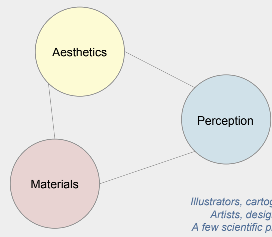
Color in Information Display

Maureen Stone
StoneSoup Consulting

Effective Color



Illustrators, cartographers
Artists, designers
A few scientific principles

What is Color?

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

Perception and Cognition

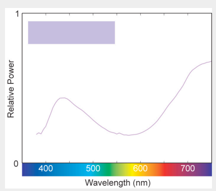
Color Models

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

Physical World

Spectral Distribution
- Visible light
- Power vs. wavelength

Any source
- Direct
- Transmitted
- Reflected
- Refracted



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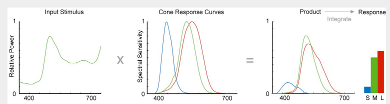
Cone Response

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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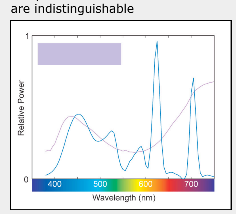
Effects of Retinal Encoding

All spectra that stimulate the same cone response are indistinguishable



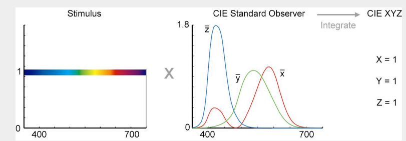
Metameric match

Color Measurement

CIE Standard Observer

CIE tristimulus values (XYZ)

All spectra that stimulate the same tristimulus (XYZ) response are indistinguishable



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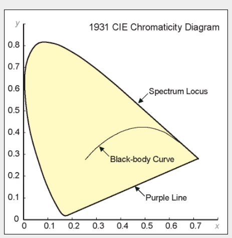
Chromaticity Diagram

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

$x = X/(X+Y+Z)$
$y = Y/(X+Y+Z)$
$z = Z/(X+Y+Z)$

$1 = x+y+z$

$XYZ \Rightarrow xyY$

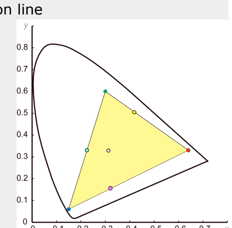


RGB Chromaticity

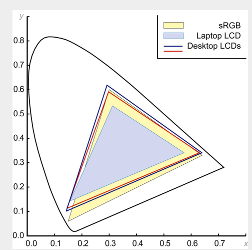
R,G,B are points (varying lightness)

Sum of two colors lies on line

Gamut is a triangle
- White/gray/black near center
- Saturated colors on edges



Display Gamuts



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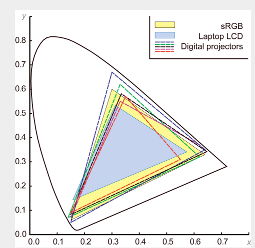
Projector Gamuts



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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

Intensity Transfer Function (ITF), or "gamma"

Color Models

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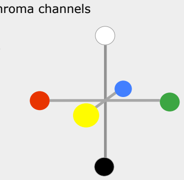
Trichromacy
Metamerism
Color matching
Color measurement

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"

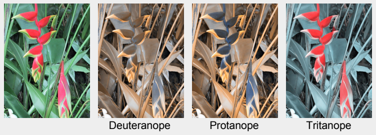


Vischeck

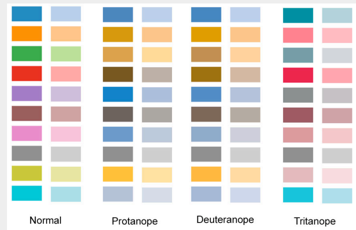
Simulates color vision deficiencies

- Web service or Photoshop plug-in
- Robert Dougherty and Alex Wade

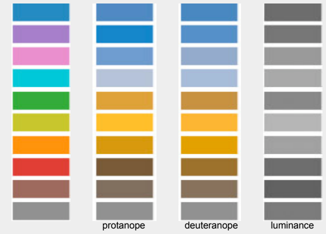
www.vischeck.com



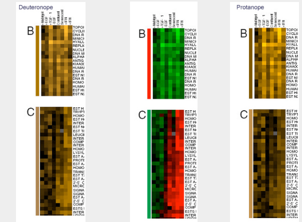
2D Color Space

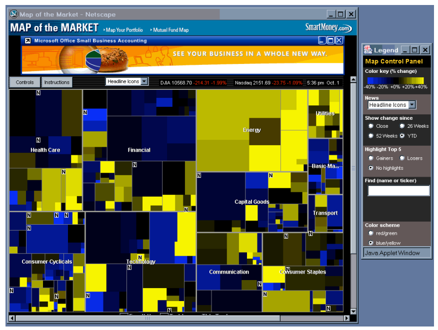


Similar Colors

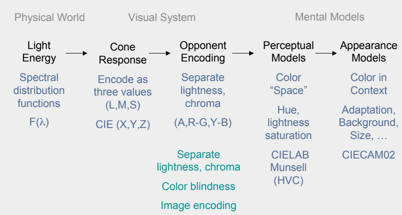


Genes in Vischeck

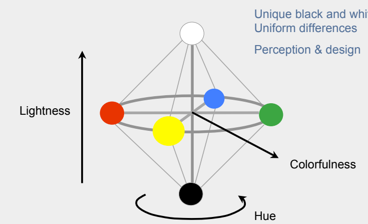




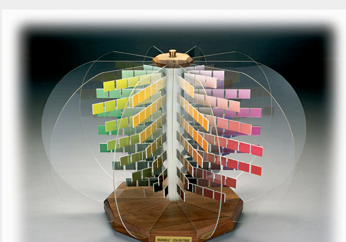
Color Models



Perceptual Color Spaces



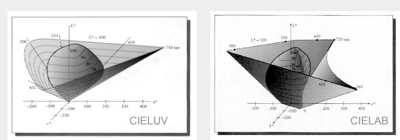
Munsell Atlas



Courtesy Gretag-Macbeth

CIELAB and CIELUV

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



From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64
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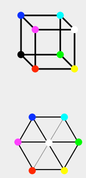
Psuedo-Perceptual Models

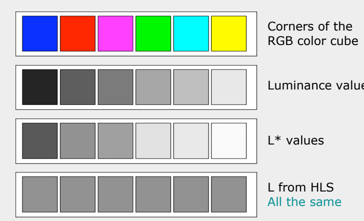
HLS, HSV, HSB
NOT perceptual models
Simple renotation of RGB

- View along gray axis
- See a hue hexagon
- L or V is grayscale pixel value

Cannot predict perceived lightness



L vs. Luminance, L*



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
- Variation defined by luminous efficiency function
- Equivalent to CIE Y

L* is perceptually uniform lightness

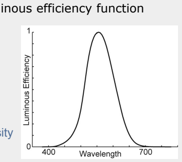
Luminance & Intensity

Intensity

- Integral of spectral distribution (power)

Luminance

- Intensity modulated by wavelength sensitivity
- Integral of spectrum × luminous efficiency function



Green and blue lights of equal intensity have different luminance values

Luminance from RGB

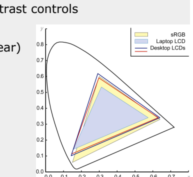
$L = rL_R+gL_G+bL_B$ Not a fixed equation!

L_R, L_G, L_B

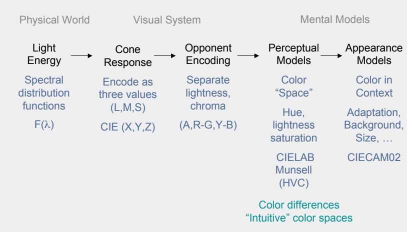
- Maximum luminance of RGB primaries
- Different for different displays
- Affected by brightness & contrast controls

r,g,b

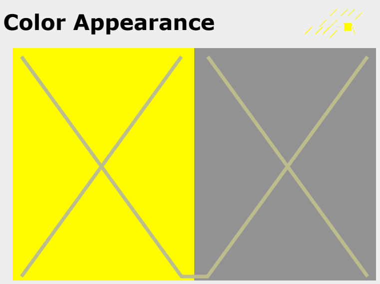
- Relative intensity values (linear)
- Depends on "gamma curve"
- Not pixel values

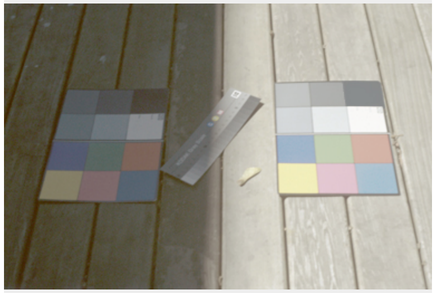


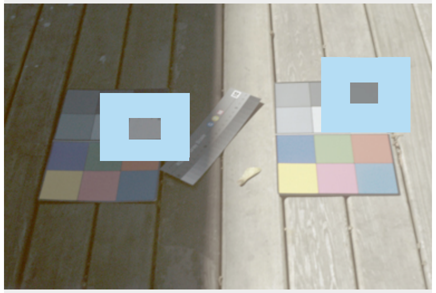
Color Models



Color Appearance







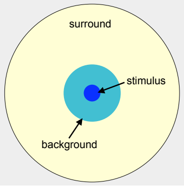
Color Appearance

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

Appearance effects
- Adaptation
- Simultaneous contrast
- Spatial effects

Color in context

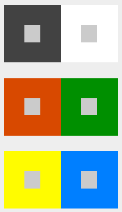
Color Appearance Models
Mark Fairchild



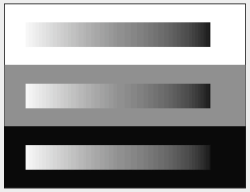
Simultaneous Contrast

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

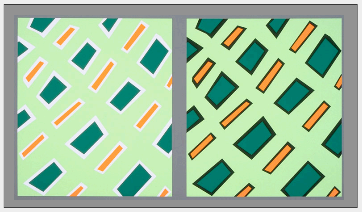
These samples will have both light/dark and hue contrast



Affects Lightness Scale

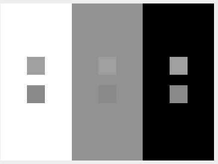


Bezold Effect



Crispening

Perceived difference depends on background

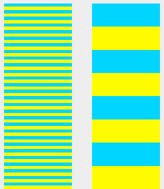


From Fairchild, *Color Appearance Models*

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

Color Models

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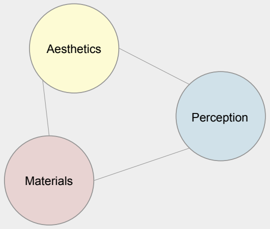
Spectral distribution functions	Encode as three values (L,M,S)	Separate lightness, chroma	Color "Space"	Color in Context
F(λ)	CIE (X,Y,Z)	(A,R-G,Y-B)	Hue, lightness saturation	Adaptation, Background, Size, …
			CIELAB Munsell (HVC)	CIECAM02
				Adaptation Contrast effects Image appearance Complex matching

Effective Color



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

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

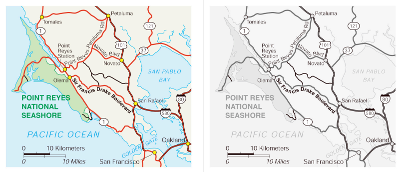
Information Display

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

Color is a key component
- Color labels and groups
- Color scales (colormaps)
- Multi-variate color encoding
- Color shading and textures
- And more…

www.nps.gov

"Color" includes Gray



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

Color Design

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

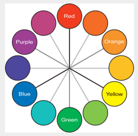
Color harmony

"…successful color combinations, whether these please the eye by using analogous colors, or excite the eye with contrasts."
–*Principles of Color Design*, by Wucius Wong

Color Design Terminology

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

*See www.handprint.com for examples



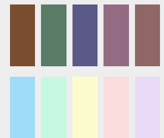
Chroma (saturation)
- Intensity or purity
- Distance from gray

Value (lightness)
- Dark to light
- Applies to all colors, not just gray

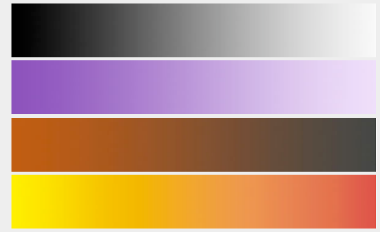
Tints and Tones

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

Tint
- Hue + white
- Decrease saturation
- Increase lightness



Gradations



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
- Control impact of color
- Minimize simultaneous contrast

Envisioning Information

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

—*E. R. Tufte*

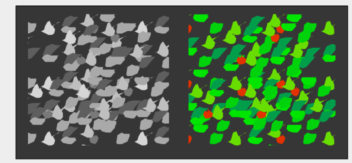
www.edwardtufte.com

Fundamental Uses

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

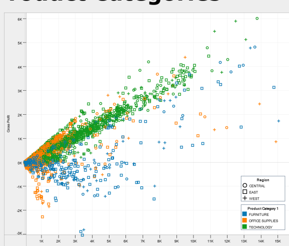
To Label

Identify by Color



Information Visualization
Colin Ware

Product Categories



Created by Tableau - Visual Analysis for Databases™

Grouping, Highlighting

	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
red	25.37	13.70	0.05	26.27	14.13	0.04	18.41	10.16	0.05	17.43	9.30	0.00
green	22.14	51.24	0.35	20.68	49.17	0.44	21.11	46.00	0.20	16.36	37.95	0.12
blue	13.17	3.71	74.89	15.38	5.20	86.83	11.55	3.37	65.53	9.96	3.44	56.14
gray	63.46	73.30	78.05	64.66	71.99	90.08	52.96	62.49	67.99	45.54	53.65	58.14
black	0.66	0.70	0.77	0.63	0.66	1.09	0.47	0.58	0.70	0.44	0.54	0.71

	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
red	25.37	13.70	0.05	26.27	14.13	0.04	18.41	10.16	0.05	17.43	9.30	0.00
green	22.14	51.24	0.35	20.68	49.17	0.44	21.11	46.00	0.20	16.36	37.95	0.12
blue	13.17	3.71	74.89	15.38	5.20	86.83	11.55	3.37	65.53	9.96	3.44	56.14
gray	63.46	73.30	78.05	64.66	71.99	90.08	52.96	62.49	67.99	45.54	53.65	58.14
black	0.66	0.70	0.77	0.63	0.66	1.09	0.47	0.58	0.70	0.44	0.54	0.71

Considerations for Labels

How critical is the color 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 colors?

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"

13579345978274055
24937916478254137
23876597277103866
19874367259047362
95637283649105676
32543787954836754
56840378465485690

Time proportional to the number of digits

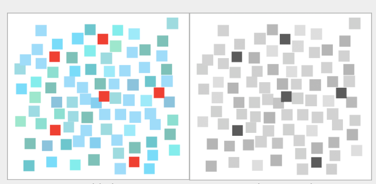
13579345978274055
24937916478254137
23876597277103866
19874367259047362
95637283649105676
32543787954836754
56840378465785690

Time proportional to the number of 7's

13579345978274055
24937916478254137
23876597277103866
19874367259047362
95637283649105676
32543787954836754
56840378465785690

Both 3's and 7's "Pop out"

Contrast Creates Pop-out



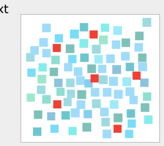
Hue and lightness

Lightness only

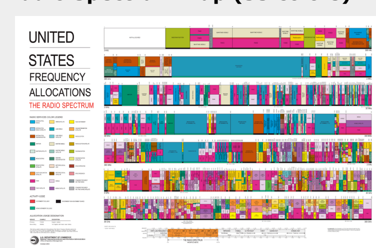
Pop-out vs. Distinguishable

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



Radio Spectrum Map (33 colors)



http://www.cybergeography.org/atlas/us_spectrum_map.pdf

Distinguishable on Inspection

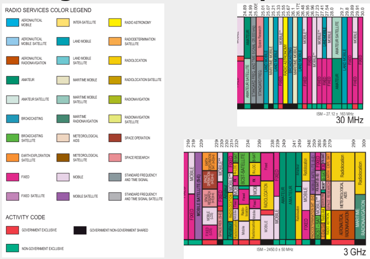
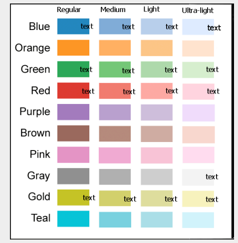


Tableau Color Example

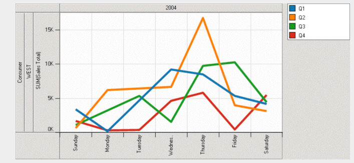
- Color palettes
  - How many? Algorithmic?
  - Basic colors (regular and pastel)
  - Extensible? Customizable?
- Color appearance
  - As a function of size
  - As a function of background
- Robust and reliable color names

Tableau Colors

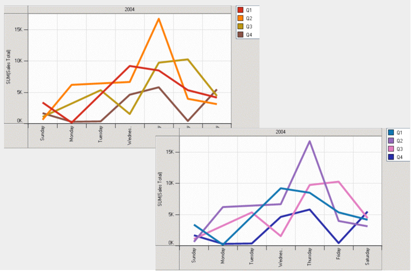


www.tableausoftware.com

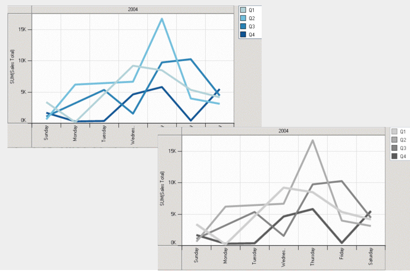
Maximum hue separation

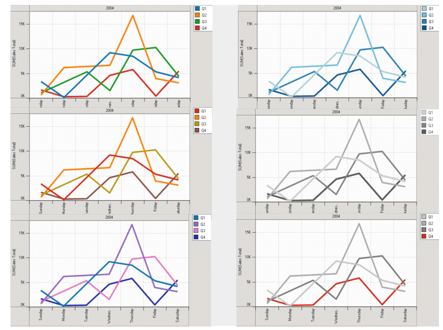


Analogous, yet distinct



Sequential





Color Names

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

Perceptual primaries

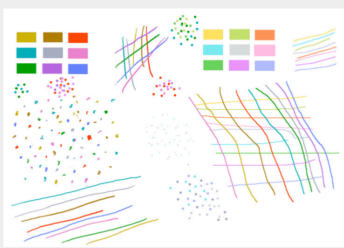
black
white
gray

red
green
blue
yellow

orange
purple
brown
pink

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 Color Survey (Kay & Cook)
  - http://www.icsi.berkeley.edu/wcs/

To Measure

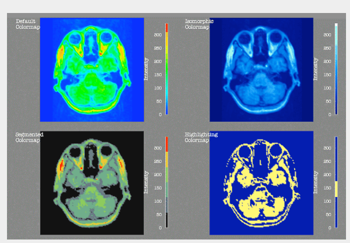
Data to Color

- 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

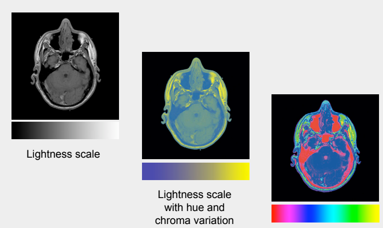
- Long history in graphics and visualization
  - Ware, Robertson et. al
  - Levkowitz et. al
  - Rheingans
- PRAVDA Color
  - Rogowitz and Treinish
  - IBM Research
- Cartography
  - Cynthia Brewer
  - ColorBrewer

Different Scales



Rogowitz & Treinish, "How not to lie with visualization"

Density Map



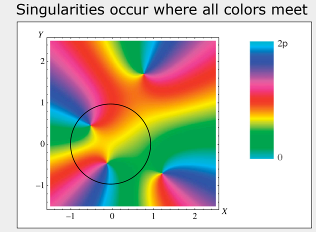
Lightness scale

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

Phases of the Tides

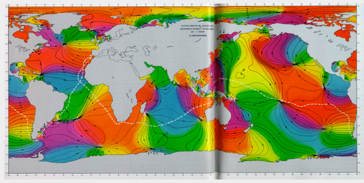


Figure 1.9. Cotidal chart. Tide phases relative to Greenwich are plotted for all the world's oceans. Phase progresses from red to orange to yellow to green to blue to purple. The lines converge on anphidromic points, singularities on the earth's surface where there is no defined tide. [Winfree, 1987 #1195 , p. 17].

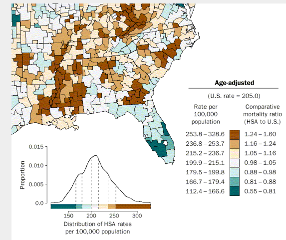
Brewer Scales

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"

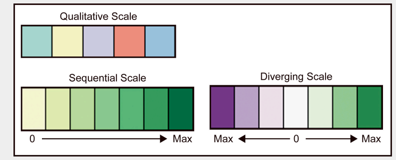
Thematic Maps



US Census Map

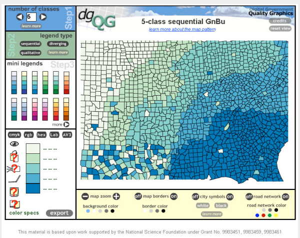
Mapping Census 2000: The Geography of U.S. Diversity

Brewer's Categories



Cynthia Brewer, Pennsylvania State University

Color Brewer



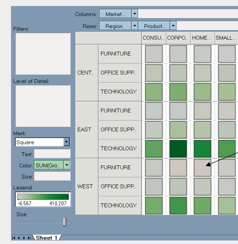
www.colorbrewer.org

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"
- Legible different than distinguishable
- Center, balance of diverging ramps

Heat Map (default ramp)

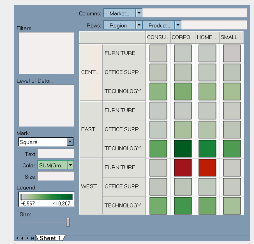


Skewed Data

Slightly negative

www.tableausoftware.com

Full Range



Skewed Data

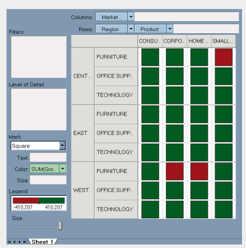
www.tableausoftware.com

Stepped

Skewed Data

www.tableausoftware.com

Threshold



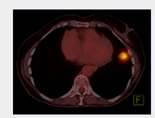
Skewed Data

www.tableausoftware.com

Color and Shading

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

CT image (defines shape)

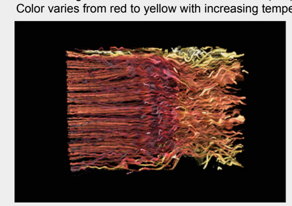


PET color highlights tumor

Image courtesy of Siemens

Color Overlay (Temperature)

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

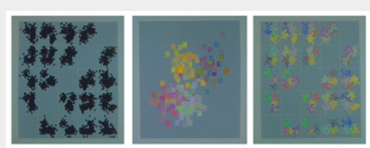


Victoria Interrante and Chester Grosch, U. Minnesota

http://www-users.cs.umn.edu/~interran/3Dflow.html

Multivariate Color Sequences

Multi-dimensional Scatter plot



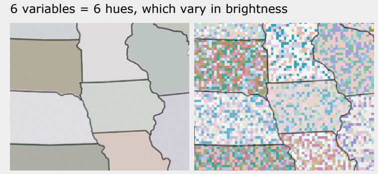
Variable 1, 2 → X, Y
Variable 3, 4, 5 → R, G, B

Do people interpret color blends as sums of variables?

Using Color Dimensions to Display Data Dimensions
Beatty and Ware

Color Weaves

6 variables = 6 hues, which vary in brightness

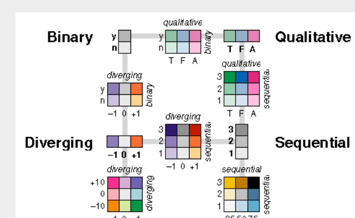


Additive mixture (blend)

Spatial texture (weave)

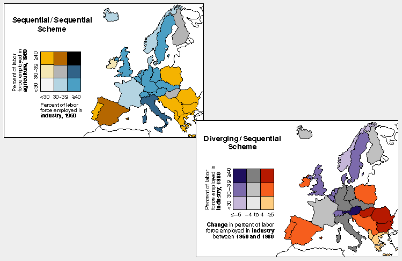
Weaving versus Blending (APGV06 and SIGGRAPH poster)
Haleh Hagh-Shenas, Victoria Interrante, Christopher Healey and Sunghee Kim

Brewer System



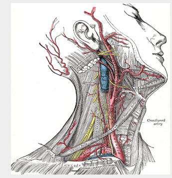
http://www.colorbrewer.org

Brewer Examples



To Represent or Imitate Reality

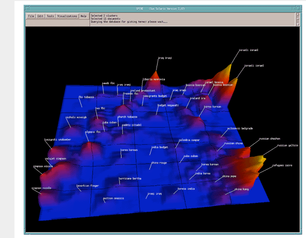
Illustrative Color



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

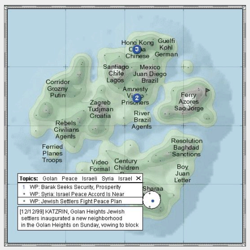
Map of Point Reyes
www.nps.gov

ThemeView (original)

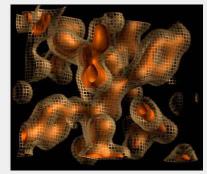


Courtesy of Pacific Northwest National Laboratories

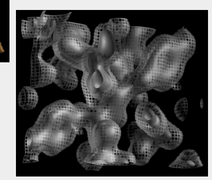
ThemeScape (commercial)



Courtesy of Cartia



Which has more information?
Which would you rather look at?



Visualization of isoelectron density surfaces around molecules

Marc Levoy (1988)

More Tufte Principles

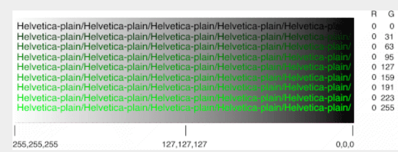
- Limit the use of bright colors
  - Small bright areas, dull backgrounds
- Use the colors found in nature
  - Familiar, naturally harmonious
- Use grayed colors for backgrounds
  - Quiet, versatile
- Create color unity
  - Repeat, mingle, interweave

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
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?

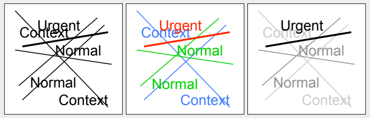
Value Control

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

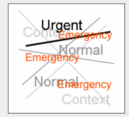
Value contrast creates layering

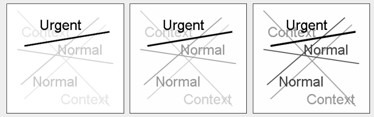


colorusage.arc.nasa.gov

What Defines Layering?

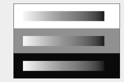
- Perceptual features
  - Contrast (especially lightness)
  - Color, shape and texture
- Task and attention
  - Attention affects perception
- Display characteristics
  - Brightness, contrast, "gamma"





Contrast

- General formulation
  - Luminance difference (L_f, L_b)
  - Depends on adaptation and size
- Small symbols, solid background (Weber)
  - $C = (L_f - L_b)/L_b$
  - Adapted to background
- Textures, high frequency patterns (Michelson)
  - $C = (L_f - L_b)/(L_f + L_b)$
  - Adapted to average



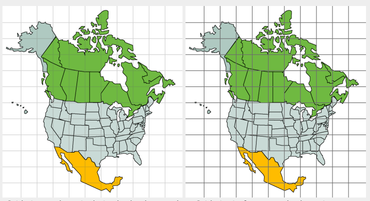
Luminance is intensity
modulated by wavelength sensitivity

Contrast (continued)

L* is the same as Munsell Value, computed as a function of L

- Contrast using ΔL^*
  - 1 is ideally visible
  - 10 is easily visible
  - 20 is legible for text
- Reasons to use a light background
  - More like a reflective surface
  - Contrast metrics are more accurate
  - Easier to look at in mixed environment
- Dark background better for dark environments

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

- My website
  - http://www.stonesc.com/Vis06
  - Final copy of slides, references
- *A Field Guide to Digital Color*
  - A.K. Peters