CPSC 583
Colour

Sheelagh Carpendale
References

Effective Colour

Aesthetics

Materials

Perception

Illustrators, cartographers
Artists, designers
A few scientific principles

From: M. Stone
What is Colour?

Physical World: Lights, surfaces, objects
Visual System: Eye, optic nerve, visual cortex
Mental Models: Red, green, brown, bright, light, dark, vivid, colorful, dull, warm, cool, bold, blah, attractive, ugly, pleasant, jarring

Perception and Cognition

From: M. Stone
Physical World

- Spectral Distribution
  - Visible light
  - Power vs. wavelength
- Any source
  - Direct
  - Transmitted
  - Reflected
  - Refracted

Colour

The Retina

**Photoreceptors**: rods and cones

**Neurons** (receptive fields): intermediate neural layers - image processing


Cone Response

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

Effects of Retinal Encoding

All spectra that stimulate the same cone response are indistinguishable

Metameric match

• [PDF] **Elements of Color Perception - Metamerism**
Chromaticity Diagram

The corners of this triangle is approximately where the phosphors of a typical color monitor plot.
RGB Chromaticity

- R, G, B are points (varying lightness)
- Sum of two colors lies on line
- Gamut is a triangle
  - White/gray/black near center
  - Saturated colors on edges
Display Gamuts

Projector Gamuts

Opponent Colour

• 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”
Colour Blindness

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

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

![Images of flowers showing color vision deficiencies for Deuteranope, Protanope, and Tritanope](http://www.vischeck.com/examp)
Colour Blindness

normal

protanope

deuteranope

tritanope

colorvisiontesting.com
Genes in Vischeck
2D Colour Space

Normal | Protanope | Deuteranope | Tritanope
Colour Blindness

small-field tritanopia
**Colour Addition**
- computer monitors
- red, green, and blue
- absence all three colors gives black,
- all three gives white.

**Colour Subtraction**
- printers ink
- cyan, magenta, and yellow
- absence all three colors gives white,
- all three gives black.
Colour Paint

primary

secondary

tertiary
Perceptual Color Spaces

- Lightness
- Hue
- Colorfulness

Unique black and white
Uniform differences
Perception & design
Munsell Atlas

Courtesy Gretag-Macbeth
Color Appearance
Color Appearance
• colour constancy
• colour perception
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
Simultaneous Contrast

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

These samples will have both light/dark and hue contrast
Bezold Effect

http://web.missouri.edu/~hoard/colortheory/Syllabus/Projects/Bezold_Effect/bezold_effect.
http://web.missouri.edu/~hoarda/colortheory/Syllabus/Projects/Bezold_Effect/bezold_effect.html
http://www.sapdesignguild.org/resources/optical_illusions/contrast_phenomena.html
Checker-shadow illusion:
The squares marked A and B
are the same shade of gray.

Edward H. Adelson
Spreading

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

• Adjacent colors blend

Redrawn from Foundations of Vision
© Brian Wandell, Stanford University
What makes colour effective?

• “Good ideas executed with superb craft”
  —E.R. Tufte

• Effective colour needs a context
  - Immediate vs. studied
  - Anyone vs. specialist
  - Critical vs. contextual
  - Culture and expectations
  - Time and money
Why Should You Care?

• Poorly designed colour 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
Information Display

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

• Colour is a key component
  – Colour labels and groups
  – Colour scales (colourmaps)
  – Multi-variate colour encoding
  – Colour shading and textures
  – And more…

www.nps.gov
“Color” includes Gray

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

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

• Colour harmony

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

–Principles of Color Design, by Wucius Wong
Colour Design Terminology

• Hue (colour wheel)
  – Red, yellow, blue (primary)
  – Orange, green, purple (secondary)
  – Opposites complement (contrast)
  – Adjacent are analogous
  – Many different colour wheels*

• Chroma (saturation)
  – Intensity or purity
  – Distance from gray

• Value (lightness)
  – Dark to light
  – Applies to all colours, not just gray

*See www.handprint.com for examples
Tints and Tones

• Tone or shade
  - Hue + black
  - Decrease saturation
  - Decrease lightness

• Tint
  - Hue + white
  - Decrease saturation
  - Increase lightness
Colour

Hi-Key/Low Key Colours
- choosing a value range
- another way to unify

Hi-Key colour schemes
- **tints** of colours (paler)
- bright, cheerful.

Low-Key colour scheme.
- **Shades (tones)** of colours (darker)
- subdued gloomy mysterious
Gradations
Colour

Colour Triads

- color scheme composed of three colours spaced equally apart on the colour wheel
- tend to be uncomfortable
- good visual distinction
- Primary colours form one triad
  - (red, blue, yellow).

- Secondary colours
  - (orange, green, purple)
Maximum hue separation
Colour

Analogous Colours

- colours next to each other on the colour wheel with a common hue
- the common hue creates a feeling of unity in the design
Analogous, yet distinct
Colour

Complementary Colors

- Complementary colors are opposite each other on the color wheel
- Two pure complementary hues placed next to each other attract attention
Colour

Split Complements

- two colors on either side of its complement are used together.
- similar to complementary colors
- offers a little more variety to work with
Colour

Warm and Cool Colours

• two specific sets of analogous colours.

Cool

– blue, green and purple
– cold, icy feeling

Warm

– red, orange and yellow
– warm, sunny feeling.

When used together

– cool colours seem to move away
– warm colours move towards
Colour

Monochromatic Colors

- shades, tints and tones of only one color.
- causes an immediate unifying or harmonious effect.
- all parts of the design have something in common,
- pulls it all together.
Sequential
Colouring categorical data

- limited number readily distinct (spatially separate colour patches)
- think about selection, association, and adjacent distinction
- Ware’s maximally discriminable colours
Colour Design Principles

• Control value (lightness)
  – Ensure legibility
  – Avoid unwanted emphasis

• Use a limited hue palette
  – Control colour “pop out”
  – Define colour grouping
  – Avoid clutter from too many competing colours

• Use neutral backgrounds
  – Control impact of colour
  – Minimize simultaneous contrast
Envisioning Information

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

—E. R. Tufte

www.edwardtufte.com
Fundamental Uses

- To label
- To measure
- To represent or to imitate reality
- To enliven or decorate
To Label
Colour Cross-cultural naming

Appearance of colour names in languages around the world (Berlin and Kay 1969)
Many lines of scientific evidence worth examining

- **Naming**
- **Cross-Cultural naming**
- **Unique Hues**
- **Neurophysiology**
- **Categorical colours**
Color Names

• Basic names (Berlin & Kay)
  - Linguistic study of names
  - Similar names
  - Similar evolution
  - Many different languages

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

• World Colour Survey (Kay & Cook)
  – http://www.icsi.berkeley.edu/wcs/
Identify by Color

Information Visualization
Colin Ware
Product Categories
Categorizing data by colour

The Internet: 2002
Categorizing data by colour

The Internet: 2002

22 colours, only ~8 distinguishable
## Grouping, Highlighting

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Considerations for Labels

• How critical is the colour encoding?
  – Unique specification or is it a “hint”?  
  – Quick response, or time for inspection?  
  – Is there a legend, or need it be memorized?

• Contextual issues
  – Are there established semantics?
  – Grouping or ordering relationships?
  – Surrounding shapes and colours?

• Shape and structural issues
  – How big are the objects?
  – How many objects, and could they overlap?
  – Need they be readable, or only visible?
Controls and Alerts

- Aircraft cockpit design
  - Quick response
  - Critical information and conditions
  - Memorized
  - 5-7 unique colors, easily distinguishable
- Highway signs
  - Quick response
  - Critical but redundant information
  - 10-15 colors?
- Typical color desktop
  - Aid to search
  - Redundant information
  - Personal and decorative
  - How many colors?
Psychophysics of Labeling

- Preattentive, “pop out”

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<th>Both 3’s and 7’s “Pop out”</th>
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Time proportional to the number of digits.
Contrast Creates Pop-out

Hue and lightness

Lightness only
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 controlled context
  - Usually need a legend
To Measure
Heat maps
Data to Color

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

- Types of color scales
  - Hue scale
    - Nominal (labels)
    - Cyclic (learned order)
  - Lightness or saturation scales
    - Ordered scales
    - Lightness best for high frequency
    - More = darker (or more saturated)
    - Most accurate if quantized
Color Scales

- Long history in graphics and visualization
  - Ware, Robertson et. al
  - Levkowitz et. al
  - Rheingans
- PRAVDA Color
  - Rogowitz and Treinish
  - IBM Research
- Cartography
  - Cynthia Brewer
  - ColorBrewer
Colour scales (maps)

Rainbow (hue)
- No ordering
- Good name space

Greyscale/luminance/saturation
- ordered

Rainbow scale

- No ordering - Good name space (green part, yellow part ....)
- Jet engine noise simulation


Two-Hue scale

- Easier to see small variations


Heat scale

- Ordering? (Surface Magnetic Field)

Heat scale

- Ordering? (Surface Magnetic Field)

Different Scales

Rogowitz & Treinish, “How not to lie with visualization”
Density Map

Lightness scale

Lightness scale with hue and chroma variation

Hue scale with lightness variation
Phase Diagrams (hue scale)

Singularities occur where all colors meet.

The optical singularities of bianisotropic crystals, by M. V. Berry
Figure 1.9. Cotidal chart. Tide phases relative to Greenwich are plotted for all the world’s oceans. Phase progresses from red to orange to yellow to green to blue to purple. The lines converge on anphidromic points, singularities on the earth’s surface where there is no defined tide. [Winfree, 1987 #1195, p. 17].
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”
Thematic Maps

US Census Map

Brewer's Categories

- Qualitative Scale
- Sequential Scale
- Diverging Scale

Cynthia Brewer, Pennsylvania State University
Colour Brewer

This material is based upon work supported by the National Science Foundation under Grant No. 9963461, 9983469, 9983461

[www.colorbrewer.org]
Colour and Shading

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

CT image (defines shape)   PET color highlights tumor

Image courtesy of Siemens
Colour Overlay (Temperature)

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

Victoria Interrante and Chester Grosch, U. Minnesota

http://www-users.cs.umn.edu/~interran/3Dflow.html
Multivariate Colour Sequences
Multi-dimensional Scatter plot

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

Do people interpret colour blends as sums of variables?
Colour Weaves

6 variables = 6 hues, which vary in brightness

Additive mixture (blend)  Spatial texture (weave)

Weaving versus Blending (APGV06 and SIGGRAPH poster)
Haleh Hagh-Shenas, Victoria Interrante, Christopher Healey and Sunghee Kim
Brewer System

http://www.colorbrewer.org
Brewer Examples

Sequential/Sequential Scheme

Diverging/Sequential Scheme

Change in percent of labor force employed in industry between 1960 and 1980
To Represent or Imitate Reality
Illustrative Color

Gray’s Anatomy of the Human Body
www.bartleby.com/107/illus520.html

Map of Point Reyes
www.nps.gov
ThemeView (original)

Courtesy of Pacific Northwest National Laboratories
ThemeScape (commercial)
To Enliven or Decorate
Visualization of isoelectron density surfaces around molecules
Marc Levoy (1988)

Which has more information? Which would you rather look at?
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
Controlling Value
Get it right in black & white

• Value
  – Perceived lightness/darkness
  – Controlling value primary rule for design

• Value defines shape
  – No edge without lightness difference
  – No shading without lightness variation

• Value difference (contrast)
  – Defines legibility
  – Controls attention
  – Creates layering
Controls Legibility

colorusage.arc.nasa.gov
Legibility

Drop Shadows

Drop Shadow

Drop shadow adds edge

Primary colors on black
Primary colors on black
Primary colors on black
Primary colors on black
Primary colors on black
Primary colors on black
Primary colors on white
Primary colors on white
Primary colors on white
Primary colors on white
Primary colors on white
Readability

If you can’t use color wisely, it is best to avoid it entirely.
Above all, do no harm.

If you can’t use color wisely, it is best to avoid it entirely.
Above all, do no harm.
Why does the logo work?
Value Control
Legibility and Contrast

• Legibility
  – Function of contrast and spatial frequency
  – “Psychophysics of Reading” Legge, et. al.

• Legibility standards
  – 5:1 contrast for legibility (ISO standard)
  – 3:1 minimum legibility
  – 10:1 recommended for small text

• How do we specify contrast?
  – Ratios of foreground to background luminance
  – Different specifications for different patterns
Contrast and Layering

• Value contrast creates layering
What Defines Layering?

• Perceptual features
  – Contrast (especially lightness)
  – Color, shape and texture

• Task and attention
  – Attention affects perception

• Display characteristics
  – Brightness, contrast, “gamma”
Grid Example

Grid sits unobtrusively in the background  
Grid sits in foreground, obscuring map

Great Grids: How and Why? (APGV06 and SIGGRAPH poster)  
Maureen Stone, Lyn Bartram and Diane Gromala
Additional Resources

• Maureen Stone’s website
  – http://www.stonesc.com/Vis06

• A Field Guide to Digital Color
  – A.K. Peters