6.859: Interactive Data Visualization

Color

Arvind Satyanarayan
Modeling Color Perception

Low-Level

Physical World

Visible Light

Visual System

Cone Response

Opponent Encoding

Abstraction

Perceptual Models

Mental Models

High-Level

“Teal”

Cognitive Models

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Appearance Models

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Visible Light

Light is an electromagnetic wave.

Wavelength ($\lambda$) between 370nm – 730nm.

Color depends on the spectral distribution function (or spectrum): distribution of “relative luminance” at each wavelength.

Area under the spectrum is intensity: or how bright each wavelength is.
Visible Light

Light is an electromagnetic wave.

Wavelength (\(\lambda\)) between \(370\text{nm} - 730\text{nm}\).

Color depends on the *spectral distribution function* (or *spectrum*): distribution of “relative luminance” at each wavelength.

Area under the spectrum is *intensity*: or how bright each wavelength is.

**Additive**: Perceived color is due to a combination of source lights (e.g., RGB).

**Subtractive**: Start from a white spotlight, and materials absorb specific \(\lambda\)s (e.g., RYB or CMYK).
Modeling Color Perception

- **Low-Level**
  - Physical World
  - Visible Light

- **Abstraction**
  - Visual System
  - Cone Response
  - Opponent Encoding

- **High-Level**
  - Mental Models
  - Perceptual Models
  - Appearance Models
  - “Teal”
  - Cognitive Models
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“Teal”
Photoreceptors on retina are responsible for vision: *rods* – low-light levels, poor spatial acuity, little color vision.
Photoreceptors on retina are responsible for vision:

**rods** – low-light levels, poor spatial acuity, little color vision

**cones** – sensitive to different wavelengths = color vision!
short, middle, long ~ blue, green, red
The Retina

Firefox and Chrome have built in simulators.

[Helga Kolb Simple Anatomy of the Retina.]
Photoreceptors on retina are responsible for vision: 

**rods** – low-light levels, poor spatial acuity, little color vision

**cones** – sensitive to different wavelengths = color vision!

short, middle, long ~ blue, green, red
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- **rods** – low-light levels, poor spatial acuity, little color vision
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  - short, middle, long ~ blue, green, red
  - integrate against different input stimuli

**tri-stimulus response** — color can be modeled as 3 values.

Photoreceptors on retina are responsible for vision:

- **rods** – low-light levels, poor spatial acuity, little color vision
- **cones** – sensitive to different wavelengths = color vision!
  - short, middle, long ~ blue, green, red
  - integrate against different input stimuli

**tri-stimulus response** – color can be modeled as 3 values.

**metamers** – spectra that stimulate the same LMS response are indistinguishable.

CIE XYZ

Color space standardized in 1931 to mathematically represent tri-stimulus response curves.

Red = 645nm
Green = 525nm
Blue = 444nm

empirically determined

CIE XYZ

Color space standardized in 1931 to mathematically represent tri-stimulus response curves.

empirically determined

Red = 645nm
Green = 525nm
Blue = 444nm

What's odd about these curves?

Raise your hand

Post in the chat

CIE XYZ

Color space standardized in 1931 to mathematically represent tri-stimulus response curves.

*empirically determined*

Red = 645nm
Green = 525nm
Blue = 444nm

*mathematic transformation*

No real lights can produce the x, y, z response curves.

CIE XYZ

Color space standardized in 1931 to mathematically represent tri-stimulus response curves.

$X = 1$

$Y = 1$

$Z = 1$
CIE XYZ Color Space

**Chromaticity diagram**: Project into a 2D plane to separate colorfulness from brightness.

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

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

\[
z = \frac{Z}{X + Y + Z} = 1 - x - y
\]
CIE XYZ Color Space

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

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

\[
z = \frac{Z}{X + Y + Z} = 1 - x - y
\]

**Straight line** = mixture of two light sources.
Purple line – not possible to recreate with a monochromatic light source.

Mixture of spectral violet + red (i.e., short and long wavelengths).
CIE XYZ Color Space

\[ x = \frac{X}{X + Y + Z} \]
\[ y = \frac{Y}{X + Y + Z} \]
\[ z = \frac{Z}{X + Y + Z} = 1 - x - y \]

*Spectral locus* — set of pure colors (i.e., lasers of a single wavelength).

Slowly shifts from S → M → L.
CIE XYZ Color Space

*Display gamut* = portion of the color space that can be reproduced by a display.
CIE XYZ Color Space

*Display gamut* = portion of the color space that can be reproduced by a display.
**CIE XYZ Color Space**

*Display gamut* = portion of the color space that can be reproduced by a display.

The angry rainbow in sRGB.

Corners of sRGB

Photoshop grayscale

No linear brightness gradient within a single hue.

[Gregor Aisch: How to Avoid Equidistant HSV Colors.]
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Opponent Encoding

- Blue
- Yellow
- Green
- Red
- Luminosity
CIE LAB Color Space

Axes correspond to opponent signals:

\[ L^* = \text{luminance} \]
\[ a^* = \text{red-green contrast} \]
\[ b^* = \text{yellow-blue contrast} \]
CIE LAB Color Space

Axes correspond to opponent signals:

\[ L^* = \text{luminance} \]
\[ a^* = \text{red-green contrast} \]
\[ b^* = \text{yellow-blue contrast} \]
CIE LAB Color Space

More perceptually uniform than sRGB.

Scaling of axes such that distance in color space is proportional to perceptual distance.

The angry rainbow in sRGB.

Better. But still be wary.

A happier rainbow in LAB.

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“Teal”
Simultaneous Contrast

When two colors are side-by-side, they interact and affect our perception.

The inner and outer thin rings are, in fact, the same physical purple!
Simultaneous Contrast

When two colors are side-by-side, they interact and affect our perception

Josef Albers
Simultaneous Contrast

When two colors are side-by-side, they interact and affect our perception.
Simultaneous Contrast

When two colors are side-by-side, they interact and affect our perception

Josef Albers
Bezold Effect

Color appearance depends on adjacent colors

E.g., adding a dark border around a color can the color appear darker.
Chromatic Adaptation

Our ability to adjust to color perception based on illumination
Chromatic Adaptation

Our ability to adjust to color perception based on illumination

Jason Su
Chromatic Adaptation

Our ability to adjust to color perception based on illumination
Chromatic Adaptation

Our ability to adjust to color perception based on illumination
Chromatic Adaptation

Perceived difference depends on background.
Quantitative Color Encoding

Sequential Color Scale
Ramp in luminance, possibly also hue.
Typically higher values map to darker colors.

Diverging Color Scale
Useful when data has a meaningful "midpoint."
Use neutral color (e.g., gray) for midpoint.
Use saturated colors for endpoints.

Limit number of steps in color to 3–9
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“Teal”
Is color naming universal? Do languages evolve color terms in similar ways?

Surveyed speakers from 20 languages.
Literature from 69 languages.

World Color Survey. 1976.
110 languages (including tribal), 25 speakers each.
Analysis published in 2009.
Is color naming universal? Do languages evolve color terms in similar ways?

Surveyed speakers from 20 languages.
Literature from 69 languages.

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110 languages (including tribal), 25 speakers each.
Analysis published in 2009.

Name 320 Munsell color chips.
(Shares perceptual properties with CIE LAB, but predates it.)
Is color naming universal? Do languages evolve color terms in similar ways?

Surveyed speakers from 20 languages.
Literature from 69 languages.

World Color Survey. 1976.
110 languages (including tribal), 25 speakers each.
Analysis published in 2009.
Color Naming

Is color naming universal? Do languages evolve color terms in similar ways?

WCS stimulus array. For each basic color term \((t)\) participants named, they were asked:
1. Mark all chips that you would call \(t\).
2. Which chip is the best example(s) of \(t\).
Color Naming

Is color naming universal? Do languages evolve color terms in similar ways?
Color Naming

Is color naming universal? Do languages evolve color terms in similar ways?

Basic color terms recur across languages:

- White
- Black
- Grey
- Red
- Yellow
- Green
- Blue
- Pink
- Brown
- Orange
- Purple
Color Naming

Is color naming universal? Do languages evolve color terms in similar ways?


Russian makes obligatory distinction between lighter blues ("goluboy") and darker blues ("siniy").

How does this affect color perception?
Color Naming

Is color naming universal? Do languages evolve color terms in similar ways?


Russian makes obligatory distinction between lighter blues ("goluboy") and darker blues ("siniy").

How does this affect color perception?

Russian speakers were faster at discriminating 2 colors if they fell into different categories (1 siniy, 1 goluboy) than if they were both from the same category (both siniy, or both goluboy).

Fig. 1. The 20 blue colors used in this study are shown at the top of the figure. An example triad of color squares used in this study is shown at the bottom of the figure. Subjects were instructed to pick which one of the two bottom squares matched the color of the top square.
Color Naming Effects Perception
What's bad about these color choices?
Minimize overlap and ambiguity of colors.

http://vis.stanford.edu/color-names/analyzer/
Minimize overlap and ambiguity of colors.

<table>
<thead>
<tr>
<th>Color Name Distance</th>
<th>Salience</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Distance</td>
<td></td>
</tr>
<tr>
<td>blue 61.5%</td>
<td>.44</td>
<td></td>
</tr>
<tr>
<td>red 21.1%</td>
<td>.21</td>
<td></td>
</tr>
<tr>
<td>green 42.8%</td>
<td>.39</td>
<td></td>
</tr>
<tr>
<td>purple 57.8%</td>
<td>.42</td>
<td></td>
</tr>
<tr>
<td>blue 40.4%</td>
<td>.24</td>
<td></td>
</tr>
<tr>
<td>orange 36.3%</td>
<td>.28</td>
<td></td>
</tr>
<tr>
<td>blue 25.6%</td>
<td>.16</td>
<td></td>
</tr>
<tr>
<td>pink 21.8%</td>
<td>.10</td>
<td></td>
</tr>
<tr>
<td>green 30.8%</td>
<td>.21</td>
<td></td>
</tr>
<tr>
<td>purple 22.7%</td>
<td>.25</td>
<td></td>
</tr>
</tbody>
</table>

Excel-10

Average 0.86 .27

http://vis.stanford.edu/color-names/analyzer/
Minimize overlap and ambiguity of colors. Select semantically resonant colors.

<table>
<thead>
<tr>
<th>Fruits</th>
<th>A</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Banana</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blueberry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cherry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tangerine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vegetables</th>
<th>A</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Celery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eggplant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mushroom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tomato</td>
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</table>

<table>
<thead>
<tr>
<th>Drinks</th>
<th>A</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>A&amp;W Root Beer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coca-Cola</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dr. Pepper</td>
<td></td>
<td></td>
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<tr>
<td>Pepsi</td>
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</tr>
<tr>
<td>Sprite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunkist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welch's Grape</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Brands</th>
<th>A</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
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<td></td>
</tr>
<tr>
<td>AT&amp;T</td>
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</tr>
<tr>
<td>Home Depot</td>
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<tr>
<td>Kodak</td>
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<td>Starbucks</td>
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</tr>
<tr>
<td>Target</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yahoo!</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 6: Color assignments for categorical values in Experiment 1. (A = Algorithm, E = Expert)*

https://github.com/StanfordHCl/semantic-colors
Use **only a few** colors (~6 ideally).

Colors should be **distinctive** and **named**.

Strive for color **harmony** (natural colors?).

Use/respect **cultural conventions**; appreciate symbolism.

Get it right in **black and white**.

Respect the **color blind**.

Take advantage of **perceptual color spaces**.