Color

Maneesh Agrawala

CS 294-10: Visualization
Fall 2007

Final project

Design new visualization method
- Pose problem, Implement creative solution

Deliverables
- Implementation of solution
- 8-12 page paper in format of conference paper submission
- 2 design discussion presentations

Schedule
- Project proposal: 10/24
- Initial problem presentation: 10/24, 10/29 or 10/31
- Midpoint design discussion: 11/19, 11/21 or 11/26
- Final paper and presentation: To be determined

Grading
- Groups of up to 3 people, graded individually
- Clearly report responsibilities of each member

Schedule

Nate Agrin, Ken-ichi Ueda, Andrew McDiarmid	10/24
Jimmy Andrews	10/31
Andy Carle	10/31
Robert Carroll	10/29
Robin Held	10/24
Jamie O'Shea	10/31
David Purdy, Daisy Wang	10/29
Amanda Alvarez	10/29
Jonathan Chung	10/31
Mark Howison	10/31
Omar Khan	10/24
Wes Willett	10/24
Hannes Hesse, Kesava Mallela	10/29
Kenghao Chang	10/29
Jimmy Chen, Jerry Ye	10/24

Identifying Design Principles

Approach

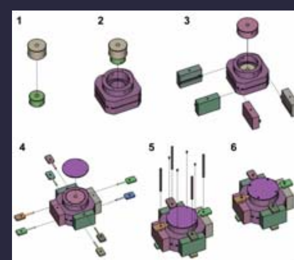
Identify design principles

- Cognition and perception

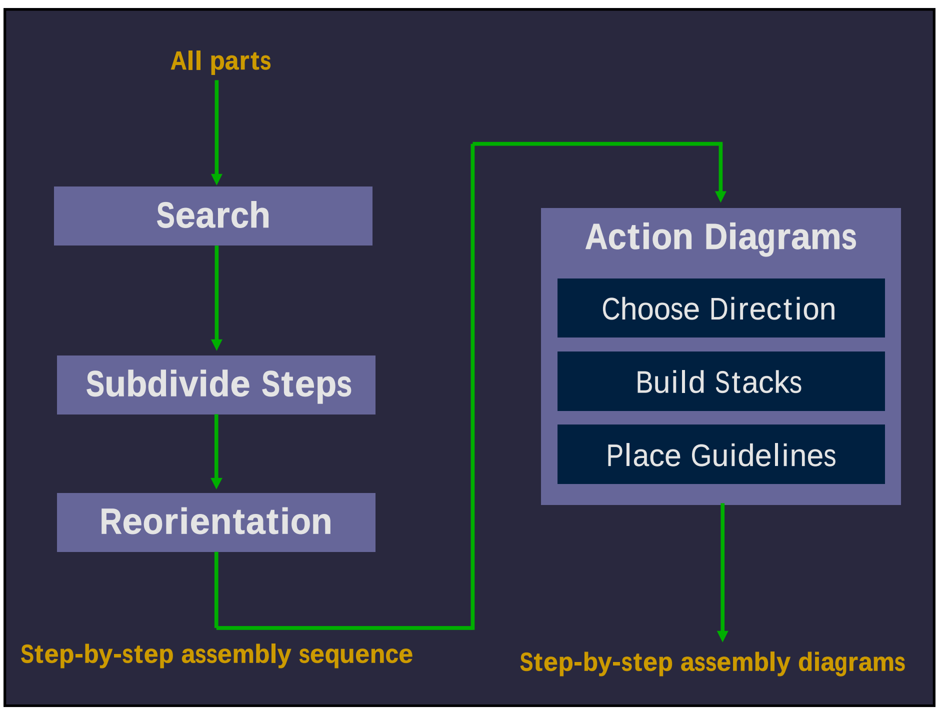
Instantiate design principles

- Principles become constraints that guide an optimization process

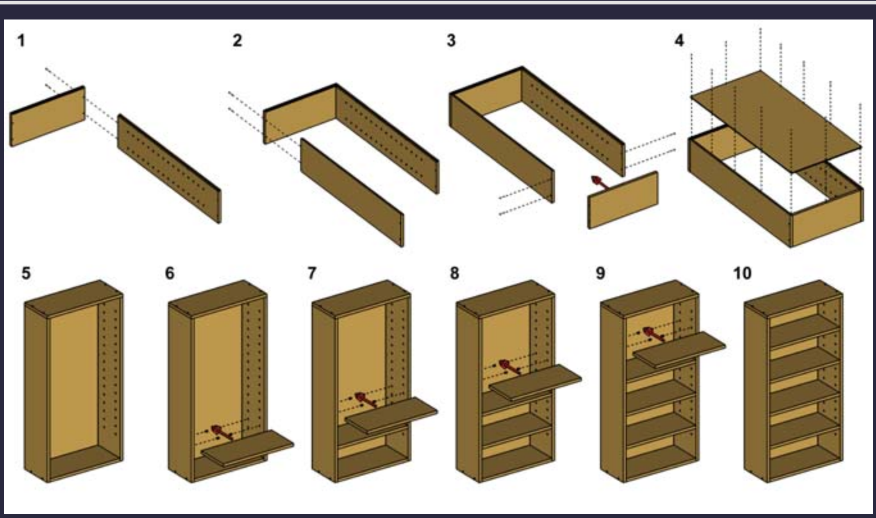
Route maps



Assembly instructions

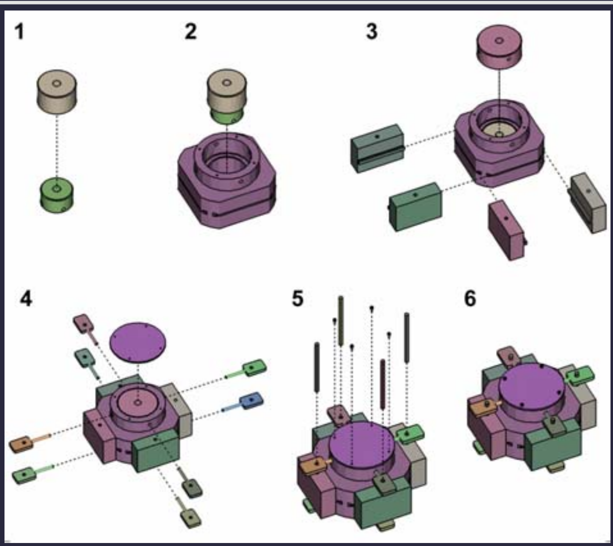


Bookcase



9 Parts Design: 48s

Test Object

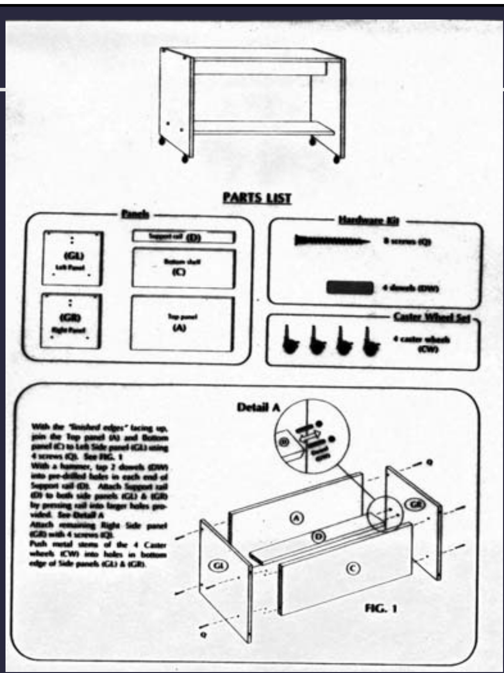


25 Parts Design: 53s

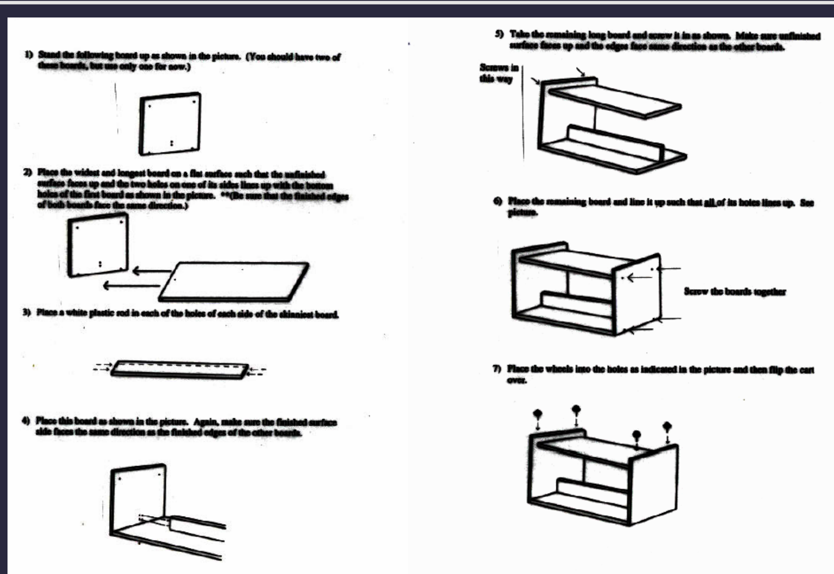
Evaluation

- 30 Participants
- Given 1 of 3 instruction sets: factory, hand-drawn, computer
- Assemble TV stand using instructions

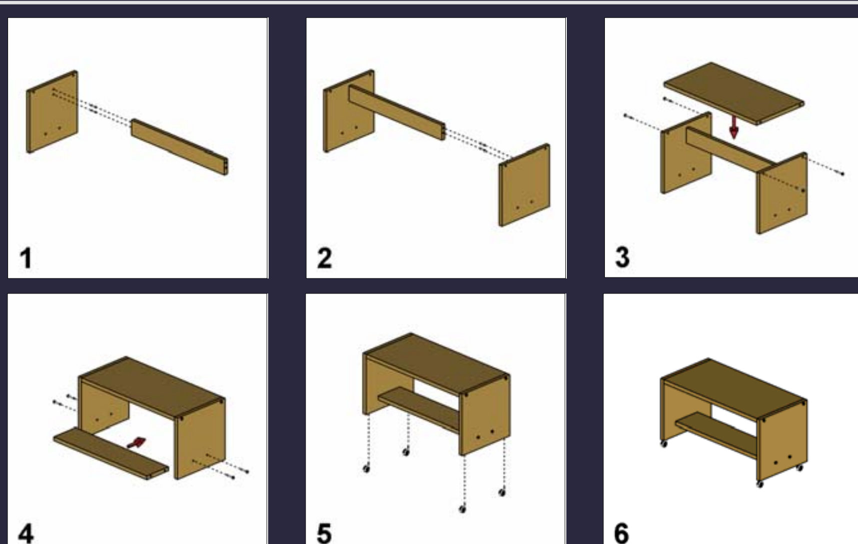
Factory



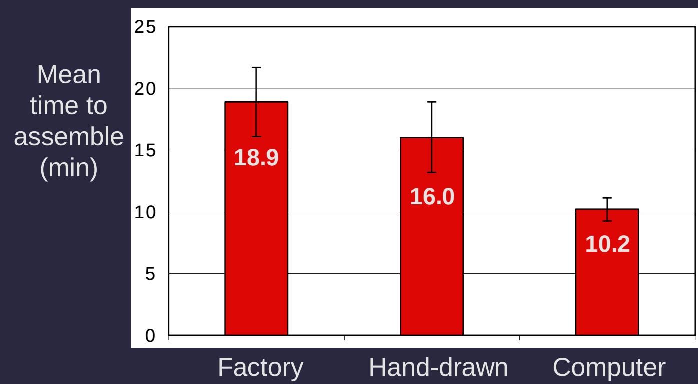
Hand-drawn



Computer Generated



Results



Errors: Factory **1.6** Hand-drawn **0.6** Computer **0.5**

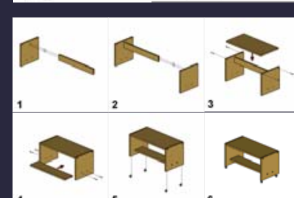
Task rated easiest in computer condition

Summary

Identification of design principles

- Production
- Preference
- Comprehension

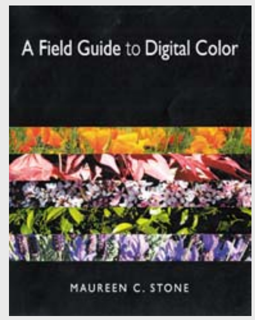
Instantiation of design principles



Validation of design principles

Color in Information Display

Maureen Stone
StoneSoup Consulting



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	Encode as three values (L,M,S)	Separate lightness, chroma	Color “Space”	Color in Context
$F(\lambda)$	CIE (X,Y,Z)	(A,R-G,Y-B)	Hue lightness saturation	Adaptation Background Size …
			CIELAB Munsell (HVC)	CIECAM02

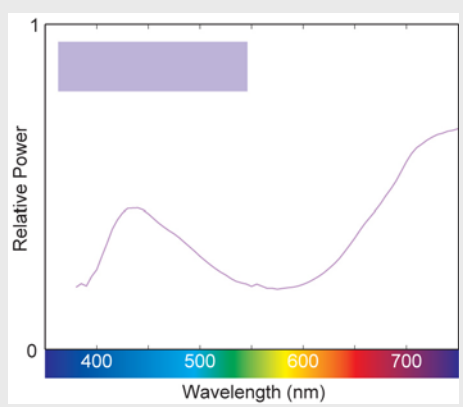
Physical World

Spectral Distribution

- Visible light
- Power vs. wavelength

Any source

- Direct
- Transmitted
- Reflected
- Refracted



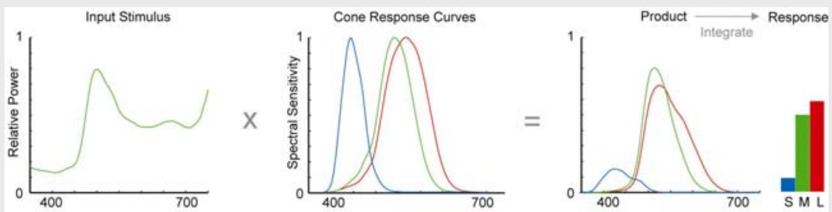
From *A Field Guide to Digital Color*, © A.K. Peters, 2003

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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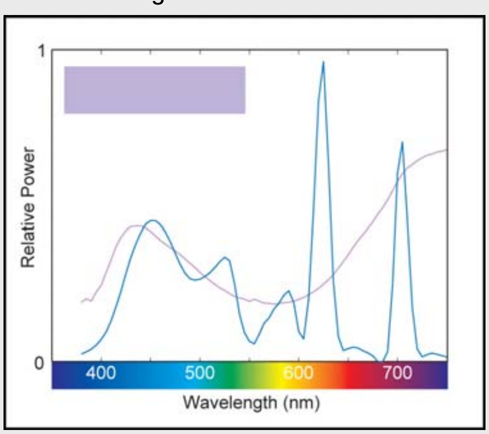
Effects of Retinal Encoding

All spectra that stimulate the same cone response are indistinguishable



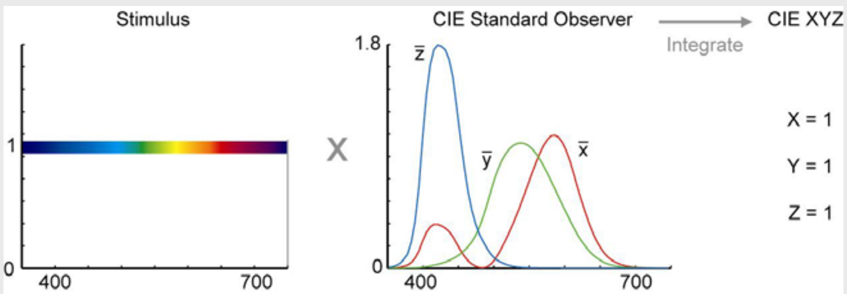
Metameric match

Color Measurement

CIE Standard Observer

CIE tristimulus values (XYZ)

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



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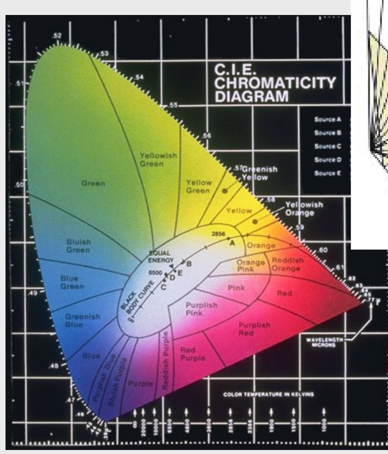
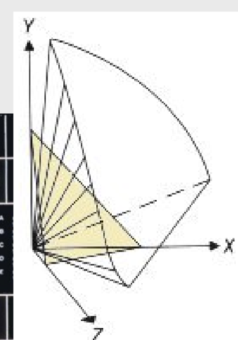
Chromaticity Diagram

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

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

$1 = x+y+z$





Courtesy of PhotoResearch, Inc.

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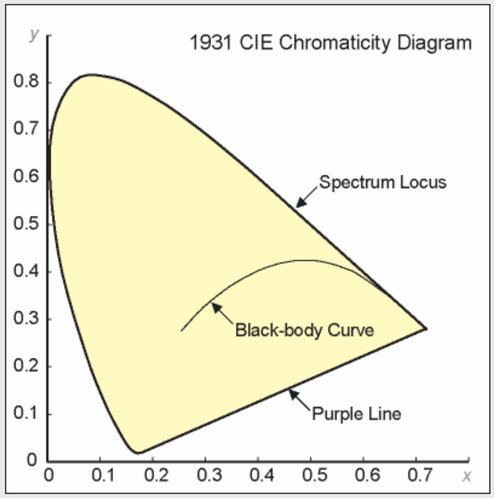


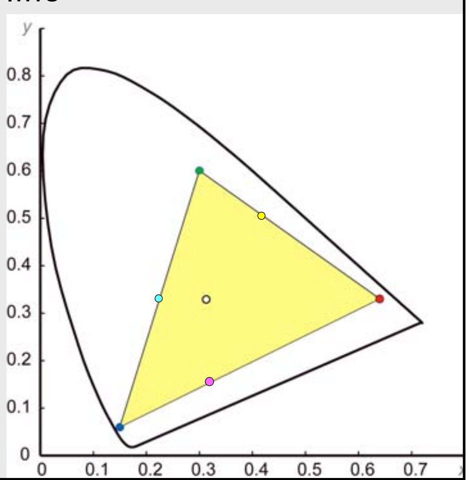
RGB Chromaticity

R,G,B are points (varying lightness)

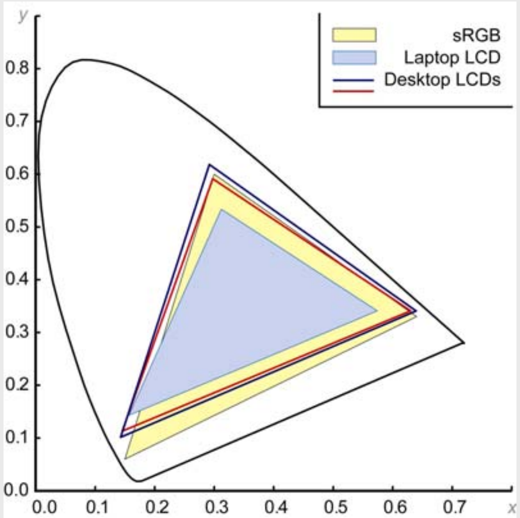
Sum of two colors lies on line

Gamut is a triangle

- White/gray/black near center
- Saturated colors on edges



Display Gamuts



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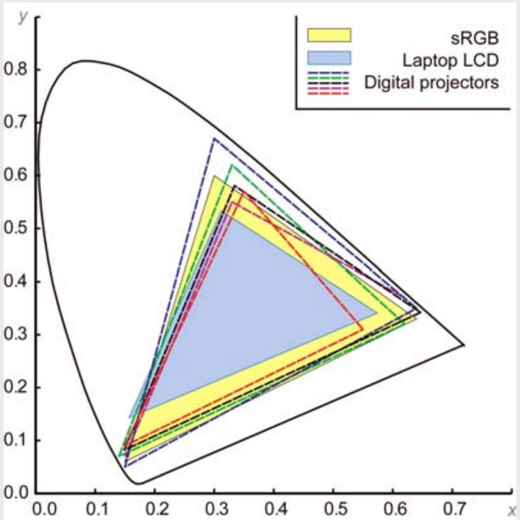
Projector Gamuts



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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, …
		Separate lightness, chroma	CIELAB Munsell (HVC)	CIECAM02
		Color blindness		
		Image encoding		

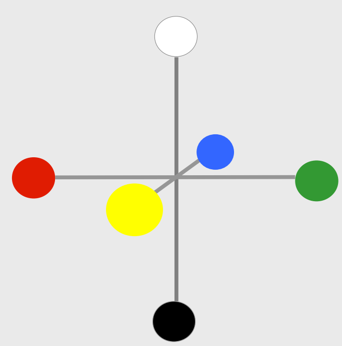
Opponent Color

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

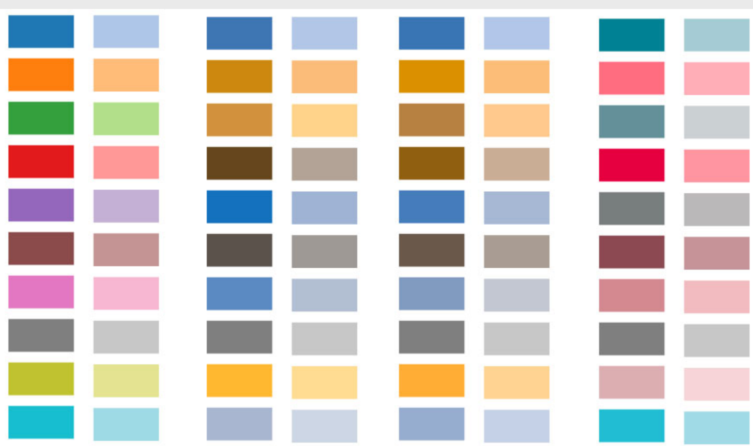
Simulates color vision deficiencies

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

www.vischeck.com

Deuteranope Protanope Tritanope

2D Color Space

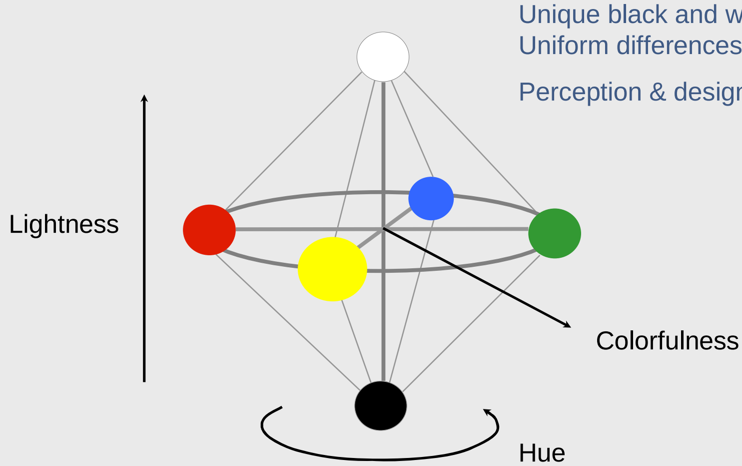


Normal Protanope Deuteranope Tritanope

Perceptual Color Spaces

Unique black and white
Uniform differences

Perception & design

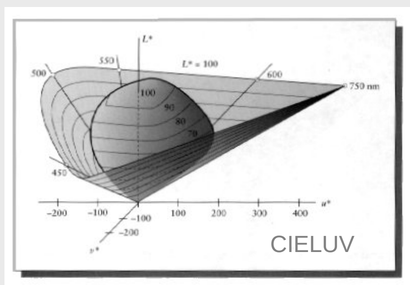


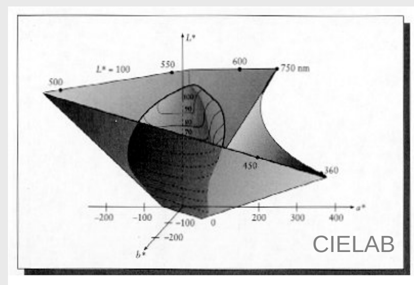
Munsell Atlas

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)



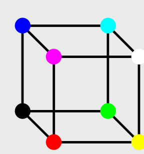


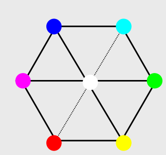
From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64

Psuedo-Perceptual Models

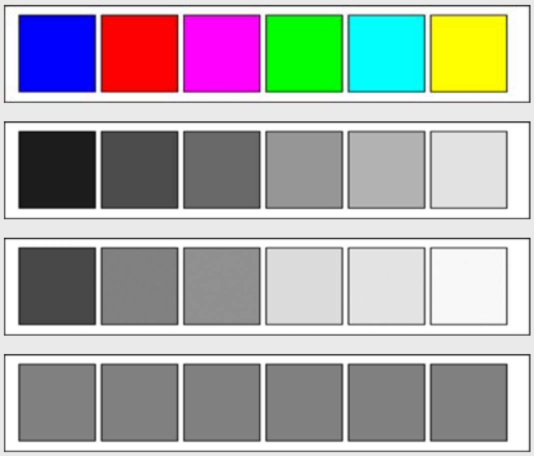
HLS, HSV, HSB
NOT perceptual models
Simple renotation of RGB
- View along gray axis
- See a hue hexagon
- L or V is grayscale pixel value

Cannot predict perceived lightness





L vs. Luminance, L*



Corners of the RGB color cube

Luminance values

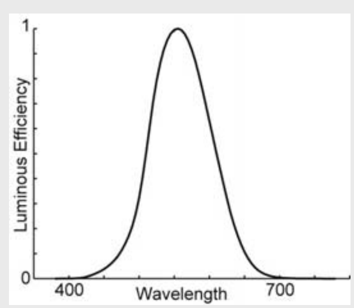
L* values

L from HLS
All the same

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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Color differences
"Intuitive" color spaces

Color scales

Color Appearance

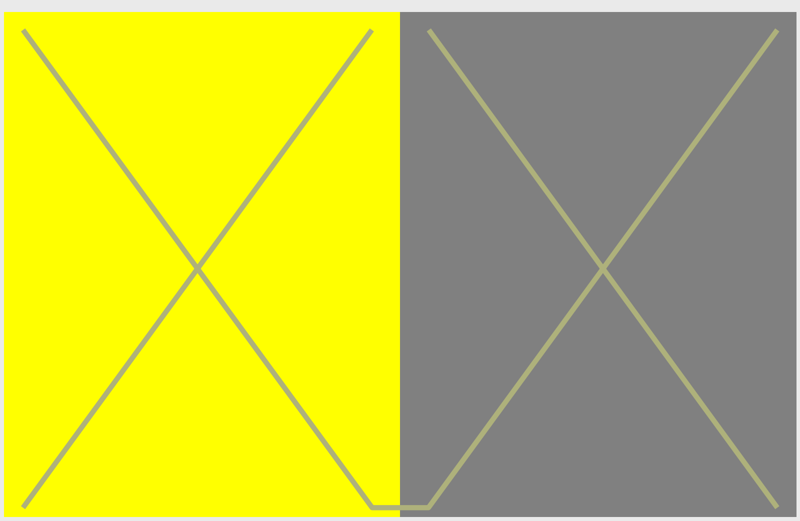


Image courtesy of John MCann

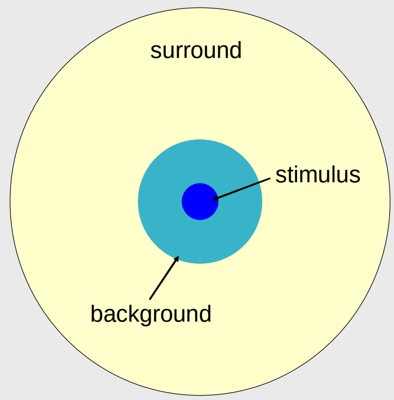
Image courtesy of John MCann

Color Appearance

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

Appearance effects
- Adaptation
- Simultaneous contrast
- Spatial effects

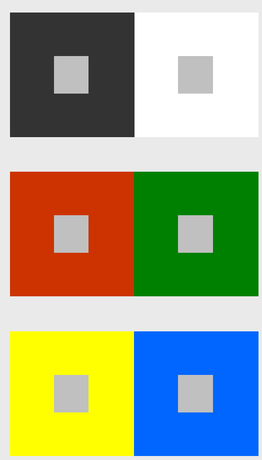
Color in context



Color Appearance Models
Mark Fairchild

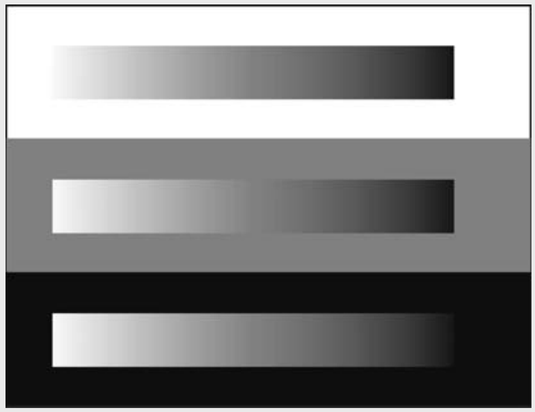
Simultaneous Contrast

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

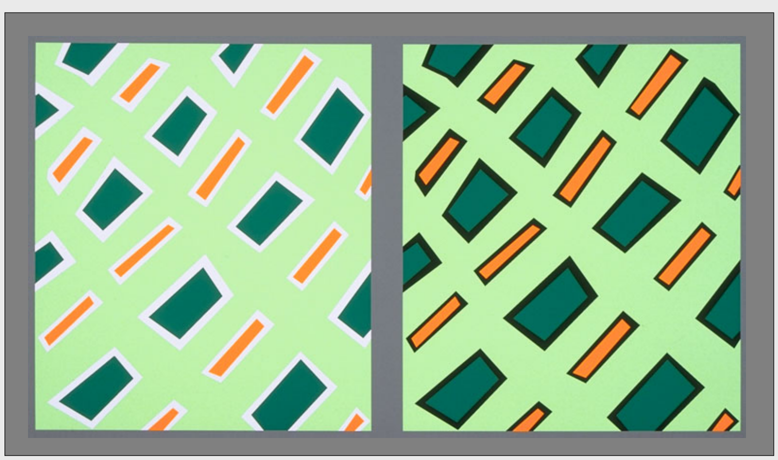


These samples will have both light/dark and hue contrast

Affects Lightness Scale

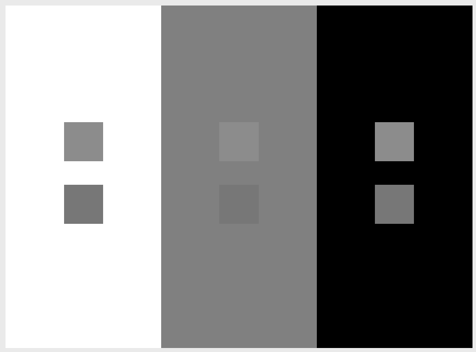


Bezold Effect



Crispening

Perceived difference depends on background



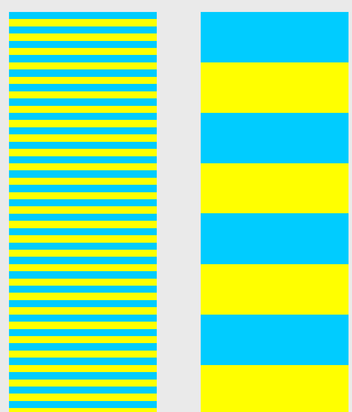
From Fairchild, *Color Appearance Models*

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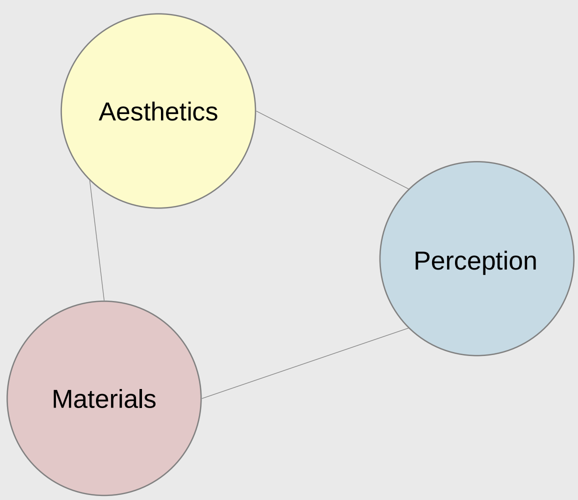
			CIELAB Munsell (HVC)	CIECAM02
				Adaptation Contrast effects Image appearance Complex matching

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

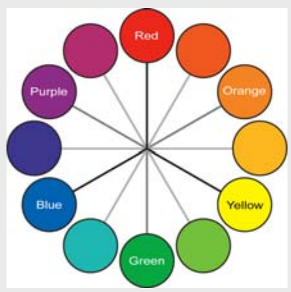
Color is a key component
- Color labels and groups
- Color scales (colormaps)
- Multi-variate color encoding
- Color shading and textures
- And more…

www.nps.gov

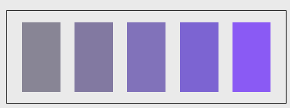
Color Design Terminology

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

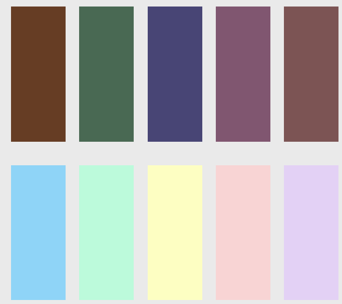
Tints and Tones

Tone or shade

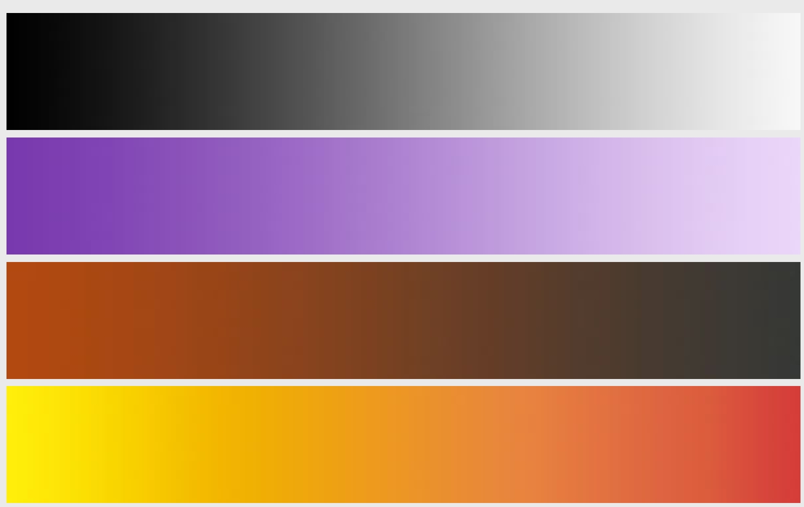
- Hue + black
- Decrease saturation
- Decrease lightness

Tint

- Hue + white
- Decrease saturation
- Increase lightness



Gradations



Color Design Principles

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

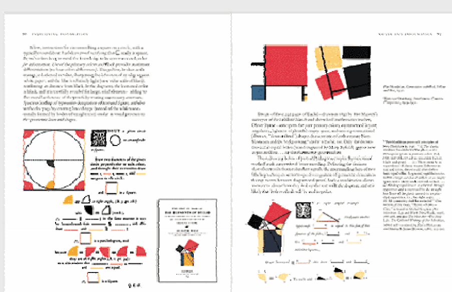
Use a limited hue palette
- Control color "pop out"
- Define color grouping
- Avoid clutter from too many competing colors

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



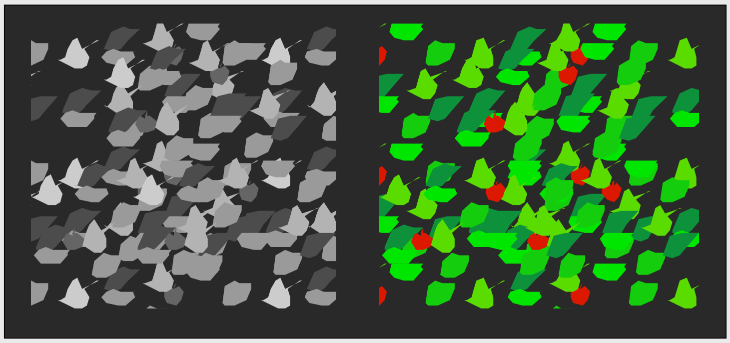
www.edwardtufte.com

Fundamental Uses

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

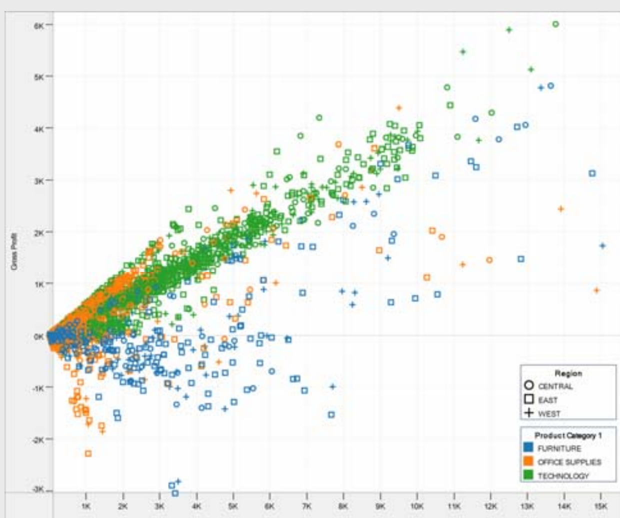
To Label

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?

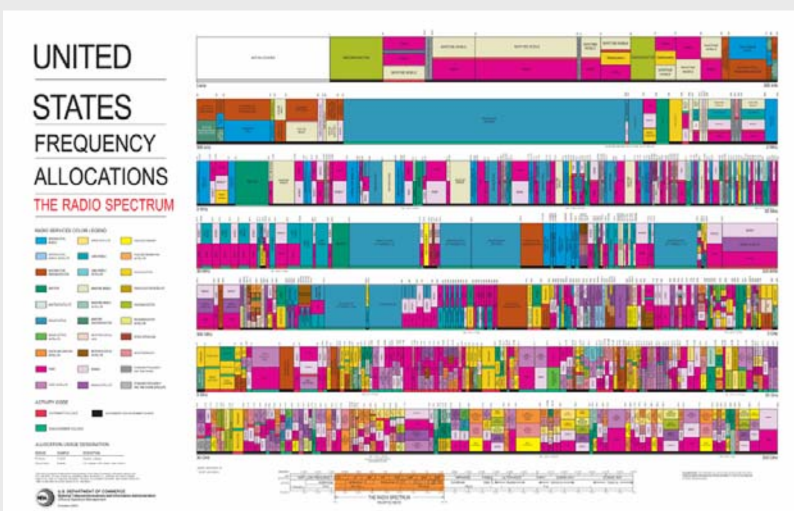
Controls and Alerts

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?

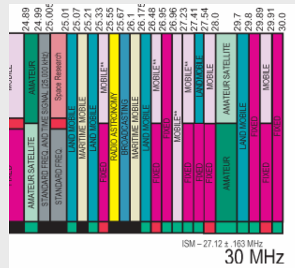
Typical color desktop
- Aid to search
- Redundant information
- Personal and decorative
- How many colors?

Radio Spectrum Map (33 colors)



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

Distinguishable on Inspection



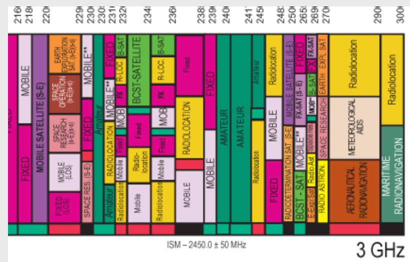


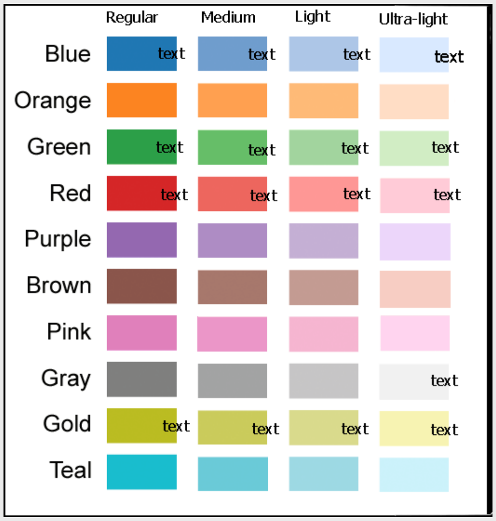
Tableau Color Example

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

Color appearance
- As a function of size
- As a function of background

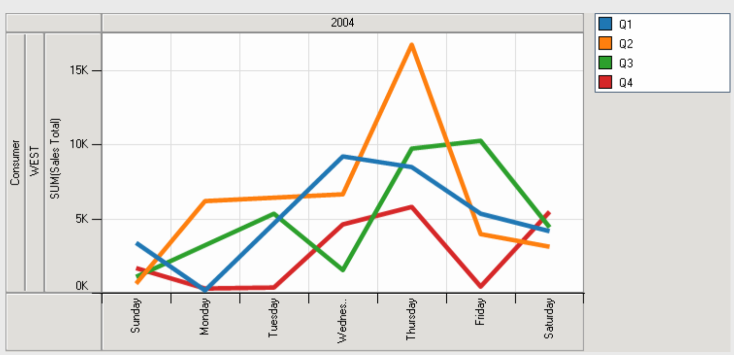
Robust and reliable color names

Tableau Colors

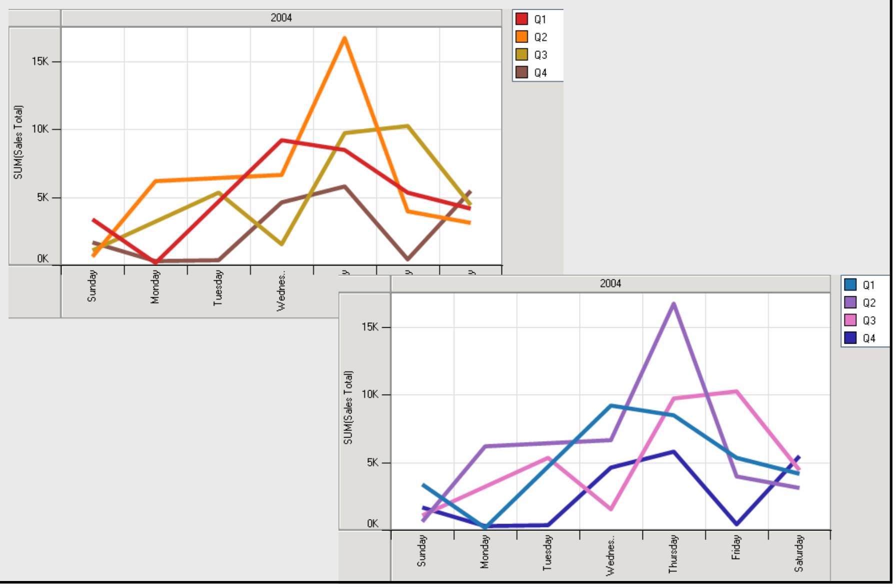


www.tableausoftware.com

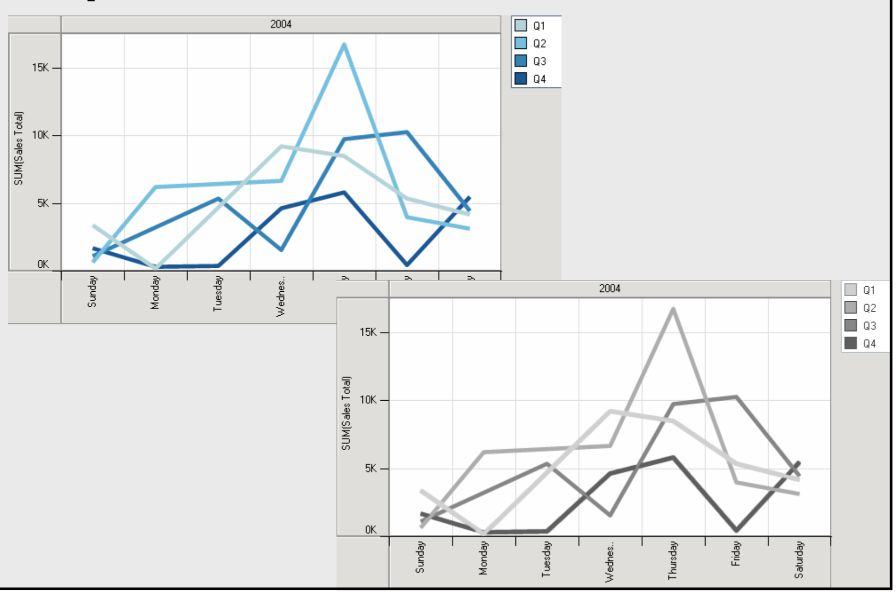
Maximum hue separation

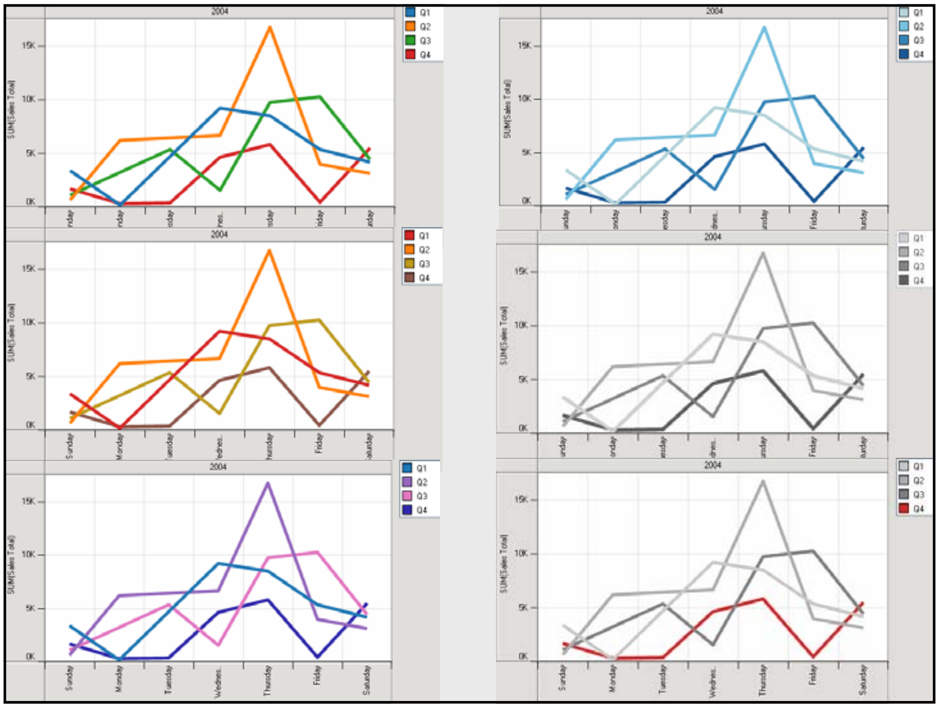


Analogous, yet distinct

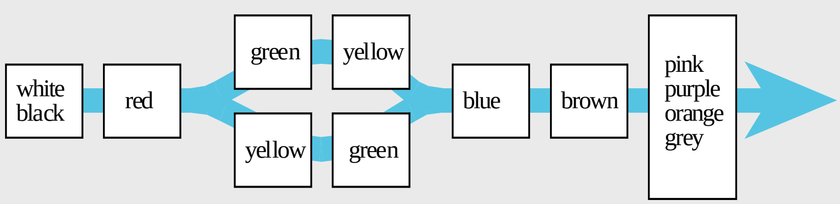


Sequential





Color Names

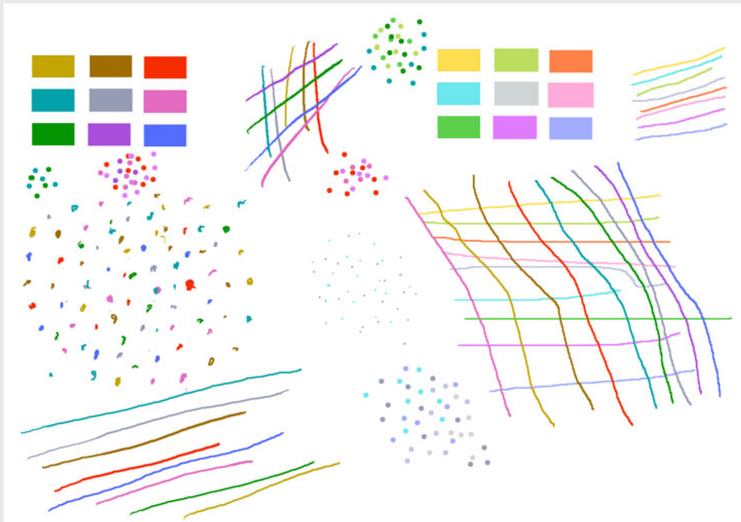


Basic names (Berlin & Kay)

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

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

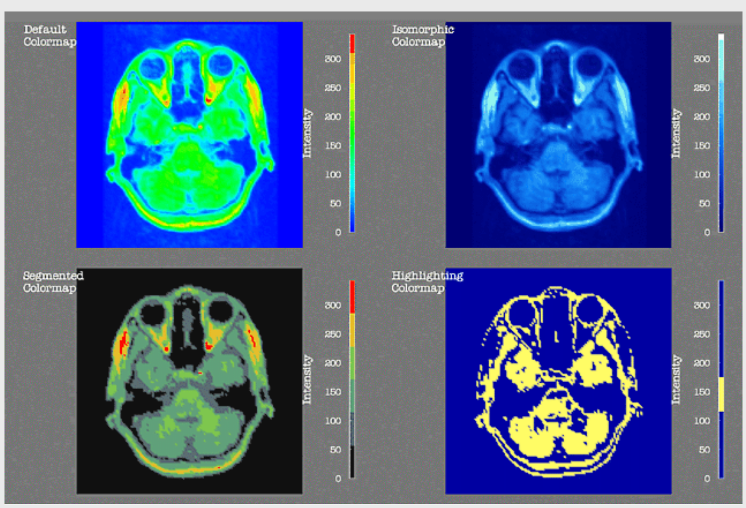
PRAVDA Color

- Rogowitz and Treinish
- IBM Research

Cartography

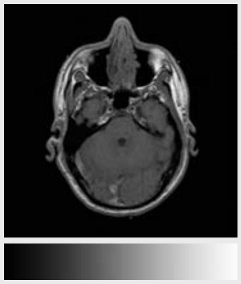
- Cynthia Brewer
- ColorBrewer

Different Scales

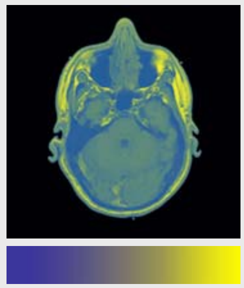


Rogowitz & Treinish, “How not to lie with visualization”

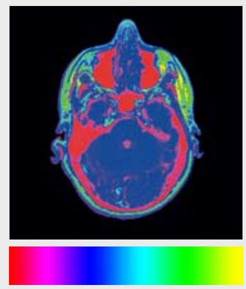
Density Map



Lightness scale



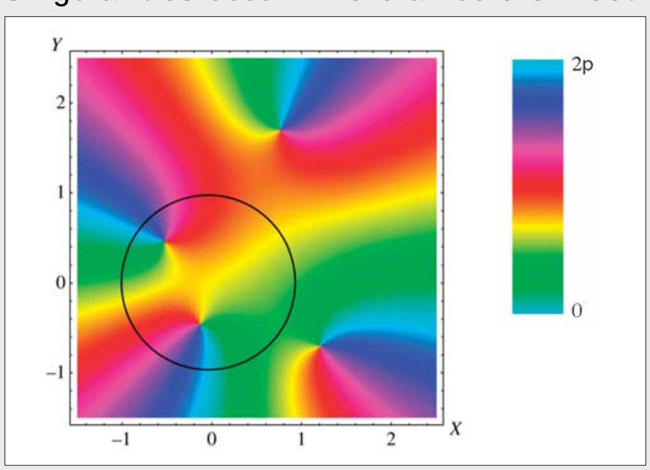
Lightness scale
with hue and
chroma variation



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

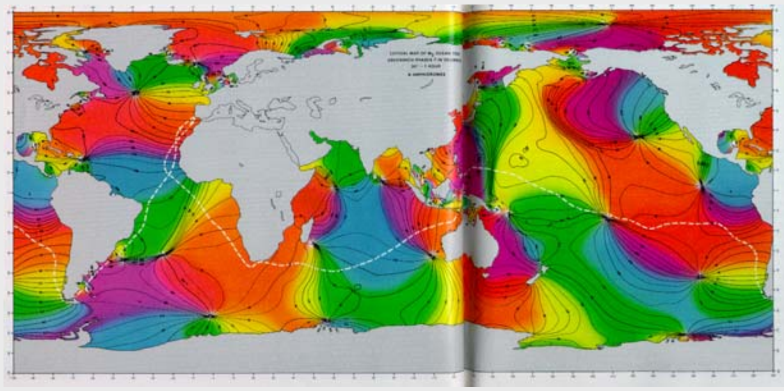


Figure 1.9. Cotidal chart. Tide phases relative to Greenwich are plotted for all the world's oceans. Phase progresses from red to orange to yellow to green to blue to purple. The lines converge on anphidromic points, singularities on the earth's surface where there is no defined tide. [Winfree, 1987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

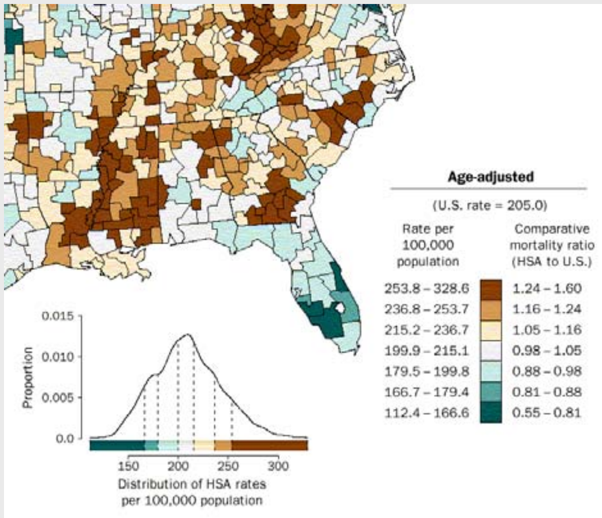
Brewer Scales

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"

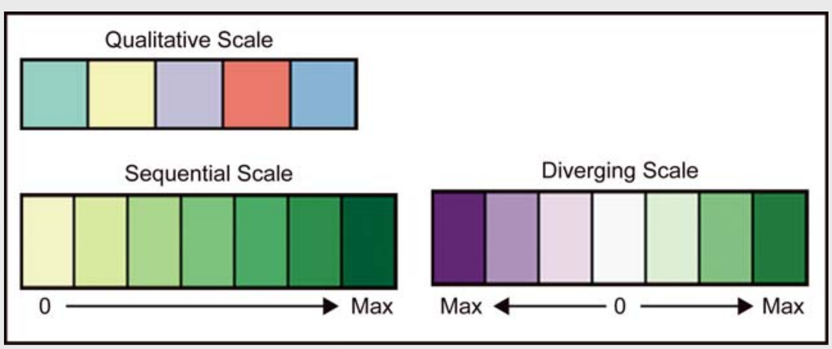
Thematic Maps



US Census Map

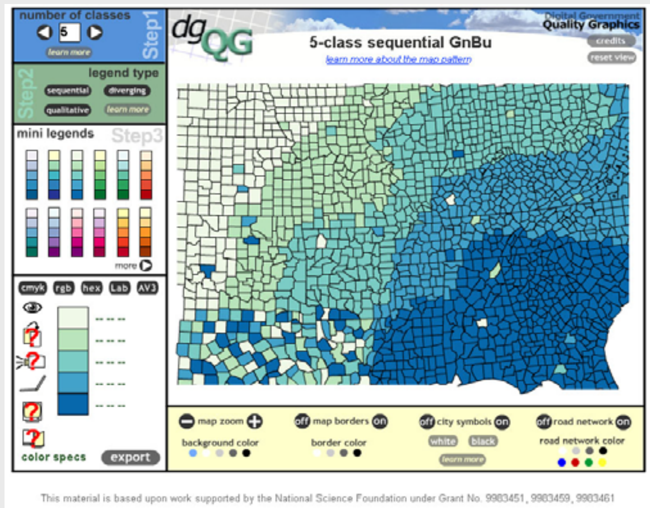
Mapping Census 2000: The Geography of U.S. Diversity

Brewer’s Categories



Cynthia Brewer, Pennsylvania State University

Color Brewer



www.colorbrewer.org

Multivariate Color Sequences

Multi-dimensional Scatter plot

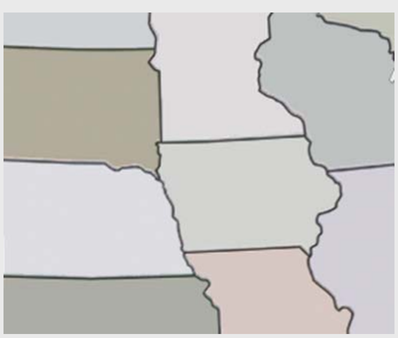
Variable 1, 2 → X, Y
Variable 3, 4, 5 → R, G, B

Do people interpret color blends as sums of variables?

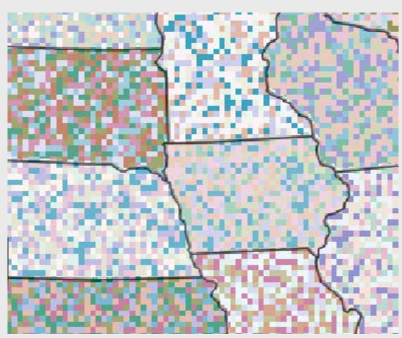
Using Color Dimensions to Display Data Dimensions
Beatty and Ware

Color Weaves

6 variables = 6 hues, which vary in brightness



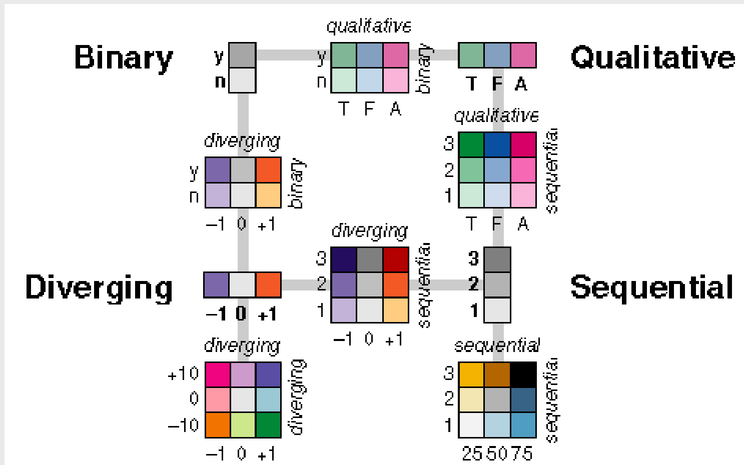
Additive mixture (blend)



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