Color
Color in Visualization

Identify, Group, Layer, Highlight
Purpose of Color

To label
To measure
To represent and imitate
To enliven and decorate

“Above all, do no harm.”

- Edward Tufte
Topics

Perception of Color
Light, Visual system, Mental models

Color in Information Visualization
Nominal, Ordinal & Quantitative color encoding
Guidelines for color palette design
Perception of Color
What color is this?
What color is this?

“Yellow”
What color is this?
What color is this?

“Blue”
What color is this?
What color is this?

“Teal”?
Perception of Color

Light

Cone Response

Opponent Signals

“Yellow”

Color Cognition

Color Appearance

Color Perception
Physicist’s view

Light as electromagnetic wave

Wavelength

Energy or

“Relative luminance”
Emissive vs. reflective light

Additive (digital displays)

Subtractive (print, e-paper)
Perception of Color

Light -> Cone Response -> Opponent Signals

A R-G Y-B

“Yellow” -> Color Cognition -> Color Appearance -> Color Perception
Retina

Simple Anatomy of the Retina, Helga Kolb
As light enters our retina...

LMS (Long, Middle, Short) Cones
Sensitive to different wavelength
As light enters our retina...

LMS (Long, Middle, Short) Cones
Sensitive to different wavelength
Integration with input stimulus

A Field Guide to Digital Color, Maureen Stone
Effects of retina encoding

Spectra that stimulate the same LMS response are indistinguishable (a.k.a. “metamers”).

“Tri-stimulus”
Computer displays
Digital scanners
Digital cameras
CIE XYZ color space

Standardized in 1931 to mathematically represent tri-stimulus response.
“Standard observer” response curves
CIE XYZ color space
CIE chromaticity diagram

Colorfulness vs. Brightness

\[ x = \frac{X}{X+Y+Z} \]

\[ y = \frac{Y}{X+Y+Z} \]
CIE chromaticity diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.

Courtesy of PhotoResearch, Inc.
CIE chromaticity diagram

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Courtesy of PhotoResearch, Inc.
Display gamuts

Typically defined by:

3 Colorants

Convex region
Display gamuts

Deviations from sRGB specification
Color blindness

Missing one or more retina cones or rods

Protanope
Deuteranope
Luminance
VisCheck

Simulates color vision deficiencies
Web service or Photoshop plug-in
Robert Dougherty and Alex Wade
Perception of Color

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Color Perception
Primary colors?

To paint “all colors”:

Leonardo da Vinci, circa 1500 described in his notebooks a list of simple colors...

Yellow
Blue
Green
Red
Opponent processing

LMS are combined to create:
Lightness
Red-green contrast
Yellow-blue contrast
Opponent processing

LMS are combined to create:
Lightness
Red-green contrast
Yellow-blue contrast
Opponent processing

LMS are combined to create:
Lightness
Red-green contrast
Yellow-blue contrast

Experiments:
No reddish green, no bluish yellow
Color after images
CIE LAB and LUV color spaces

Standardized in 1976 to mathematically represent opponent processing theory.
Non-linear transformation of CIE XYZ
Axes of CIE LAB

Correspond to opponent signals
L* = Luminance
a* = Red-green contrast
b* = Yellow-blue contrast

Scaling of axes to represent “color distance”
JND = Just noticeable difference (~2.3 units)
Perception of Color

Light

Cone Response

Opponent Signals

“Yellow”

Color Cognition

Color Appearance

Color Perception

Light Cone Response Opponent Signals “Yellow” Color Cognition Color Appearance Color Perception
Albert Munsell

Developed the first perceptual color system based on his experience as an artist (1905).
Hue, Value, Chroma
Hue, Value, Chroma
Hue, Value, Chroma
Hue, Value, Chroma
Munsell color system

Perceptually-based
Precisely reference a color
Intuitive dimensions
Look-up table (LUT)
Munsell color system
Perceptual brightness

Color palette
Perceptual brightness

Color palette

HSL Lightness (Photoshop)
Perceptual brightness

Color palette

Luminance Y (CIE XYZ)
Perceptual brightness

Color palette

Munsell Value
Perceptual brightness

Color palette

Munsell Value
L* (CIE LAB)
Perceptually-uniform color space

Munsell colors in CIE LAB coordinates
Color Appearance

If we had a perceptually-uniform color space, can we predict how we perceive colors?
Simultaneous Contrast

The inner and outer thin rings are in fact the same physical purple.
Simultaneous Contrast
Simultaneous Contrast
Chromatic Adaptation
Chromatic Adaptation
Bezold effect

Color appearance depends on adjacent colors.
Crispening

Perceived difference depends on background

Color Appearance Models, Fairchild
Spreading

Spatial frequency
- The paint chip problem
- Small text, lines, glyphs
- Image colors

Adjacent colors blend
Color Appearance

If we had a perceptually-uniform color space, can we predict how we perceive colors?

Chromatic adaptation
Luminance adaptation
Simultaneous contrast
Spatial effects
Viewing angle
iCAM models (2002)
Chromatic adaptation
Appearance scales
Color difference
Crispening
Spreading
HDR tone mapping
(see also CIECAM02)
Perception of Color

Light

Cone Response

Opponent Signals

“Yellow”

Color Cognition

Color Appearance

Color Perception
Colors according to XKCD...
Basic color terms

Chance discovery by Brent Berlin and Paul Kay.
Basic color terms

Chance discovery by Brent Berlin and Paul Kay.
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.

Initial study in 1969

- Surveyed speakers from 20 languages
- Literature from 69 languages
World color survey
World color survey
World color survey

Naming information from 2616 speakers from 110 languages on 330 Munsell color chips
Results from WCS
Results from WCS
Universal (?) Basic Color Terms

Basic color terms recur across languages.

- White
- Grey
- Black
- Red
- Yellow
- Green
- Blue
- Pink
- Brown
- Orange
- Purple
Evolution of Basic Color Terms

Proposed universal evolution across languages.
Rainbow color ramp

We associate and group colors together, often using the name we assign to the colors.
Rainbow color ramp

We associate and group colors together, often using the name we assign to the colors.
Rainbow color ramp

We associate and group colors together, often using the name we assign to the colors.
Naming affects color perception

Color name boundaries

Green | Blue
Color naming models [Chuang et al., Heer & Stone]

Model 3 million responses from XKCD survey

Bins in LAB space sized by saliency:
How much do people agree on color name?
Modeled by entropy of $p(\text{name} \mid \text{color})$

$L^* = 55$

Blue / green confusion
Orange / red boundary
Icicle tree with colors

Naming confusion conflicts with tree structure!
Perception of Color

- Light
- Cone Response
- Opponent Signals
  - A
  - R-G
  - Y-B
- "Yellow"
- Color Cognition
- Color Appearance
- Color Perception
Color in Data Visualization
Hints for the colorist

Use only a few colors (~6 ideal)
Colors should be distinctive and named
Strive for color harmony (natural colors?)
Use cultural conventions; appreciate symbolism
Beware of bad interactions (red/blue etc.)
Get it right in black and white
Respect the color blind
Categorical Color
Gray’s anatomy

Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)
Molecular models

Organic Chemistry Molecular Model Set
http://www.indigo.com/models/gphmodel/62003.html
Resistor color codes

<table>
<thead>
<tr>
<th>COLOR</th>
<th>1st BAND</th>
<th>2nd BAND</th>
<th>3rd BAND</th>
<th>MULTIPLIER</th>
<th>TOLERANCE</th>
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<td>± 1%</td>
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<td>Orange</td>
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<td>237Ω</td>
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Electronix Express / RSR
http://www.elexp.com
1-800-972-2225
In NJ 732-381-8020
Allocation of the radio spectrum

http://www.ntia.doc.gov/osmhome/allochrt.html
<table>
<thead>
<tr>
<th>Radio Services Color Legend</th>
<th>Activity Code</th>
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<td>Mobile Satellite</td>
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<tr>
<td>Standard Frequency and Time Signal</td>
<td>Satellite</td>
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Palette Design + Color Names

Minimize overlap and ambiguity of color names.

http://vis.stanford.edu/color-names
Palette Design + Color Names

Minimize overlap and ambiguity of color names.

http://vis.stanford.edu/color-names
Quantitative Color
Default rainbow maps
Avoid rainbow color maps!

1. People segment colors into classes
2. Hues are not naturally ordered
3. Different lightness emphasizes certain scalar values
4. Low luminance colors (blue) hide high frequencies
Singularity in Phase (M. Berry)

Phase is periodic $\Rightarrow$ Hue circle which is also periodic
Classing quantitative data

Age-adjusted mortality rates for the United States.
Classing quantitative data

1. Equal interval (arithmetic progression)
2. Quantiles \textit{(recommended)}
3. Standard deviation
4. Classification [Jenks’ “natural breaks”]
5. Equal area
6. Minimal length boundaries
7. Minimal gaps
ColorBrewer: Color advice for maps
Quantitative color encoding

**Sequential color scale**
Constrain hue, vary luminance/saturation
Map higher values to darker colors

**Diverging color scale**
Useful when data has a meaningful “midpoint”
Use neutral color (e.g., grey) for midpoint
Use saturated colors for endpoints

Limit number of steps in color to 3-9
Sequential color scheme

Sequential Scheme
One Hue

Percent of labor force employed in services 1980

60 to 63
50 to 59
40 to 48
33 to 39
26
18
Sequential color scheme
Design of sequential color scales

Hue-Lightness  (*Recommended*)
Higher values mapped to darker colors
ColorBrewer schemes have 3-9 steps

Hue Transition
Two hues
Neighboring hues interpolate better
Couple with change in lightness
Design of sequential data scales

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

Hue Transition

- Carefully handle midpoint
  - Critical class
    - Low, Average, High
    - ‘Average’ should be gray
  - Critical breakpoint
    - Defining value e.g. 0
    - Positive & negative should use different hues

- Extremes saturated, middle desaturated
Diverging color scheme

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