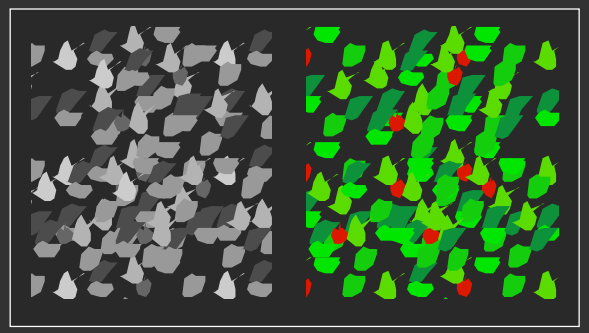
CS448B :: 1 Nov 2012

Color

Jeffrey Heer Stanford University

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."

- Edward Tufte

Topics

Perception of Color
Light, Visual system, Mental models

Color in Information Visualization
Nominal, Ordinal & Quantitative color encoding
Guidelines for color palette design

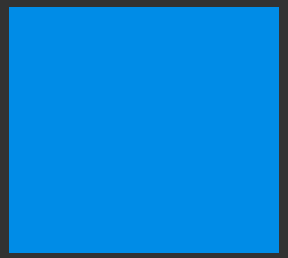
Perception of Color

What color is this?

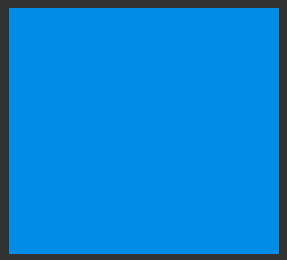
What color is this?

"Yellow"

What color is this?

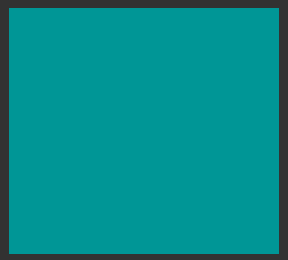


What color is this?

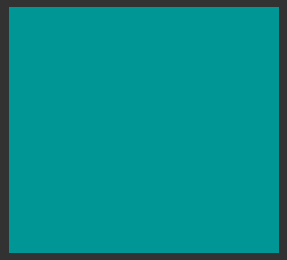


"Blue"

What color is this?

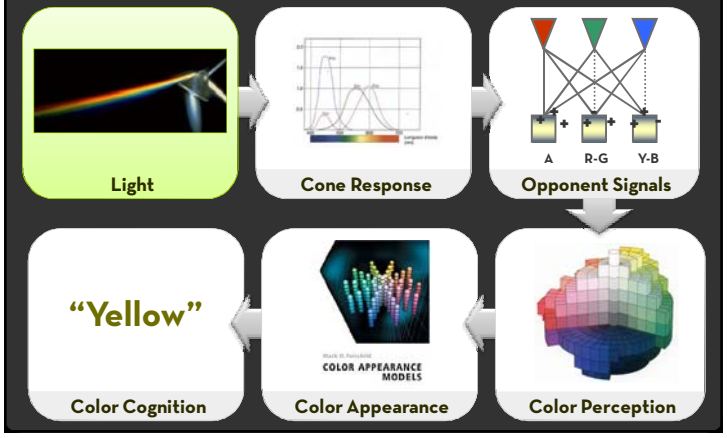


What color is this?



"Teal" ?

Perception of Color



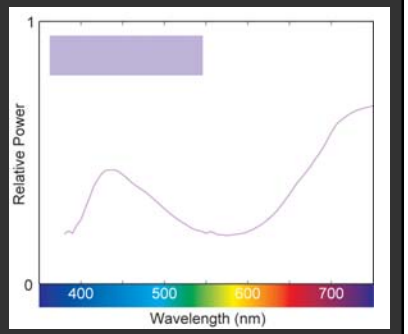
Physicist's view

Light as electromagnetic wave

Wavelength

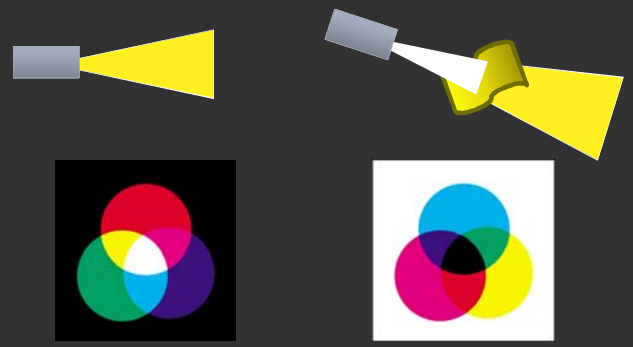
Energy or

"Relative luminance"



A Field Guide to Digital Color, A.K. Peters

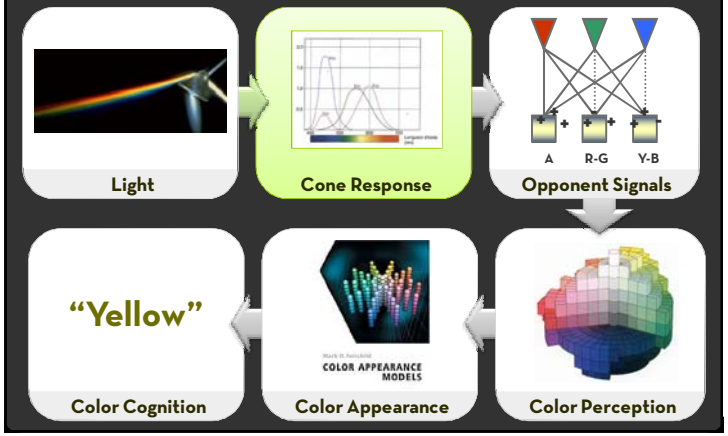
Emissive vs. reflective light



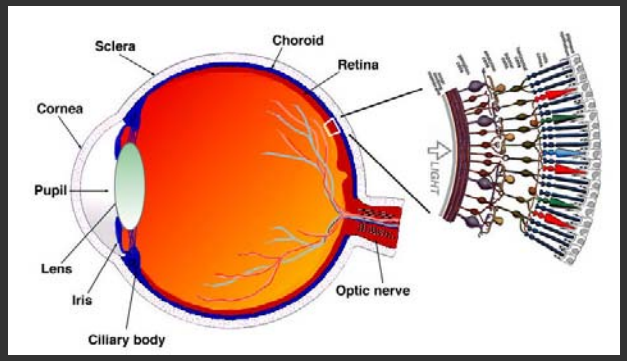
Additive (digital displays)

Subtractive (print, e-paper)

Perception of Color



Retina

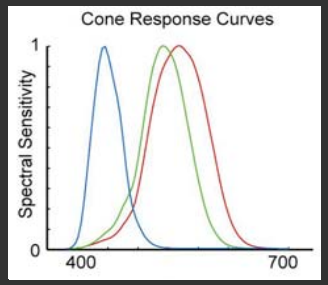


Simple Anatomy of the Retina, Helga Kolb

As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength



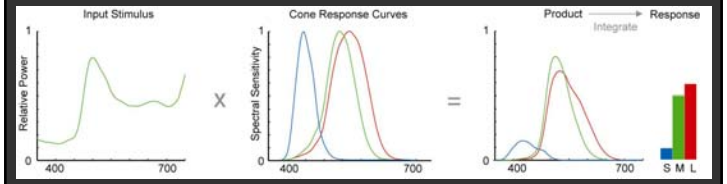
A Field Guide to Digital Color, Maureen Stone

As light enters our retina...

LMS (Long, Middle, Short) Cones

Sensitive to different wavelength

Integration with input stimulus



A Field Guide to Digital Color, Maureen Stone

Effects of retina encoding

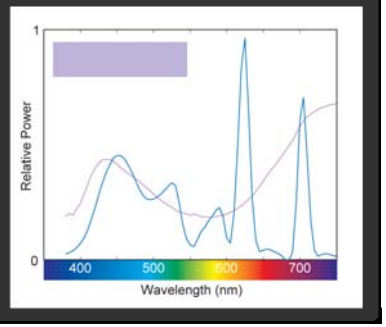
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

"Tri-stimulus"

Computer displays

Digital scanners

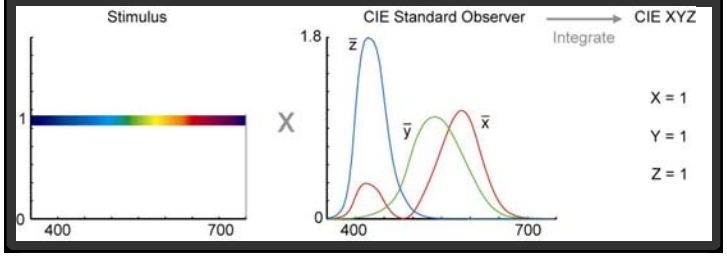
Digital cameras



CIE XYZ color space

Standardized in 1931 to mathematically represent tri-stimulus response.

"Standard observer" response curves



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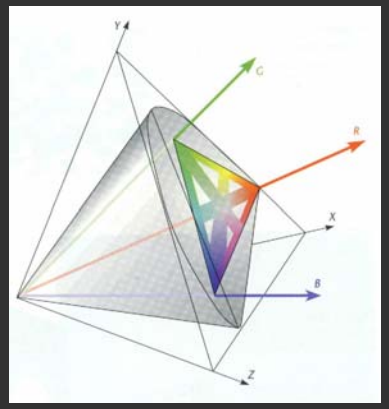


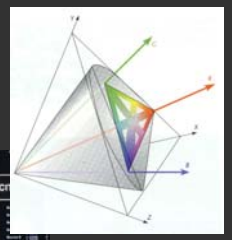
Colin Ware

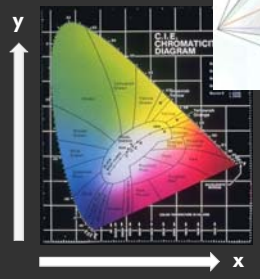
CIE chromaticity diagram

Colorfulness vs. Brightness

x = X/(X+Y+Z)

y = Y/(X+Y+Z)





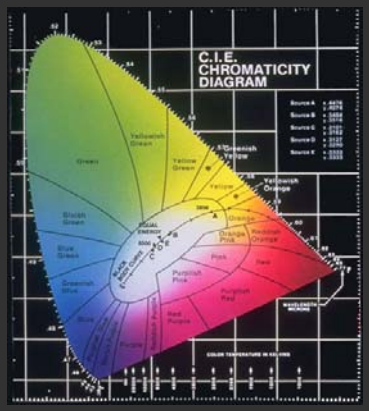
Colin Ware

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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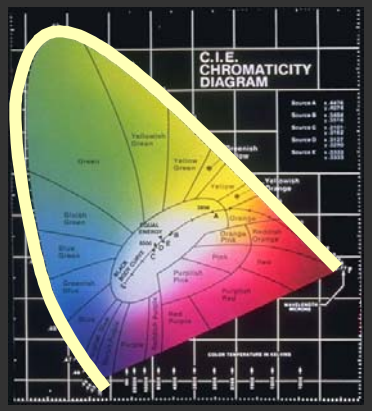

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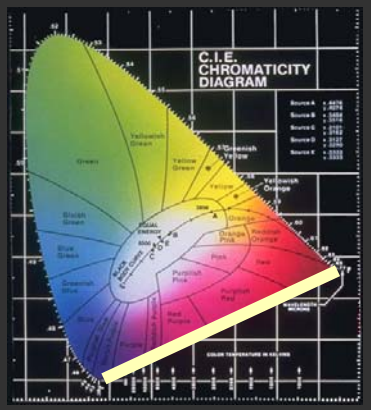

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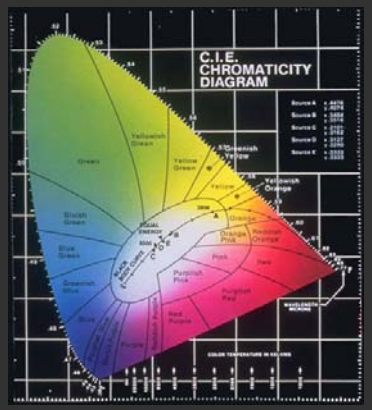


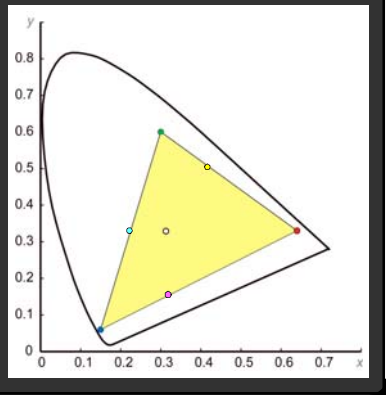
Courtesy of PhotoResearch, Inc.

Display gamuts

Typically defined by:

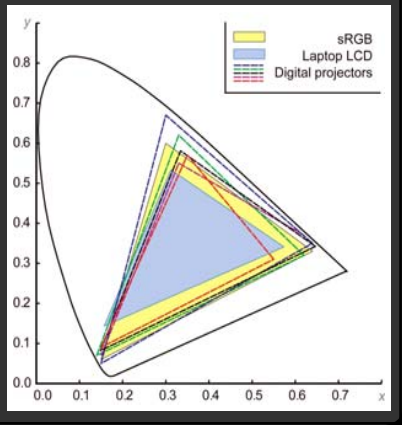
3 Colorants

Convex region



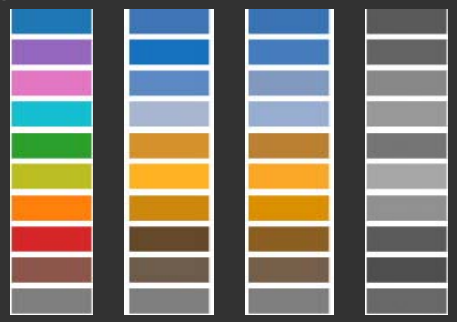
Display gamuts

Deviations from sRGB specification



Color blindness

Missing one or more retina cones or rods

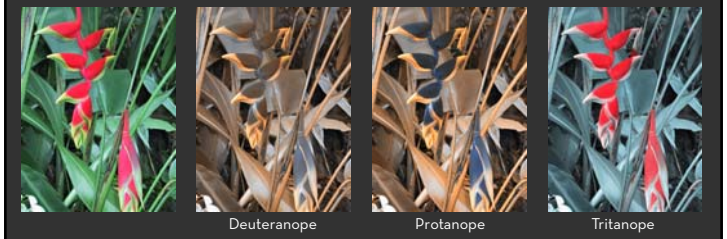


VisCheck

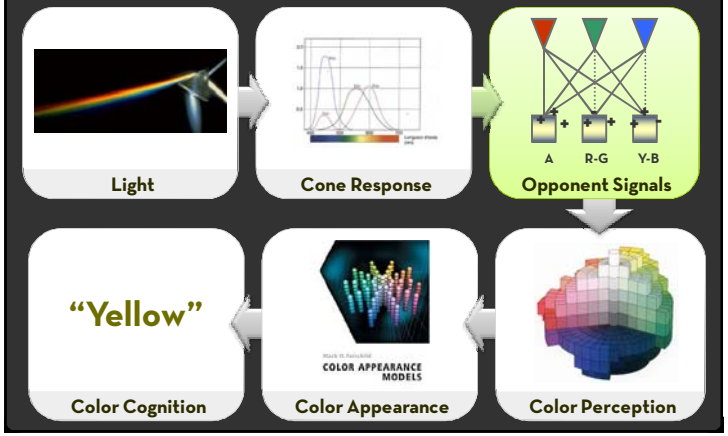
Simulates color vision deficiencies

Web service or Photoshop plug-in

Robert Dougherty and Alex Wade



Perception of Color



Primary colors?

To paint "all colors":

Leonardo da Vinci, circa 1500 described in his notebooks a list of simple colors...

Yellow

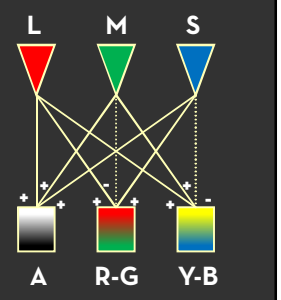
Blue

Green

Red

Opponent processing

LMS are combined to create:
Lightness
Red-green contrast
Yellow-blue contrast



Fairchild

Opponent processing

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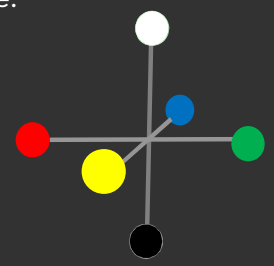

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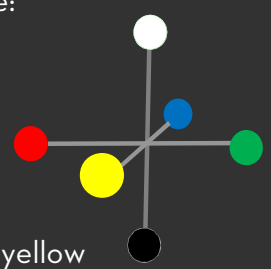
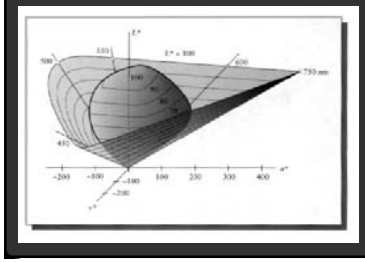


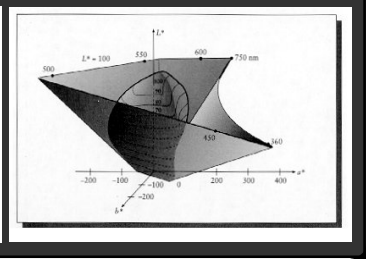
Experiments:
No reddish green, no bluish yellow
Color after images

CIE LAB and LUV color spaces

Standardized in 1976 to mathematically represent opponent processing theory.

Non-linear transformation of CIE XYZ





Axes of CIE LAB

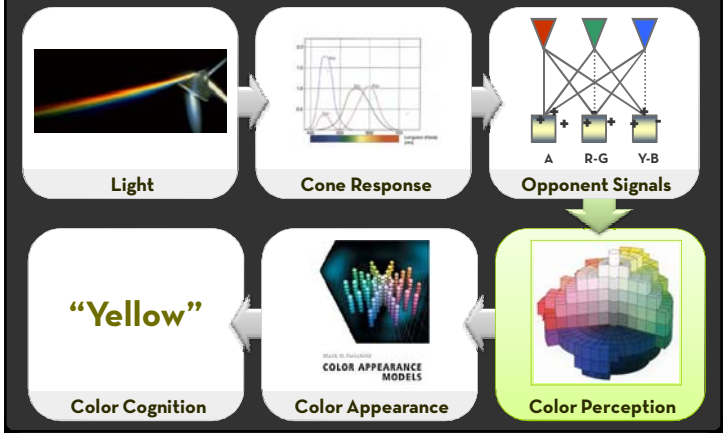
Correspond to opponent signals

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

Scaling of axes to represent "color distance"

JND = Just noticeable difference (~2.3 units)

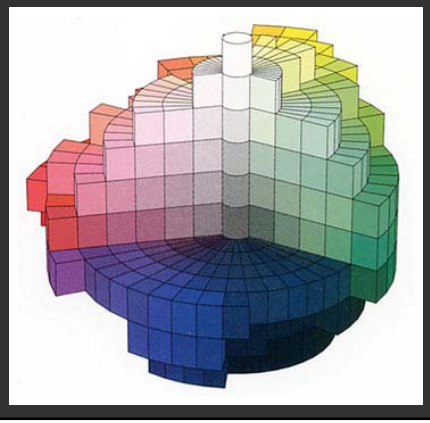
Perception of Color



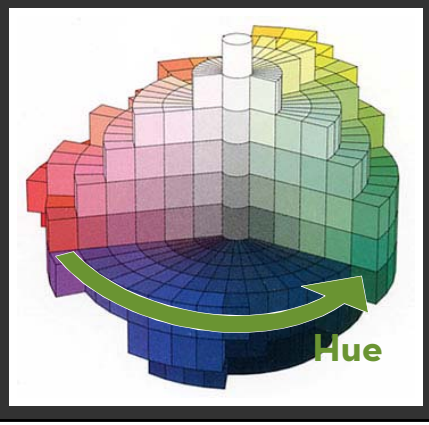
Albert Munsell

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

Hue, Value, Chroma



Hue, Value, Chroma



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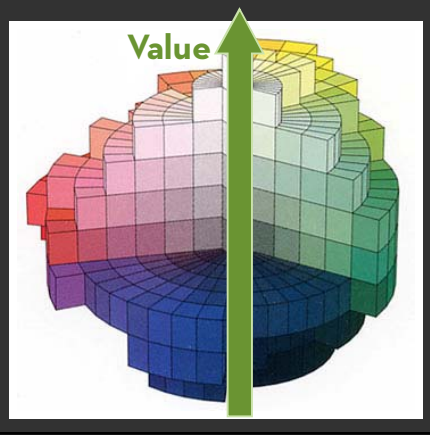

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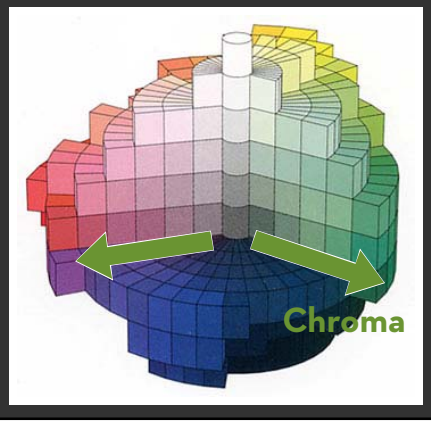
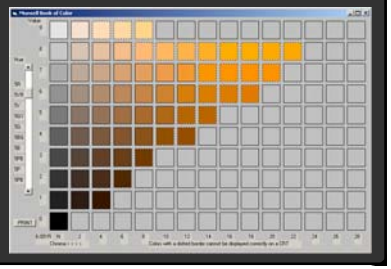
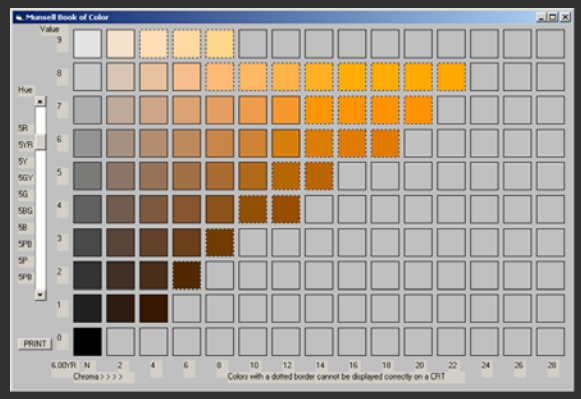


Munsell color system

Perceptually-based
Precisely reference a color
Intuitive dimensions
Look-up table (LUT)



Munsell color system



Perceptual brightness

Color palette

HSL Lightness
(Photoshop)

Perceptual brightness

Color palette

Luminance Y
(CIE XYZ)

Perceptual brightness

Color palette

Munsell Value

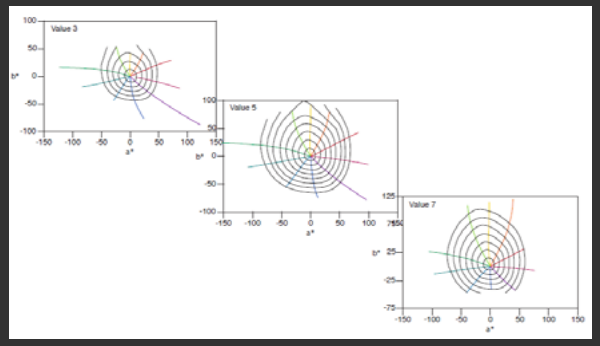
Perceptual brightness

Color palette

Munsell Value
L* (CIE LAB)

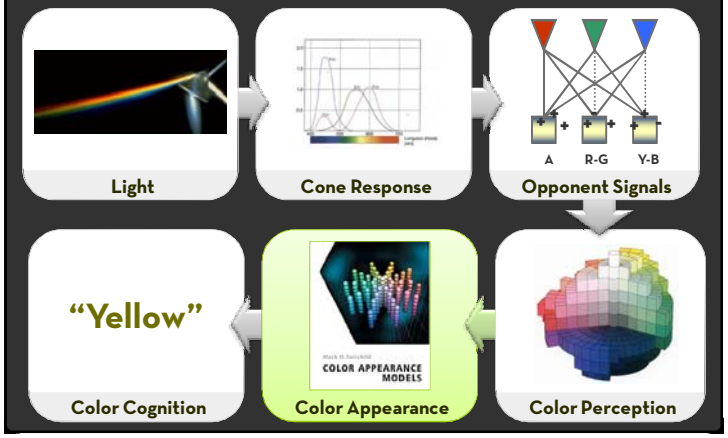
Perceptually-uniform color space

Munsell colors in CIE LAB coordinates



Mark Fairchild

Perception of Color

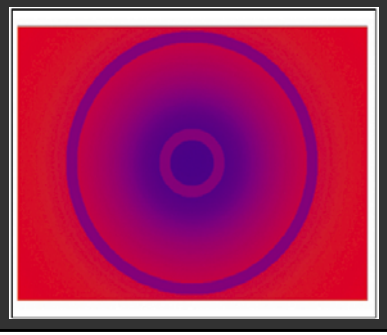


Color Appearance

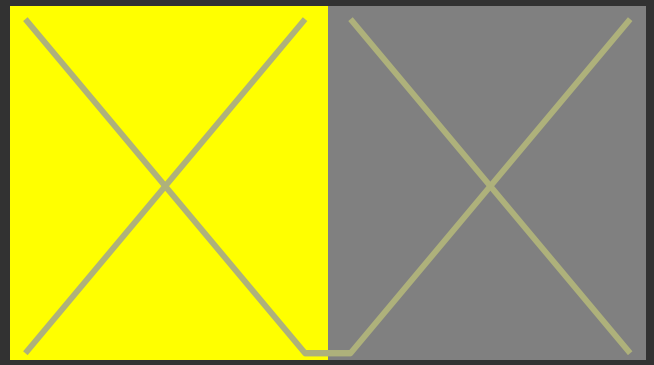
If we had a perceptually-uniform color space, can we predict how we perceive colors?

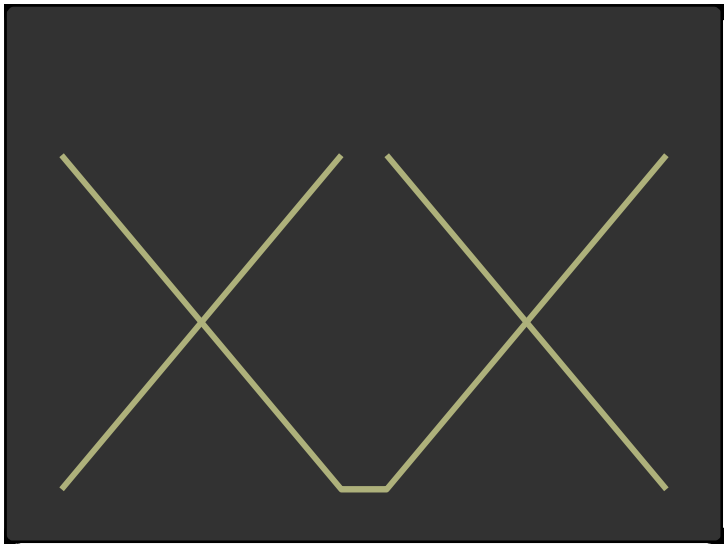
Simultaneous Contrast

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

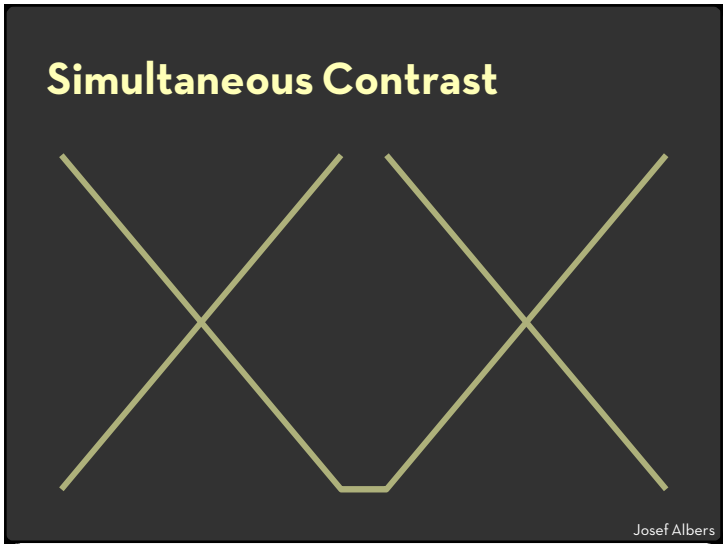


Donald MacLeod



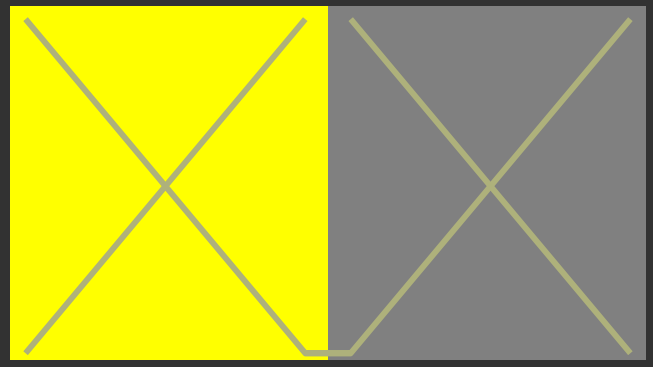


Simultaneous Contrast



Josef Albers

Simultaneous Contrast



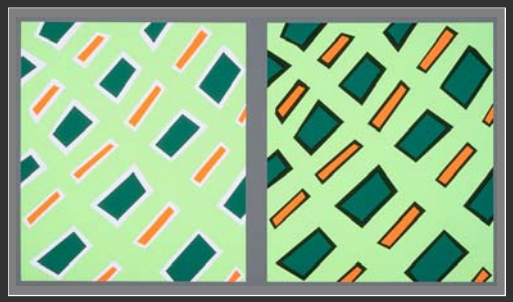
Josef Albers

Chromatic Adaptation

Chromatic Adaptation

Bezold effect

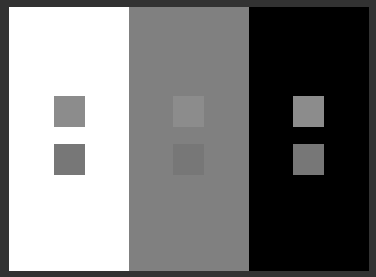
Color appearance depends adjacent colors



Color Appearance Tutorial by Maureen Stone

Crispening

Perceived difference depends on background

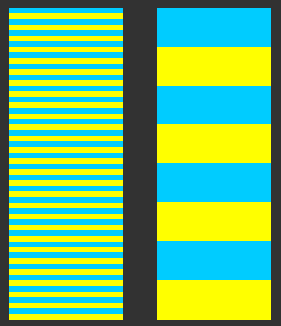


Color Appearance Models, Fairchild

Spreading

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

Adjacent colors blend



Foundations of Vision, Brian Wandell

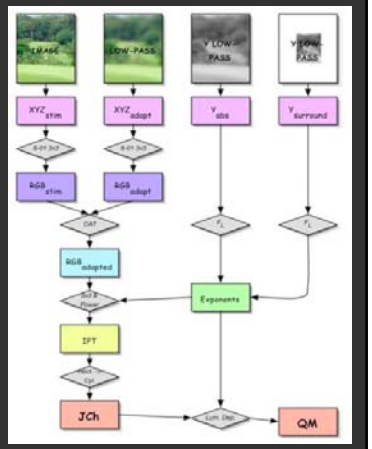
Color Appearance

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

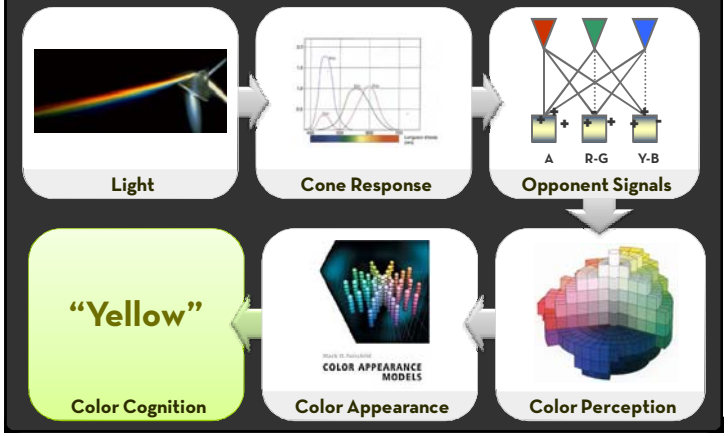
iCAM

iCAM models (2002)
Chromatic adaptation
Appearance scales
Color difference
Crispening
Spreading
HDR tone mapping
(see also CIECAM02)



Mark Fairchild

Perception of Color



Colors according to XKCD...

Basic color terms

Chance discovery by Brent Berlin and Paul Kay.

Basic color terms

Chance discovery by Brent Berlin and Paul Kay.

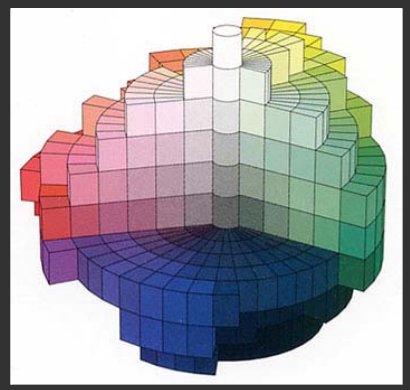
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay

Initial study in 1969

- Surveyed speakers from 20 languages
- Literature from 69 languages

World color survey



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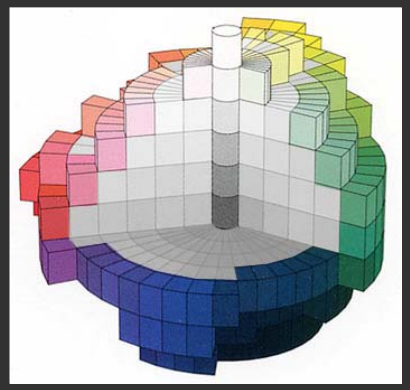
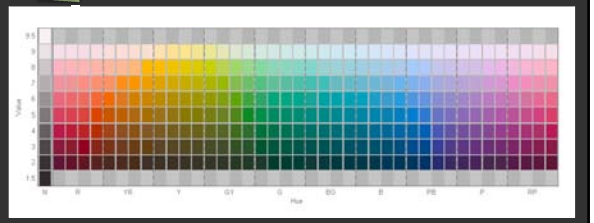
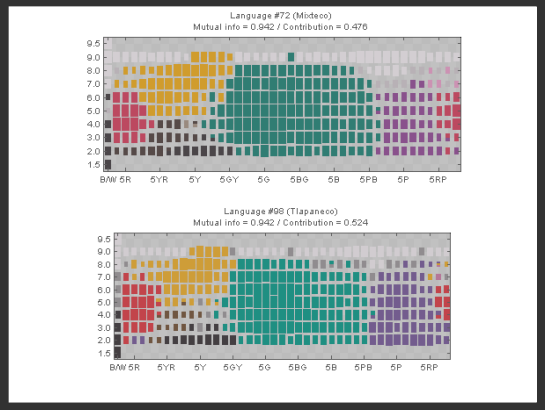


World color survey

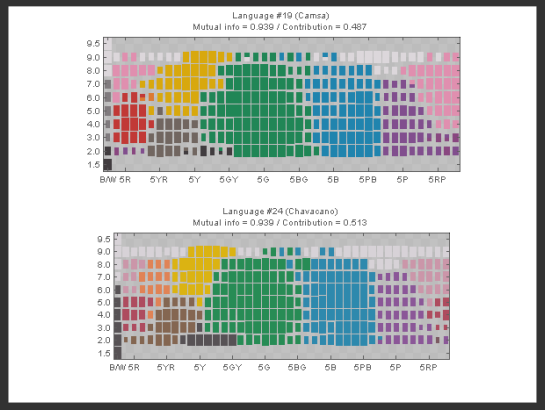
Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



Results from WCS



Results from WCS



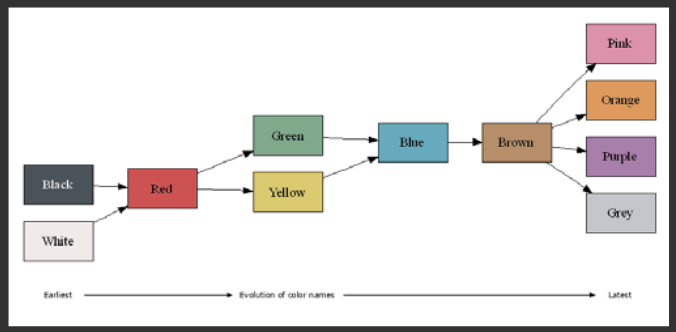
Universal (?) Basic Color Terms

Basic color terms recur across languages.

White	Red	Pink
Grey	Yellow	Brown
Black	Green	Orange
	Blue	Purple

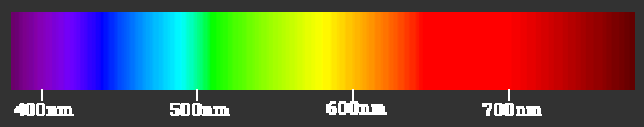
Evolution of Basic Color Terms

Proposed universal evolution across languages.



Rainbow color ramp

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



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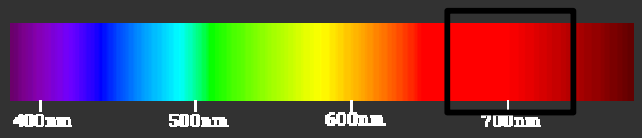

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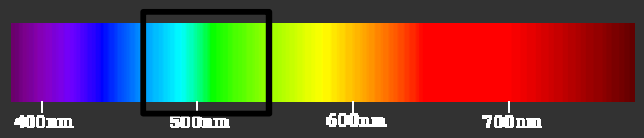
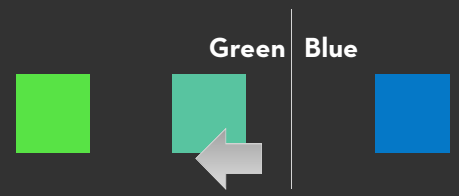


Naming affects color perception

Color name boundaries



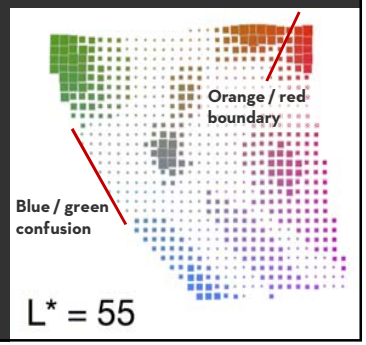
Color naming models [Chuang et al., Heer & Stone]

Model 3 million responses from XKCD survey

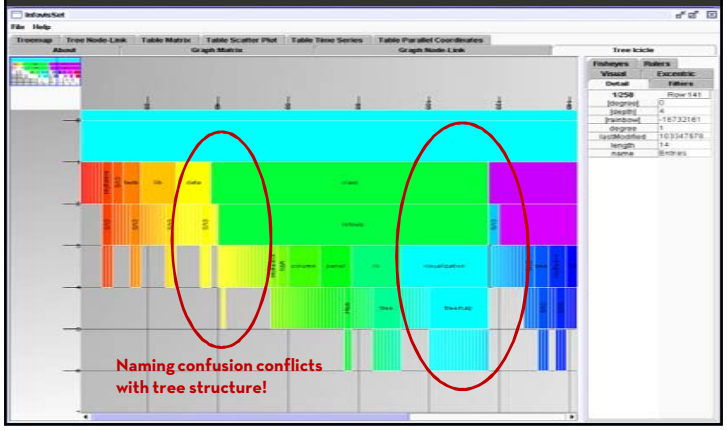
Bins in LAB space sized by *saliency*:

How much do people agree on color name?

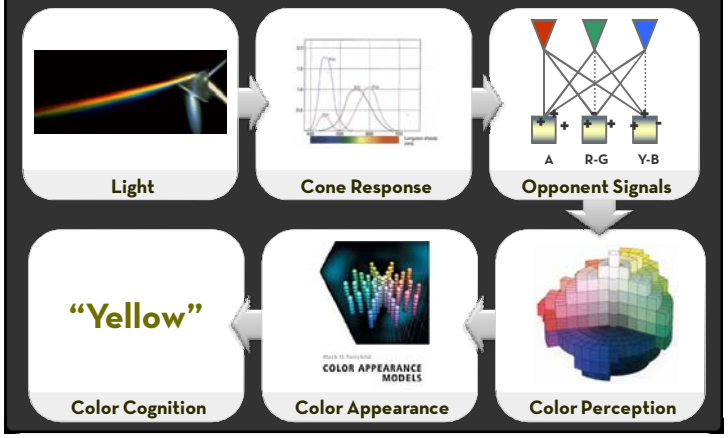
Modeled by entropy of *p(name | color)*



Icicle tree with colors

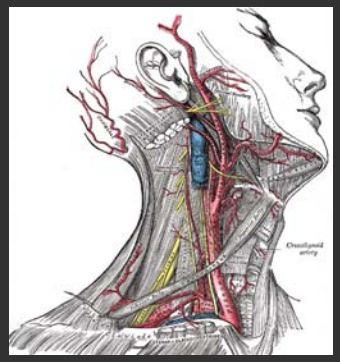


Perception of Color



Color in Information Visualization

Gray's anatomy

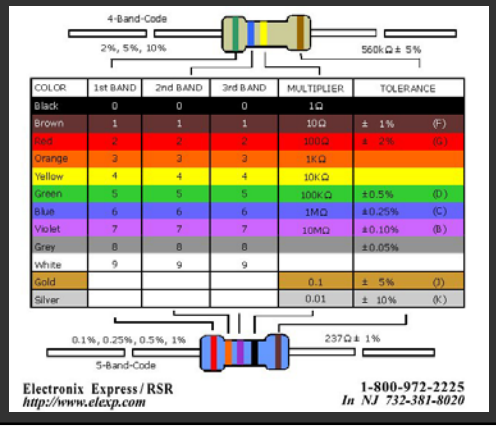


Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)

Molecular models

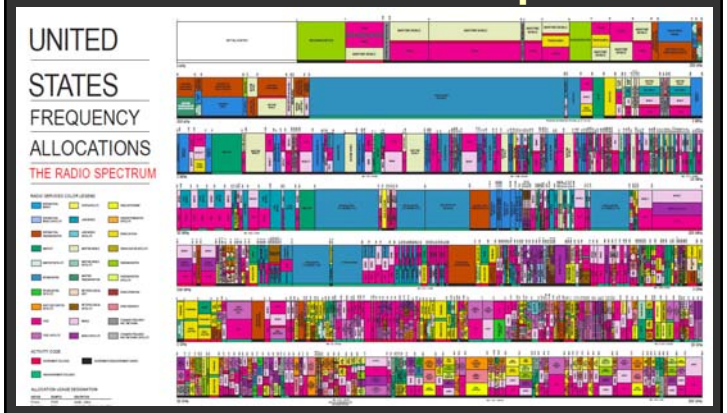
Organic Chemistry Molecular Model Set
http://www.indigo.com/models/gphmodel/62003.html

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

Allocation of the radio spectrum

Palette Design + Color Names

Minimize overlap and ambiguity of color names.

Color Name Distance										Salience	Name
0.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.20	.47	**blue** 62.9%
1.00	0.00	1.00	0.97	1.00	1.00	1.00	1.00	0.96	1.00	.90	**orange** 93.9%
1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.90	0.99	.67	**green** 79.8%
1.00	0.97	1.00	0.00	1.00	0.95	0.99	1.00	1.00	1.00	.66	**red** 80.4%
0.98	1.00	1.00	1.00	0.00	0.96	0.91	0.97	1.00	0.99	.47	**purple** 51.4%
1.00	1.00	1.00	0.95	0.96	0.00	0.97	0.93	0.98	1.00	.37	**brown** 54.0%
1.00	1.00	1.00	0.99	0.91	0.97	0.00	1.00	1.00	1.00	.58	**pink** 71.7%
1.00	1.00	1.00	1.00	0.97	0.93	1.00	0.00	1.00	1.00	.67	**grey** 79.4%
1.00	0.96	0.90	1.00	1.00	0.98	1.00	1.00	0.00	1.00	.18	**yellow** 31.2%
0.20	1.00	0.99	1.00	0.99	1.00	1.00	1.00	1.00	0.00	.25	**blue** 25.4%
Tableau-10								*Average*	*0.97*	*.52*	

http://vis.stanford.edu/color-names

Palette Design + Color Names

Minimize overlap and ambiguity of color names.

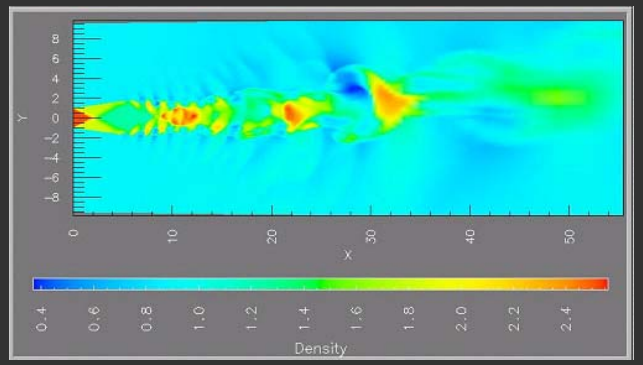
Color Name Distance										Salience	Name
0.00	1.00	1.00	0.89	0.07	1.00	0.35	0.99	1.00	0.89	.30	**blue** 50.5%
1.00	0.00	0.99	1.00	1.00	0.92	1.00	0.84	0.98	0.99	.21	**red** 27.8%
1.00	0.99	0.00	1.00	0.98	1.00	1.00	1.00	0.17	1.00	.34	**green** 36.8%
0.89	1.00	1.00	0.00	0.98	1.00	0.71	0.93	1.00	0.32	.55	**purple** 67.3%
0.07	1.00	0.98	0.98	0.00	1.00	0.36	1.00	0.97	0.95	.20	**blue** 36.6%
1.00	0.92	1.00	1.00	1.00	0.00	1.00	0.97	0.99	1.00	.39	**orange** 51.9%
0.35	1.00	1.00	0.71	0.36	1.00	0.00	0.95	0.92	0.42	.13	**blue** 15.7%
0.99	0.84	1.00	0.93	1.00	0.97	0.95	0.00	0.98	0.85	.16	**pink** 29.4%
1.00	0.98	0.17	1.00	0.97	0.99	0.92	0.98	0.00	0.97	.12	**green** 21.7%
0.89	0.99	1.00	0.32	0.95	1.00	0.42	0.85	0.97	0.00	.30	**purple** 23.9%
Excel-10								*Average*	*0.87*	.27	

http://vis.stanford.edu/color-names

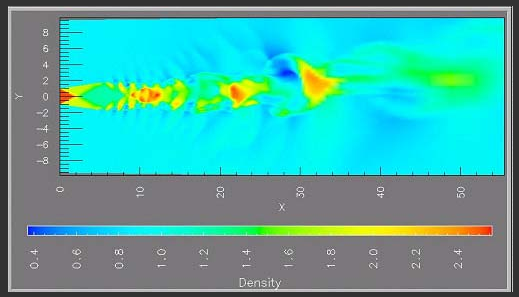
Hints for the colorist

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**

Default rainbow maps

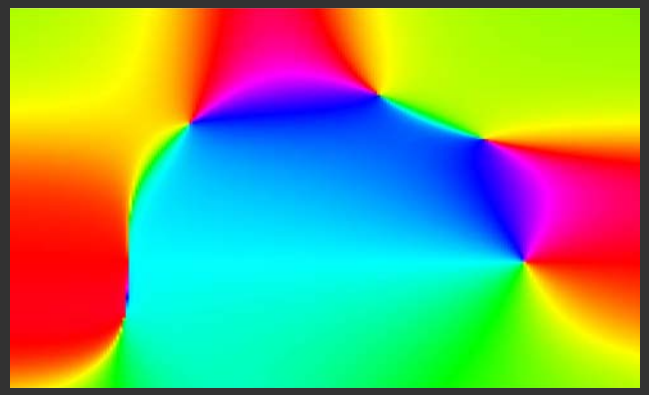


Avoid rainbow color maps!

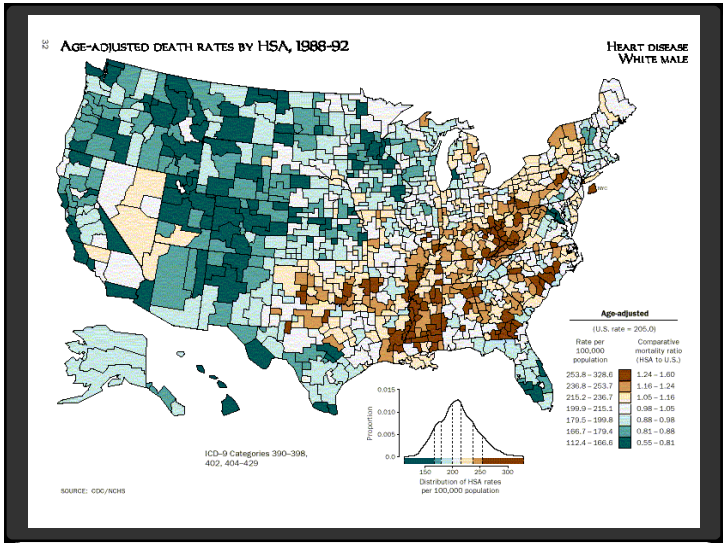


1. People segment colors into classes
2. Hues are not naturally ordered
3. Different lightness emphasizes certain scalar values
4. Low luminance colors (blue) hide high frequencies

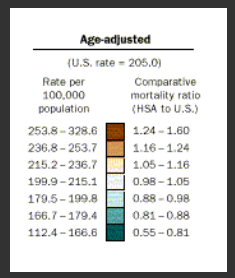
Singularity in Phase (M. Berry)



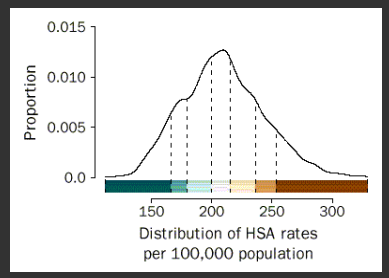
Phase is periodic ⇒ Hue circle which is also periodic



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

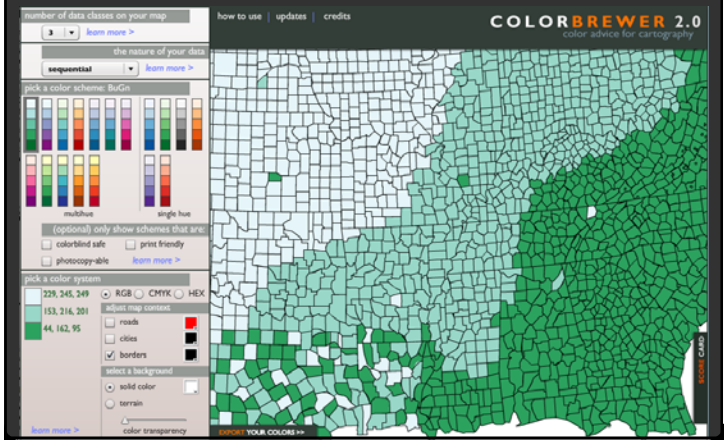


Age-adjusted mortality rates for the United States.

Classing quantitative data

1. Equal interval (arithmetic progression)
2. Quantiles *(recommended)*
3. Standard deviation
4. Classification [Jenks' "natural breaks"]
5. Equal area
6. Minimal length boundaries
7. Minimal gaps

ColorBrewer: Color advice for maps



Quantitative color encoding

Sequential color scale

Constrain hue, vary luminance/saturation

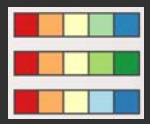
Map higher values to darker colors

Diverging color scale

Useful when data has a meaningful "midpoint"

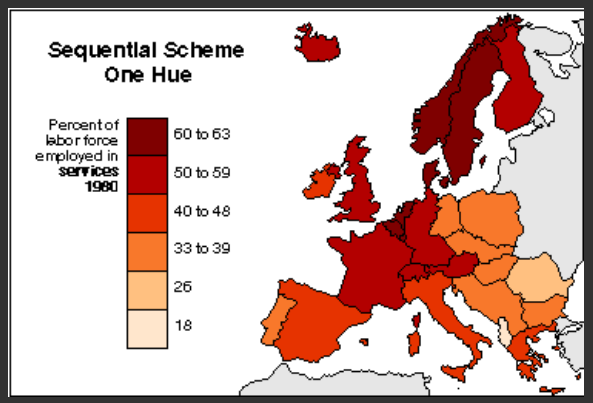
Use neutral color (e.g., grey) for midpoint

Use saturated colors for endpoints



Limit number of steps in color to 3-9

Sequential color scheme



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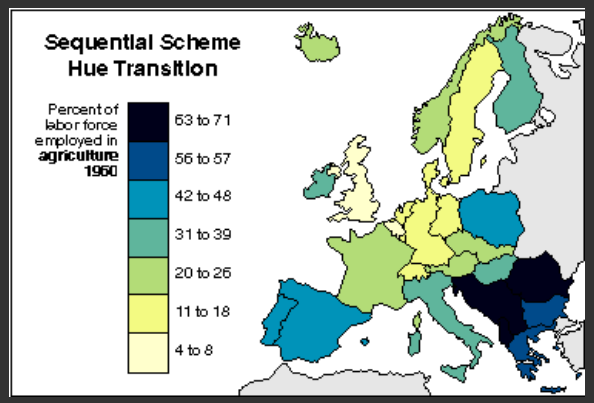


Design of sequential color scales

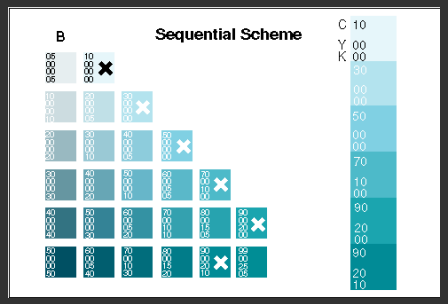
Hue-Lightness *(Recommended)*

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

Hue Transition

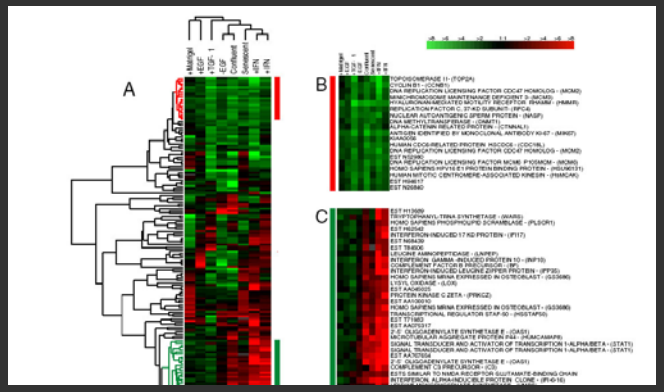
- Two hues
- Neighboring hues interpolate better
- Couple with change in lightness

Design of sequential data scales



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

Diverging color scheme



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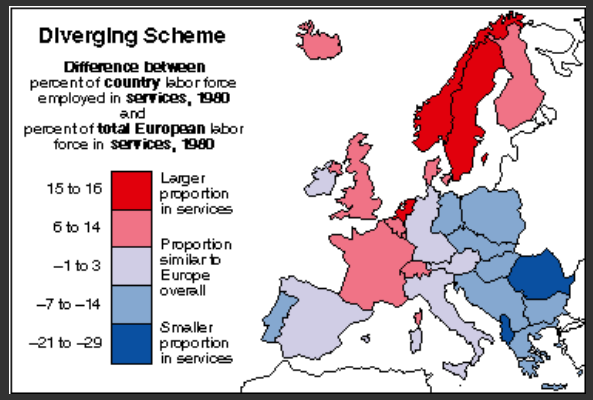
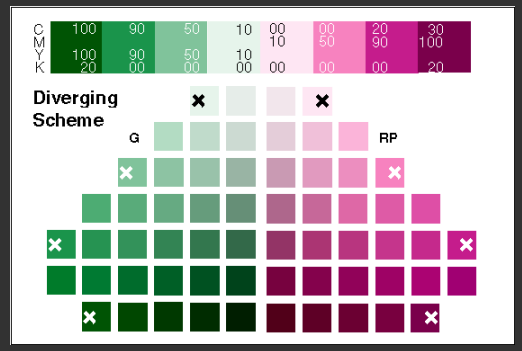


Diverging color scheme

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

Diverging color scheme



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