A Brief Plug

Information Display

Graphical presentation of information
- Charts, graphs, diagrams, maps, illustrations
- Originally hand-crafted, static
- Now computer-generated, dynamic

Color is a key component

“Color” includes Gray

Maps courtesy of the National Park Service (www.nps.gov)

Tableau Color

Color Scales (Colormaps)

Courtesy of IBM Research, from the PR/A/V/D/A Color System
Color and Shading

Images Courtesy of TeraRecon, Inc

Color Overlay
3D line integral convolution to visualize 3D flow (LIC).
Color varies from red to yellow with increasing temperature

Victoria Interrante and Chester Grosch, U. Minnesota
http://www-users.cs.umn.edu/~interran/3Dflow.html

Multi-dimensional Color

Variable 1, 2 → X, Y
Variable 3, 4, 5 → R, G, B
Using Color Dimensions to Display Data Dimensions.
Beatty and Ware

What makes color effective?
“Good ideas executed with superb craft”
• E. R. Tufte

Effective color needs a context
• Immediate vs. studied
• Anyone vs. specialist
• Critical vs. contextual
• Culture and expectations
• Time and money

Effective Color
Aesthetics
Perception
Materials
Illustrators, cartographers
Artists, designers
A few scientific principles
**Why Should You Care?**

Poorly designed color is confusing
- Creates visual clutter
- Misdirects attention

Poor design devalues the information
- Visual sophistication
- Evolution of document and web design

"Attractive things work better"
- Don Norman

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**Effective Color: Perception**

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**What is Color?**

<table>
<thead>
<tr>
<th>Physical World</th>
<th>Visual System</th>
<th>Mental Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lights, surfaces, objects</td>
<td>Eye, optic nerve, visual cortex</td>
<td>Red, green, brown Bright, light, dark, vivid, colorful, dull Warm, cool, bold, blah, attractive, ugly, pleasant, jarring</td>
</tr>
</tbody>
</table>

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**Why Color?**

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**Color in Information Display**

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<td>Lines, patches, shaded regions</td>
<td>Eye, optic nerve, visual cortex</td>
<td>Roads, lakes Profit, loss, trends Failures, threats …and then to action</td>
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</tbody>
</table>

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**Color Models**

<table>
<thead>
<tr>
<th>Physical World</th>
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<tbody>
<tr>
<td>Light Energy Cone Response</td>
<td>Opponent Encoding</td>
<td>Perceptual Models</td>
</tr>
<tr>
<td>Spectral distribution functions F(λ)</td>
<td>Encode as three values (L,M,S)</td>
<td>Separate lightness, chroma (A,R-G,Y-B)</td>
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<tr>
<td>CIE (X,Y,Z)</td>
<td>CIELAB Munsell (HVC)</td>
<td></td>
</tr>
<tr>
<td>Color “Space” Hue, lightness saturation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIECAM02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Physical World**

**Spectral Distribution**
- Visible light
- Power vs. wavelength

**Any source**
- Direct
- Transmitted
- Reflected
- Refracted

**Visual System**

**Light path**
- Cornea, pupil, lens, retina
- Optic nerve, brain

**Retinal cells**
- Rods and cones
- Unevenly distributed

**Cones**
- Three “color receptors”
- Concentrated in fovea

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**Cone Response**

Encode spectra as three values
- Long, medium and short (LMS)
- Trichromacy: only LMS is “seen”
- Different spectra can “look the same”

Sort of like a digital camera*

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**Effects of Retinal Encoding**

All spectra that stimulate the same cone response are indistinguishable

**Metameric match**

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**Color Measurement**

- CIE Standard Observer
- CIE tristimulus values (XYZ)
- All spectra that stimulate the same tristimulus (XYZ) response are indistinguishable

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**Chromaticity Diagram**

Project X,Y,Z on a plane to separate colorfulness from brightness

\[ x = X/(X+Y+Z) \]
\[ y = Y/(X+Y+Z) \]
\[ z = Z/(X+Y+Z) \]
\[ 1 = x+y+z \]

\[ XYZ = xyY \]
### Color Models

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<td>Trichromacy</td>
<td></td>
<td>Color blindness</td>
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<tr>
<td>Metamerism</td>
<td></td>
<td>Foundation for perceptual models</td>
</tr>
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</table>

### Opponent Color

**Definition**
- Achromatic axis
- R-G and Y-B axis
- Separate lightness from chroma channels

**First level encoding**
- Linear combination of LMS
- Before optic nerve
- Basis for perception
- Defines "color blindness"

### Vischeck

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

[www.vischeck.com](http://www.vischeck.com)

### 2D Color Space

[Image of 2D color space with protanope, deuteranope, and luminance]

### Perceptual Color Spaces

- Unique black and white
- Uniform differences
- Perception & design

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Maureen Stone, StoneSoup Consulting
Munsell Atlas

Interactive Munsell Tool

Munsell Renotation System maps between HVC and XYZ
Emissive simulations of reflective samples

www.munsell.com

CIELAB and CIELUV

Lightness (L*) plus two color axis (a*, b*)
Non-linear function of CIE XYZ
Defined for computing color differences (reflective)

Lightness Scales

Lightness, brightness, luminance, and L*
- Lightness is relative, brightness absolute
- Absolute intensity is light power
Luminance is perceived intensity
- Luminance varies with wavelength
- Equivalent to CIE Y
L* is perceptually uniform luminance
- Relative to white (0-100)
- CIELAB and CIELUV

Green and blue lights of equal intensity
have different luminance values

Color Models

Physical World
- Light Energy
  - Spectral distribution functions: F(λ)
Visual System
- Cone Response
  - Encode as three values (L,M,S)
  - CIE (X,Y,Z)
Mental Models
- Opponent Encoding
  - Separate lightness, chroma (A,R,G,Y,B)
Perceptual Models
- Color "Space"
  - Hue, lightness saturation
  - CIELAB, Munsell
Appearance Models
- Color in Context
  - Adaptation, Background, Size, ...
  - CIECAM02

Color differences
- "Intuitive" color spaces
- Image encoding
- Color scales

Color Appearance

Maureen Stone, StoneSoup Consulting
The Interaction of Color

"Color is the most relative medium in art."

- Josef Albers

Color Appearance

More than a single color
- Adjacent colors (background)
- Viewing environment (surround)

Appearance effects
- Adaptation
- Simultaneous contrast
- Spatial effects

Color in context

Color Appearance Models
Mark Fairchild

Chromatic Adaptation

Inspired by Hunt's yellow cushion
Simultaneous Contrast

Add Opponent Color
- Dark adds light
- Red adds green
- Blue adds yellow

These samples will have both light/dark and hue contrast

Affects Lightness Scale

Bezold Effect

Spreading

Color Models

Maureen Stone, StoneSoup Consulting
What about RGB?

Method for creating color (input to visual system)
Additive sum of red, green, blue light
  • Linear transform to XYZ
  • Tied to perception via color matching
  • More later…

Only “additive color” has this simple relationship.
Not true for CMYK, paint, dyes, etc.

Effective Color: Aesthetics

Envisioning Information

“… avoiding catastrophe becomes the first principle in bringing color to information:
Above all, do no harm.”

—E. R. Tufte

Fundamental Uses

To label
To measure
To represent or to imitate reality
To enliven or decorate

To Label

Information Visualization
Colin Ware

Grouping, Highlighting

Maureen Stone, StoneSoup Consulting
Cluster Calendar

Jarke van Wijk, Edward van Selow Cluster and Calendar based Visualization of Time Series Data

Preattentive “Pop-out”

<table>
<thead>
<tr>
<th>Time proportional to the number of digits</th>
<th>Time proportional to the number of 7’s</th>
<th>Both 3’s and 7’s “Pop out”</th>
</tr>
</thead>
<tbody>
<tr>
<td>13579345978274055 24937916478254137</td>
<td>135/194/59/82/4055 2493/19164/8254137</td>
<td>135/194/59/27101876</td>
</tr>
<tr>
<td>2387597277103876 19874367259047362</td>
<td>238/1659/27101876 198/436/25904/362</td>
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<tr>
<td>35637894836754 56840378465785690</td>
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Time proportional to the number of digits

Pop-out vs. Distinguishable

Pop-out
- Typically, 5-6 distinct values simultaneously
- Up to 9 under controlled conditions

Distinguishable
- 20 easily for reasonable sized stimuli
- More if in a context

What is the color for?

Radio Spectrum Map (33 colors)


Distinguishable on Inspection

Distinct colors = distinct names?

Color Names

Basic names (Berlin & Kay)
- Linguistic study of names
- Similar names
- Similar evolution

Perceptual primaries

black
white
gray
green
blue
yellow
orange
purple
brown
pink

Distinct colors = distinct names?
Distinct, but hard to name

Tableau Color Example

- Color palettes
  - How many? Algorithmic?
  - Basic colors (regular and pastel)
  - Extensible? Customizable?

- Color appearance
  - As a function of size
  - As a function of background
- Robust and reliable color names

Color Names Research

- Selection by name
  - Berk, Brownston & Kaufman, 1982
  - Meier, et. al. 2003
- Image recoloring
  - Saito, et. al.
- Labels in visualization
  - D’Zmura, Cowan (pop out conditions)
  - Healey & Booth (automatic selection)
- Web experiment
  - Moroney, et. al. 2003

Color Scales

- Long history in graphics and visualization
  - Ware, Robertson et. al
  - Levkowitz et. al
  - Rheingans
- PRAVDA Color
  - Rogowitiz and Treinish
  - IBM Research
- Cartography
  - Cynthia Brewer
  - ColorBrewer

To Measure

- Color as quantity
  - Density map
  - Thematic maps
  - Color scales/maps

Almost always wrong

Different Scales

Rogowitiz & Treinish, “How not to lie with visualization”
Thematic Maps

Data to Color

Type of data values
- Nominal, ordinal, numeric
- Qualitative, sequential, diverging

Hue = nominal

Lightness or saturation scales
- Lightness best for high frequency
- More = darker (or more saturated)

Brewer’s Categories

Brewer Scales

Nominal scales
- Distinct hues, but similar emphasis

Sequential scale
- Vary in lightness and saturation
- Vary slightly in hue

Diverging scale
- Complementary sequential scales
- Neutral at “zero”
Color Brewer

Color Brewer

Tableau Color Example

Color scales for encoding data
- Displayed as charts and graphs
- Quantized or continuous

Issues
- Color ramps based on Brewer’s principles
- Not single hue/chroma varying in lightness
- Create a ramp of the “same color”
- Center, balance of diverging ramps

Heat Map (default ramp)

Full Range

Skewed Data

www.colorbrewer.org

Stepped

Threshold

www.tableausoftware.com

www.tableausoftware.com

www.tableausoftware.com

www.tableausoftware.com

Maureen Stone, StoneSoup Consulting
Color and Shading

Shape is defined by lightness (shading)
“Color” (hue, saturation) labels

CT image (defines shape)    PET color highlights tumor

Image courtesy of Siemens

Shaded Terrain

http://graphics.stanford.edu/~mcammara/
Mike Cammarano, Pat Hanrahan

Visualizing Flow

Color is used to represent the magnitude of the vorticity across the flow volume. Note the pressure waves

Victoria Interrante and Chester Grosch, U. Minnesota
http://www-users.cs.umn.edu/~interran/3Dflow.html

Multivariate Color Sequences

http://hubblesite.org/sci.d.tech/behind_the_pictures/

Multi-dimensional Scatter plot

Variable 1, 2 → X, Y
Variable 3, 4, 5 → R, G, B

Using Color Dimensions to Display Data Dimensions. Beatty and Ware

Multispectral Color Imaging
To Represent or Imitate Reality

Color as representation
- Key color to real world
- Iconographic vs. photographic

ThemeView (original)

ThemeScape (commercial)

To Enliven or Decorate

Color as beauty
- Aesthetic use of color
- Emotional, personal
“Attractive things work better” —Don Norman

More Tufte Principles

Limit the use of bright colors
- Small bright areas, dull backgrounds
Use the colors found in nature
- Familiar, naturally harmonious
Use grayed colors for backgrounds
- Quiet, versatile
Create color unity
- Repeat, mingle, interweave

Storm example
Storm Example (continued)

From "After the Storm," Bates and Bushell

Color Design

Goals
- Highlight, emphasize
- Create regions, group
- Illustrate depth, shape
- Evoke nature
- Decorate, make beautiful

Color harmony
“...successful color combinations, whether these please the eye by using analogous colors, or excite the eye with contrasts.” – Wucius Wong

Color Design Principles

Control value (lightness)
- Ensure legibility
- Avoid unwanted emphasis

Use a limited hue palette
- Control color pop out
- Define color grouping
- Avoid clutter from too many competing colors

Use neutral backgrounds
- Minimize simultaneous contrast

Design Color Models

Hue (color wheel)
- Red, yellow, blue
- Orange, green, purple

Chroma (saturation)
- Intensity or purity
- Distance from gray

Value (lightness)

Perceptual models, like Munsell
See www.handprint.com for examples

Modeling Color Design

Design spaces are perceptual spaces
- Munsell, OSA, Ostwald
- Created as design spaces
- Wong uses Munsell

Geometric interpretation of color design
- Color schemes based on hue circle
- Contrast and analogy as distance
- Smooth paths for tints, tones and gradations

Subject to gamut limitations

Colortool in CIELAB

NASA Color Usage Research Lab, Larry Arend
Psuedo-Perceptual Models

HLS, HSV, HSB
NOT perceptual models
Simple renotation of RGB
• View along gray axis
• See a hue hexagon
• L or V is grayscale pixel value
Cannot predict perceived lightness

L vs. Luminance vs. L*

Corners of the RGB color cube
Luminance of these colors
L* for these colors
L from HLS
All the same

Get it right in black & white

Value
• Perceived lightness/darkness
• Controlling value primary rule for design
Value alone defines shape
• No edge without lightness change
• No shading with out lightness variation
Value difference defines contrast
• Defines legibility
• Controls attention

Controls Legibility

Controls Attention, Clutter

Urgent
Normal
Context
Urgent
Normal
Context
Urgent
Normal
Context

Legibility and Contrast

Legibility (luminance contrast)
• 5:1 contrast for legibility (ISO standard)
• 3:1 minimum legibility
• 10:1 recommended for small text
How do we define contrast?
Contrast ratios for contextual information?
Effective Color: Materials

Aesthetics

Perception

Materials

The Craft of Digital Color

Good ideas executed with superb craft”

E. R. Tufte

Good ideas
• Unique, specific examples?
• Or, broadly applicable principles?
• Simple, or subtle and complex?
“Superb craft” means control

What does RGB Mean?

Values used to drive a display
Values encoded in an image
Values captured by a camera or scanner

All the same purple?

RGB values → Light

RGB for Displays

Emissive RGB
• CRT
• LCD
• Plasma
• Projectors

RGB from Cameras

Image capture
• Scanners, cameras
• RGB filters (not cones)
Spectra to RGB values

RGB in Image Encoding

Array of RGB pixels (or equivalent)
• Spatial encoding
• Color/Intensity encoding
Image reproduction
• Link capture and reproduction
• Optimized process
Making RGB Quantitative

Specify primary colors
- Precise hue
- Maximum brightness

Map numbers (pixels) to intensity
- Linear encodings
- Non-linear encodings
- Both are valid

RGB Color Cube

Three primaries
- RGB lights
- Variable brightness (0..max)
- Add to create color

Characteristics
- Primaries sum to white
- Saturated colors on surface
- Gray scale along diagonal
- Cube bounds color gamut

RGB in XYZ

R,G,B are vectors
Add like vectors
- (1,1,0) = XYZ_R + XYZ_G

Scale like vectors
- (s_1,0,0) = s_2 XYZ_R
- if linear intensity encoding, s_1 = s_2
- If non-linear, s_2 is different than s_1

Color Cube in XYZ

Transformation
- Specify XYZ for R,G and B
- 3 x 3 Matrix

Characteristics
- Primaries sum to white
- Saturated colors on surface
- Gray scale along diagonal
- Bounds color gamut

RGB to XYZ to xy

RGB Chromaticity

R,G,B are points
Sum of two colors falls on line between them
Gamut is a triangle
- White/gray/black near center
- Saturated colors on edges
Display Gamuts


Projector Gamuts


Pixels to Intensity

Linear
- \( I = kp \) (\( I \) = intensity, \( p \) = pixel value, \( k \) is a scalar)
- Best for computation

Non-linear
- \( I = kp^{1/\gamma} \)
- Perceptually more uniform
- More efficient to encode as pixels
- Best for encoding and display

Pixel to Intensity Variation

Display Appearance

Tristimulus characterization
- Relatively easy to accomplish
- But, not a total solution

Want RGB to color appearance
- Robust and reliable color names
- Robust and reliable contrast control
- As robust as print appearance

Visual feedback and simple controls

Effective Color: Summary

- Aesthetics
- Perception
- Materials
- Design principles
- Tufte, Wong
- Albers
- Color Science
- Color appearance models
- RGB
- Digital media
- Color Management

Maureen Stone, StoneSoup Consulting