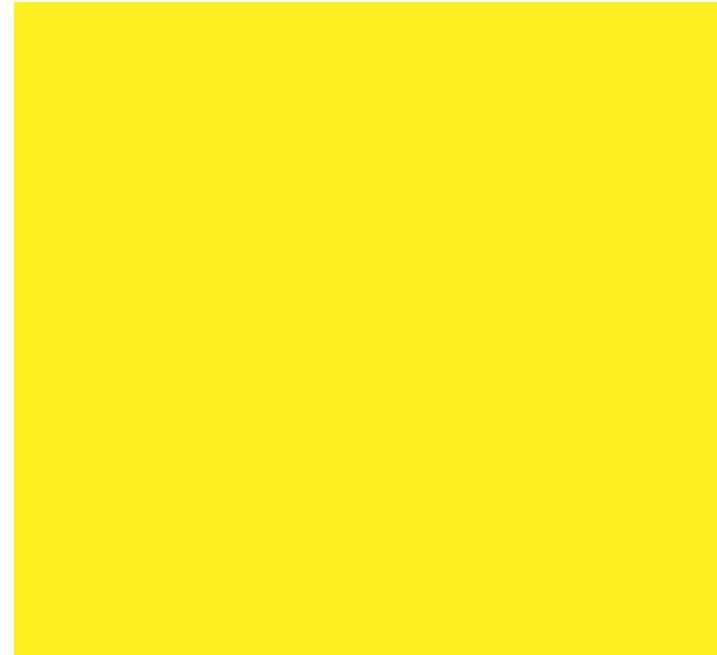
- Used in TVs, LCDs, phones, ...
- BUT is device-dependent
(without color management colors don't look the same on every screen)
- Cannot display all visible colors

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...

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

Color names if
you're a guy...

Color according to XKCD

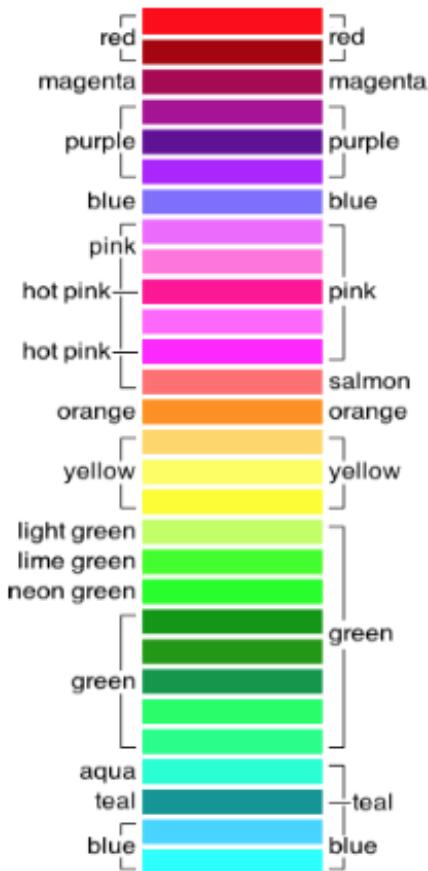


A crowdsourced color-labeling game
~5 million colors
~222,500 user sessions

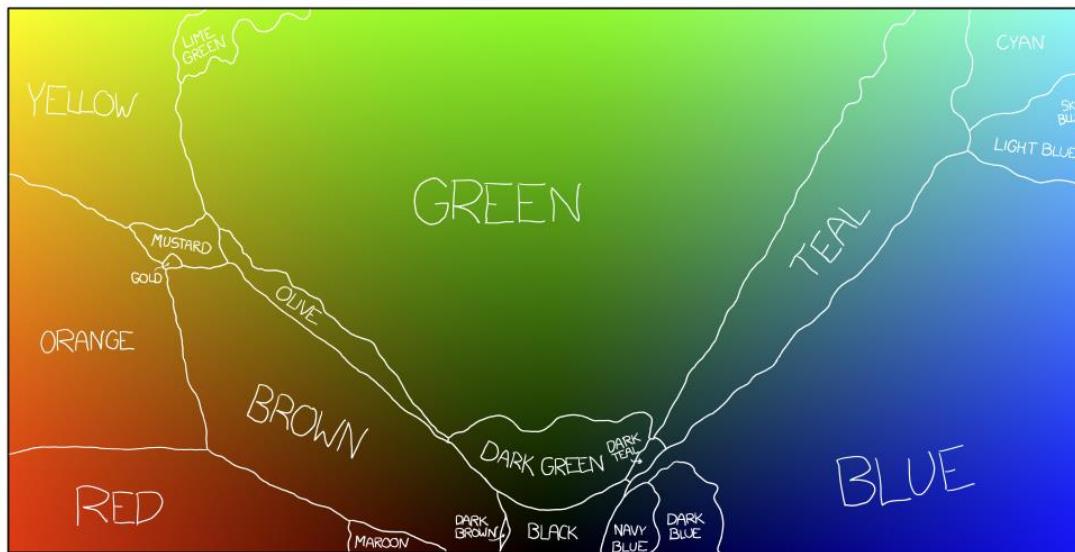
<http://blog.xkcd.com/2010/05/03/color-survey-results/>

Color according to XKCD

*Actual color names
if you're a girl ...* *Actual color names
if you're a guy ...*



Are there natural boundaries?



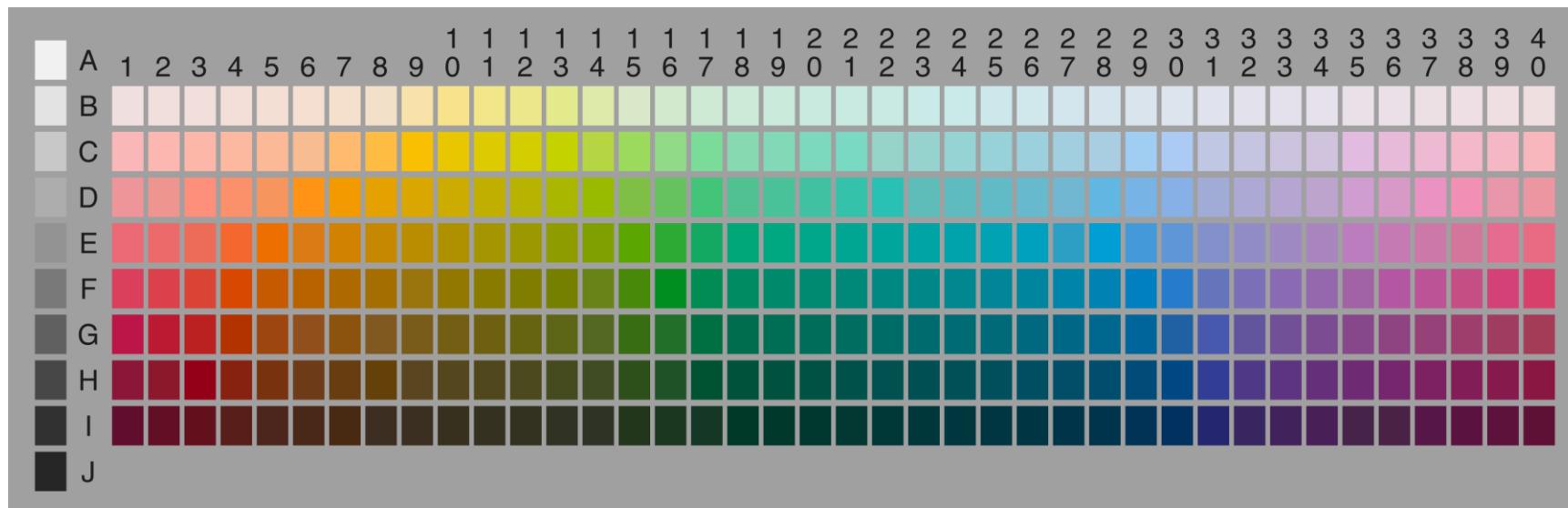
THIS CHART SHOWS THE DOMINANT COLOR NAMES OVER THE THREE FULLY-SATURATED FACES OF THE RGB CUBE (COLORS WHERE ONE OF THE RGB VALUES IS ZERO)



World Color Survey

Brent Berlin & Paul Kay 1969

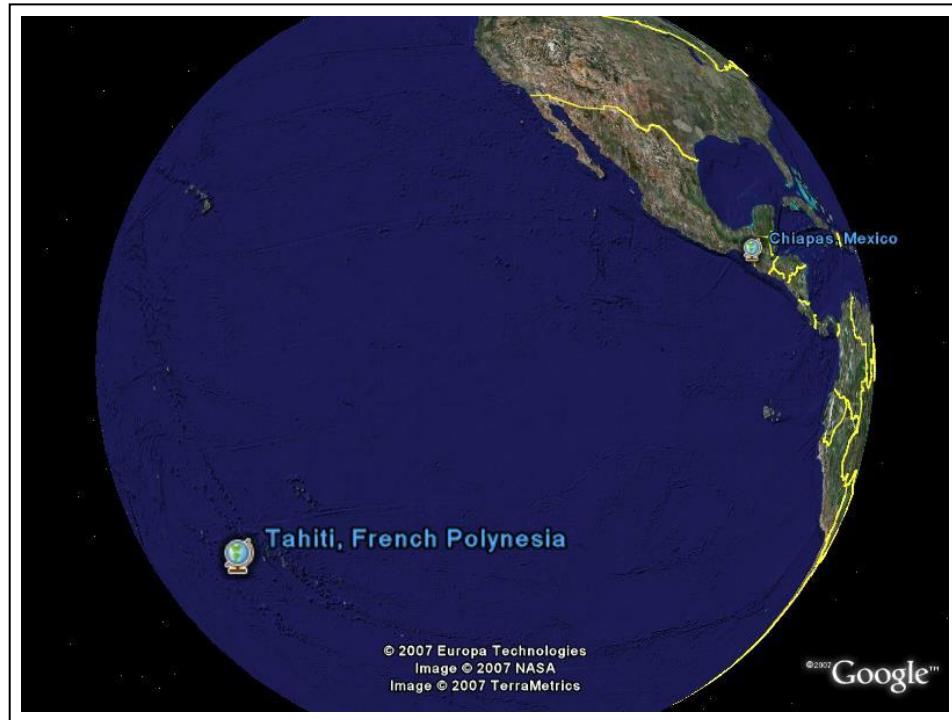
Surveyed 2616 speakers of 110 languages using 330 different color chips



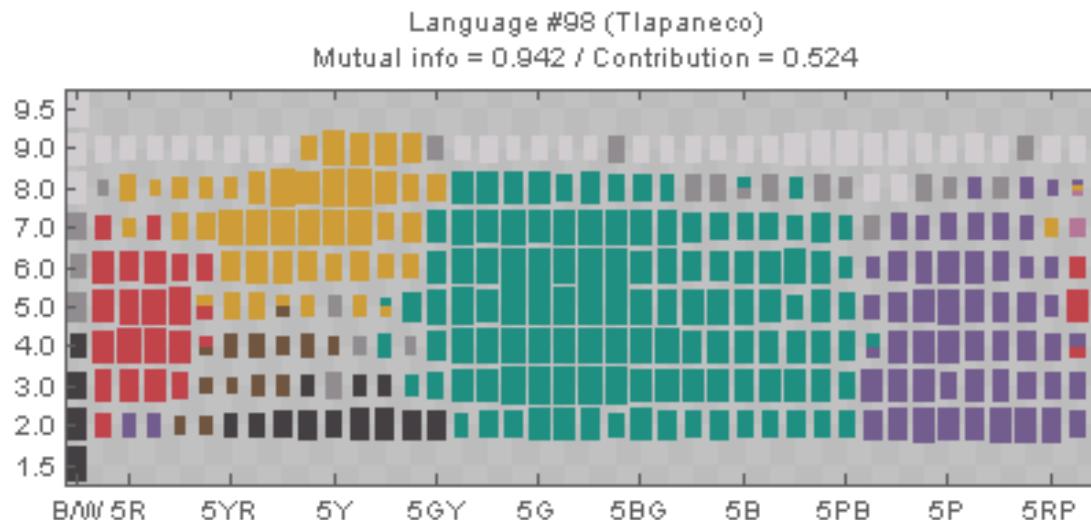
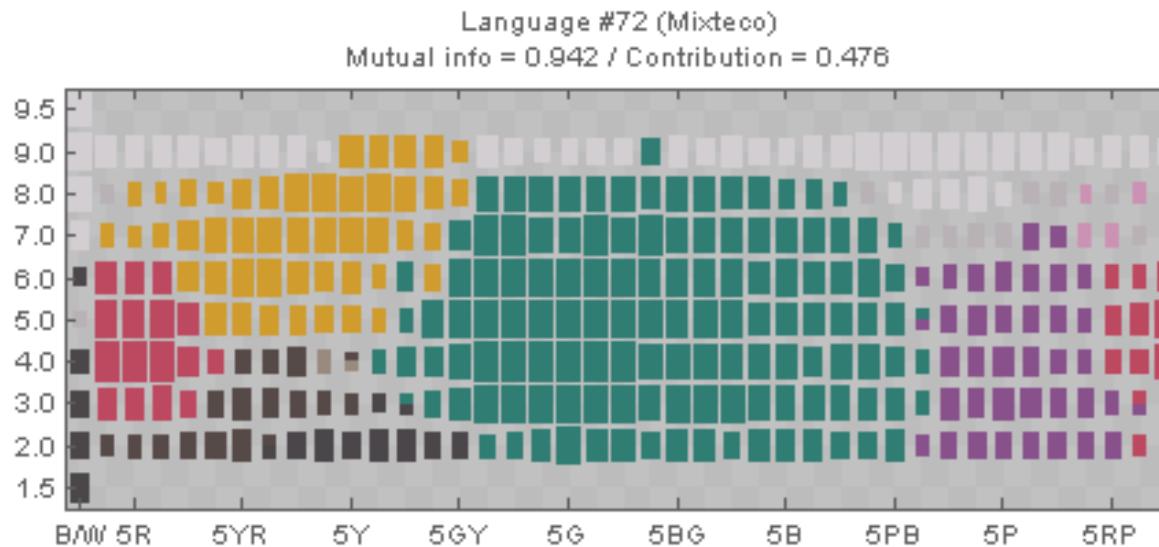
see also: http://wals.info/feature/132A?tg_format=map#2/32.5/153.5

Basic Color Terms

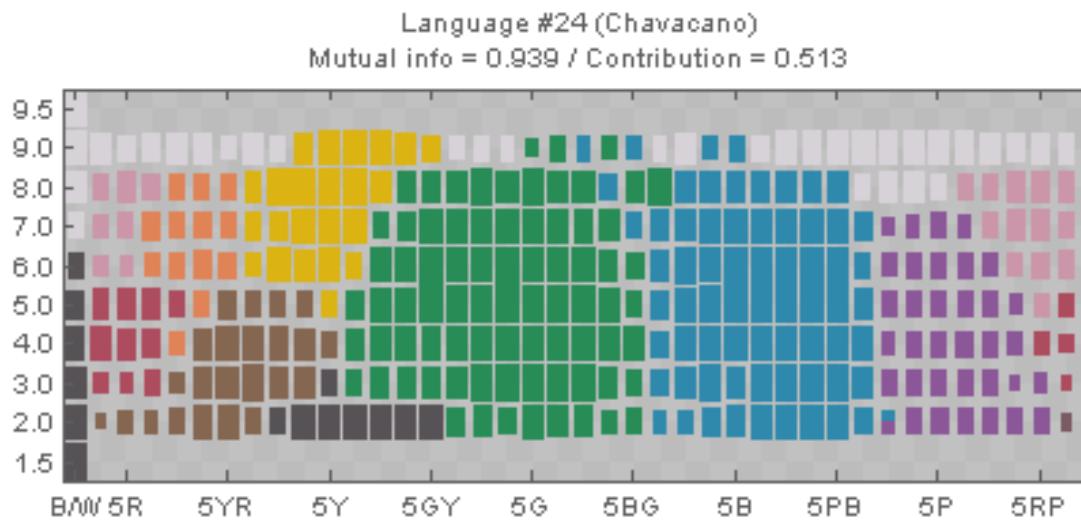
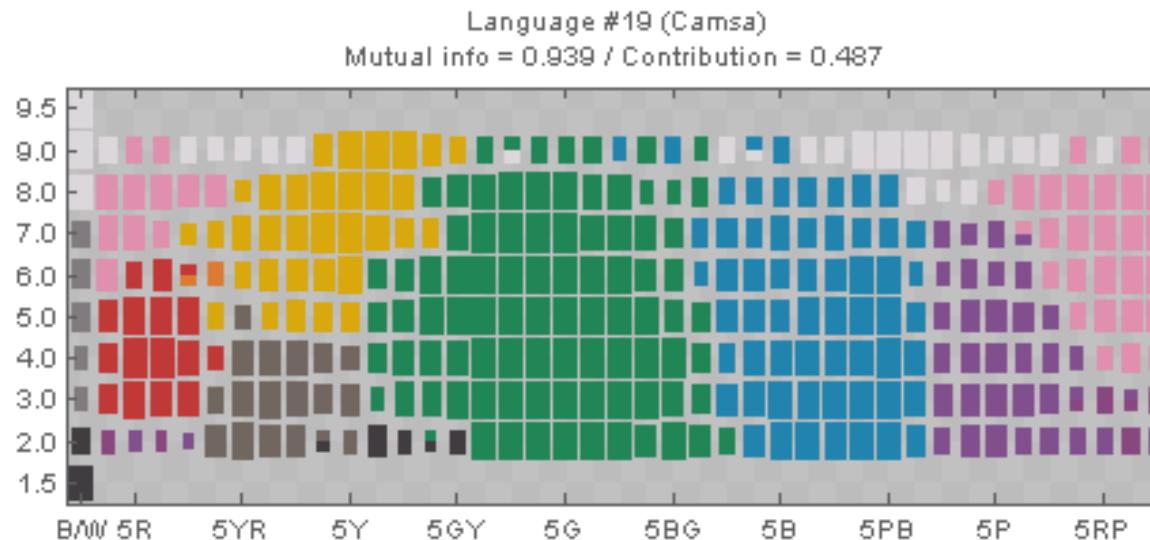
let's look at two specific places



Results from WCS (Mexico)



Results from WCS (South Pacific)



Language-color interaction

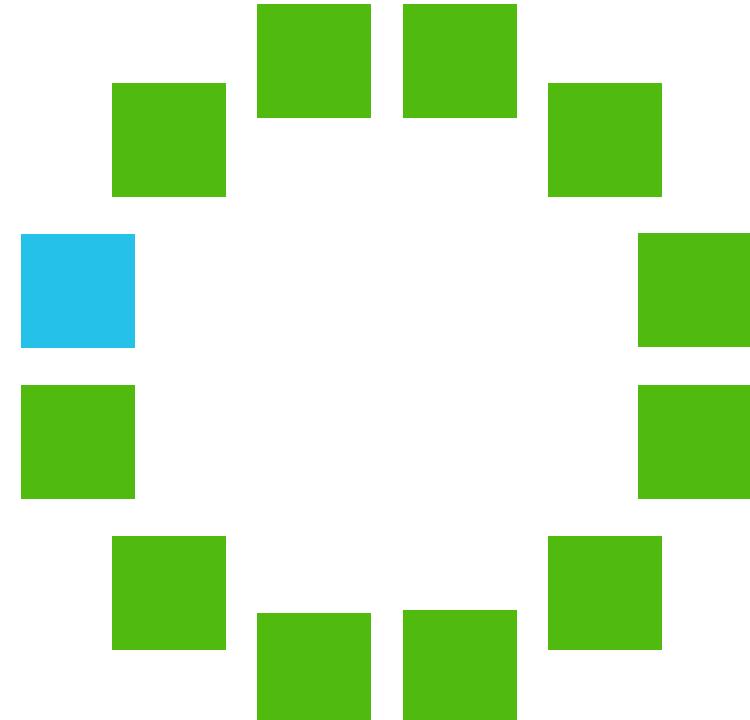
- Himba tribe in Namibia – only few color words:
 - **zoozu**: most dark colors (red, blue, green, violet)
 - **vapa**: white, also some yellow
 - **borou**: some green and blue colors
 - **dumbu**: many green but also red colors



© Hans Hillewaert

But language-color interaction

- experiment: how long to find a differing color?

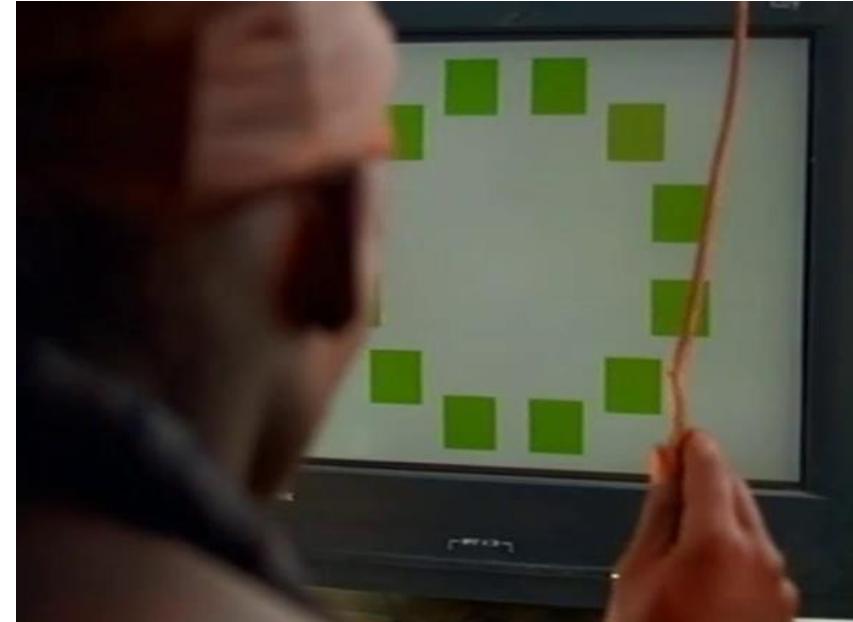
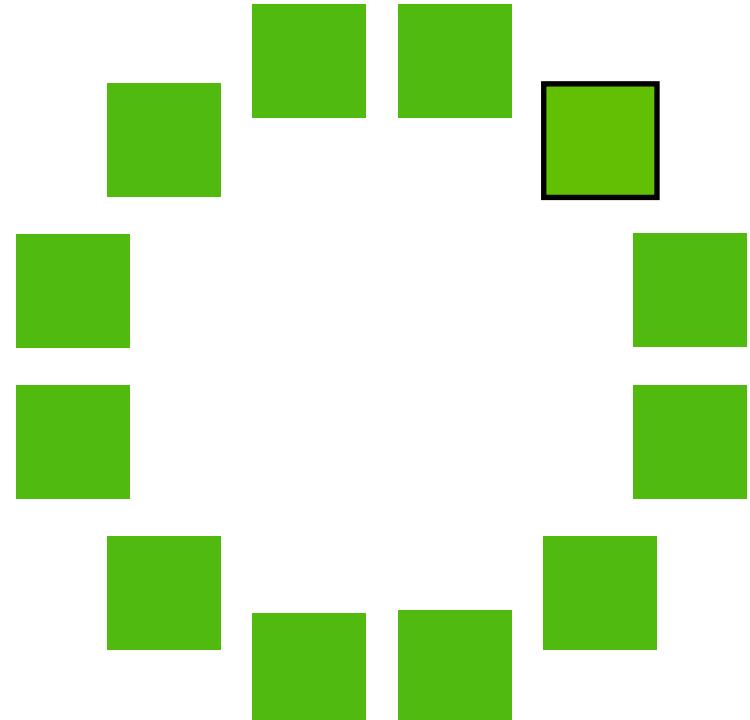


© BBC

difficult to impossible for Himba people

But language-color interaction

- experiment: how long to find a differing color?

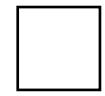


© BBC

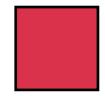
easy for Himba people: different words for both types of green

Universal (?) Basic Color Terms

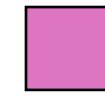
Basic color terms recur across languages



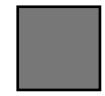
White



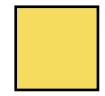
Red



Pink



Grey



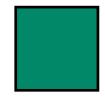
Yellow



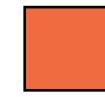
Brown



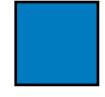
Black



Green



Orange



Blue



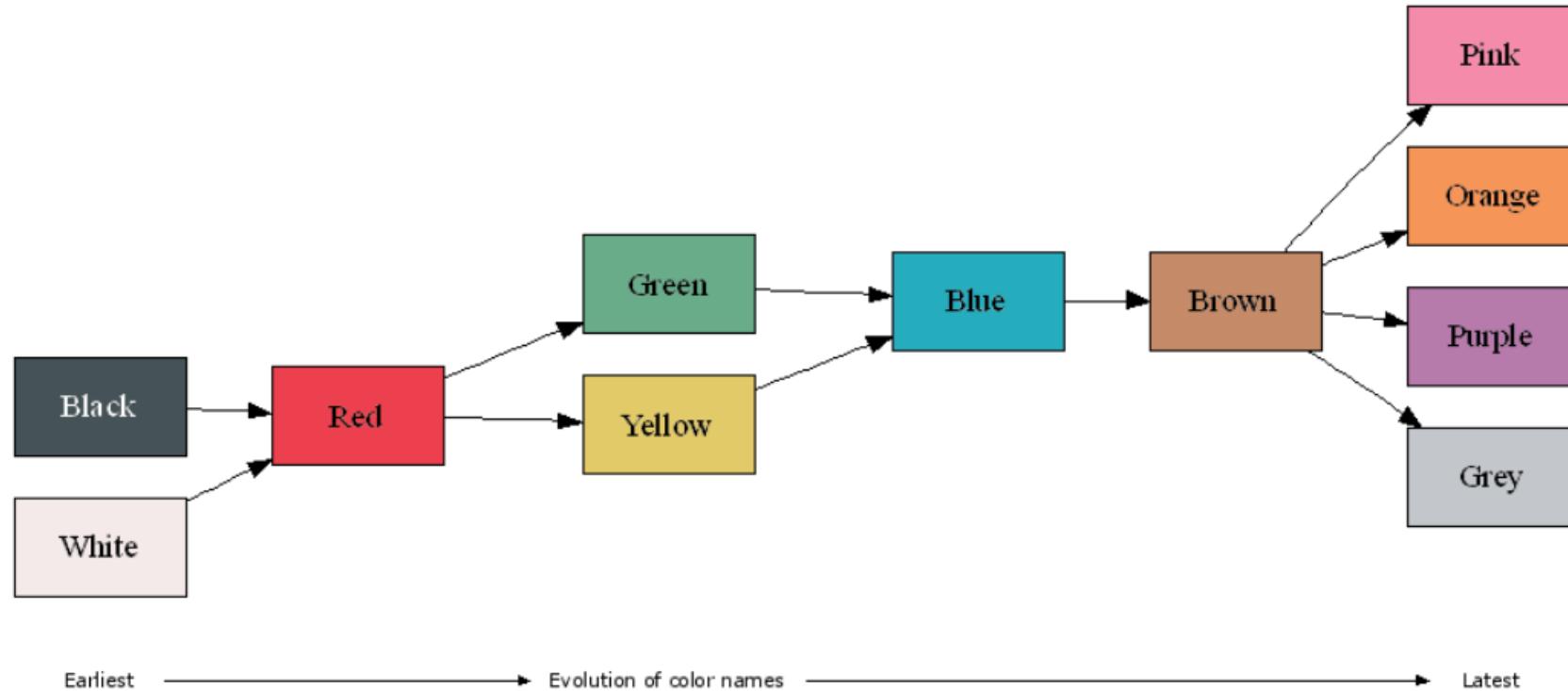
Purple



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

Fruits
Apple
Banana
Blueberry
Cherry
Grape

Brands
Apple
AT&T
Home Depot
Kodak
Starbucks

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



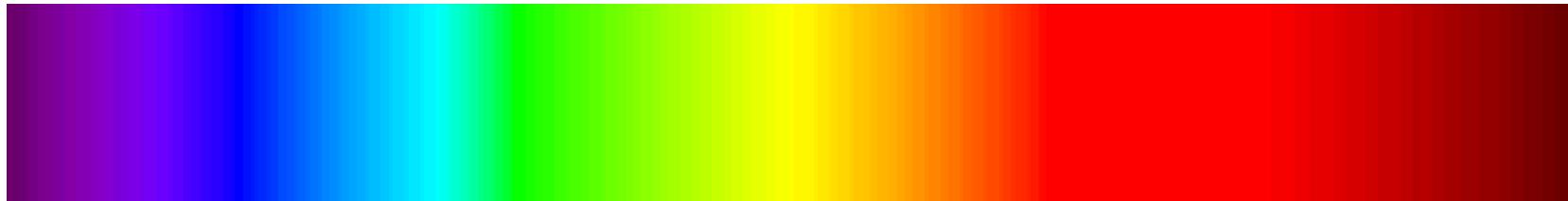
For **diverging scales**, use a lighter, desaturated value for the critical mid-point and darker hues for the ends



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

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

mericals, 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

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DEPARTMENT: VISUALIZATION VIEWPOINTS

Rainbow Colormaps Are Not All Bad

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Maureen Stone, *Tableau Research, Seattle, WA, 98103, USA*

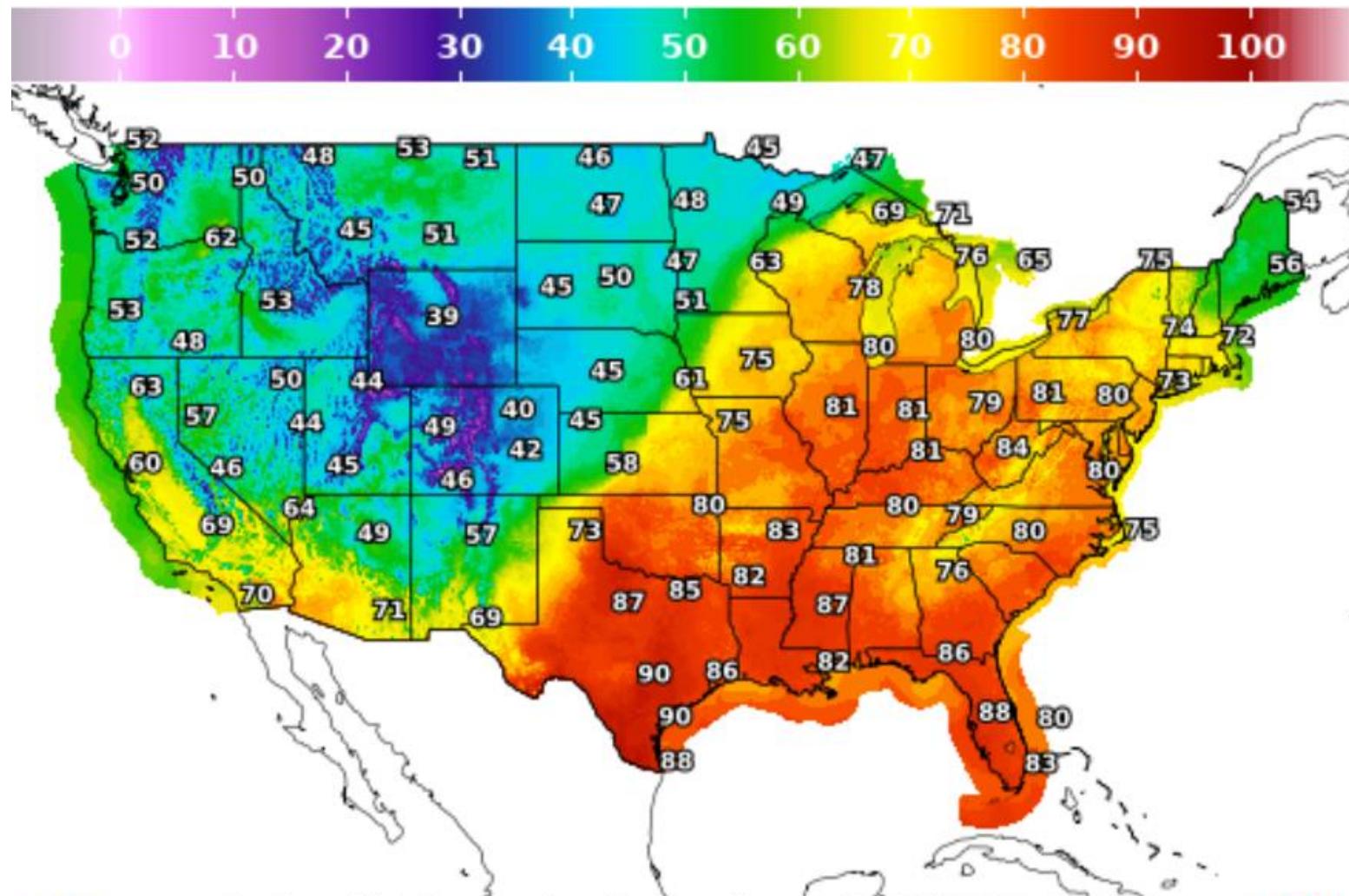
Danielle Albers Szafir, *University of North Carolina at Chapel Hill, Chapel Hill, NC, 27599, USA*

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



Daytime High Temperature Ending: Thu, Oct 31 2024, 12 AM UTC

National Digital Forecast Database

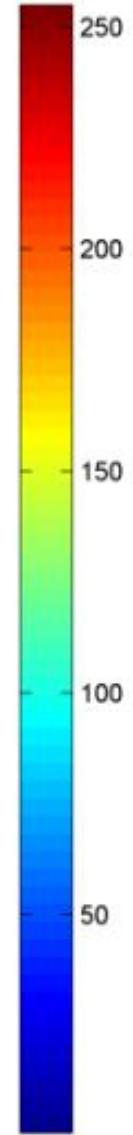
Issued: Oct 30 2024, 5:30 PM UTC

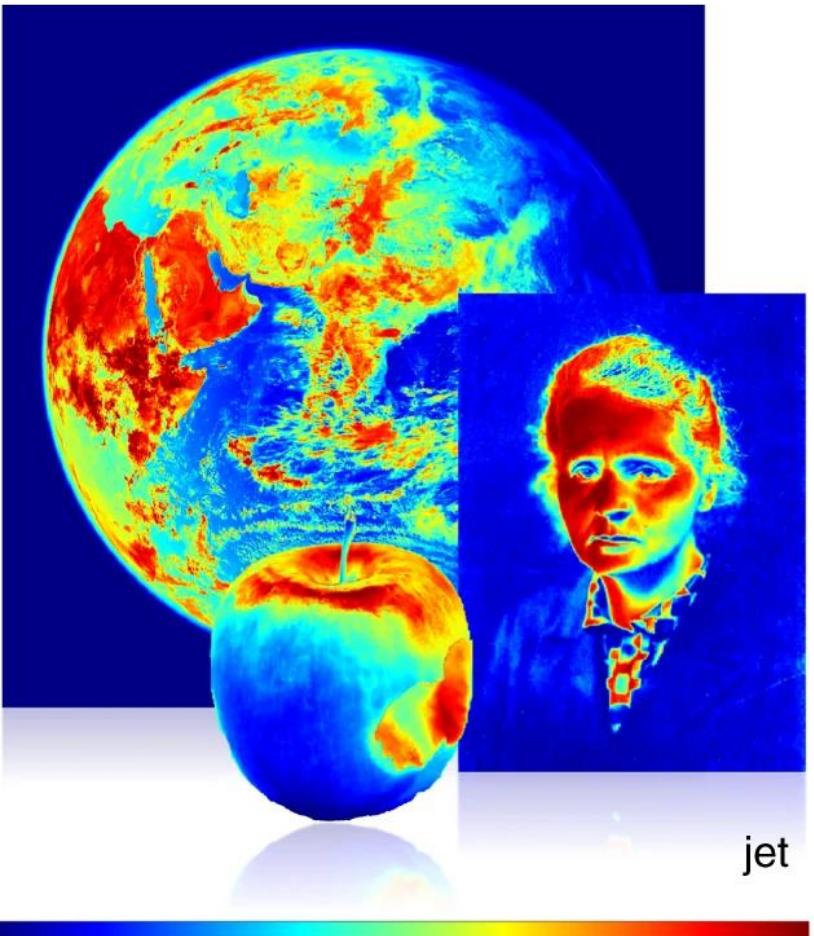
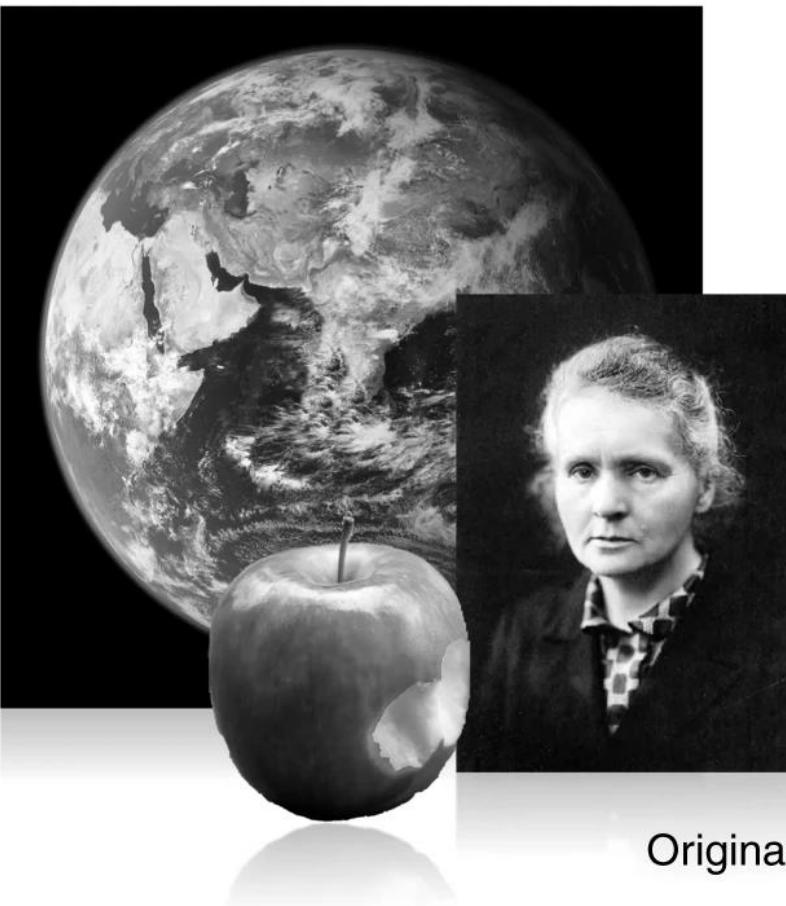
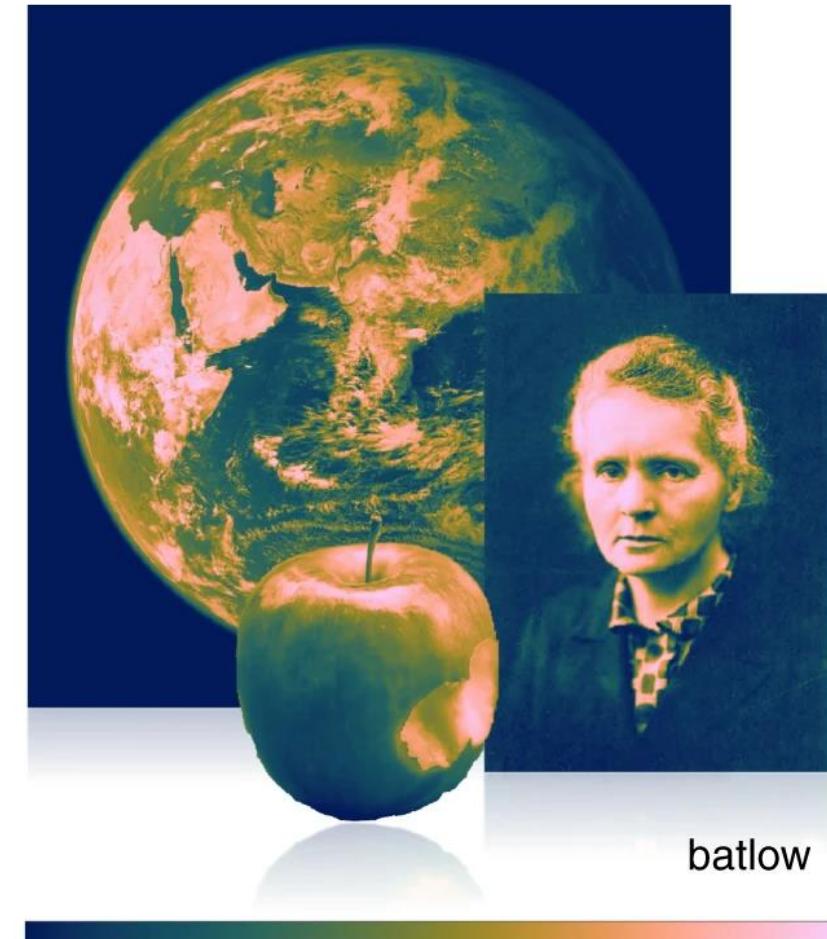


Original X-ray - left wrist



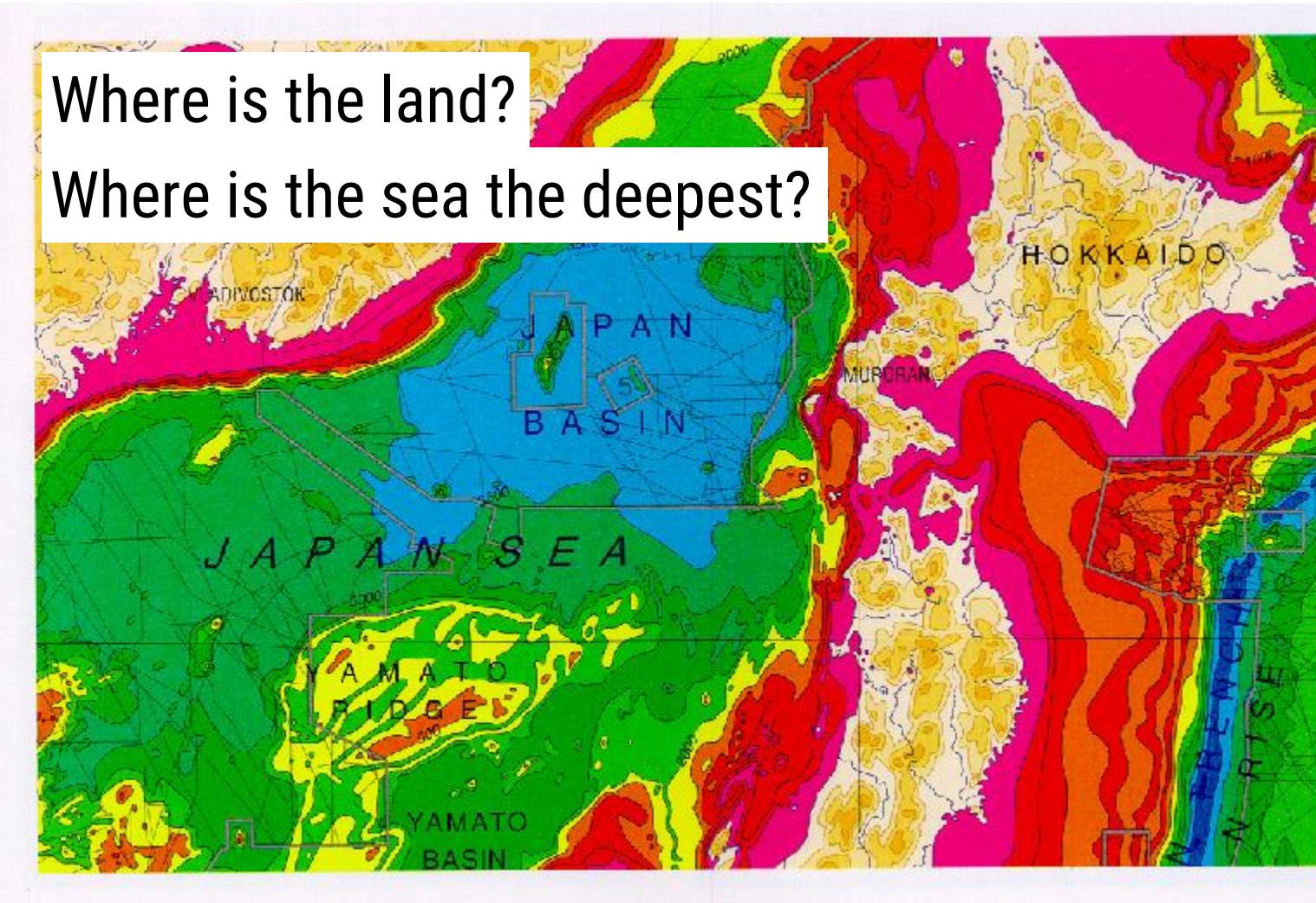
Original X-ray - left wrist - jet (rainbow) colormap



b**a****c**

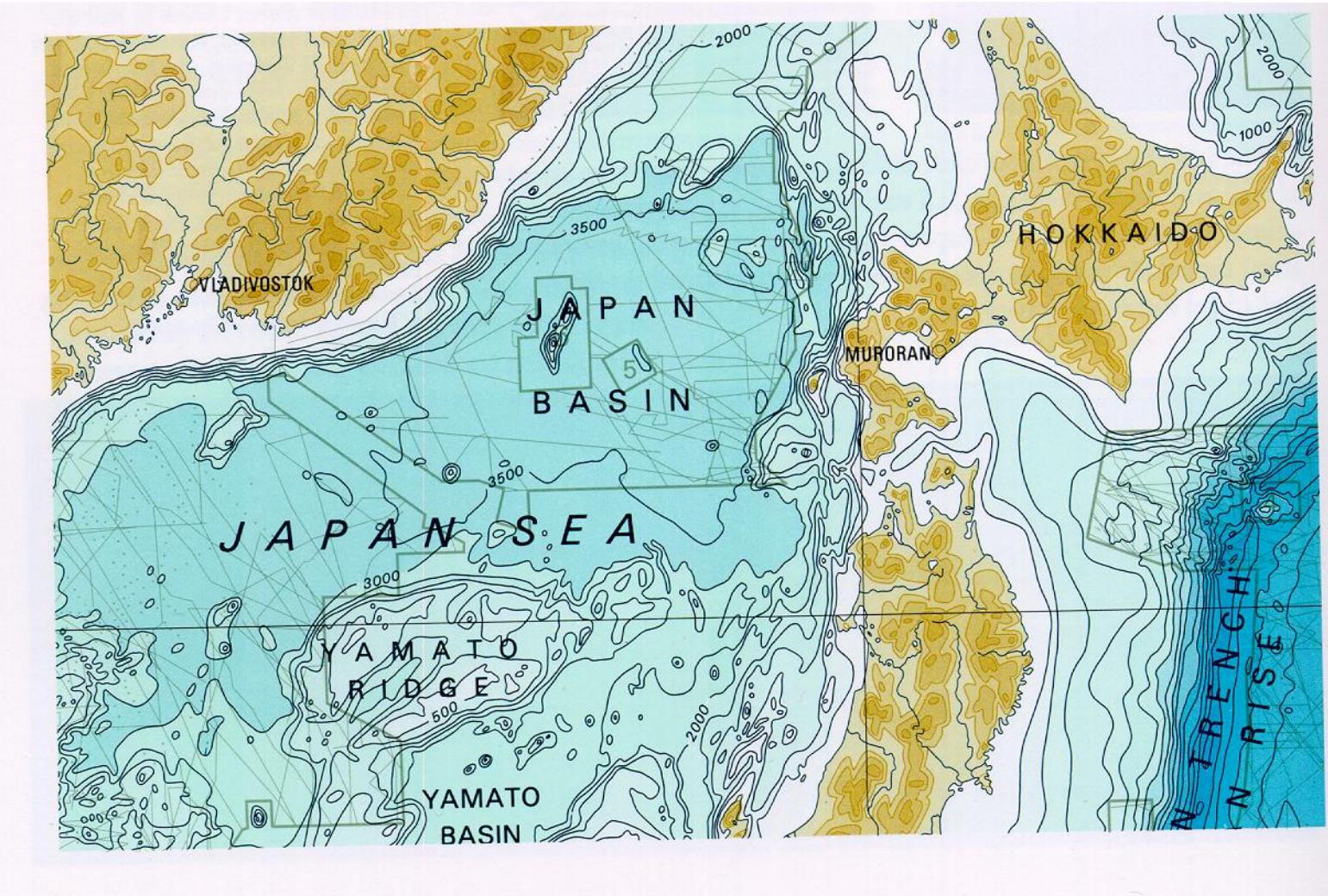
General Bathymetric Chart of the Ocean

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

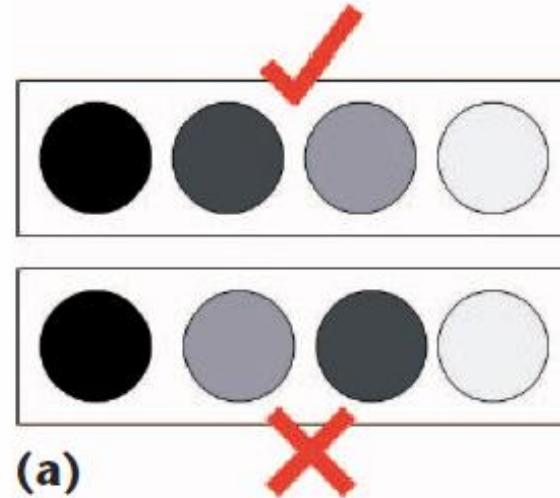
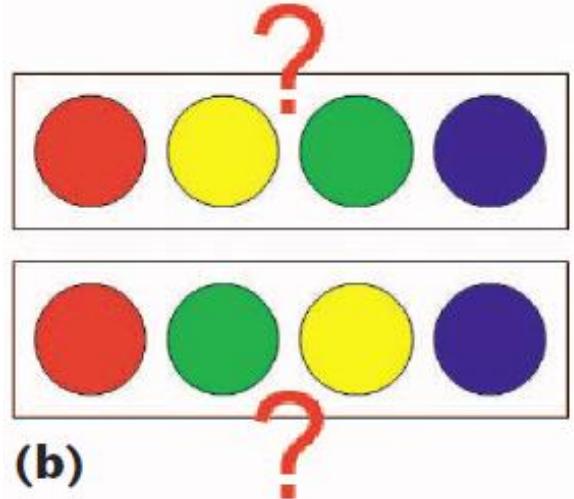


General Bathymetric Chart of the Ocean

Now describe what kind of color scale was possibly used here



Perceptual Ordering



Rainbow Color Scale

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

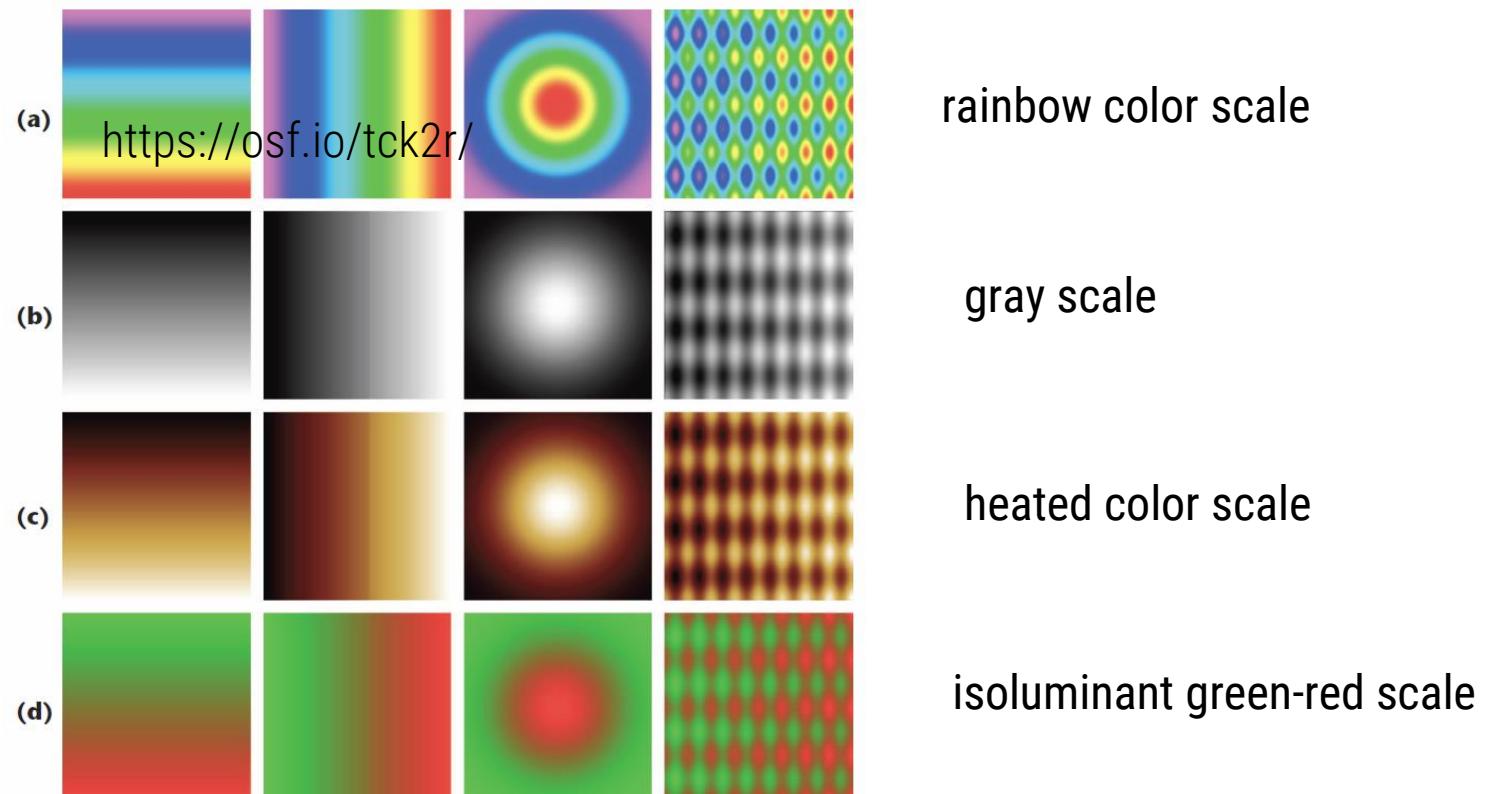
Gray Scale

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

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

BUT...

There are different rainbows

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



HSV rainbow



ParaView Blue-Red (no magenta)



Jet – dark ends



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 people resolve smaller features

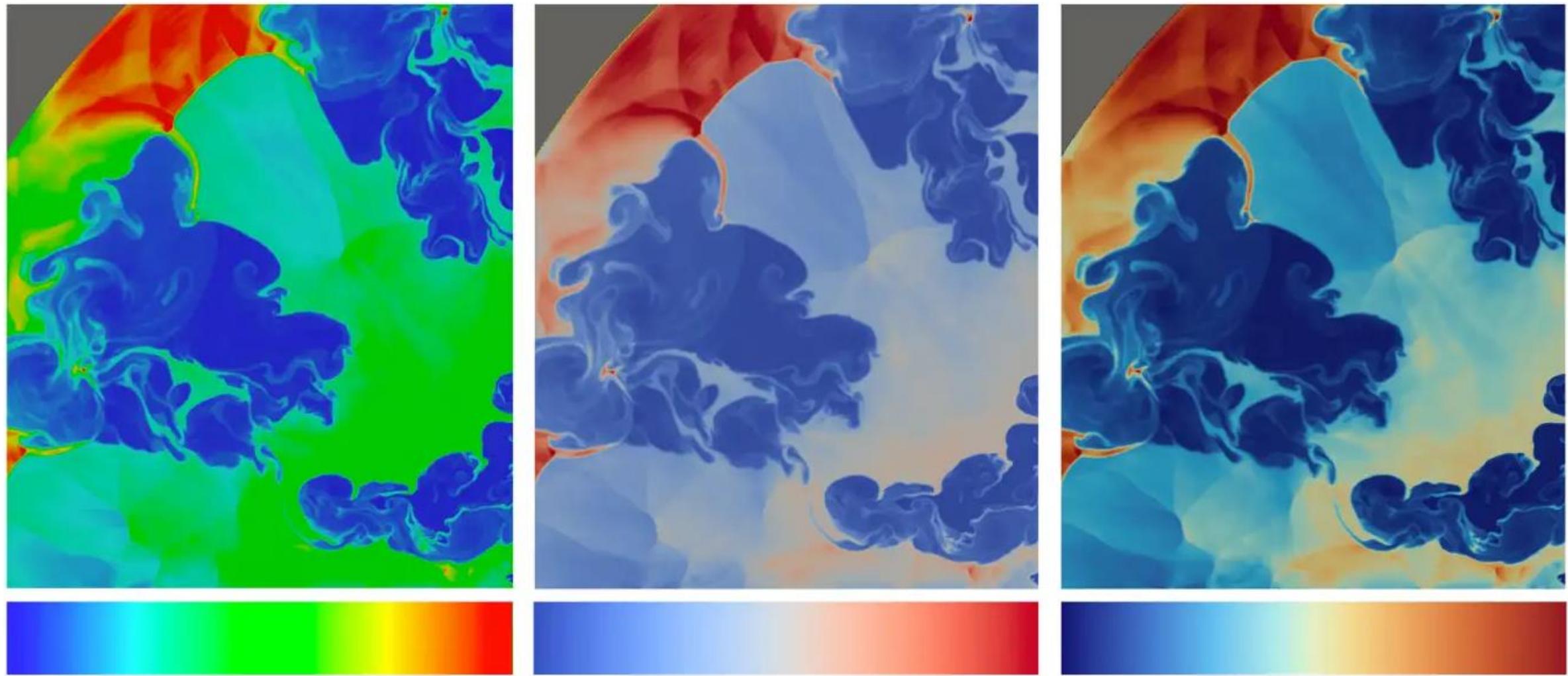
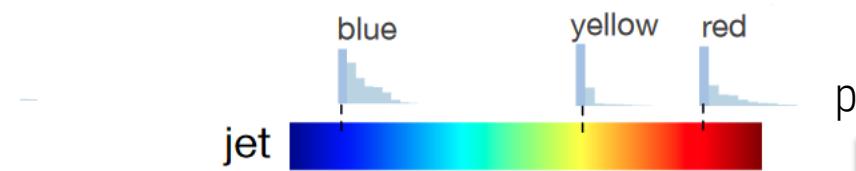


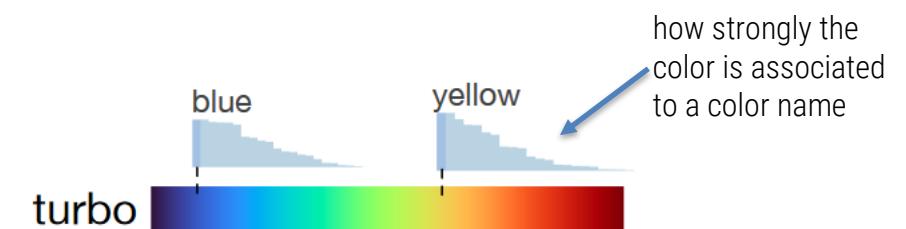
FIGURE 1. Paraview's first default colormap was the *Hue Wheel*, left, which was improved upon with the adoption of *Cool to Warm*, center. The new default, *Fast*, is on the right. All are shown on combustion data,² illustrating the improving feature resolution power progression.

BUT...

- Studies have shown that with a legend people can read values well
- Allow people to associate names to colors – which helps them to recognize patterns <https://onlinelibrary.wiley.com/doi/10.1111/cgf.14288>



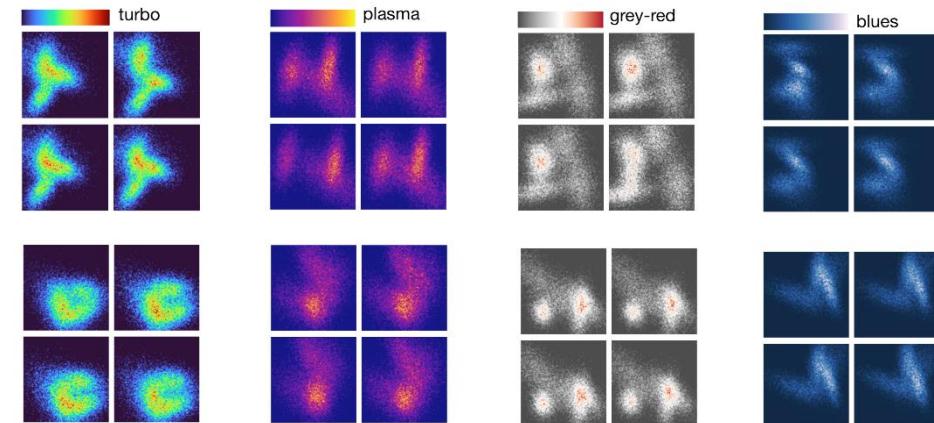
performed better than



- Help people to reason about color distributions

which of the four plots appear to stand out as different? This graphical inference test enables us to determine the discriminative power of competing colormap designs.

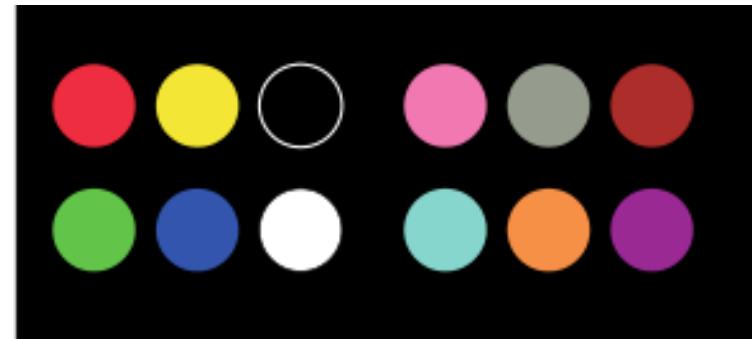
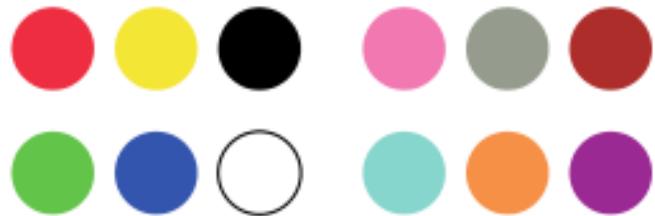
<https://osf.io/tck2r/>



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**



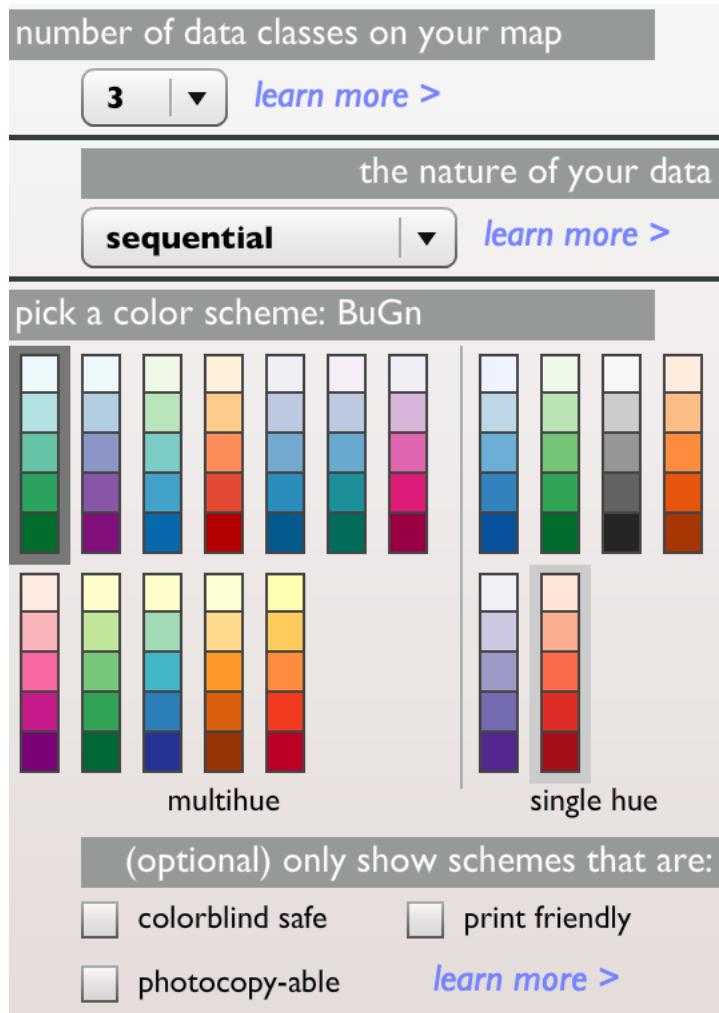
> 12 colors will likely not work
~5 colors recommended

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

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

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

pick a color scheme: Paired



(optional) only show schemes that are:

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

pick a color system

166, 206, 227	<input checked="" type="radio"/> RGB <input type="radio"/> CMYK <input type="radio"/> HEX
31, 120, 180	
178, 223, 138	
51, 160, 44	
251, 154, 153	

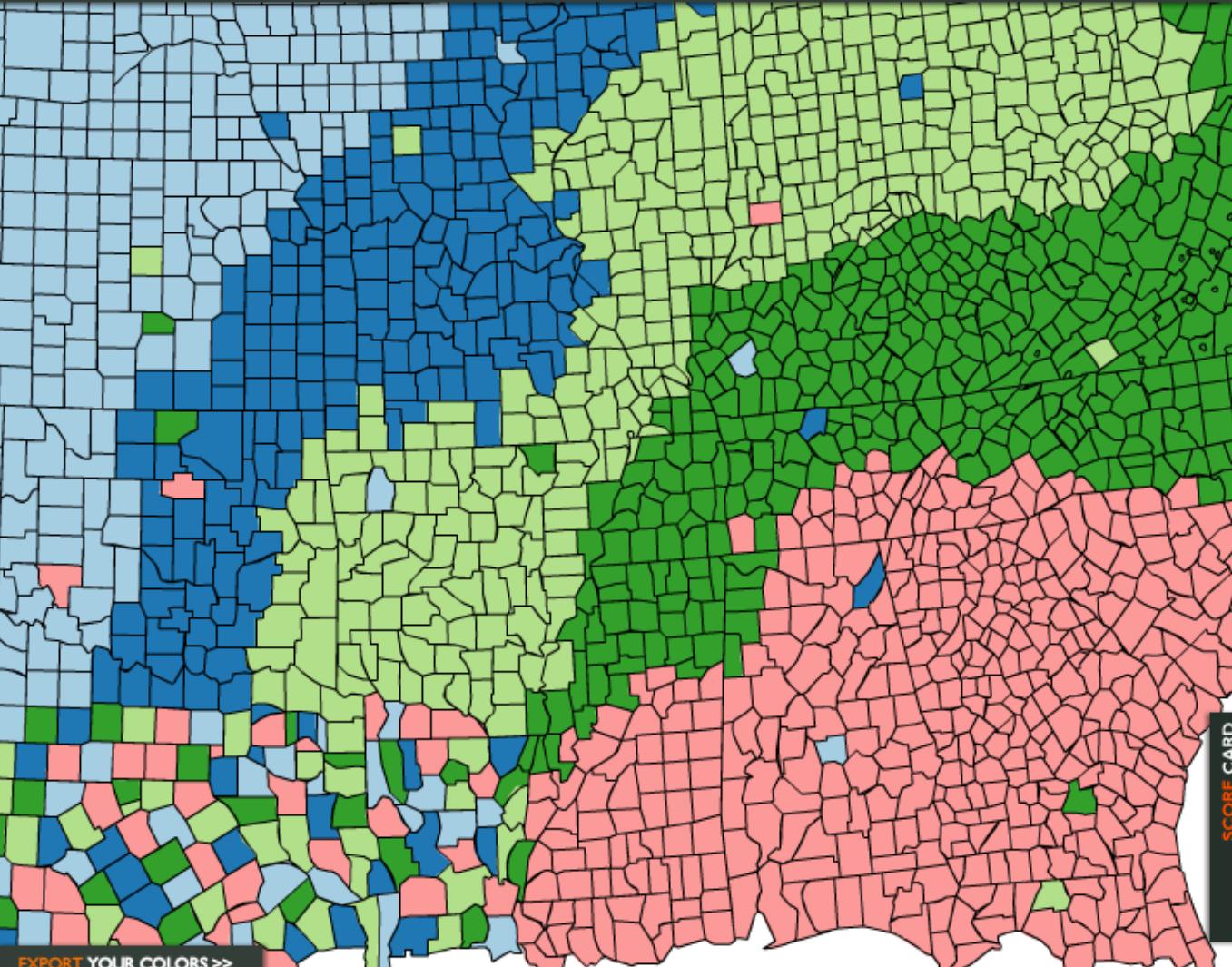
adjust map context

roads 
 cities 
 borders 

select a background

solid color terrain

color transparency 

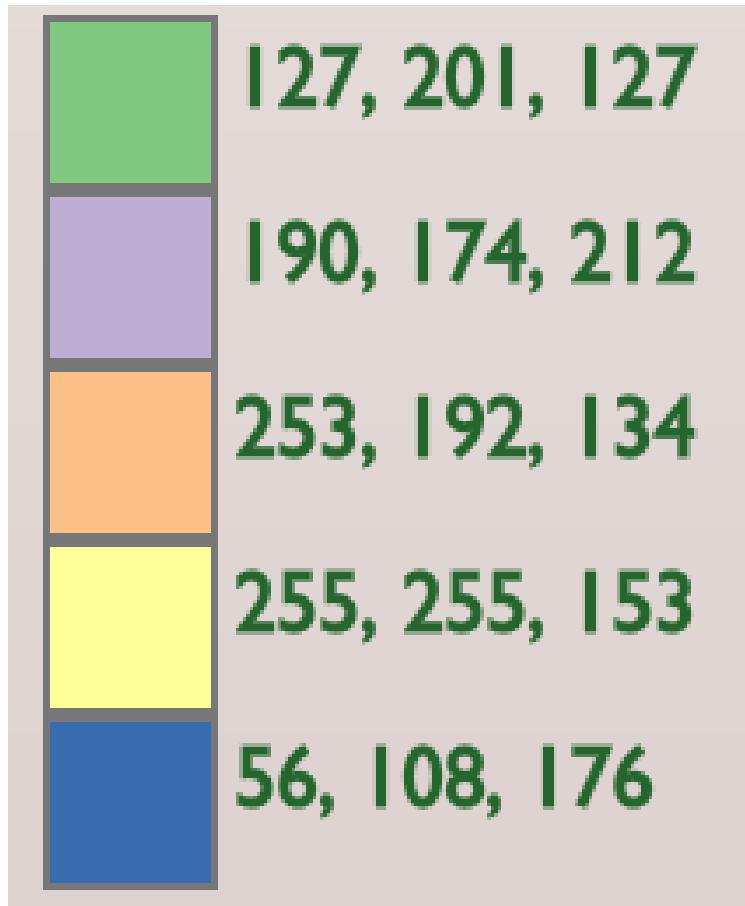


[EXPORT YOUR COLORS >>](#)

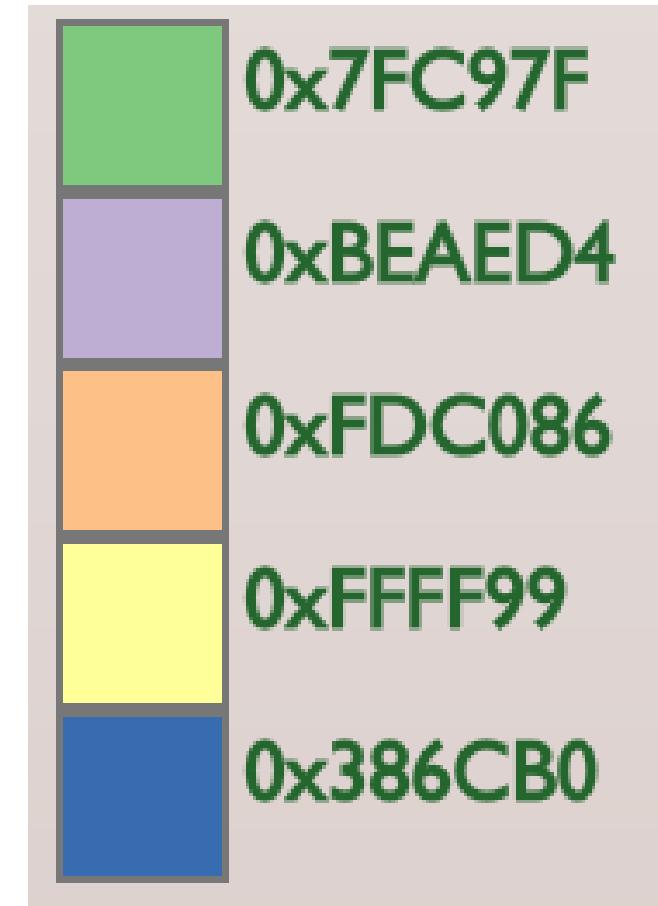
[SCORE CARD](#)

<http://colorbrewer2.org/>

ColorBrewer

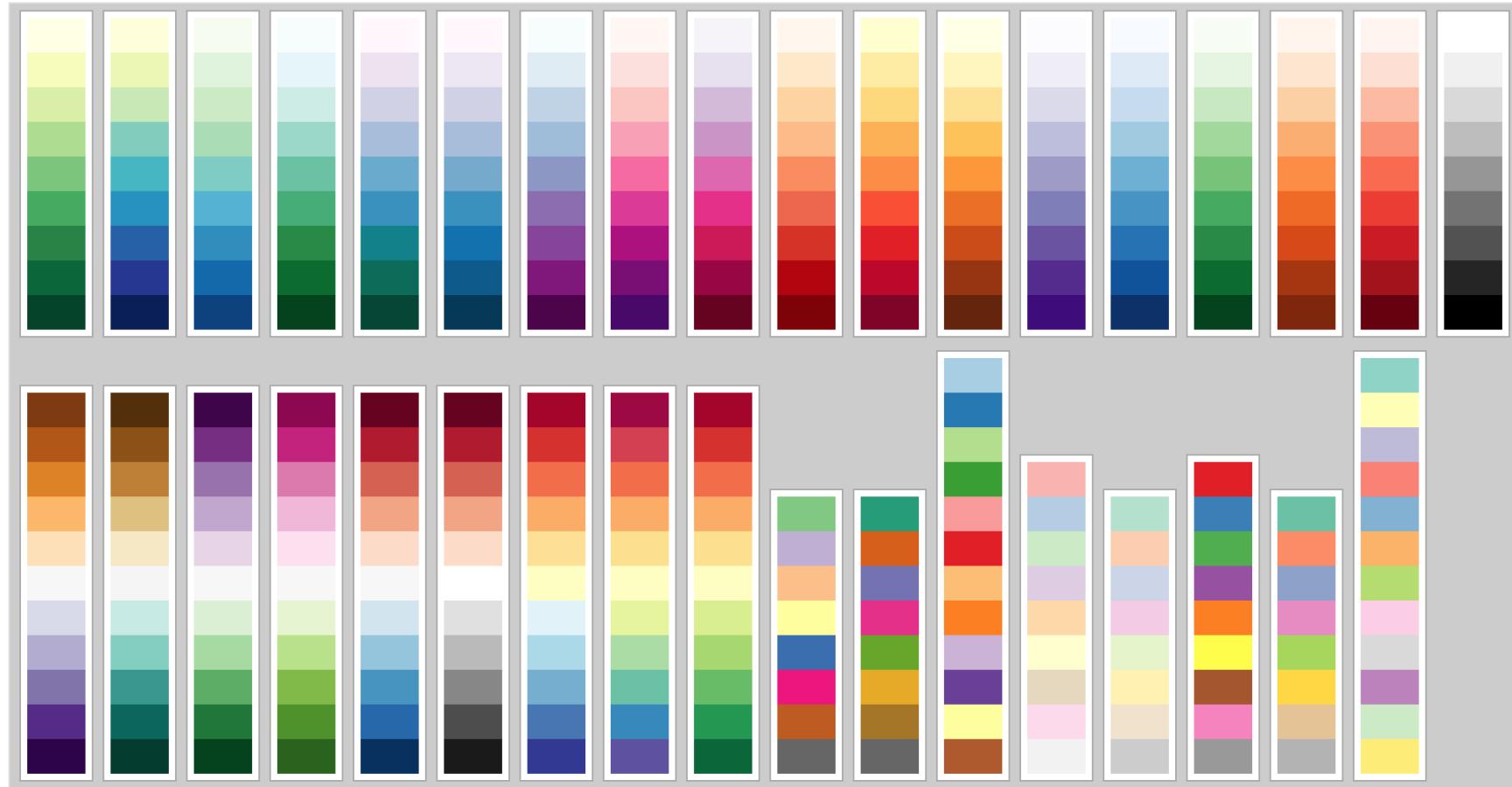


(RGB)



(Hex)

Every ColorBrewer Scale



For CSS and JavaScript (by Mike Bostock)
<http://bl.ocks.org/mbostock/5577023>

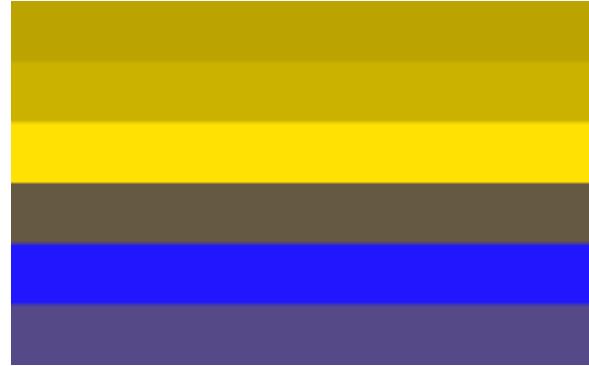
7% of the viewers may not see anything if you use red-green,

ONE WARNING ABOUT RED-GREEN

Color Vision Deficiency



normal color vision

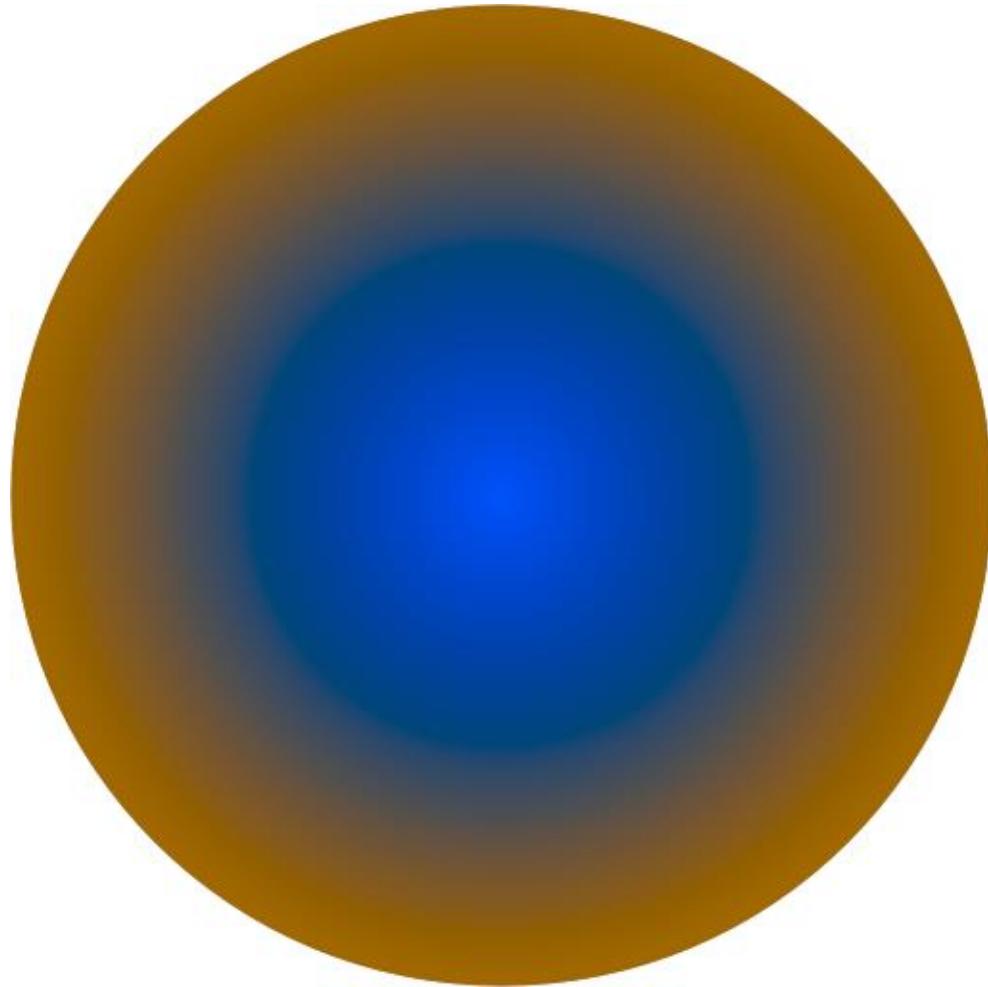


**simulation of color contrast
for deutanopic color vision**
(green receptors absent)

approx. 7% of male population color-deficient

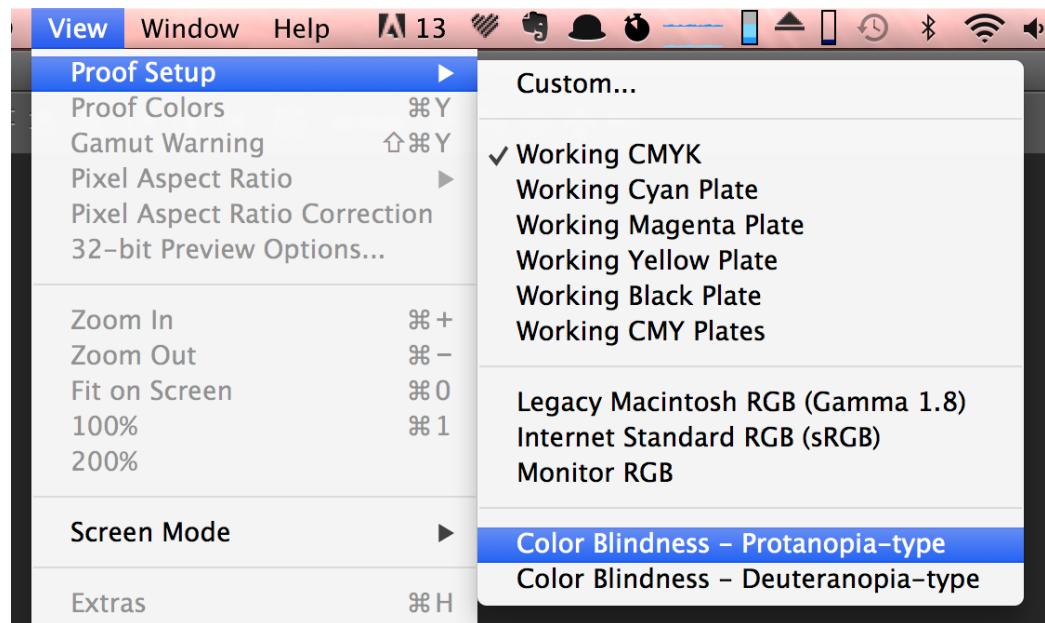
mostly red-green color deficiency (deutanopia or protanopia) – but other forms exist as well

Better: Red-Blue Contrast



Check Your Visualizations!

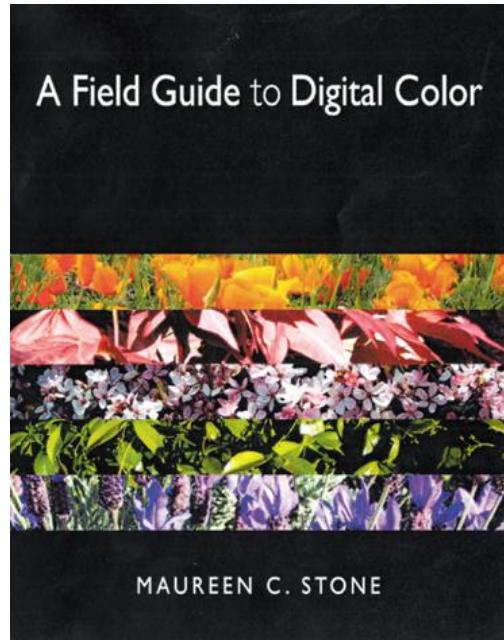
When possible, avoid red-green color contrasts for visualization purposes.



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>

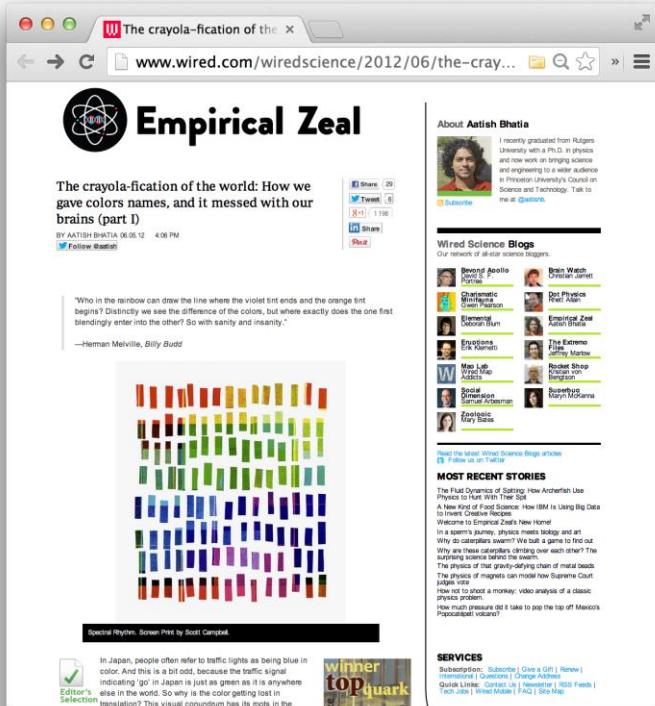
Community Palette Sharing
<http://www.colourlovers.com>
<http://kuler.adobe.com>
<https://colors.co/palettes/trending>
<https://paletton.com>

(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/>

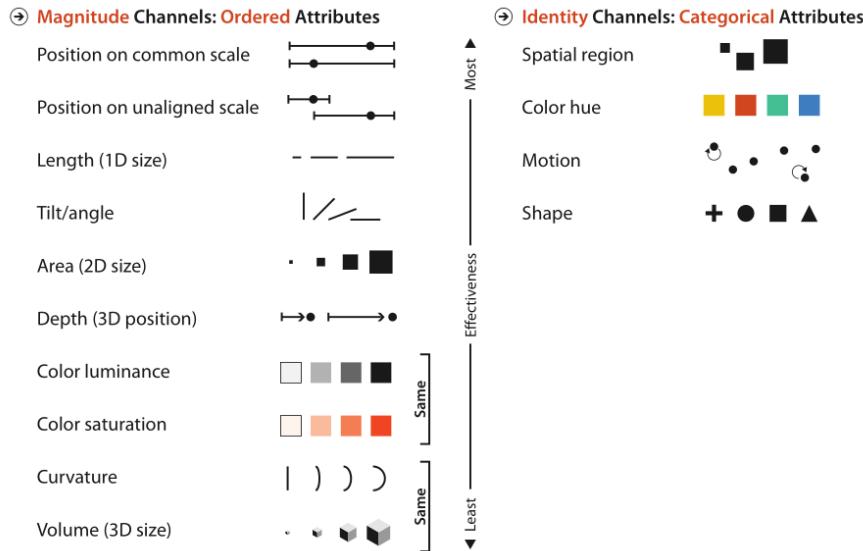


RadioLab “Colors” WNYC Podcast

<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)

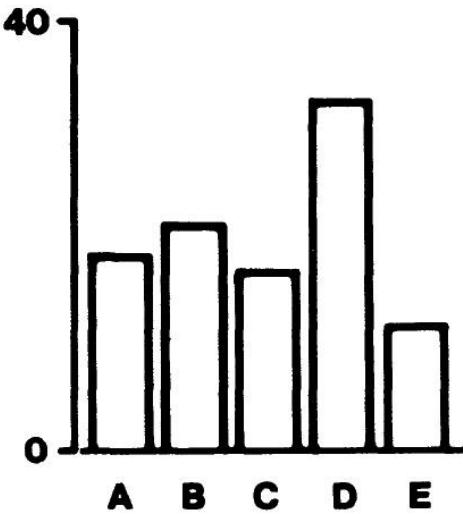
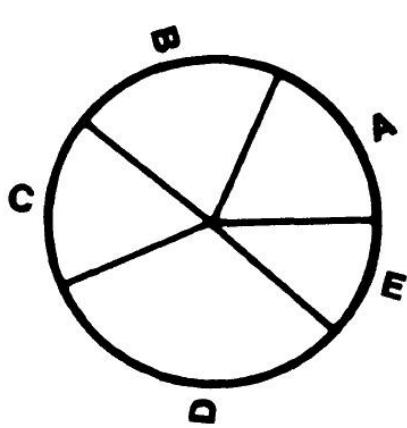


Figure 3. Graphs from position–angle experiment.

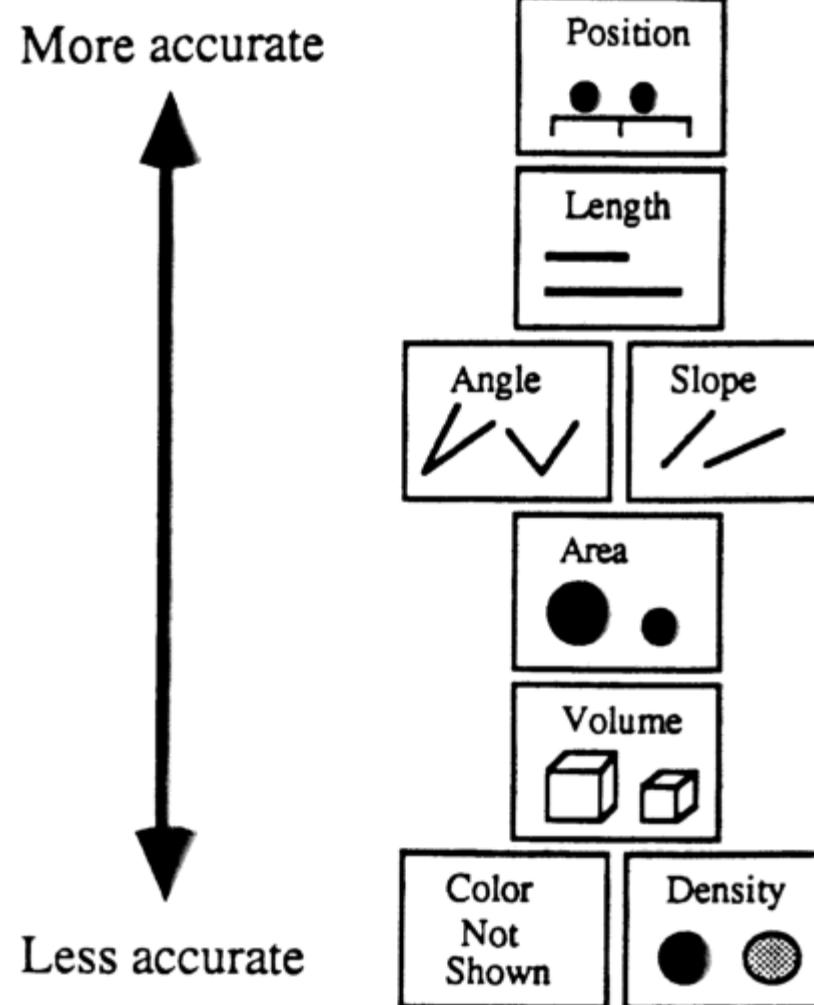
Performed **controlled experiments** to determine how effectively people could judge **changes in visual features**

Focus on **quantitative information**

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

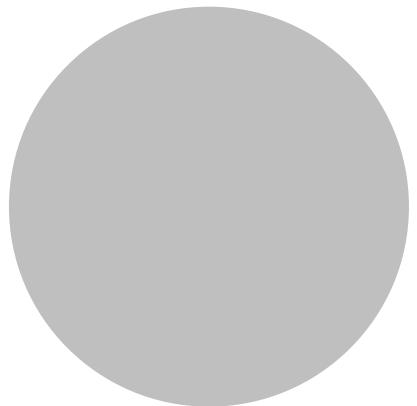
Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

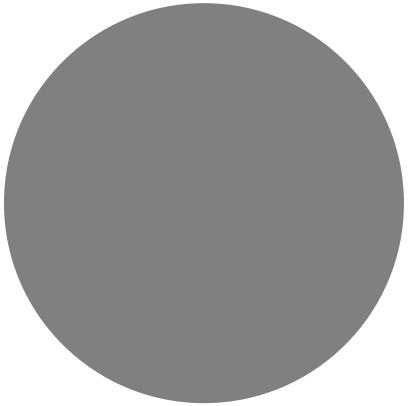


Color Value

What percentage in value is the right from the left?



100%

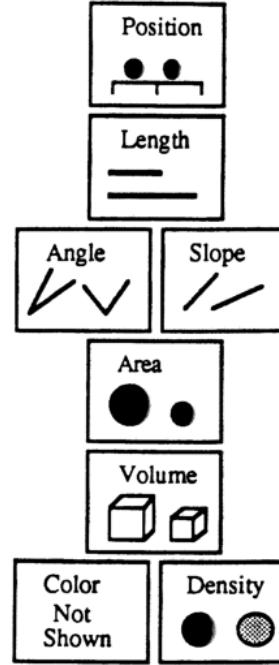


66%

More accurate

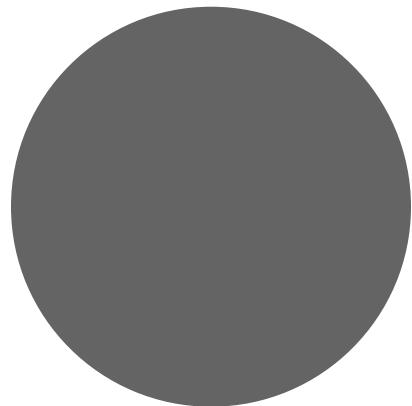


Less accurate

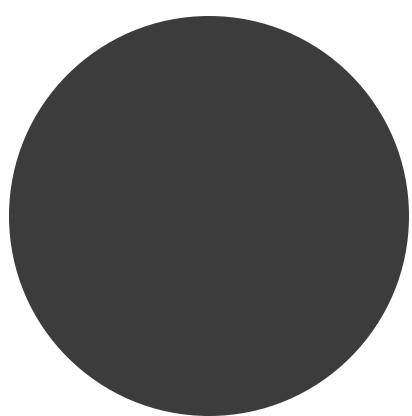


Color Value

What percentage in value is the right from the left?



100%

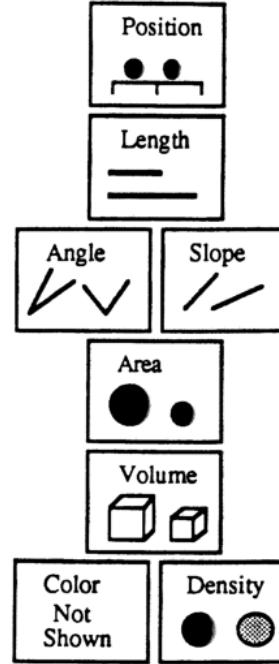


60%

More accurate

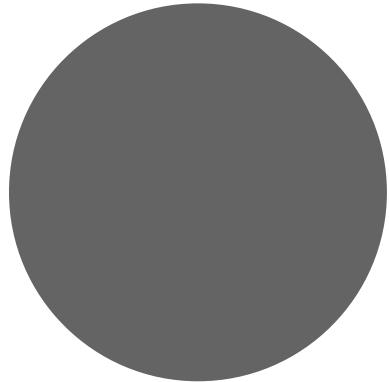


Less accurate

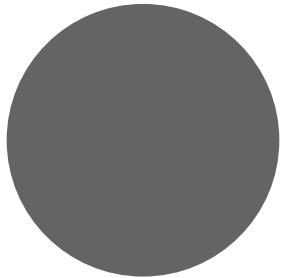


Area

What percentage in size is the right from the left?



100%

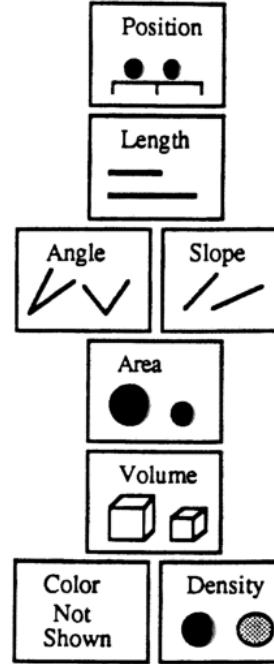


52%

More accurate

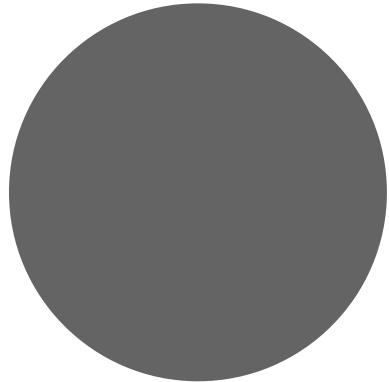


Less accurate

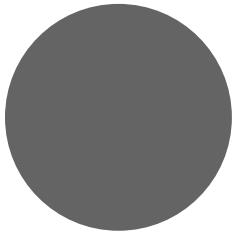


Area

What percentage in size is the right from the left?



100%

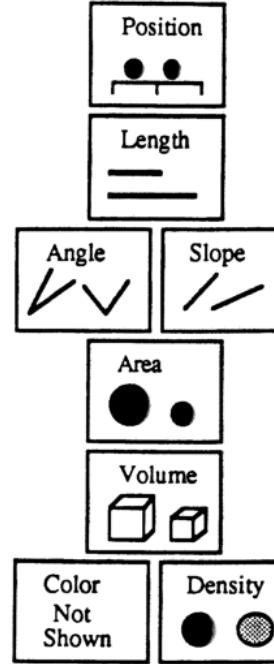


36%

More accurate

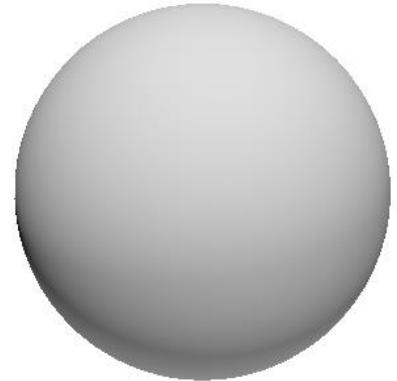


Less accurate

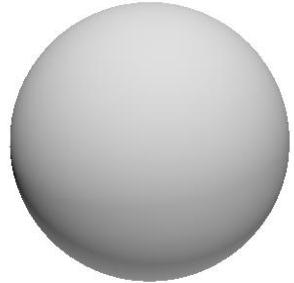


Volume

What percentage in size is the right from the left?



100%

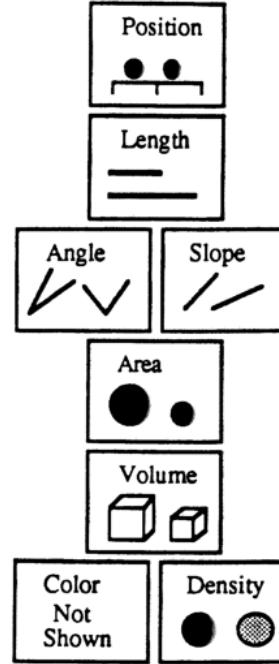


40%

More accurate



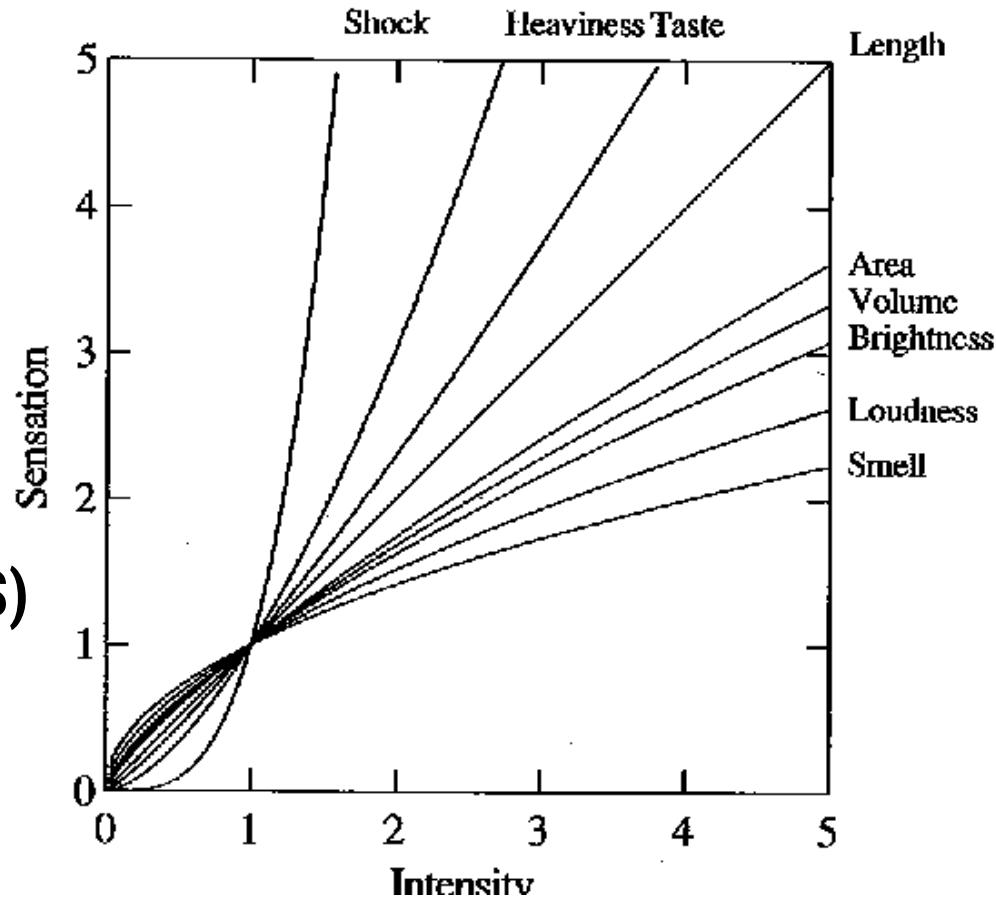
Less accurate



Why are people so bad at this?

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

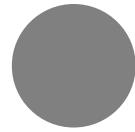
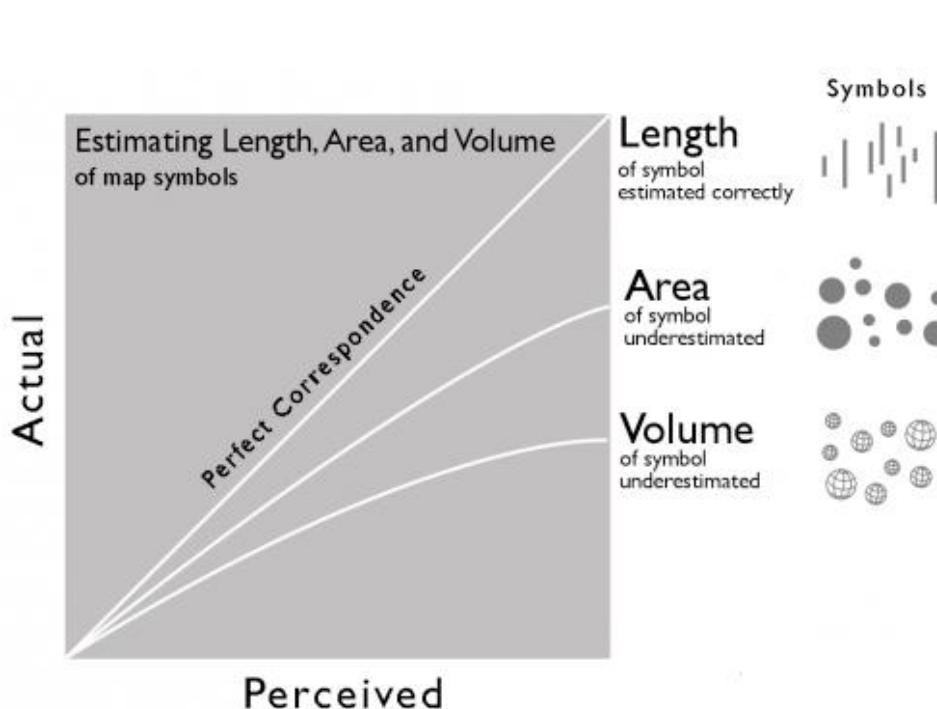
Stevens' power law describes a relationship between a physical stimulus (S) and its perceived intensity or strength (P)



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!**

Volum

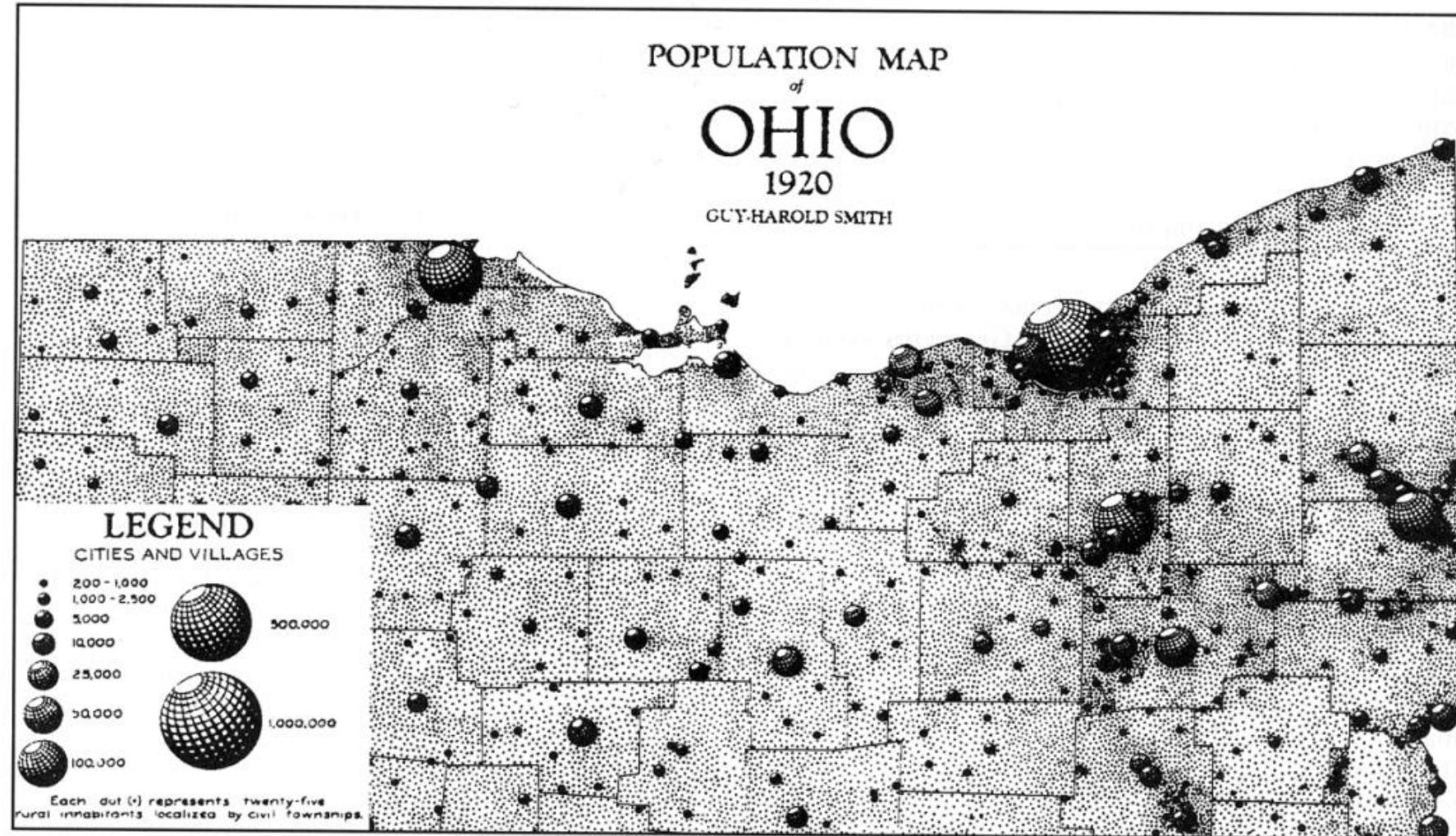
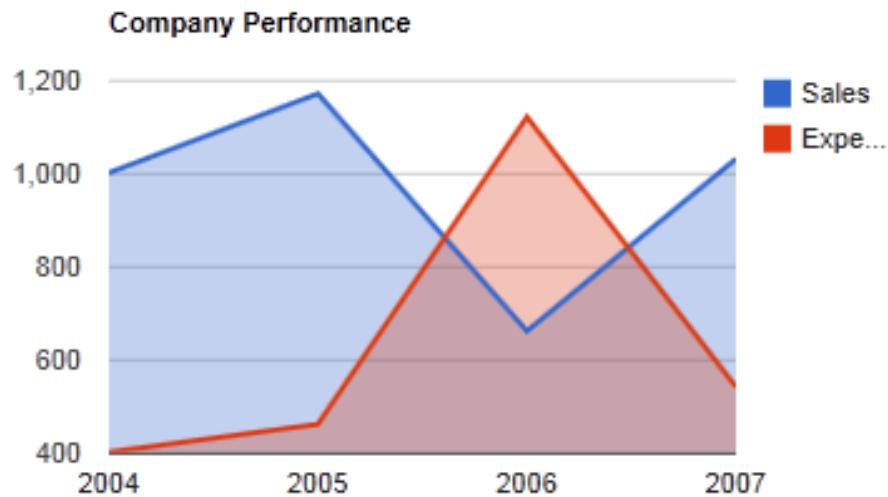


FIGURE 7.4. An eye-catching map created using three-dimensional geometric symbols. (After Smith, 1928. First published in *The Geographical Review*, 18(3), plate 4. Reprinted with permission of the American Geographical Society.)

Area

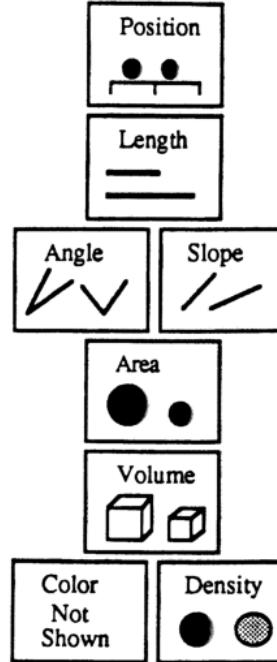
- What percentage in size is the red from the blue (=100%)?



More accurate



Less accurate



no idea – this is very difficult

Length

What percentage in length is the right from the left?

100%

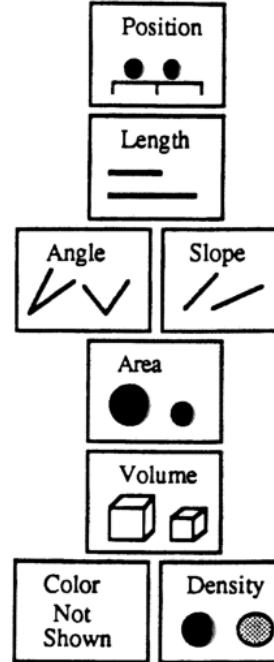


75%

More accurate



Less accurate



Length / Position

What percentage in length is the right from the left?

100%

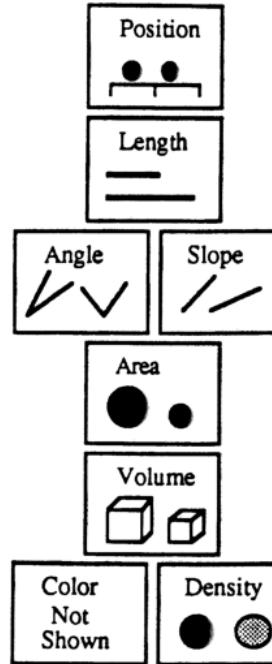


25%

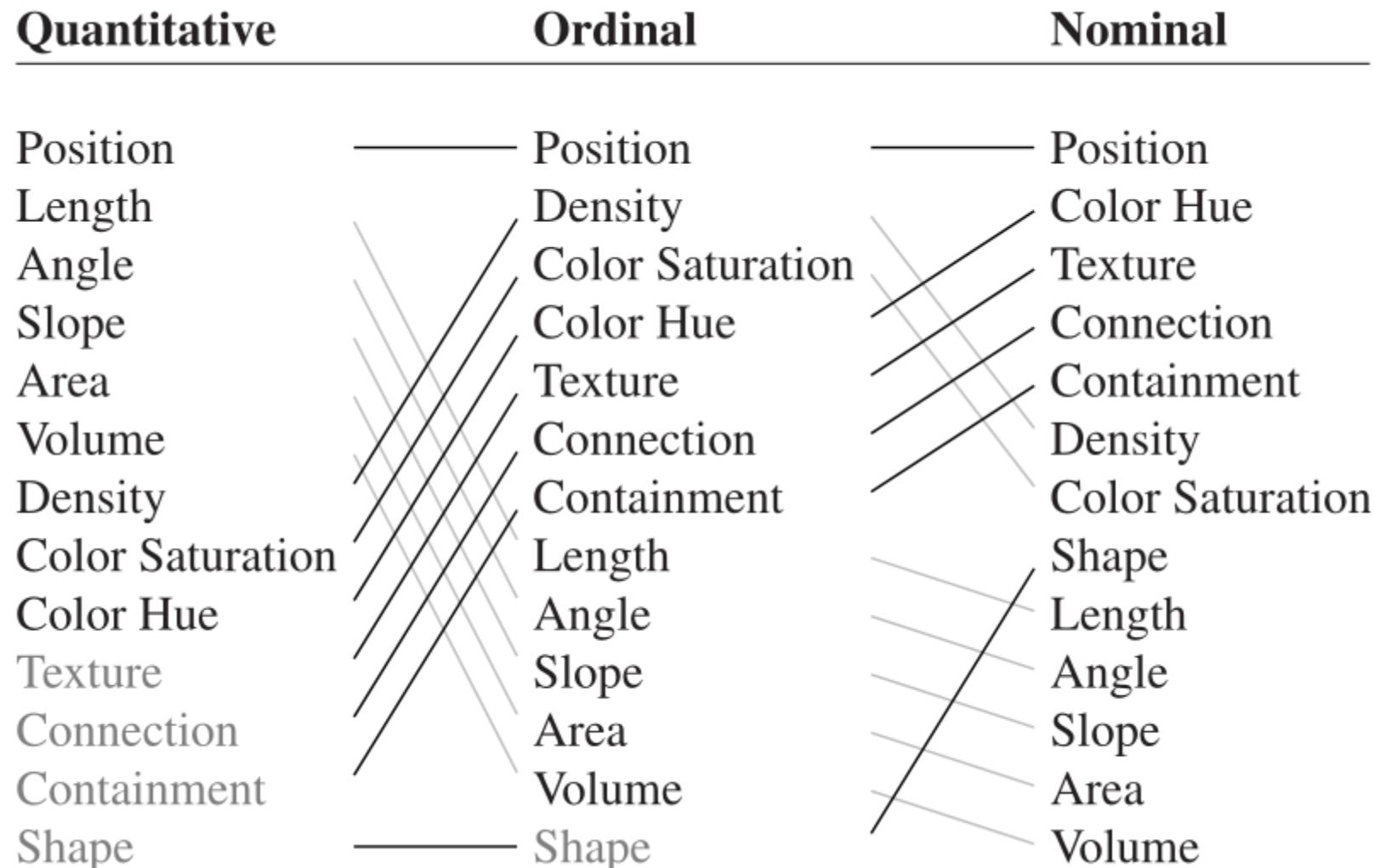
More accurate



Less accurate



Effectiveness of Data Encodings (Conjecture)

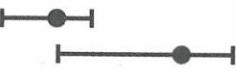


⇒ **Magnitude Channels: Ordered Attributes**

Position on common scale



Position on unaligned scale



Length (1D size)



Tilt/angle



Area (2D size)



Depth (3D position)



Color luminance



Same

Color saturation



Same

Curvature



Same

Volume (3D size)



⇒ **Identity Channels: Categorical Attributes**

Spatial region



Color hue



Motion



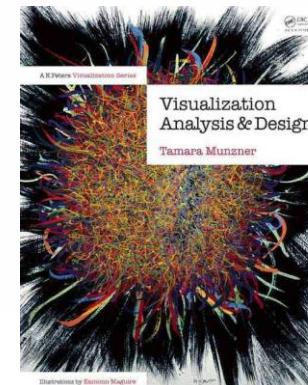
Shape



Most

Effectiveness

Least



a distinct item stands out from many others immediately

2) POPOUT

How many 3's do you see?

1281768756138976546984506985604982826762
9809858458224509856458945098450980943585
90910302099059595772564675050678904567
8845789809821677654876364908560912949686

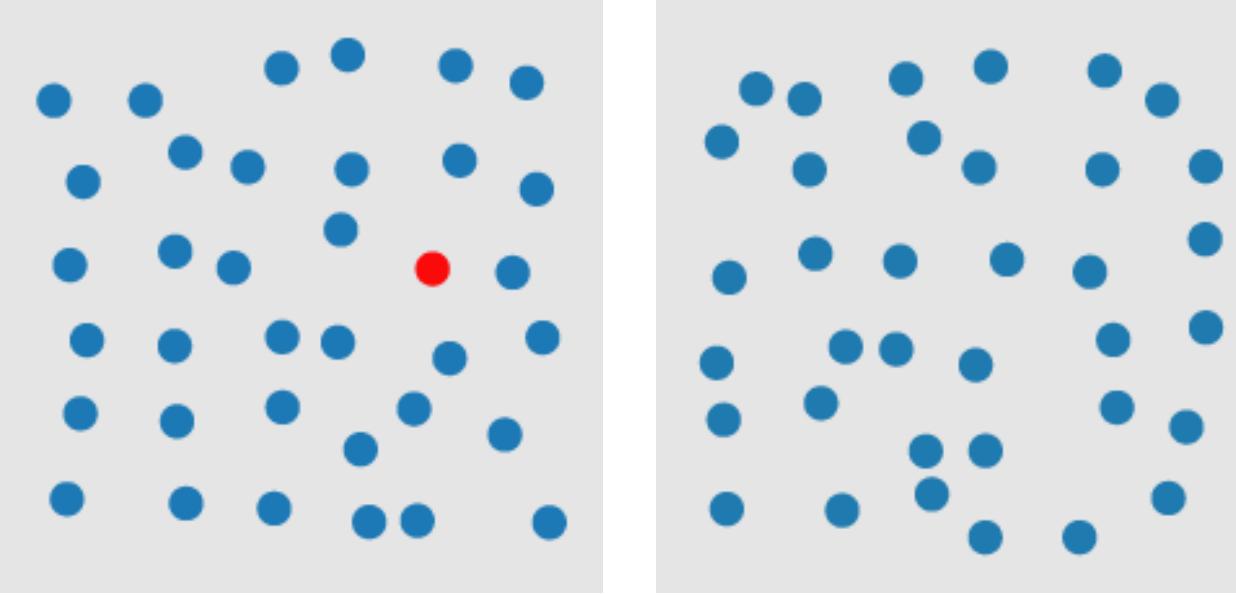
How about now?

12817687561**3**8976546984506985604982826762
980985845822450985645894509845098094**3**585
90910**3**02099059595772564675050678904567
8845789809821677654876**3**64908560912949686

Visual encodings influence popout

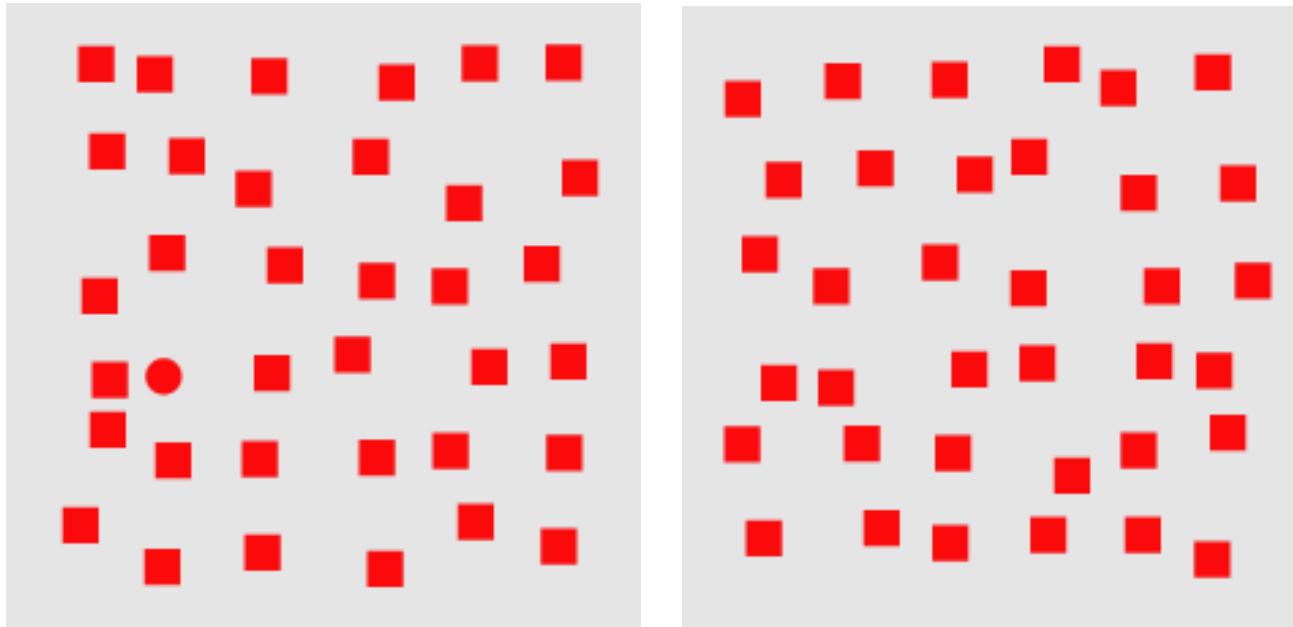
**DETERMINE IF A RED CIRCLE
IS PRESENT**

Hue



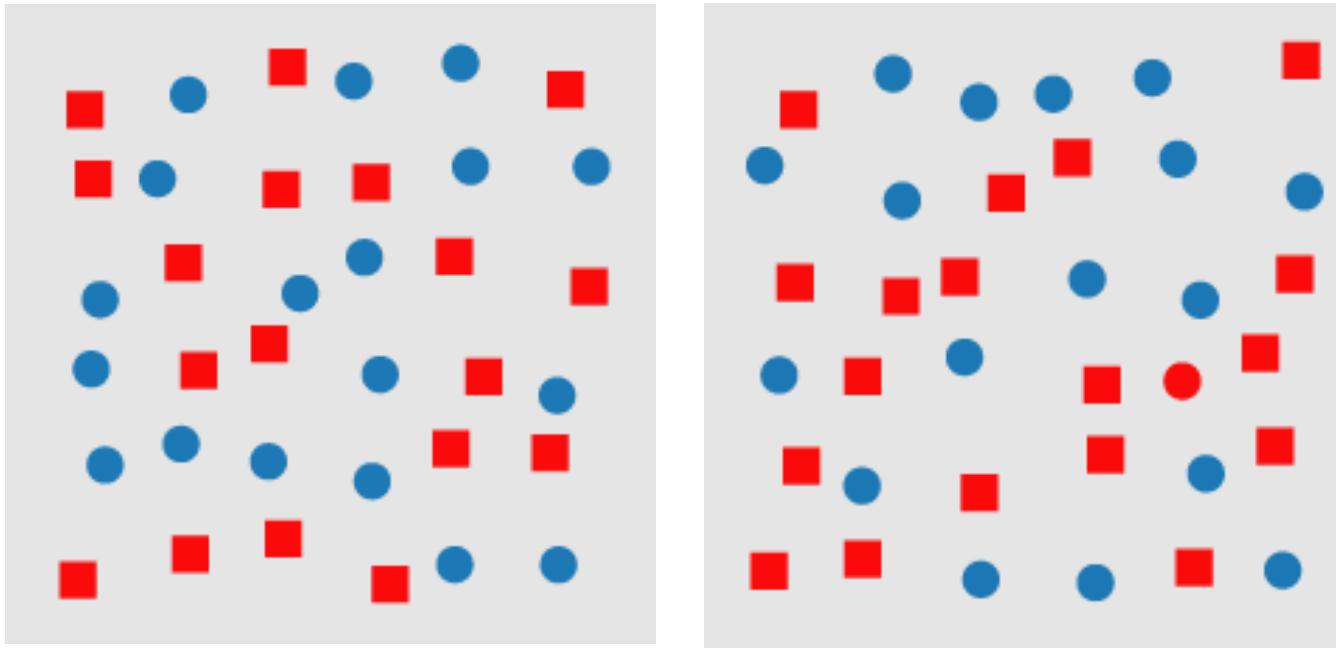
Hue pops out, no matter if we have 15 or 50 blue circles

Shape



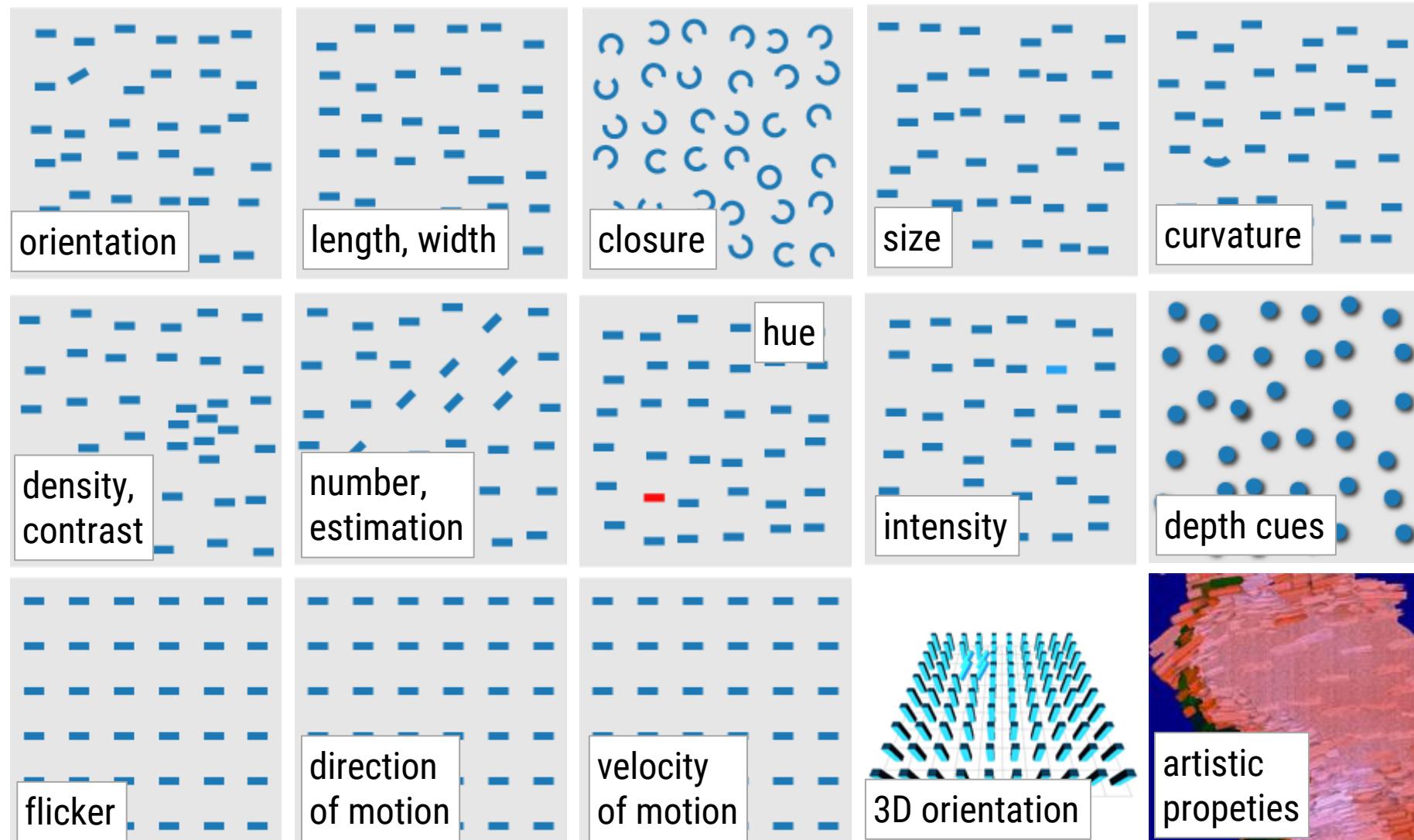
Yes, can be done quickly but a bit more slowly than before

Hue and Shape

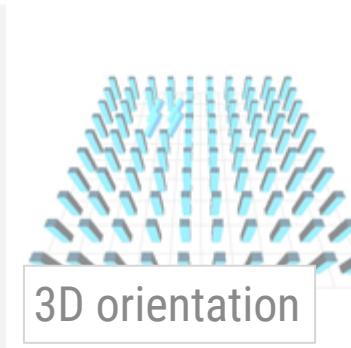
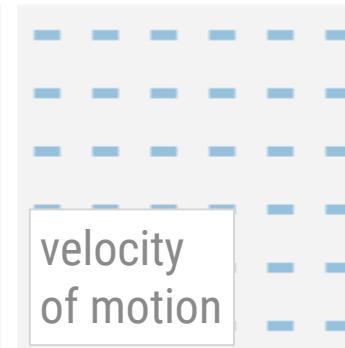
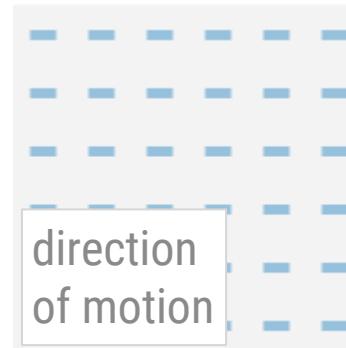
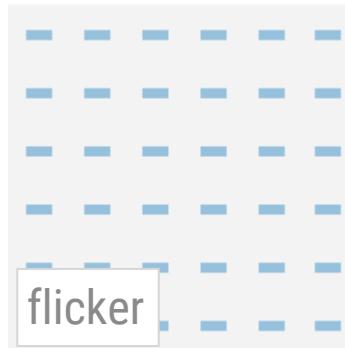
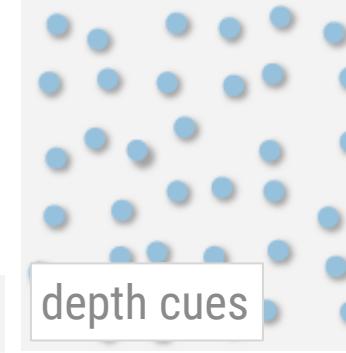
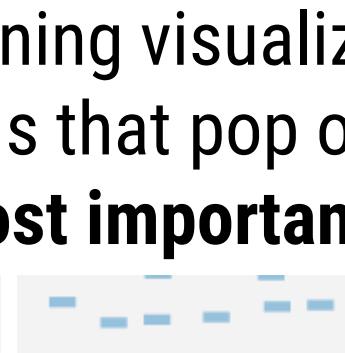
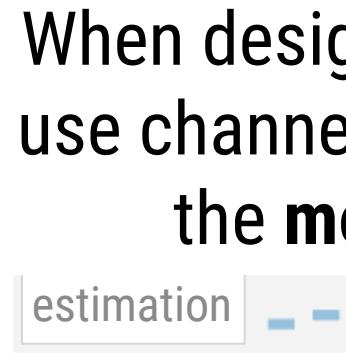
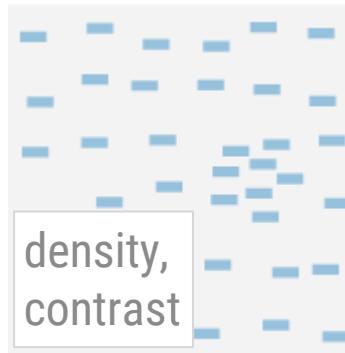
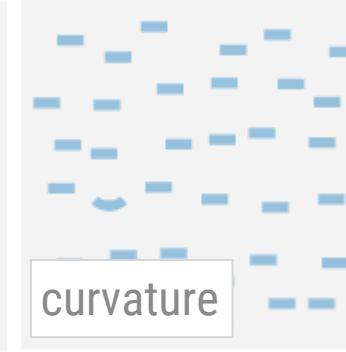
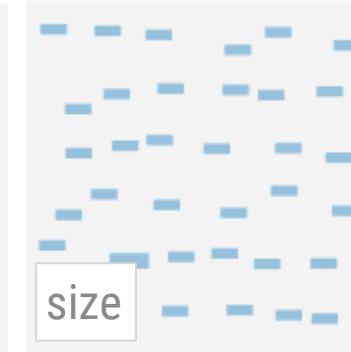
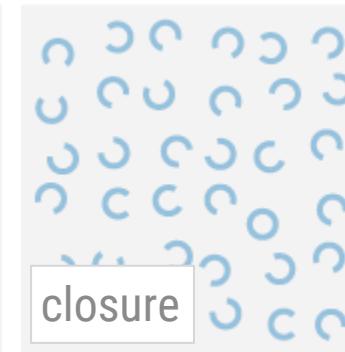
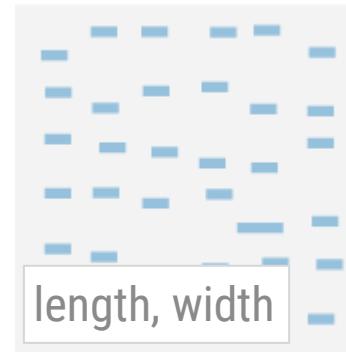
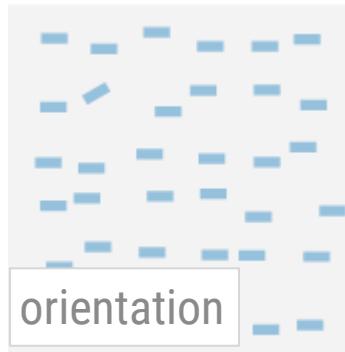


Cannot be done quickly due to the
conjunction of shape and hue
→ need to search

Channels that support popout (some)



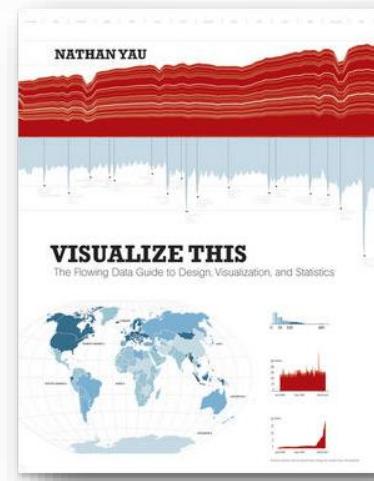
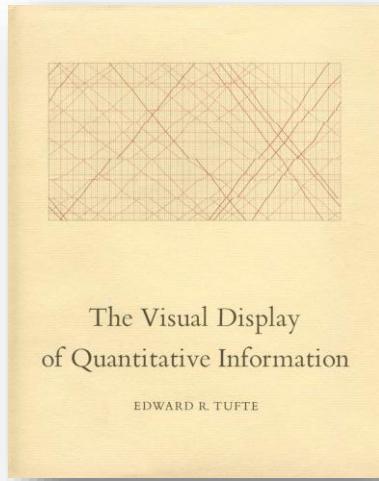
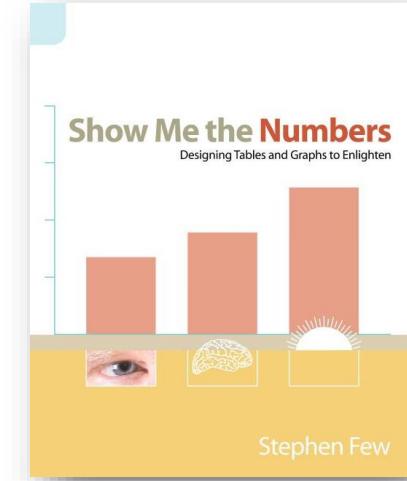
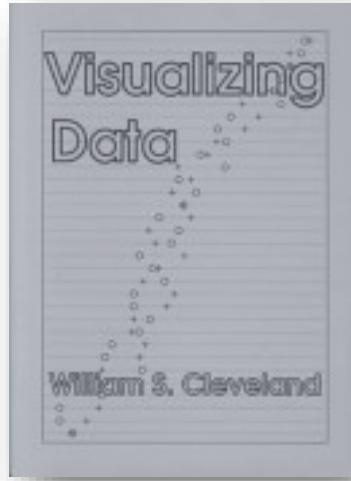
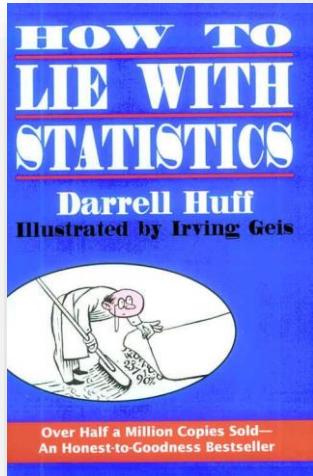
Channels that support popout (some)



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

- 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...

