STANFORD / CS448B

Color

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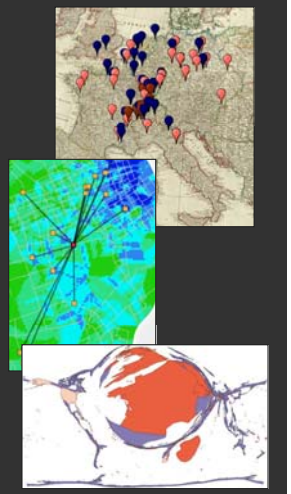
http://cs448b.stanford.edu

Spatial History Data for Visualization Projects

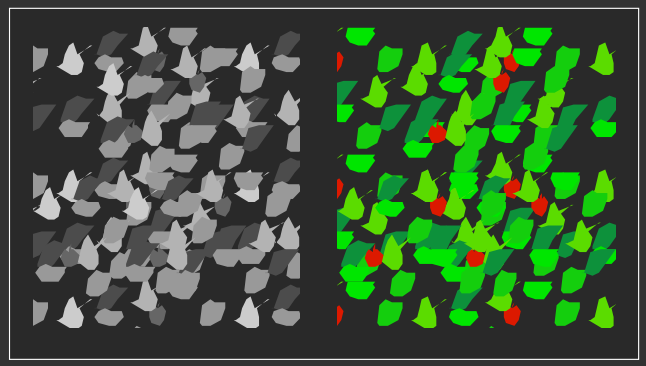
- 10 rich data sets, 10s of 1,000s of historical records, over 100s of years, for visualizing spatial, temporal, and network patterns in:

- The Republic of Letters and the Enlightenment
- Travelers on the Grand Tour in Italy
- Railroads in the American West
- Social Life in 19th Century Rio de Janeiro
- Mapping botanical discoveries and scientific networks in California, 1840-2009



Color in Visualization

Identify, Group, Layer, Highlight



Colin Ware

Purpose of Color

To label

To measure

To represent and imitate

To enliven and decorate

Above all, do no harm. - *E. R. Tufte*

Topics

Perception of Color

- Light, Visual system, Mental models

Color in Information Visualization

- Categorical color
- Color sequences
- ColorBrewer

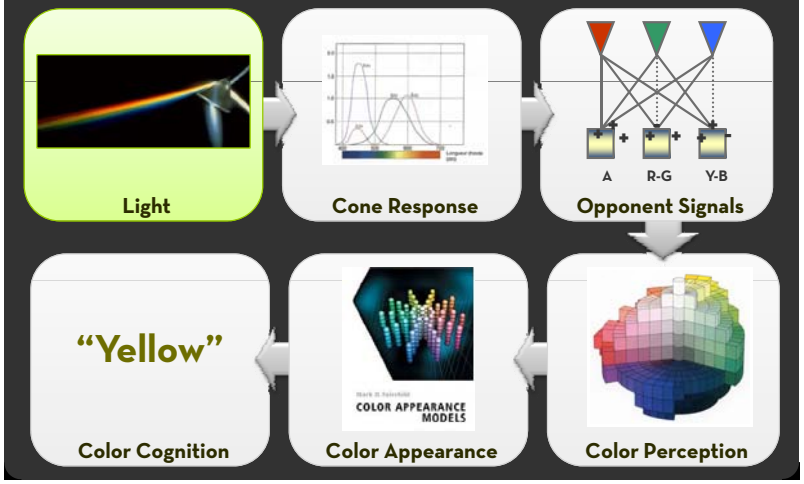
Perception of Color

What color is this?

What color is this?

"Yellow"

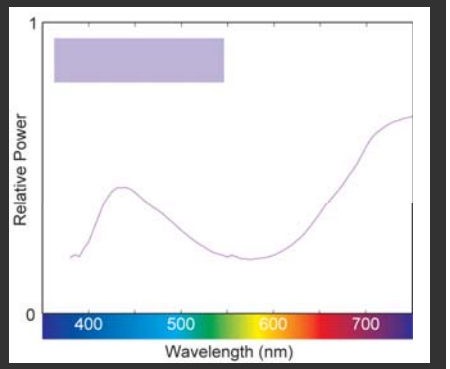
Perception of Color



Physicist's view of color

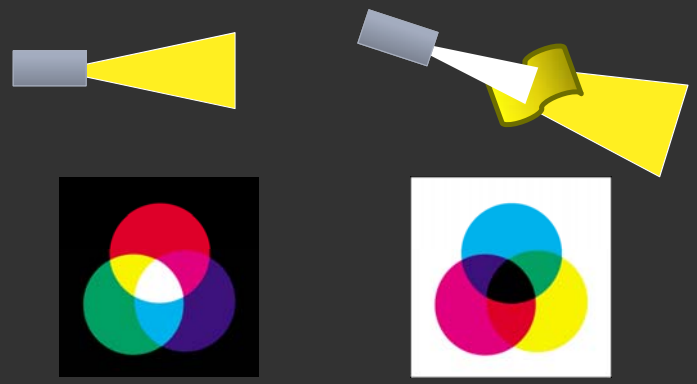
Light with different spectral distribution

- Light energy
- Wavelength



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

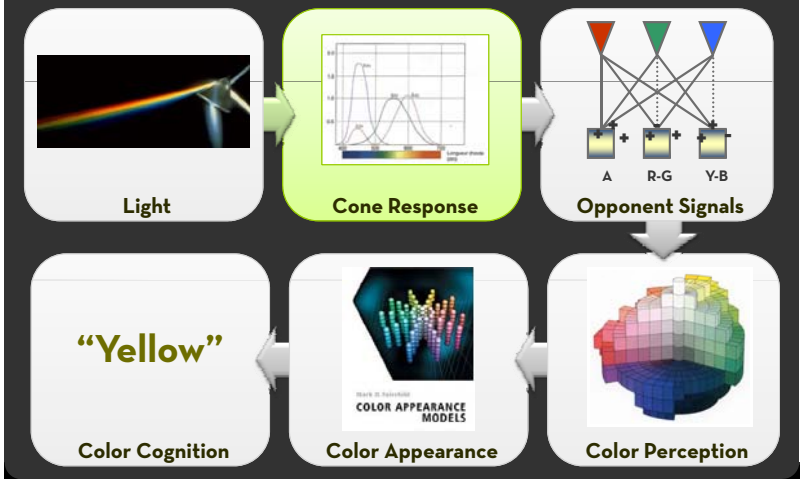
Emissive vs. reflective colors



Additive
RGB Space

Subtractive
CMY Space

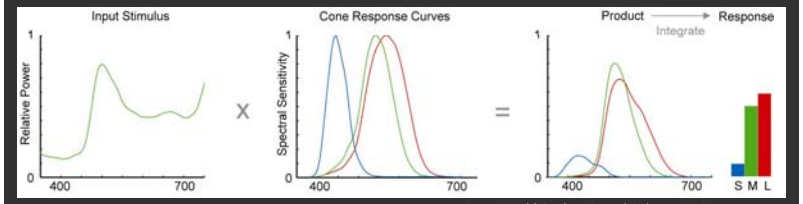
Perception of Color



As light enters our retina...

Cone responses

- Long, Median, Short (LMS)
- Integration with cone response curves



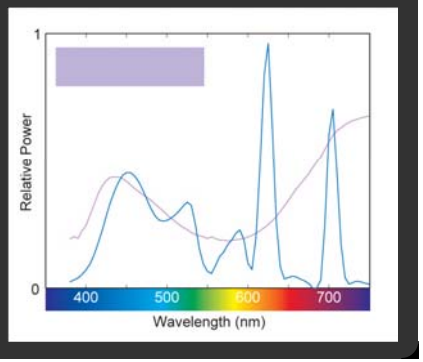
From *A Field Guide to Digital Color*, © A.K. Peters, 2003

Effects of retina encoding

Spectra that stimulate the same LMS response are indistinguishable.

"Tri-stimulus"

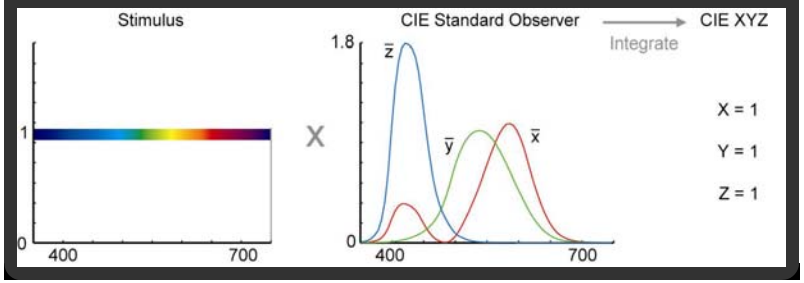
- Computer displays
- Digital scanners
- Digital cameras



CIE XYZ color space

Standardized in 1931 to mathematically represent tri-stimulus response.

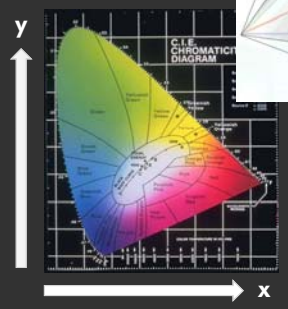
- Standard observer response curves

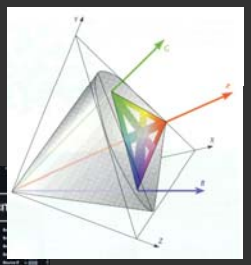


CIE chromaticity diagram

Colorfulness vs. Brightness

- x = X/(X+Y+Z)
- y = Y/(X+Y+Z)





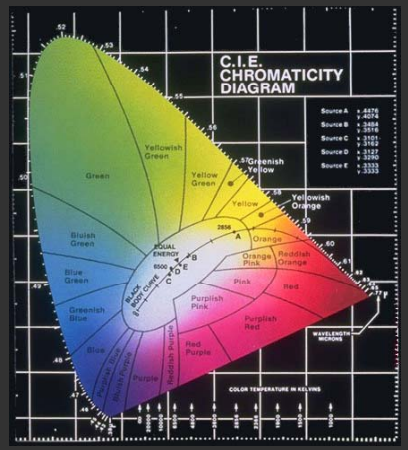
Colin Ware

CIE chromaticity diagram

Spectrum locus

Purple line

- Mixture of two lights appears as a straight line.



Courtesy of PhotoResearch, Inc.

CIE chromaticity diagram

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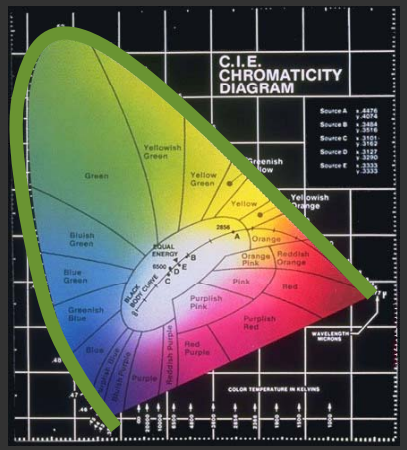

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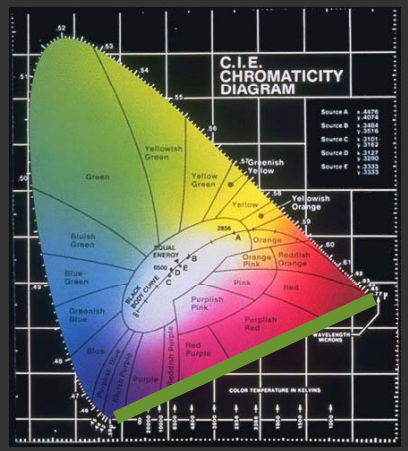

Courtesy of PhotoResearch, Inc.

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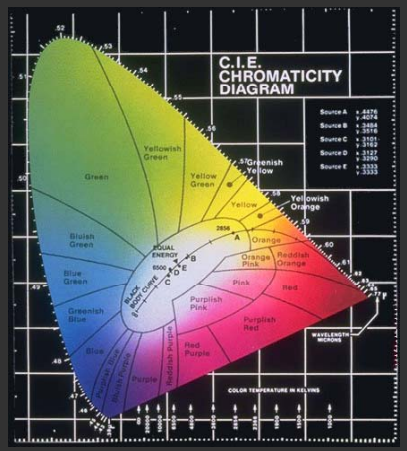
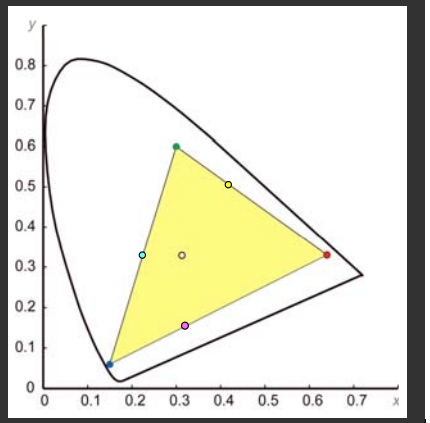


Courtesy of PhotoResearch, Inc.

RGB chromaticity

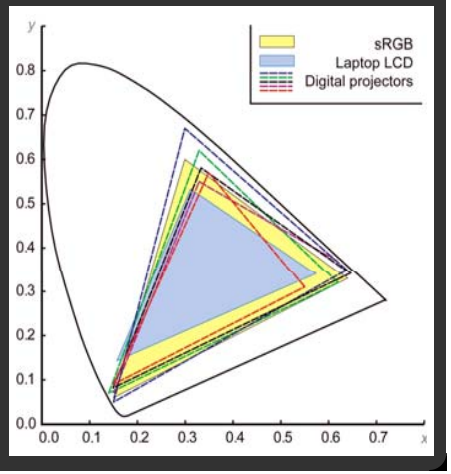
Display gamut

- Convex regions defined by RGB colorants

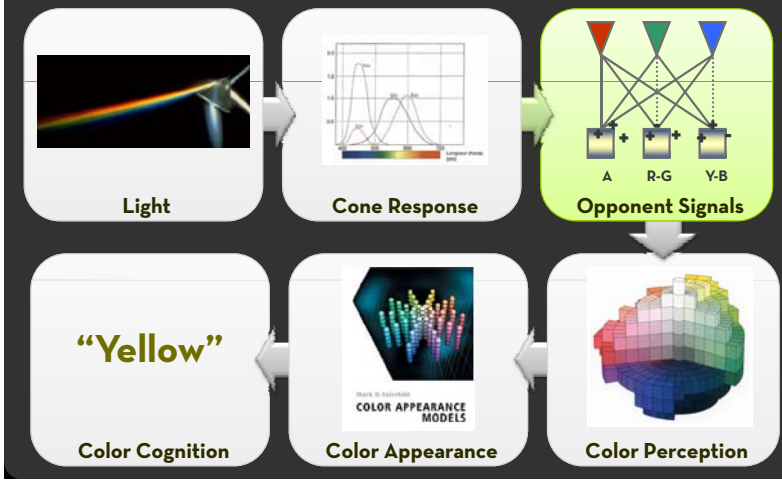


Display gamuts

Deviation from sRGB specification



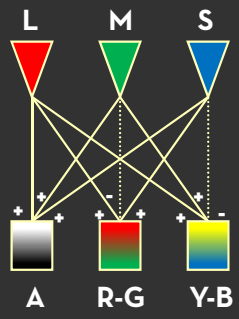
Perception of Color



Opponent processing

LMS are recombined to create

- Lightness
- Red-green contrast
- Yellow-blue contrast



Fairchild

Opponent processing

LMS are recombined to create

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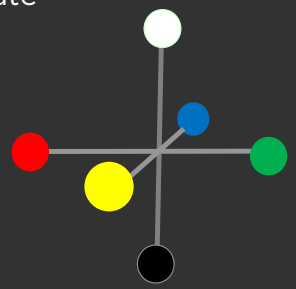
- Yellow-blue contrast



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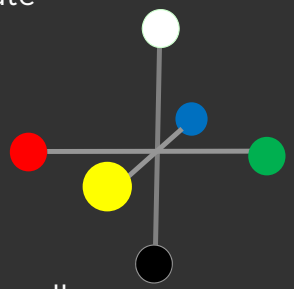


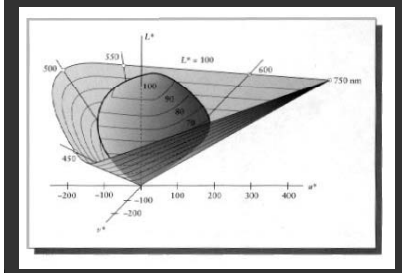
Experiments

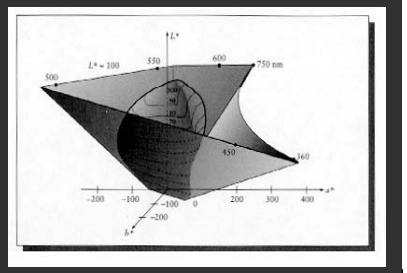
- No reddish green, or bluish yellow
- Color after images

CIE LAB and LUV color spaces

Standardized in 1976 to mathematically represent opponent processing theory.

- Non-linear function of CIE XYZ





Axes of CIE LAB

Correspond to opponent signals

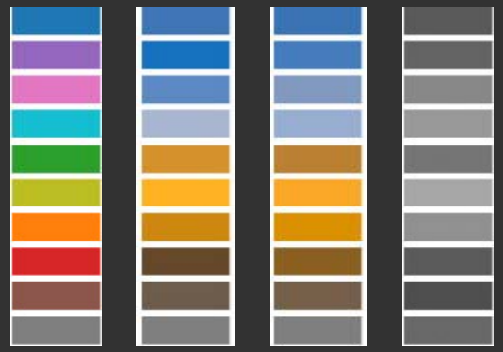
- L* = Luminance
- a* = Red-green contrast
- b* = Yellow-blue contrast

Scaling of axes to represent "color distance"

- JND = Just noticeable difference

Color blindness

Missing one or more retina cones or rods

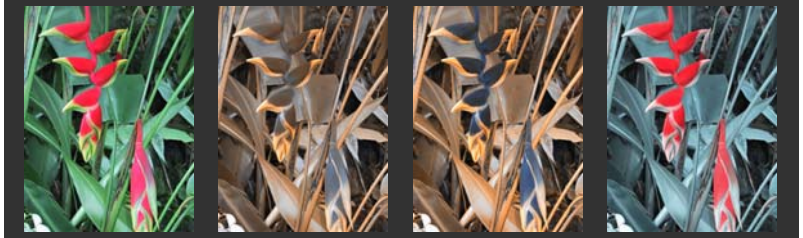


Protanope Deuteranope Luminance

VisCheck

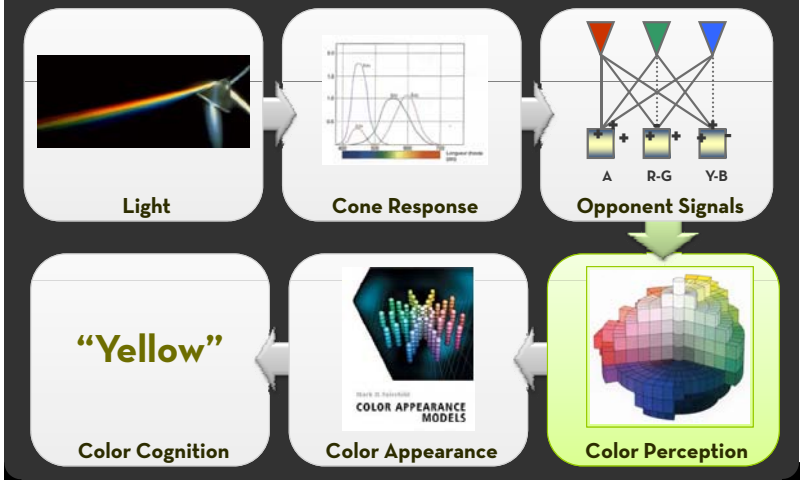
Simulates color vision deficiencies

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



Deuteranope Protanope Tritanope

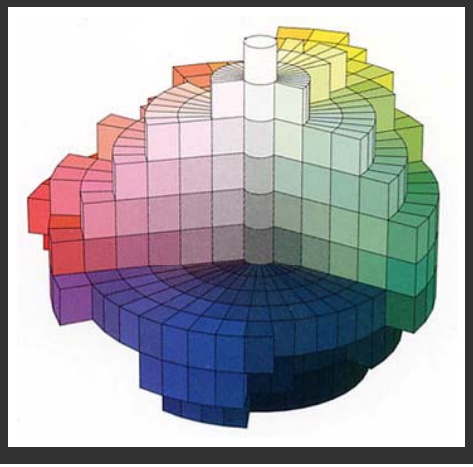
Perception of Color



Albert Munsell

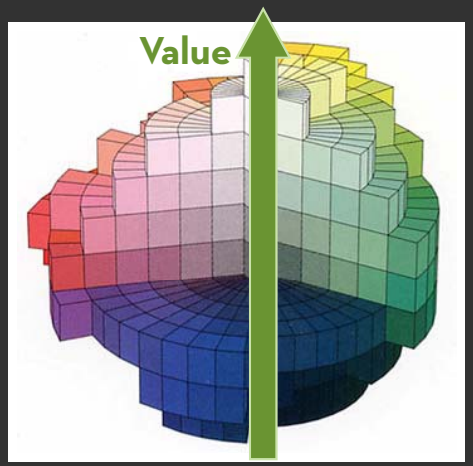
Developed the first perceptual color system based on his experience as an artist (1905).

Hue, Value, Chroma

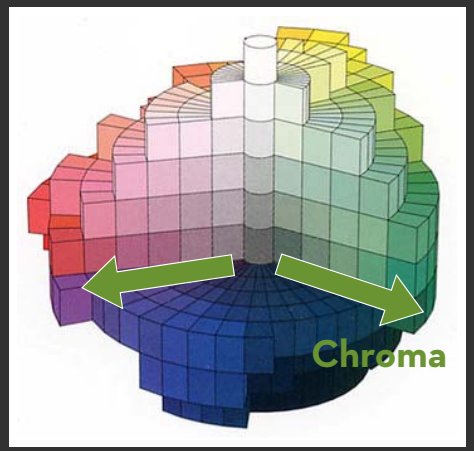


Hue, Value, Chroma

Hue, Value, Chroma



Hue, Value, Chroma



Munsell color system

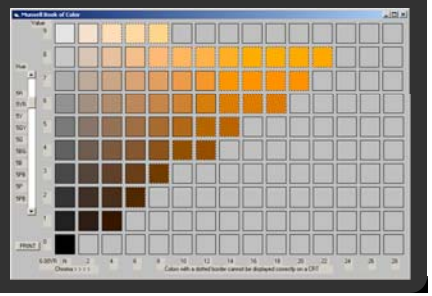
Munsell color system

Perceptually-based

Precisely reference a color

Intuitive dimensions

Look-up table (LUT)



Perceptual brightness

Color palette

Luminance Y
(CIE XYZ)

Perceptual brightness

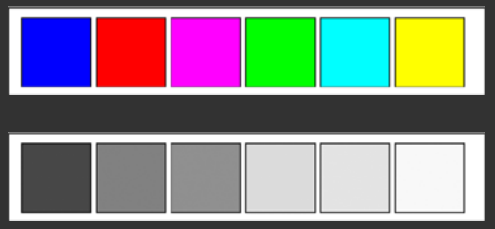
Color palette

HLS
(Photoshop)

Perceptual brightness

Color palette

Munsell Value



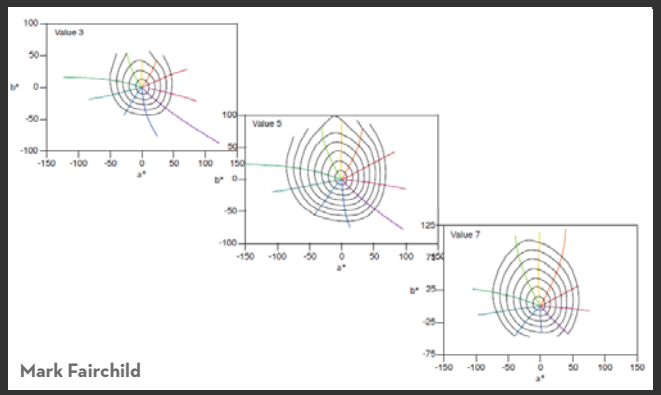
Perceptual brightness

Color palette

Munsell Value
L* (CIE LAB)

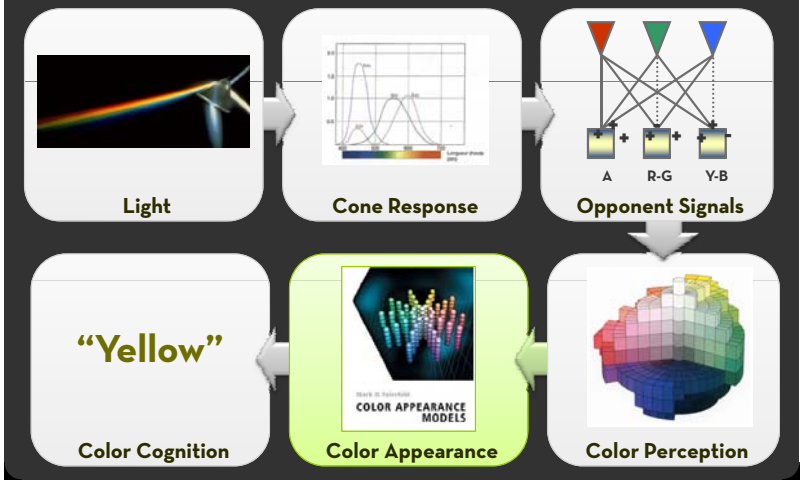
Perceptually-uniform color space

- Munsell colors in CIE LAB coordinates



Mark Fairchild

Perception of Color

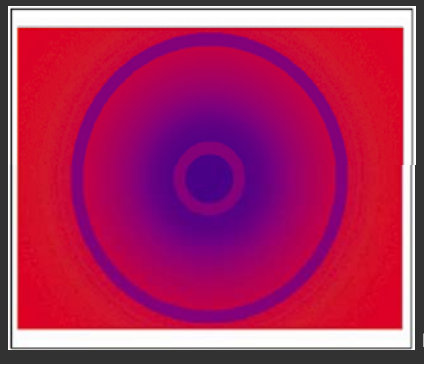


Color appearance

If we had a perceptually-uniform color space, can we predict how we perceive colors?

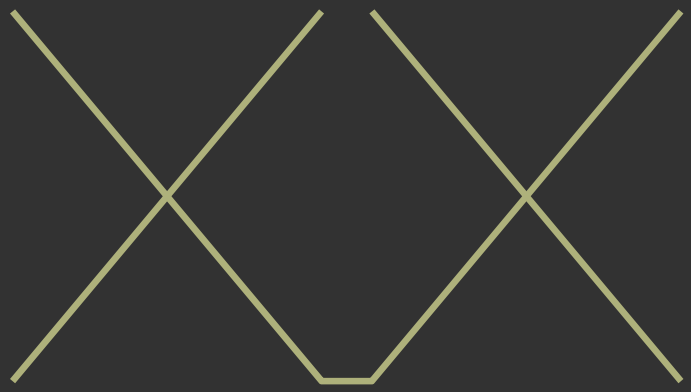
Simultaneous contrast

The inner and outer thin rings are in fact the same physical purple.



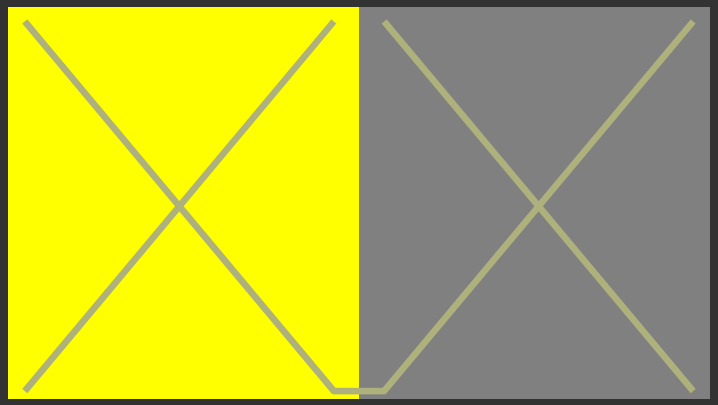
Donald MacLeod

Simultaneous contrast



Josef Albers

Simultaneous contrast

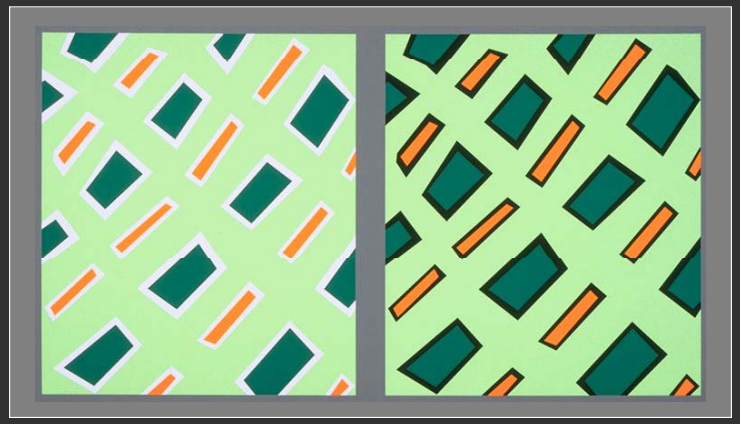


Josef Albers

Chromatic adaptation

Chromatic adaptation

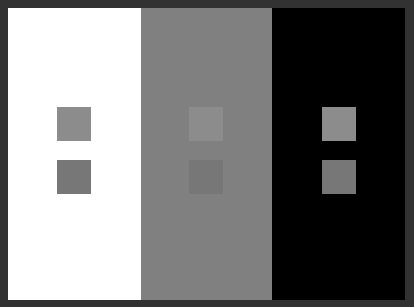
Bezold effect



Color Appearance Tutorial by Maureen Stone

Crispening

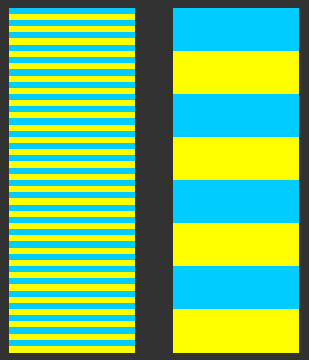
- Perceived difference depends on background



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 appearance

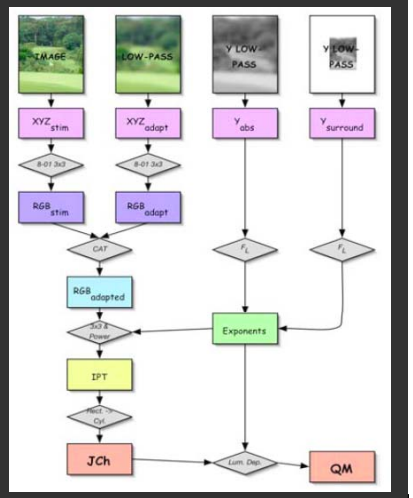
If we had a perceptually-uniform color space, can we predict how we perceive colors?

- Chromatic adaptation
- Luminance adaptation
- Simultaneous contrast
- Spatial effects
- Viewing angle

Meet iCAM

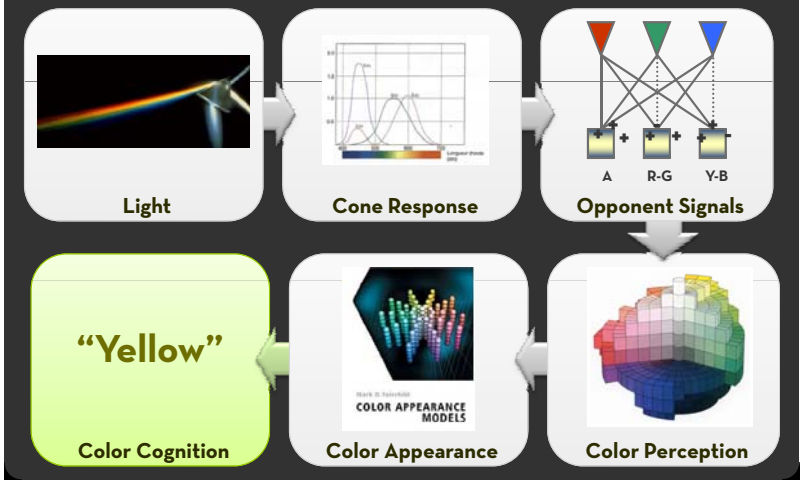
iCAM models (2002)

- Chromatic adaptation
- Appearance scales
- Color difference
- Crispening
- Spreading
- HDR tone mapping



Mark Fairchild

Perception of Color



Basic color terms

Chance discovery by Brent Berlin and Paul Kay.

Basic color terms

Chance discovery by Brent Berlin and Paul Kay.

Basic color terms

Chance discovery by Brent Berlin and Paul Kay

Initial study in 1969

- Surveyed speakers from 20 languages
- Literature from 69 languages

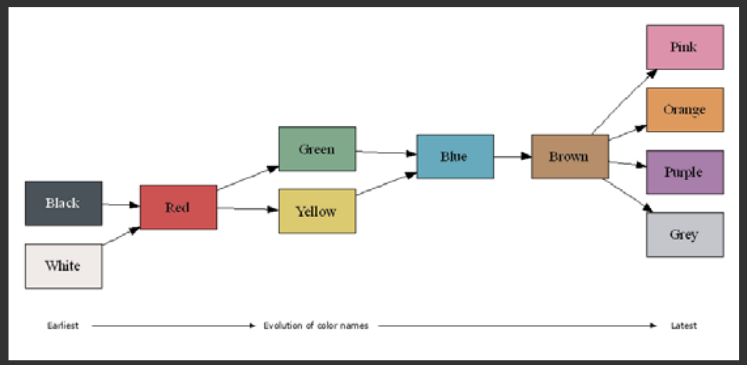
Universality of BCT

Basic color terms are universal across languages.

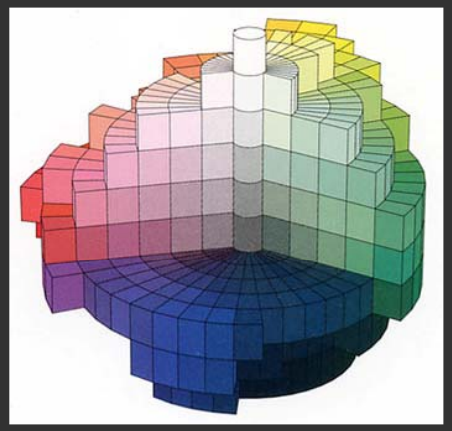
White	Red	Pink
Grey	Yellow	Brown
Black	Green	Orange
	Blue	Purple

Evolution of BCT

Universal evolution model across languages.



World color survey



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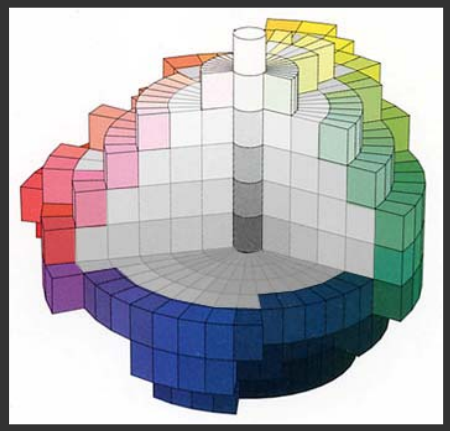
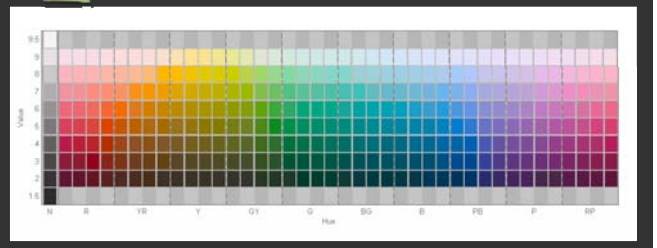
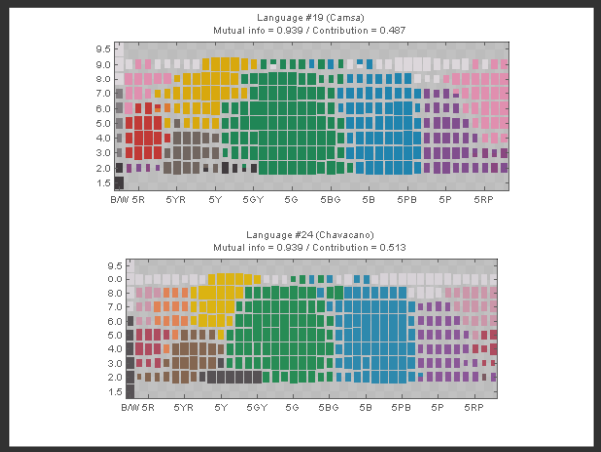


World color survey

Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



Results from WCS



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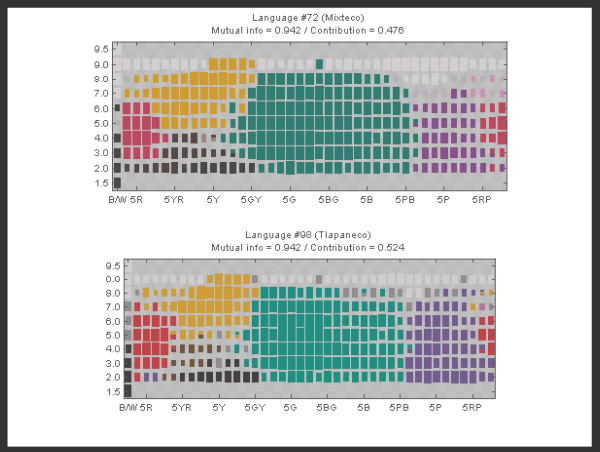
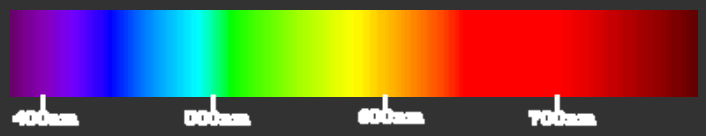


Rainbow color ramp

We associate and group colors together, often the name we assign to the colors.



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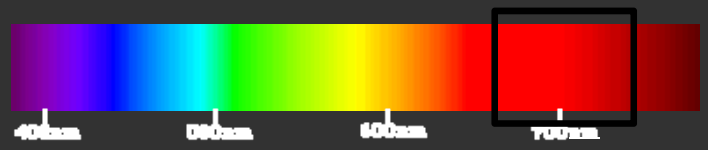
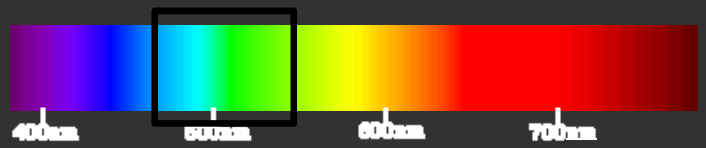


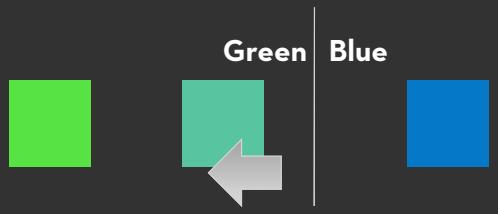
Rainbow color ramp

We associate and group colors together, often the name we assign to the colors.

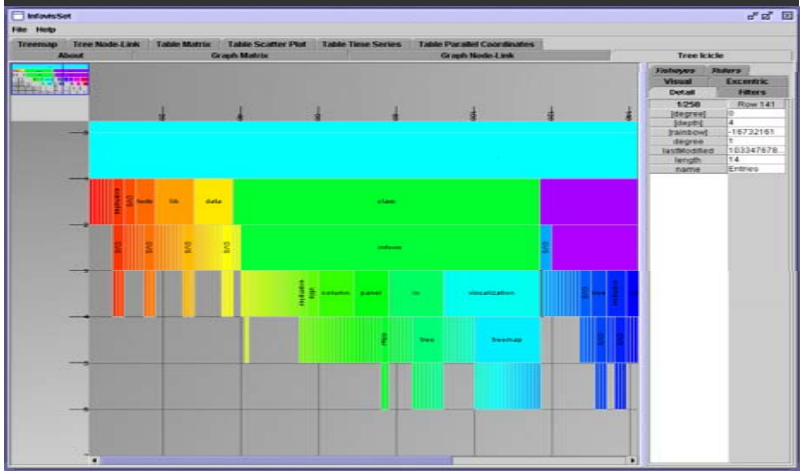


Naming affects color perception

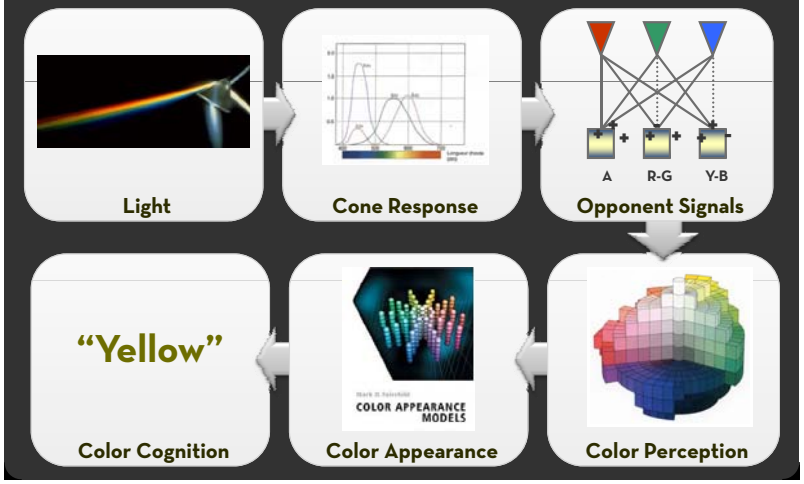
- Color name boundaries



Icicle tree with colors



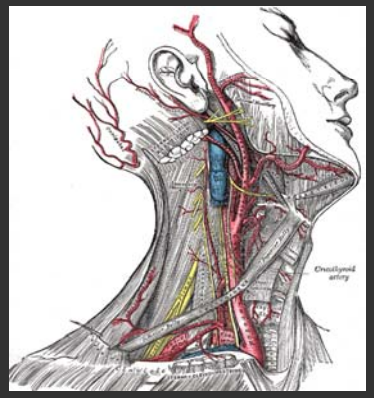
Perception of Color



Color in Information Visualization

Categorical Color

Gray's anatomy

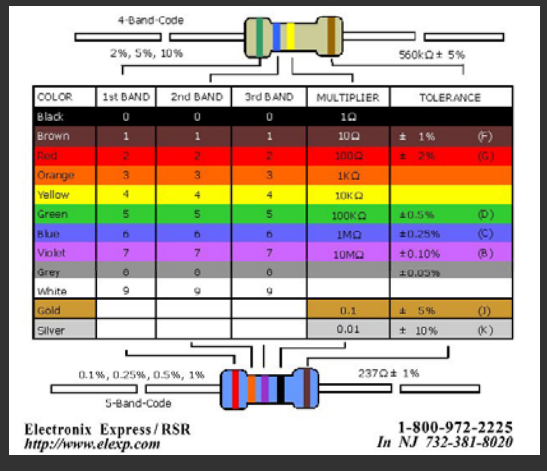


Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)

Molecular models

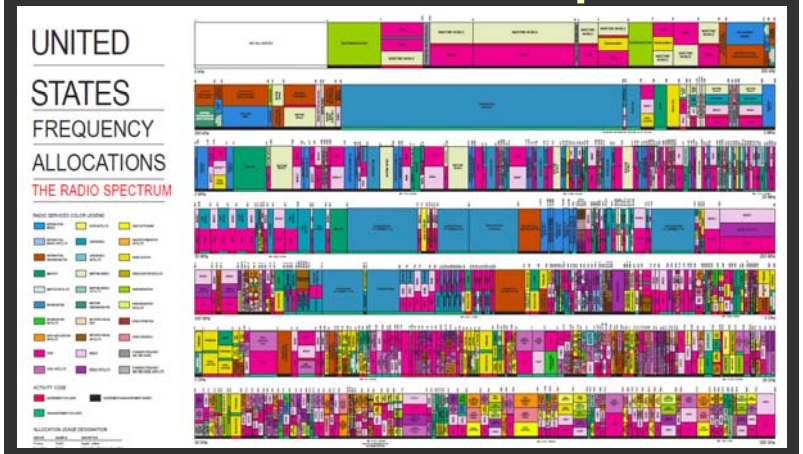
Organic Chemistry Molecular Model Set
http://www.indigo.com/models/gphmodel/62003.html

Resistor color codes



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE	
Black	0	0	0	1Ω		
Brown	1	1	1	10Ω	± 1%	(F)
Red	2	2	2	100Ω	± 2%	(G)
Orange	3	3	3	1KΩ		
Yellow	4	4	4	10KΩ		
Green	5	5	5	100KΩ	±0.5%	(D)
Blue	6	6	6	1MΩ	±0.25%	(C)
Violet	7	7	7	10MΩ	±0.10%	(B)
Grey	8	8	8		±0.05%	
White	9	9	9			
Gold				0.1	± 5%	(J)
Silver				0.01	± 10%	(K)

Allocation of the radio spectrum



http://www.ntia.doc.gov/osmhome/allochrt.html

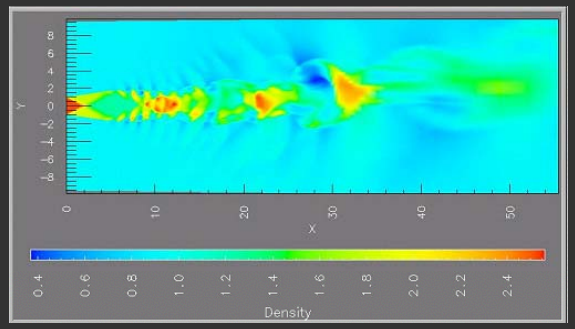
Hints for the colorist

Use only a few colors (~6 ideal)
Colors should be distinctive and named
Strive for color harmony (natural colors)
Use cultural conventions; appreciate symbolism
Beware of bad interactions (red/blue etc.)
Get it right in black and white
Respect the color blind

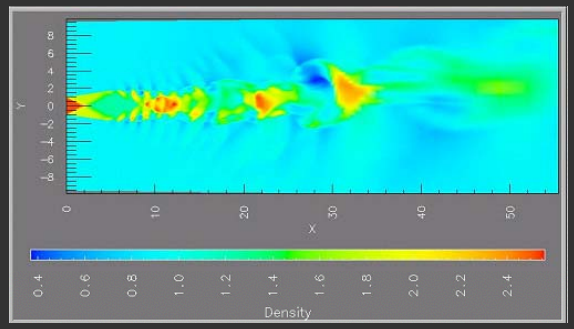
Color in Information Visualization

Color sequences

Default rainbow maps

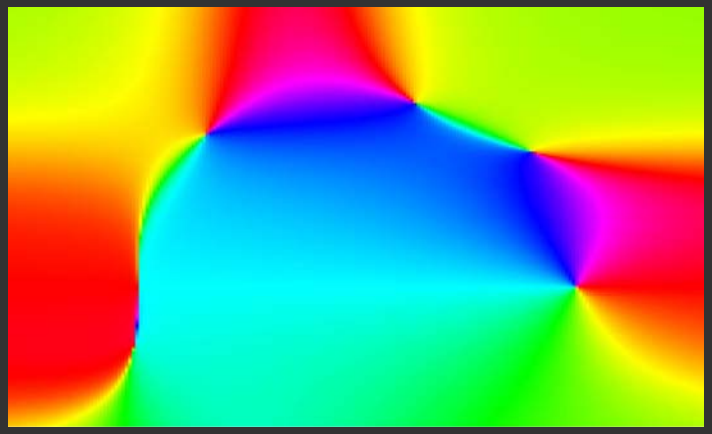


Default rainbow maps



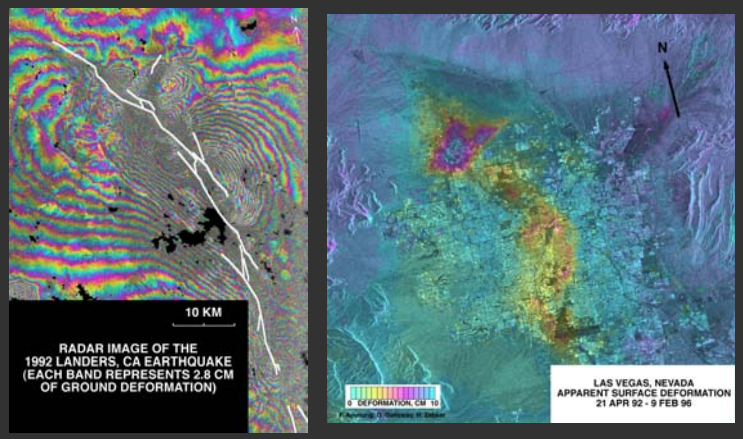
1. People segment colors into classes
2. Hues are not naturally ordered
3. Different lightness emphasizes certain scalar values
4. Low luminance colors (blue) hide high frequencies

Singularity in Phase (M. Berry)



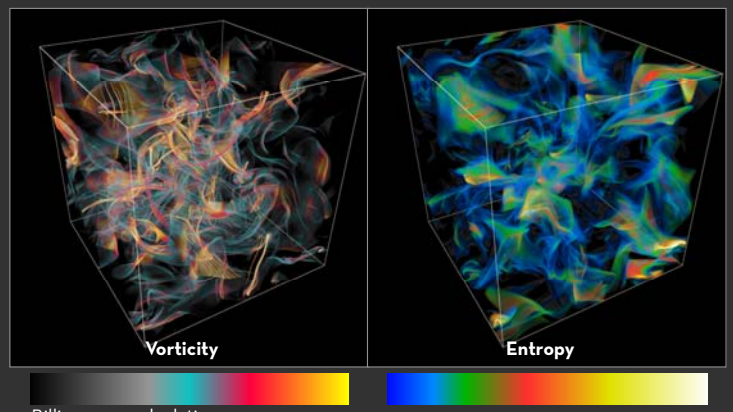
Phase is periodic ⇒ Hue circle which is also periodic

Radar interferogram



From Howard Zebker

Compressible turbulence



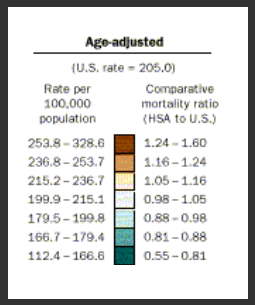
Billion zone calculation

http://www.lcse.umn.edu/research/lanlrun/imagery.html

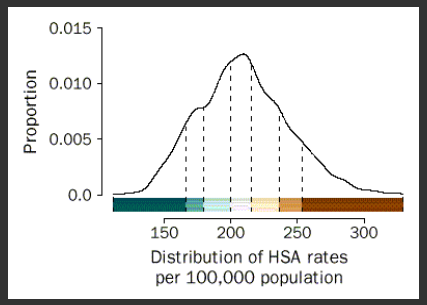
Color in Information Visualization

ColorBrewer

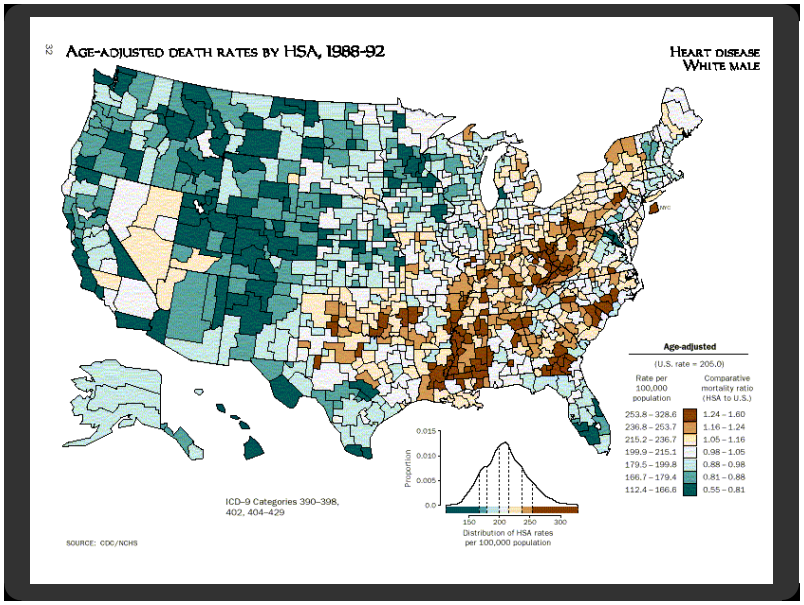
Classing quantitative data



Age-adjusted (U.S. rate = 205.0) Rate per 100,000 population	Comparative mortality ratio (HSA to U.S.)
253.8 – 328.6	1.24 – 1.60
236.8 – 253.7	1.16 – 1.24
215.2 – 236.7	1.05 – 1.16
199.9 – 215.1	0.98 – 1.05
179.5 – 199.8	0.88 – 0.98
166.7 – 179.4	0.81 – 0.88
112.4 – 166.6	0.55 – 0.81



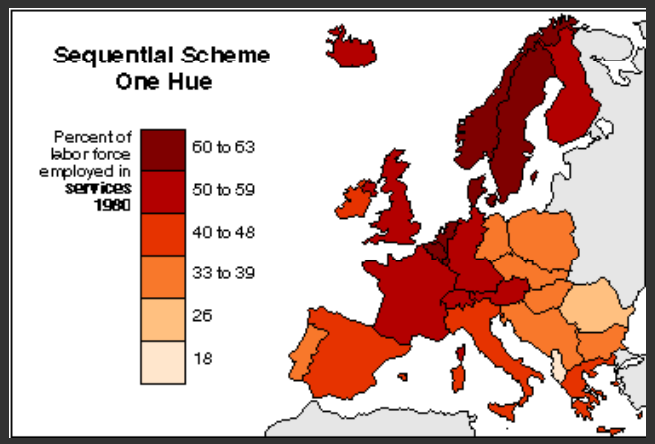
Age-adjusted mortality rates for the United States.



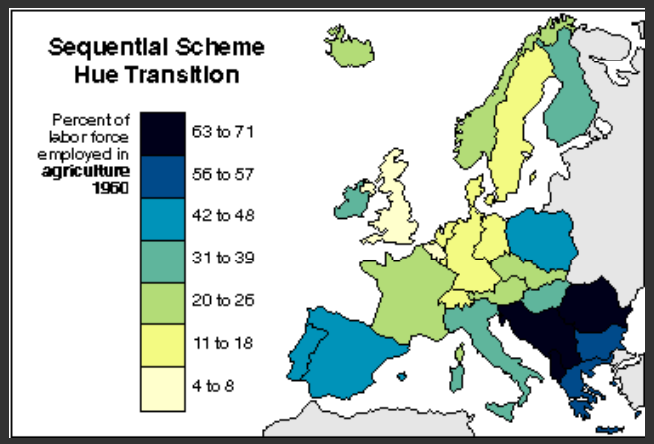
Classing quantitative data

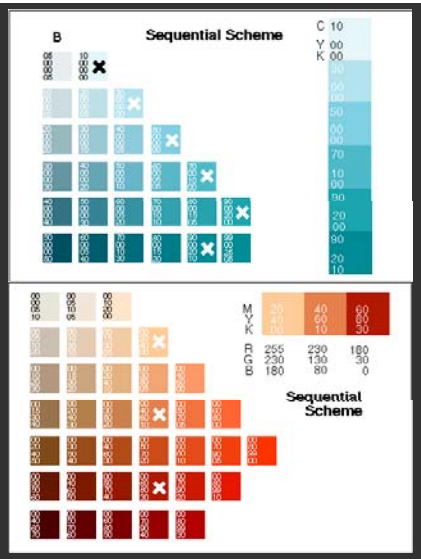
1. Equal interval (arithmetic progression)
2. Quantiles (recommended)
3. Box-plot
4. Standard deviation
5. Optimal [Jenks] (minimize error)
6. Equal area
7. Minimal length boundaries
8. Natural breaks
9. Minimal gaps

Sequential color scheme



Sequential color scheme





http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Sequential color scales

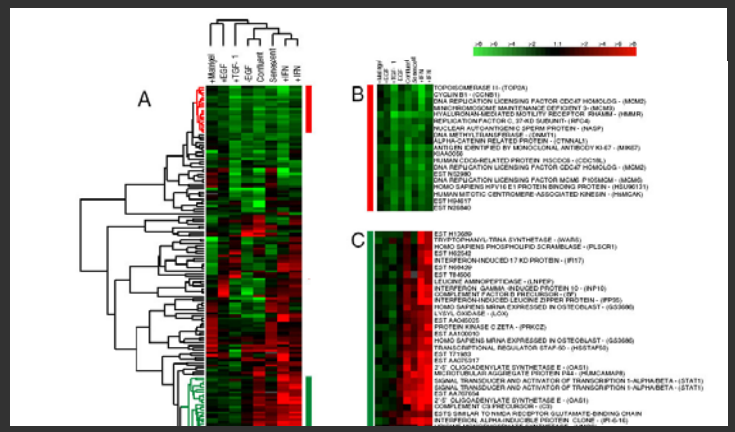
Hue-Lightness (Recommended)

- Higher values mapped to darker colors
- ColorBrewer schemes have 3-9 steps

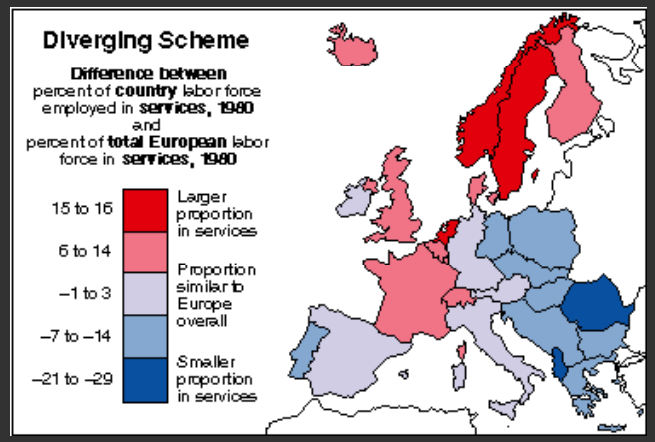
Hue Transition

- Two hues
- Neighboring hues interpolate better
- Couple with change in lightness

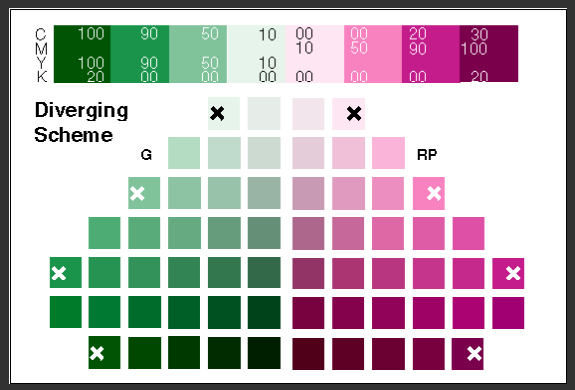
Diverging color scheme



Diverging color scheme



Diverging color scheme



http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

Diverging color scheme

Hue Transition

- Carefully handle midpoint
  - Critical class
    - Low, Average, High
    - 'Average' should be gray
  - Critical breakpoint
    - Defining value e.g. 0
    - Positive & negative should use different hues
- Extremes saturated, middle desaturated

Class Project in Color?

Automated color design

Color palettes

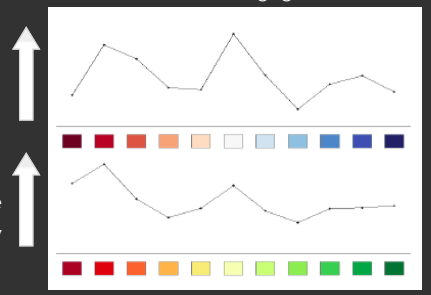
- Aesthetics & color harmony
- Well-named colors

Automated color design

Color ramps

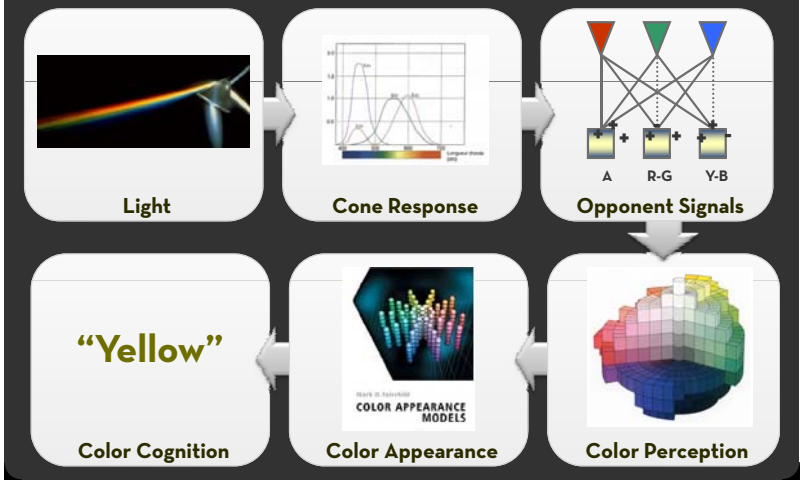
- Data with multimodal distributions?

ColorBrewer diverging schemes



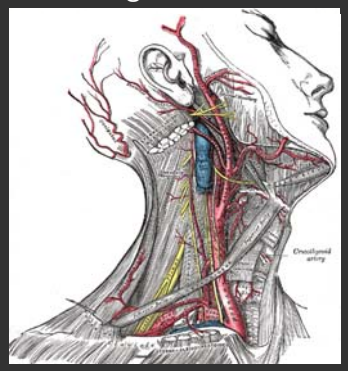
Color name saliency

Perception of Color



Color in Information Visualization

Categorical color



Color sequences