
Calvin and Hobbes
by WATTERSON
WOW, HONEY, YOU'RE MISSING A BEAUTIFUL SUNSET OUT HERE!
I'LL COUNT TO 10, AND THEN... POW!
DAD, HOW COME OLD PHOTOGRAPHS ARE ALWAYS BLACK AND WHITE? DIDN'T THEY HAVE COLOR FILM BACK THEN?
SURE THEY DID. IN FACT, THOSE OLD PHOTOGRAPHS ARE IN COLOR. IT'S JUST THE WORLD WAS BLACK AND WHITE THEN.
REALLY?
YEP. THE WORLD DIDN'T TURN COLOR UNTIL SOMETIME IN THE 1930s, AND IT WAS PRETTY GRAINY COLOR FOR A WHILE, TOO.
THAT'S REALLY WEIRD.
WELL, TRUTH IS STRANGER THAN FICTION.
BUT THEN WHY ARE OLD PAINTINGS IN COLOR?! IF THE WORLD WAS BLACK AND WHITE, WOULDN'T ARTISTS HAVE PAINTED IT THAT WAY?
NOT NECESSARILY. A LOT OF GREAT ARTISTS WERE INSANE.
BUT... BUT HOW COULD THEY HAVE PAINTED IN COLOR ANYWAY? WOULDN'T THEIR PAINTS HAVE BEEN SHADES OF GRAY BACK THEN?
OF COURSE, BUT THEY TURNED COLORS LIKE EVERYTHING ELSE DID IN THE '30s.
SO WHY DIDN'T OLD BLACK AND WHITE PHOTOS TURN COLOR TOO?
BECAUSE THEY WERE COLOR PICTURES OF BLACK AND WHITE, REMEMBER?
THE WORLD IS A COMPLICATED PLACE, HOBBES.
WHENEVER IT SEEMS THAT WAY, I TAKE A NAP IN A TREE AND WAIT FOR DINNER.
10-29

CSC 544
Data Visualization

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Lecture 09
Color

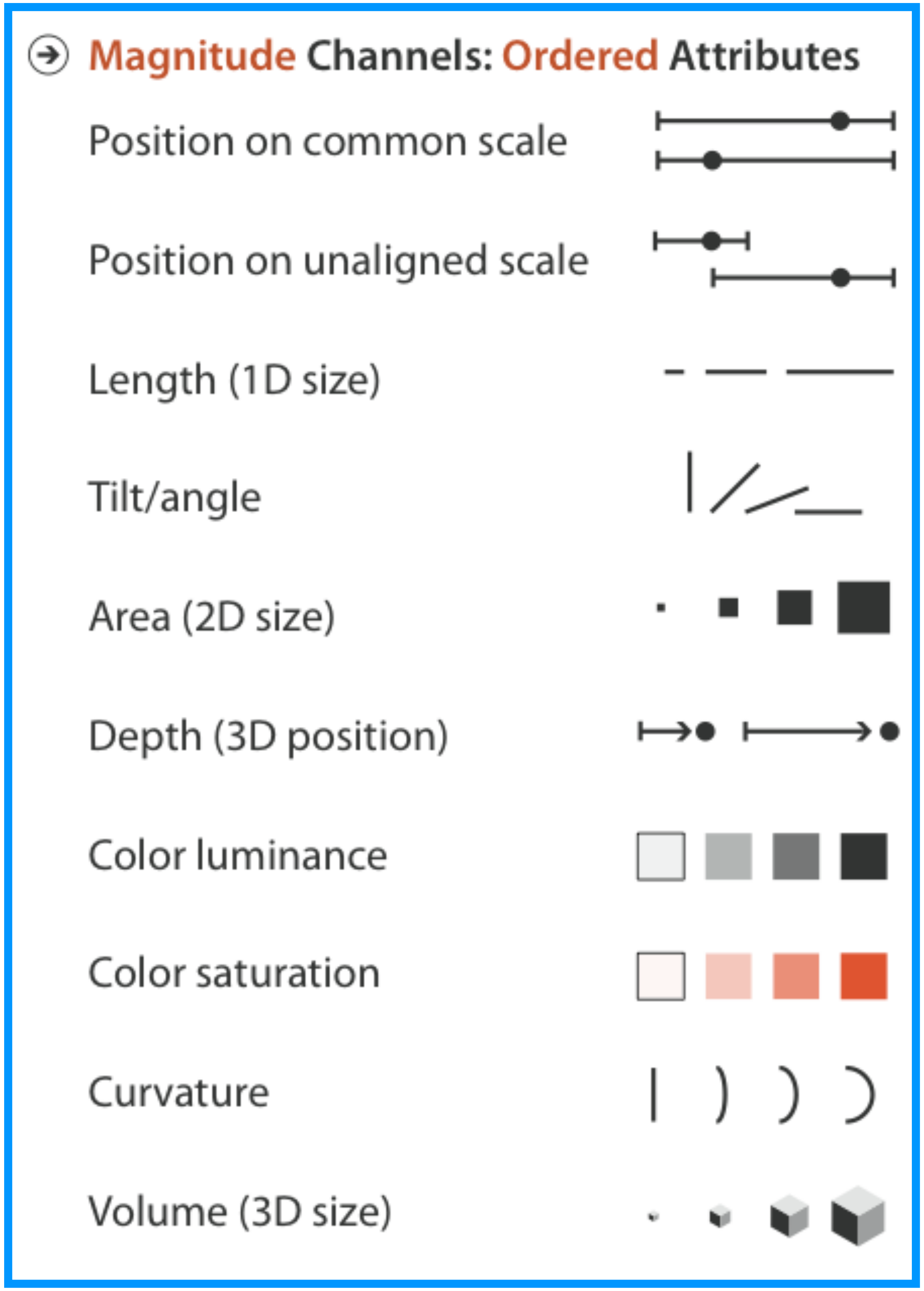
Feb. 13, 2023

Today’s Agenda

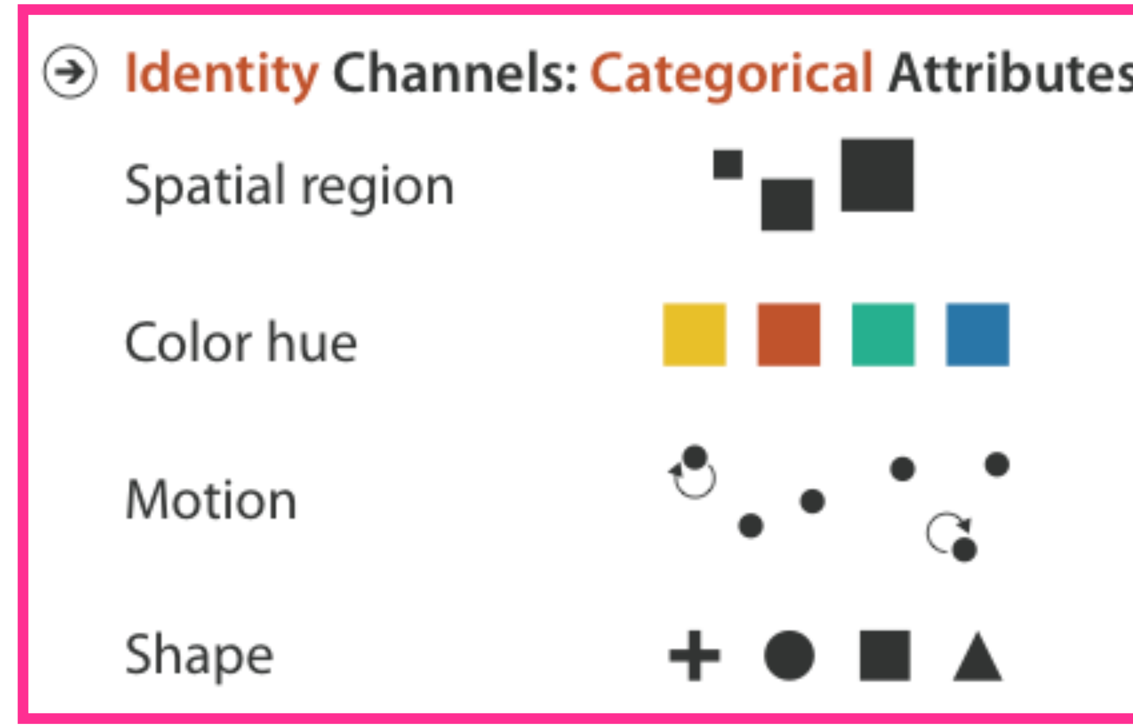
- Reminders:
    - A01 Graded
    - P01, A02 questions?
- Goals for today: discuss color

Recall from Last Time

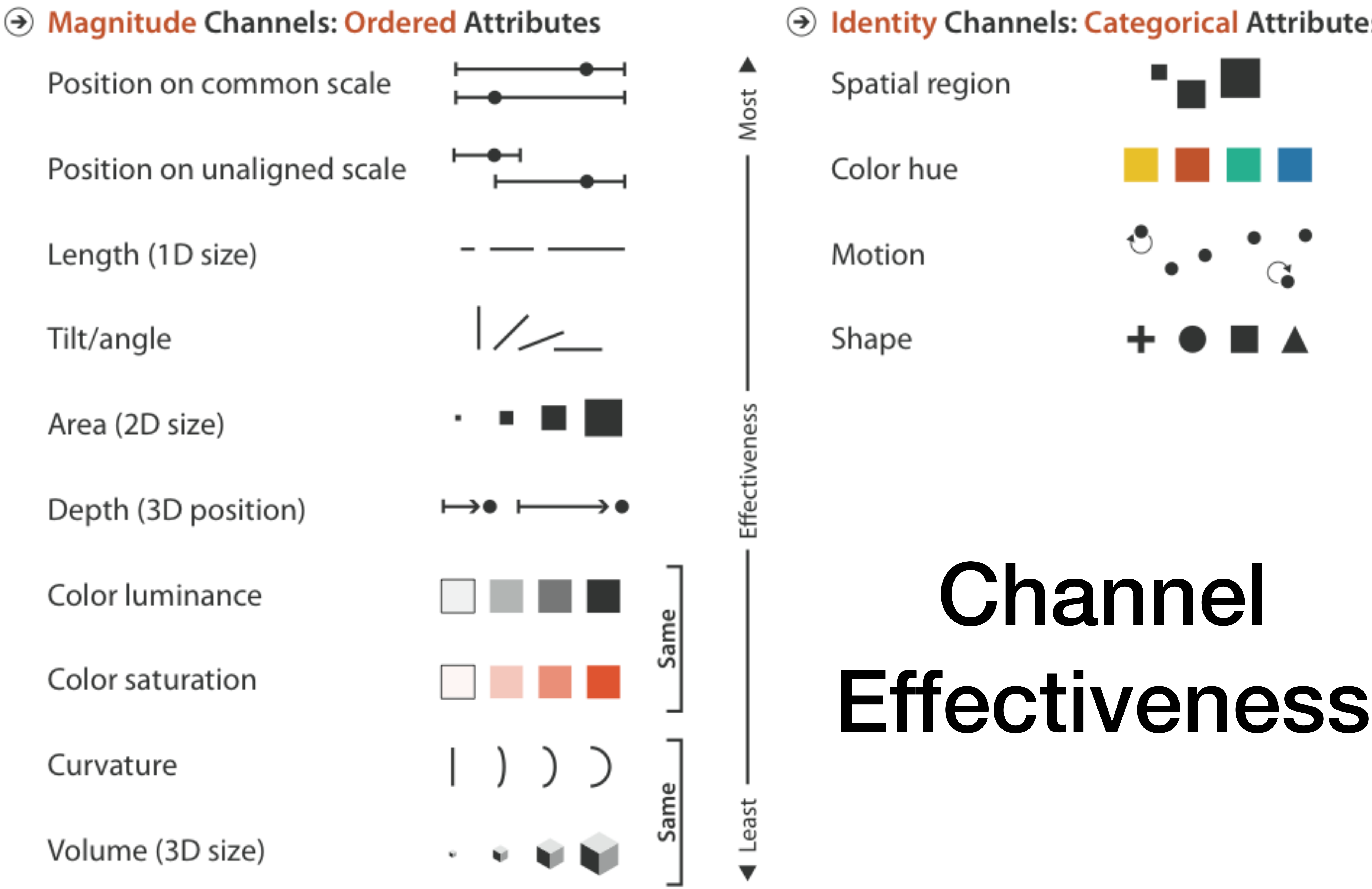
(how much)



(what or where)



Channel Expressiveness

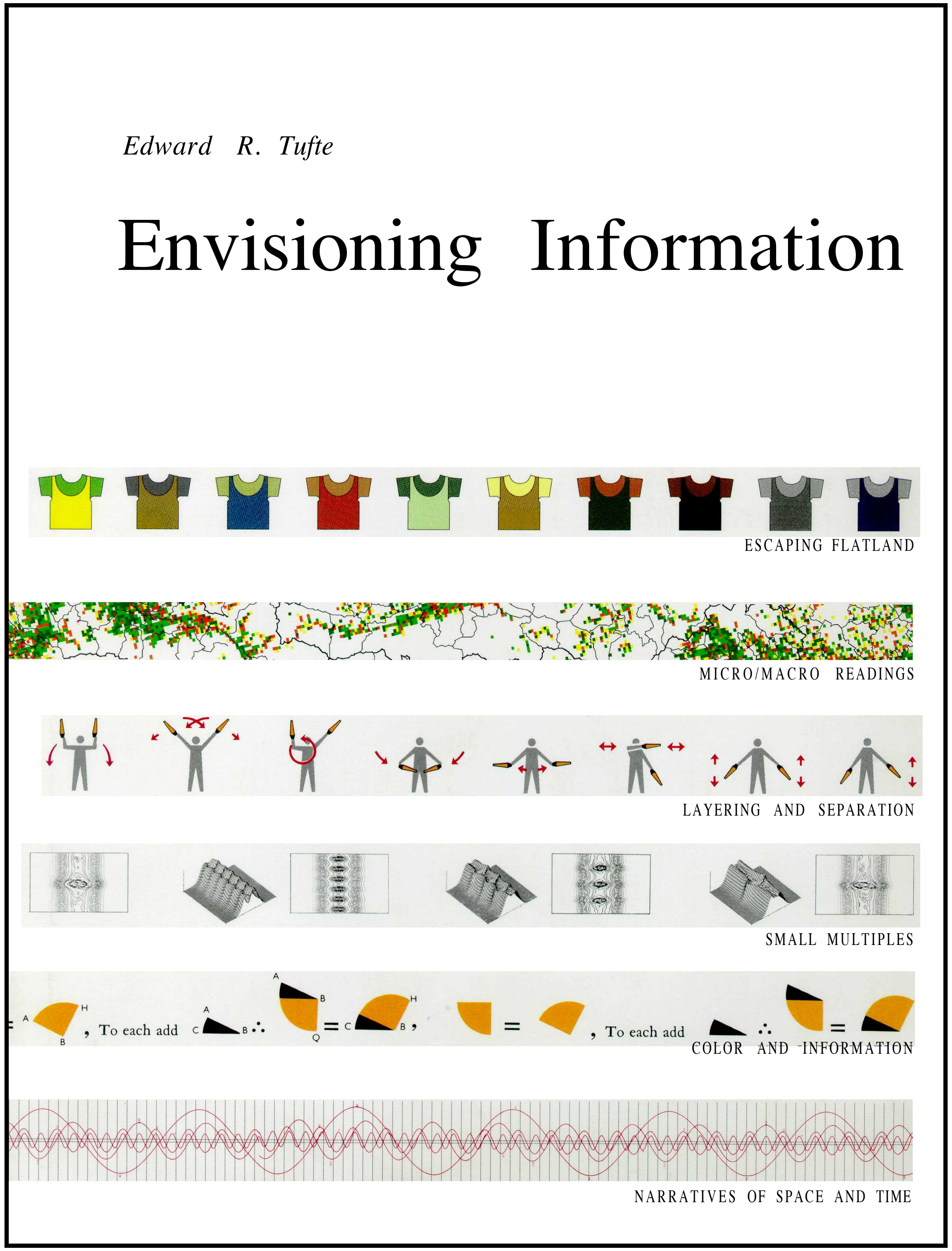


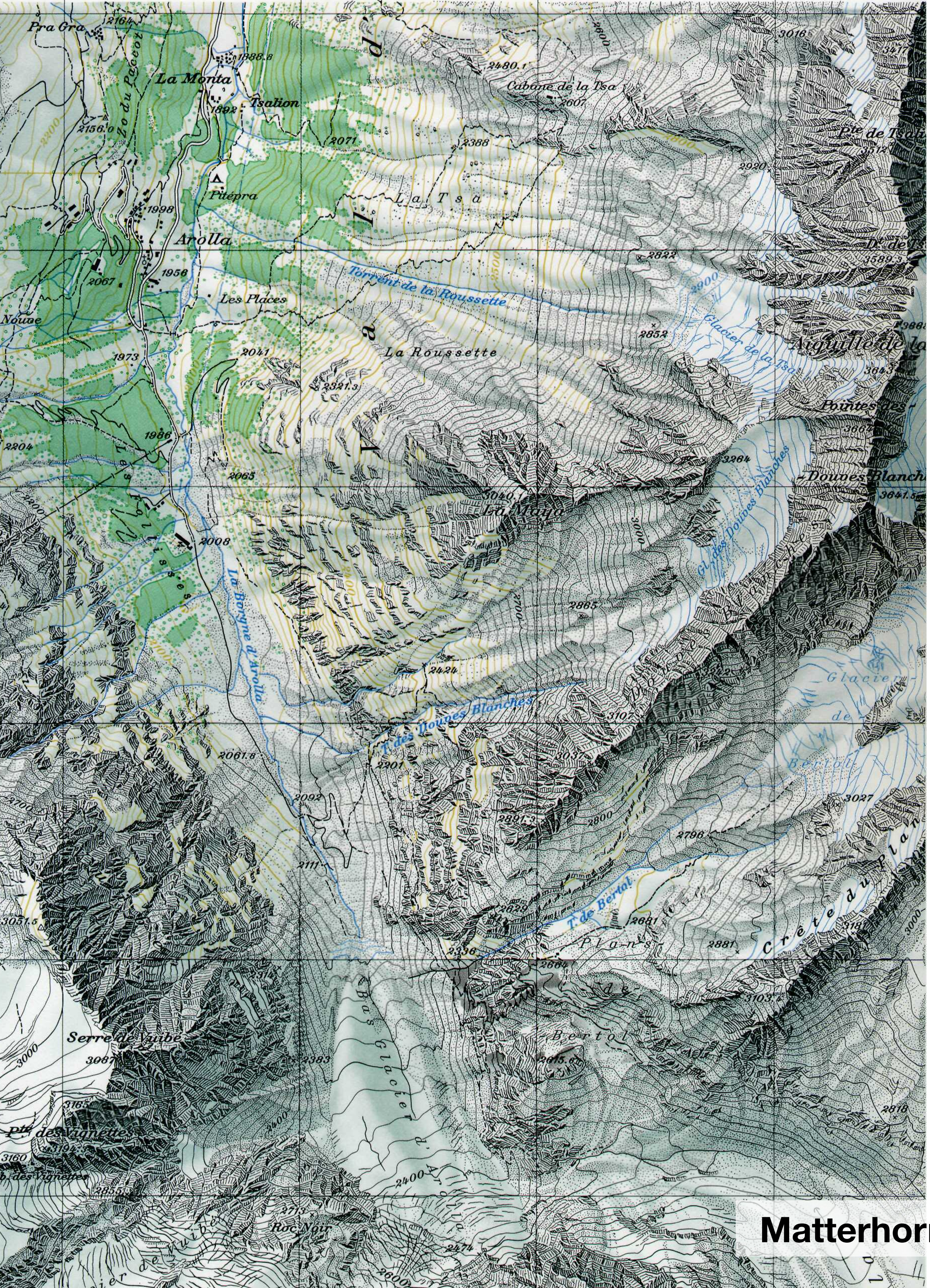
Channel Effectiveness

Why Use Color?

Tufte

Tying color to information is as elementary and straightforward as color technique in art, “To paint well is simply this: to put the right color in the right place,” in Paul Klee’s ironic prescription. The often scant benefits derived from coloring data indicate that even putting a good color in a good place is a complex matter. Indeed, so difficult and subtle that **avoiding catastrophe becomes the first principle in bringing color to information: Above all, do no harm.**





Matterhorn, Landeskarte der Schweiz (Wabern, 1983)

Purposes of Color

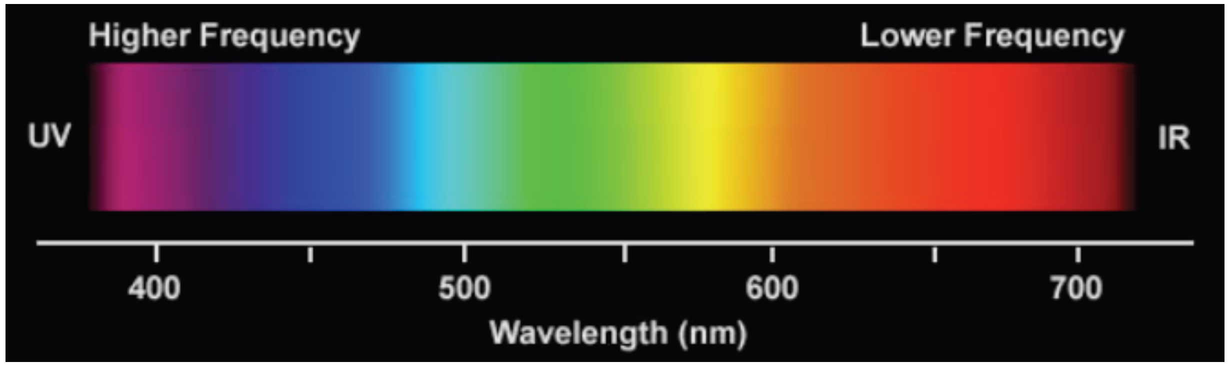
- To label (color as a noun)
- To measure (color as a quantity)
- To represent and imitate (color as a symbol)
- To enliven and decorate (color as beauty)

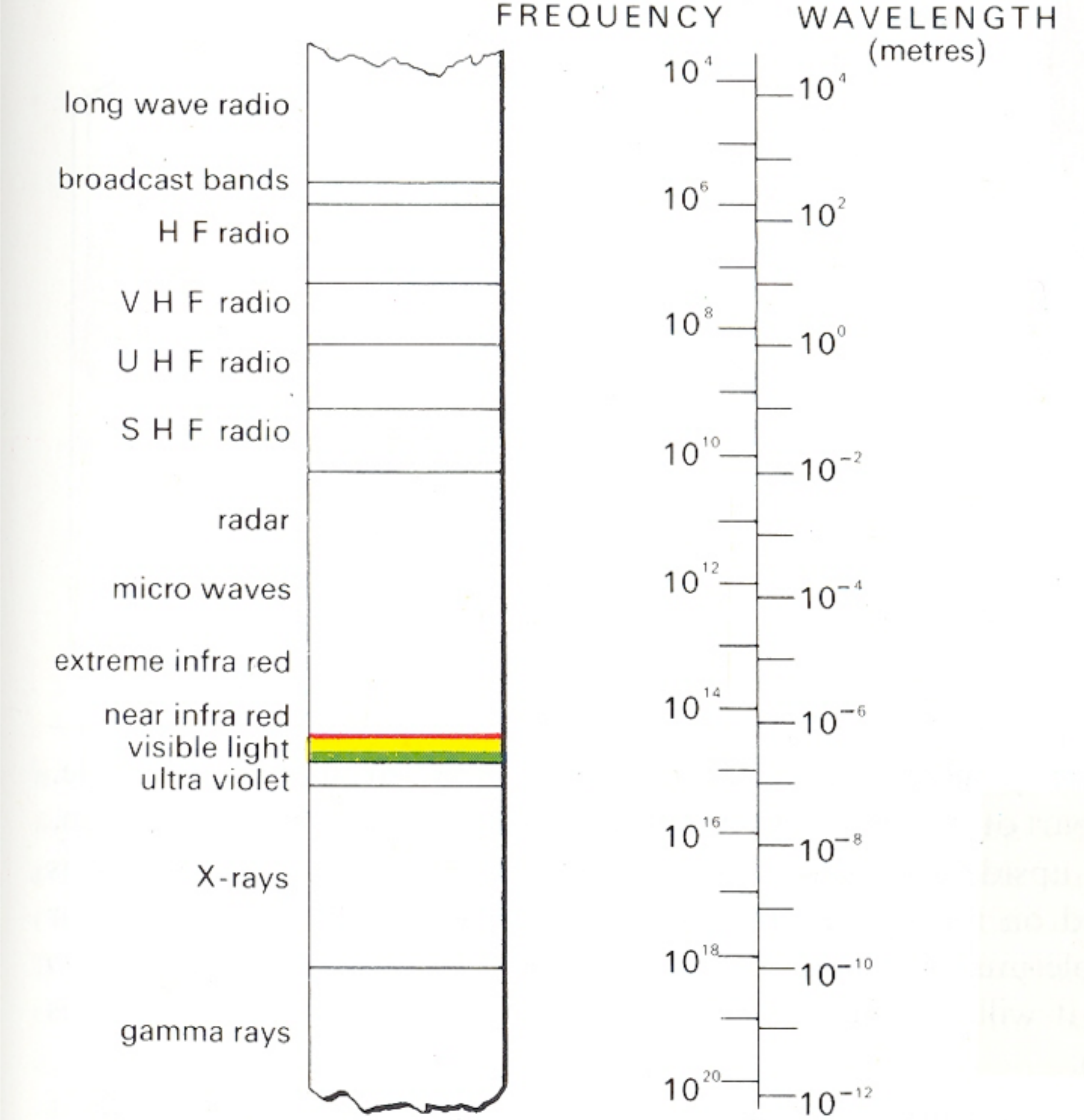
What is Color?

(A Brief Introduction to the Physics of Light)

Light is Electromagnetic Radiation

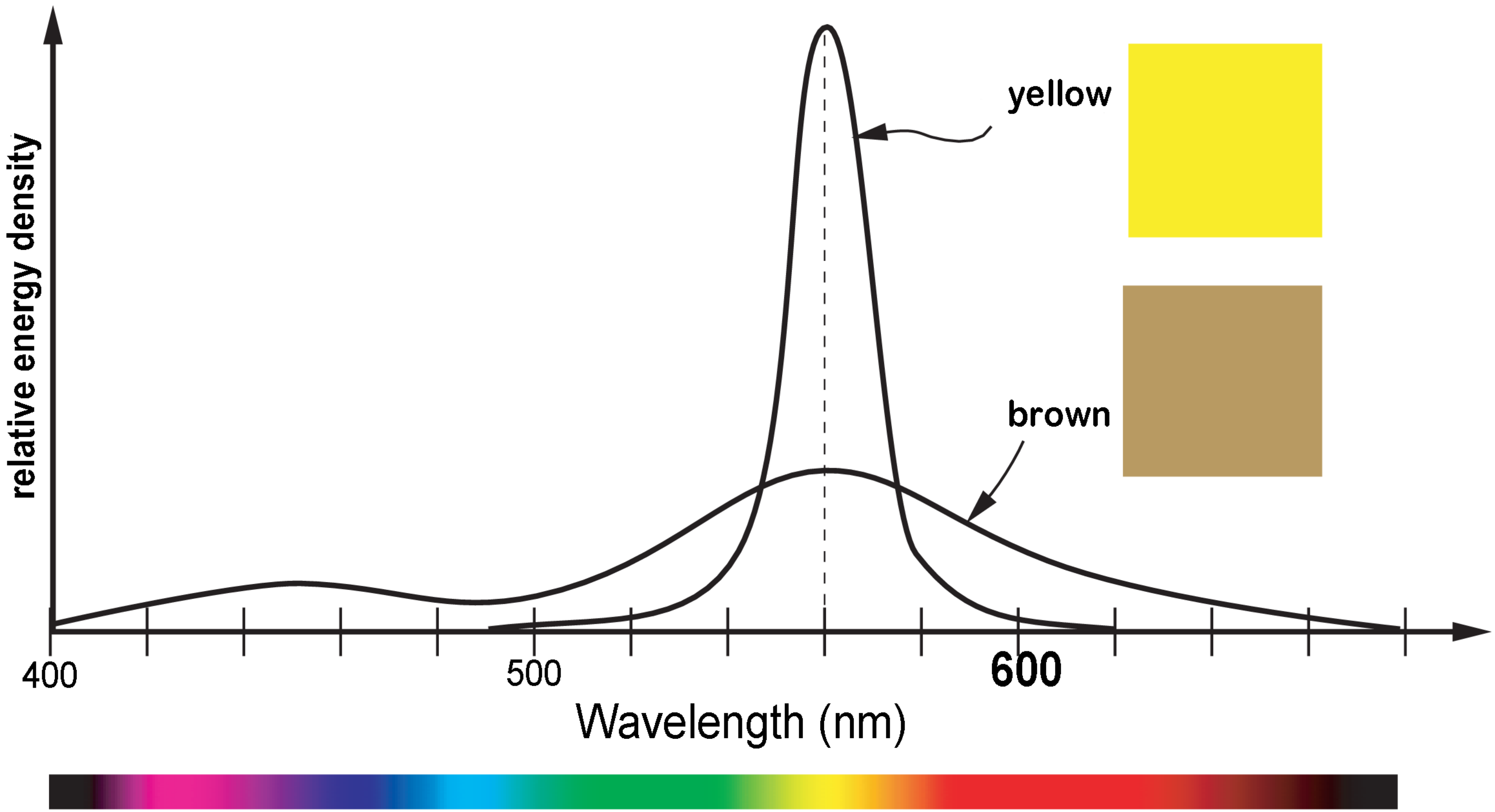
- Visible spectrum is “tiny”
- Wavelength range: 380-740 nm



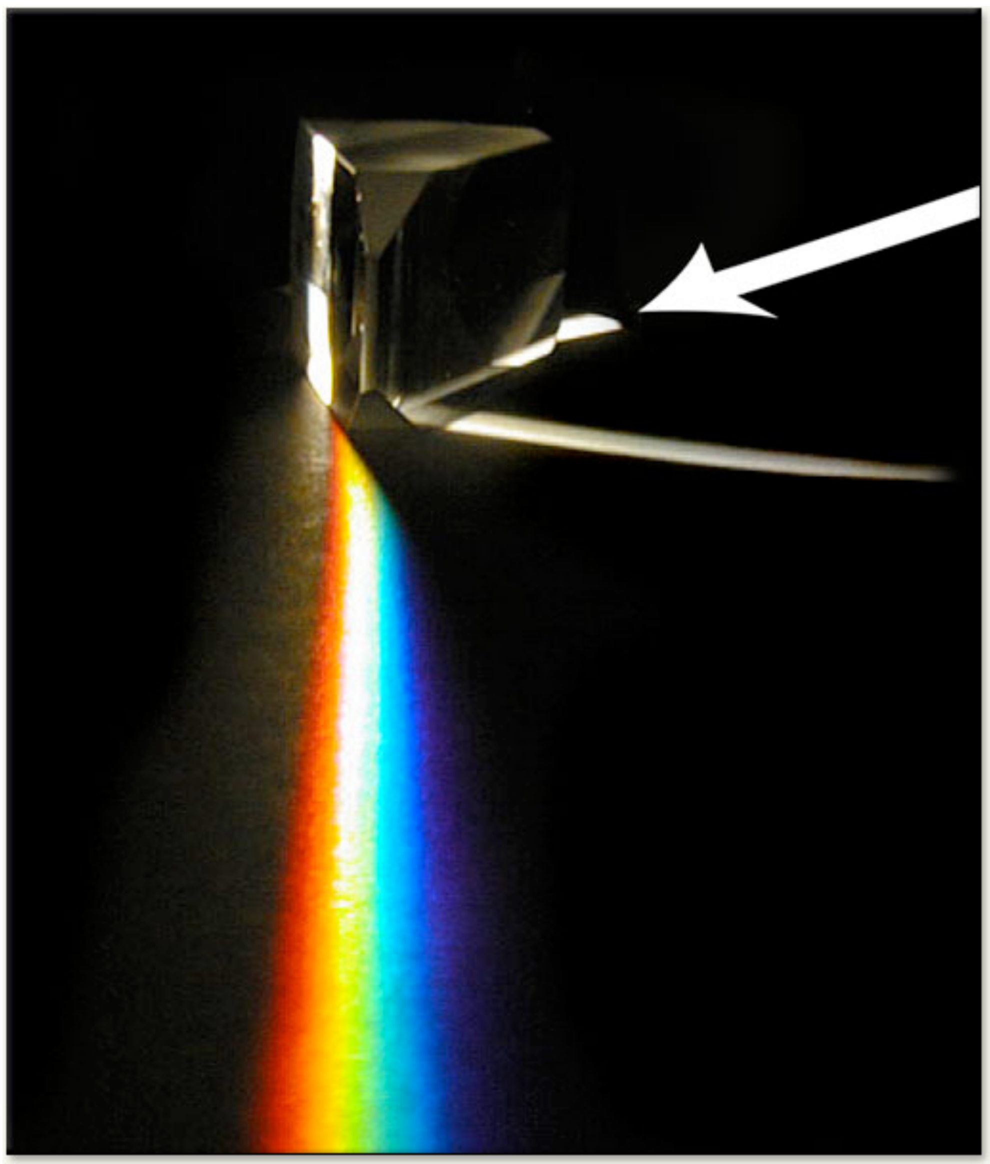


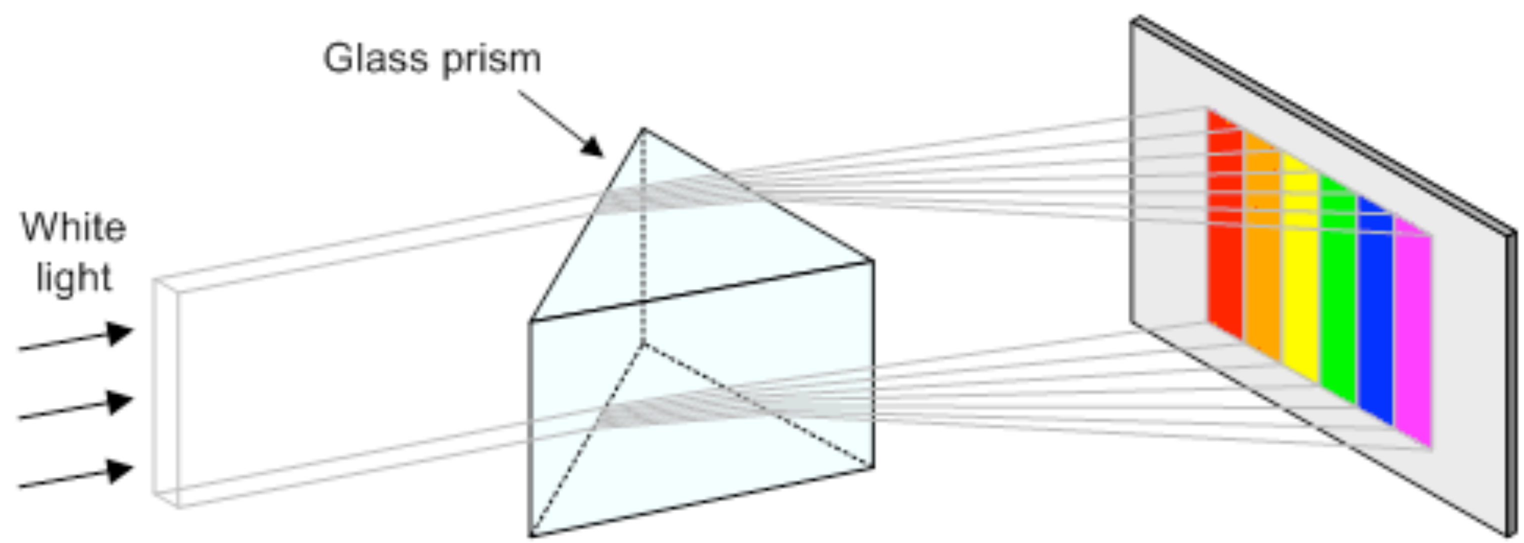
Color != Wavelength

- But rather, an integral over the wavelengths of the energy encoded of some **power spectrum**



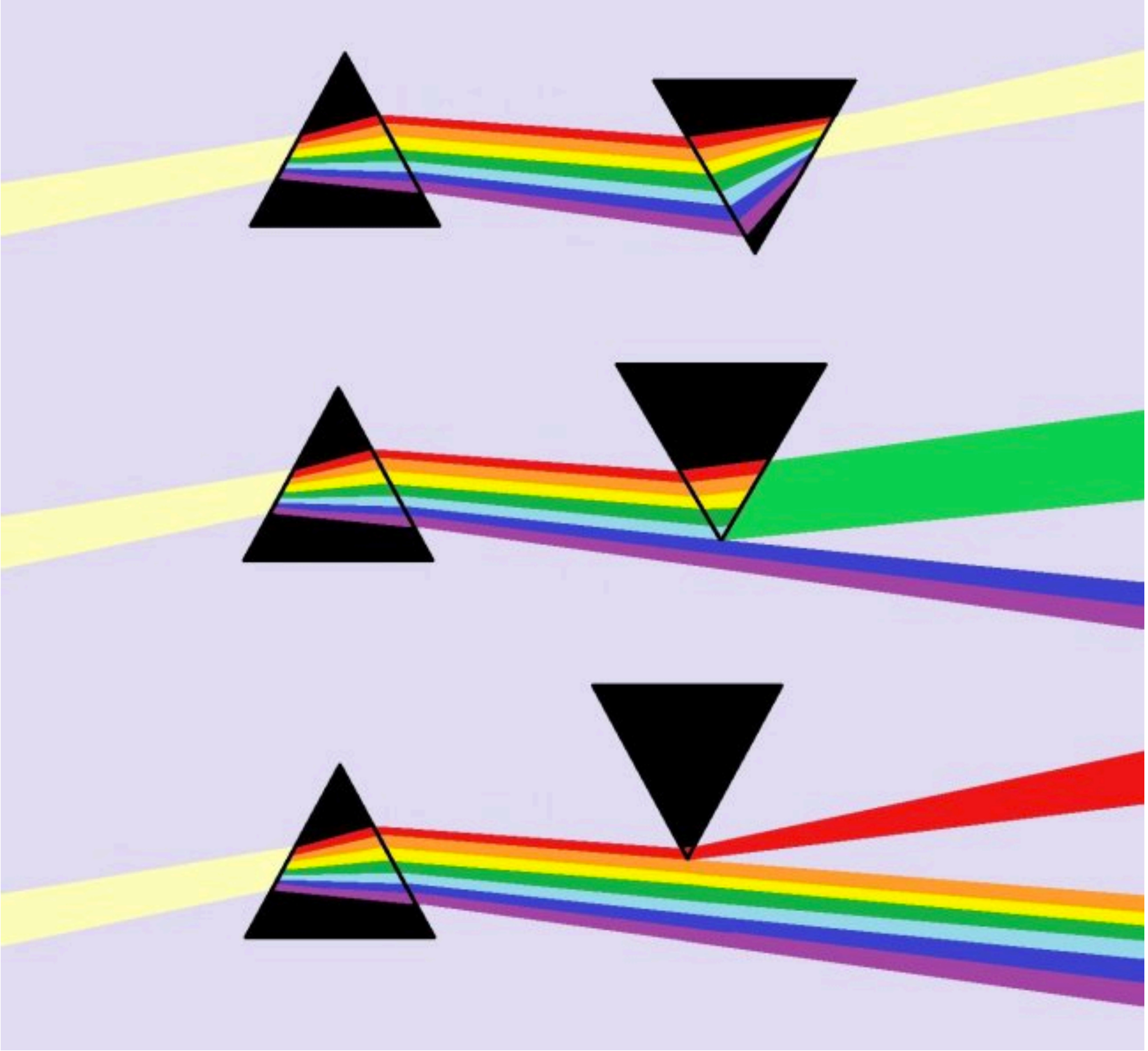
Isaac Newton, 1666





Newton's experiment for splitting white light into a spectrum

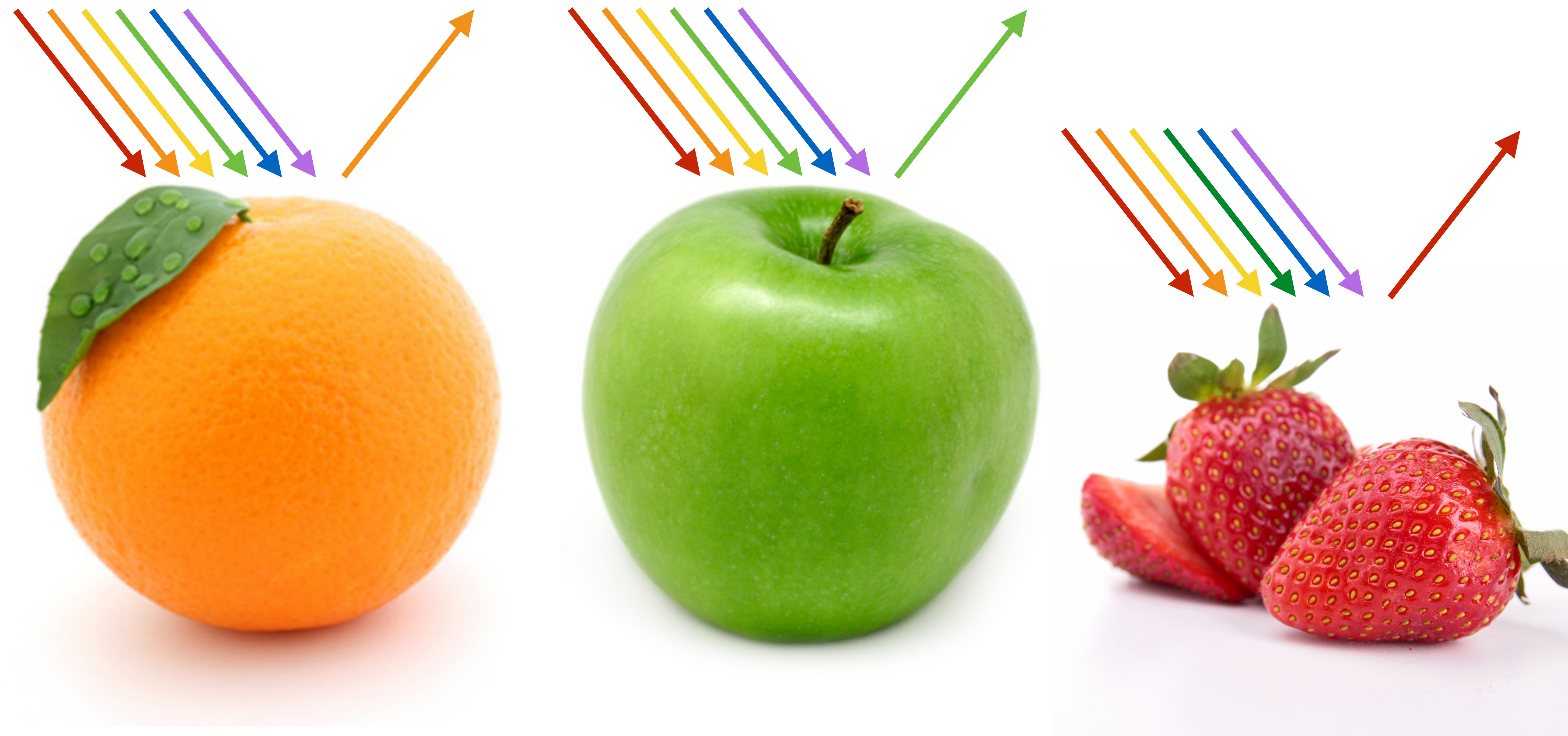
http://www.webexhibits.org/colorart/bh.html
https://www.clivemaxfield.com/diycalculator/popup-m-cvision.shtml



http://www.thestargarden.co.uk/Newtons-theory-of-light.html

The Role of Objects

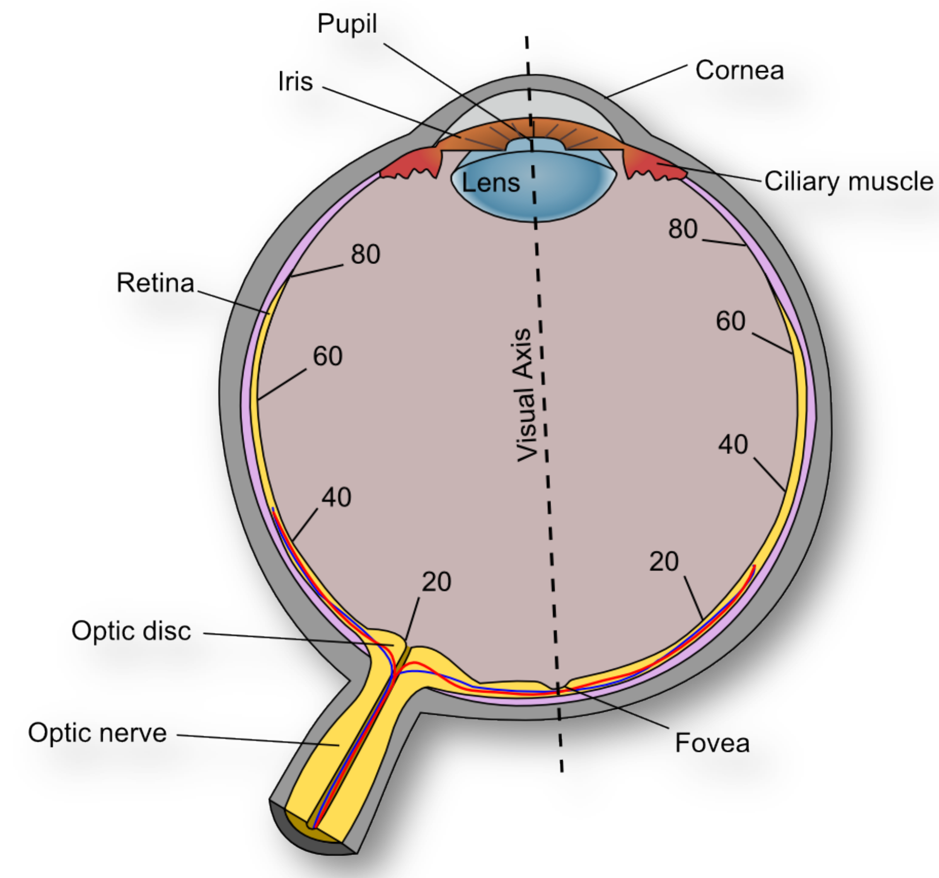
(Reflect vs. Emit)

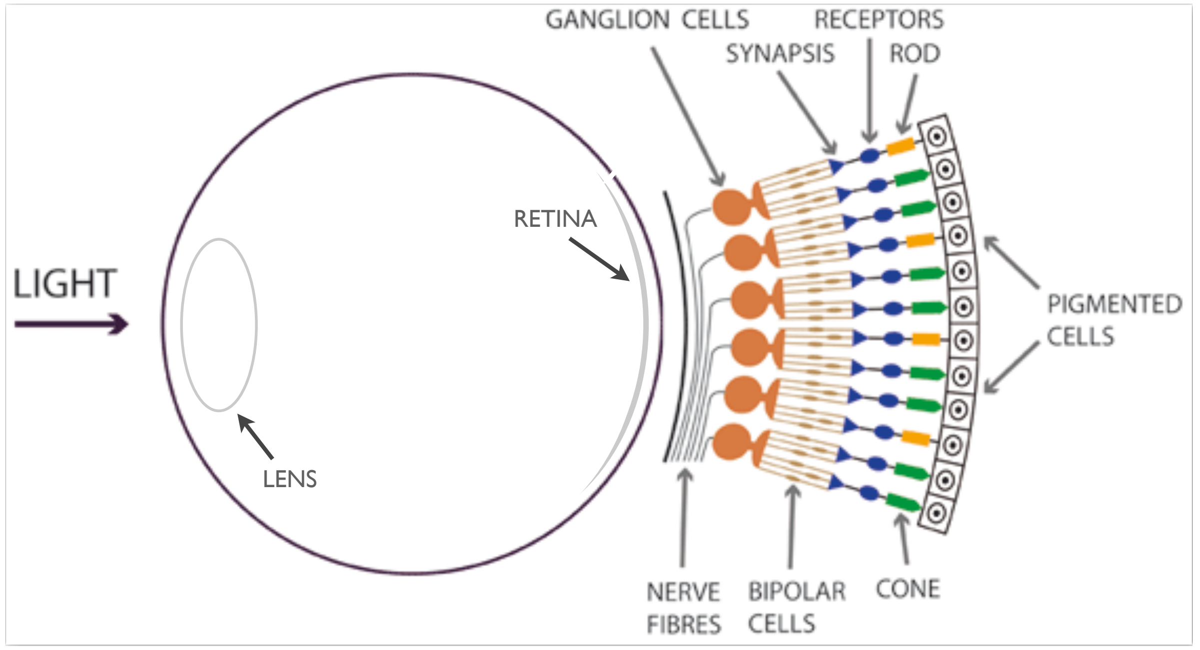


Color and Human Physiology

Recall: Human Optics

- In human vision, the **cornea** acts as a protective lens that roughly focuses incoming light
- Iris controls the amount of light that enters the eye
- The **lens** sharply focuses incoming light onto the retina
  - Absorbs both infrared and ultraviolet light which can damage the lens
- The **retina** is covered by **photoreceptors** (light sensors) which measure light

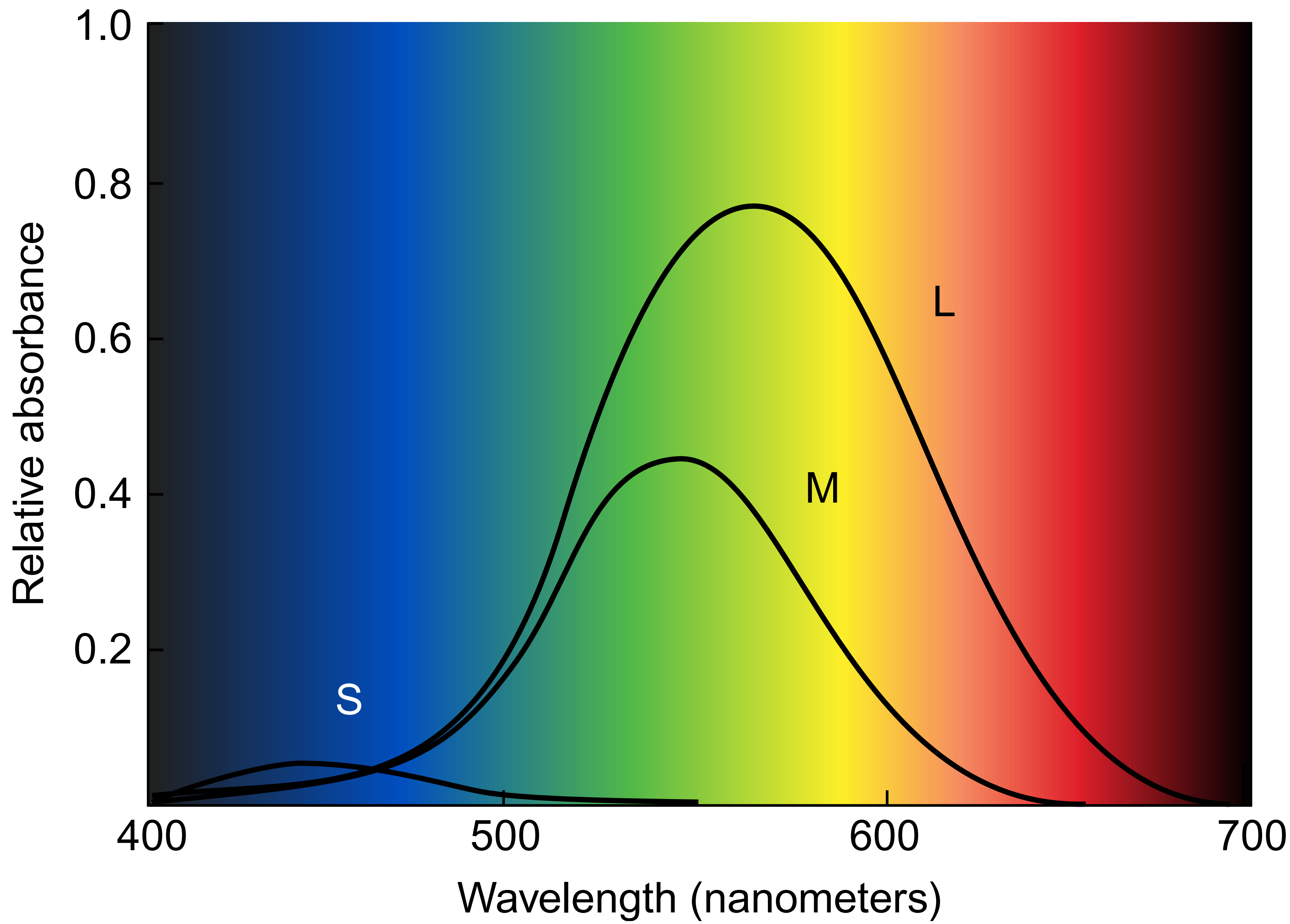




Recall: Photoreceptors

- **Rods** (detect low-light / scotopic vision)
  - Approximately 100-150 million rods (Non-uniformly distributed across the retina)
- **Cones** (detect day-light / photopic vision)
  - Approximately 6-7 million cones.
  - Detects color with 3 different kinds:
    - Red (L cone): 65% of all cones
    - Green (M cone): 30% of all cones
    - Blue (S cone): 5% of all cones

We have three types of cones (<u>S</u>hort, <u>M</u>edium, and <u>L</u>ong)



Colin Ware, Information Visualization: Perception for Design

Hunters

Gatherers

Trichromacy

- Our 3 cones cover the visible spectrum (theoretically, all we might are 2 though)
- Most birds, some fish, reptiles, and insects have 4, some as many as 12 (e.g. the mantis shrimp)
- This is one “reason” why many of our acquisition devices and displays use 3 channels, and why many of our color spaces are three dimensional


Mantis Shrimp
16 Photoreceptors, 12 for color sensitivity!

Opponent Process Model

- Trichromacy explains **how** the eye receives the signals while opponent process theory explains **how the signals are processed**

- Visual system is oriented around **differences** between the responses

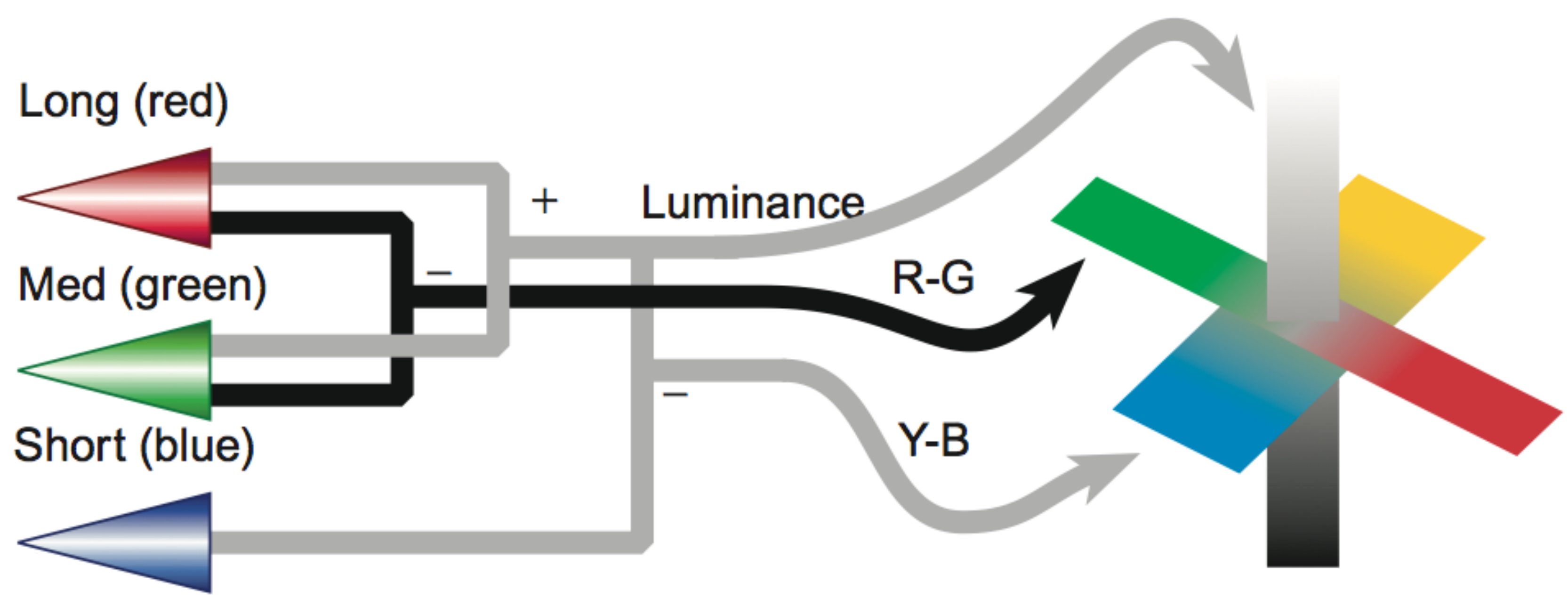


Figure 4.10 In the color opponent process model, cone signals are transformed into black–white (luminance), red–green, and yellow–blue channels.

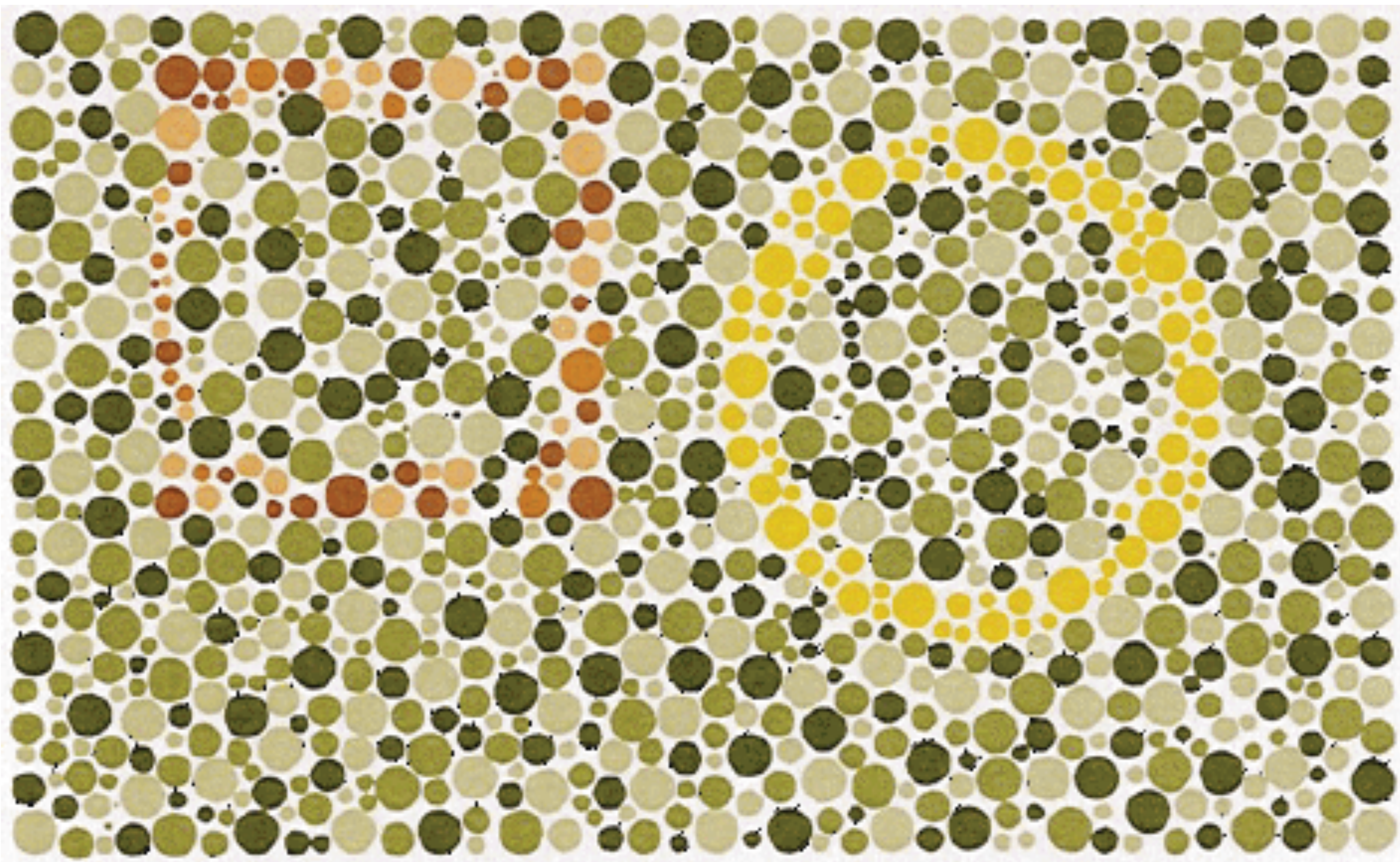
Colin Ware, Information Visualization: Perception for Design

Key Idea: Perception of color

- Ultimately, color is a perceptual phenomenon. Given the same stimulus, each of use will perceive it differently

Understanding Color Perception

RG Color Blindness



What Goes Wrong?

- Two broad classes of problems:

    1. Only some types of cones present in the eye (rare)

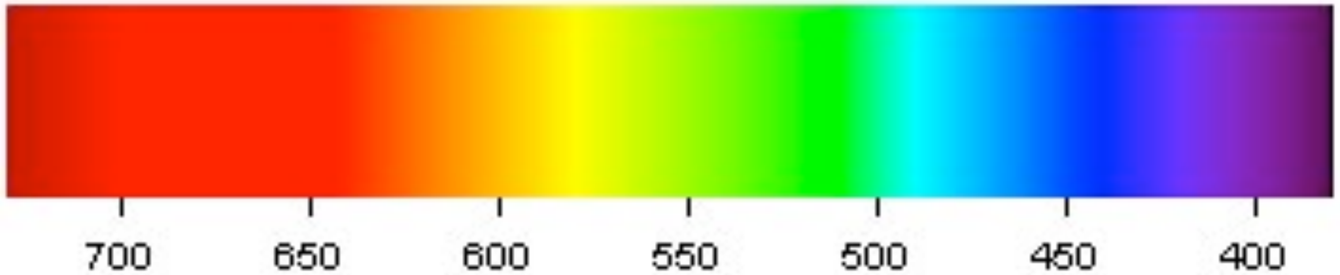
        - red-green dichromacy, blue-yellow dichromacy

    2. Two types of cones with abnormally close response curves

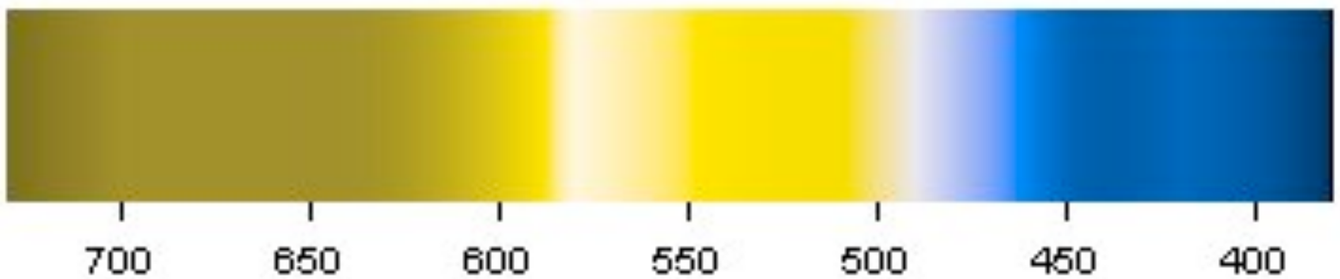
        - relatively common for red-green

Missing Cones

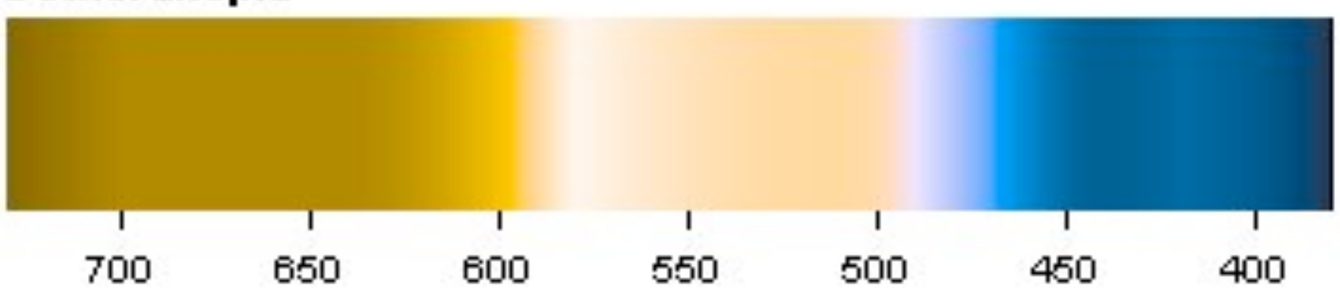
Normal



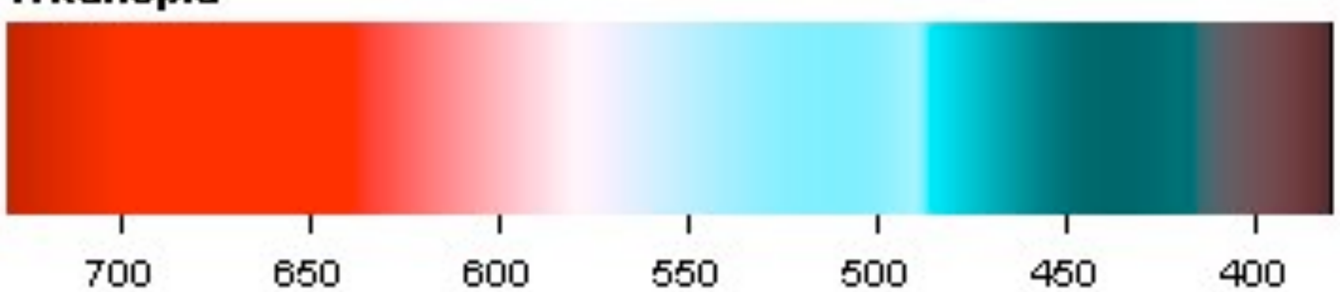
Protanopia

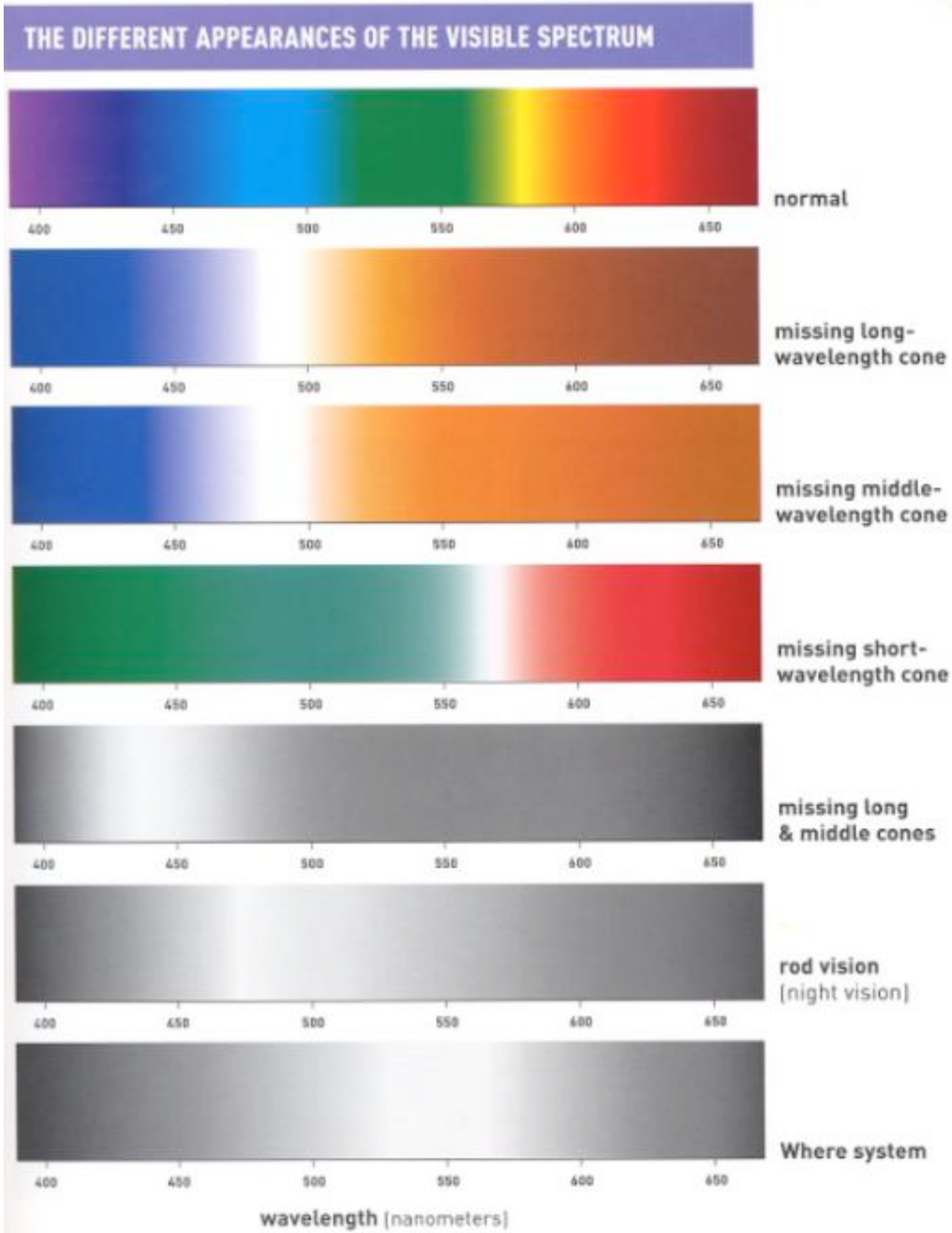


Deuteranopia

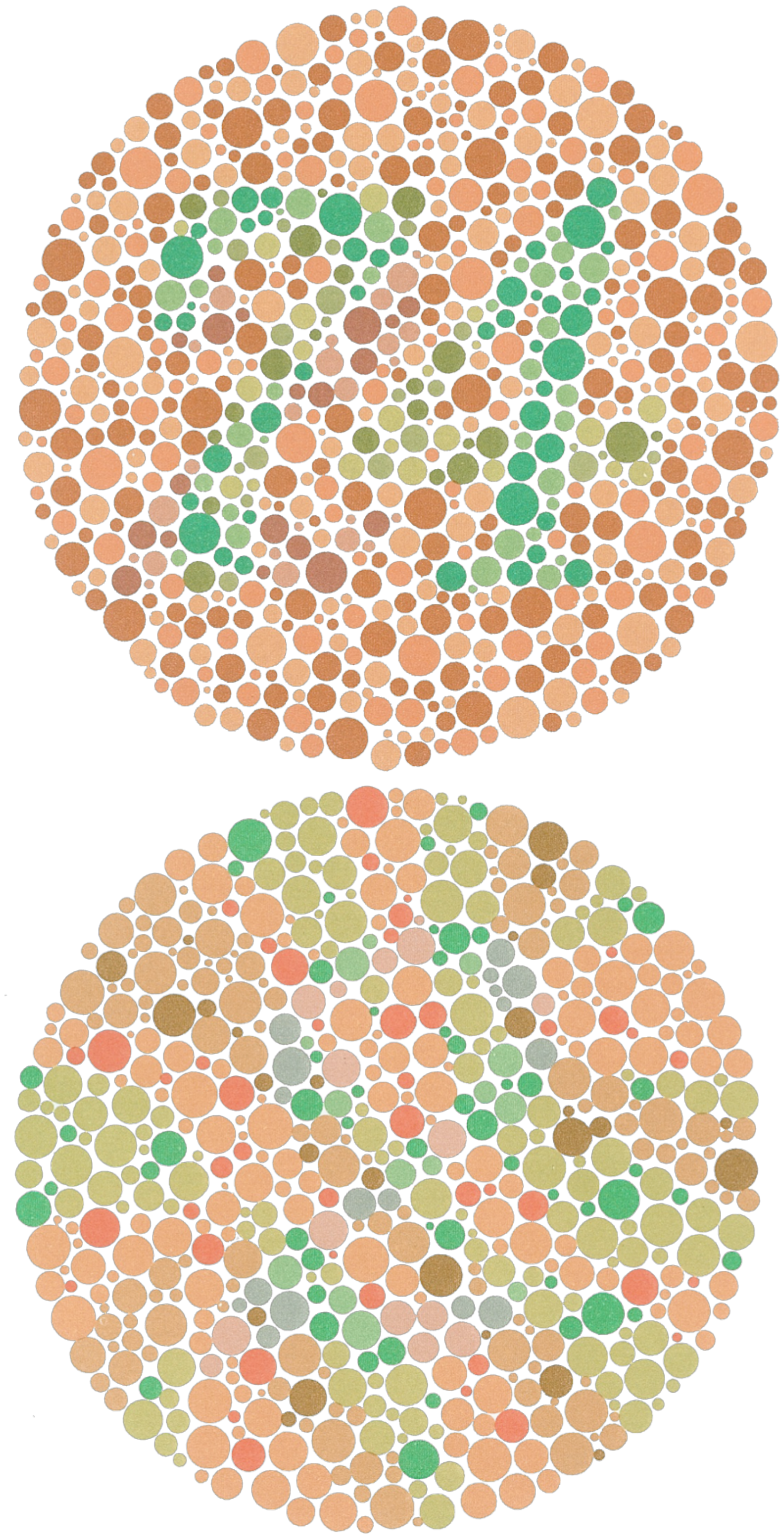


Tritanopia



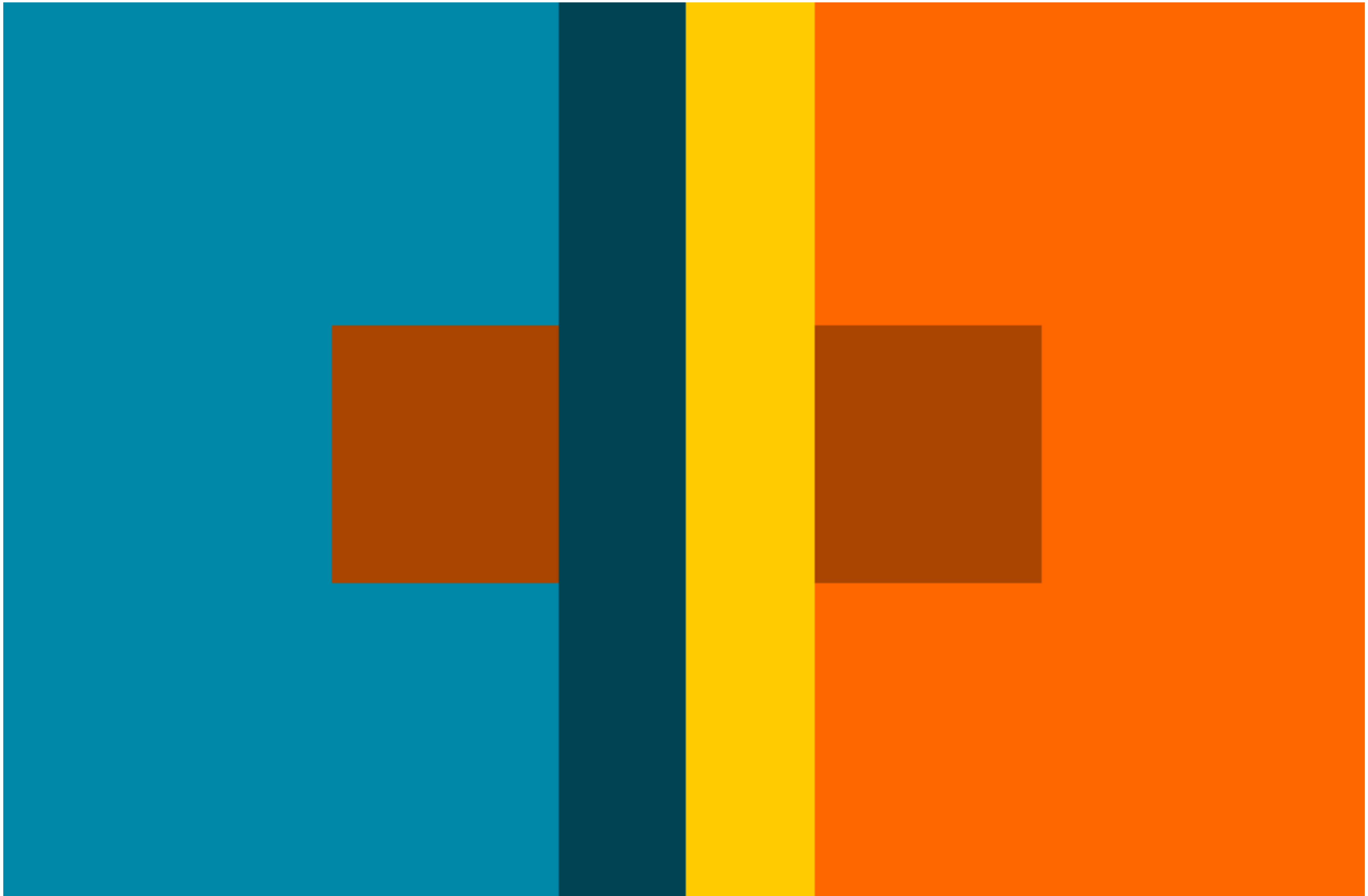


Ishihara Plates

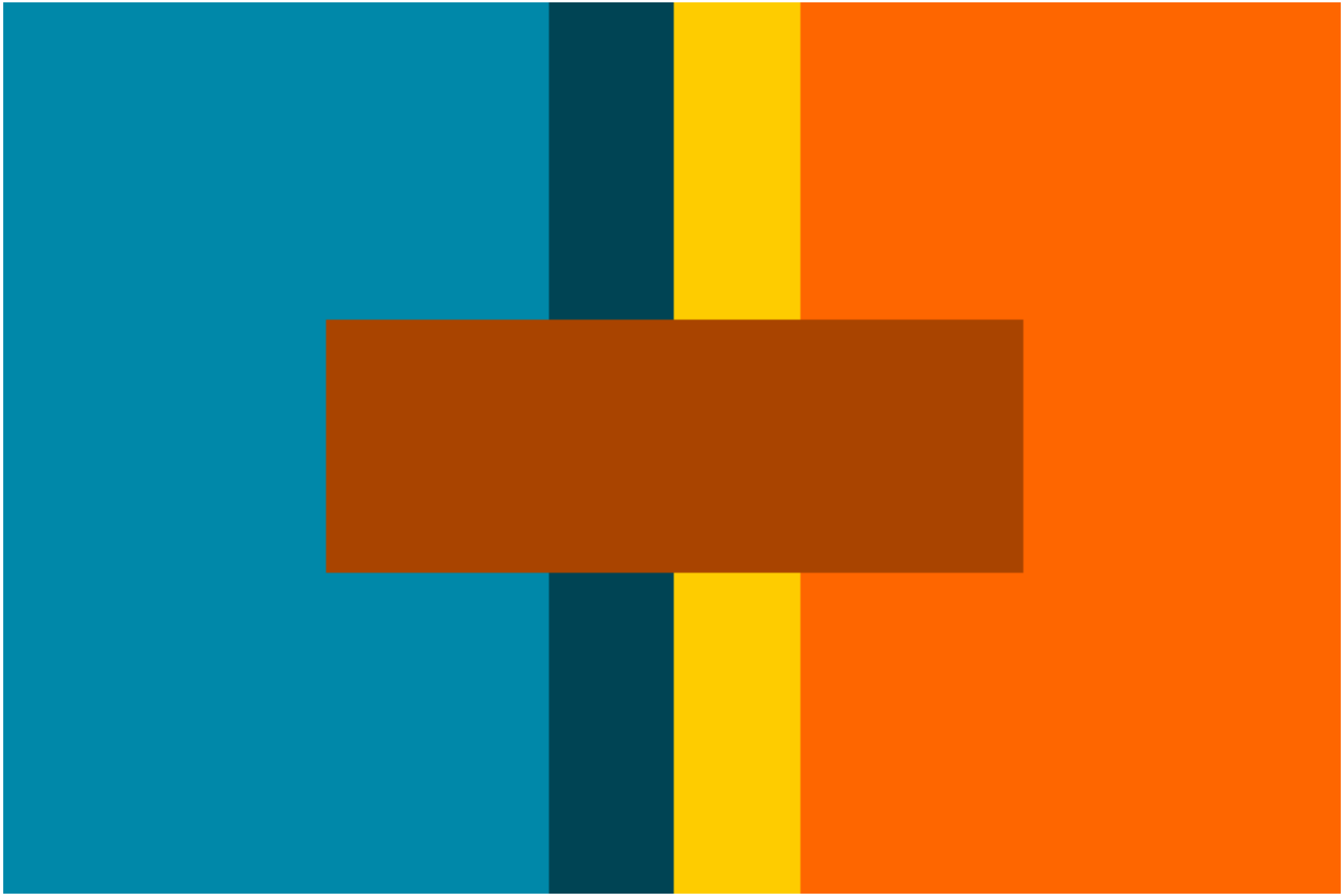


Color Illusions

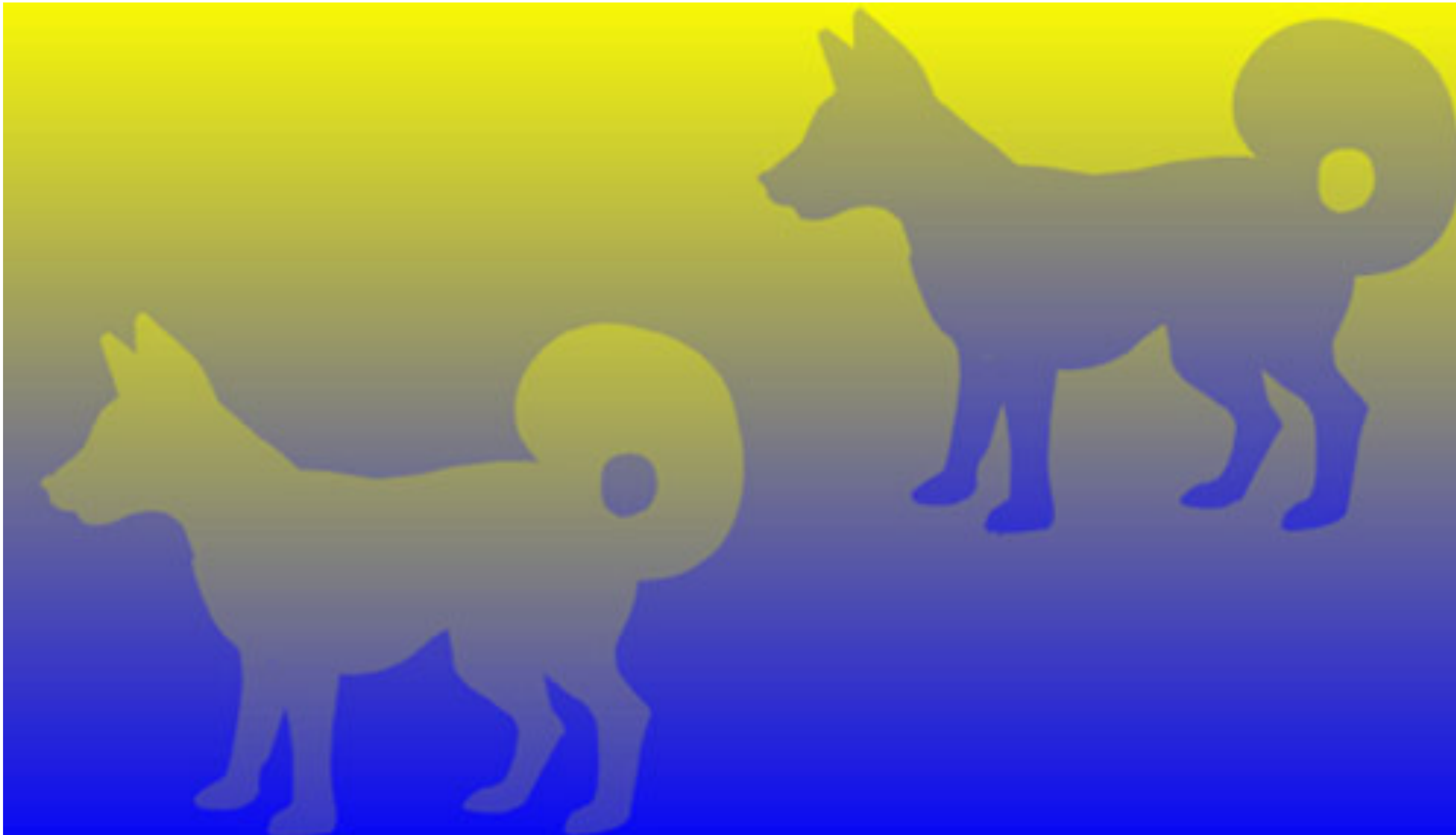
Simultaneous Contrast



Simultaneous Contrast



Simultaneous Contrast



Simultaneous Contrast

Chromatic Adaptation

Chromatic Adaptation

What color is the flower?

Chromatic Adaptation

What color is the flower?

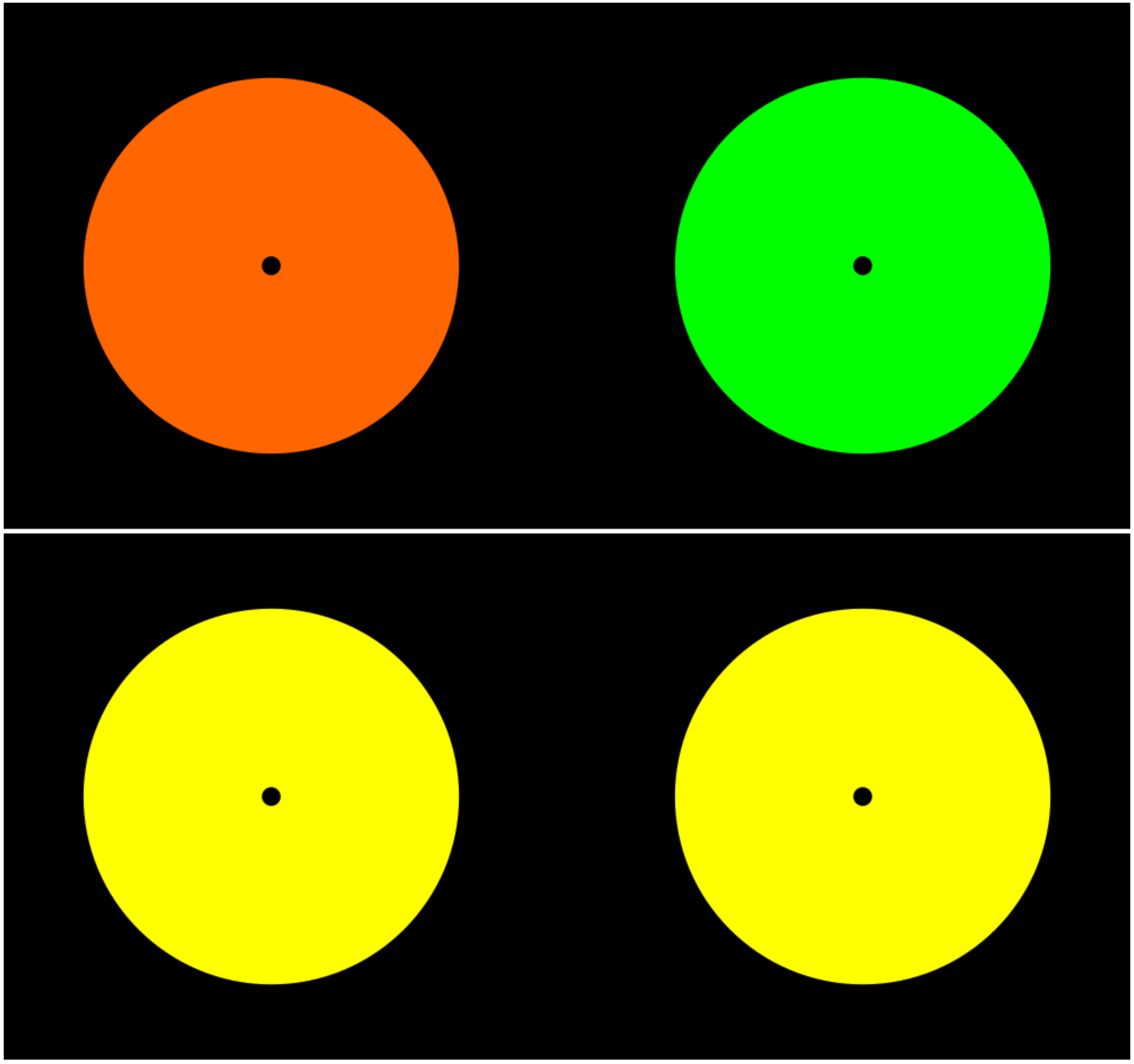
Chromatic Adaptation

What color is the flower?

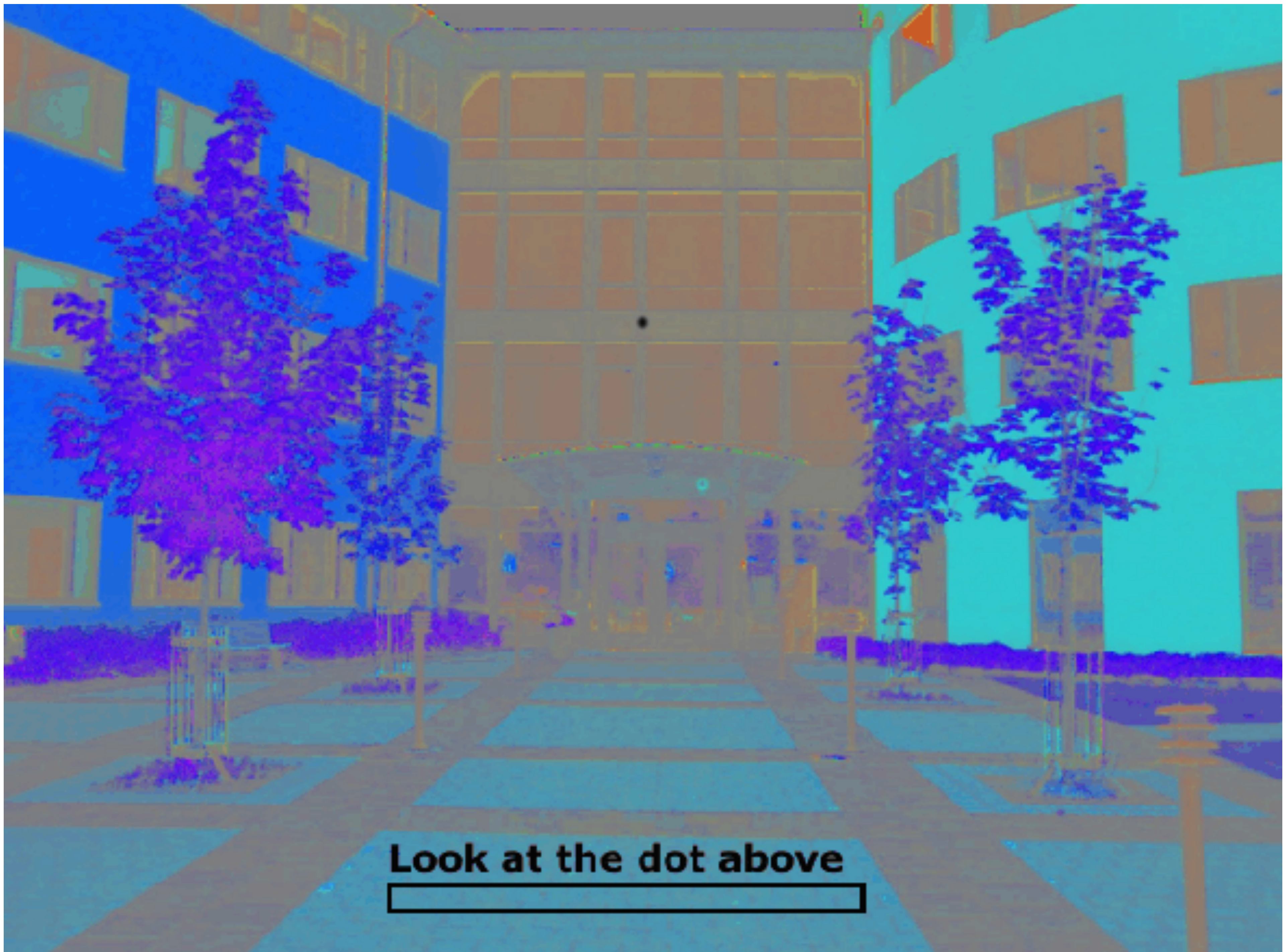
Chromatic Adaptation (what color is the dress?)

https://en.wikipedia.org/wiki/The_dress

Successive Contrast



Temporal Adaptation



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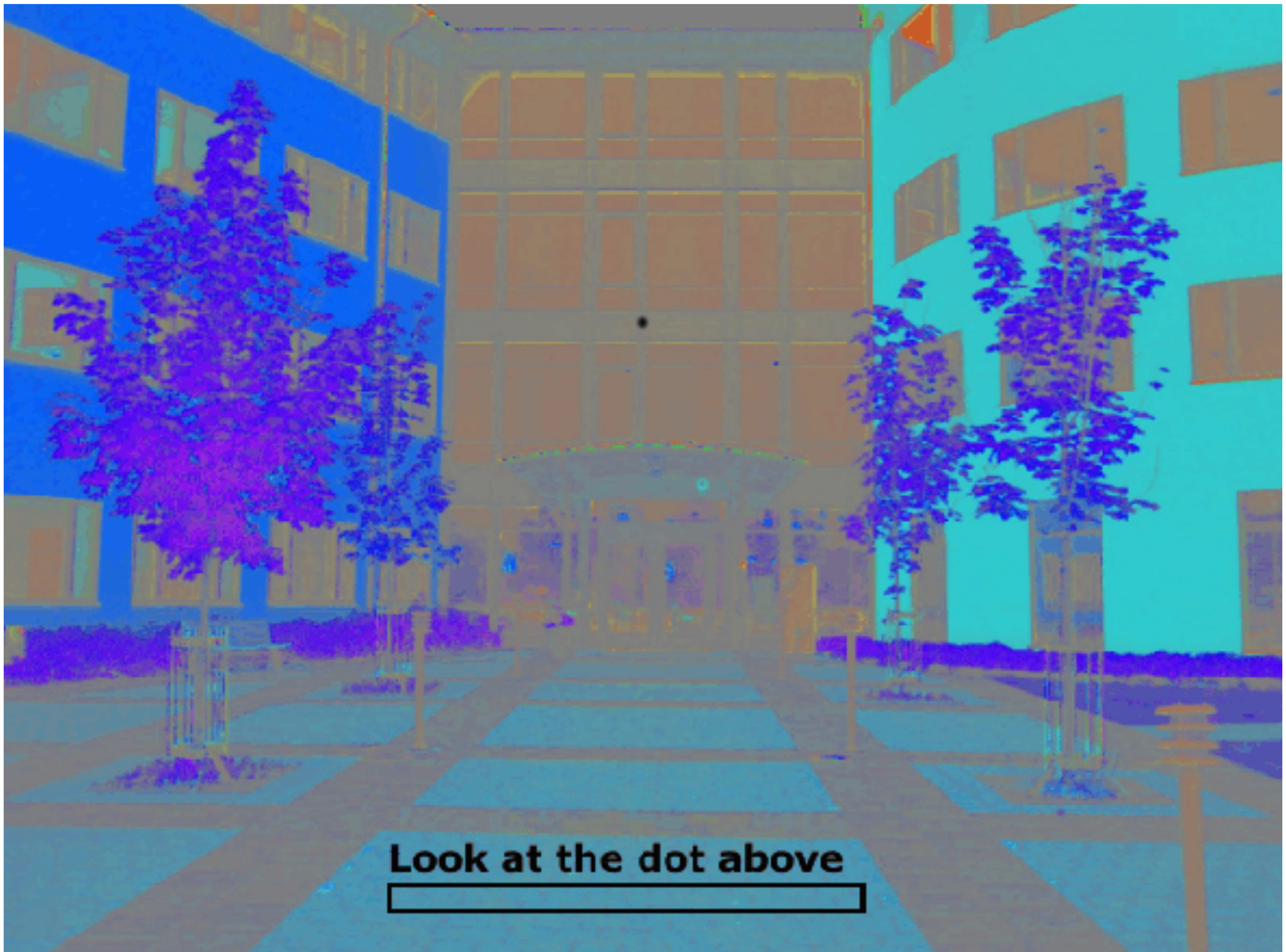
Temporal Adaptation



https://www.moillusions.com/wp-content/uploads/2012/10/13191556xTEEoCm7.gif

Color Models and Color Spaces

Poll: What are the primary colors?

1. Red, Green, Blue
2. Red, Yellow, Blue
3. Orange, Green, Violet
4. Cyan, Magenta, Yellow

Poll: What are the primary colors?

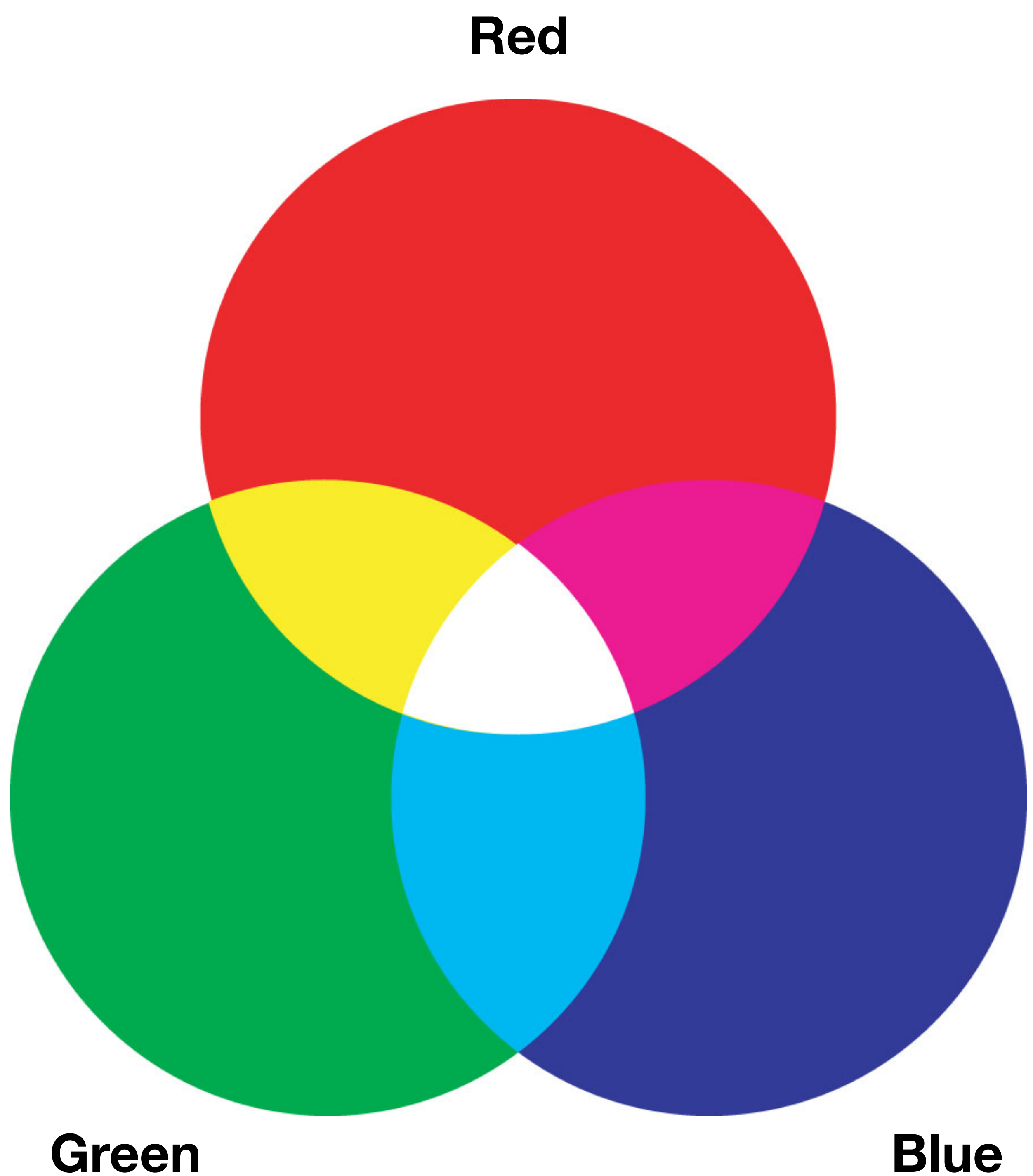
1. Red, Green, Blue
2. Red, Yellow, Blue
3. Orange, Green, Violet
4. Cyan, Magenta, Yellow
5. All of the above

Any three “independent” ways of combining color works (!)

Color Terminology

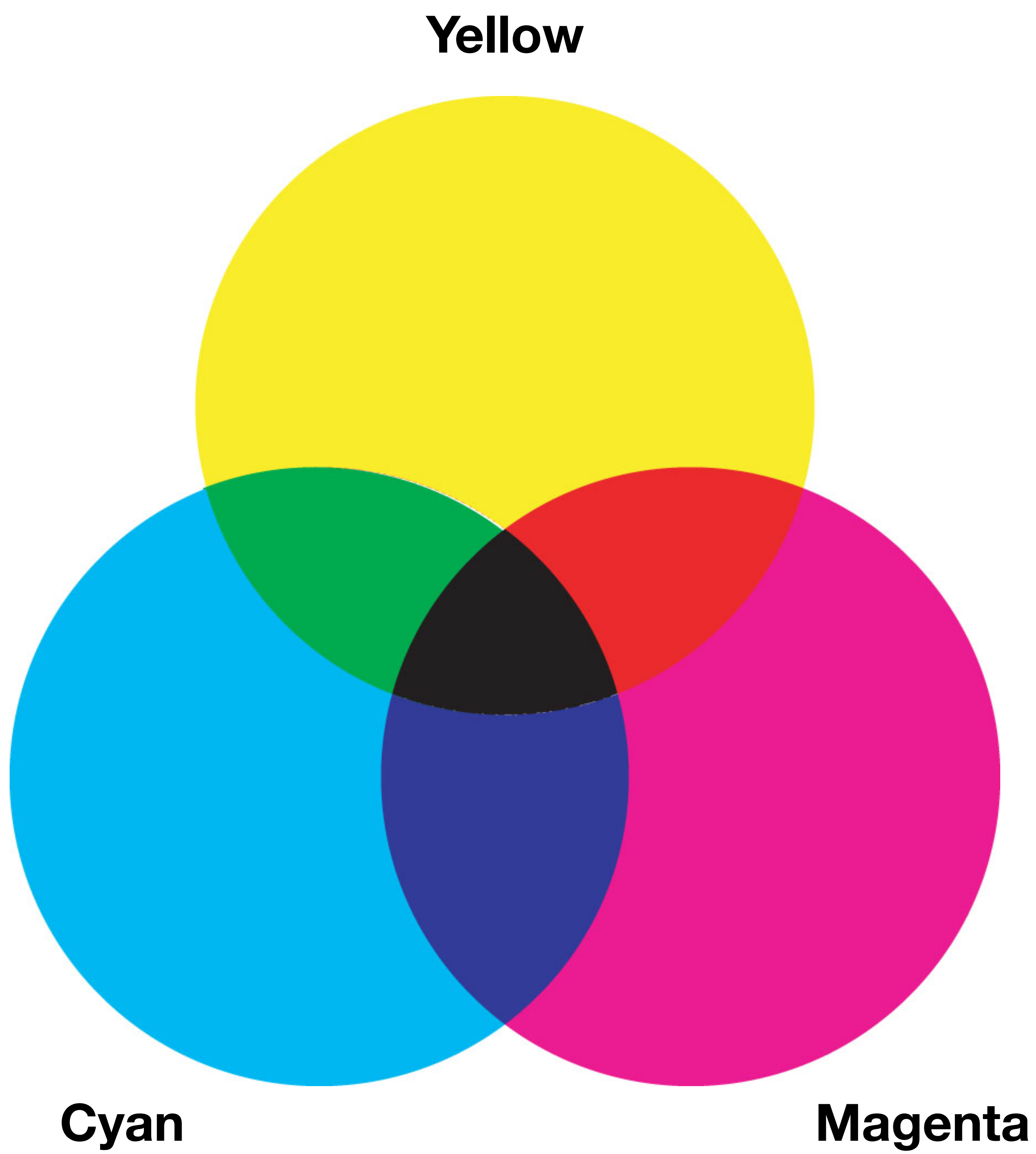
- **Color Model**
  - Is an abstract mathematical system for representing color.
  - Is often 3-dimensional, but not necessarily.
  - Is typically limited in the range of colors they can represent and hence often can't represent all colors in the visible spectrum
- **Gamut** or **Color Space**
  - The range of colors that are covered by a color model.

Light Mixing



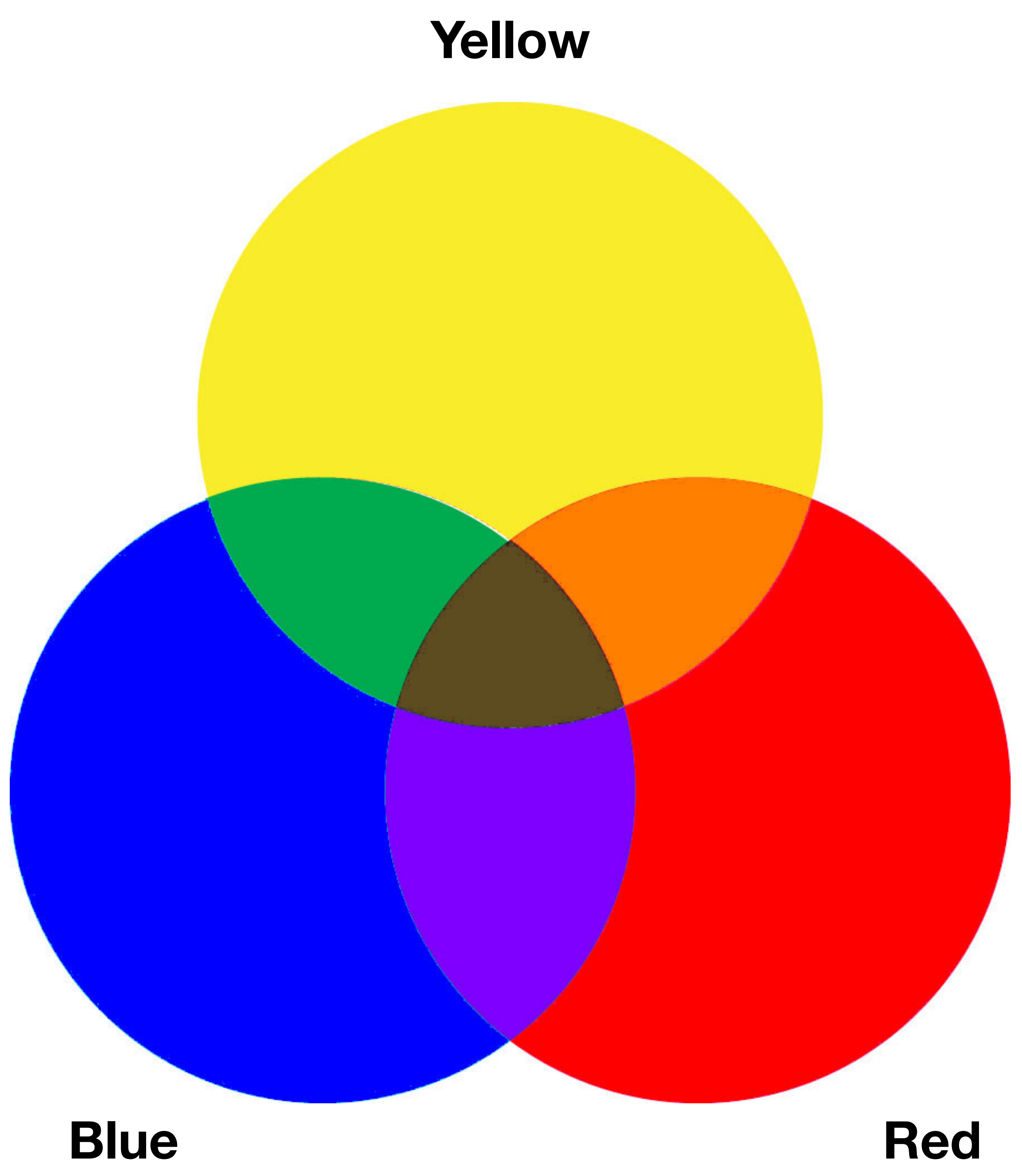
- **Additive** mix of colored lights
  - Add up wavelengths of light to make new colors
- Primary: RGB
- Secondary: CMY
- Neutral = R + G + B
- Commonly used by monitors, projectors, etc.

Ink Mixing



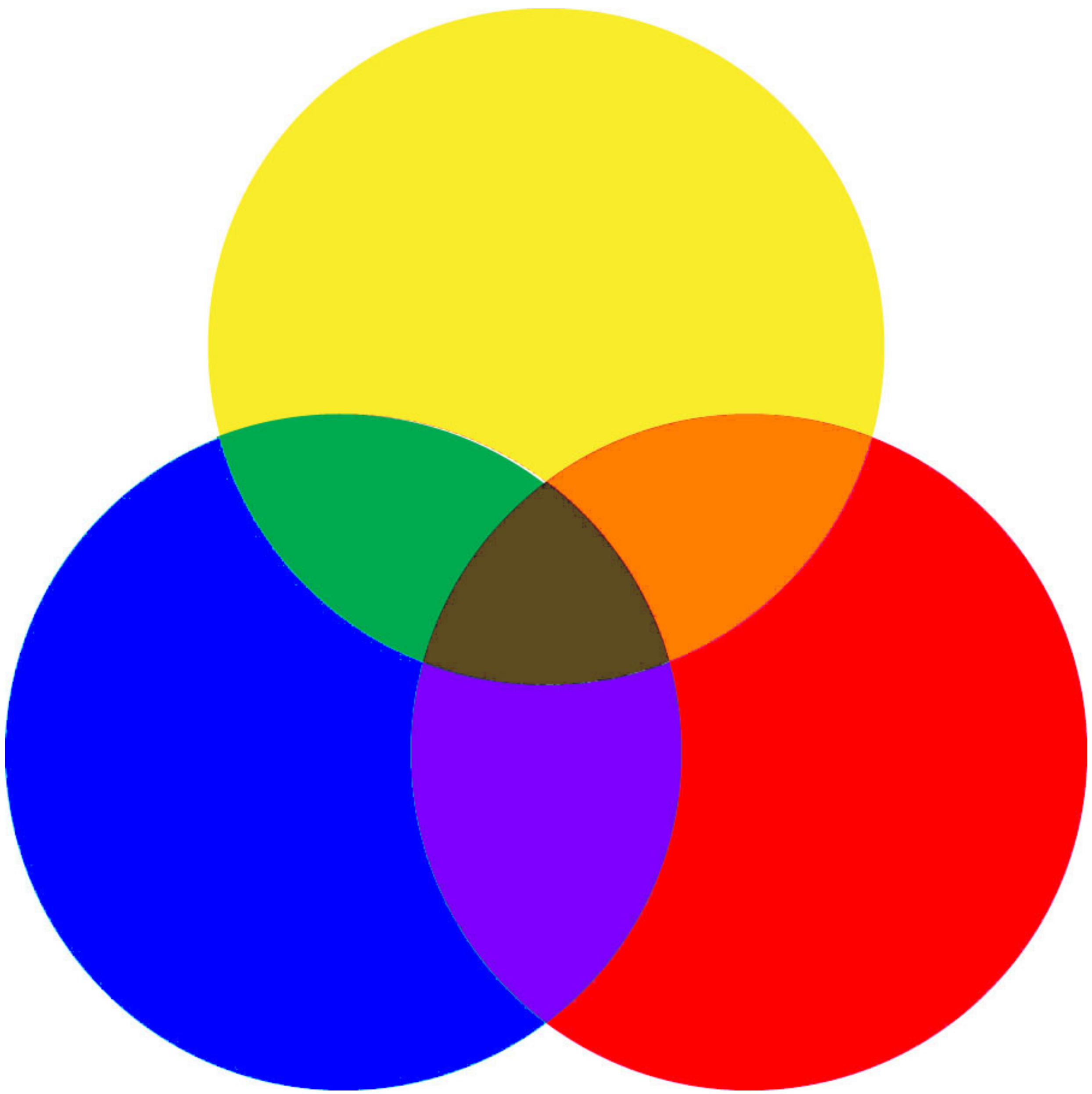
- **Subtractive** mix of transparent inks
  - Start with white and other wavelengths are selectively filtered.
- Primary: CMY
- Secondary: RGB
- ~Black: C + M + Y
- In practice, we use CMYK, with some amount K of black ink, to get true black

Paint Mixing



- Physical mix of opaque paints that reflect light
- Primary: RYB
- Secondary: OGV
- Neutral: R + Y + B
- Additive or Subtractive?

Paint Mixing

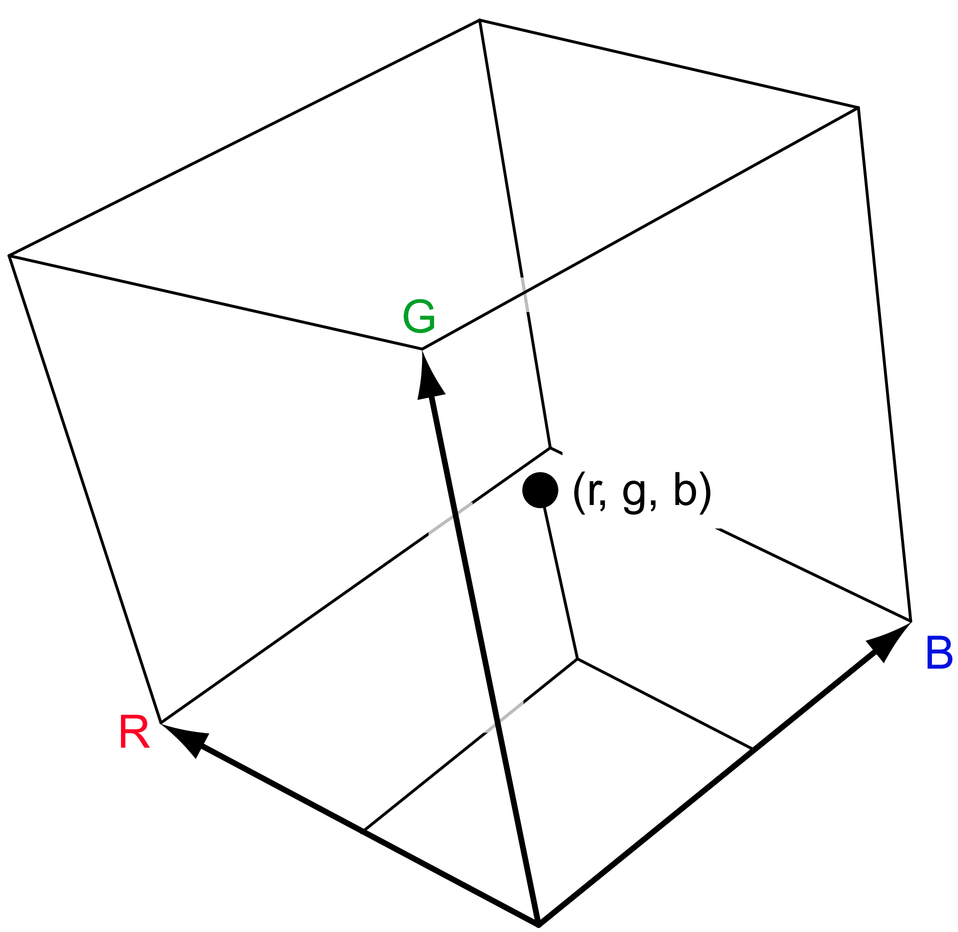


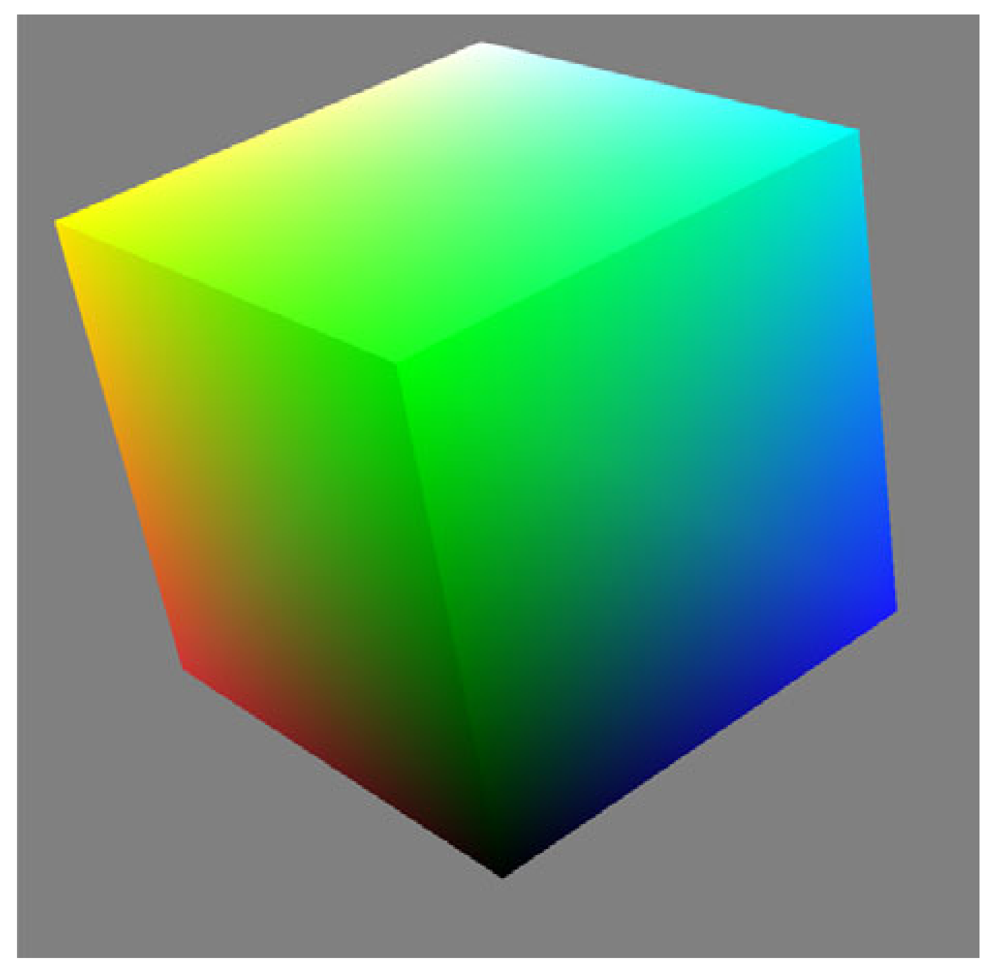
- Physical mix of opaque paints that reflect light
- Primary: RYB
- Secondary: OGV
- Neutral: R + Y + B
- Additive or Subtractive?

(Mostly Subtractive! The mixing isn't perfect and includes reflection off the paint.)

RGB Color Space

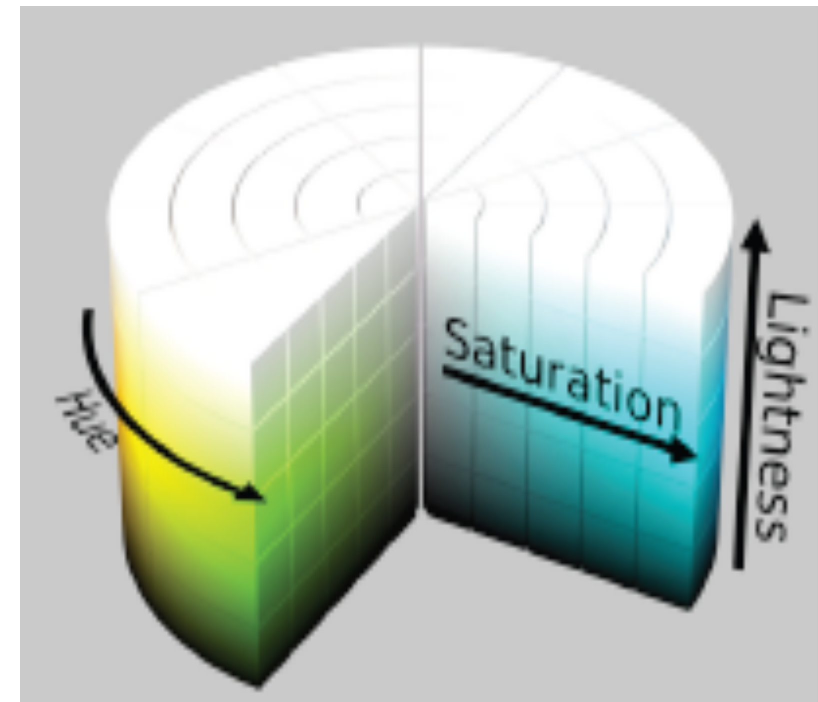
- Additive, useful for computer monitors (but that’s about it!)
- Not perceptually uniform and the channels are not visually separable
    - For example, more “greens” than “yellows”

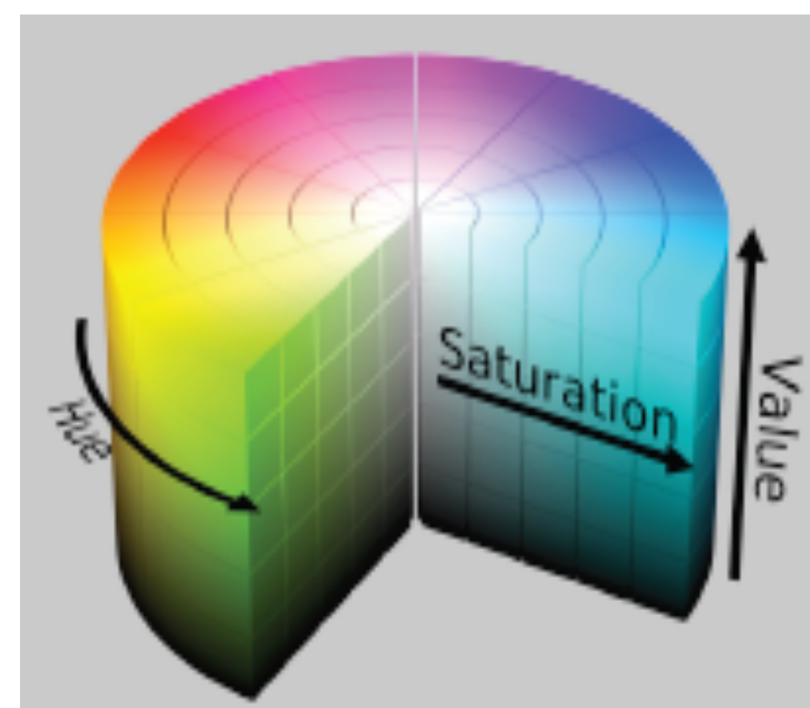




(H,S,L/V) Color Space

- **<u>H</u>**ue - what people think of as color
- **<u>S</u>**aturation - purity, distance from grey
- **<u>L</u>**ightness - from dark to light
    - Also called **<u>V</u>**alue or sometimes **<u>B</u>**rightness
- HSL directly supported in d3





HSL Lacks Perceptual Uniformity

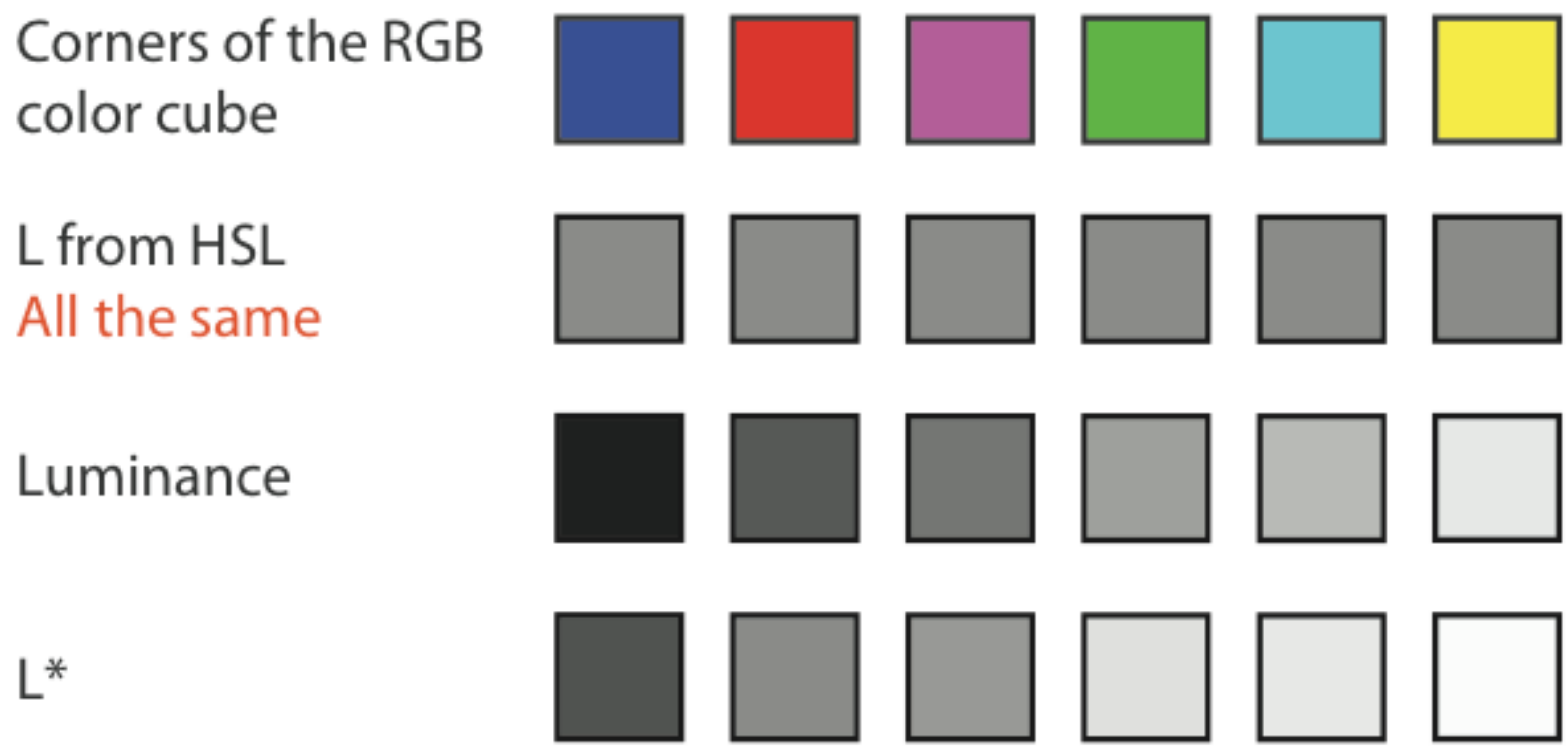
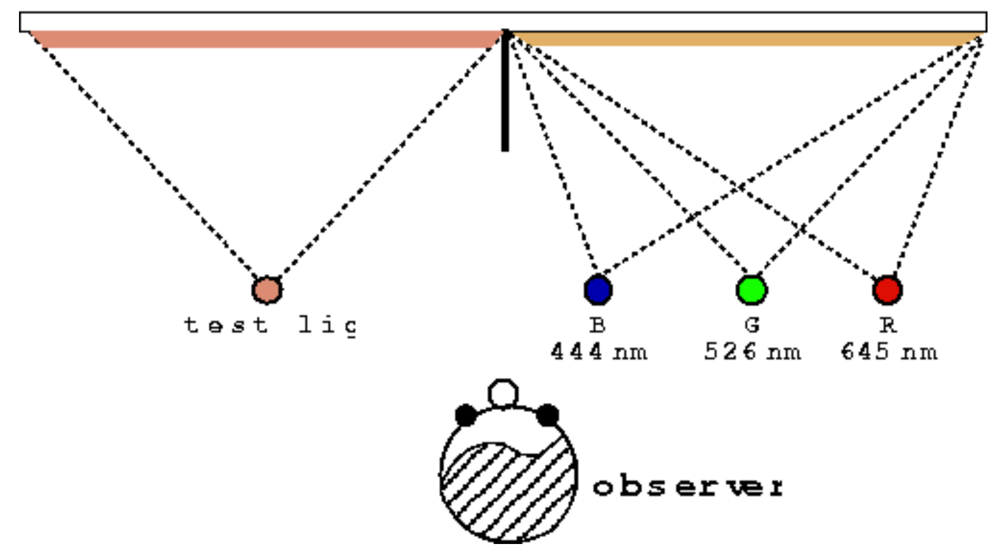


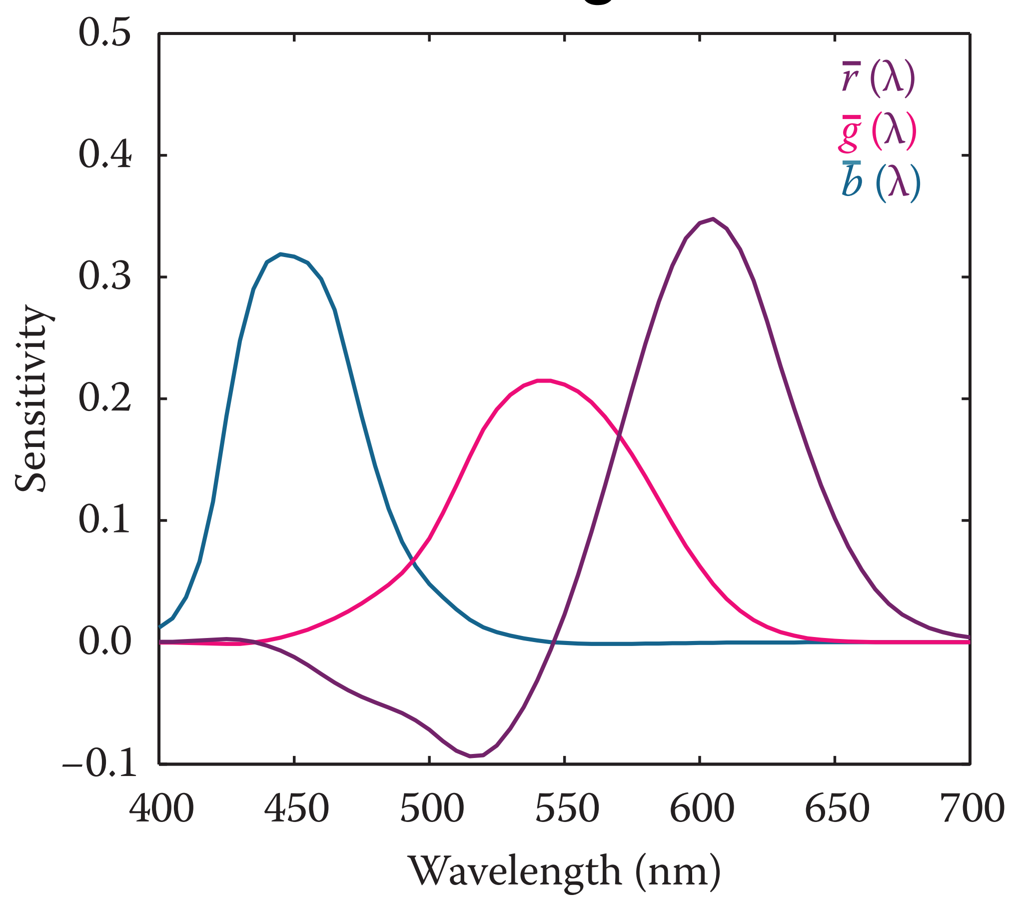
Figure 10.3. Comparing HSL lightness, true luminance, and perceptually linear luminance L^* for six colors. The computed HSL lightness L is the same for all of these colors, showing the limitations of that color system. The true luminance values of these same six colors, as could be measured with an instrument. The computed perceptually linear luminance L^* of these colors is the best match with what we see. After [Stone 06].

Tristimulus Experiment

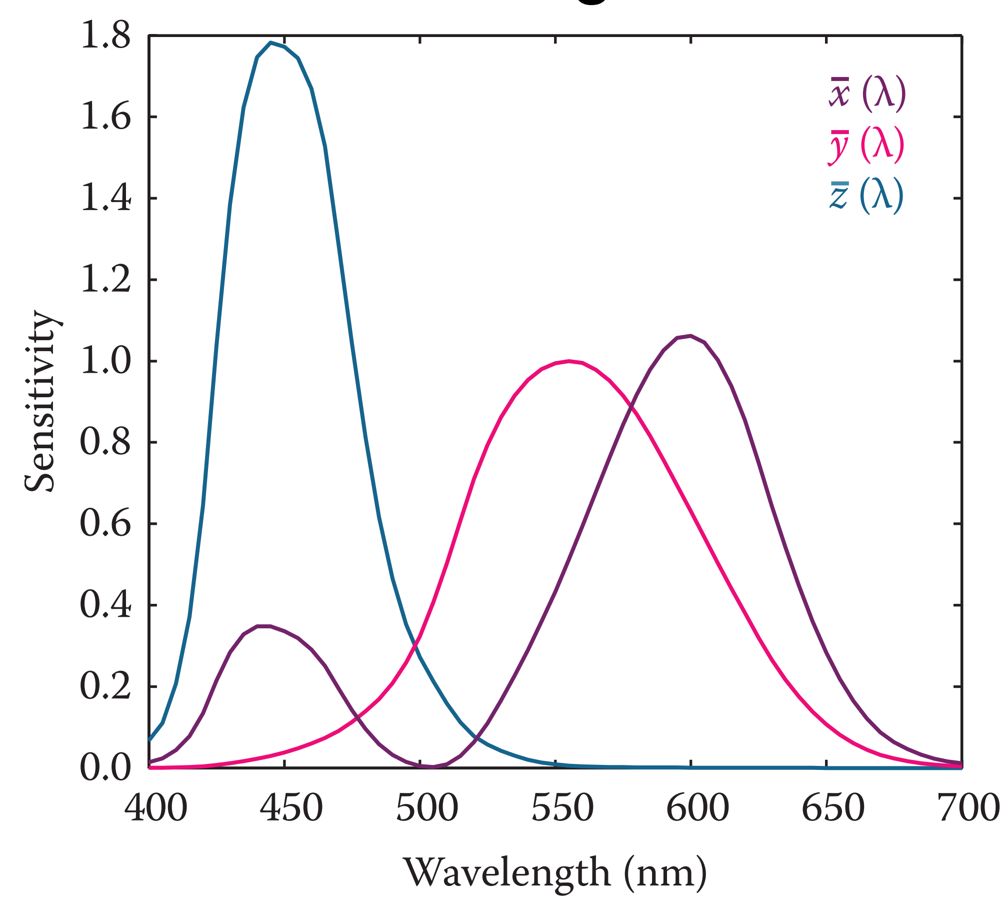
- Color Matching Experiment in 1931
- CIE = International Commission on Illumination (Commission internationale de l'éclairage)
- Since some weighting factors for R,G,B lights are negative, they computed a new set of weights for a new of components X,Y,Z



RGB Weights

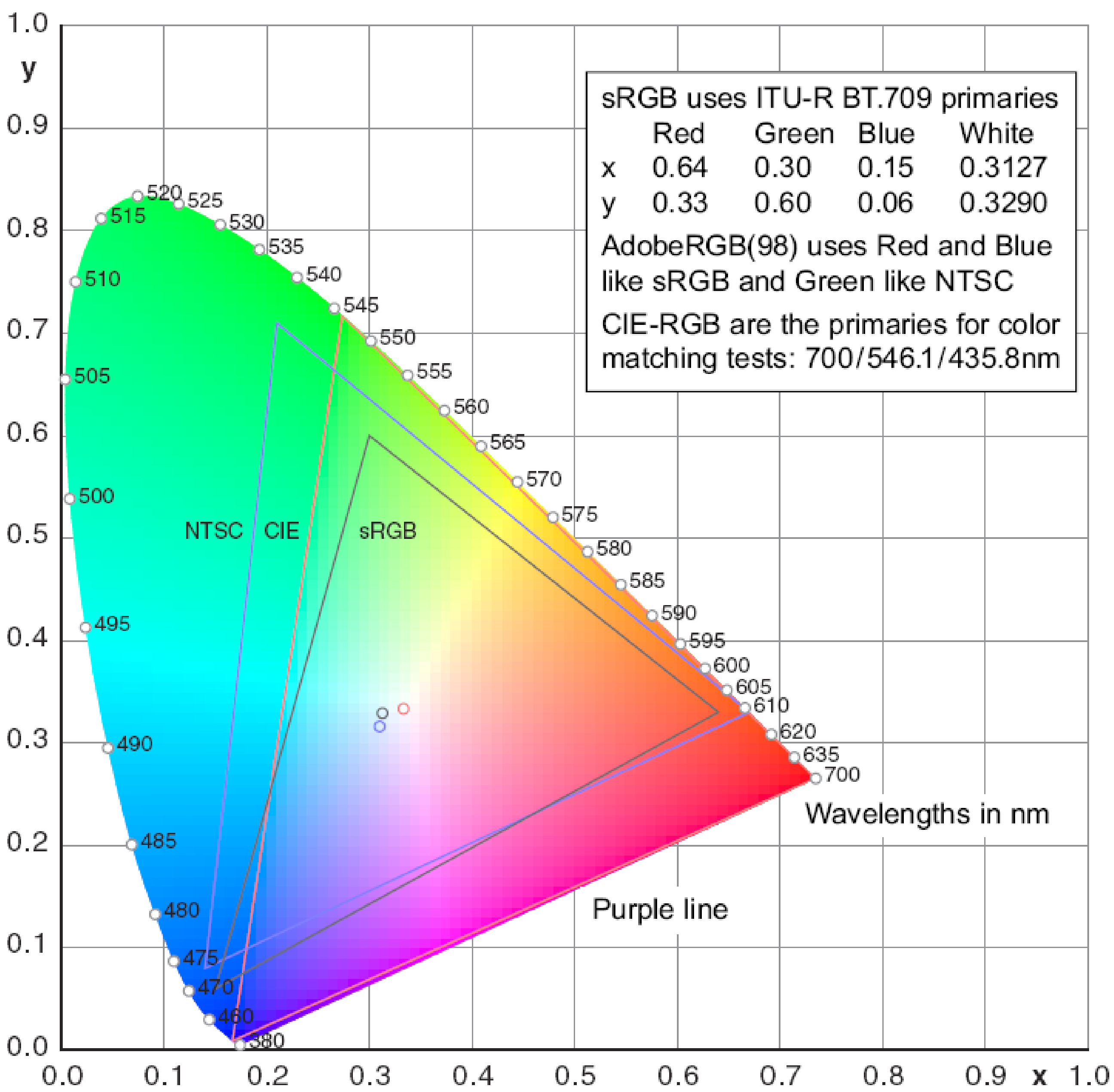


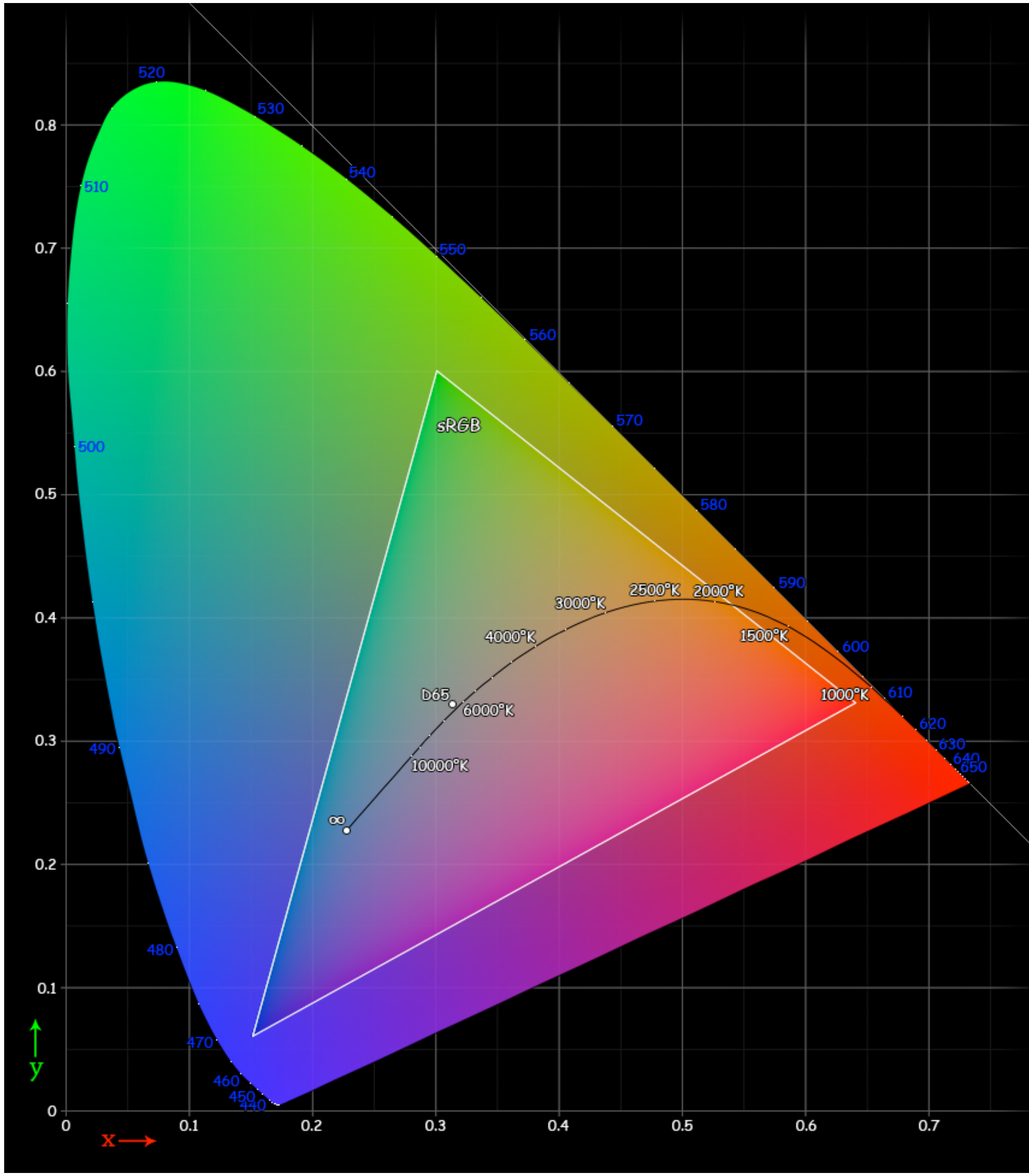
XYZ Weights



CIE Space

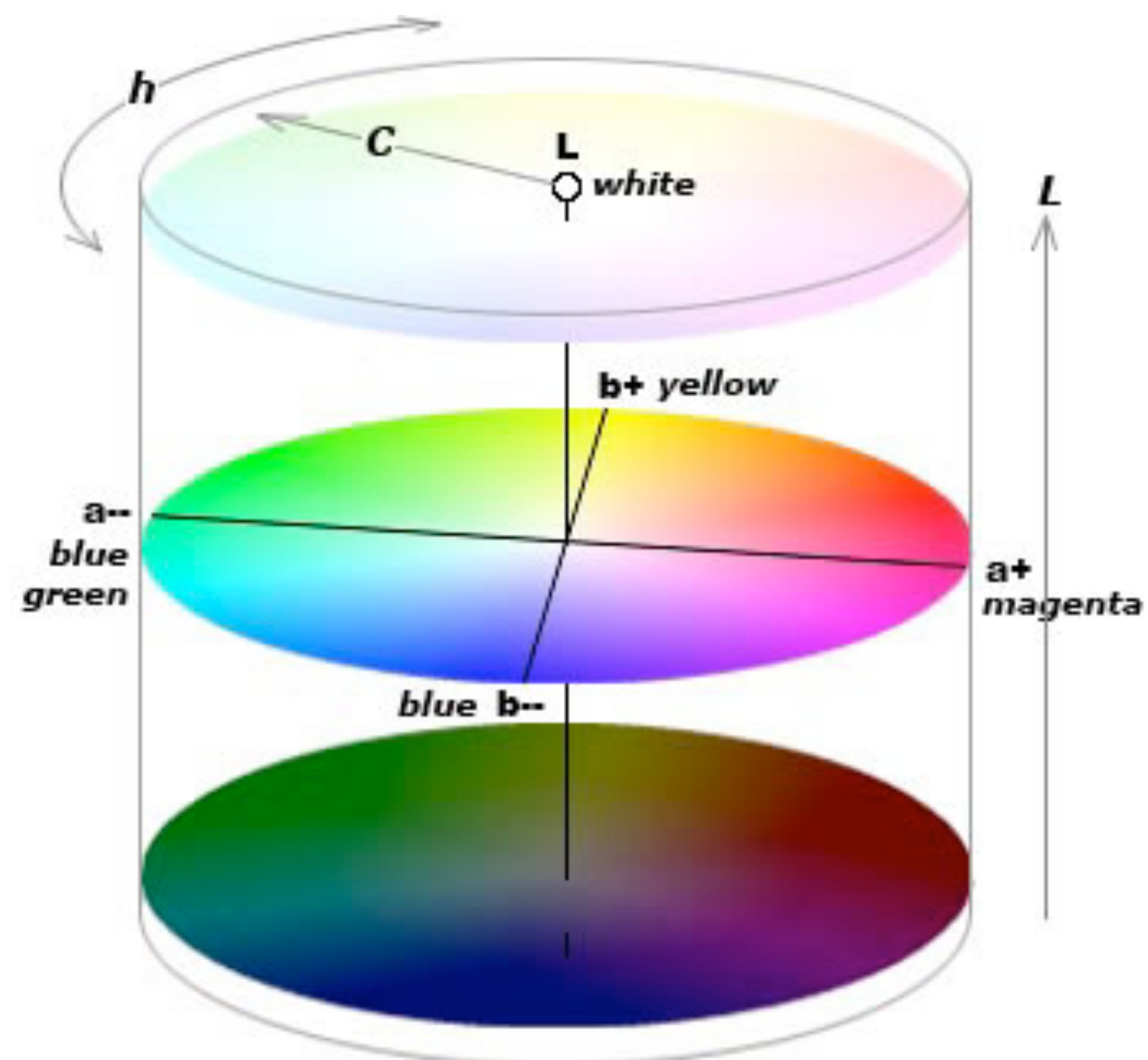
Note: Colors outside the triangle cannot be accurately displayed!





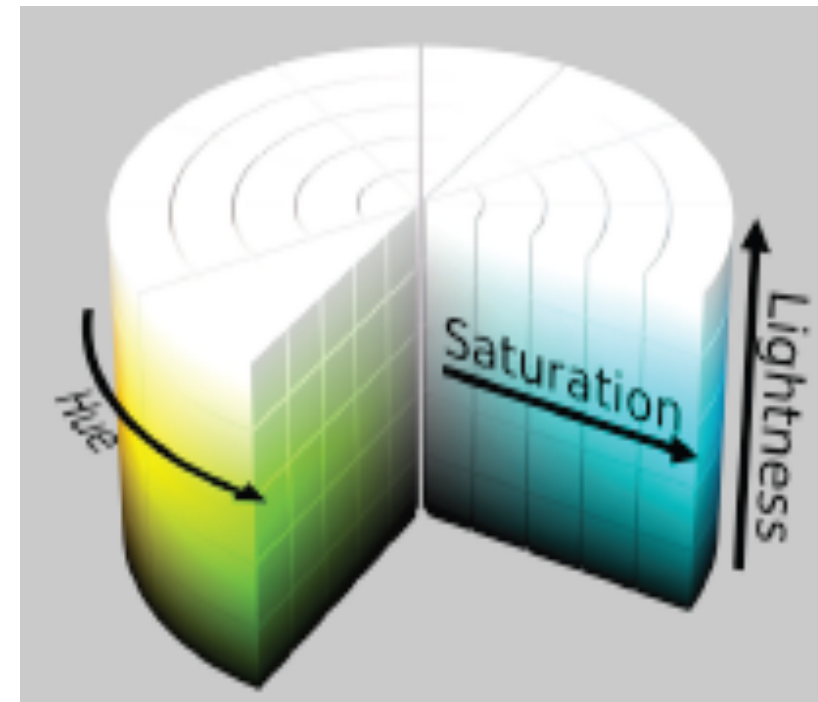
CIELab/Luv

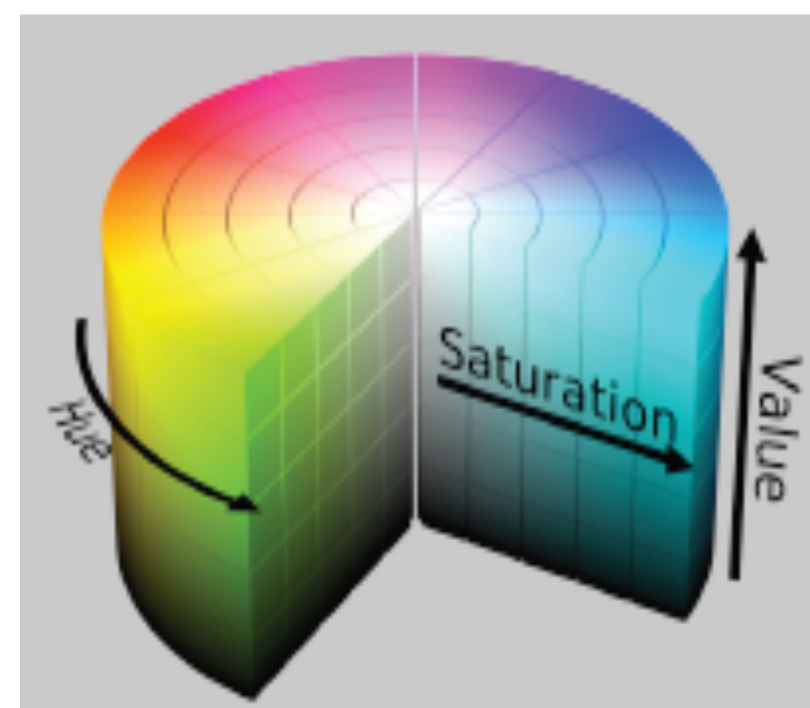
- Perceptual uniform transformation of XYZ
- L approximates luminance or Y in XYZ
- (a,b) & (u,v) approximate chromaticity or M-to-G and Y-to-B channels (the XZ in XYZ)



From HSV to HCL

- HSL/HSV are intuitive, so convert them to be “perceptually uniform” like Lab
- Transform ab to polar coordinates: radius is Chroma, Angle is Hue
- Conversion to/from RGB is complicated, but distances in HCL make sense, **and** it makes sense for humans
- Like HSV, but good. **All else being equal, think HCL first**





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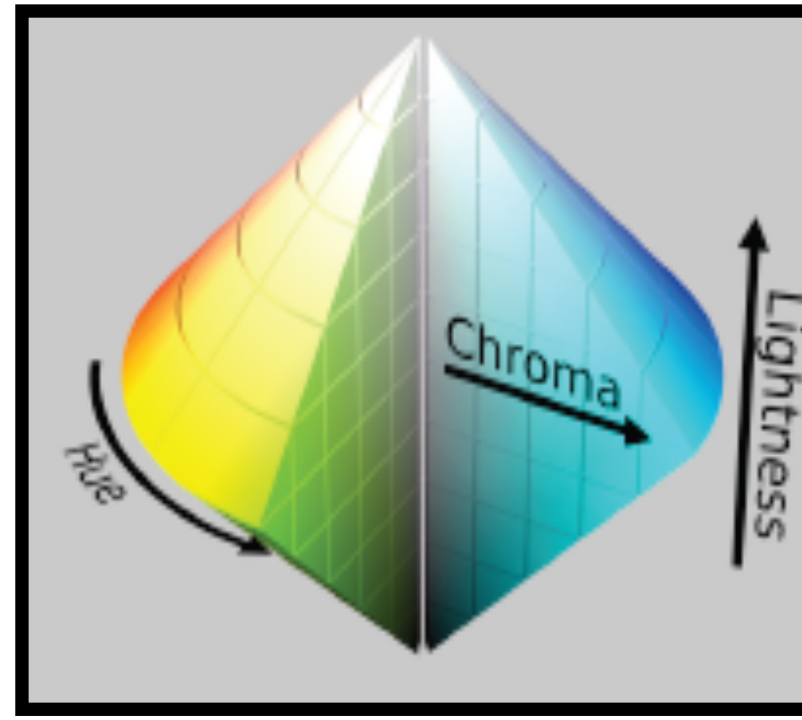
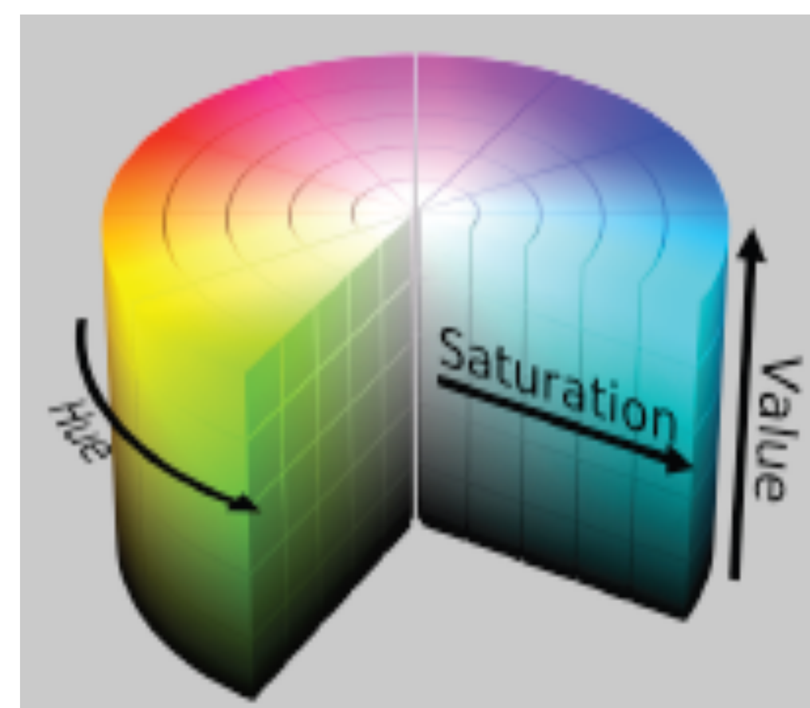




Representing Colors as Three Numbers

Editor: Frank Bliss

Maureen C. Stone
StoneSoup Consulting

How do three numbers, such as RGB or XYZ, represent color perception, and how are these representations related to each other and to physical color? When do they fail?

RGB in graphics is both a way of specifying color and a way of viewing color. Graphics algorithms manipulate RGB colors, and the images produced by graphics algorithms are encoded as RGB pixels and displayed on devices that render these pixels by emitting RGB light. Colored images are also used to specify color in graphics. These images may be captured by cameras or scanners, interactively drawn using tools such as Adobe PhotoShop, or algorithmically generated. But, what do all of these RGB values mean with respect to color perception? How does the RGB triple captured by a digital camera relate to the RGB pixels displayed on a monitor? How does the RGB triple selected with an interactive color tool relate to the RGB triple used to color an object in a 3D rendering?

Most computer graphics texts and tutorials provide a description of human color vision and measurement as defined by the CIE tristimulus values, XYZ. Often missing, however, is an in-depth discussion of the relationship between the different applications of RGB and XYZ, and any discussion of color models beyond trichromacy. The goal of this tutorial is to provide a complete, concise analysis of RGB color specification and its relationship to perceptual and physical specifications of color, and to introduce some models for color perception beyond tristimulus theory.

Representing color as three numbers

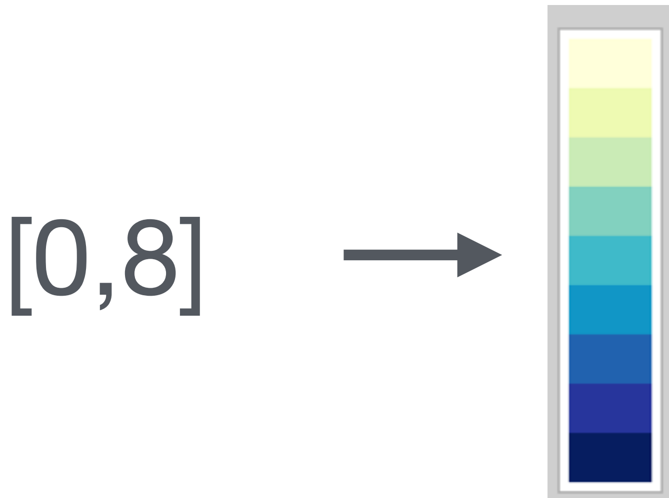
That color can be represented by three numbers—whether RGB or XYZ—is a direct result of the physiology of human vision. Electromagnetic radiation whose wavelength is in the visible range (370 to 730 nanometers) is converted by photopigments in the retinal cones into three signals, which correspond to the response of the three types of cones. This response is a function of wavelength and is described by the spectral sensitivity curves for the cones, as Figure 1 shows.

Colored light can be represented as a spectral distribution, which plots power as a function of wavelength. (Other fields, such as signal processing, plot spectra as a function of frequency, which is the inverse of wavelength.) The cones convert this to three cone response

Using Color to Encode Data

What is a Colormap?

- Specifies a mapping between color and values
  - Sometimes called a **transfer function**
- Colormaps can be:



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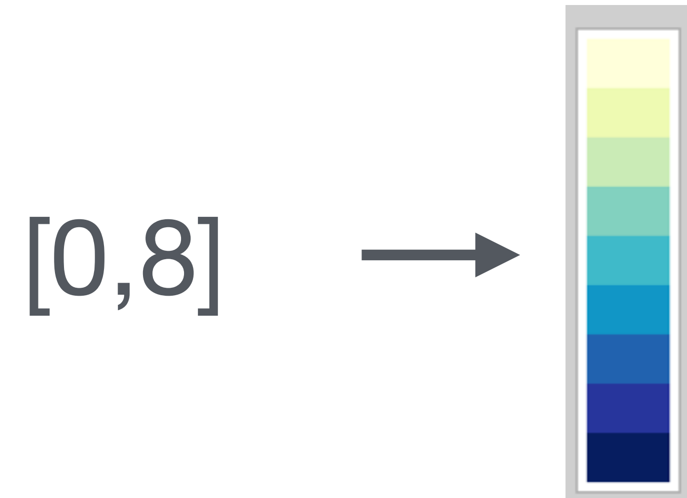
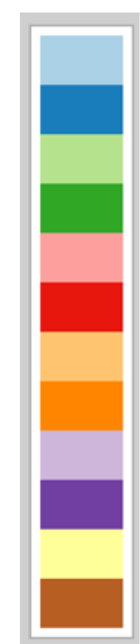


- Colormaps can be:
  - categorical vs. ordered



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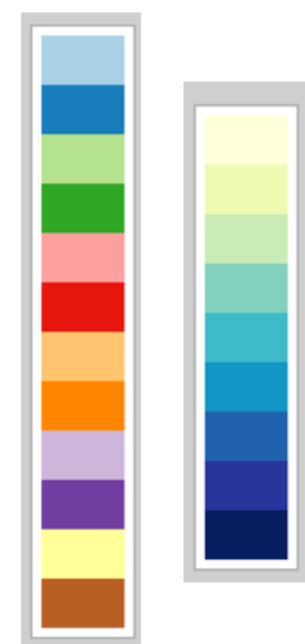
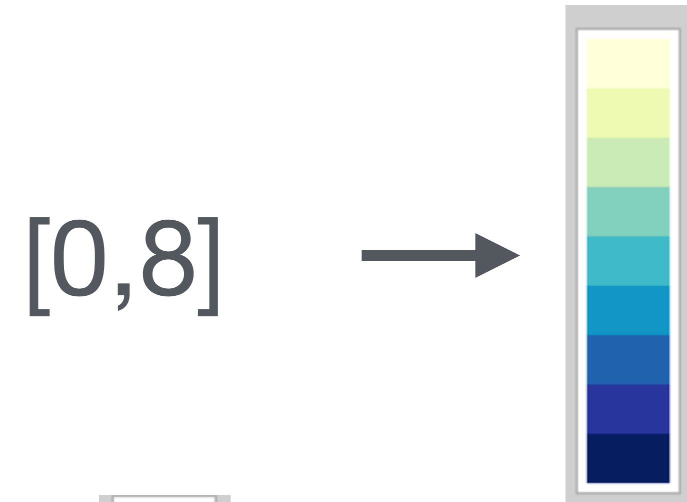
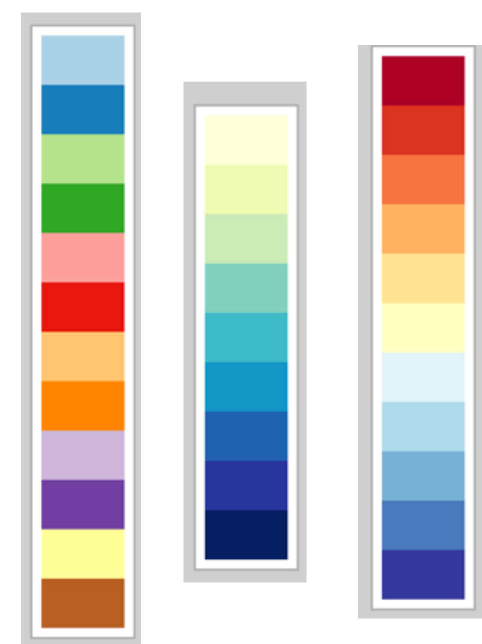


What is a Colormap?

- Specifies a mapping between color and values
  - Sometimes called a **transfer function**
- Colormaps can be:
  - categorical vs. ordered
  - sequential vs. diverging





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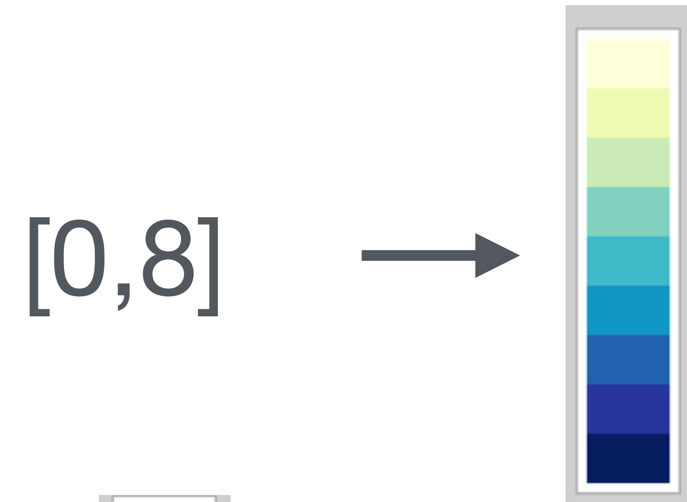
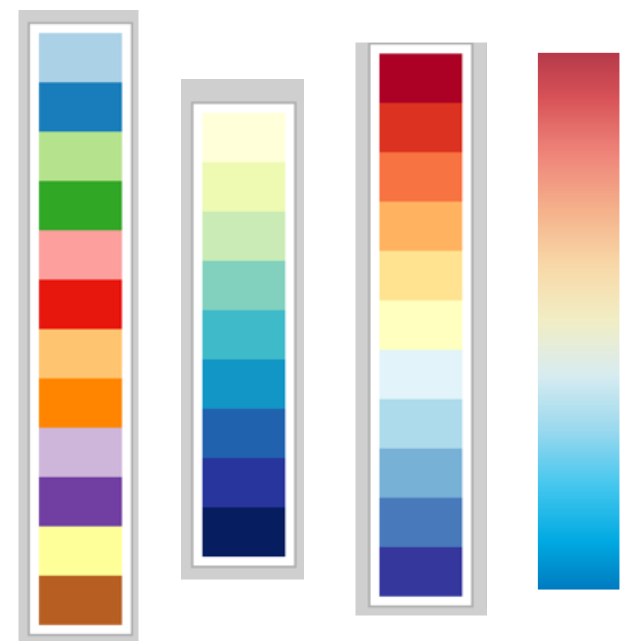


- Colormaps can be:
    - categorical vs. ordered
    - sequential vs. diverging
    - segmented vs. continuous



What is a Colormap?

- Specifies a mapping between color and values
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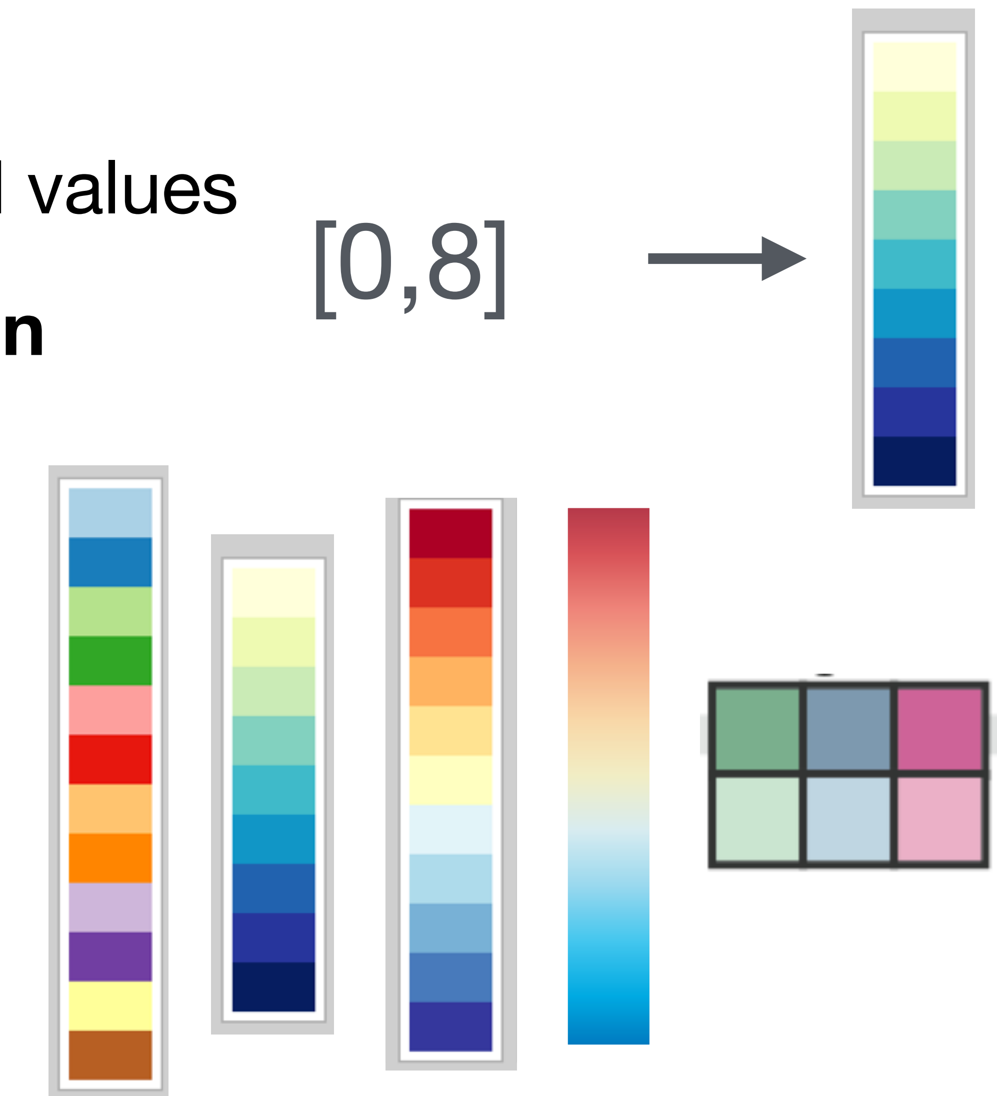
- Colormaps can be:
  - categorical vs. ordered
  - sequential vs. diverging
  - segmented vs. continuous
  - univariate vs. bivariate



What is a Colormap?

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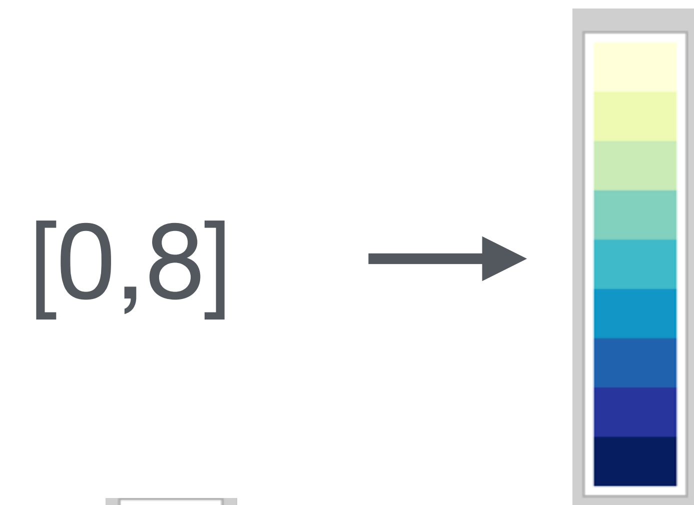

- Colormaps can be:
  - categorical vs. ordered
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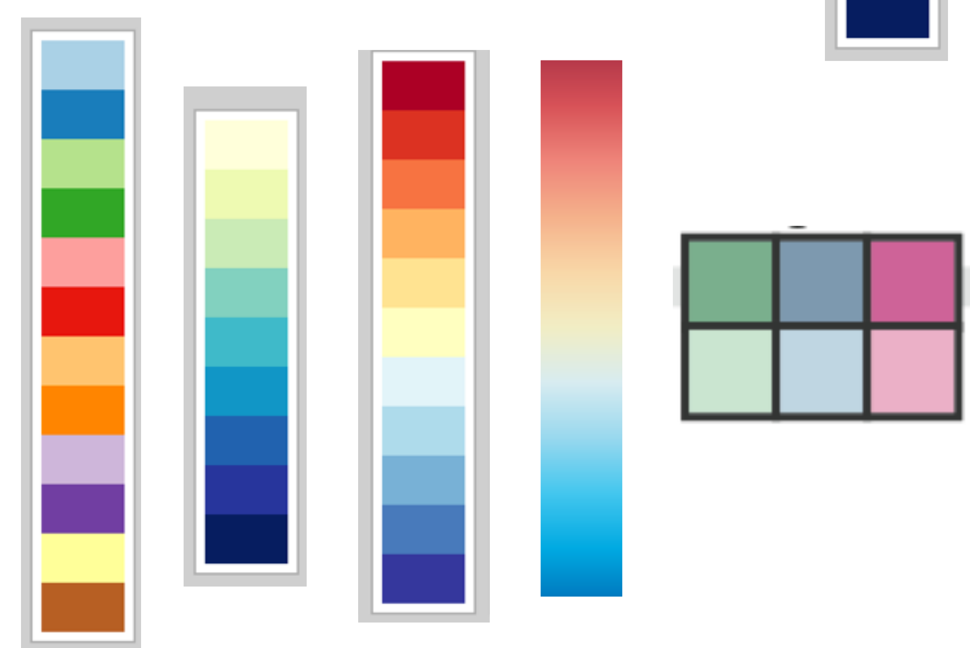
  - segmented vs. continuous
  - univariate vs. bivariate

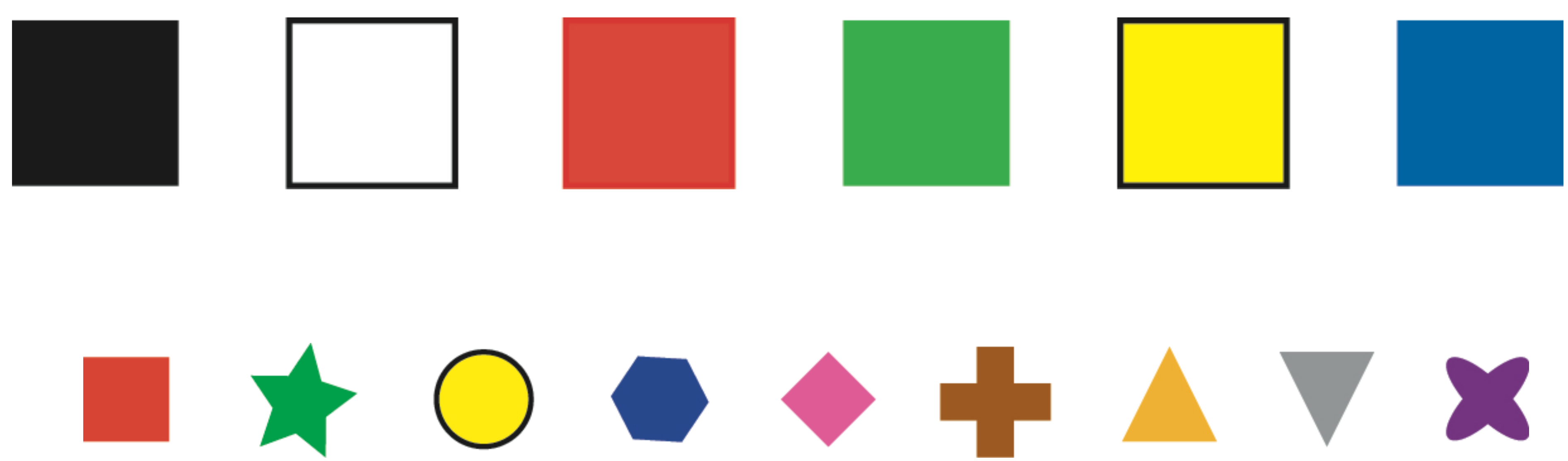


- Recall: expressiveness in visual encoding — Match colormap to attribute type characteristics!

Encoding Nominal Data

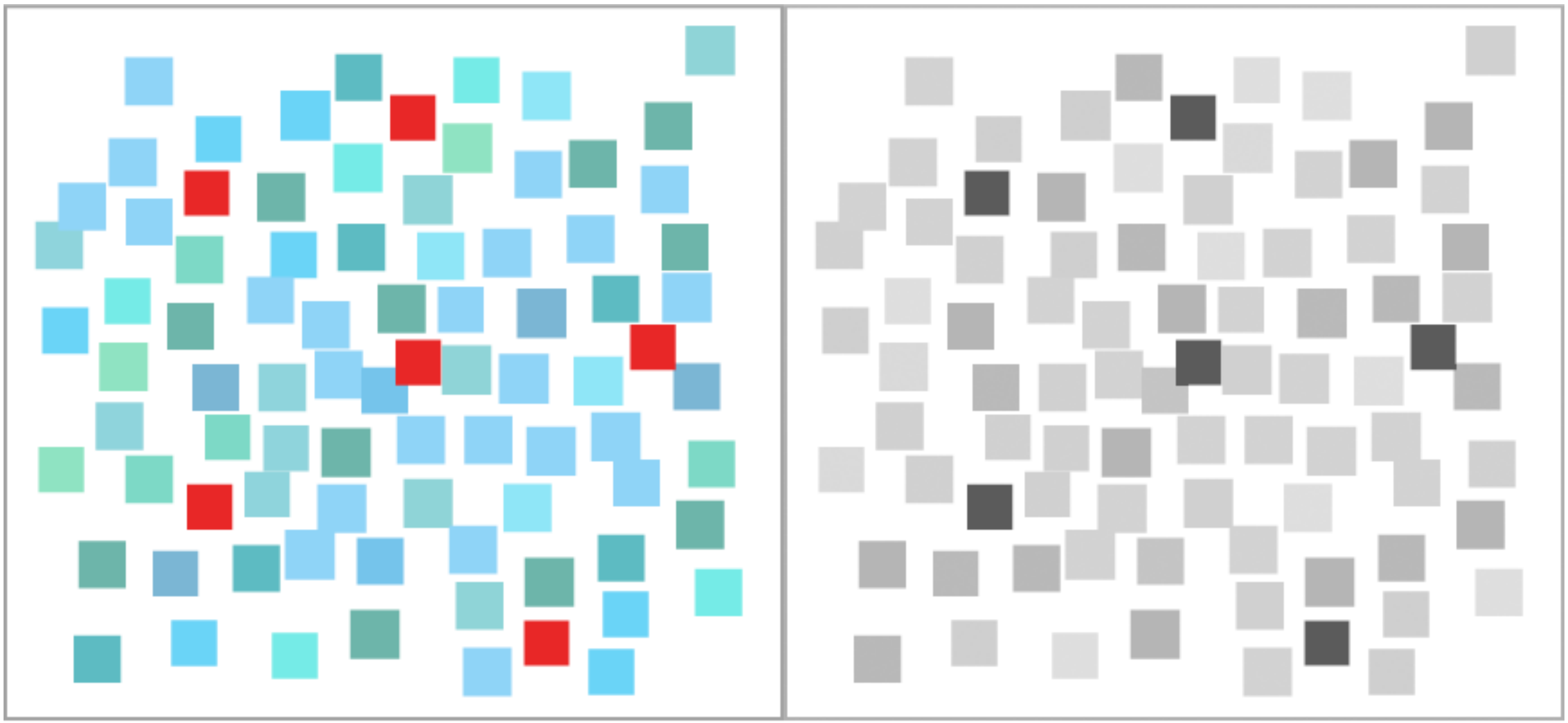
Categorical Colormaps

- Categorical colors are easier to remember if they are nameable
- Typically designed by using color as an integral identity channel to encode a single attribute



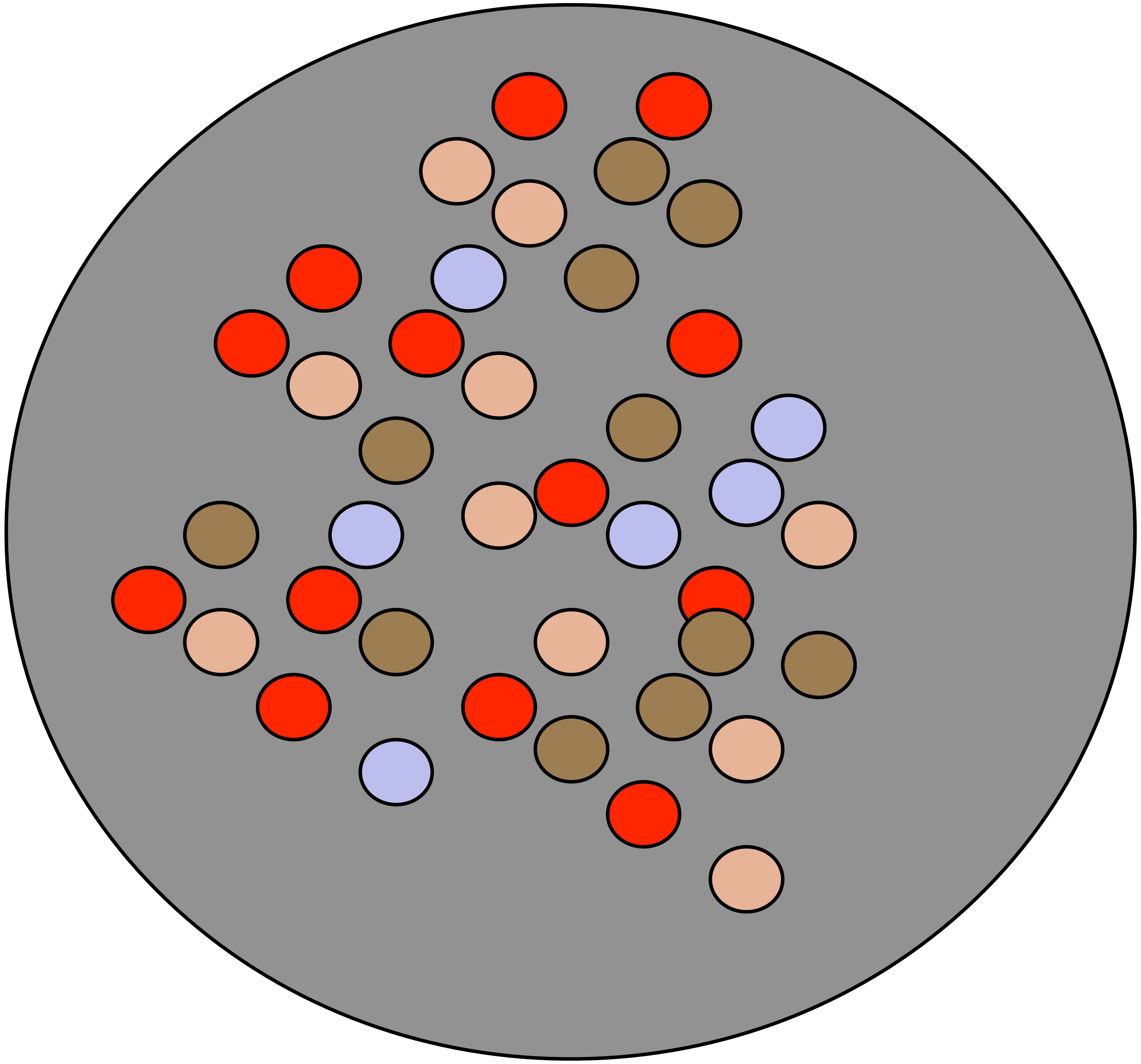
Colin Ware, Information Visualization: Perception for Design

Recall: Popout



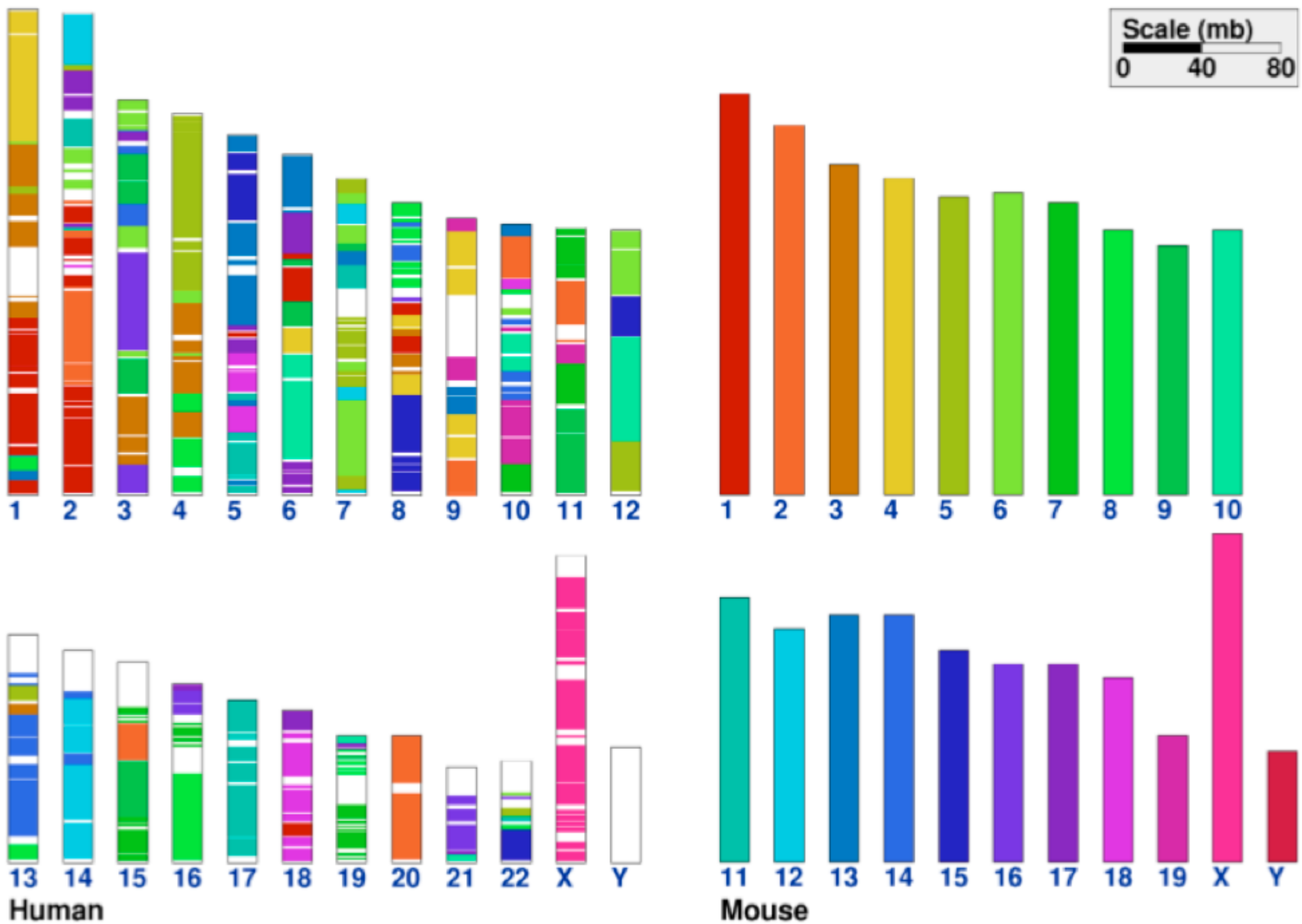
Hue and Lightness **Lightness only**

Brightness and Saturation Draw Attention



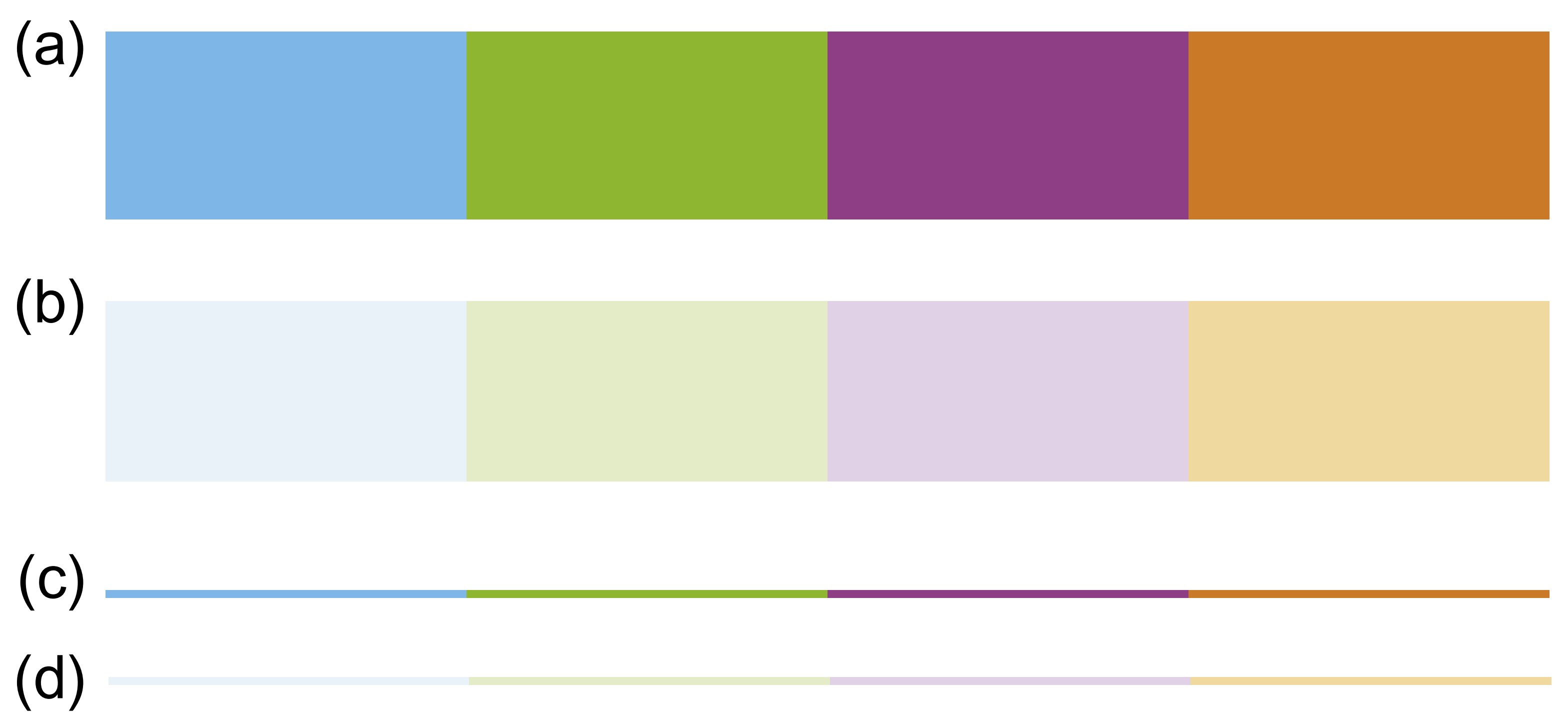
Distinguishability

Only good at distinguishing ~12 simultaneous colors

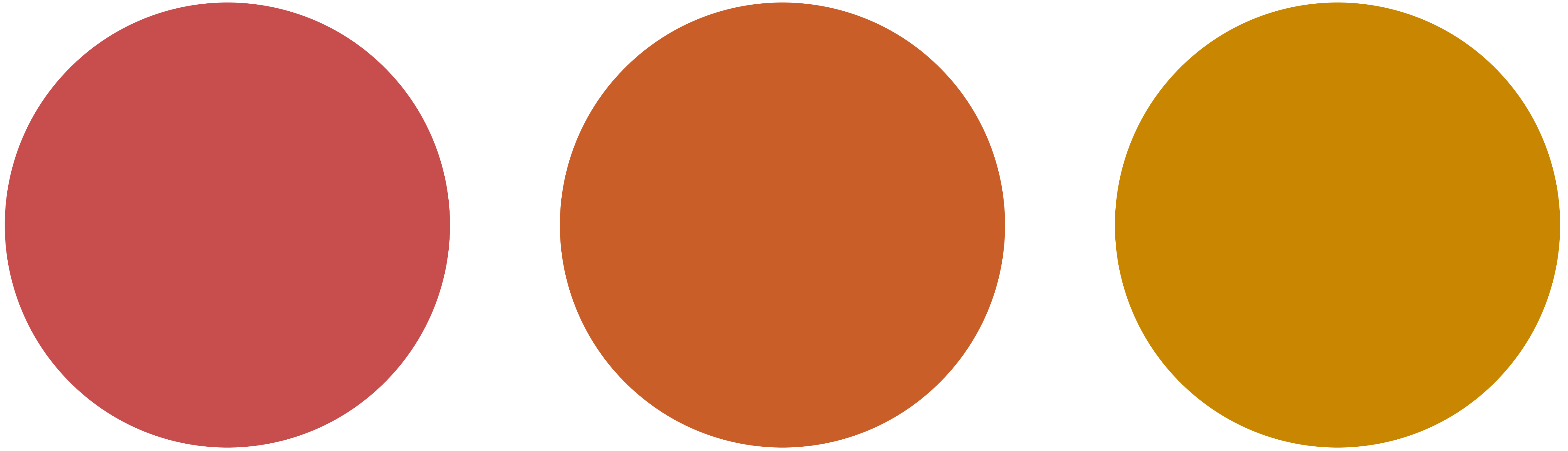


Color vs. Size

- Use more saturated colors when color coding small symbols, thin lines, or other small areas. Use less saturated colors for coding large areas.



Colin Ware, Information Visualization: Perception for Design



Luminance Contrast

- When small symbols, text, or other detailed graphical representations of information are displayed using color on a differently colored background, always ensure luminance contrast with the background.

Showing small blue text on a black background is a bad idea.
There is insufficient luminance contrast.

Showing small blue text on a black background is a bad idea.
There is insufficient luminance contrast.

Showing small yellow text on a white background is a bad idea.
There is insufficient luminance contrast.

Showing small yellow text on a white background is a bad idea.
There is insufficient luminance contrast.

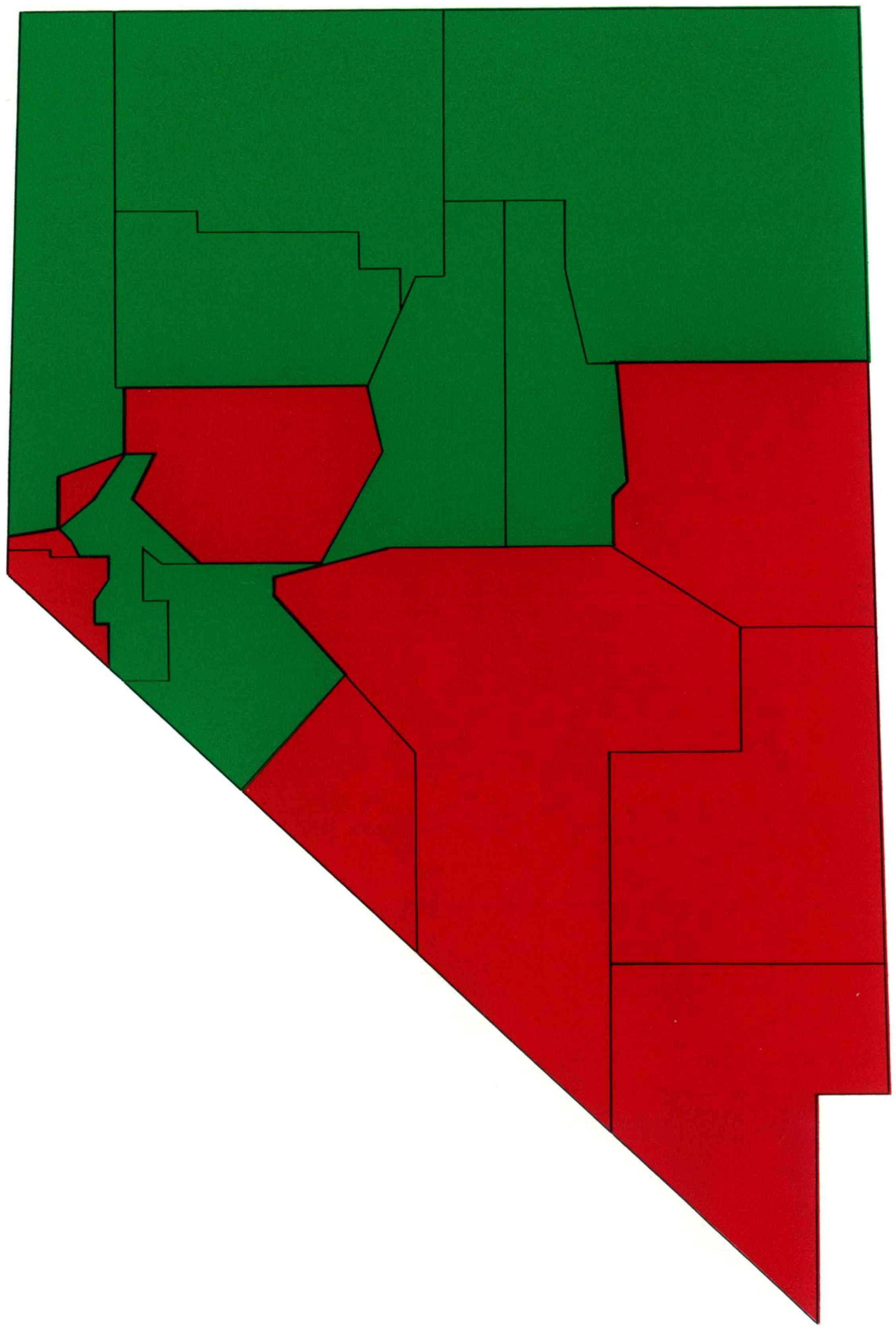
Form

- When applying shading to define the shape of a curved surface, use adequate luminance (as opposed to chromatic) variation.
- If large areas are defined using nearly equiluminous colors, consider using thin border lines with large luminance differences (from the colors of the areas) to help define the shapes.

Colin Ware, Information Visualization: Perception for Design

102 © The American Statistician, May 1983, Vol. 37, No. 2

Which area is bigger, red or green?



Cleveland & McGill, "A Color-Caused Optical Illusion on a Statistical Graph", 1983

Figure 1. Stimulus From the High-Saturation Group

Cleveland & McGill, “A Color-Caused Optical Illusion on a Statistical Graph”, 1983

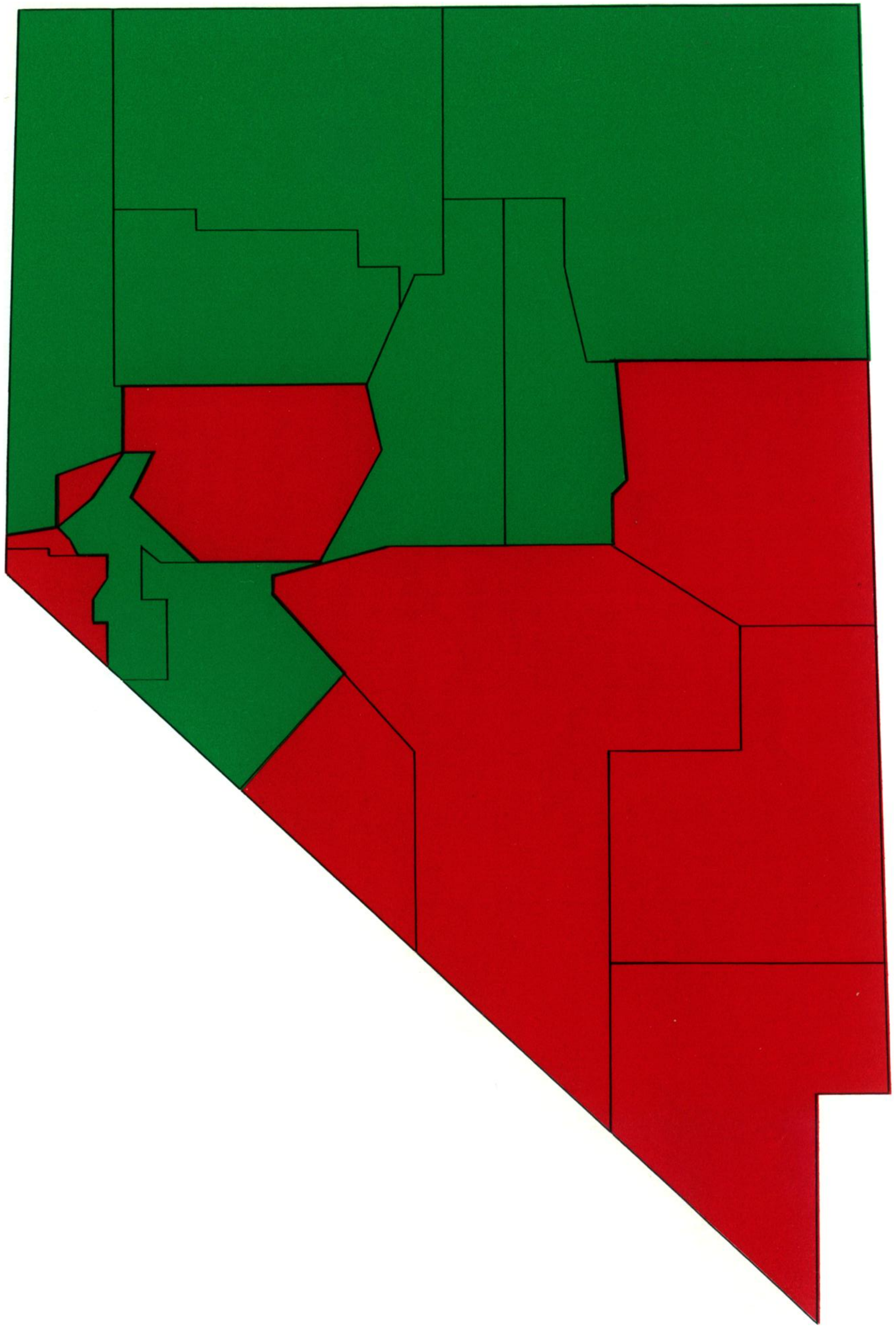


Figure 1. Stimulus From the High-Saturation Group

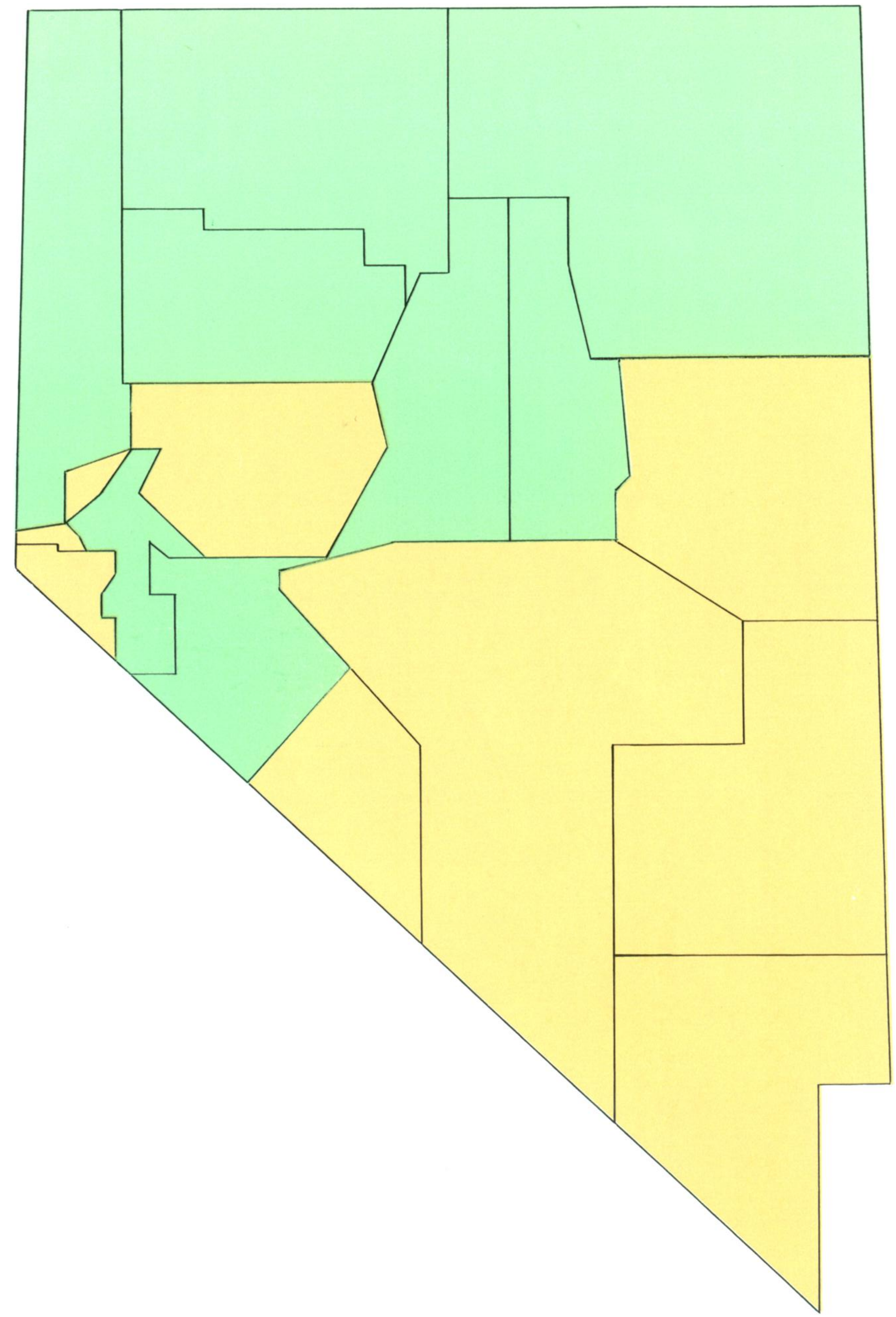
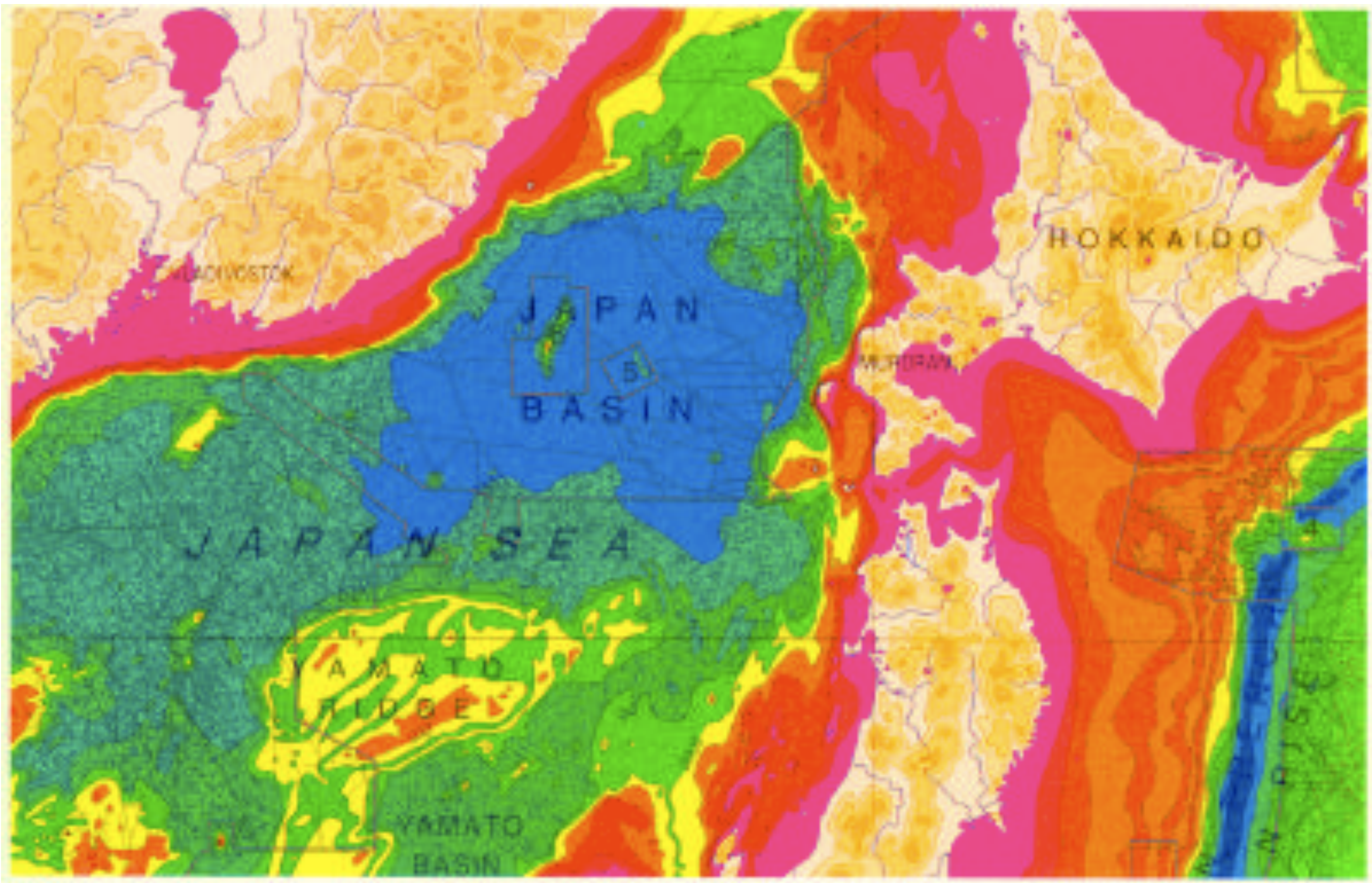


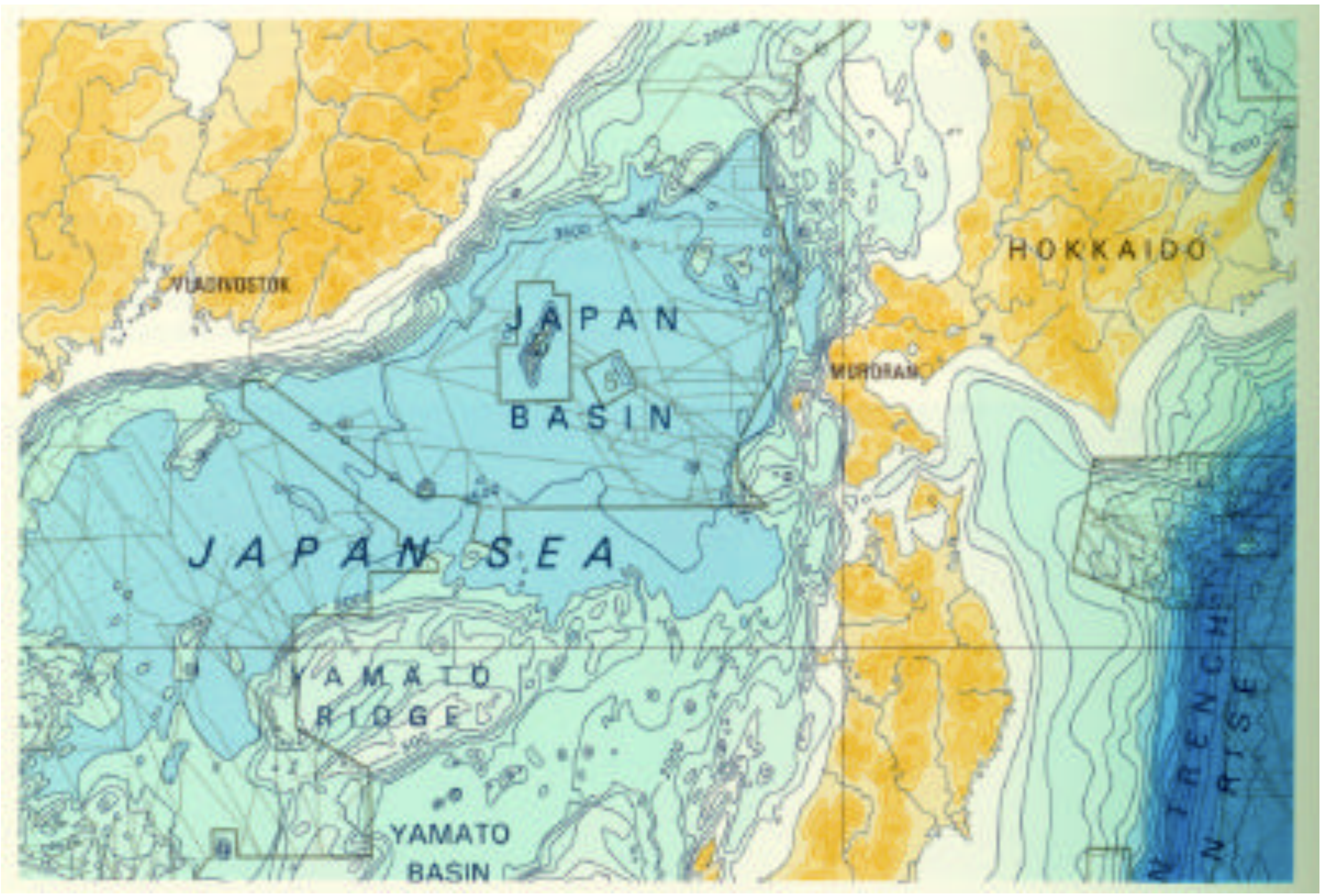
Figure 2. Stimulus From the Low-Saturation Group

Effects of Color on Large Areas



Tufte, Visual Display of Quantitative Information, pg. 77

Effects of Color on Large Areas



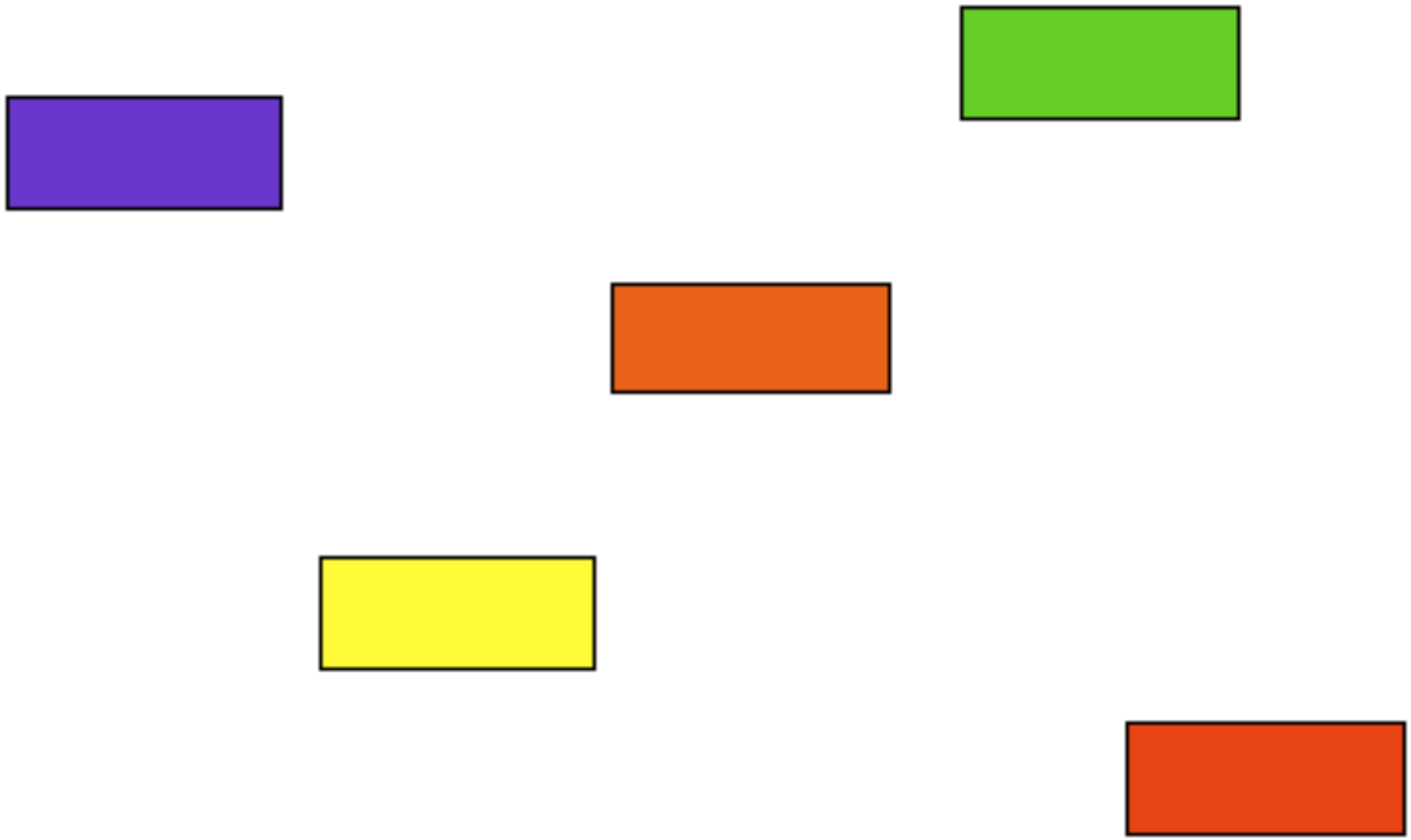
Tufte, Visual Display of Quantitative Information, pg. 77

Summary/Guidelines

- Saturation interacts strongly with size
- In small regions:
  - Saturation is more difficult to perceive, in particular saturation and hue are not separable
  - Use bright, highly saturated colors
- In large regions:
  - Higher saturation makes large areas look bigger
  - Use low saturation pastel colors for large regions and backgrounds

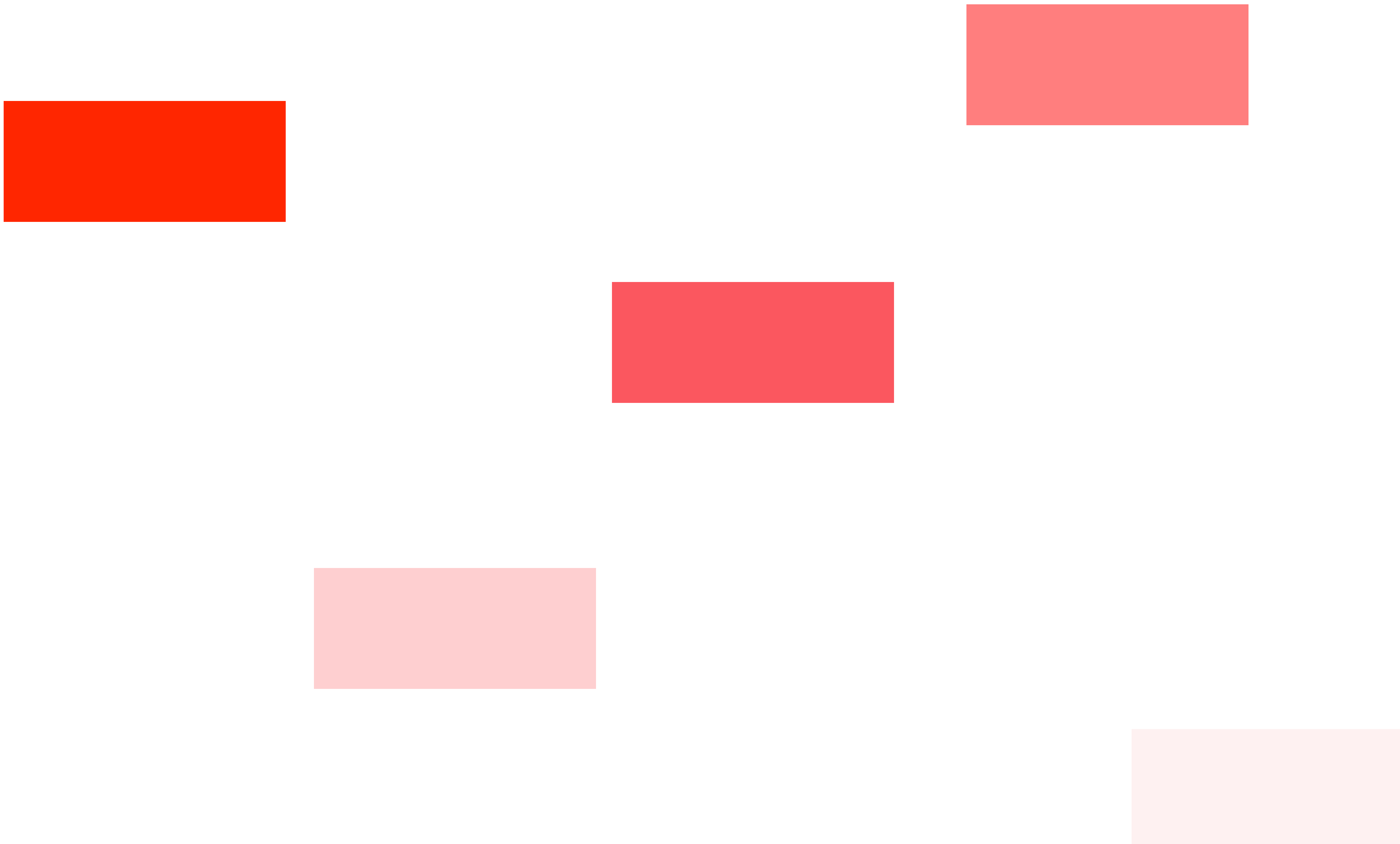
Encoding Ordered Data

Order These Colors?



Order These Colors?

Order These Colors?



Colormaps & Ordered Attributes

- Ordered colormaps are the most effective if they vary along saturation or luminance

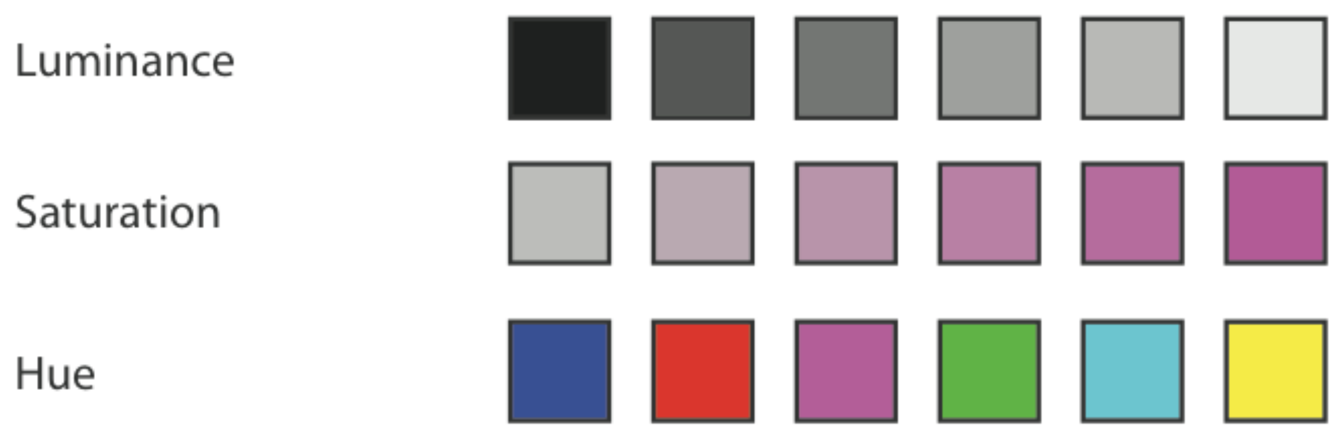
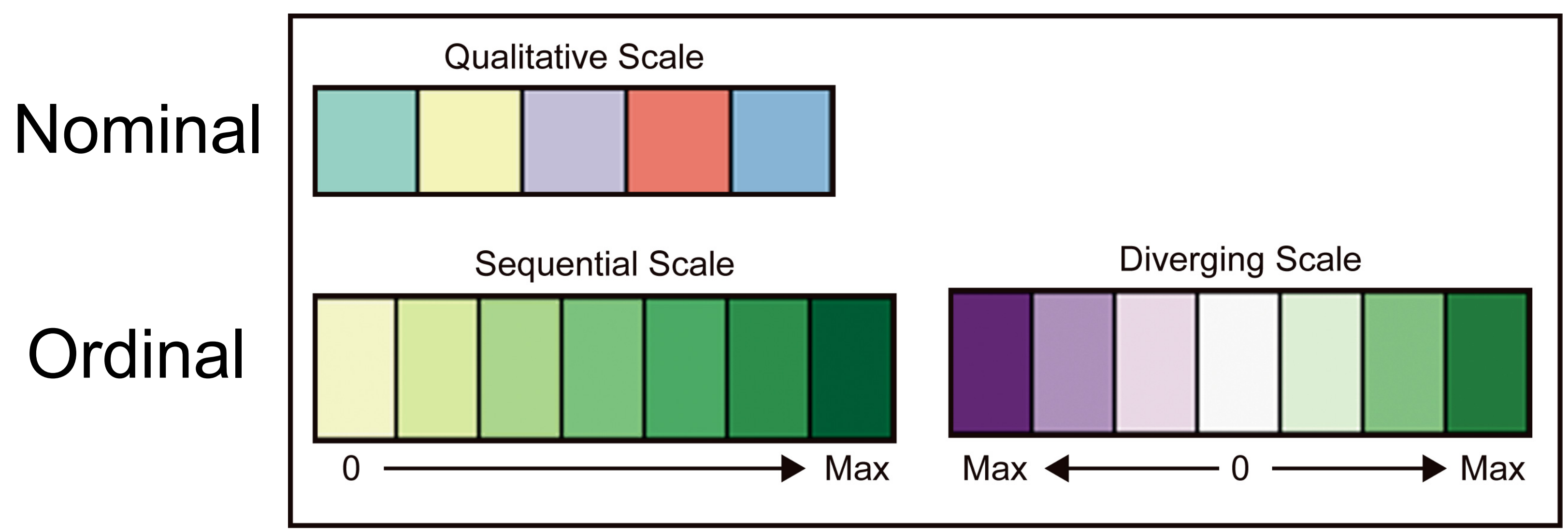


Figure 10.5. The luminance and saturation channels are automatically interpreted as ordered by our perceptual system, but the hue channel is not.



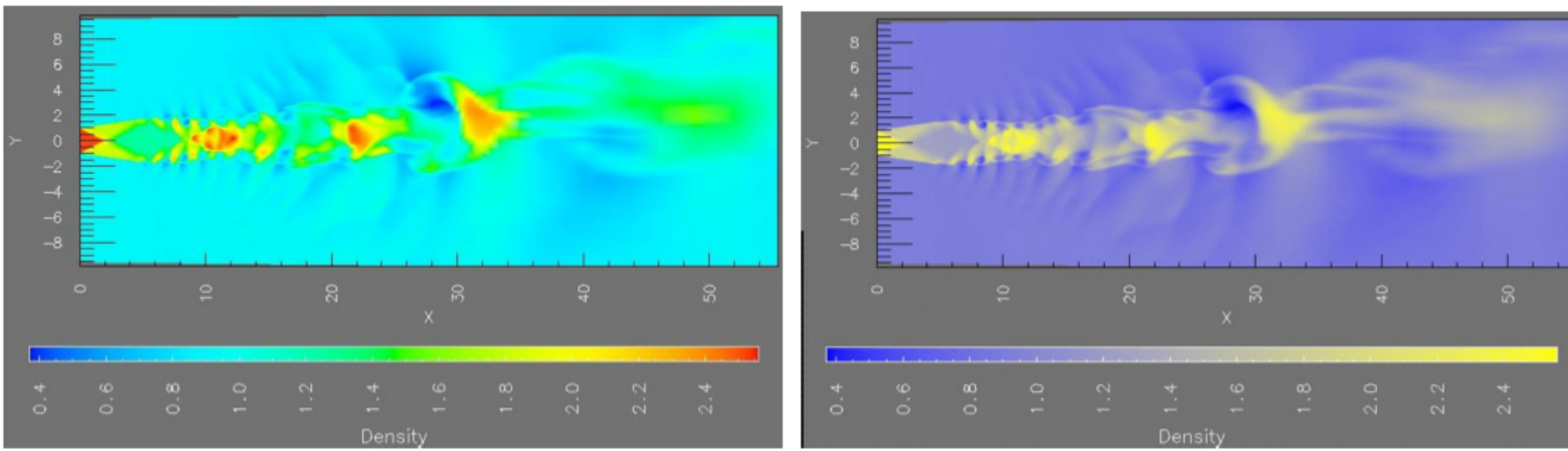
Summary/Guidelines

- Number of hues, and distribution on the colormap, should be related to which, and how many structures in the data to emphasize
    - min or max, ends or middle, etc…
- Show ordinal data with a discrete set of colors (and hence have to limit the number)
- If encoding ordinal data with color, place marks on solid, neutral background

Encoding
Quantitative Data

Quantitative Data

- Sequential vs. Diverging Colormaps



(a) (b)

Figure 10.11. Rainbow versus two-hue continuous colormap. (a) Using many hues, as in this rainbow colormap, emphasizes mid-scale structure. (b) Using only two hues, the blue–yellow colormap emphasizes large-scale structure. From [Bergman et al. 95, Figures 1 and 2].

The Rainbow Colormap

- Where is zero in (a)?

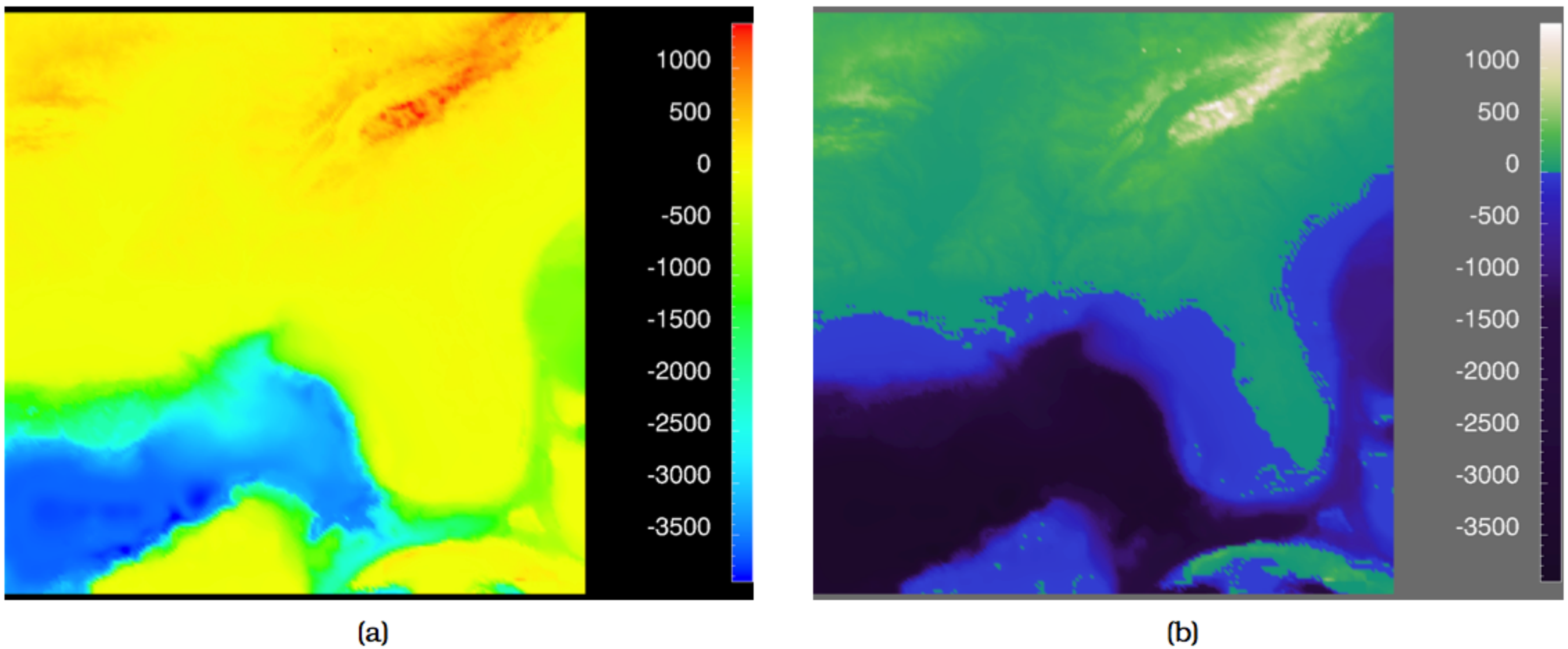


Figure 10.12. Rainbow versus multiple-hue continuous colormap with monotonically increasing luminance. (a) Three major problems with the common continuous rainbow colormap are perceptual nonlinearity, the expressivity mismatch of using hue for ordering, and the accuracy mismatch of using hue for fine-grained detail. (b) A colormap that combines monotonically increasing luminance with multiple hues for semantic categories, with a clear segmentation at the zero point, succeeds in showing high-level, mid-level, and low-level structure. From [Rogowitz and Treinish 98, Figure 1].

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.

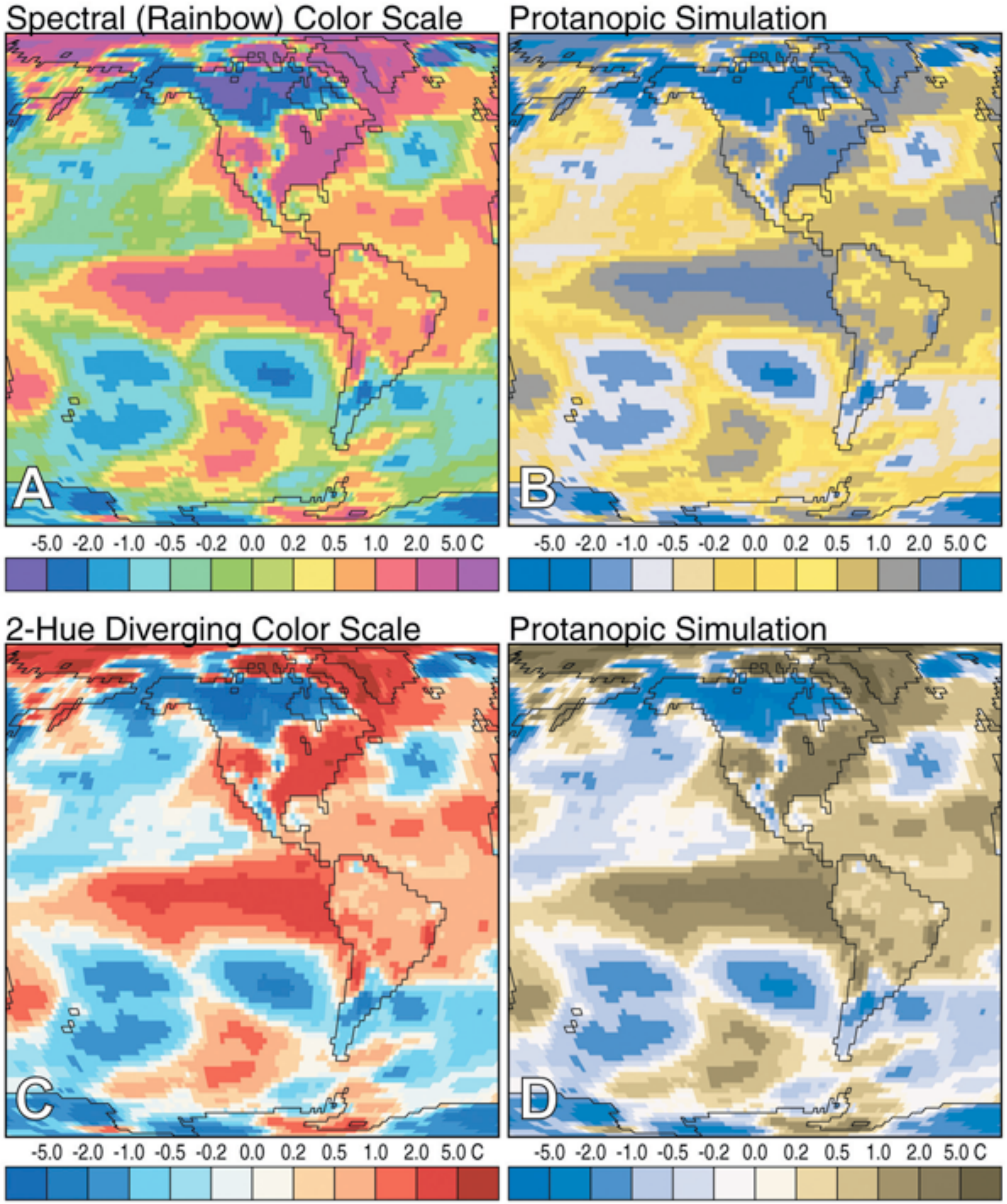
In this article, we reiterate the characteristics that make the rainbow color map a poor choice, provide examples that clearly illustrate these deficiencies even on simple data sets, and recommend better color maps mercials, weather forecasts, and even the IEEE Visualization Conference 2006 call for 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

Rainbow Colormaps and Color Deficiency

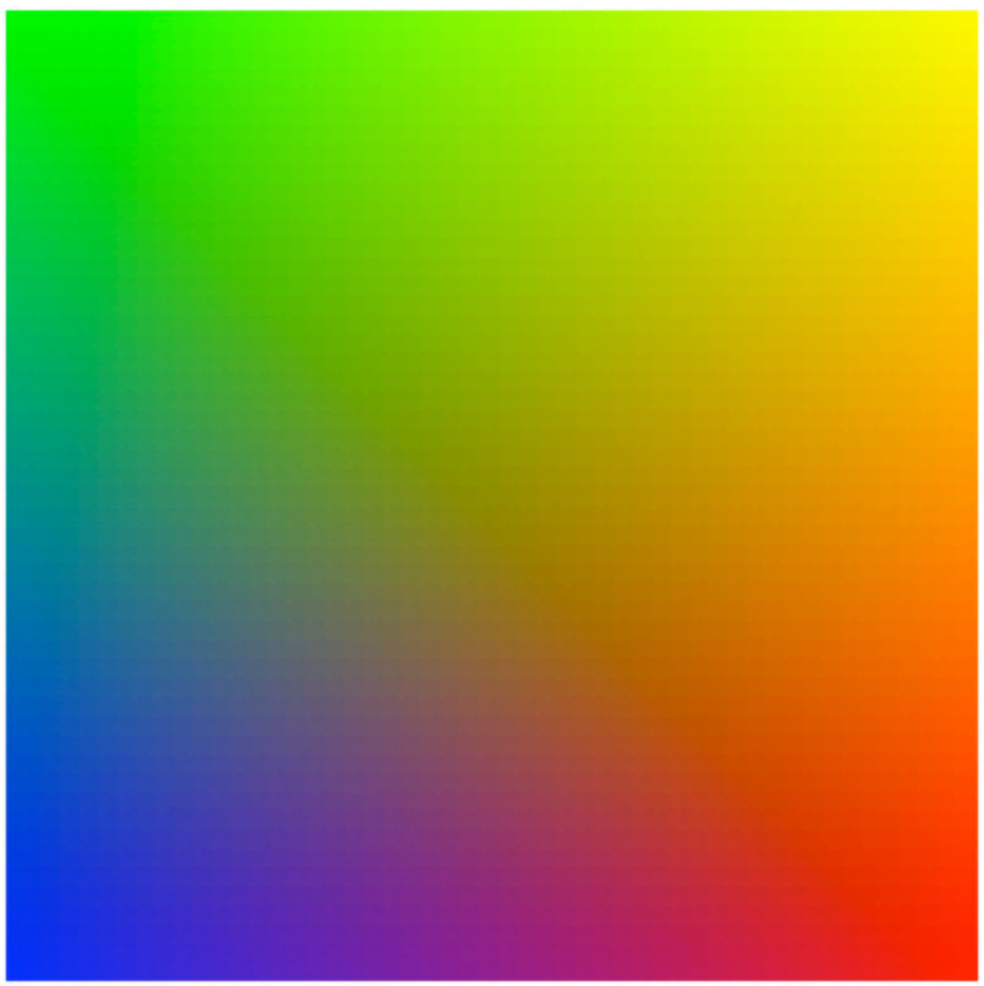


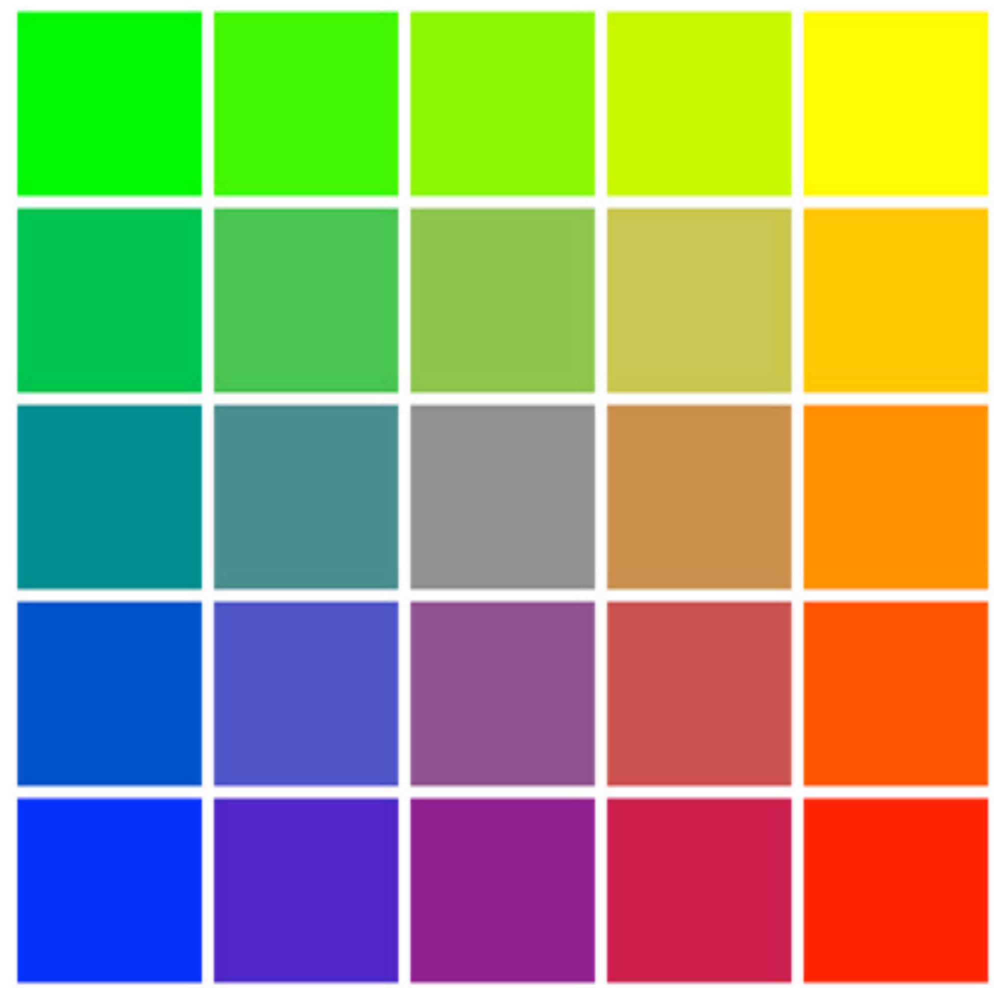
http://blog.visual.ly/rainbow-color-scales/

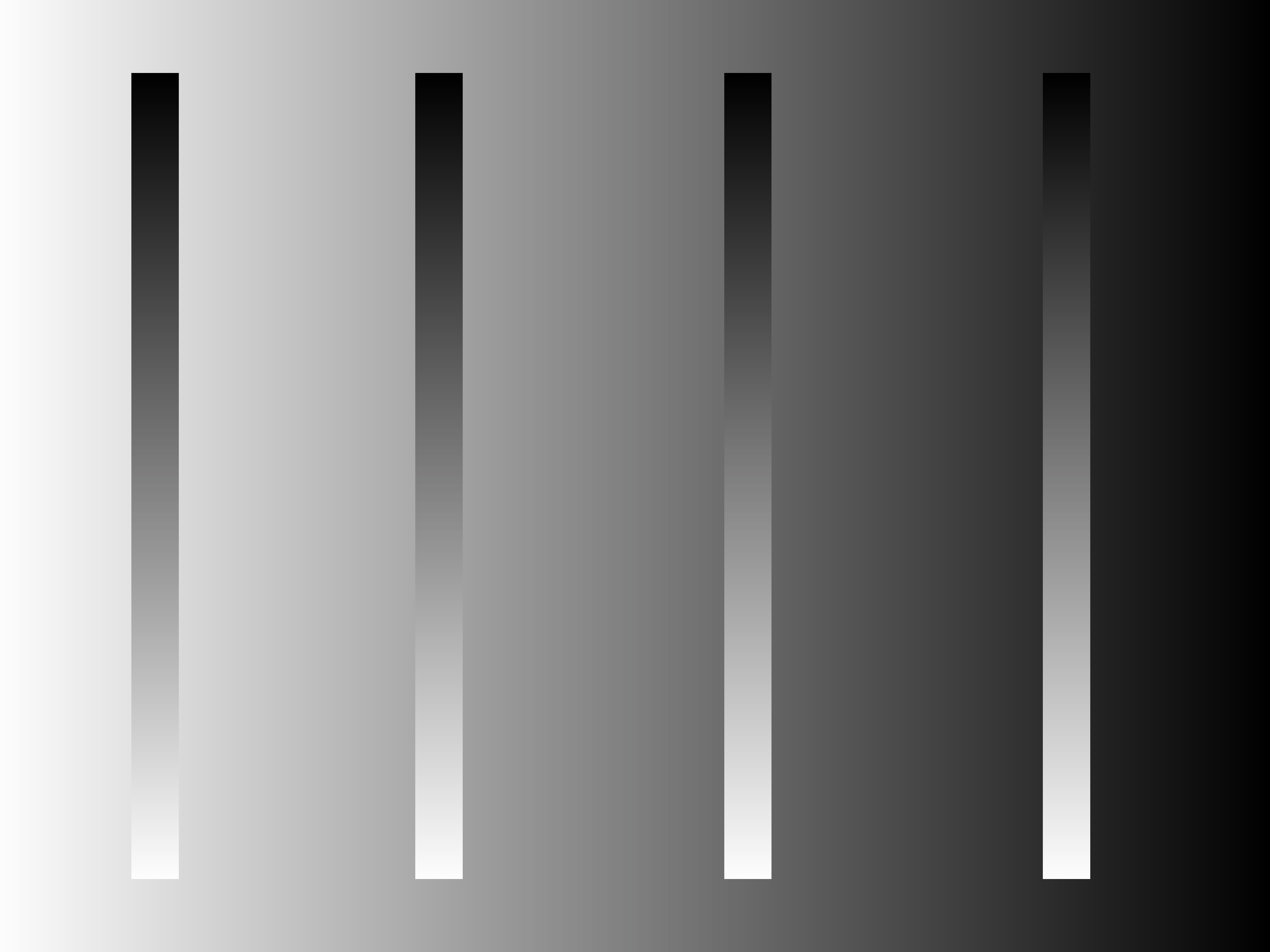
Light, A and P.J. Bartlein (2004) The end of the rainbow? Color schemes for improved data graphics. EOS Trans. of the American Geophysical Union 85(40):385

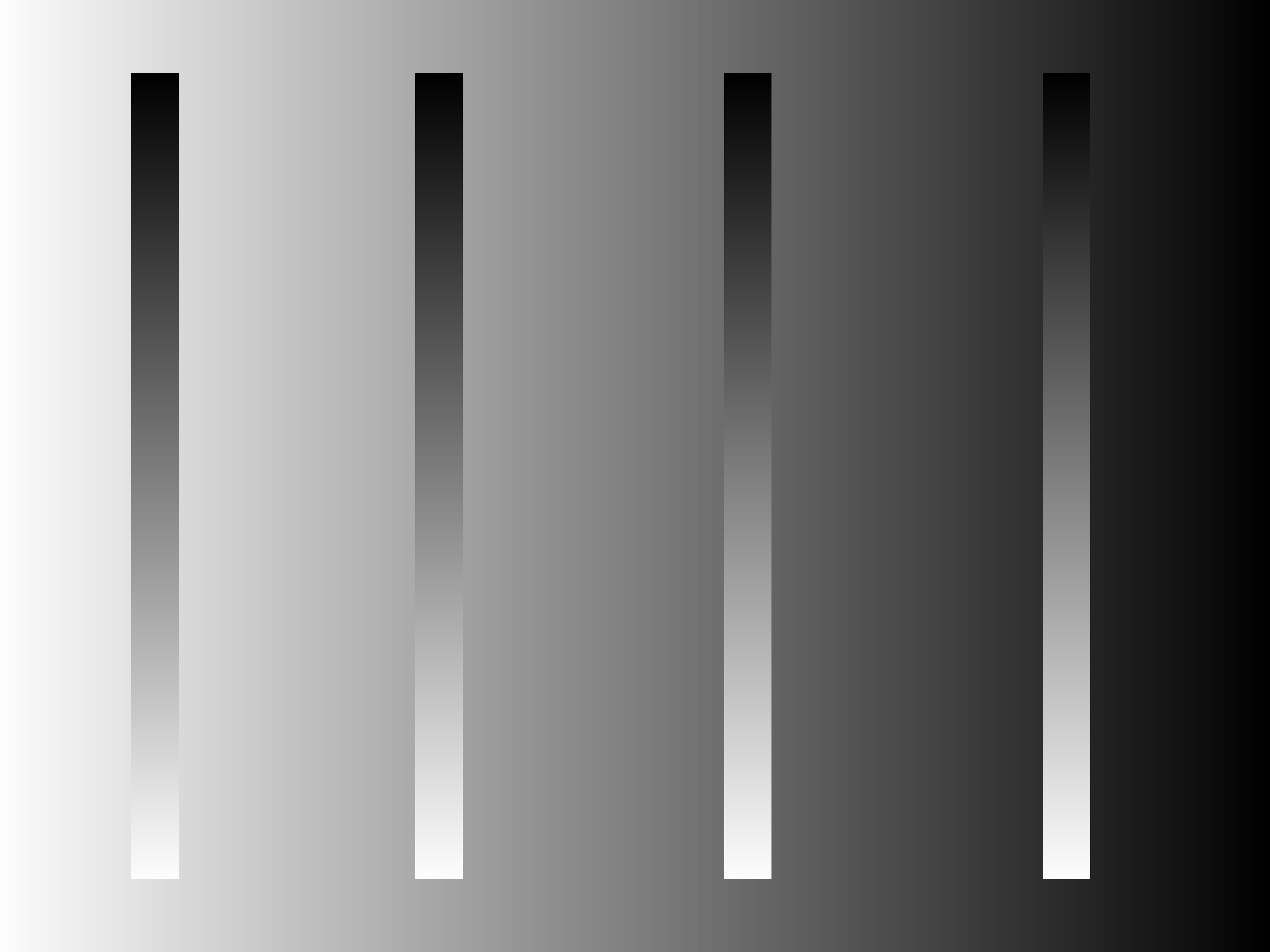
http://geog.uoregon.edu/datagraphics/EOS/

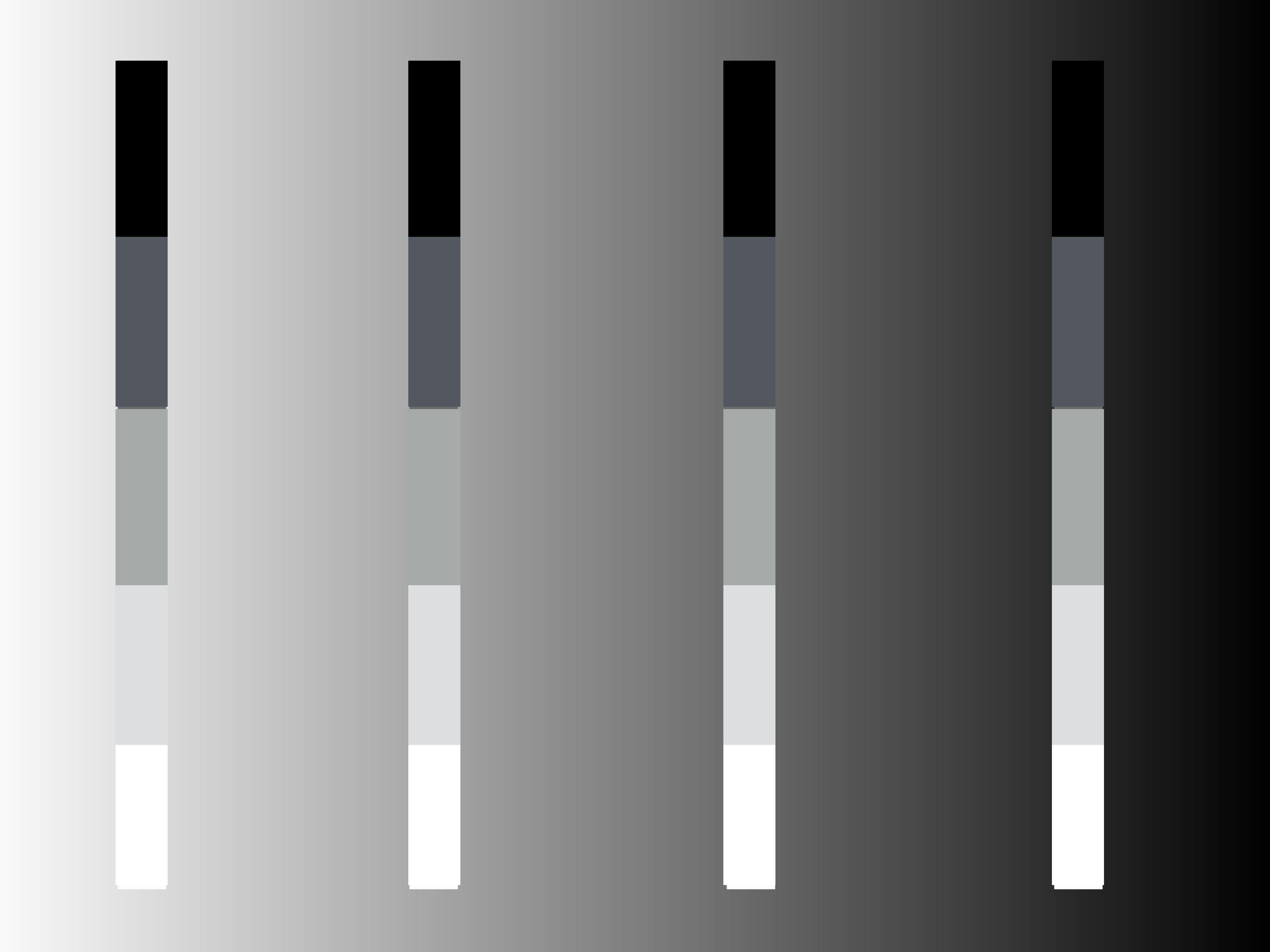
Consider Color Segmentation to Improve Accuracy



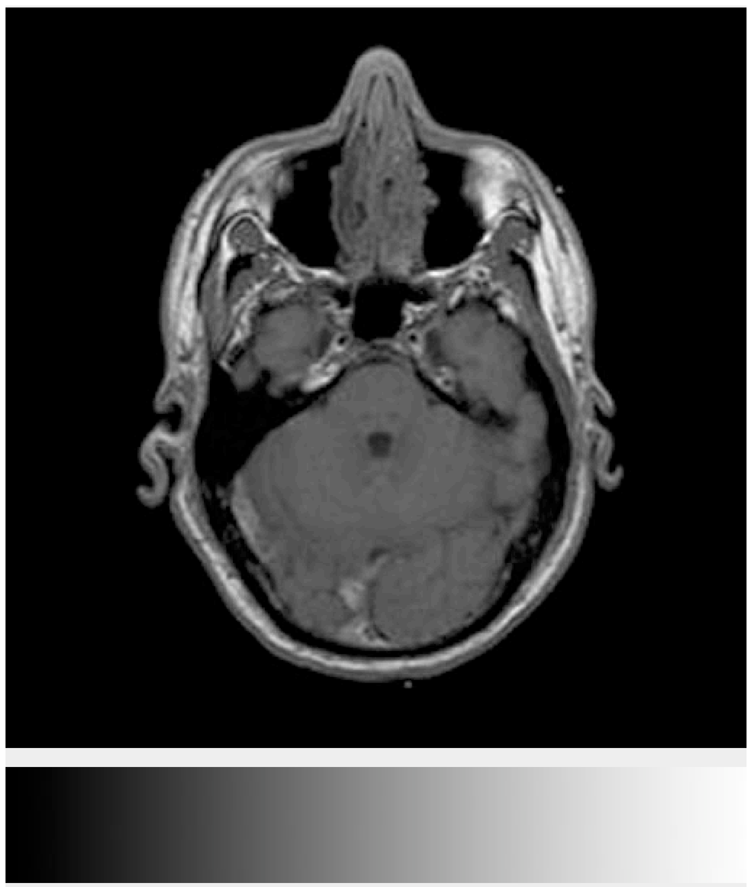




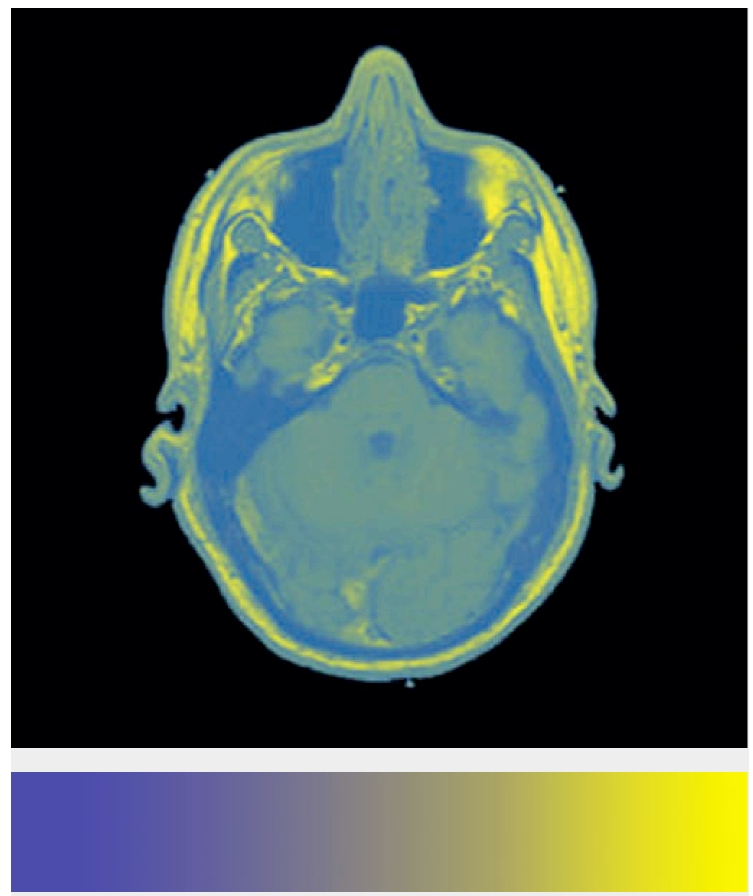




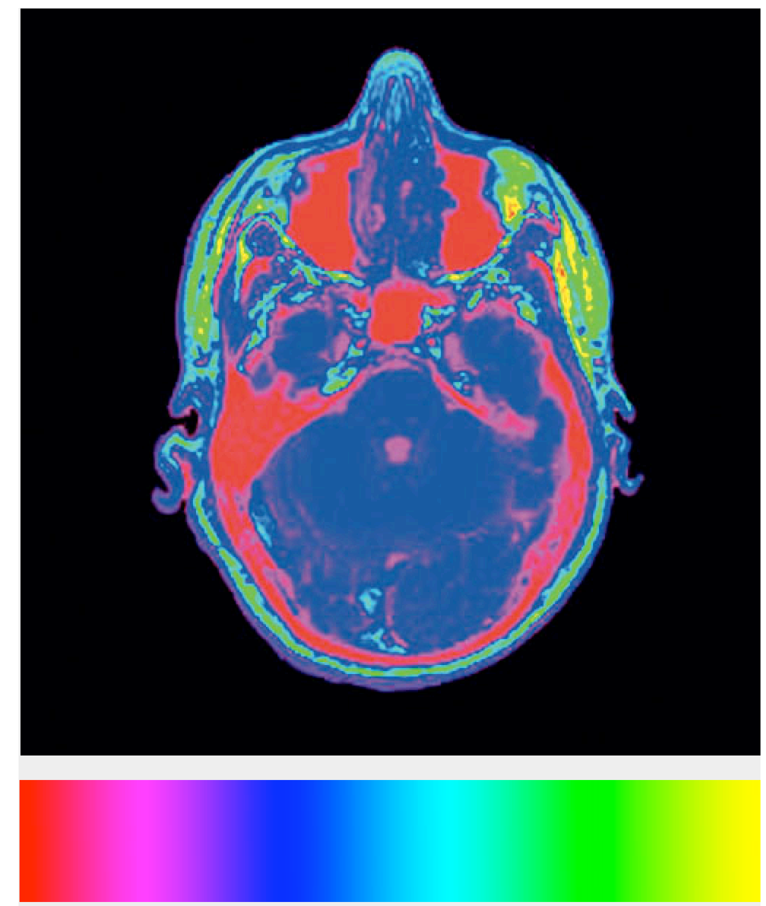
Other Colormaps for Quantitative Data



Lightness scale



Lightness scale with hue and chroma variation



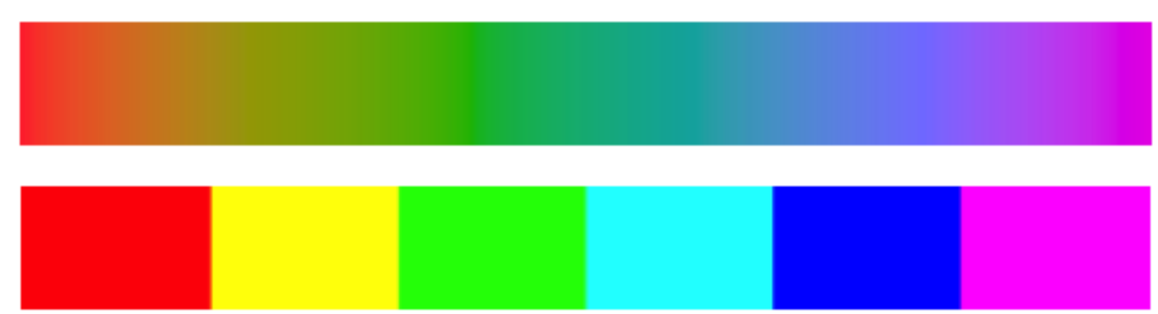
Hue scale with lightness variation

Summary/Guidelines

- Because of contrast effects, it is difficult to perceive absolute luminance of noncontiguous regions
  - Use only 2-4 bins when background is nonuniform
  - For text, ideally use 10:1 ratio, 3:1 minimum
- Show quantitative data with either a discrete set of colors or continuous (discrete for accuracy)
- Redundantly vary lightness and saturation

Poor

Better



“Get it right in black and white”

–Maureen Stone

Lec10 Reading

- Munzner, Ch. 3, 6.8, 11

Reminder
Assignment 02

Assigned: Monday, February 6
Due: Monday, February 20, 4:59:59 pm

Reminder
Project Milestone 01

Assigned: Monday, January 25
Due: Wednesday, February 22, 4:59:59 pm