Data Exploration & Visualization

Module 4

Color Vision

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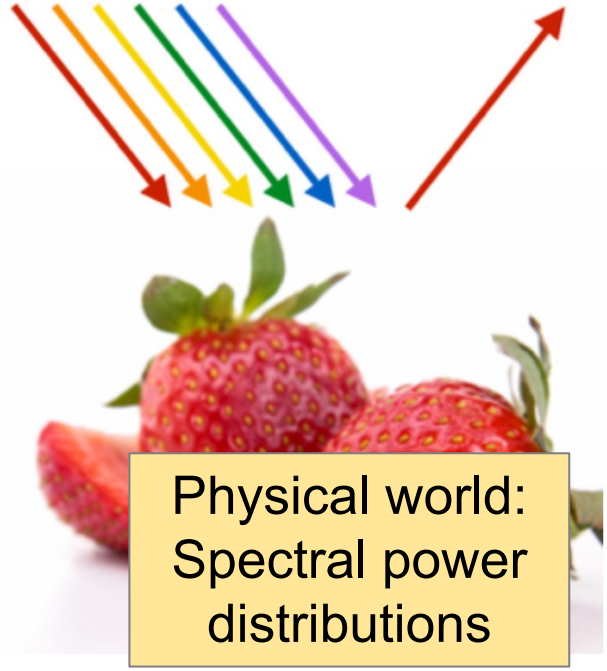
Data Exploration & Visualization

Module 4: Color Vision

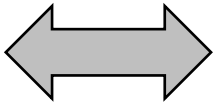
- Physics
  - Light, visible spectrum
- Color perception
  - Trichromatic theory, opponent process theory
- Color space and models
  - CIE XYZ, sRGB, Adobe RGB
  - RGB, CMYK, RYB, HSL, Lab
- Color mapping
  - Categorical, ordinal, quantitative
  - Common pitfalls in color use

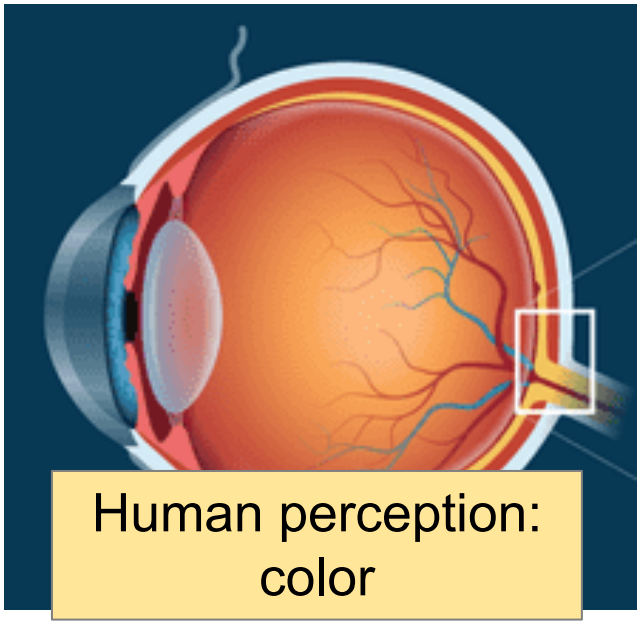
Colors of light

- Color is a function of the human visual system, and **is not** an intrinsic property.
- Objects **don't have** a color, they give off light that appears to be a color.



Physical world:
Spectral power distributions

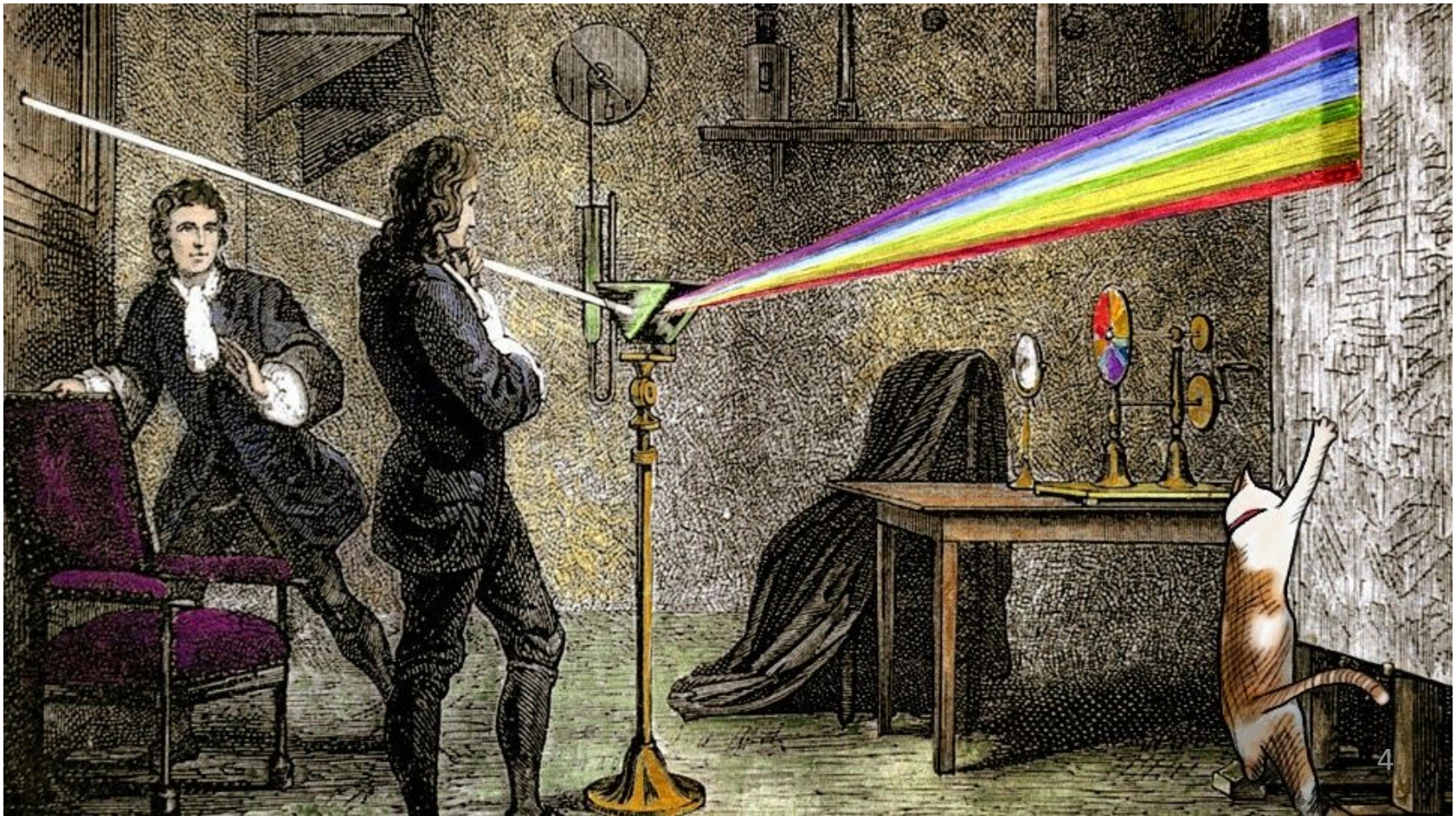




Human perception:
color

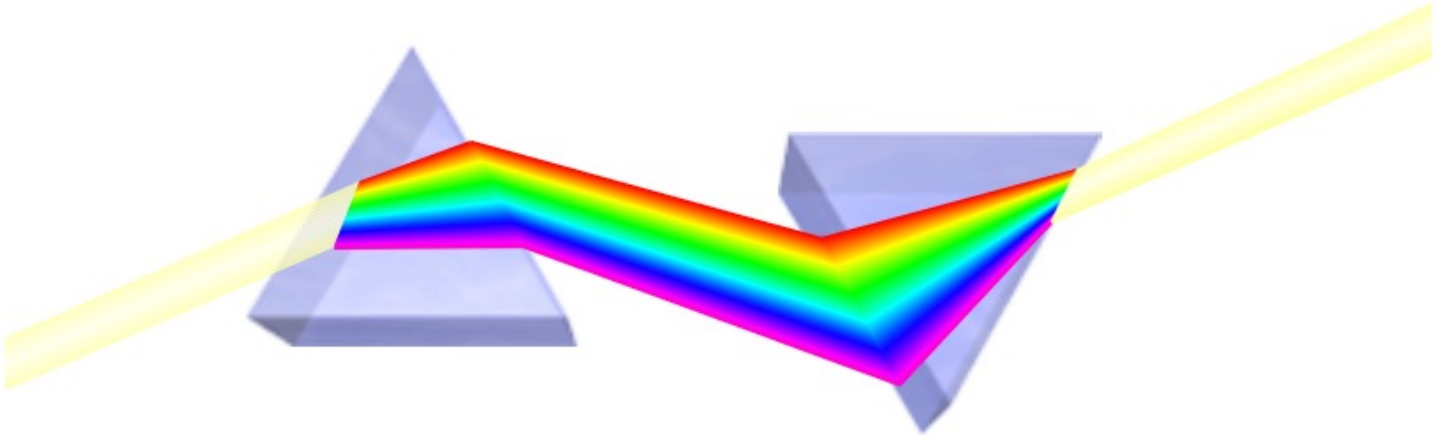
Light

- Newton's prism experiment, 1665



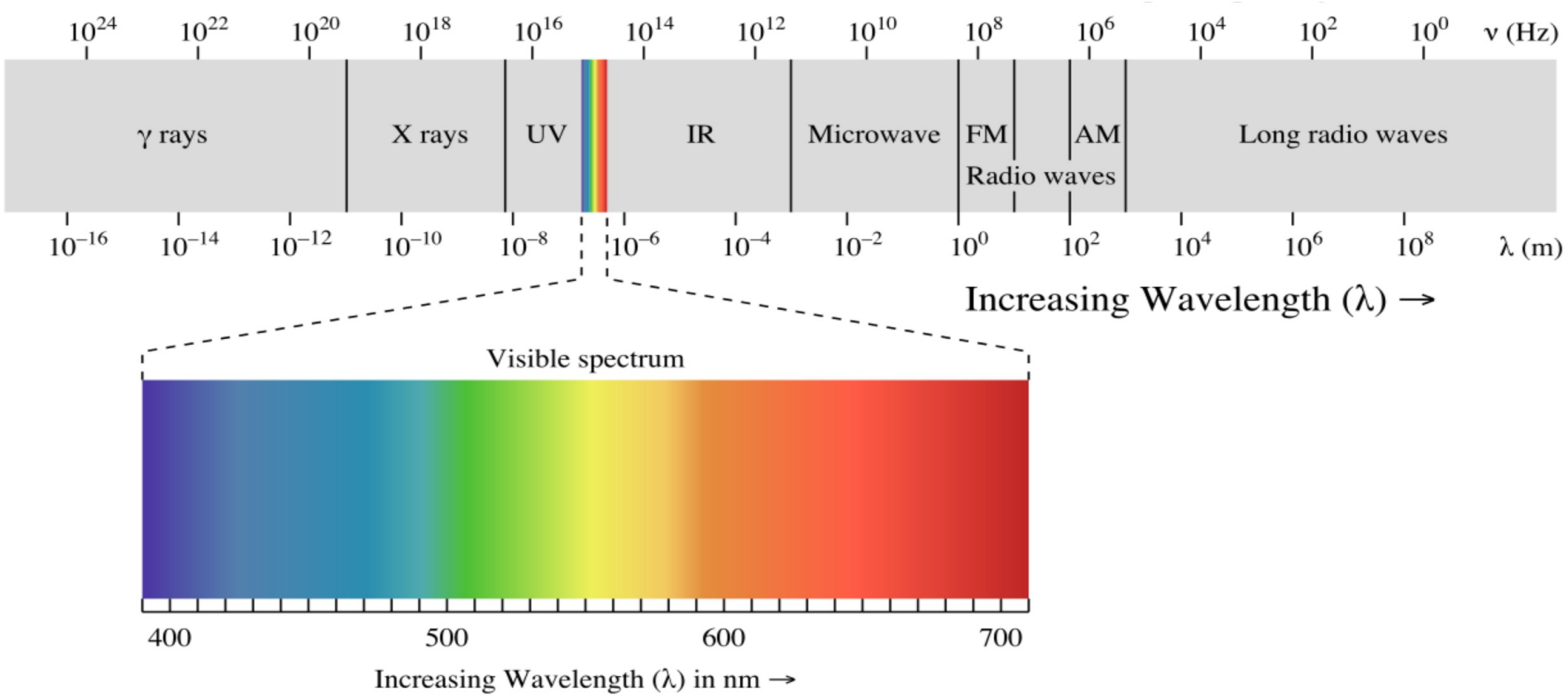
Light

- Newton's prism experiment
  - https://micro.magnet.fsu.edu/primer/java/scienceopticsu/newton/
- Light, prisms, and the rainbow connection
  - https://micro.magnet.fsu.edu/optics/activities/students/prisms.html



Visible spectrum

- Visible light is the small part within the electromagnetic spectrum



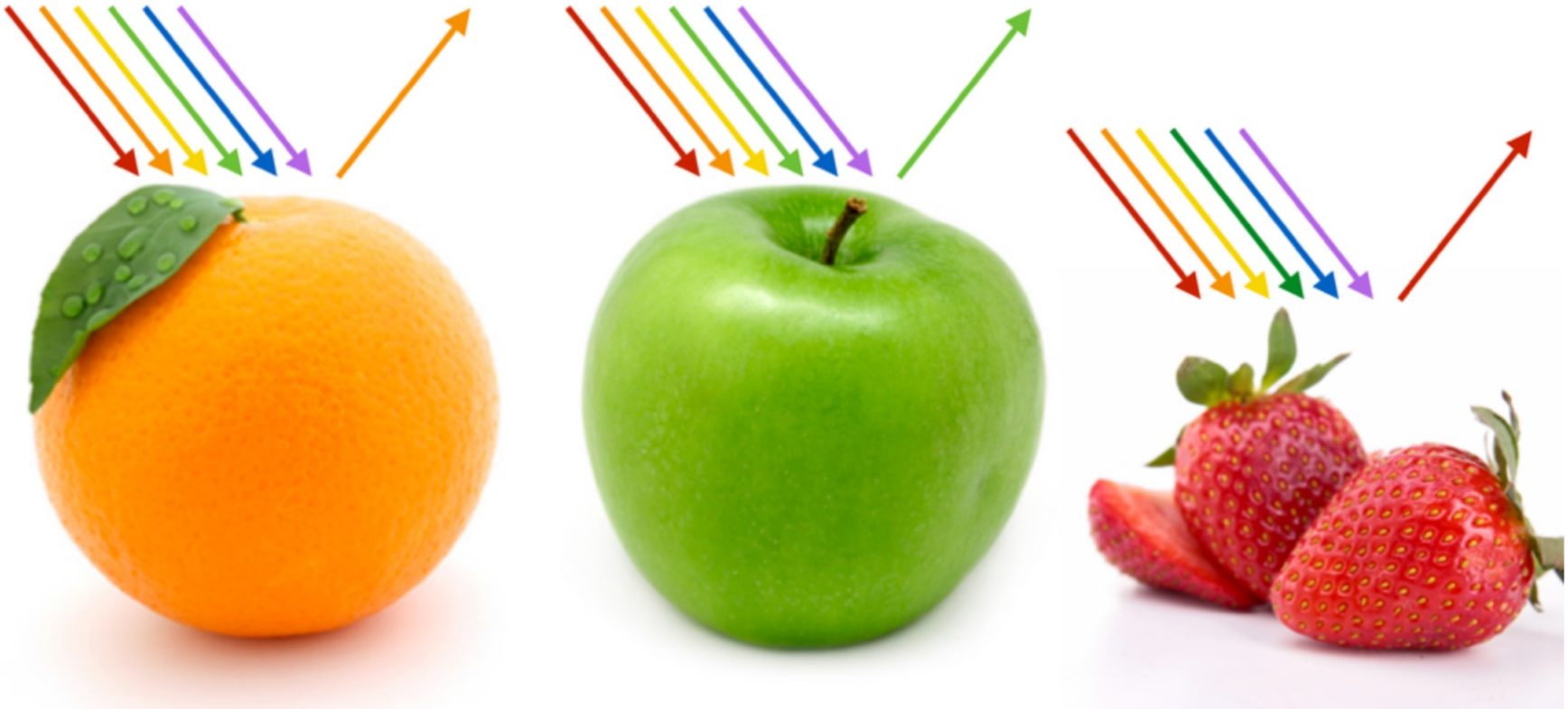
Visible spectrum

Colour, wavelength, frequency and energy of light					
Colour	/nm	/10^{14} Hz	/10^{4} cm^{-1}	/eV	/kJ mol^{-1}
Infrared	>1000	<3.00	<1.00	<1.24	<120
Red	700	4.28	1.43	1.77	171
Orange	620	4.84	1.61	2.00	193
Yellow	580	5.17	1.72	2.14	206
Green	530	5.66	1.89	2.34	226
Blue	470	6.38	2.13	2.64	254
Violet	420	7.14	2.38	2.95	285
Near ultraviolet	300	10.0	3.33	4.15	400
Far ultraviolet	<200	>15.0	>5.00	>6.20	>598

https://www.cs.mcgill.ca/~rwest/wikispeedia/wpcd/wp/c/Color.htm

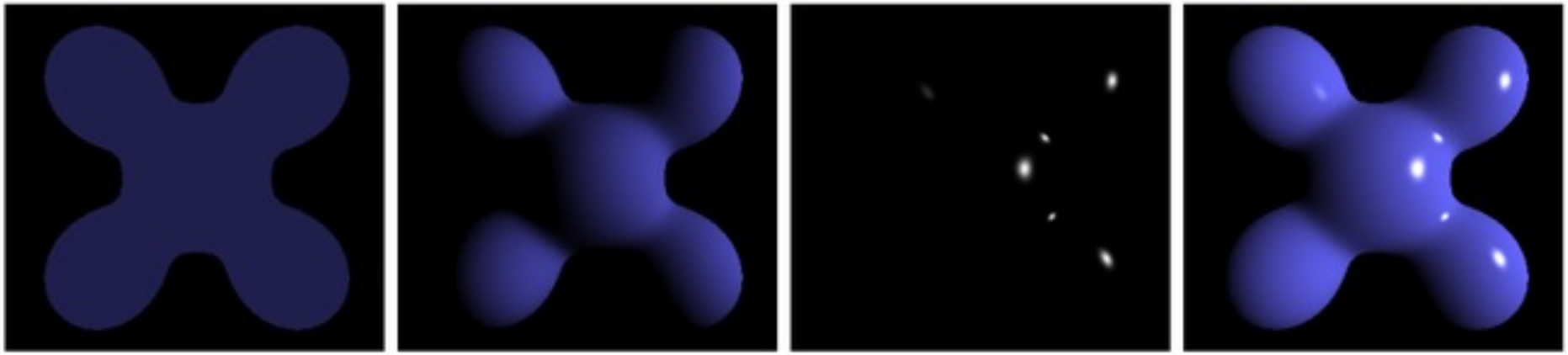
Colors of light

- Orange gives off orange color
- Apple gives off green color
- Strawberry gives off strawberry color

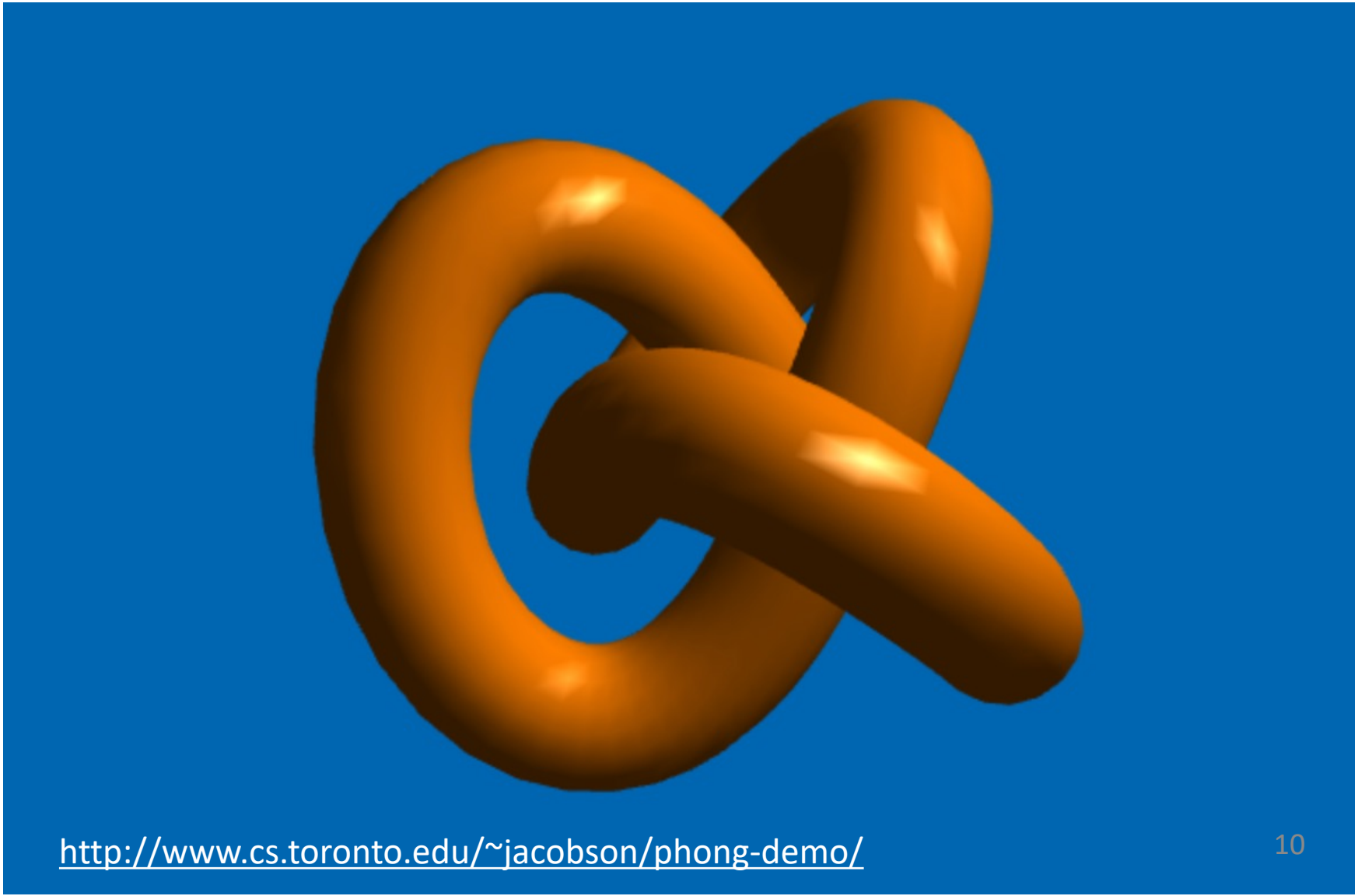


Phong illumination model

- Phong illumination model breaks the light's emitted intensity into 3 components: ambient L_a, diffuse L_d, and specular L_s.
  - Ambient: 'background' illumination
  - Diffuse: non-shiny illumination and shadows
  - Specular: bright, shiny reflections



Phong illumination model



http://www.cs.toronto.edu/~jacobson/phong-demo/

Questions?

Data Exploration & Visualization

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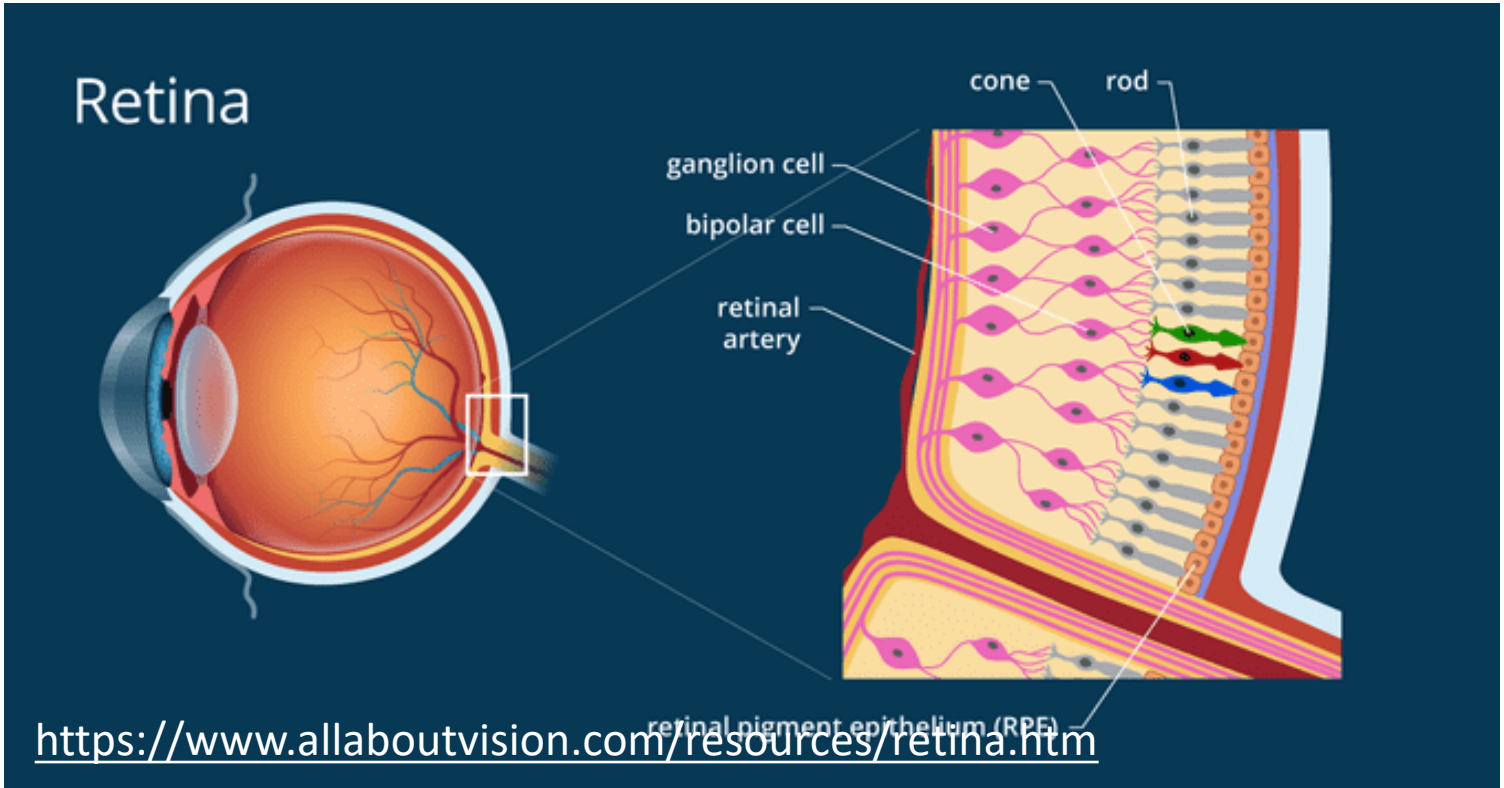
Trichromatic theory

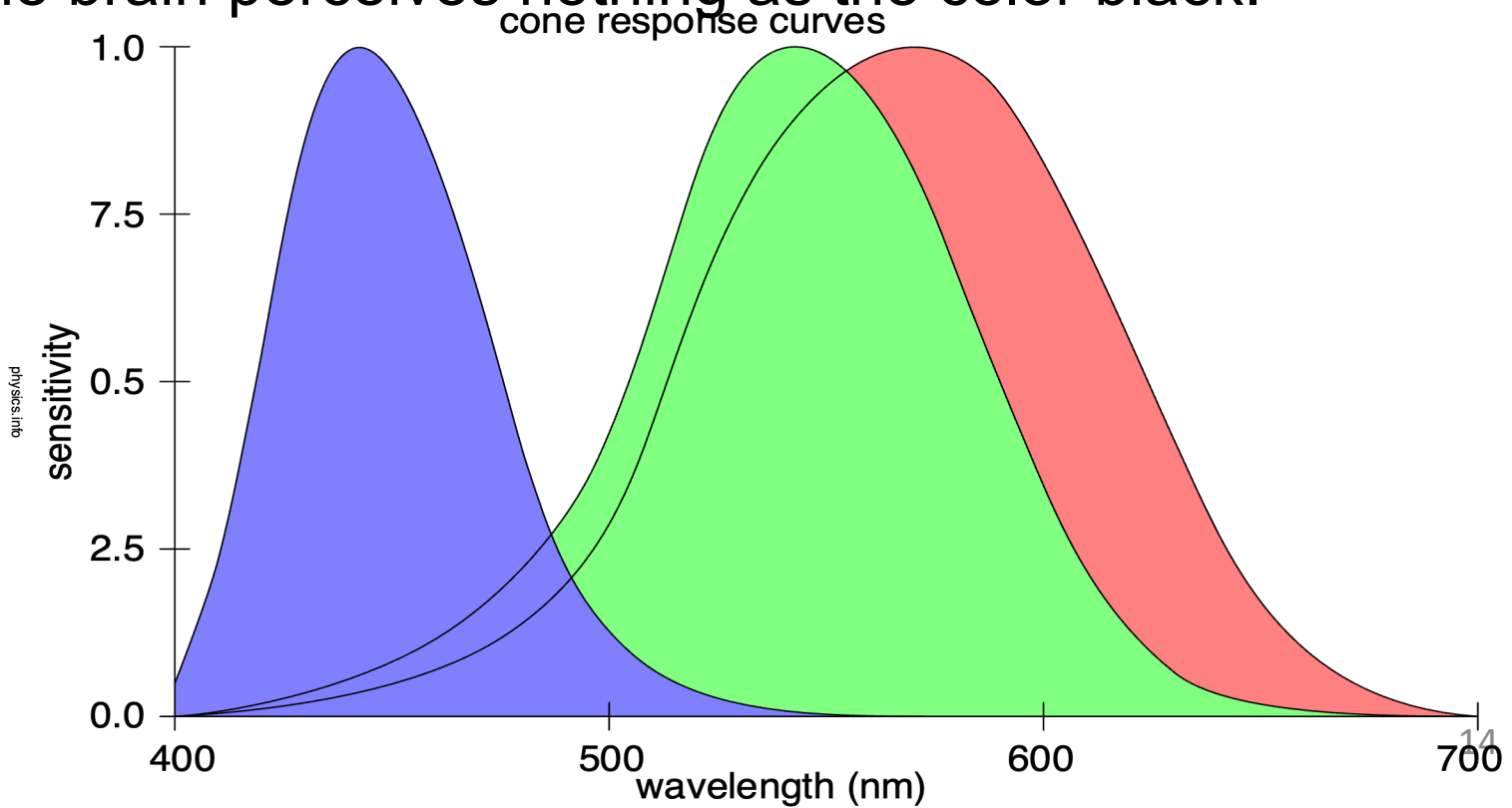
- Three types of cones, each sensitive to different band of wavelengths
  - Long wavelength: red, medium wavelength: green, short wavelength: blue



https://www.allaboutvision.com/resources/retina.htm

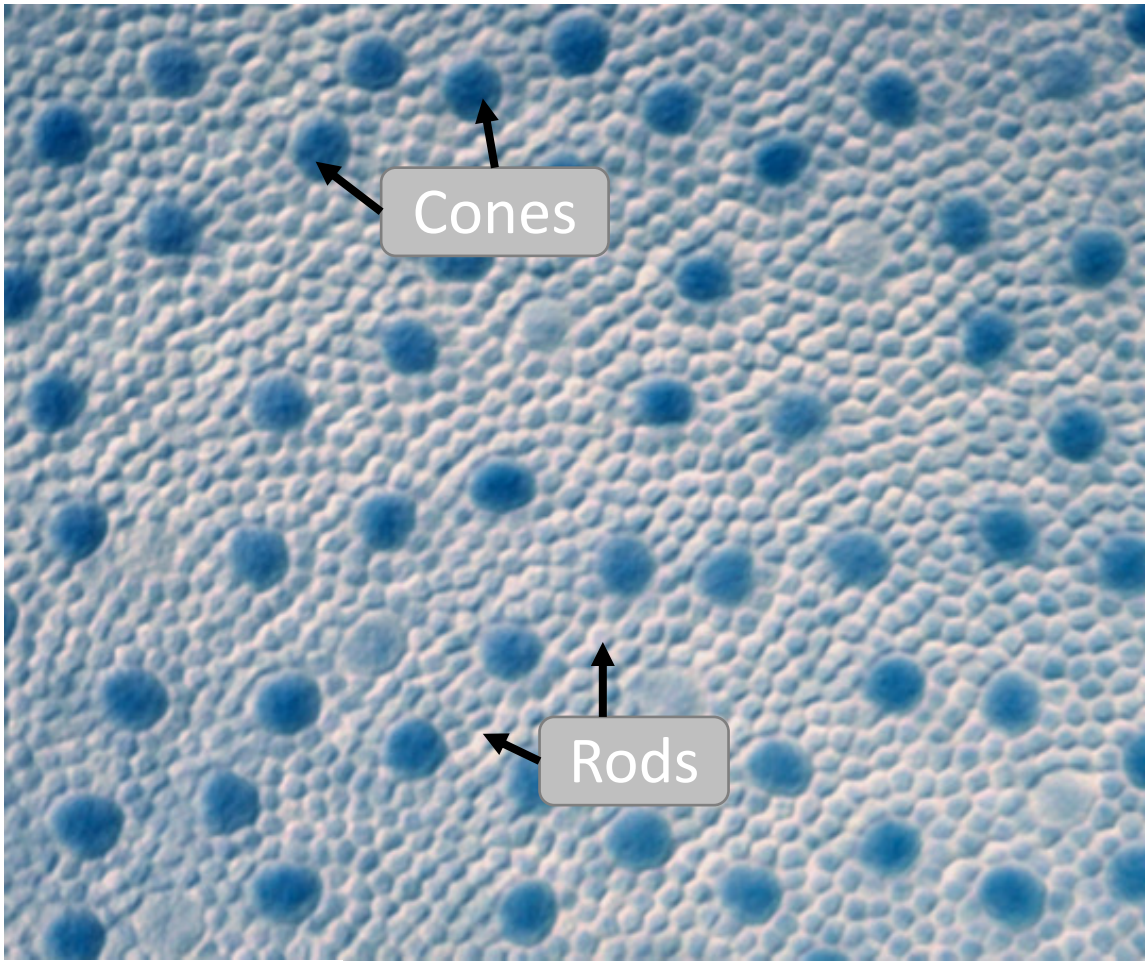
Trichromatic theory

- The normalized spectral sensitivity of human cone cells of short-, middle- and long-wavelength types.
- When no light or not enough light falls on the retina, the brain perceives nothing as the color black.



Trichromatic theory

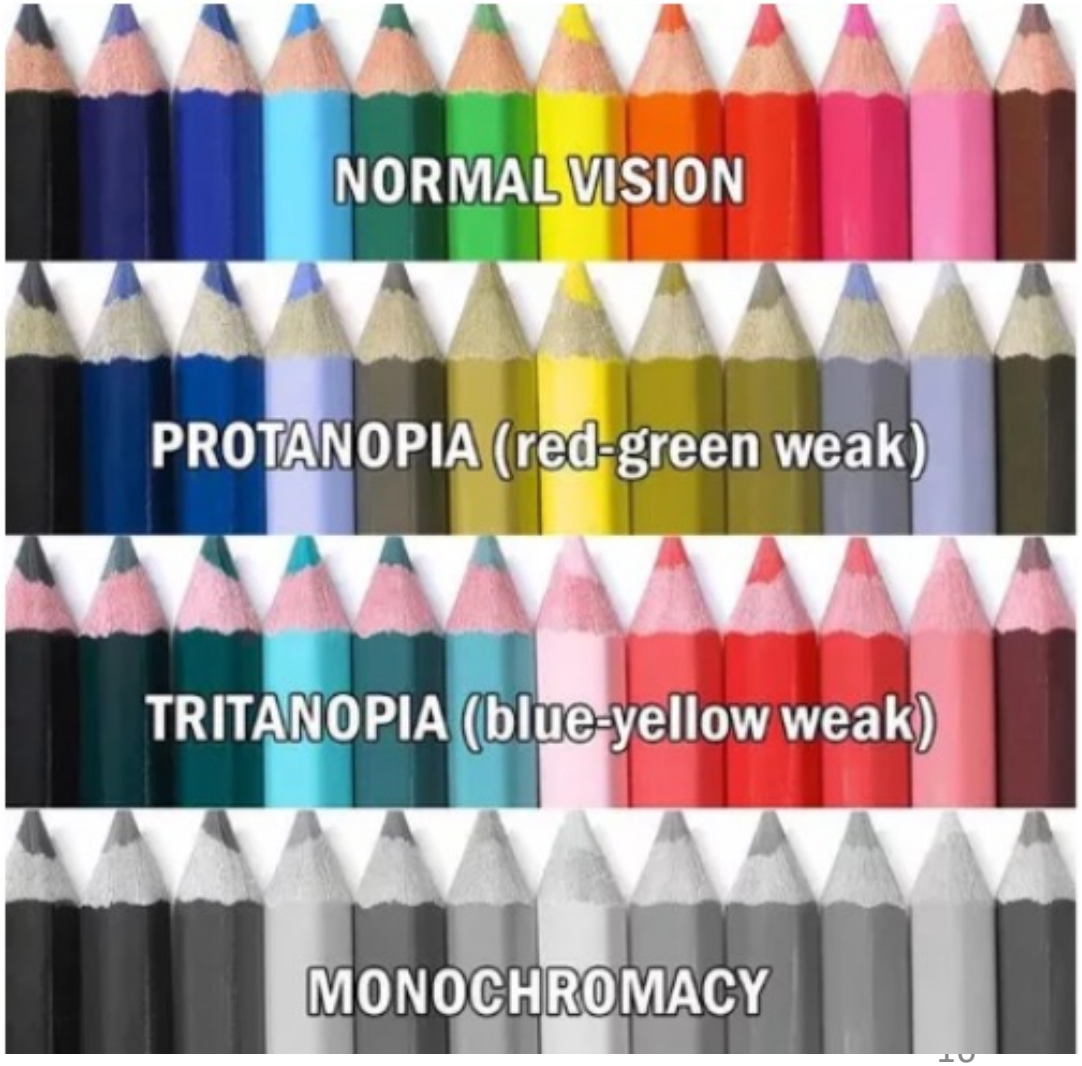
- Rods are extremely sensitive, and can be triggered by a single photon.
- Cones require significantly brighter light to produce a signal.



http://www.retinalmicroscopy.com/mosaics.html

Color blindness

- Trichromatic theory cannot explain color blindness:
  - Red-green weak instead of red weak & green week
  - Red-green week can perceive yellow
  - Can perceive white and gray



Opponent process theory

- We cannot see certain colors together in combination (**red-green, blue-yellow,** and **white-black**). These are opponent colors.

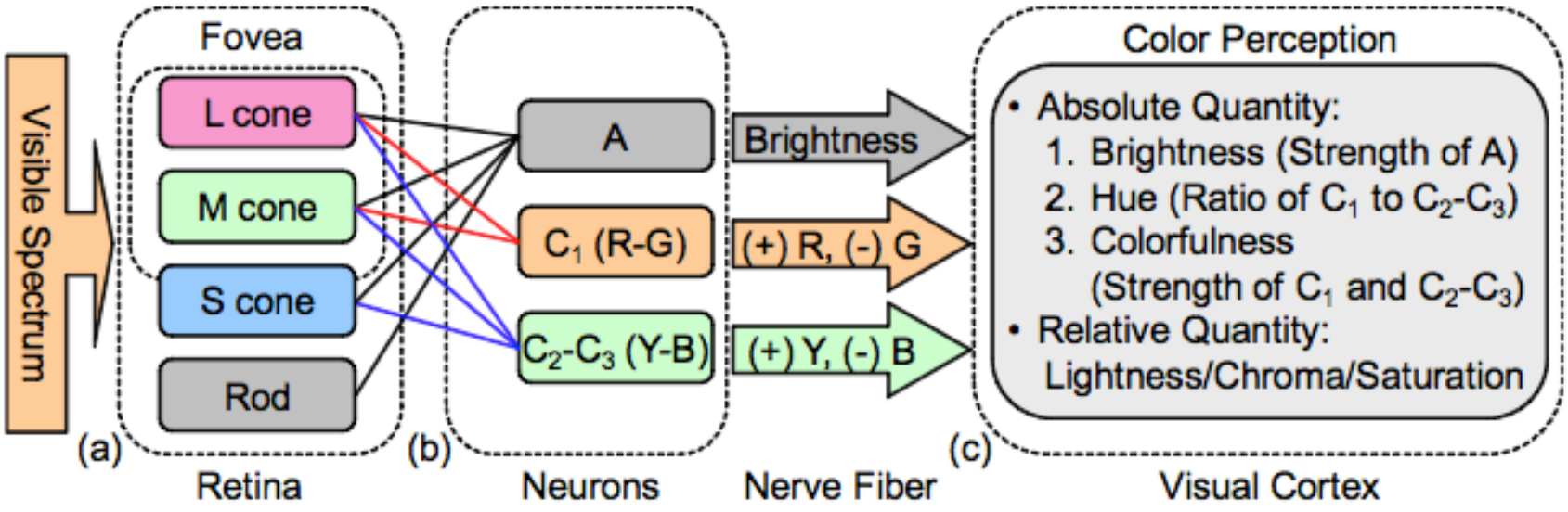
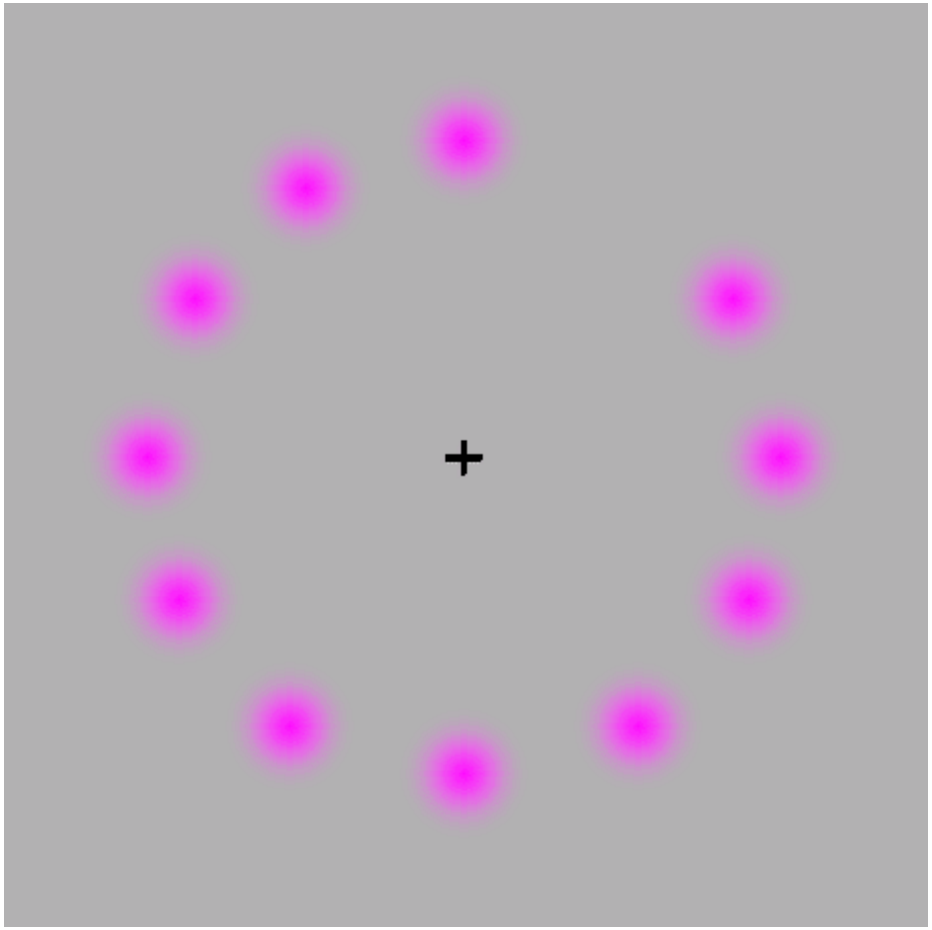


Diagram of the opponent process

Opponent process theory

- Opponent process theory explains afterimage.
  - Colors that are complementary to those of the original image.
- Look steadily at the cross in the center of the picture.



Lilac Chaser

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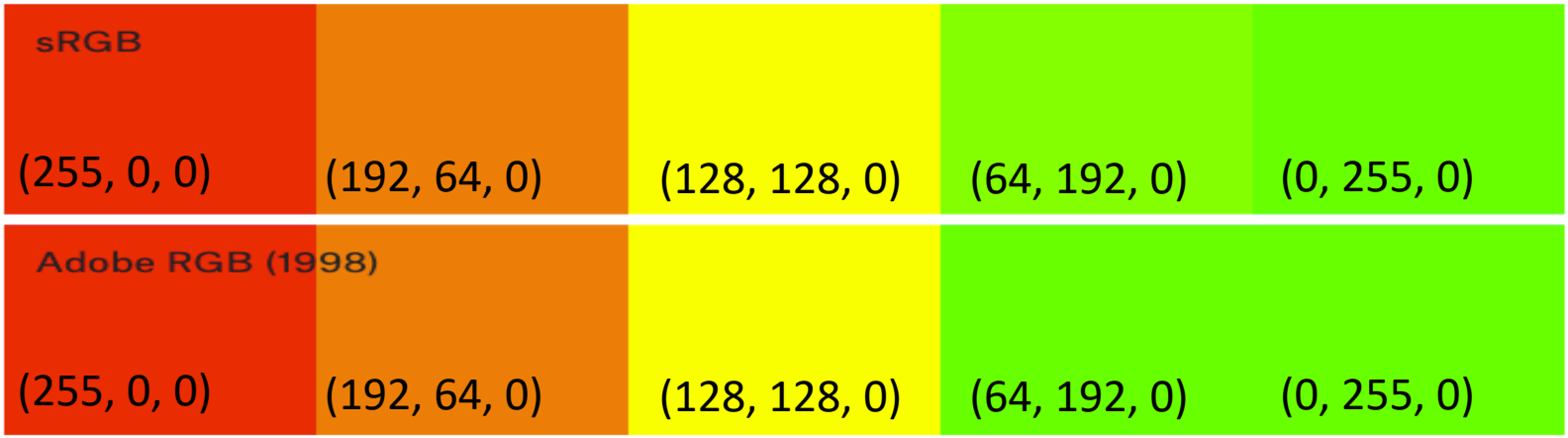
Color space *vs.* color model

- A color space is the set of colors which can be displayed or reproduced in a medium.
  - Dependent on devices and displays

- A color model is the mathematical way of describing colors.
  - independent from physical devices.

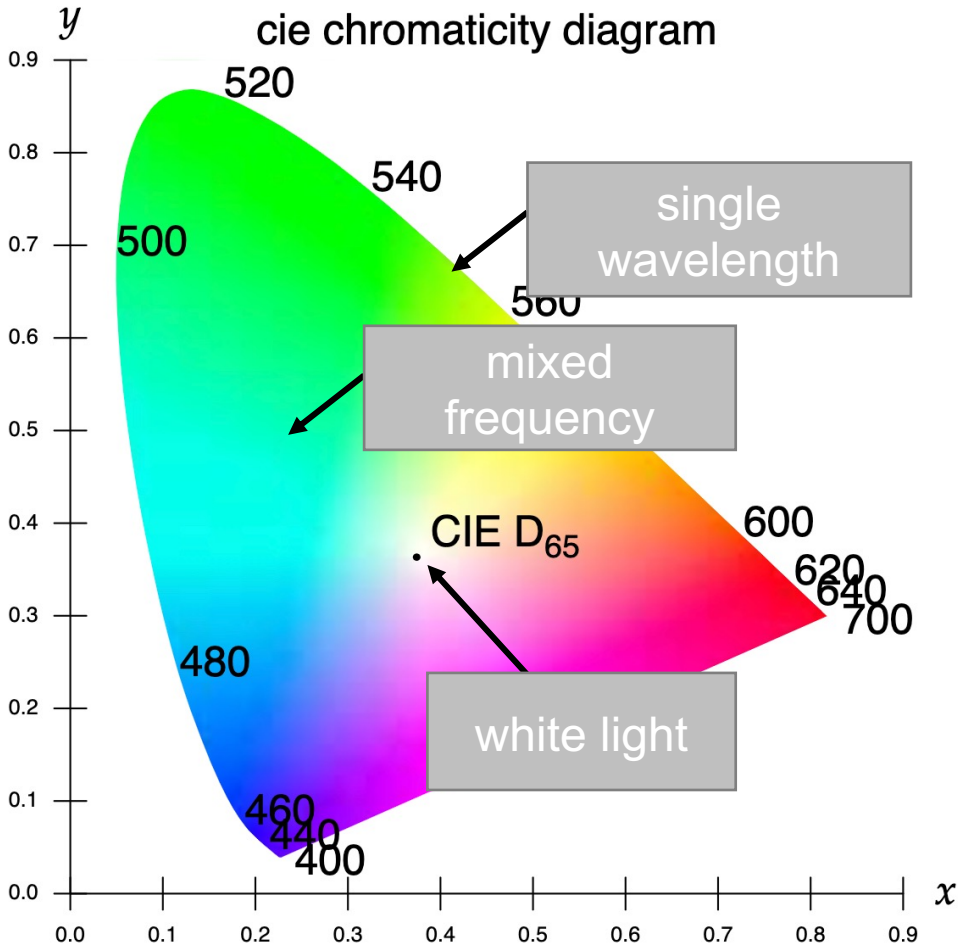
Color space *vs.* color model

- Color space is a real incarnation of an abstract color model.
  - Colors of the same RGB values may look differently on different color spaces.



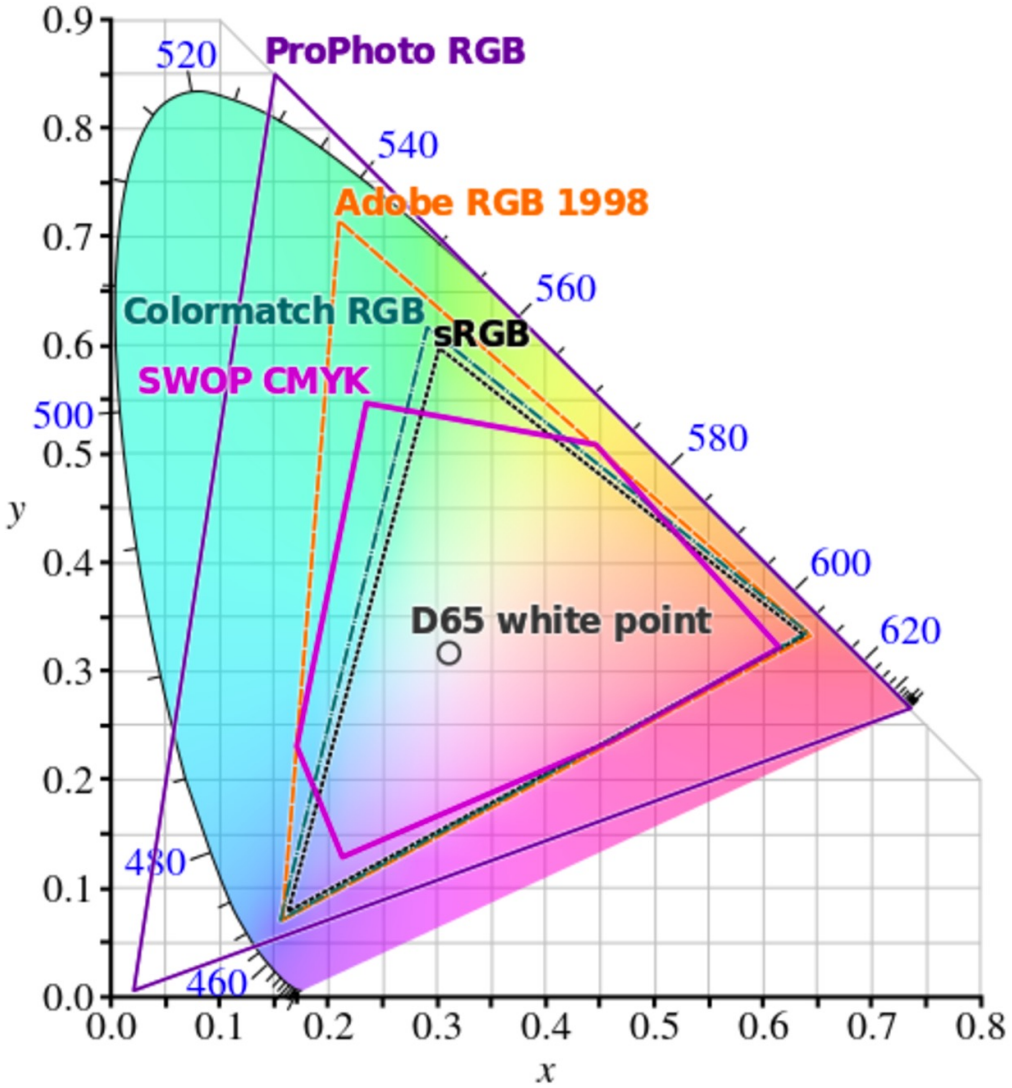
Color space

- The CIE ("Commission internationale de l'éclairage") XYZ color space, 1931 - the first defined quantitative links between
  - distributions of wavelengths in the visible spectrum
  - physiologically perceived colors in human color vision



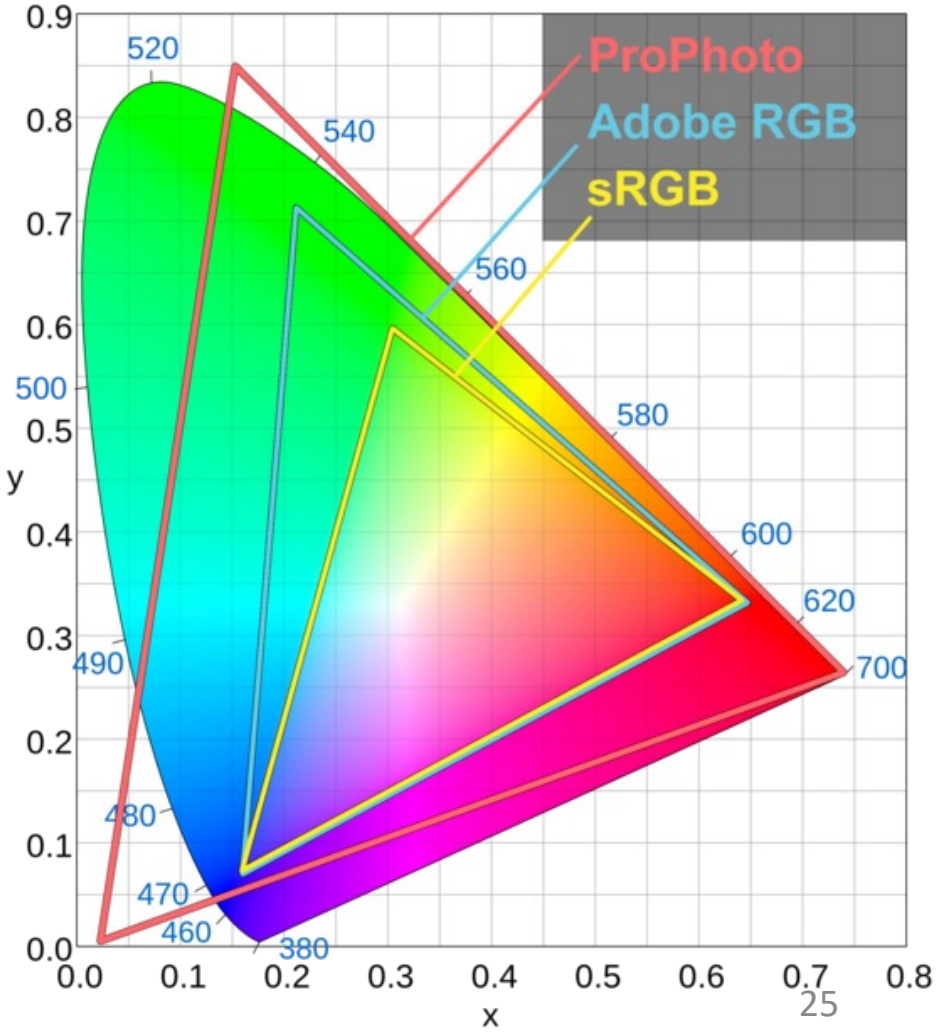
Color space

- Color space defines the range of colors
  - sRGB
  - Adobe RGB
  - SWOP CMYK
  - …



Color space

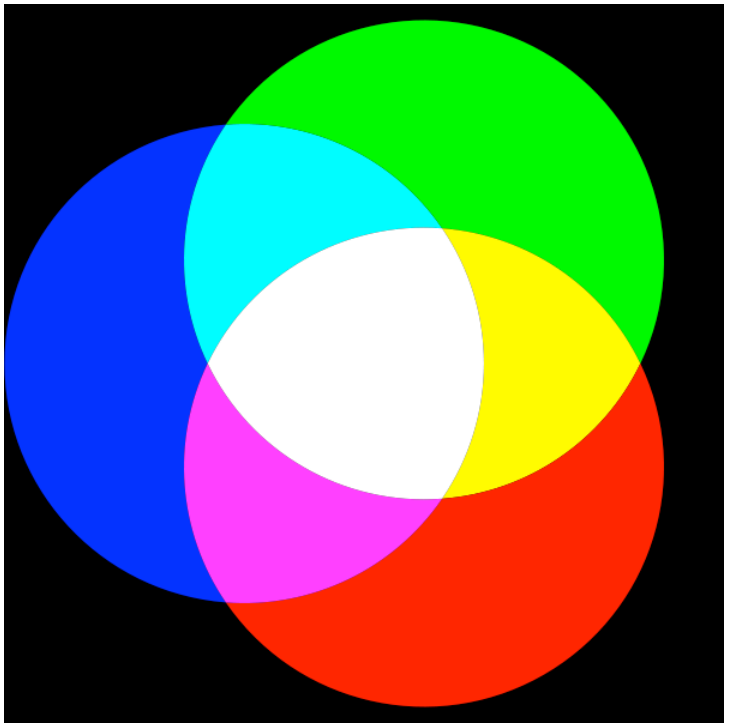
- Larger gamut
  - More, brighter, more saturated colors
- sRGB *vs.* Adobe RGB
  - sRGB: display correctly on Web
  - Adobe RGB: usually better for printing, but wont display correctly on web without conversion.



RGB

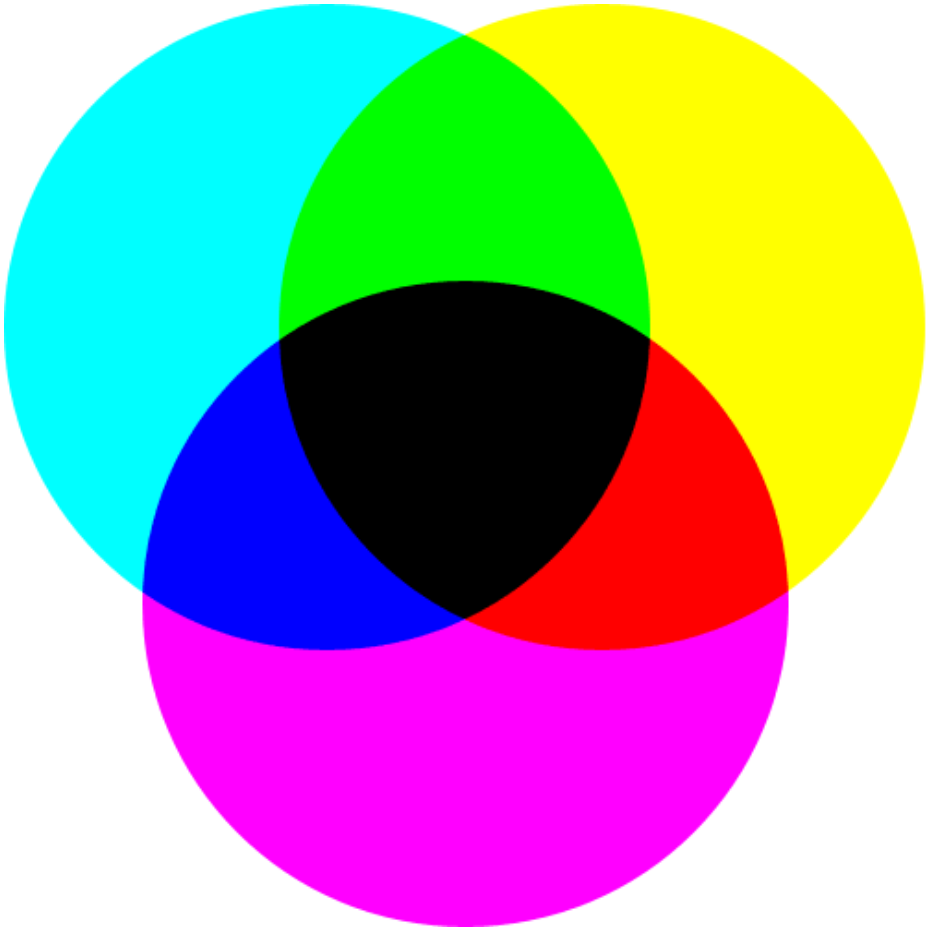
- Primary colors: **R**ed, **G**reen, **B**lue
  - Syntax in CSS: rgb(163, 212, 86) or hex decimal #A3D456

- Additive color mixing
  - Nothing = black
  - Red + green = yellow
  - Green + blue = cyan
  - Blue + red = magenta
  - Red + green + blue = white
- Usage
  - Web
  - TV, computer display



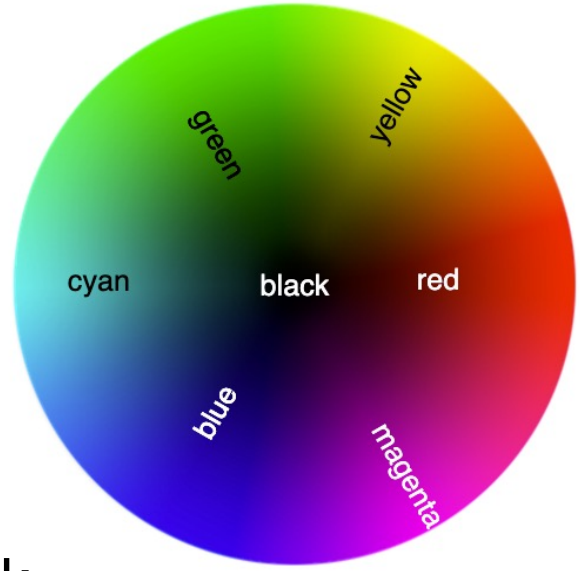
CMYK

- Primary colors: **C**yan, **M**agenta, **Y**ellow, blac**K**



CMYK

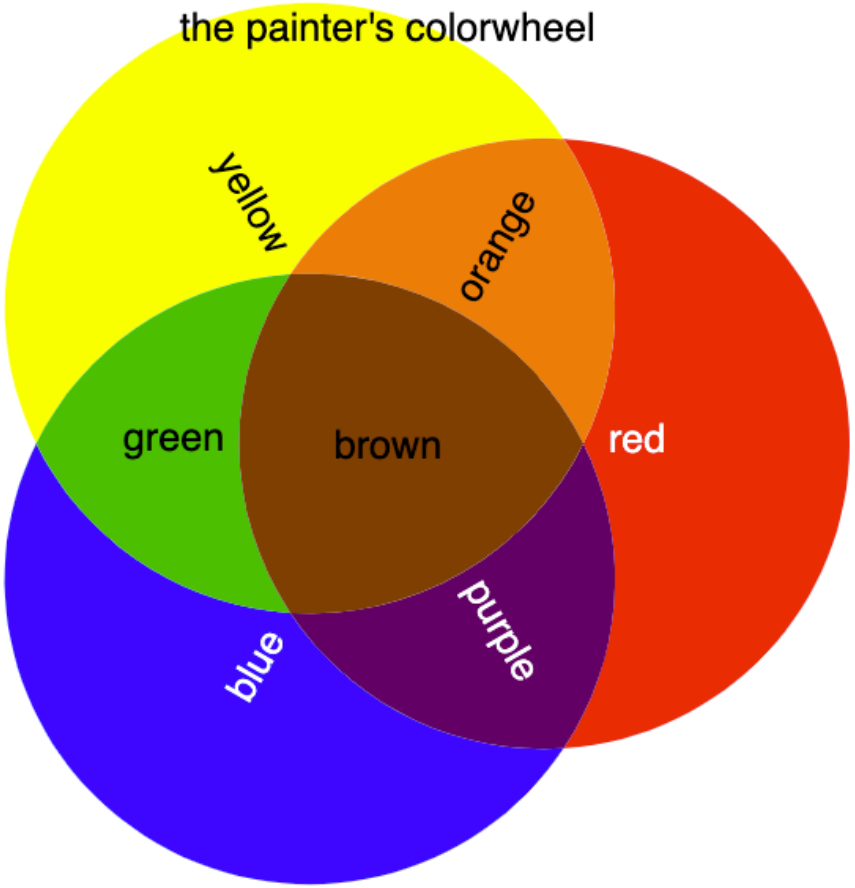
- Subtractive color mixing
  - Nothing = white
  - Cyan + magenta = blue
  - Magenta + yellow = red
  - Yellow + cyan = green
  - Cyan + magenta + yellow = black



- Usage
  - Color printing

RYB

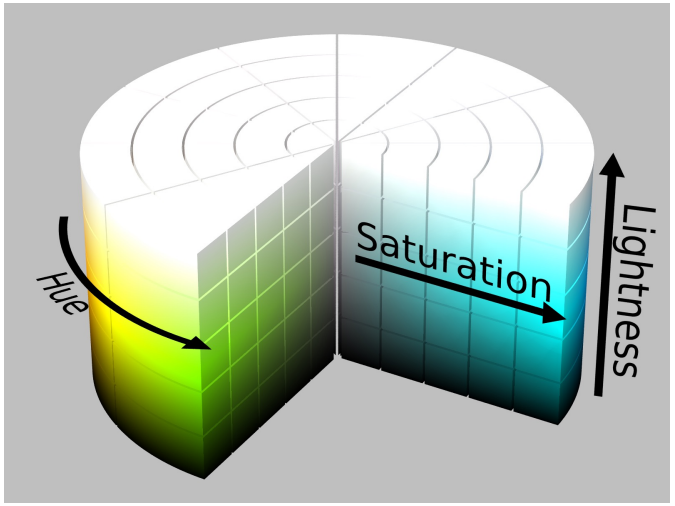
- Red, Yellow, Blue are not primary colors

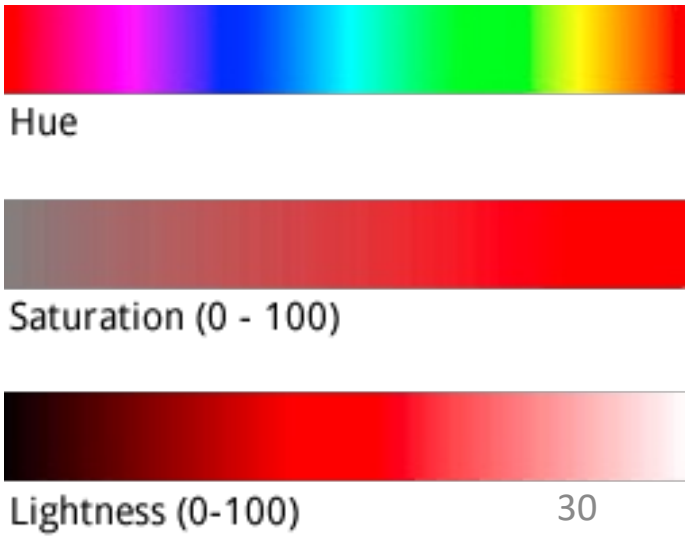


https://physics.info/color/

HSL

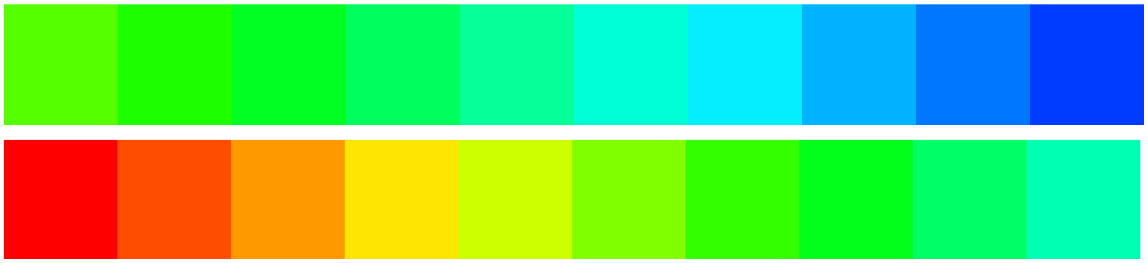
- More closely align with the way human vision perceives color-making attributes
  - ***Hue:*** human perceived colors
  - ***Saturation:*** colorfulness, distance to gray
  - ***Lightness:*** relative degree of black and white





Perceptually uniform

- RGB, CMYK, HSL are perceptually non-uniform

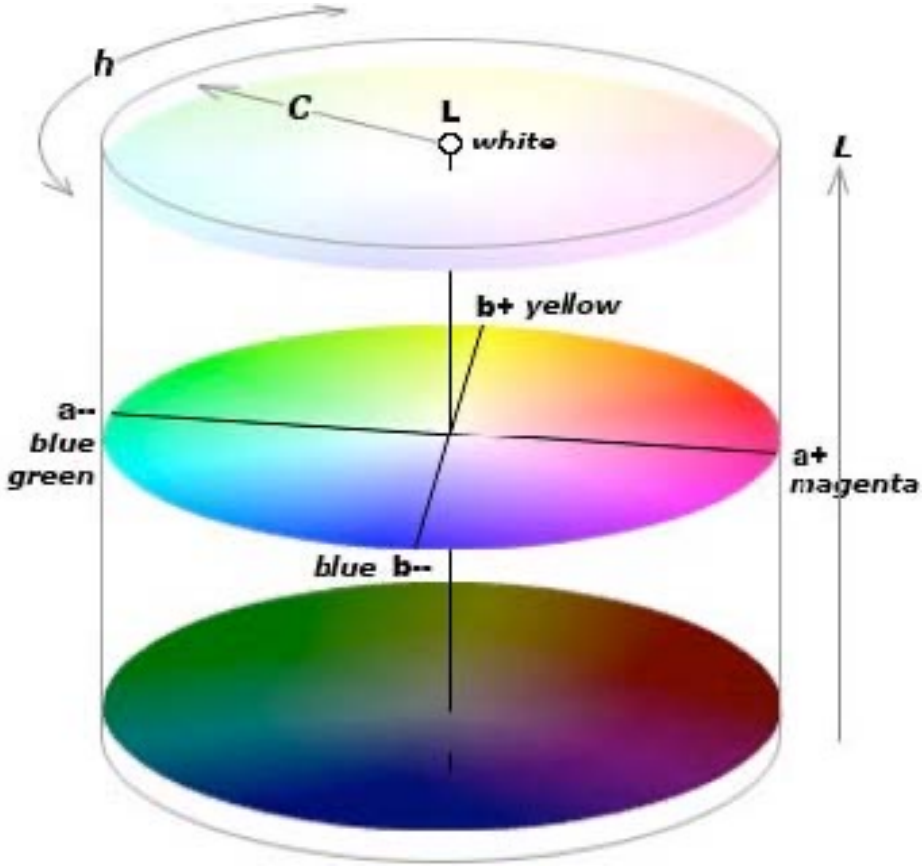


- We want a perceptual uniform color model – CIELab

  - Notice: CIELab was *intended* to be perceptually uniform, but fails, especially when quantifying small- to medium-size color difference

CIELab

- CIELab approximate human vision
  - Luminance: human perception to lightness (black to white)
  - a: green (-a) to red (+a)
  - b: blue (-b) to yellow (+b)

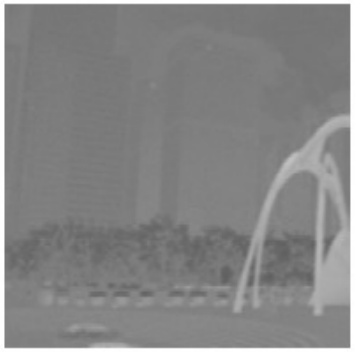


CIELab

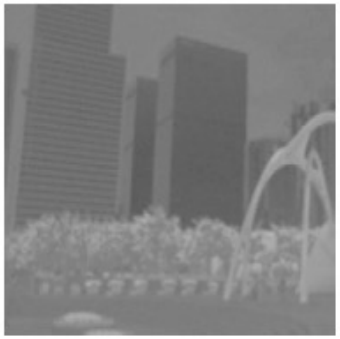
- Lab approximate human vision
  - Luminance: human perception to lightness (black to white)
  - a: green (-a) to red (+a)
  - b: blue (-b) to yellow (+b)

Lab

Luminance



a (red - green)



b (yellow - blue)

How to measure
color difference perception?

Paper:
D. A. Szafir, "Modeling Color Difference for Visualization Design," *IEEE Transactions on Visualization and Computer Graphics,* vol. 24, no. 1, pp. 392-401, 2018, doi: 10.1109/TVCG.2017.2744359. (Best paper award!!)
https://cmci.colorado.edu/visualab/VisColors/

Conclusion:
- perceived color difference varies inversely with size
- colors are more discriminable on elongated marks (bars and lines) than on points

How to measure ***color difference perception***?

Our studies use CIELAB [25], a color space comprised of three primary axes: L^* (lightness), a^* (the amount of red or green), and b^* (the amount of blue or yellow). While metrics such as CIE ΔE_{94} [32], CIEDE2000 [29], and CIECAM02 [36] provide more precise calculations of color difference, the computational simplicity of CIELAB ΔE, where perceived difference is measured using Euclidean distance, makes it a popular choice for visualization tools (e.g. [11, 22, 28, 53]). Some encodings account for imperfections in CIELAB by hand (e.g. Samsel's green-blue encodings [44]), but this process does not scale well nor does it provide quantitative guarantees of effectiveness. Instead, this work focuses on providing actionable guidance for reasoning about perceptual effectiveness by generating quantitative metrics from existing models of color perception to aid in creating and evaluating encodings for visualizations.

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Colormap

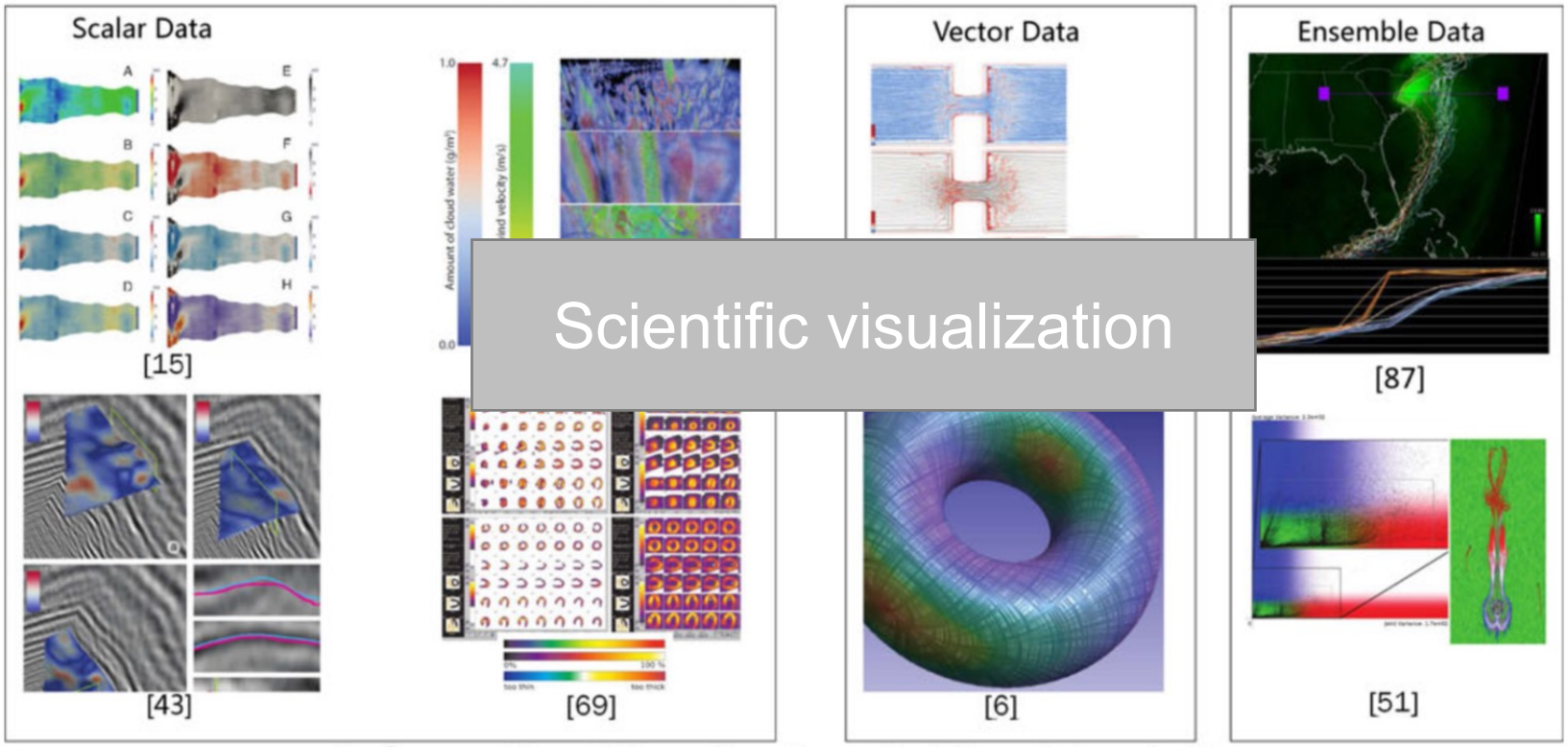
- Visualization process maps data & control parameters to images.
- Color is a pre-attentive stimulus.
- Colormaps are used to characterize the mapping from the data domain *D* to color scales *C* in visualization.

$$f : D \rightarrow C$$

- Based on data attribute types, different colormaps shall be applied.

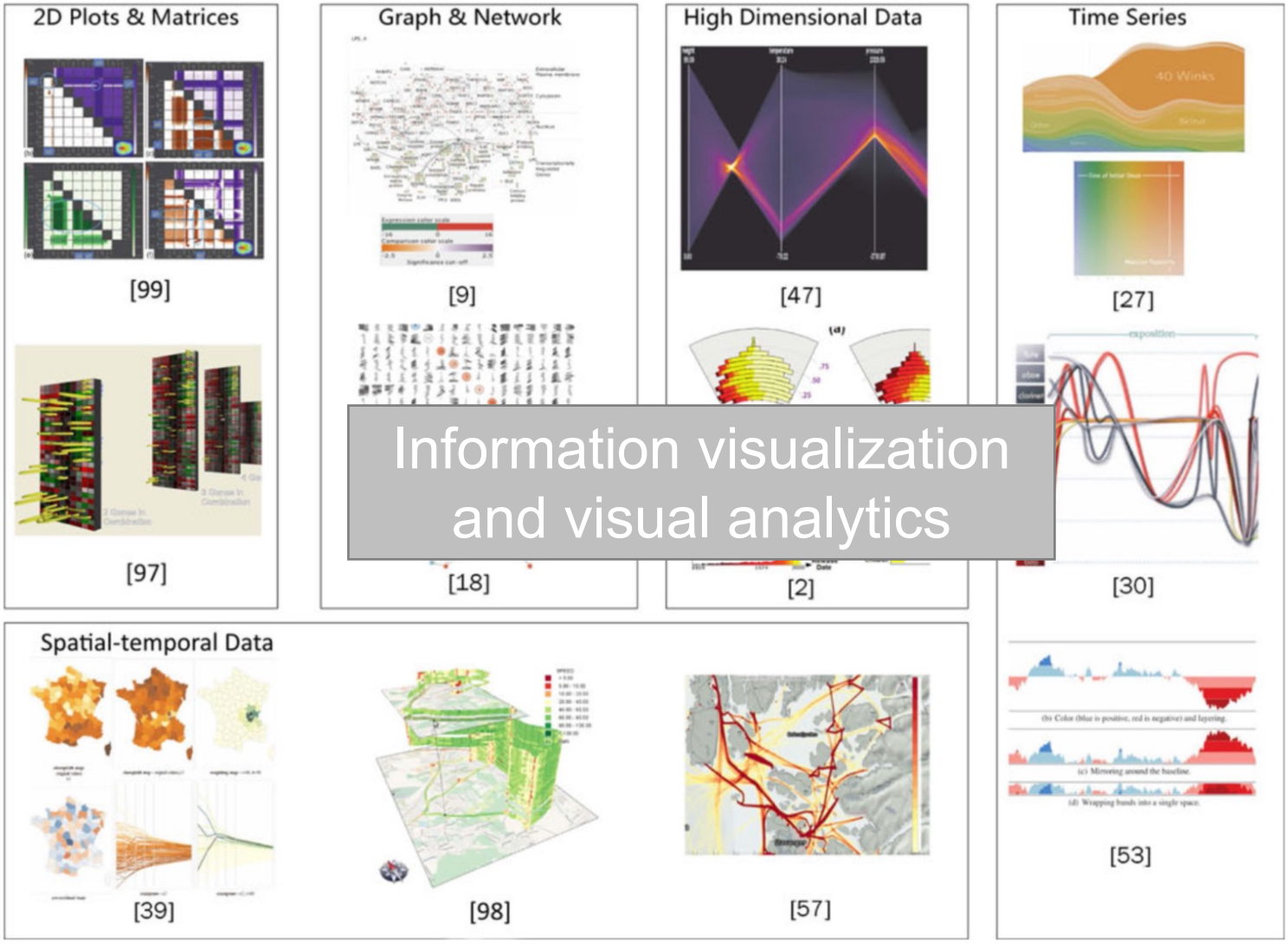
Colormap

- Transfer functions in scientific visualization



Zhou, L., and Hansen, C.D.: 'A Survey of Colormaps in Visualization', IEEE TVCG, 2016, 22, (8), pp. 2051-2069

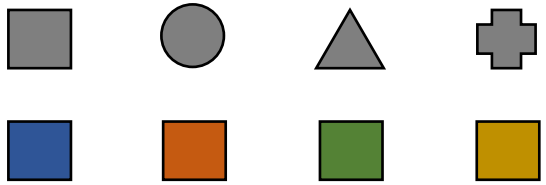
Colormap



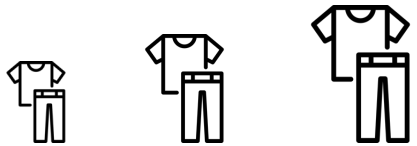
Zhou, L., and Hansen, C.D.: 'A Survey of Colormaps in Visualization', IEEE TVCG, 2016, 22, (8), pp. 2051-2069

Attribute types

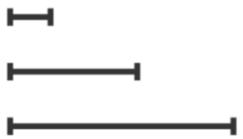
- Categorical, e.g.,
  - Apple vs. orange
  - Red vs. blue



- Ordered
  - Ordinal, e.g., clothes size



  - Quantitative, e.g., time



  - Ordering direction

➔ Sequential ➔ Diverging ➔ Cyclic

Categorical colormap

- There is no implied relationship between different levels of a variable
  - Stimuli must look different, but **only** different

d3.**schemeCategory10** <>

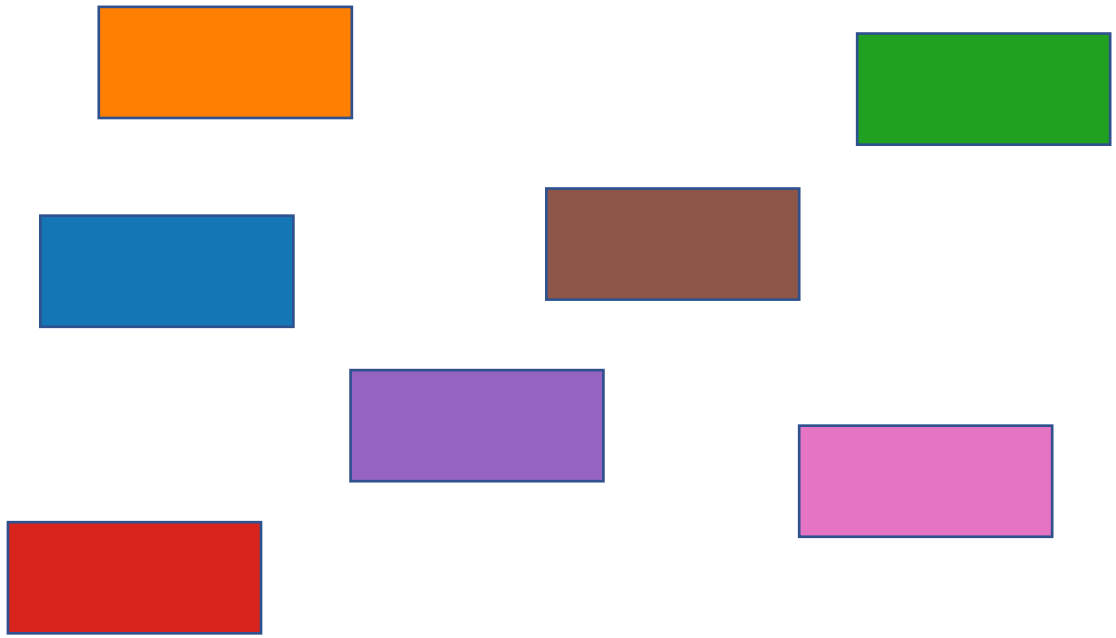
An array of ten categorical colors represented as RGB hexadecimal strings.

d3.**schemeAccent** <>

An array of eight categorical colors represented as RGB hexadecimal strings.

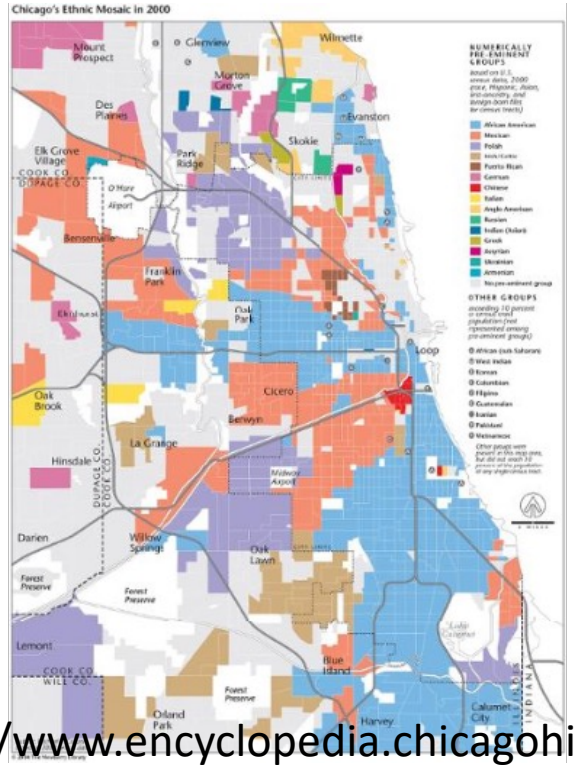
Categorical colormap

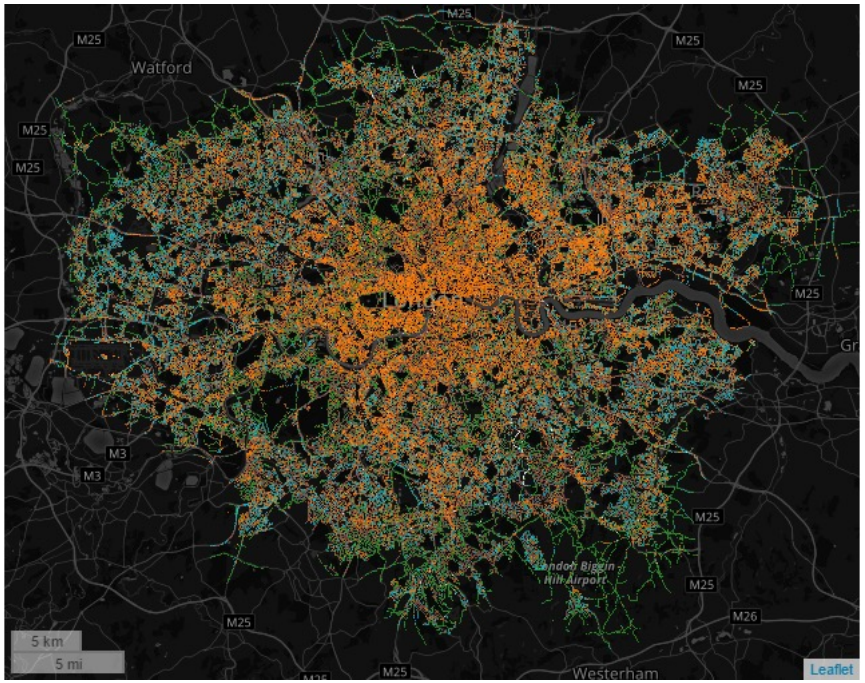
- Try to order the colors
  - Not able to order
  - **Hue** is not a perceptual cue for **order**



Categorical colormap

- Use color only when you have few categories
  - Left: Chicago's ethnic mosaic in 2000
  - Right: street view categories





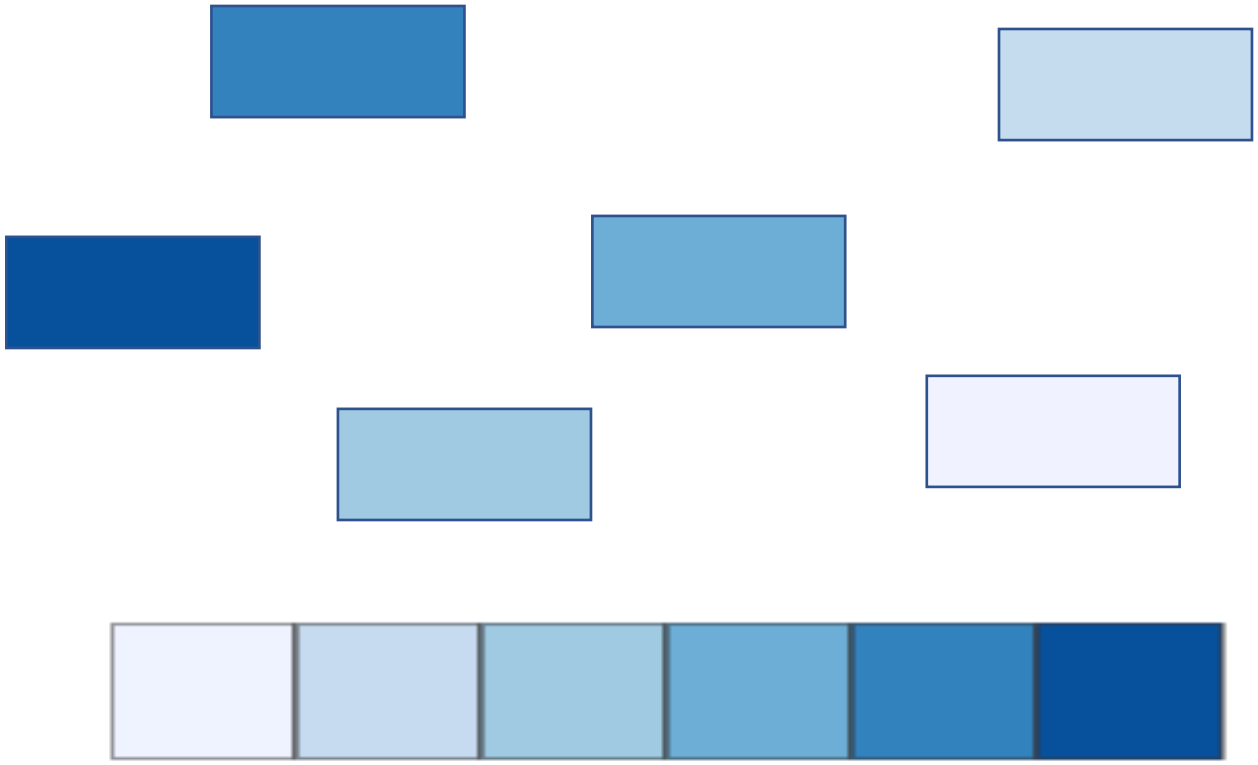
http://www.encyclopedia.chicagohistory.org/pages/3889.html

Quantitative colormap

- Quantitative colormaps are used for presenting quantitative data values
  - Sequential colormap for sequential ordering
  - Diverging colormap for diverging ordering

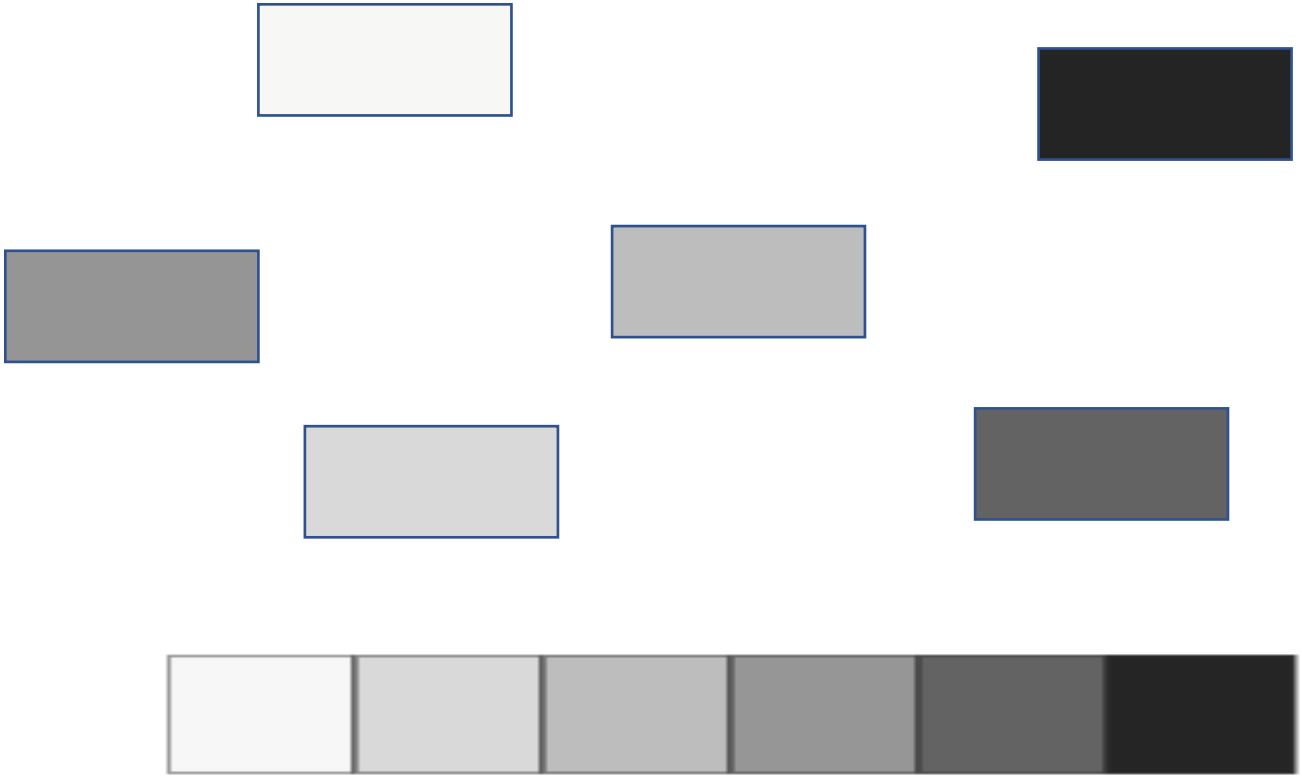
Sequential colormap

- Try to order the colors
  - **Luminance** is a strong perceptual cue for **order**



Sequential colormap

- Try to order the colors
  - **Luminance** is a strong perceptual cue for **order**



Sequential colormap

- Suitable for ordered data attributes
  - Single-hue

d3.**interpolateBlues**(*t*) <>
d3.**schemeBlues**[*k*]

Given a number *t* in the range [0,1], returns the corresponding color from the “Blues” sequential color scheme represented as an RGB string.

d3.**interpolateGreens**(*t*) <>
d3.**schemeGreens**[*k*]

Given a number *t* in the range [0,1], returns the corresponding color from the “Greens” sequential color scheme represented as an RGB string.

d3.**interpolateGreys**(*t*) <>
d3.**schemeGreys**[*k*]

https://github.com/d3/d3-scale-chromatic

Sequential colormap

- Suitable for ordered data attributes
  - Multiple-hue

d3.**interpolateTurbo**(*t*) <>

Given a number *t* in the range [0,1], returns the corresponding color from the “turbo” color scheme by Anton Mikhailov.

d3.**interpolateViridis**(*t*) <>

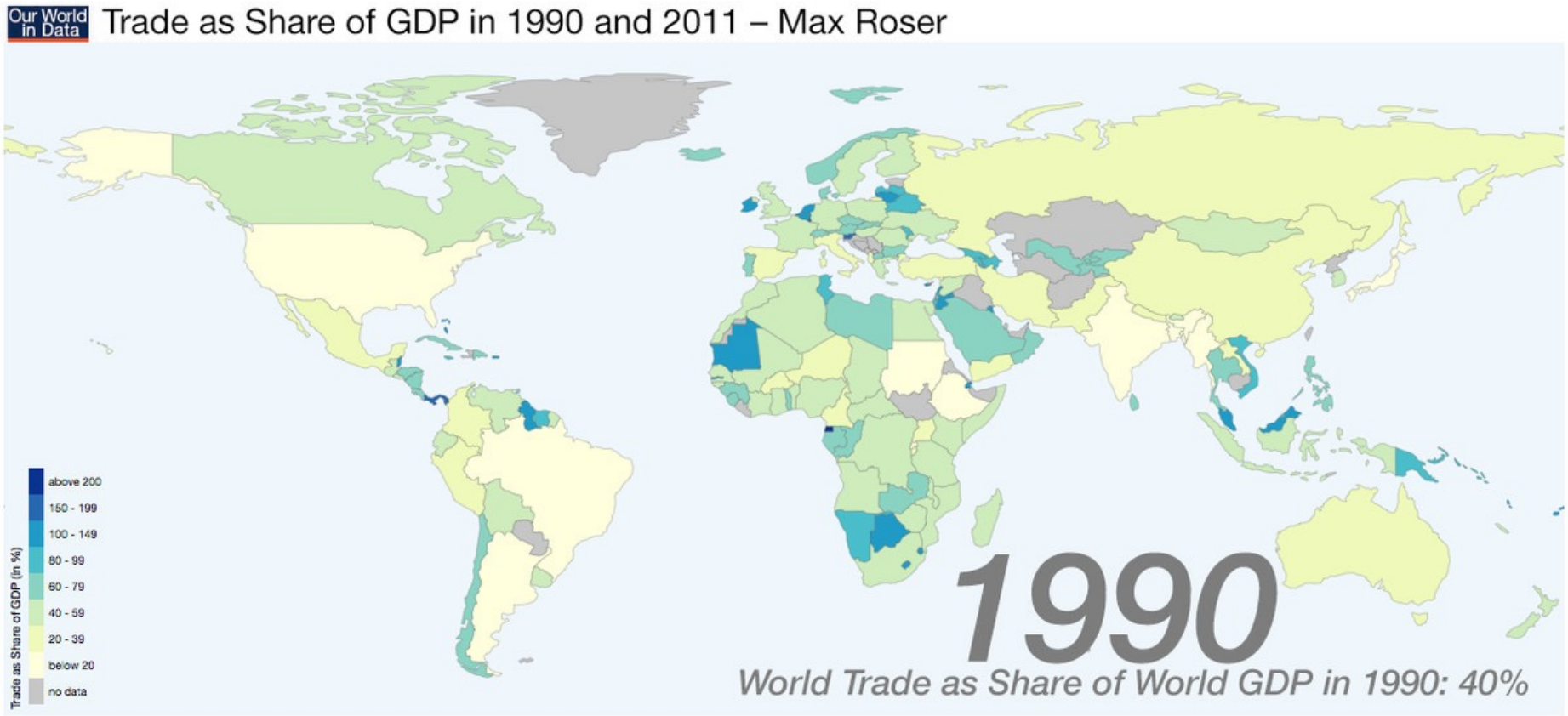
Given a number *t* in the range [0,1], returns the corresponding color from the “viridis” perceptually-uniform color scheme designed by van der Walt, Smith and Firing for matplotlib, represented as an RGB string.

d3.**interpolateInferno**(*t*) <>

https://github.com/d3/d3-scale-chromatic

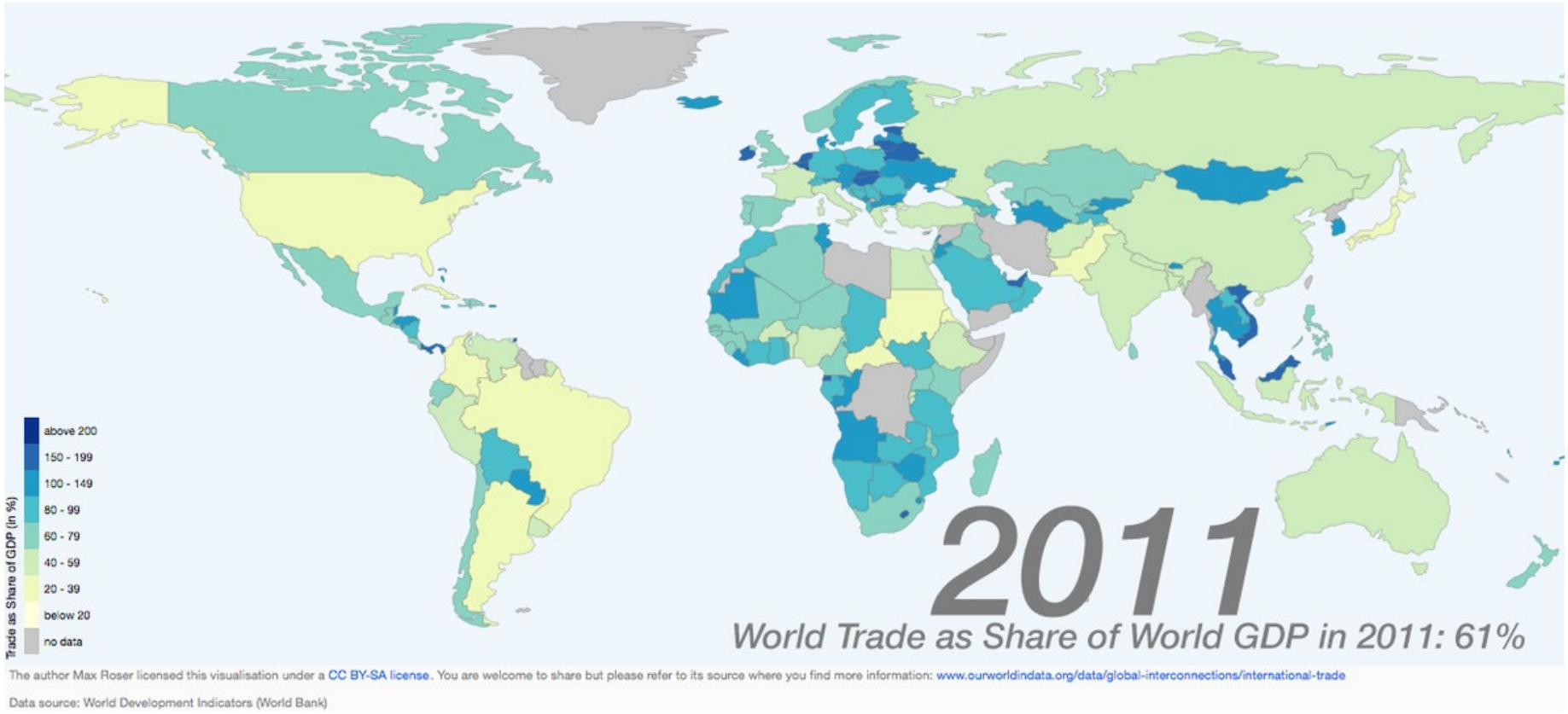
Sequential colormap

- Suitable for ordered data attributes



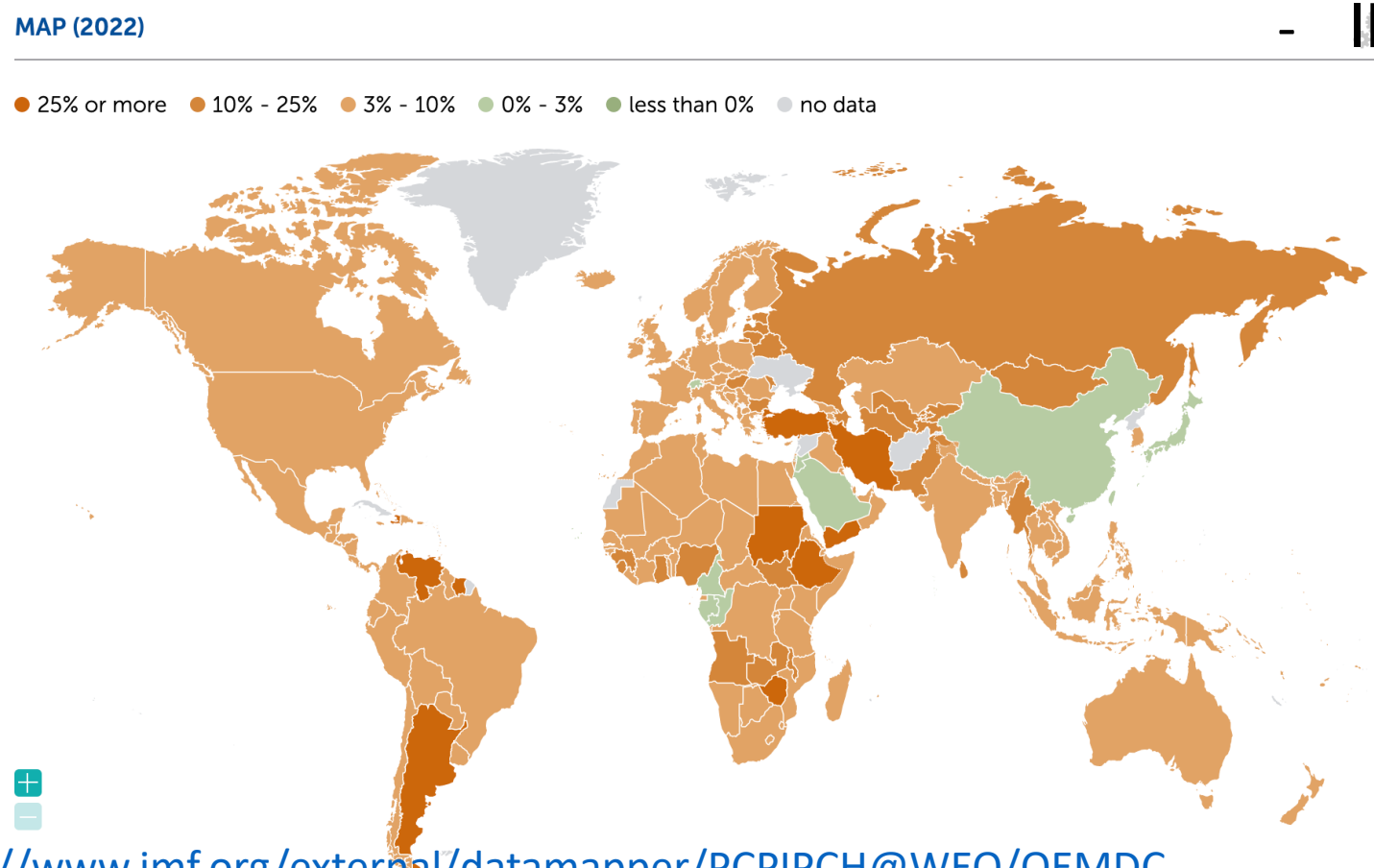
Sequential colormap

- Suitable for ordered data attributes



Sequential colormap

- Inflation rate, average consumer prices



- IMF.

https://www.imf.org/external/datamapper/PCPIPCH@WEO/OEMDC

Diverging colormap

- Suitable for ordered data with diverging values

d3.**interpolateBrBG**(*t*) <>
d3.**schemeBrBG**[*k*]

Given a number *t* in the range [0,1], returns the corresponding color from the "BrBG" diverging color scheme represented as an RGB string.

d3.**interpolatePRGn**(*t*) <>
d3.**schemePRGn**[*k*]

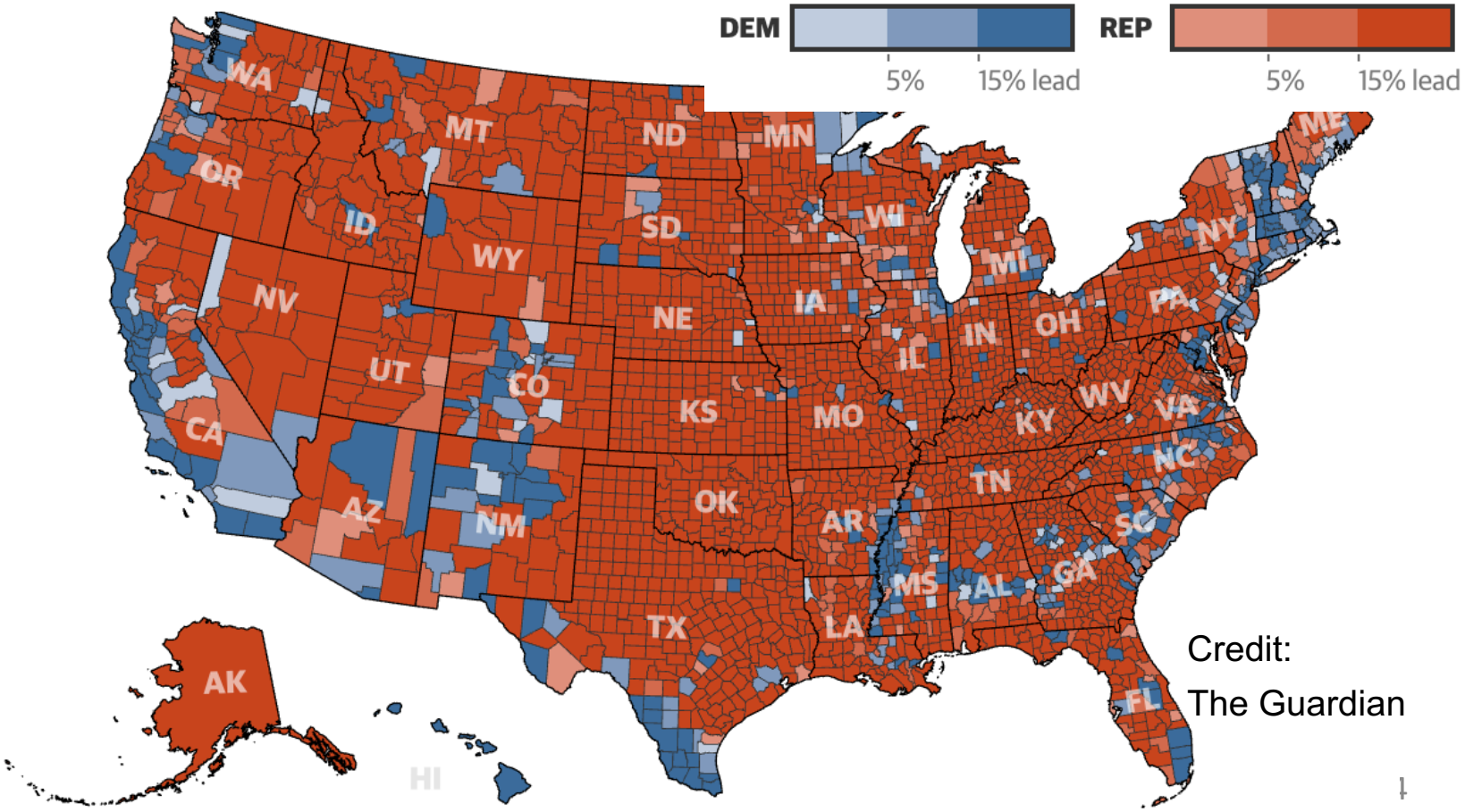
Given a number *t* in the range [0,1], returns the corresponding color from the "PRGn" diverging color scheme represented as an RGB string.

d3.**interpolatePiYG**(*t*) <>
d3.**schemePiYG**[*k*]

https://github.com/d3/d3-scale-chromatic

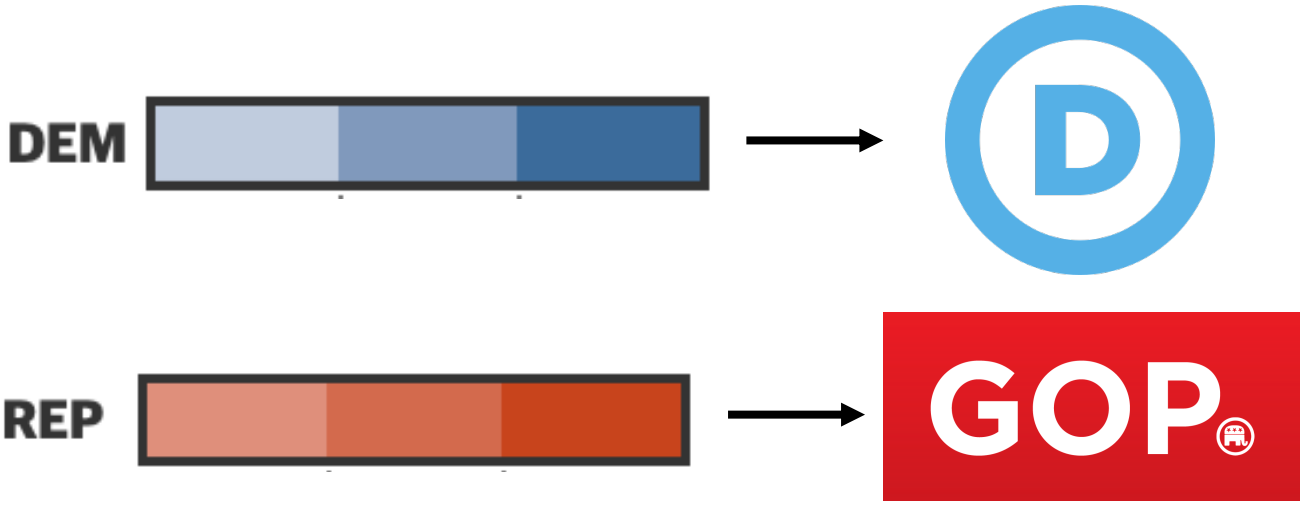
Diverging colormap

- US election 2016



Semantics of colors

- Color selection shall consider semantics
  - Democratic party blue
  - Republican part read



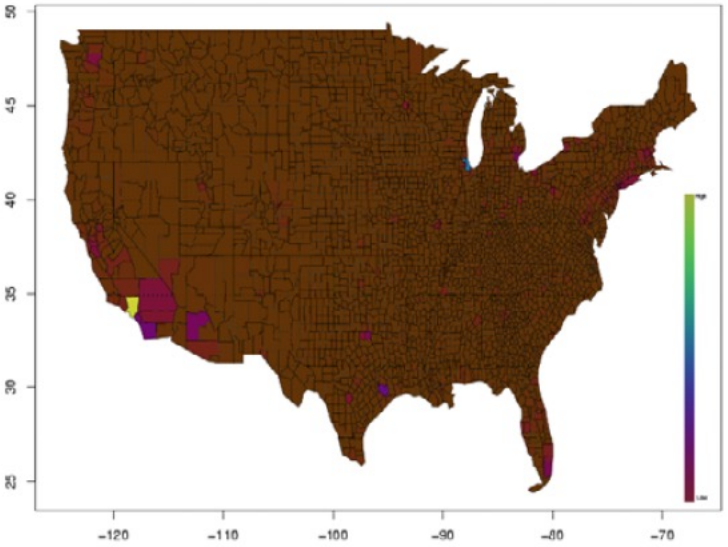
Semantics of colors

- Color selection shall consider semantics
  - Stock markets at US *vs.* China

股票名称	跌停时间	跌停价	跌幅
西陇科学	15:00:03	6.49	-9.99%
海正药业	14:56:57	13.07	-9.99%
滨化股份	14:54:38	5.33	-9.97%
星湖科技	14:54:23	7.11	-10.00%
泰林生物	14:50:30	74.66	-9.99%

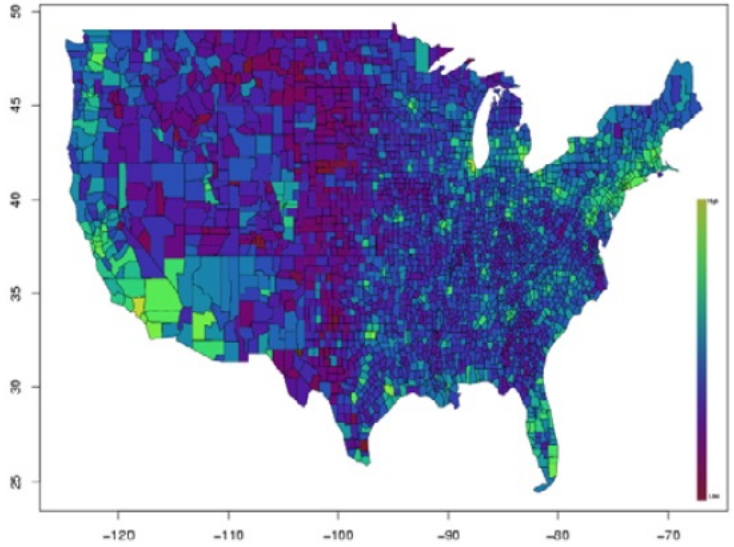
Normalization

- **Normalization** changes the values of numeric columns in the dataset to a **common scale**, such that the visualization can better reveal patterns.



Linear colormap

$f: y \rightarrow c$



Logarithmic colormap

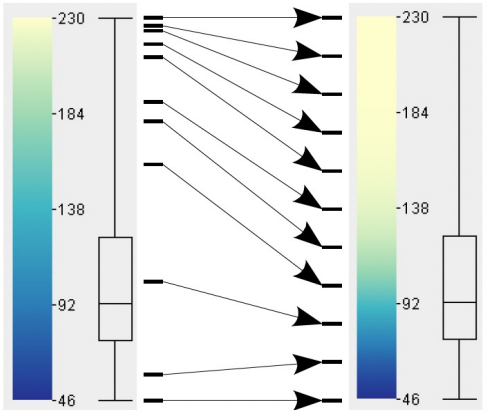
$f: y' \rightarrow c$, where y' = log(y)

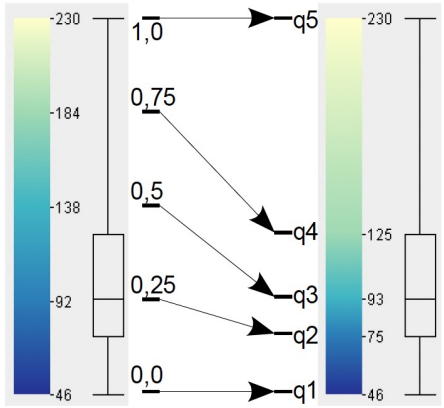
Schneidewind et al., 2006

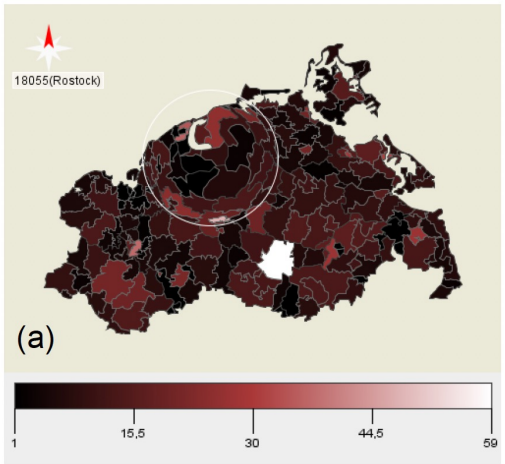
Non-linear colormaps

- Color scale adaption can also be employed to better reveal unevenly distributed data.

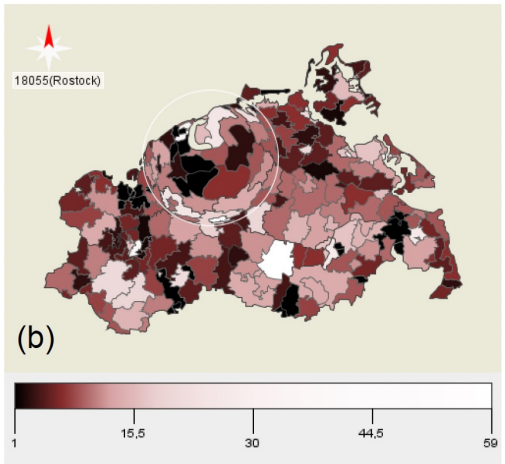
Tominski et al., 2008



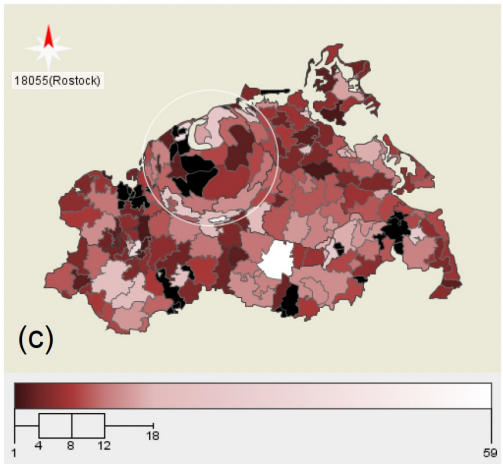




Linear color coding



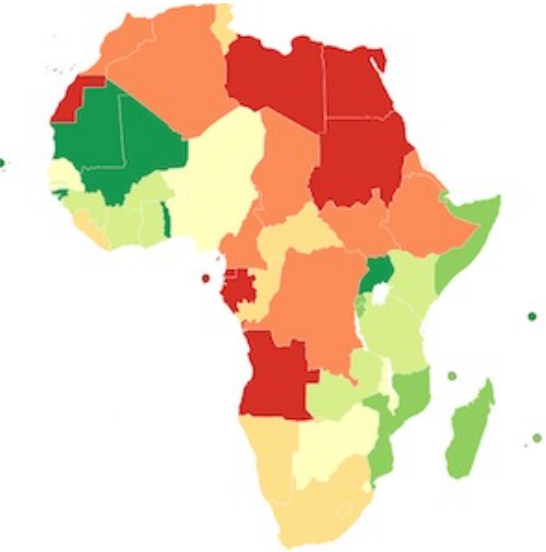
Histogram equalization

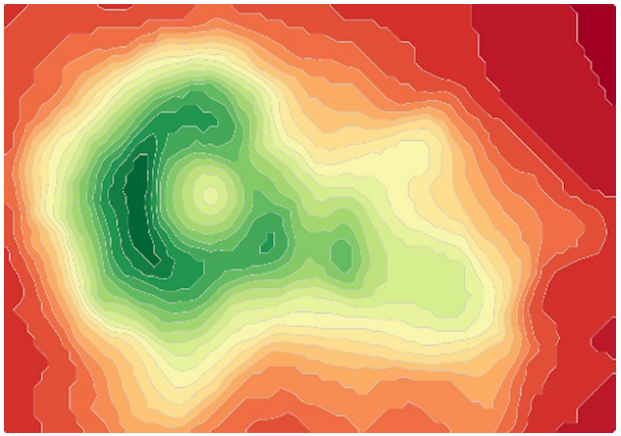


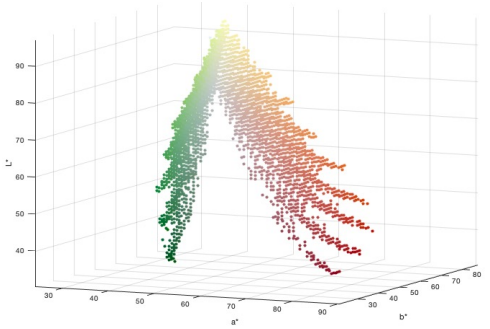
Box-Whisker plot equalization

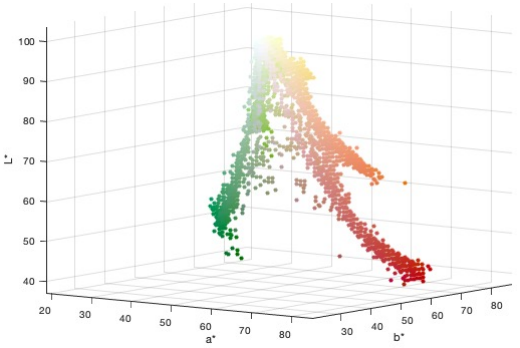
Discrete vs. Continuous Colormaps

- Discrete colormaps 
- Continuous colormaps 
- Hard to distinguish from color histograms when applied to visualizations



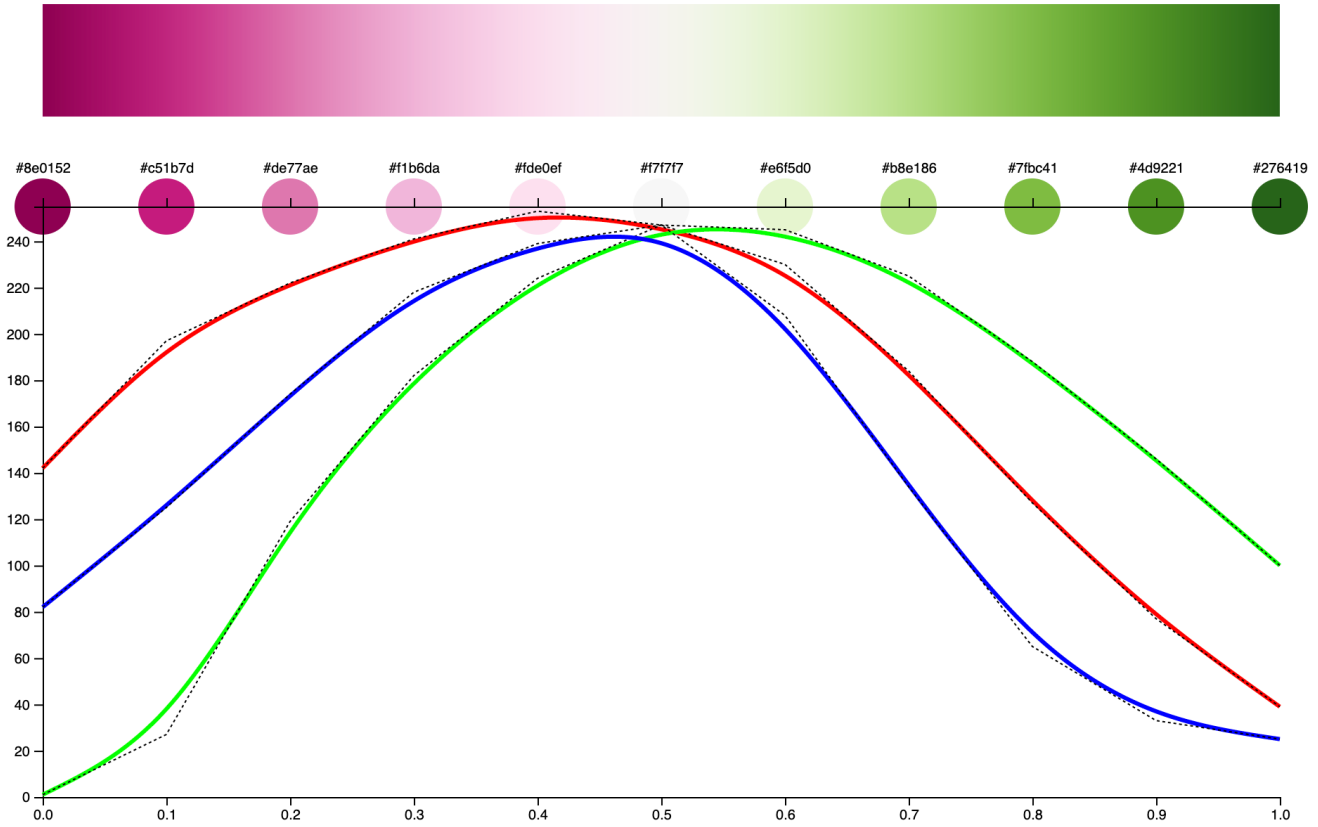




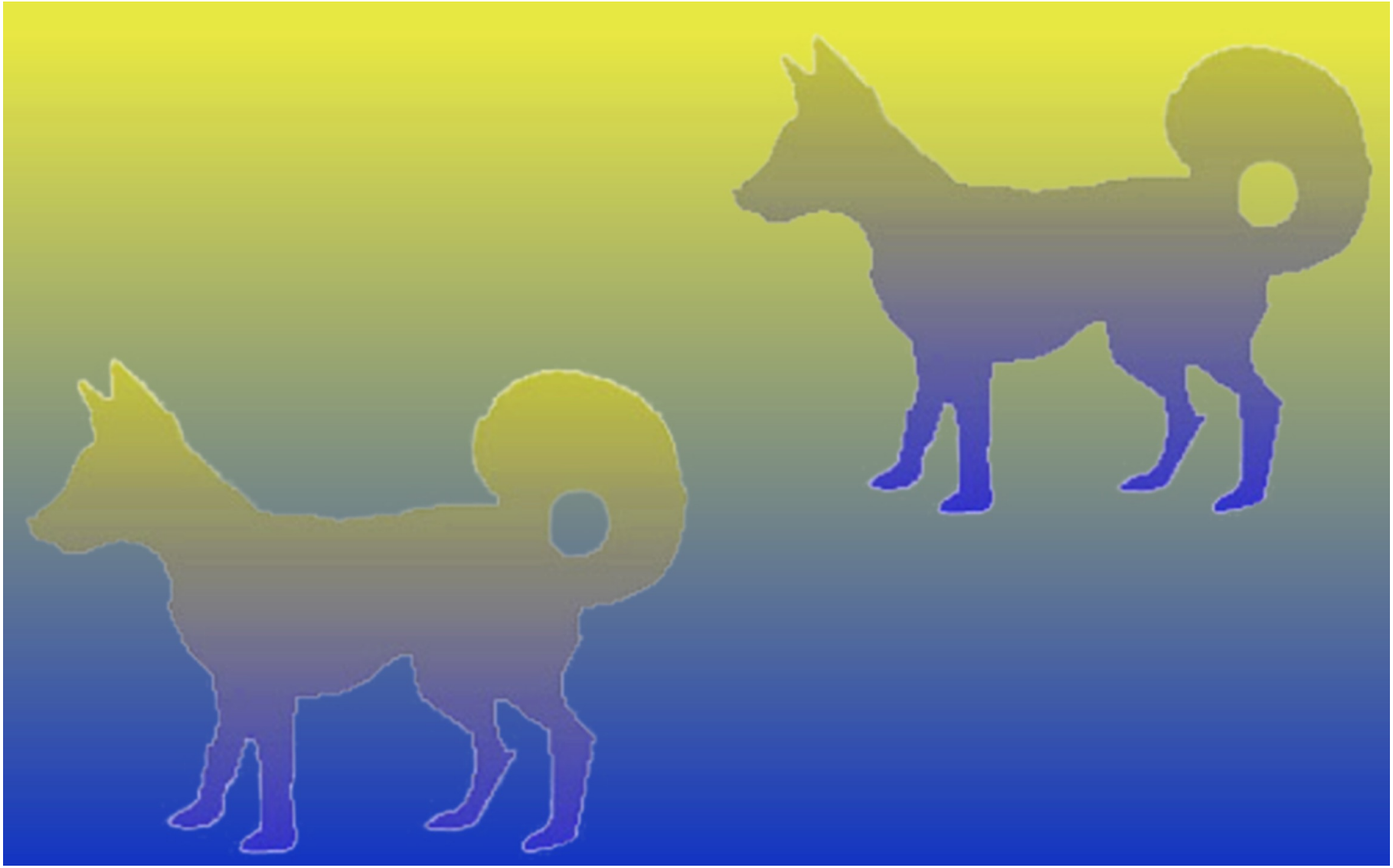


Discrete vs. Continuous Colormaps

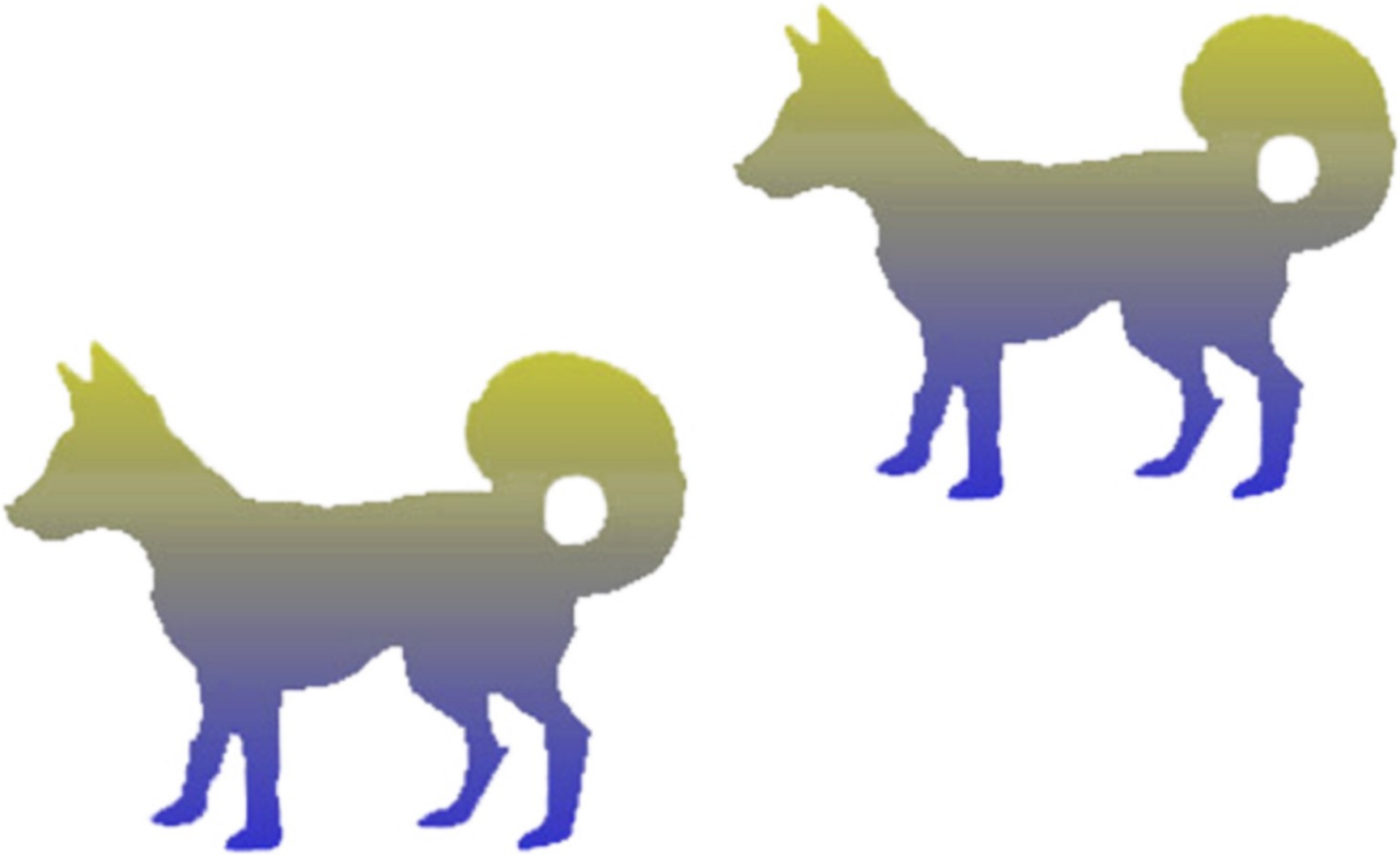
- Continuous colormaps can be created from discrete colormaps, using B-spline
  - https://bl.ocks.org/mbostock/048d21cf747371b11884f75ad896e5a5



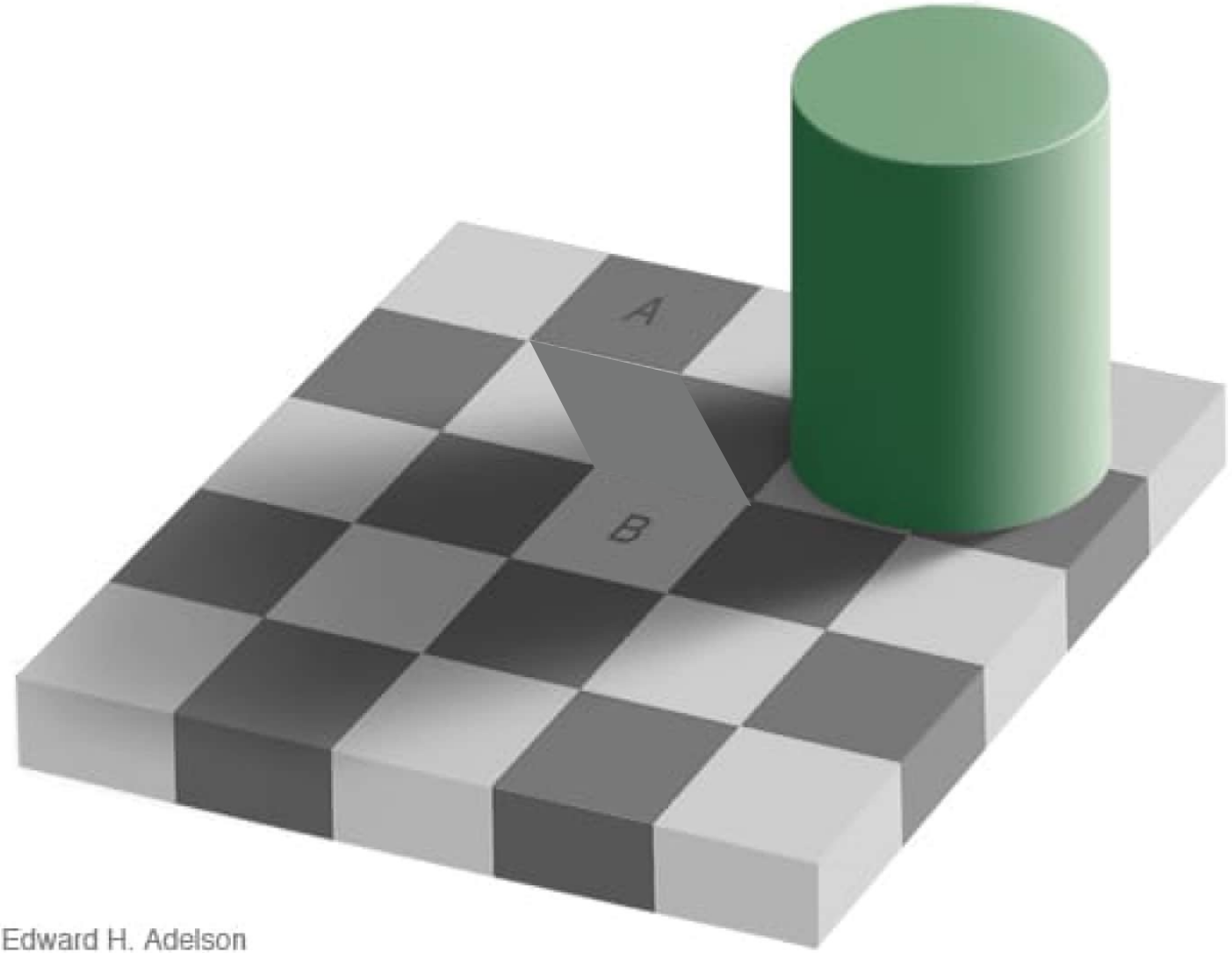
Simultaneous contrast



Simultaneous contrast

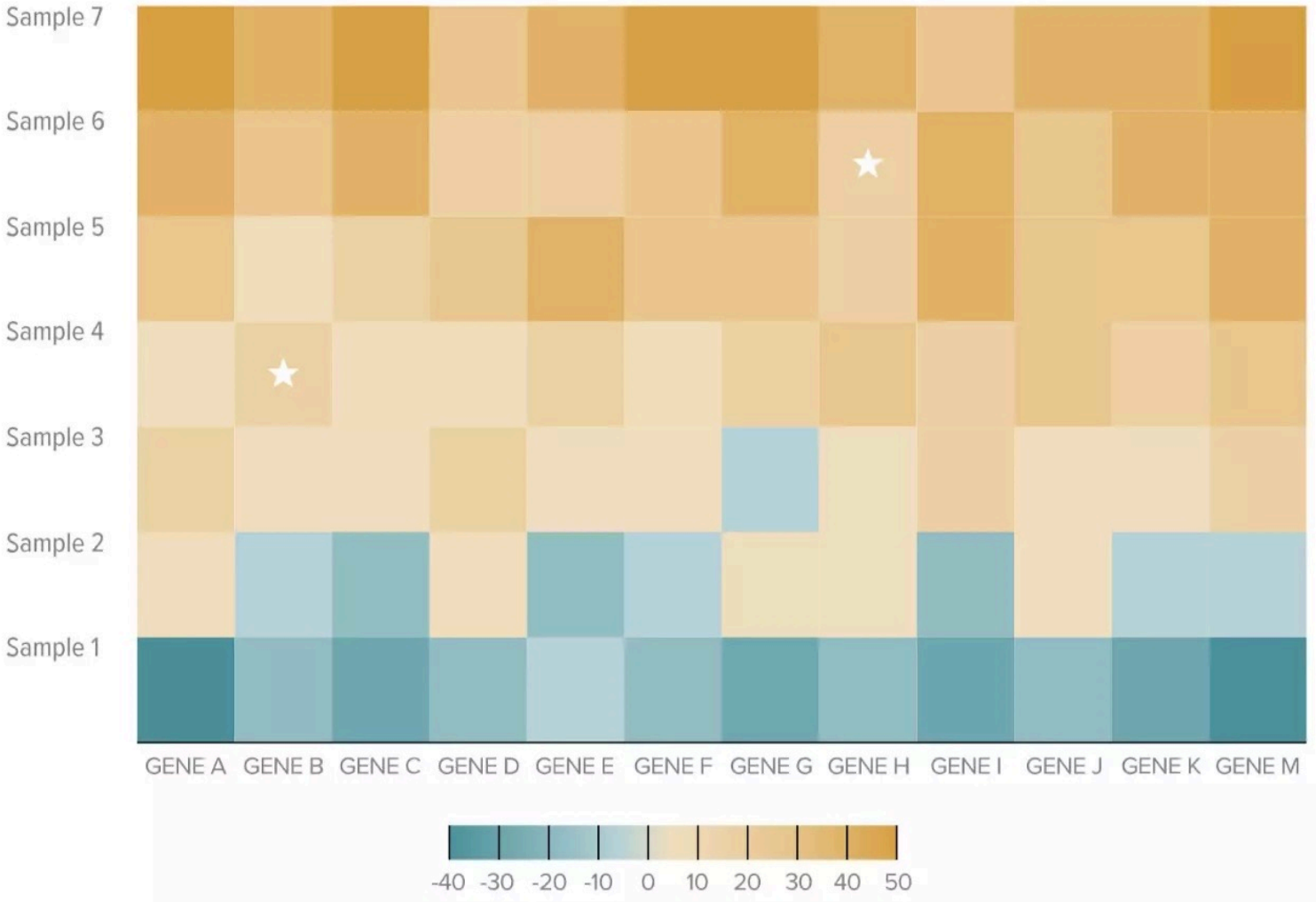


Simultaneous contrast



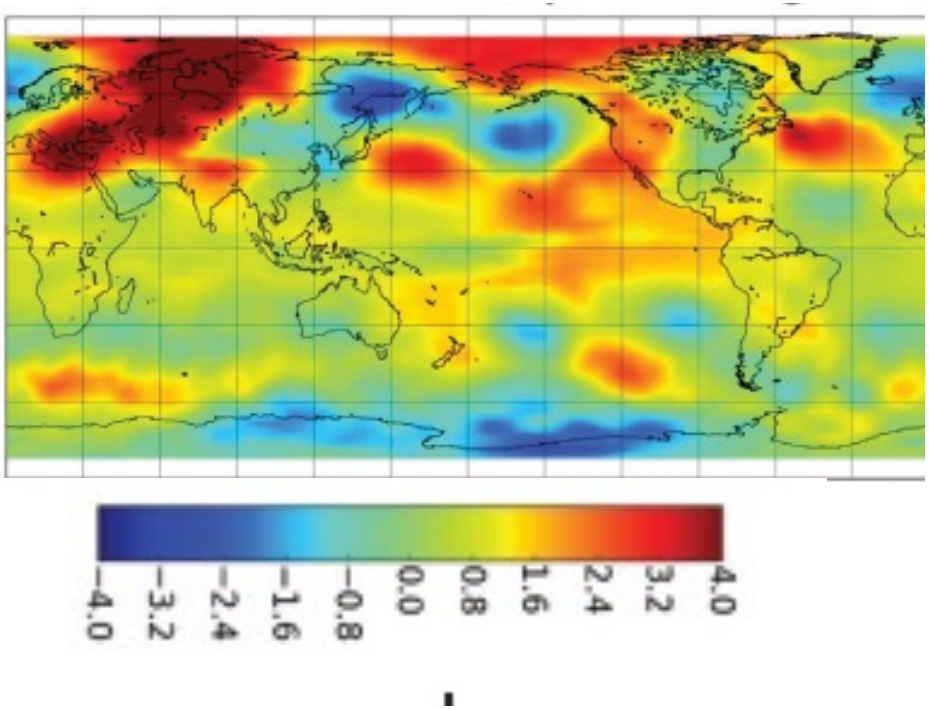
Edward H. Adelson

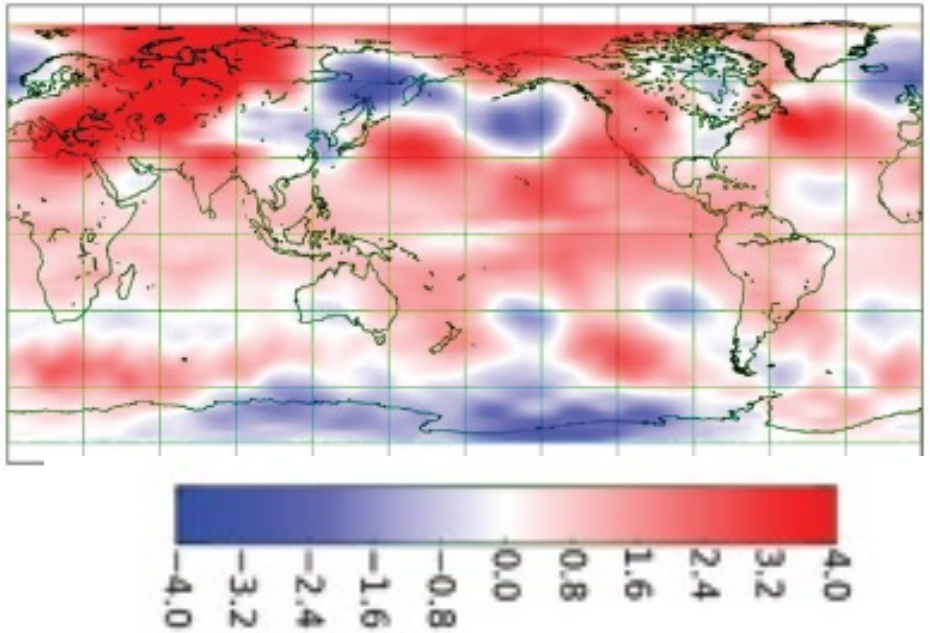
Simultaneous contrast



Dreaded rainbow colormap

- Which colormap is more effective?
  - Rainbow colormaps
  - Sequential/diverging colormaps

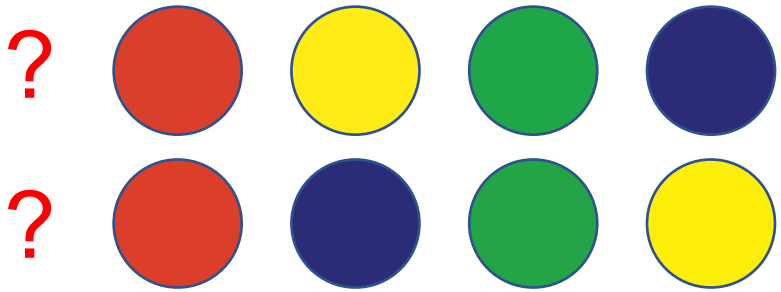


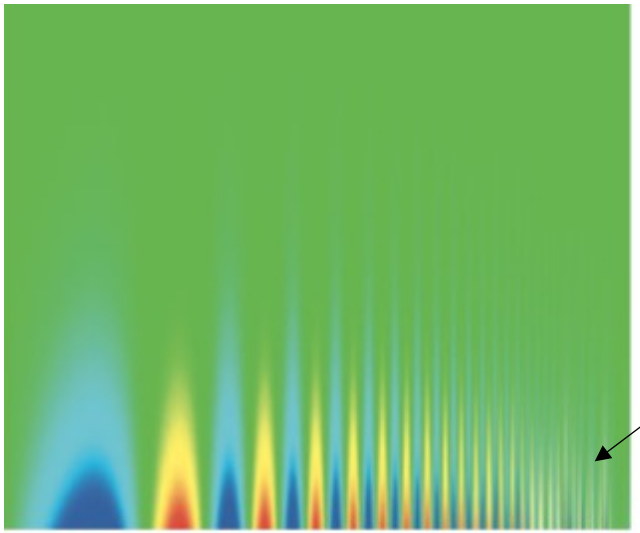


Dreaded rainbow colormap

Dreaded rainbow colormap

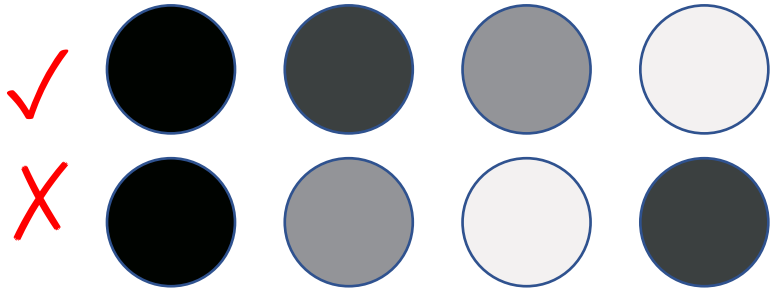
No implicit order

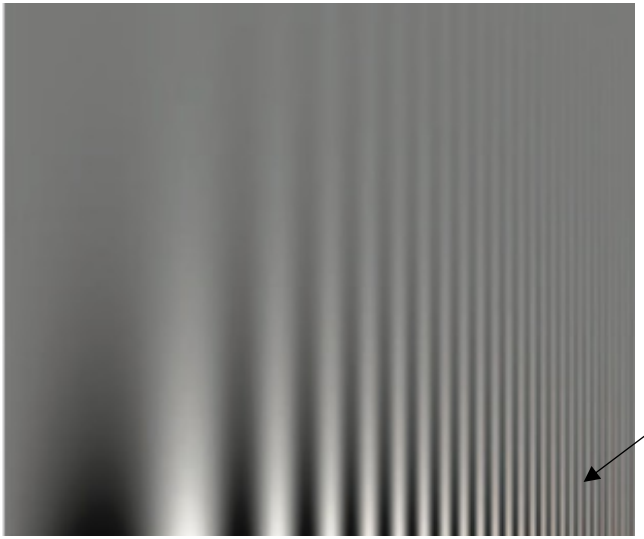




Less details

Easy to order



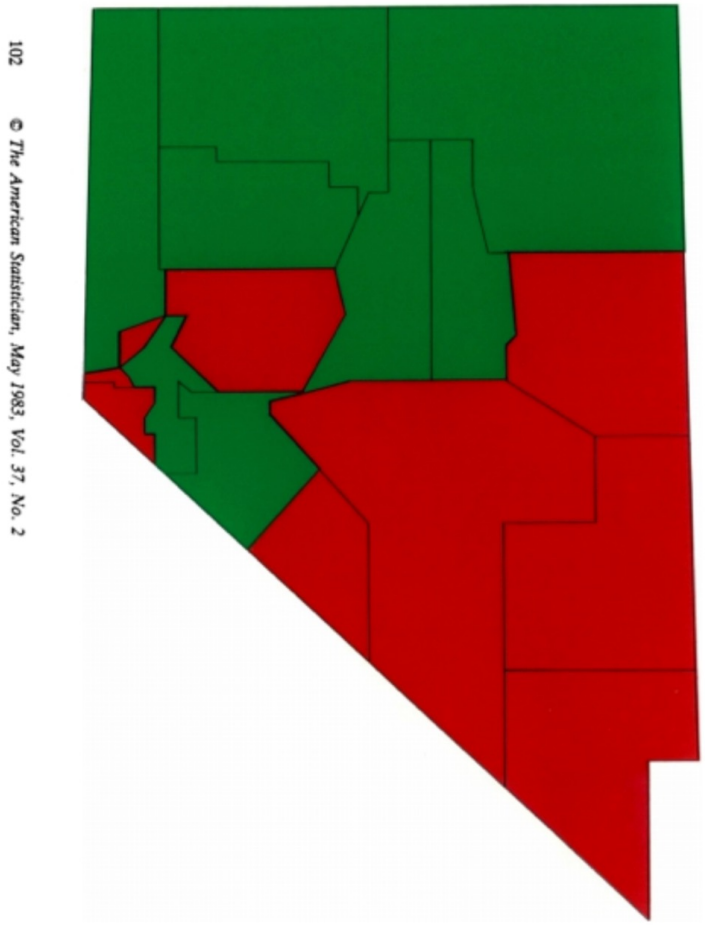


More details

Saturation vs. area perception

Saturation affects area perception

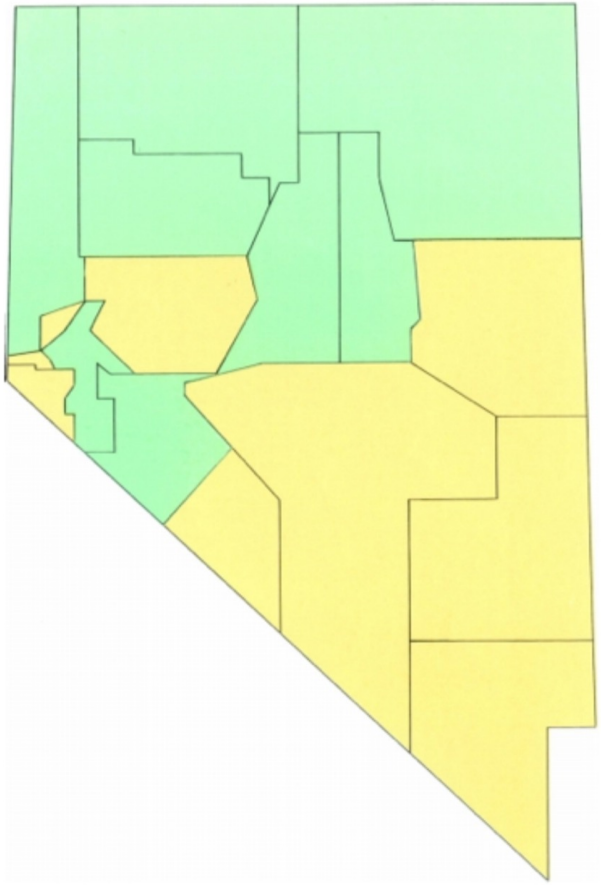
- Which color has bigger area? green or red?



Saturation vs. area perception

Saturation affects area perception

- Which color has bigger area? green or yellow?



Saturation vs. area perception

A Color-Caused Optical Illusion on a Statistical Graph

WILLIAM S. CLEVELAND and ROBERT McGILL*

Despite the great increase in the use of color in statistical graphics, we know very little about how color affects people's perception of the quantitative information on graphical displays. Perceptual psychologists have already demonstrated that color can cause optical illusions of various kinds. We ran a simple experiment to see if this can happen with a statistical map and found that an illusion did occur.

KEY WORDS: Statistical map; Psychophysics; Bootstrap; Computer graphics; Barycentric plot.

1. INTRODUCTION

Color is being used more and more in statistical graphics. The availability of color output devices for computers has greatly increased, and with easy access to these devices has come an enormous increase in the use of color graphics in the mass media, business reports, and government publications.

Scientific journals are turning to color. In the 10 April 1981 issue of *Science*, for example, substantial use is made of color: a graphical display in which two sets of data are distinguished by plotting one in black and one

areas on each map, and the experimental data were used to determine whether some colors caused areas to look bigger than others. This article describes the experiment and the results of the data analysis.

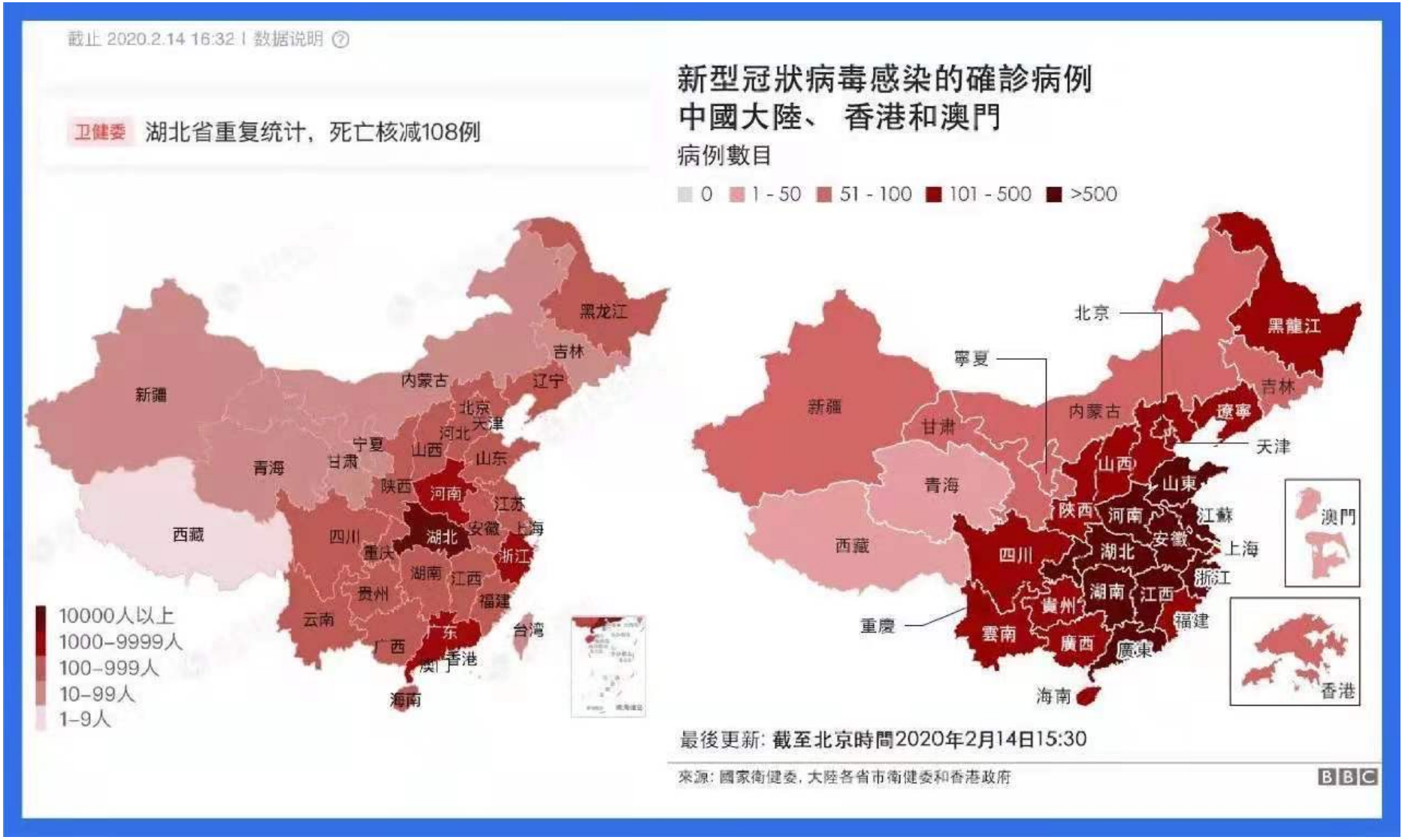
2. EXPERIMENTAL STIMULI AND PROCEDURES

The basic stimulus was a map of Nevada with county boundaries. The geometry of this map is not overly complex—most boundaries are essentially straight lines—yet the sizes and configurations of the counties are not sufficiently regular that estimates of areas could be made by counting them, as might be done on a map of Kansas or Iowa. The number of counties, 17, allows reasonably easy judgment. In no case was a subject required to mentally sum more than 10 areas.

Each stimulus in the experiment was a two-color map with the total area of the counties that were coded by one color very nearly equal to the total area of those that were coded by the second color. One stimulus is shown in Figure 1. There were 10 such divisions of counties into two groups, and in no case did the difference of the areas exceed two square miles.

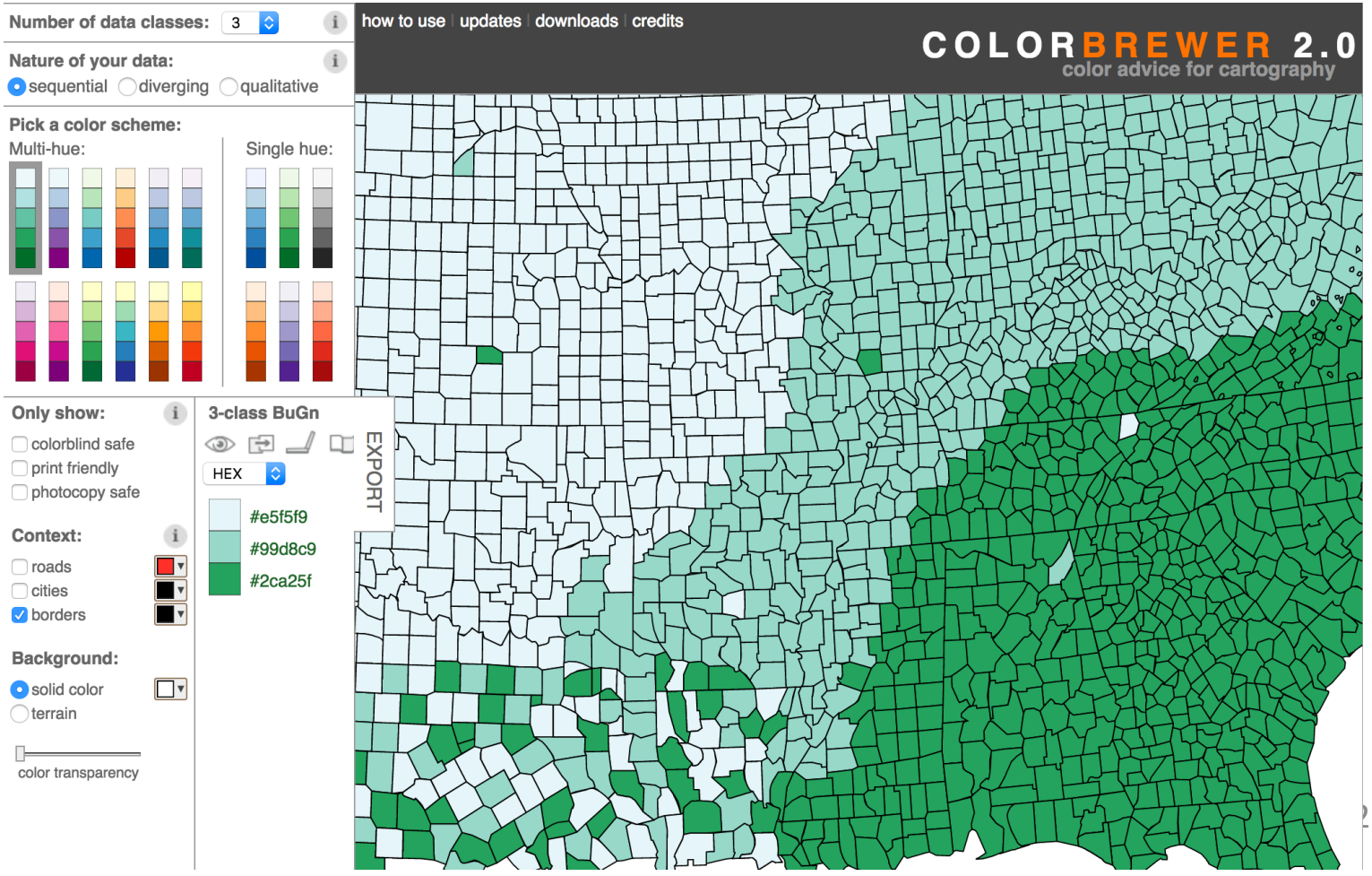
From the 10 divisions of counties into two groups, four sets of stimuli were generated, each set with the 10 maps previously described. In the first set one group of

Saturation vs. area perception



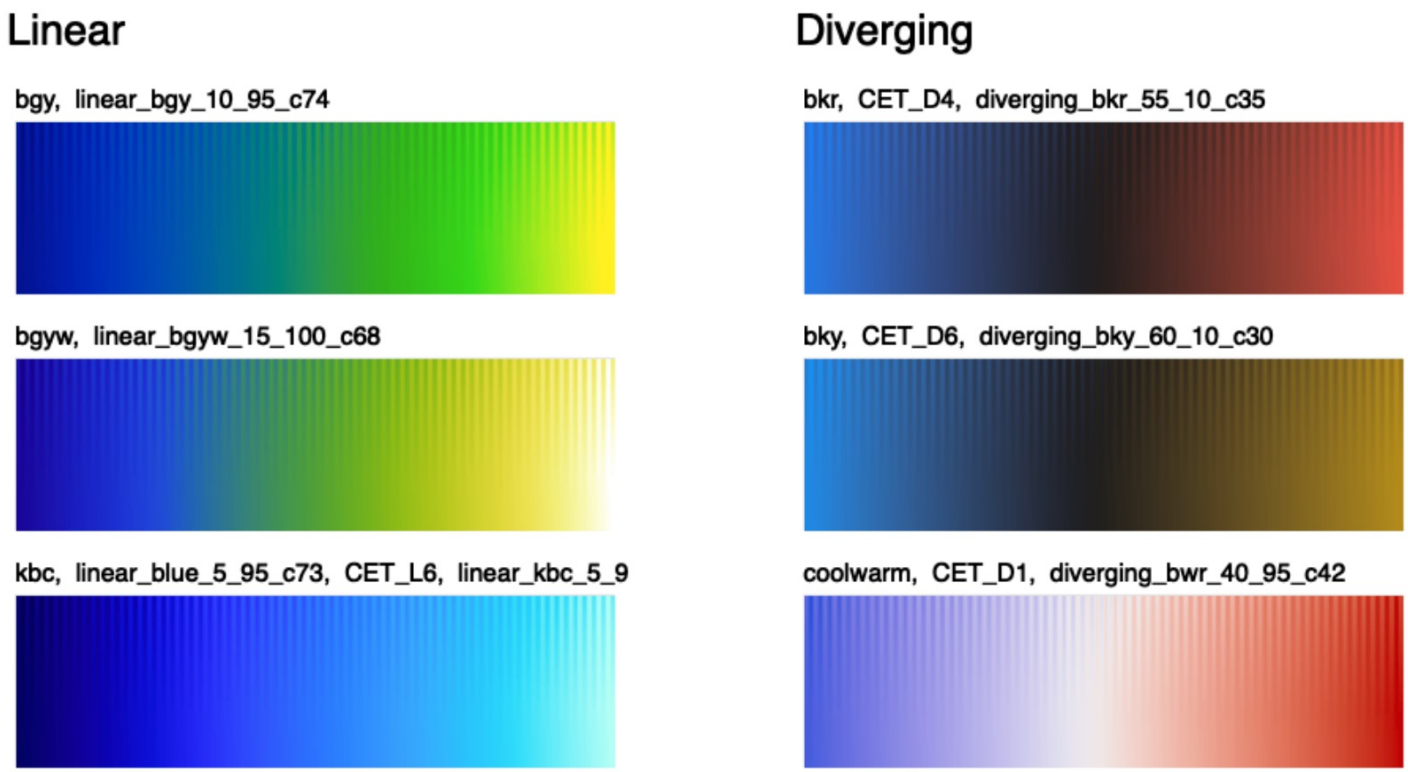
Colormap references

- ColorBrewer (http://colorbrewer2.org/)



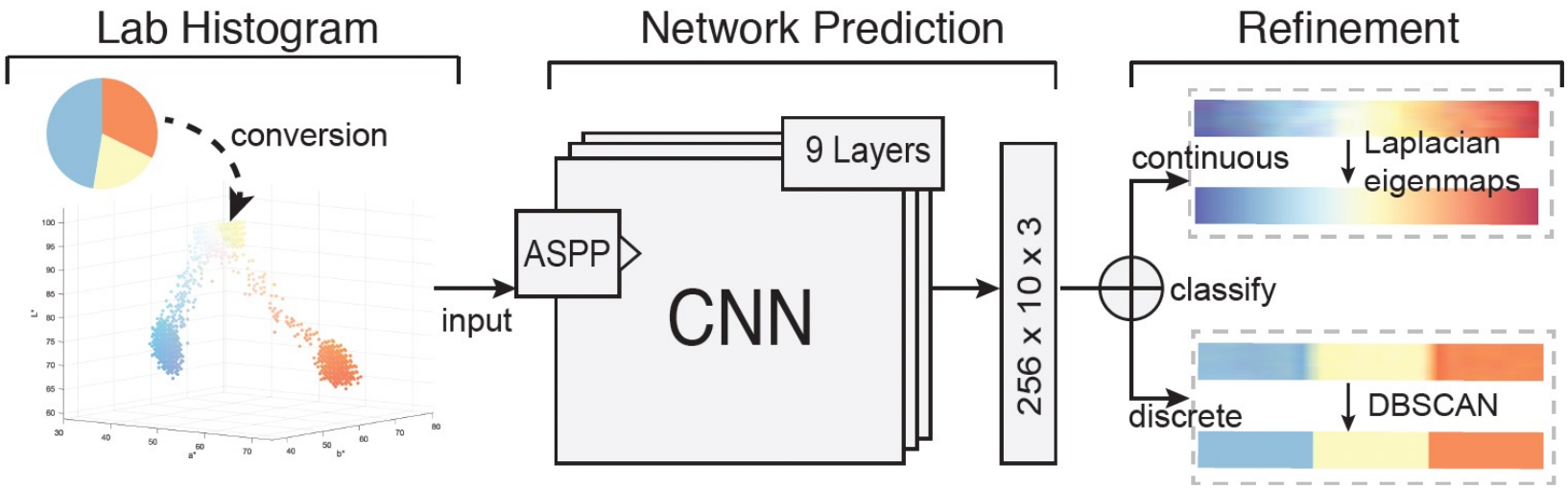
Colormap references

- https://github.com/holoviz/colorcet: perceptually uniform colormaps



Self reading

- Deep colormap extraction from visualizations
  - **Data synthesis**: consideration of data distributions, chart types, and colormaps (54 continuous + 182 discrete).
  - **Network model**: Lab histogram, CNN with ASPP.
  - **Postprocessing**: Laplacian eigenmaps for continuous, DBSCAN for discrete colormaps.



L. Yuan, W. Zeng, S. Fu, Z. Zeng, H. Li, C. W. Fu, and H. Qu, "Deep Colormap Extraction from Visualizations," *IEEE Transactions on Visualization and Computer Graphics,* pp. 1-1, 2021.