Color

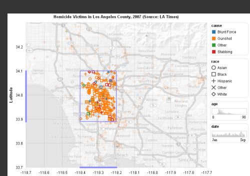
Maneesh Agrawala

CS 294-10: Visualization
Spring 2011

Last Time: Generalized Selection

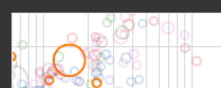
Visual Queries

Model selections as declarative queries



↕

(-118.371 ≤ lon AND lon ≤ -118.164) AND (33.915 ≤ lat AND lat ≤ 34.089)



Interactor

Query Visualizer

Query Builder

(id = 'China')

region

Query Relaxer

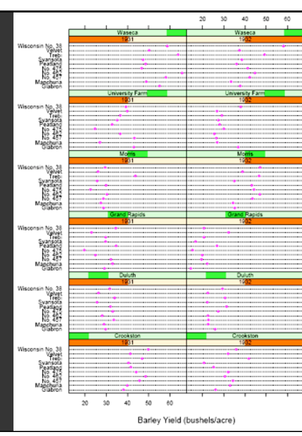
region IN SELECT region FROM data WHERE (id = 'China')

(region = 'Asia')

Reordering/Trellis

Trellis

[Becker, Cleveland, and Shyu 96]

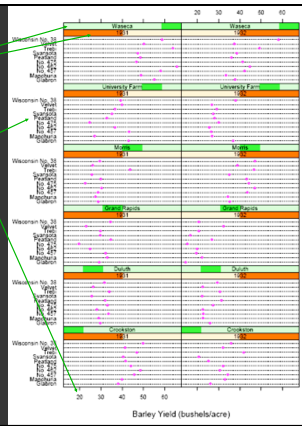


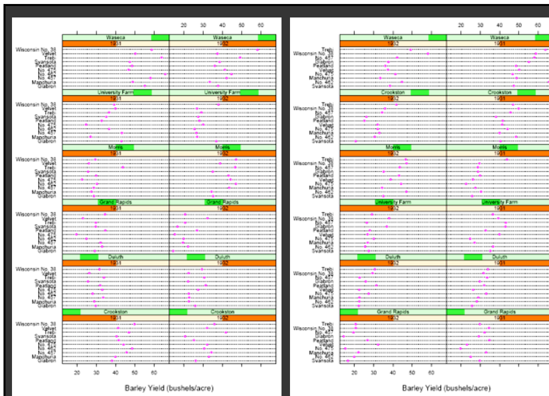
Condition variables
location, year

Panel variables
type, yield

Trellis

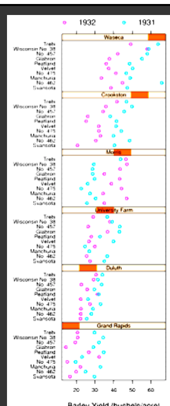
[Becker, Cleveland, and Shyu 96]





Alphabetical ordering

Main-effects ordering

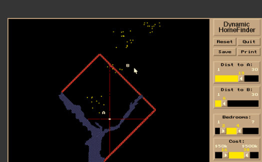


Announcements

Assignment 3: Visualization Software

Create a small interactive visualization application – you choose data domain and visualization technique.

1. Describe data and storyboard interface
2. Implement interface and produce final writeup
3. Submit the application and a final writeup on the wiki

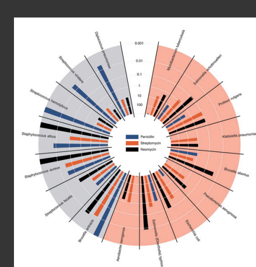


Can work alone or in pairs

Final write up due before class on Mar 7, 2011

Jeff Heer lecture: Monday Feb 28

Talking about design of Protovis



What is Color?

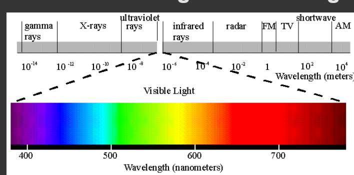
Physical World		Visual System		Mental Models
Lights, surfaces, objects	→	Eye, optic nerve, visual cortex	→	Red, green, brown Bright, light, dark, vivid, colorful, dull Warm, cool, bold, blah, attractive, ugly, pleasant, jarring

Color Models

Physical World	Visual System		Mental Models	
Light Energy →	Cone Response →	Opponent Encoding →	Perceptual Models →	Appearance Models
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

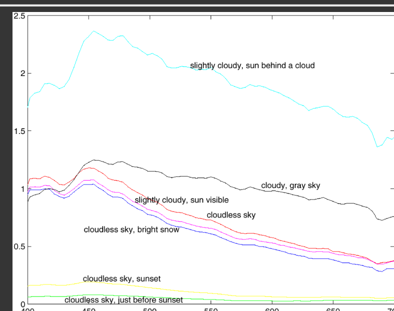
Physical World

Light is radiation in range of wavelengths



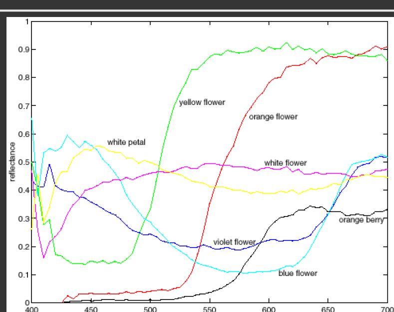
Light of single wavelength is *monochromatic*

Most Colors not Monochromatic



Curves describe spectral composition $\Phi(\lambda)$ of stimulus

Most Colors not Monochromatic



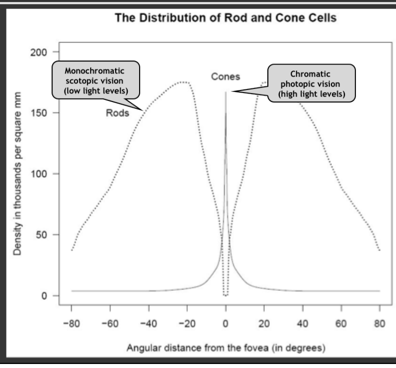
Curves describe spectral composition $\Phi(\lambda)$ of stimulus

Perception Vs. Measurement

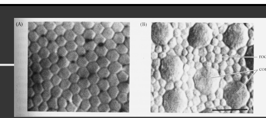
You do not see the spectrum of light

- Eyes make limited measurements
- Eyes physically adapt to circumstance
- You brain adapts in various ways
- Weird stuff also happens

Eyes as Sensors



Rods and Cones



Rods

- No color (sort of)
- Spread over the retina
- More sensitive

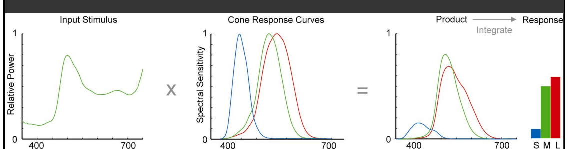
Cones

- 3 types sensitive to different frequencies
- Concentrated in fovea (center of the retina
- Less sensitive

Cone Response

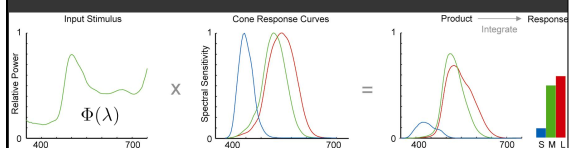
Encode spectra as three values

- Long, medium and short (LMS)
- Trichromacy: only LMS is "seen"
- Different spectra can "look the same"



From A Field Guide to Digital Color, © A.K. Peters, 2003

Computing Cone Response



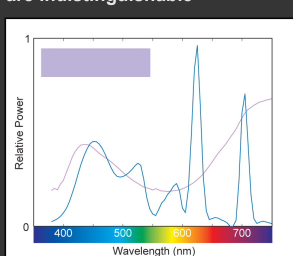
$$L = \int \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$

$$M = \int \Phi(\lambda) M(\lambda) \mathrm{d}\lambda$$

$$S = \int \Phi(\lambda) S(\lambda) \mathrm{d}\lambda$$

Metamers

All spectra that stimulate the same cone response are indistinguishable



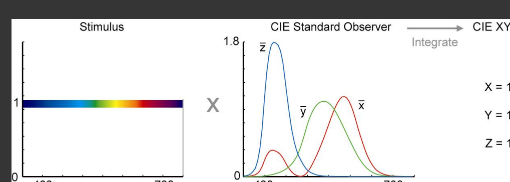
Two different spectra $\Phi_1(\lambda), \Phi_2(\lambda)$ produce same L,M,S response

Color Measurement

CIE Standard Observer

CIE tristimulus values (XYZ)

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

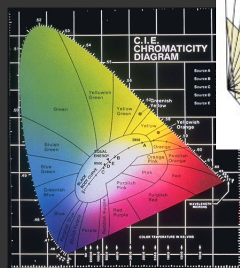


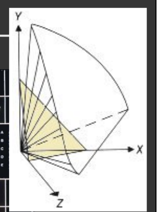
Chromaticity Diagram

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

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

$1 = x+y+z$





Courtesy of PhotoResearch, Inc.

Chromaticity Diagram

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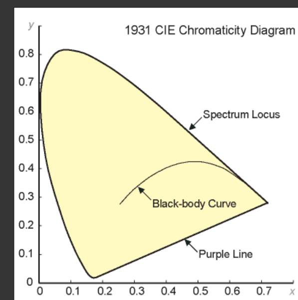


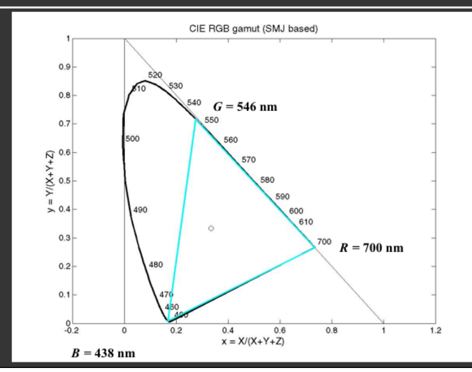
Gamut

Gamut is the chromaticities generated by a set of primaries

Because everything we've done is linear, interpolation between chromaticities on a chromaticity plot is also linear

Thus the gamut is the convex hull of the primary chromaticities

Gamut for 3 Monochomatic Points



Other Gamuts

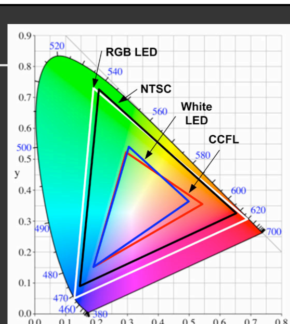
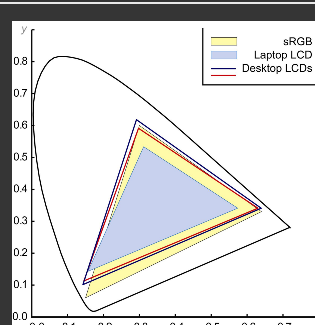


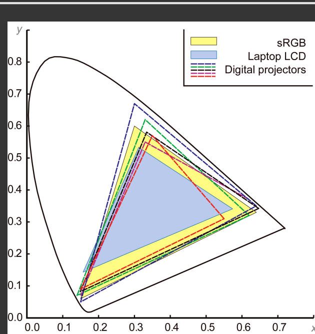
Fig. 3. The color gamut of LCDs with backlights employing CCFL, white LEDs and RGB LEDs are shown here along with the NTSC (television) color gamut.

Display Gamuts



From A Field Guide to Digital Color, © A.K. Peters, 2003

Projector Gamuts



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Color Models

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F(λ)	CIE (X,Y,Z)	(A,R-G,Y-B)	Hue, lightness saturation	Adaptation, Background, Size, …
		Separate lightness, chroma	CIELAB Munsell (HVC)	CIECAM02
		Color blindness		
		Image encoding		

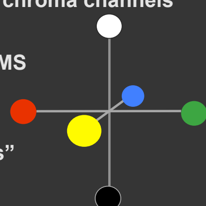
Opponent Color

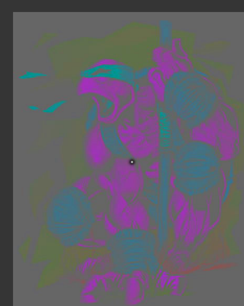
Definition

- 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"



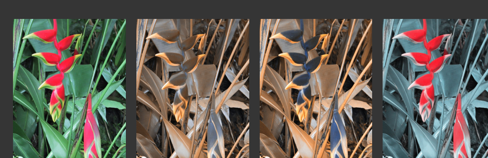


Vischeck

Simulates color vision deficiencies

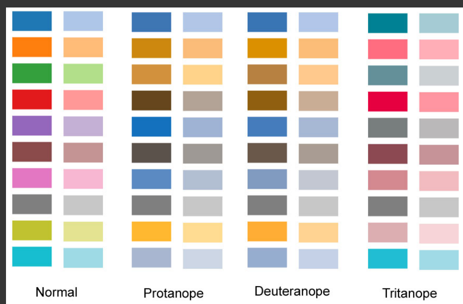
- Web service or Photoshop plug-in
- Robert Dougherty and Alex Wade

www.vischeck.com

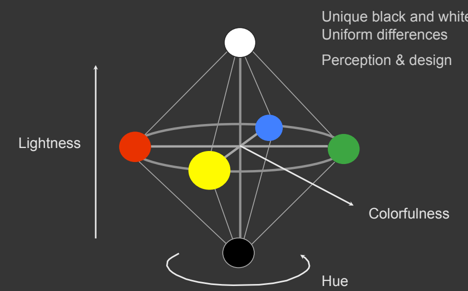


Deuteranope Protanope Tritanope

2D Color Space



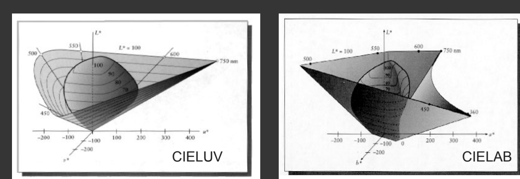
Perceptual Color Spaces



Munsell Atlas

CIELAB and CIELUV

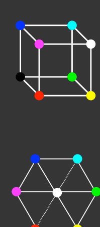
Lightness (L*) plus two color axis (a*, b*)
Non-linear function of CIE XYZ
Defined for computing color differences (reflective)



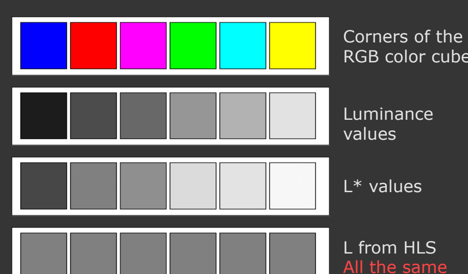
From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64

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*



Luminance & Intensity

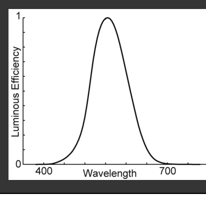
Intensity

- **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



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			CIELAB Munsell (HVC)	CIECAM02

Color differences
"Intuitive" color spaces

Color scales

Simultaneous Contrast

Simultaneous Contrast

Image courtesy of John MCann

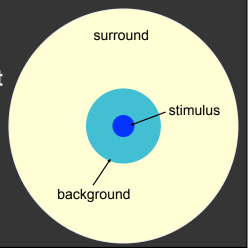
Image courtesy of John MCann

Color Appearance

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

Appearance effects
- Adaptation
- Simultaneous contrast
- Spatial effects

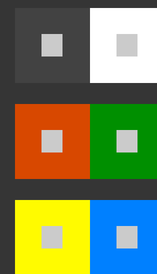
Color in context



Color Appearance Models
Mark Fairchild

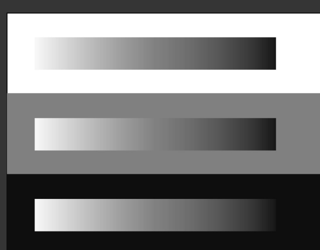
Simultaneous Contrast

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

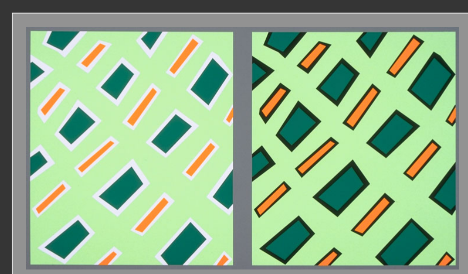


These samples will have both light/dark and hue contrast

Affects Lightness Scale

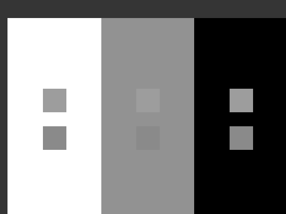


Bezold Effect



Crispening

Perceived difference depends on background

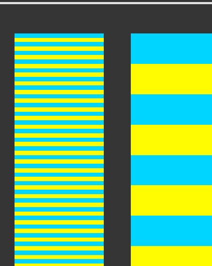


From Fairchild, *Color Appearance Models*

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

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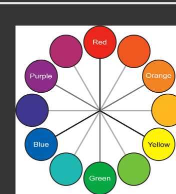
			CIELAB Munsell (HVC)	CIECAM02
				Adaptation Contrast effects Image appearance Complex matching

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



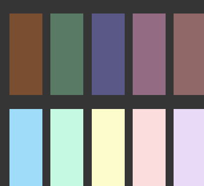
Chroma (saturation)
- Intensity or purity
- Distance from gray

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



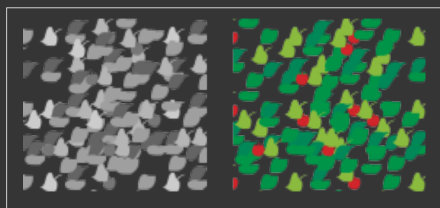
Gradations

Fundamental Uses

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

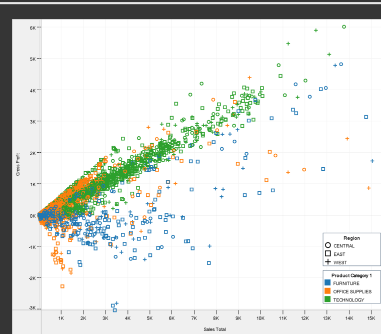
To Label

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

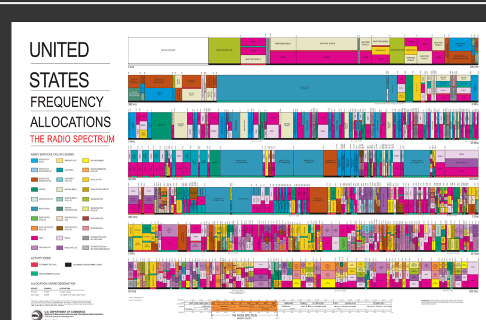
Considerations for Labels

- 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?

Radio Spectrum Map (33 colors)



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

Distinguishable on Inspection

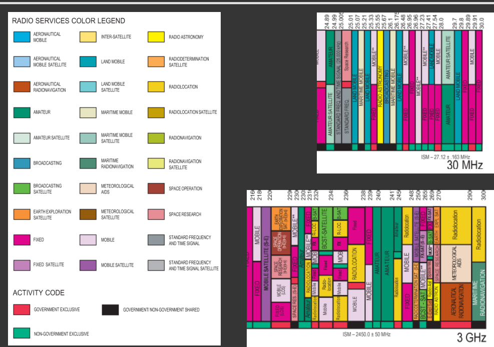


Tableau Color Example

- 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

Distinct, but hard to name

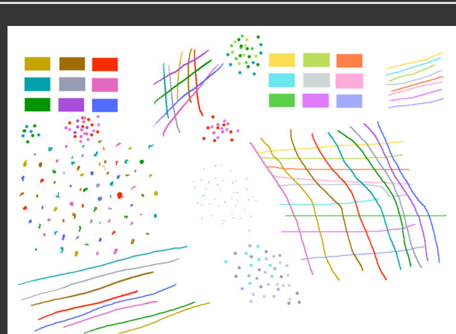
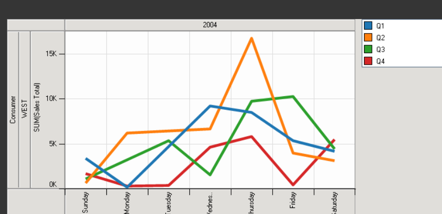


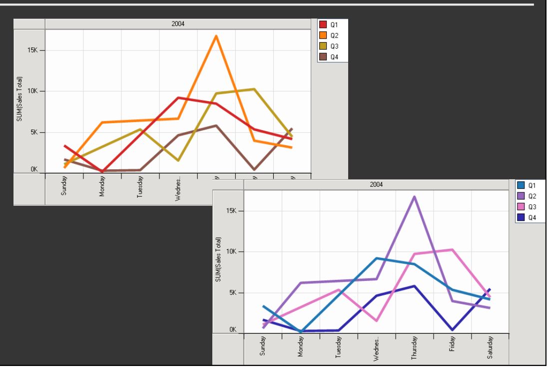
Tableau Colors

www.tableausoftware.com

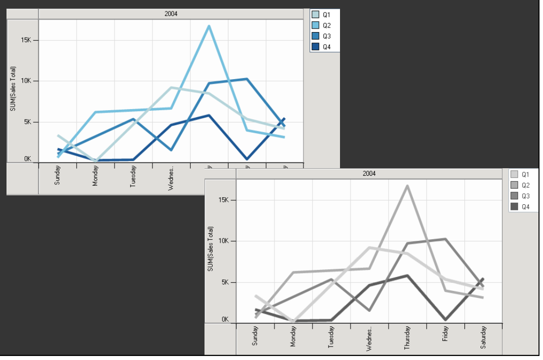
Maximum Hue Separation

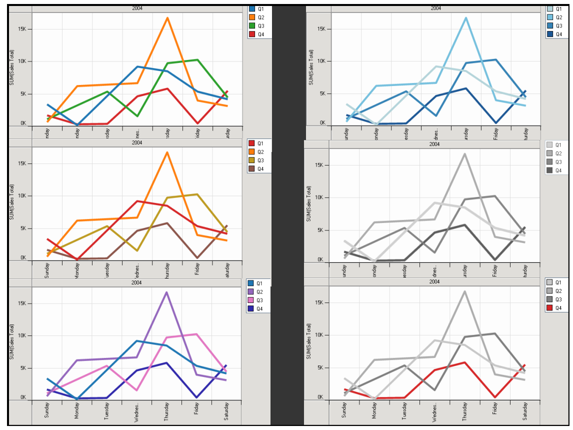


Analogous, Yet Distinct

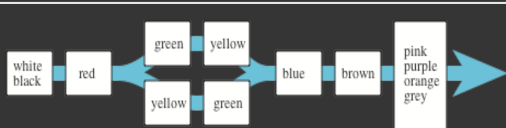


Sequential





Color Names



Basic names (Berlin & Kay)

- Linguistic study of names
- Similar names
- Similar evolution
- Hierarchy of names
  - Names appear in languages in order from left to right

Distinct colors = distinct 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

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

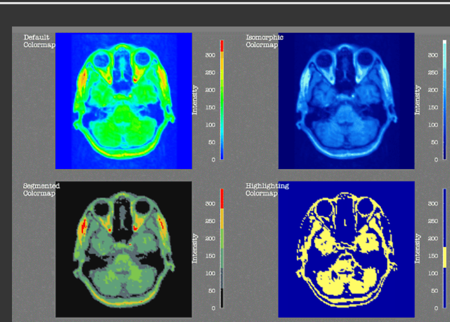
Color Scales

Long history in graphics and visualization
- Ware, Robertson et. al
- Levkowitz et. al
- Rheingans

PRAVDA Color
- Rogowitz and Treinish
- IBM Research

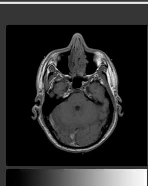
Cartography
- Cynthia Brewer
- ColorBrewer

Different Scales

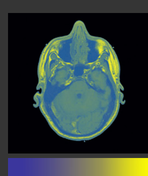


Rogowitz & Treinish, "How not to lie with visualization"

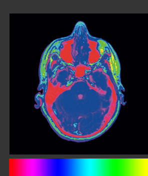
Density Map



Lightness scale



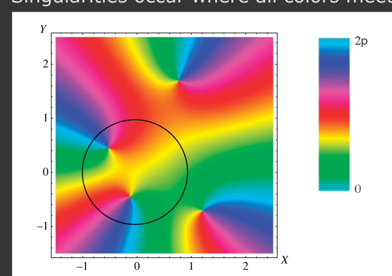
Lightness scale with hue and chroma variation



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

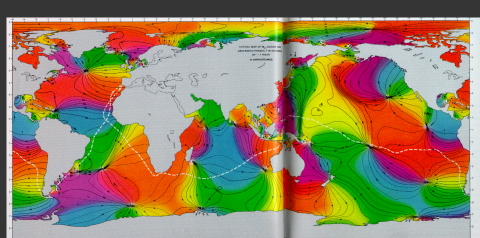


Figure 1.9. Cotidal chart. Tide phases relative to Greenwich are plotted for all the world's oceans. Phase progresses from red to orange to yellow to green to blue to purple. The lines converge on anphidromic points, singularities on the earth's surface where there is no defined tide. [Winfree, 1987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

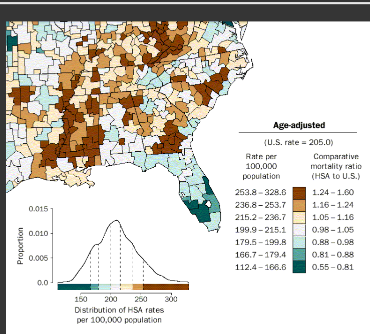
Brewer Scales

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"

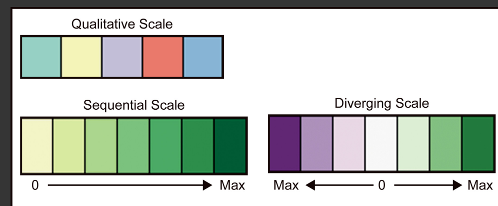
Thematic Maps



US Census Map

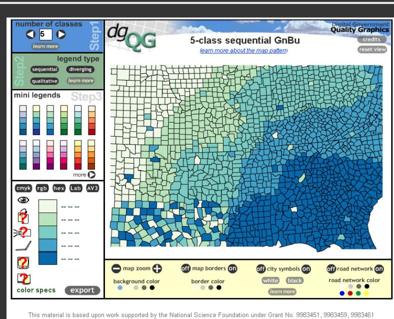
Mapping Census 2000: The Geography of U.S. Diversity

Brewer's Categories



Cynthia Brewer, Pennsylvania State University

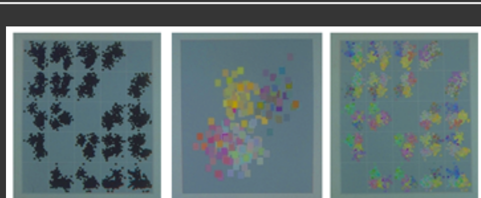
Color Brewer



www.colorbrewer.org

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