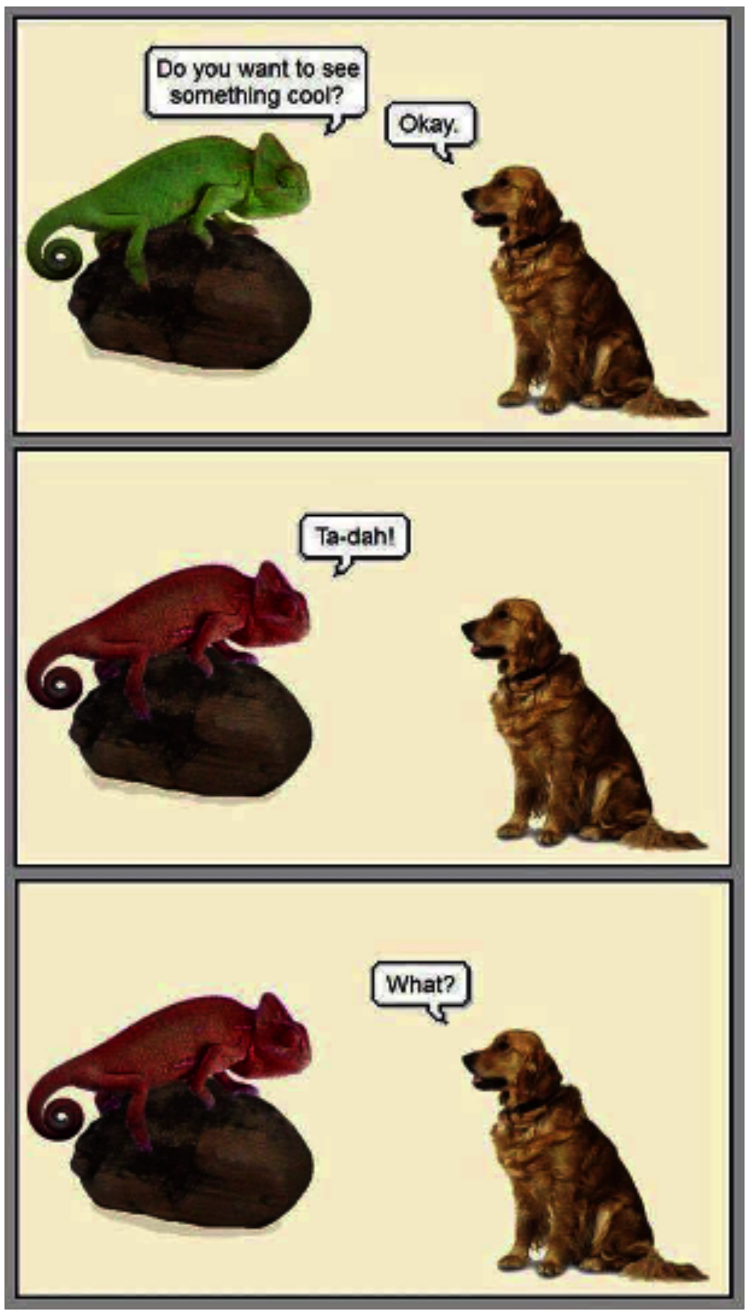
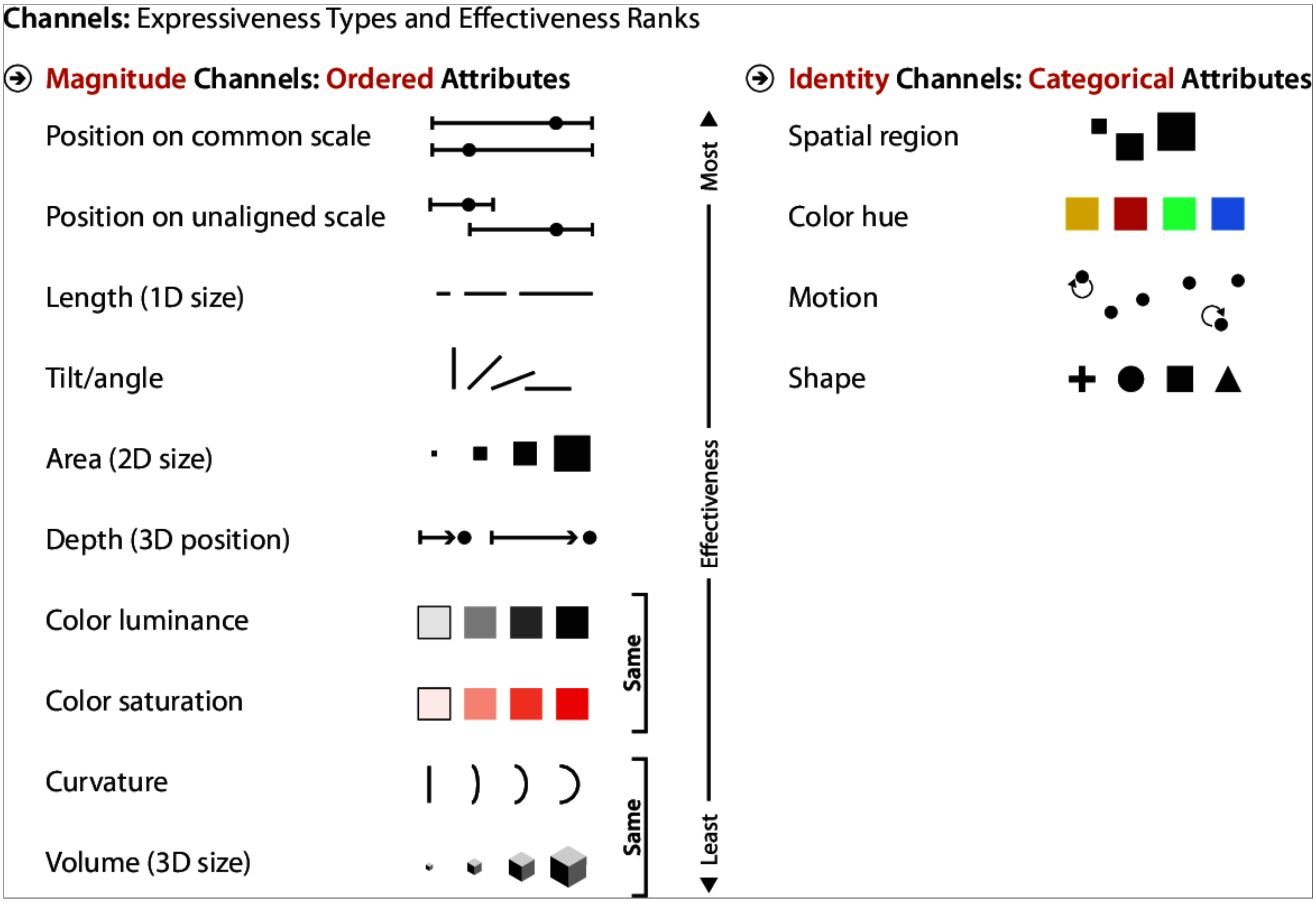
Lecture 9: Color


Do you want to see something cool?
Okay.
Ta-dah!
What?

Color

Color as a visual channel

Recall Munzner's rankings of visual channels

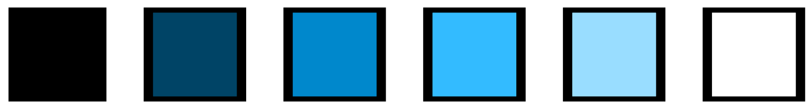


Decomposing color

Color is not a monolith: it has distinct components
Most color use decomposes into three visual channels

- RGB - suitable for building e.g. computer screens
- CMY - suitable for printing
- HSL - more suitable for visual channels
- Ordered channels show magnitudes

  Luminance (how bright)

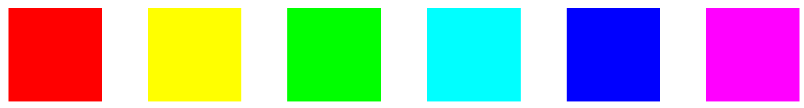
  

  Saturation (how colorful)

- Categorical channels show identity

  Hue (what color)

Decomposing color

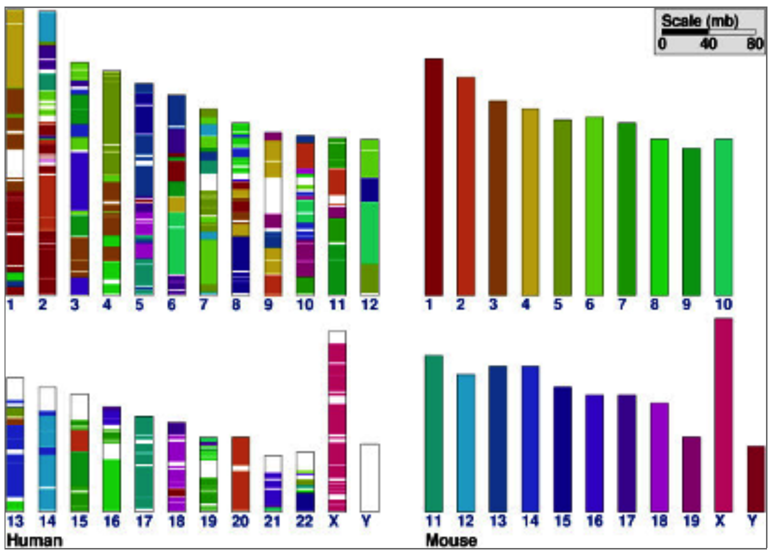
Different channels have different properties - what they convey directly, and how much they can convey.

Human perception is built on relative comparisons.

- Works great if color is contiguous.
- Surprisingly bad for absolute comparisons

Non-contiguous small regions of color

- Fewer bins than you want
- Rule of thumb: 6-12 bins **including** background and highlights



Cinteny: flexible analysis and visualization of synteny and genome rearrangements in multiple organisms. Sinha and Meller. BMC Bioinformatics, 8:82, 2007. Figure under Creative Commons CC-BY 2.0

Ordered Color

Rainbow is a poor default

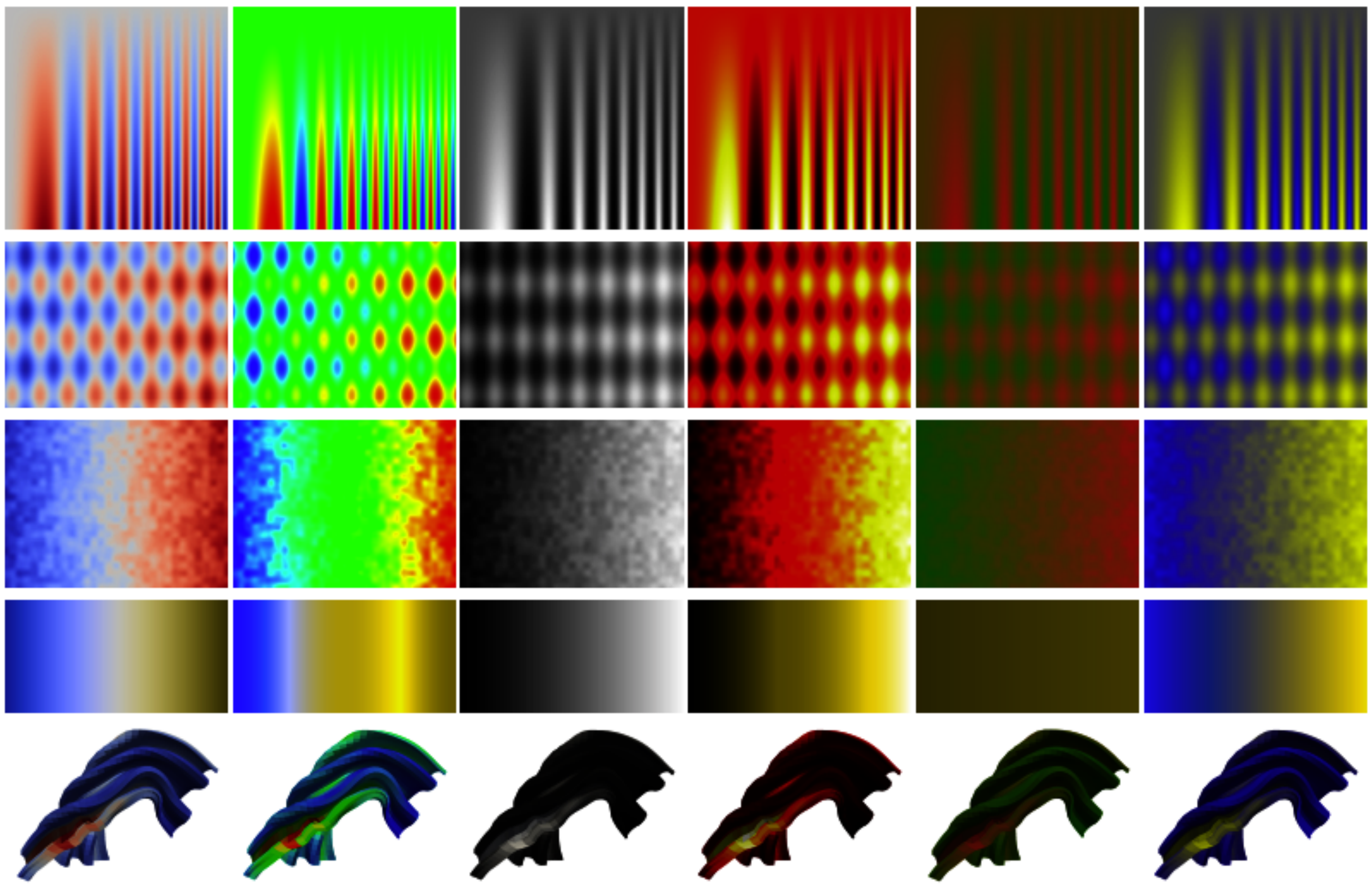


Fig. 16. Comparison of color map effectiveness. The color maps are, from left to right, cool-warm, rainbow, grayscale, heated body, isoluminant, and blue-yellow. The demonstrations are, from top to bottom, a spatial contrast sensitivity function, a low-frequency sensitivity function, high-frequency noise, an approximation of the color map viewed by someone with deuteranope color-deficient vision (computed with Vischeck), and 3D shading.

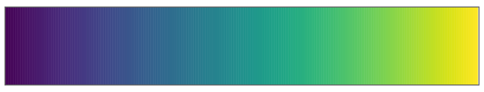
http://www.kennethmoreland.com/color-maps/ColorMapsExpanded.pdf

Ordered Color

Rainbow is a poor default

Most platforms moved away from rainbow color maps around 2015:

- **Matplotlib 2.0 (2017) introduces Viridis as new default color map (used to be `jet`)**

- **Matlab R2014b (2014) introduces Parula as new default color map (used to be `jet`)**

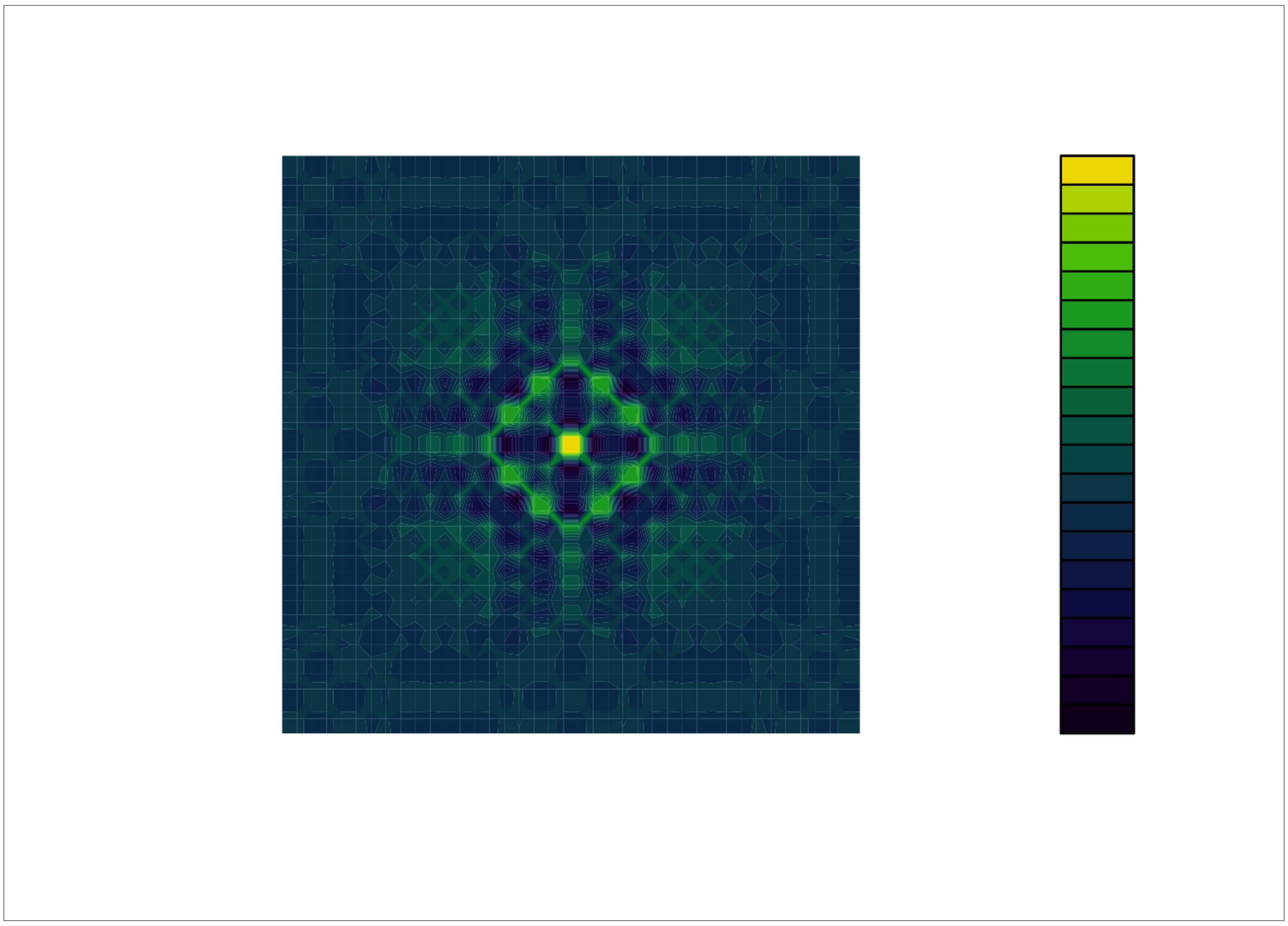
  

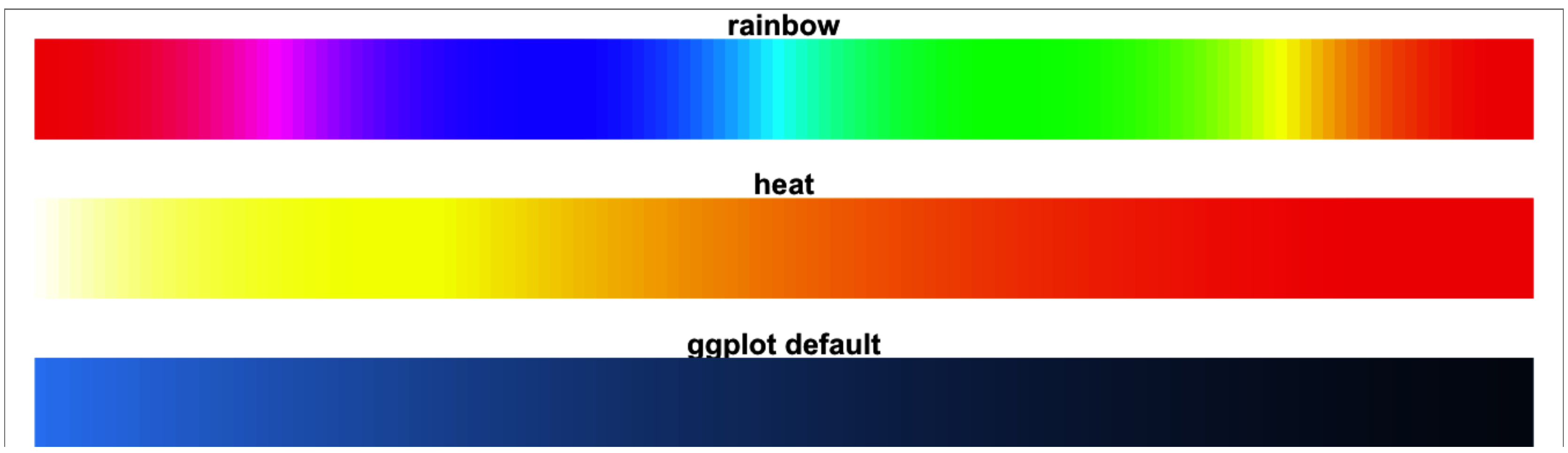
On Matplotlib's color map change, and the process for constructing new colormaps

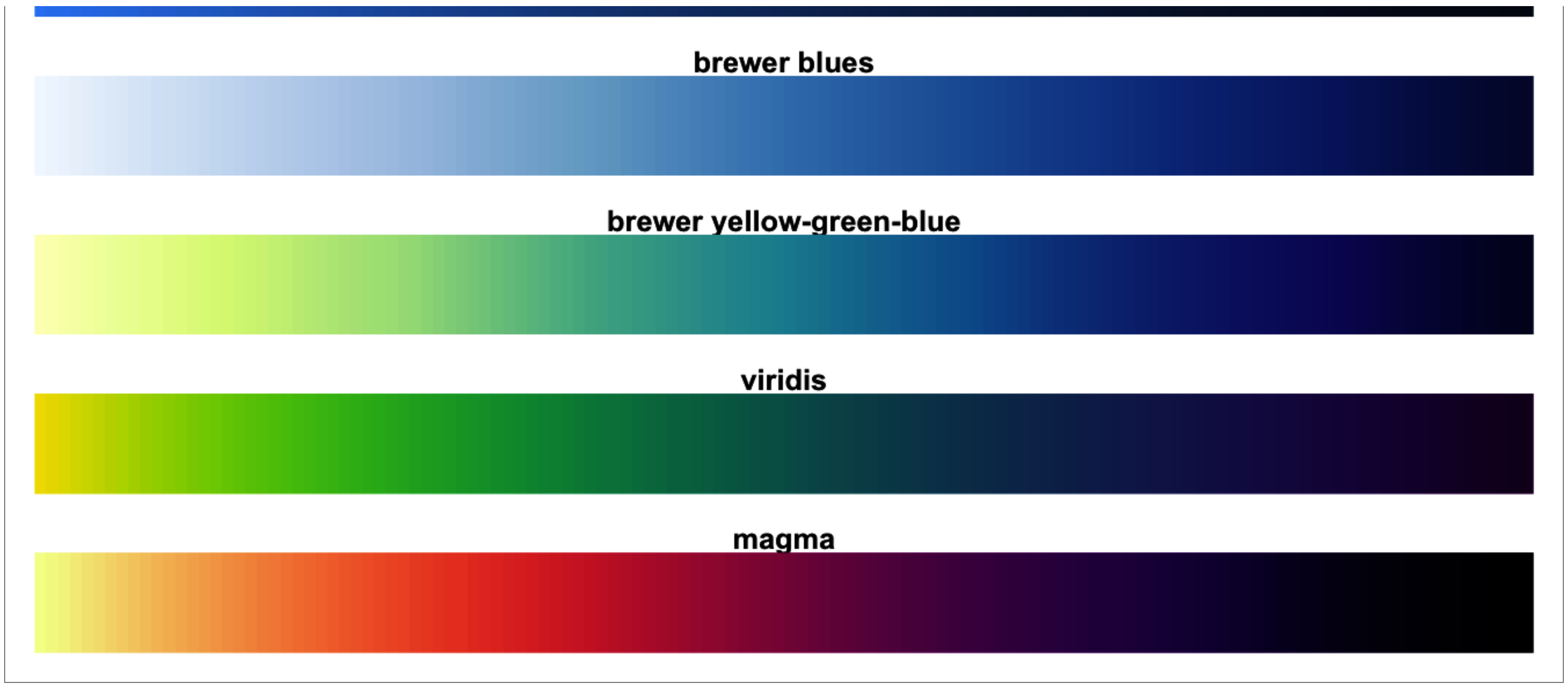
Viridis / Magma

Modern Sequential Colormaps

- Monotonically increasing luminance
- Perceptually uniform
- Colorful scales
- Colorblind-safe
- Readily available:
  - R/ggplot2: `scale_color_` or `scale_fill_`
    - `scale_color_viridis_c` - continuous
    - `scale_color_viridis_b` - binned
    - `scale_color_viridis_d` - discrete
  - Python/matplotlib: default as of matplotlib 2.0
  - d3.js: `d3.interpolateViridis`






brewer blues
brewer yellow-green-blue
viridis
magma

Interaction between visual channels

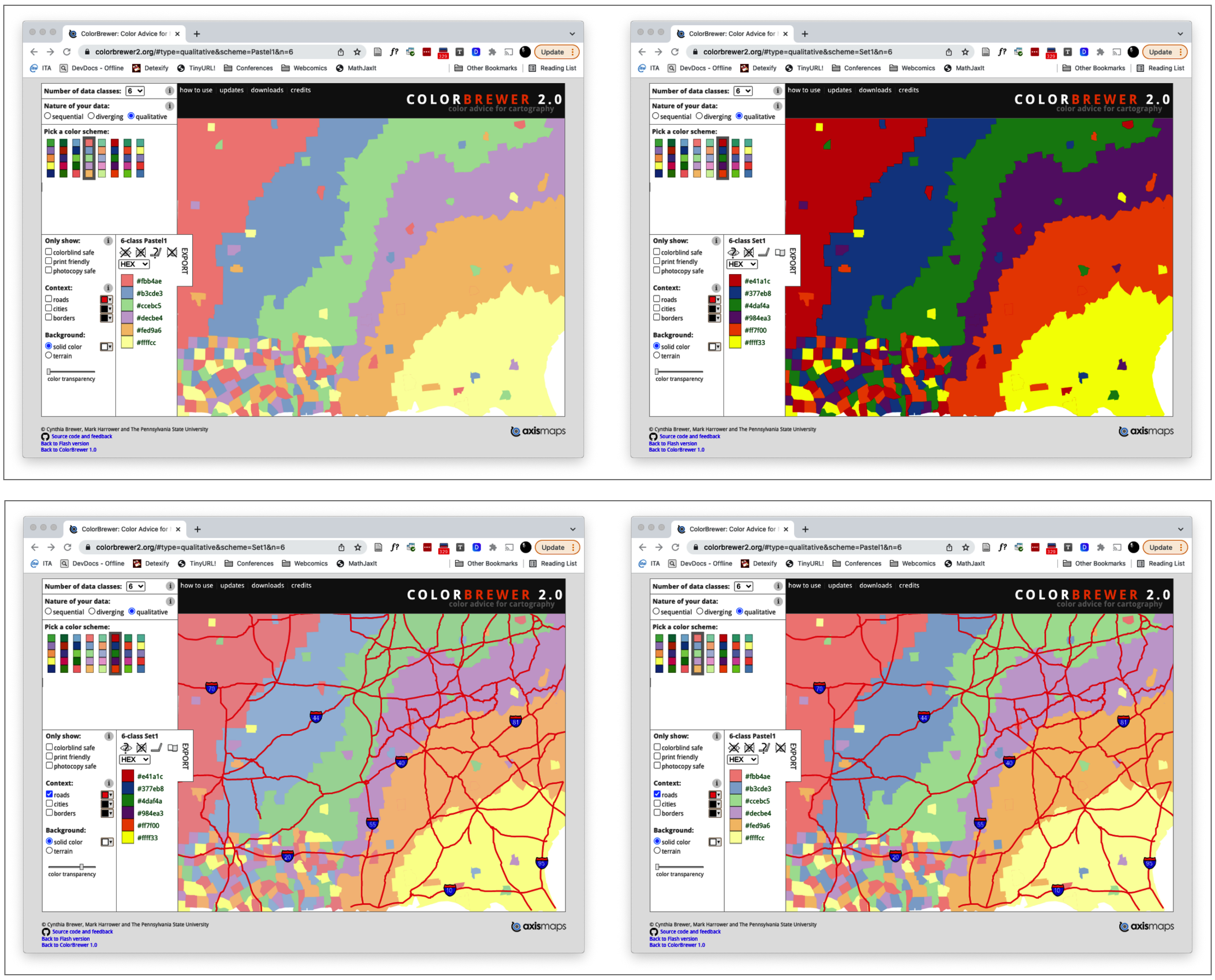
Color channels are not fully separable

Color channel interactions:

- Size affects salience
- Small regions need high saturation
- Large regions need low saturation

Saturation and Luminance:

- Not separable from each other
- Not separable from use of transparency
- Small separated regions: 2 bins(3-4 max), 1 channel
- Contiguous regions: many bins, 1 channel



colorbrewer.org

Color Palettes

1. see for instance the [1 *dataset* 100 *visualizations*] project that was highlighted in **Lecture 6**

http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Color Palette Design

Generic Guidelines

- **Choose palette type to align with the data type:**
  - categorical / ordinal / quantitative?
  - has a meaningful midpoint?
  - cyclic?
  - univariate or multivariate?
- **Segmented or Continuous?**
  - Segmented for ordinal data
  - Continuous for quantitative data (avoids banding)
- **Perceptually linear?**
  - More control if any non-linearity in the scales is intentional

Color Palette Design

Generic Guidelines

Colorblind safe?
: Use software tools to check.

Black/White printing safe?
: Order palette by luminance

External guidelines?
: If you do have a corporate design, it gives a unified look[1] if you follow that color palette.

  The CUNY Graduate Center Corporate Design suggests primary Graduate Center Blue #005DAA, and secondary colors #EC9C1D, #FFC30B, #8DC63F, #00A94F, #0093D0, #616365.

Univariate Categorical

Aim for maximum distinguishability
Use **hue** as primary color channel

- even spreads around the hue circle to maximize perceptual distance and produce harmonious color combinations
- color design guidelines:
  - complementary: primary hue, secondary with opposite hue (add 180º) 1 2
  - split-complementary: add 150º and 210º for the secondary colors 1 2 3
  - triadic (1 2 3), tetradic (1 2 3 4), pentadic (1 2 3 4 5), …: evenly distribute hue angles

Univariate Ordered

Distinguish on two axes:

- ordinal (use **segmented**) vs. quantitative (use **continuous**)
- sequential vs. diverging

Sequential (one direction)

- Ramp up luminance or saturation
- Single- or multi-hue (see **cubehelix** for linear luminance response multi-hue scheme)

Diverging (two directions)

- Use when there is a meaningful “midpoint”
- Neutral color for midpoint
- Saturated colors for endpoints
- Distinguish endpoints with hue differences

Univariate Cyclic

There are a few options available if a cyclic colormap is needed.

- **I use these in my own research:**
  - To visualize topologically generated angle-valued coordinate maps

Bivariate

Now it gets **complex**.

Best Case

Binary in one direction: paired categorical color scheme

Visual channels: saturation, hue

More complex cases

Combine desaturation with appropriate scale choices

Combine several scale choices with one another

use with care!

visual channels are not independent, interpretation can get very difficult

But sometimes showing one large graph (chart, map, …) shows more details than several side-by-side graphs would

Cynthia Brewer’s Color Scheme Chooser

Color Deficiency

…and accessibility.

Opponent Color Theory

The retina has 4 types of photo-sensitive cells: Cone cells (L/M/S) and rod cells (brightness detection)

- **Opponent Color Theory (Hering, 1892)**
  - First layer of processing records **differences** between responses, producing three opposing color pairs
  - red vs green
  - blue vs yellow
  - black vs white
- **Suggestive evidence for the opponent color theory include**
  - Phantom after-images as result from attenuation
  - Opposing colors never perceived together: no greenish red, no yellowish blue

Deviations from trichromacy

Some people have different cone cells

Tetrachromacy has been observed in humans, seems to lead to increased ability to distinguish color.
But a lot of human vision happens in subsequent processing, and perception seems connected to cultural color systems.

Monochromacy

- **rod monochromacy (achromatopsia)** - absent or non-functioning cone cells, associated with photophobia and poor vision, very rare
- **cone monochromacy** - more than one type of cone cell non-functioning

Oliver Sacks' *The island of the colorblind* describes a culture with very high hereditary rates of monochromacy, where color naming focuses on texture more than hue.

Deviations from trichromacy

Some people have different cone cells

Anomalous trichromacy

protanomaly - L-cones malfunctioning, poor red/ green discrimination, 1% males.

deuteranomaly - M-cones malfunctioning, poor red/ green discrimination, 5% European males.

tritanomaly - S-cones malfunctioning, poor blue/ green and yellow/red discrimination.

Dichromacy

protanopia - complete absence of L-cones, very poor blue/green and red/ green discrimination, limited frequency bands, 1% males.

deuteranopia - absence of M-cones, similar effects to protanopia, but with less dimming of vision, 1% males.

tritanopia - absence of S-cones, blues look green, yellow/orange look pink, purple looks deep red

Decomposing Images

Color Channels from Opponent Theory

Full Image

Luminosity

Chroma

Magenta/Green

Yellow/Blue

Color-blindness simulator

Full Image

- Protanomaly
- Deuteranomaly
- Tritanomaly
- Protanopia
- Deuteranopia
- Tritanopia
- Achromatopsia
- Blue Cone Monochromacy

Design for Accessibility

Some Guidelines

Do not encode information purely with hue

Do encode color information with luminance

Do encode information with shapes

Redundant visual channels admit information even if perception of the visual channels is imperfect or lacking

Blue vs. Orange distinction visible under all conditions

…hence the design of e.g. Viridis

Color Spaces

Putting coordinates on color.

Color is 3-dimensional

…or at least **human** color **perception** is 3-dimensional.
Color is perceived by *cone cells* in the retina. Incoming photons have an associated wavelength, producing some combination of stimulations.

L-cells
: Peak stimulus 546-580nm

M-cells
: Peak stimulus 534-545nm

S-cells
: Peak stimulus 420-440nm

This implies **any** complete color representation needs to be 3-dimensional.
Combinations of wavelengths crucial for color mixing, either **additively** (with different colored light) or **subtractively** (with different reflective inks or dyes)

RGB

Additive color space, standard for digital displays.

Three color channels: red/green/blue
HTML hex codes are structured as #**RRGGBB**, with each hexadecimal 2-digit portion encoding an intensity value 0-255.

Poor for encoding (major interference between channels)
Poor for interpolation (middle of cube is grey)

CMYK

Subtractive color space.
Standard for printing.
Cyan + Magenta + Yellow (CMY) can express full color gamut
but a **LOT** of ink needed for dark colors, usually “ink” (K) is added for black

CIE XYZ, LAB, LUV

Repeated attempts at perceptually linear spaces

CIE - Commission Internationale de l'Éclairage
(International Commission on Illumination)
: Standardization organization and international authority on light, illumination, color and color spaces

CIE 1931 RGB and XYZ
: RGB based on human experiments

: XYZ linear transformation of RGB: Y measures luminance, Z $\approx$ blue, X chosen to have a positive defining curve

CIE 1976 L*a*b*
: Based on human experiments to make distances perceptually uniform

: L*: Lightness, a*: green-red axis, b*: blue-yellow axis

: Also common: polar coordinates LCh (L*, C* (chroma) and h° (hue angle))

CIE 1976 L*u*v*
: Updated version of the intermediate CIE 1964 UVW

: Different choice of white point adaptation from L*a*b*

CIE LAB axes

CIE LUV axes

HSV, HSL

Hue, Saturation, and either Lightness or Brightness

Hue

Angle-valued color coordinate

Red at 0º, Green at 120º, Blue at 240º

Chroma and Saturation

Chroma is $\max(R, G, B) - \min(R, G, B)$

Saturation is chroma, rescaled to fit in [0,1]

HSV - Hue, Saturation, Value

Single cone model

Value = $\max(R, G, B)$

HSL - Hue, Saturation, Lightness

Double cone model

Lightness = $\frac{1}{2}(\max(R, G, B) + \min(R, G, B))$

HSL cylinder

HSV cylinder

HChV cone

HChL double cone

LSM

Color coordinates based directly on cone cell responses

Entire light spectrum convoluted with each response curve to form coordinate values L, M, S.
Color conversion usually goes through CIE XYZ and a subsequent linear transform.
Can be used to simulate color blindness.

Interpolating colors

Equidistance concerns

Linear Interpolation is an attractive option for magnitude-representing color schemes.
Choice of coordinate systems can dramatically influence results.
Distinguishability of steps is perceptually connected to **lightness**, and gets muddled when the lightness progression is not linear.

Color Contrast and Color Naming

…and their interactions with perception.

Interaction with the background

Color/Lightness Constancy

- **Color perception is not (only) about wavelengths and L*a*b*.**
  - **Background color matters**
  - **Outlines matters** (Bezold effect)
  - **Illumination matters**: for a full description of color you need to pick an *illuminant* (color, intensity of ambient light) and *observer* (how much of the retina we are considering) - both are included in the CIE standards
  - **Attenuation matters** - neurons “get tired” of stimuli, decrease response with over-stimulation. This is one source of ghost images

Impact of Illumination

Impact of Illumination

Color Naming and Perception

Different languages divide the color spectrum differently
Discriminability depends on language (Witzel-Gegenfurtner (2015) - barely discernable colors recognized faster if they straddle a color word boundary)
xkcd and linguists/psychologists study color with very different methods

Linguists

- Define *basic color word* by:
- peeling away modifiers (no *light blue*)
- requiring universal applicability (no *blonde*)
- requiring universal recognizability (no *fuchsia*)
- controlled experiments with attention to lighting, neural attenuation, …

XKCD

- Massive crowdsourced free-form data collection

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

Resources on Color

Online Resources

- ColorBrewer (color schemes) **http://colorbrewer2.org**
- **Cynthia Brewer's guidelines**
- **Matplotlib on color**
- **paletton palette picker**
- **Data Color Picker**
- i want hue (k-means clustering for palette generation) **https://medialab.github.io/iwanthue/**
- **Viz palette** (shows effects of palette, incl. color blindness, similarity, naming similarity)

Software Resources

Colorblindness Simulator

- Color Oracle (Windows/Mac/Linux) **https://colororacle.org**
- Let's get color blind

Python

- `palettable` - unified access to large families of color maps

R

- `colorspace` - can simulate greyscaling
- `dichromat` - can simulate color blindness
- `colorblindr` - can color blindness simulate ggplot objects
- `pals` - extensive palette collection
- `khroma` - palettes and tools for color blind acessible design
- `ggthemes` - mimic very many distinct looks (incl. WSJ, Economist, Excel, Tableau, …)