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?
“Yellow”

What color is this?

What color is this?
What color is this?

“Blue”

What color is this?

“Teal”?

Perception of Color

Light → Cone Response → Opponent Signals → Color Cognition → Color Appearance → Color Perception

“Yellow”
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
“Yellow”
Color Cognition
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Color Perception

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

LMS (Long, Middle, Short) Cones
Sensitive to different wavelength

Integration with input stimulus

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

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.

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Display gamuts
Typically defined by:
3 Colorants
Convex region

CIE chromaticity diagram
Spectrum locus
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Mixture of two lights appears as a straight line.

Display gamuts
Deviations from sRGB specification
**Color blindness**
Missing one or more retina cones or rods

**VisCheck**
Simulates color vision deficiencies
Web service or Photoshop plug-in
Robert Dougherty and Alex Wade

**Perception of Color**
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

Experiments:
No reddish green, no bluish yellow
Color after images
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)
Albert Munsell

Developed the first perceptual color system based on his experience as an artist (1905).
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

HSL Lightness
*(Photoshop)*
Perceptual brightness

Color palette

Luminance Y
(CIE XYZ)

Perceptual brightness

Color palette

Munsell Value

Perceptually-uniform color space

Munsell colors in CIE LAB coordinates
Perception of Color

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

Chromatic Adaptation
Chromatic Adaptation

Bezold effect
Color appearance depends on adjacent colors

Crispening
Perceived difference depends on background

Spreading
Spatial frequency
The paint chip problem
Small text, lines, glyphs
Image colors
Adjacent colors blend

Color Appearance Tutorial by Meureen Stone

Color Appearance Models, Fairchild

Foundations of Vision, Brian Wandell
**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**

iCAM models (2002)
- Chromatic adaptation
- Appearance scales
- Color difference
- Crispening
- Spreading
- HDR tone mapping
  (see also CIECAM02)

**Perception of Color**

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**Colors according to XKCD...**

Color names if you’re a girl... → Color names if you’re a guy...
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

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
- Red
- Pink
- Grey
- Yellow
- Brown
- Black
- Green
- Orange
- Blue
- 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

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 $p(\text{name} \mid \text{color})$

Icicle tree with colors
Naming confusion conflicts with tree structure!
Perception of Color

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Color in Information Visualization

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

Allocation of the radio spectrum

Palette Design + Color Names

Minimize overlap and ambiguity of color names.
Palette Design + Color Names

Minimize overlap and ambiguity of color names.

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

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

1. Equal interval (arithmetic progression)
2. Quantiles (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 color scheme
  - 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

Diverging color scheme

Diverging color scheme

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

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