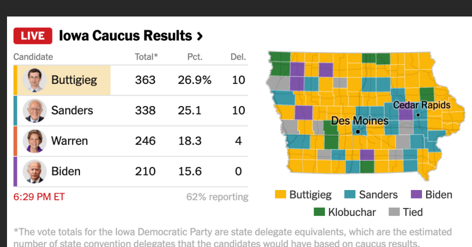
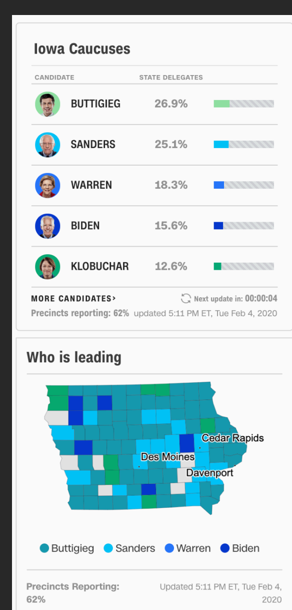
Color

Maneesh Agrawala

CS 448B: Visualization
Winter 2020

1





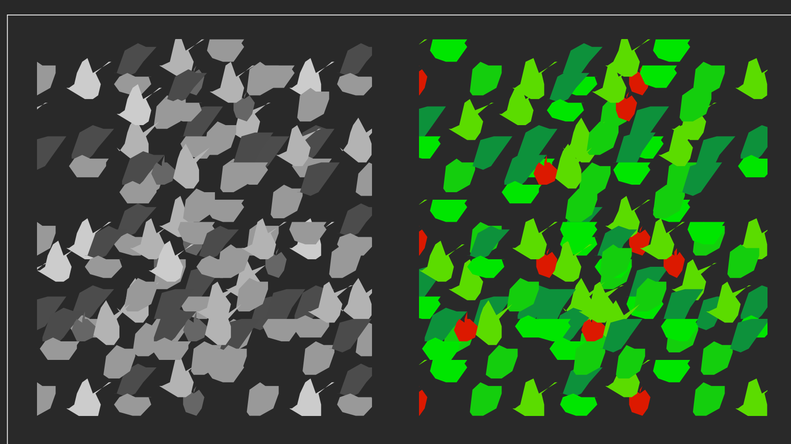
2

Color

3

Color in Visualization

Identify, Group, Layer, Highlight



Colin Ware

4

Purpose of Color

To label
To measure
To represent and imitate
To enliven and decorate

"Above all, do no harm."

- Edward Tufte

5

Topics

Color Perception
Color Naming
Using Color in Visualization

6

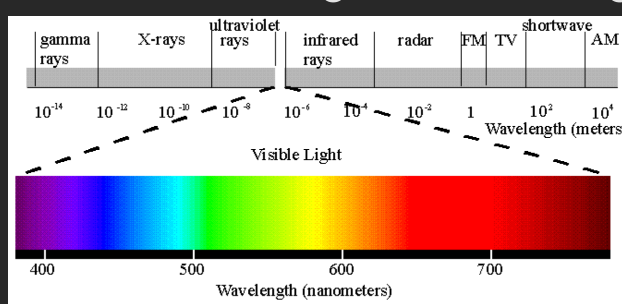
Color Perception

Physical World, Visual System, Mental Models

7

Physical World

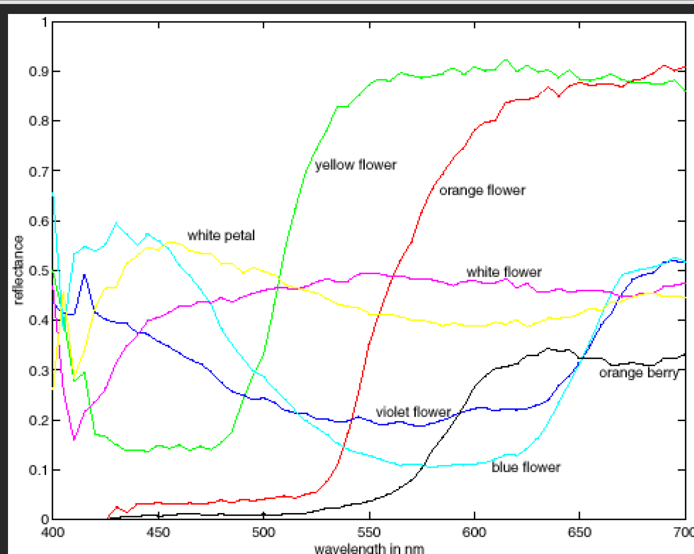
Light is radiation in range of wavelengths



Light of single wavelength is *monochromatic*

10

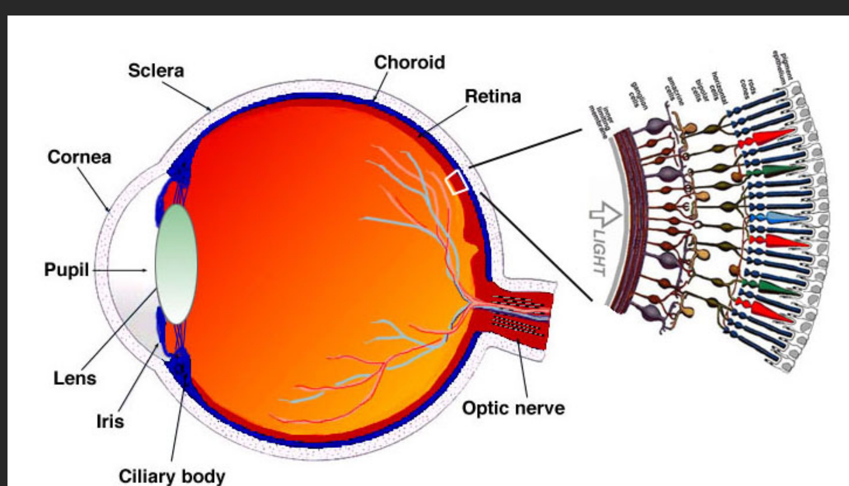
Most Colors not Monochromatic



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

12

Retina

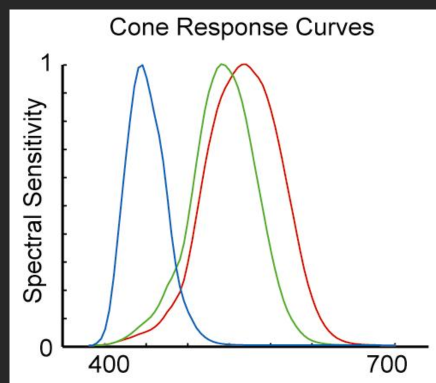


Simple Anatomy of the Retina, Helga Kolb

15

As light enters our retina...

LMS (Long, Middle, Short) Cones
Sensitive to different wavelength

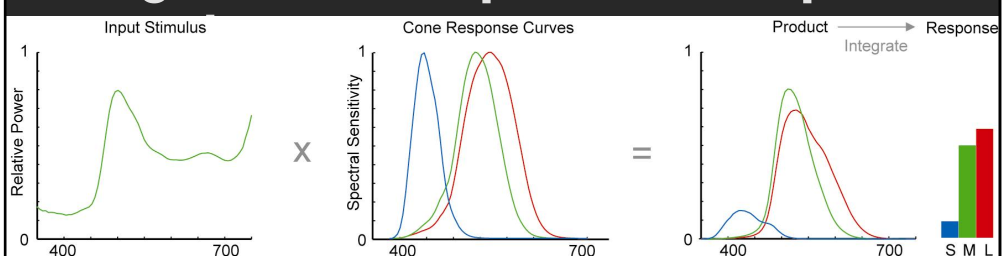


A Field Guide to Digital Color, Maureen Stone

18

Cone Response

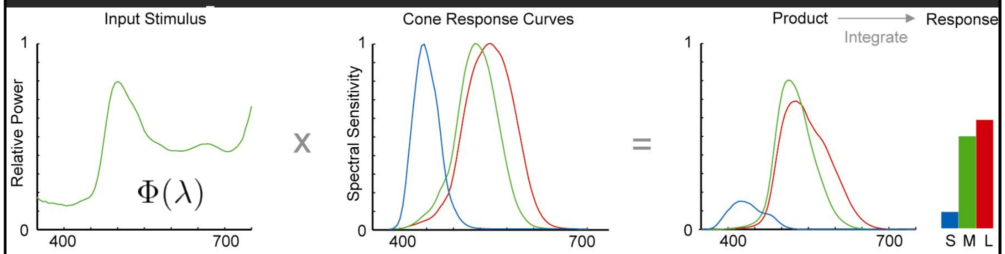
Integrate cone response with input



19

Computing Cone Response

Integrate cone response with input



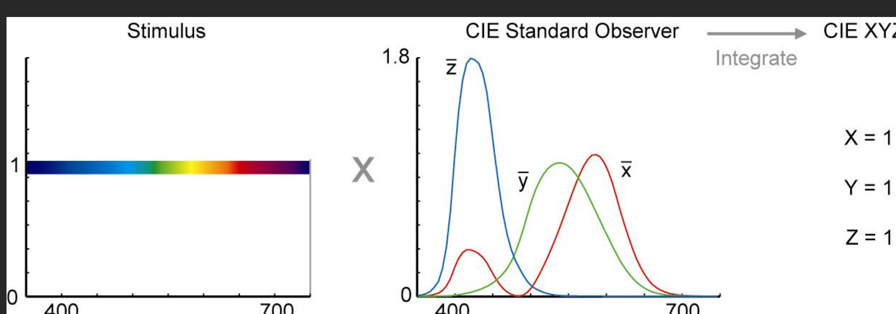
$$L = \int \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$
$$M = \int \Phi(\lambda) M(\lambda) \mathrm{d}\lambda$$
$$S = \int \Phi(\lambda) S(\lambda) \mathrm{d}\lambda$$

20

CIE XYZ Color Space

Standardized in 1931 to mathematically represent tri-stimulus response

“Standard observer” response curves

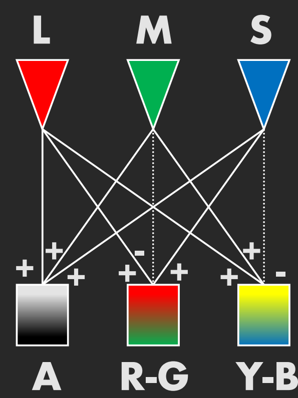


22

Opponent processing

LMS are linearly combined to create:

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



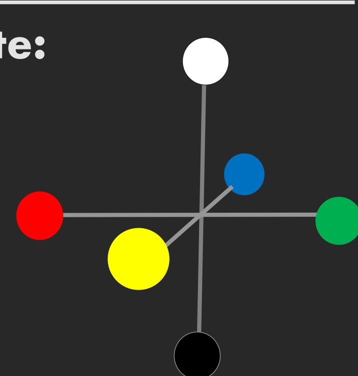
Fairchild

24

Opponent processing

LMS are combined to create:

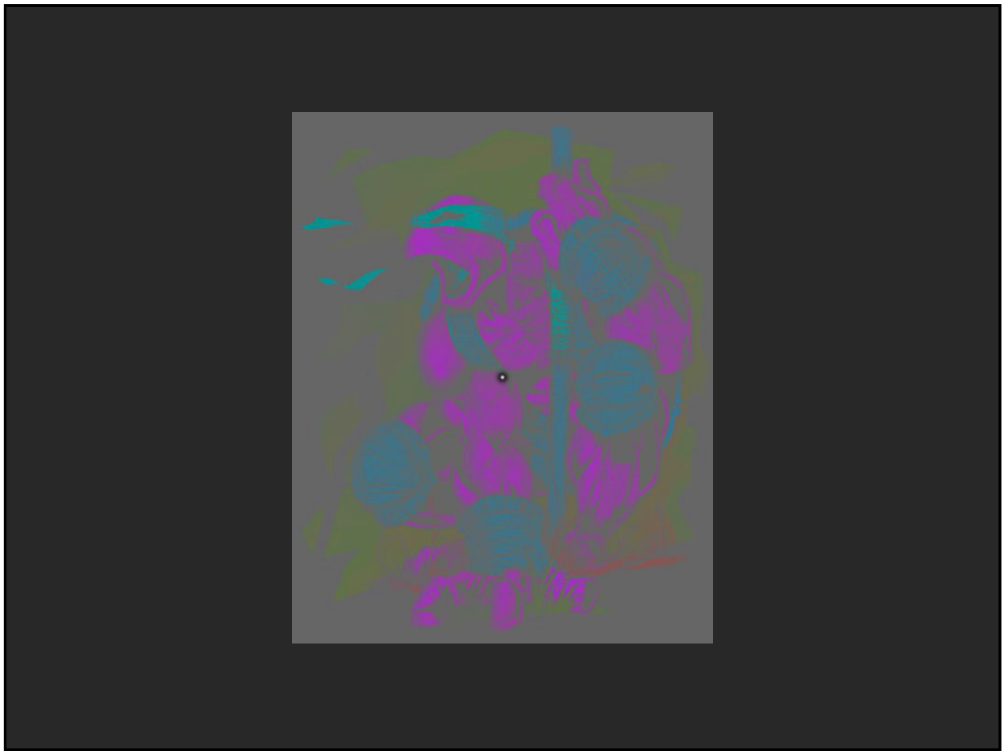
- Lightness
- Red-green contrast
- Yellow-blue contrast



Experiments:

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

26

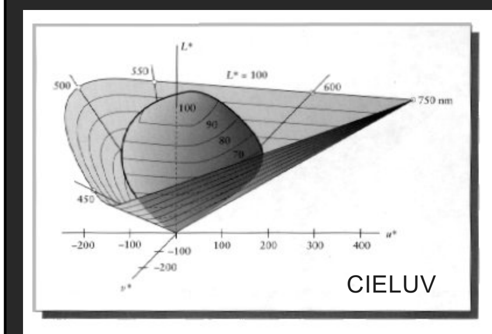


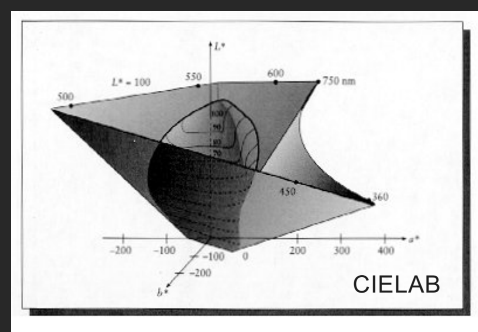
28

29

CIE LUV and LAB color spaces

Standardized in 1976 to mathematically represent opponent processing theory





33

Axes of CIE LAB

Correspond to opponent signals

L* = Luminance

a* = Red-green contrast

b* = Yellow-blue contrast

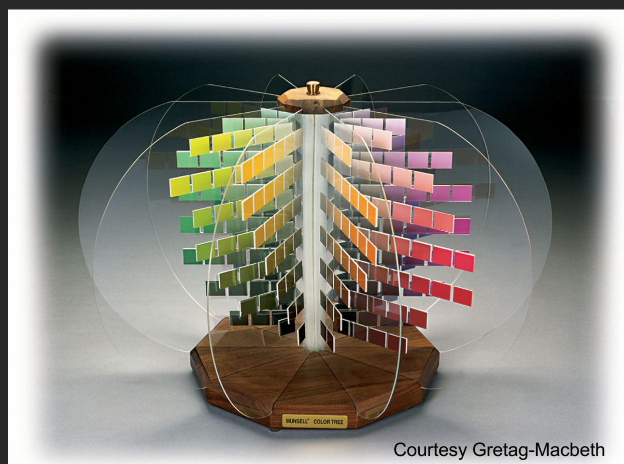
Scaling of axes to represent "color distance"

JND = Just noticeable difference (~2.3 units)

34

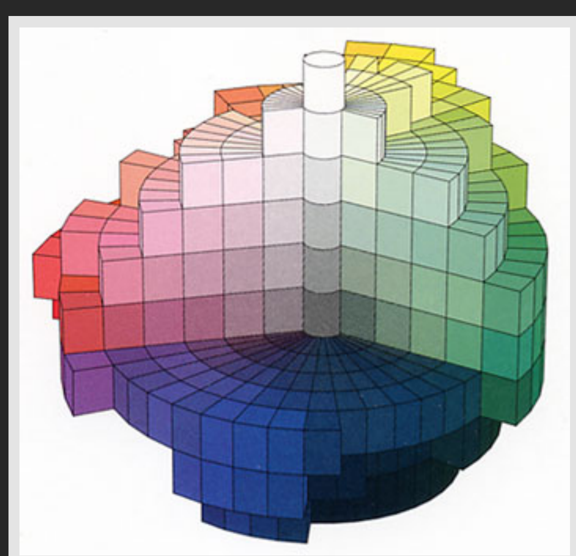
Munsell Atlas

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



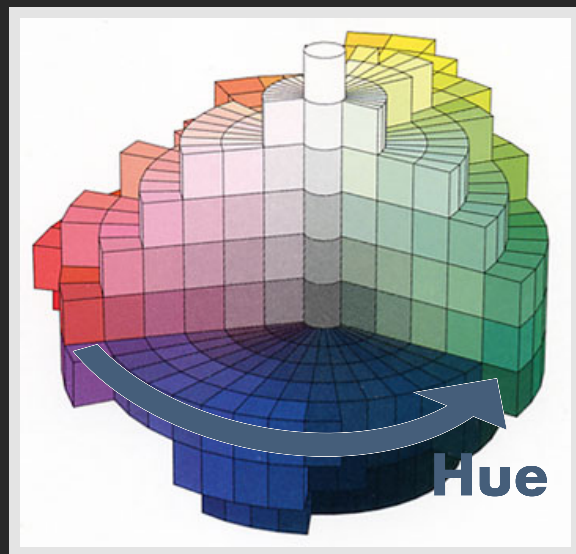
35

Hue, Value, Chroma



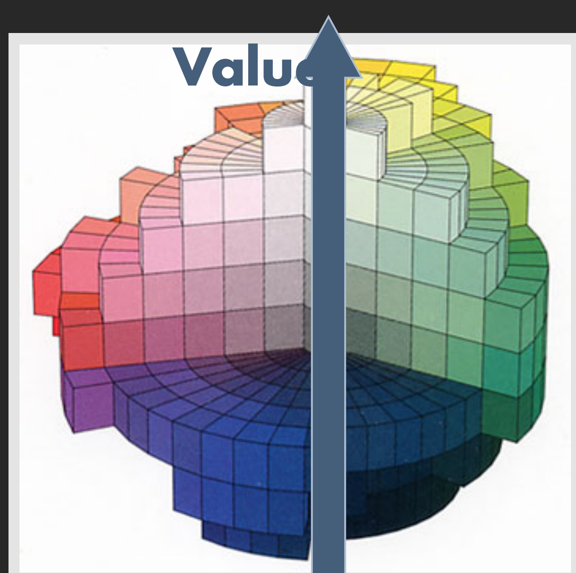
36

Hue, Value, Chroma



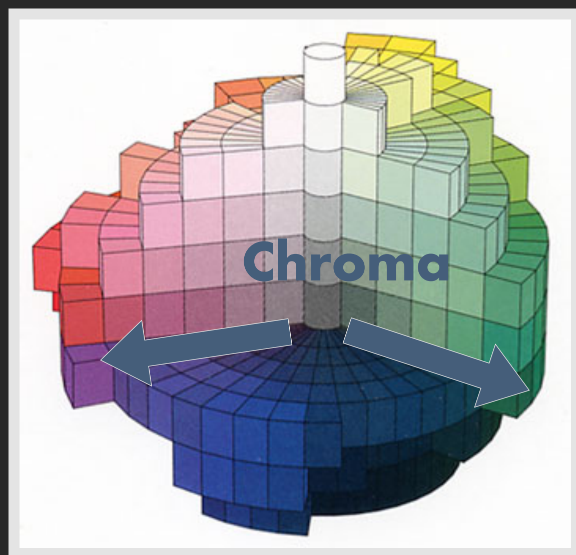
37

Hue, Value, Chroma



38

Hue, Value, Chroma



39

Psuedo-Perceptual Models

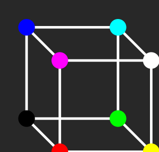
HLS, HSV, HSB

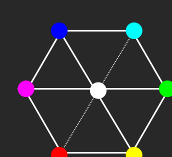
NOT perceptual models

Simple re-notation of RGB

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

Cannot predict perceived lightness



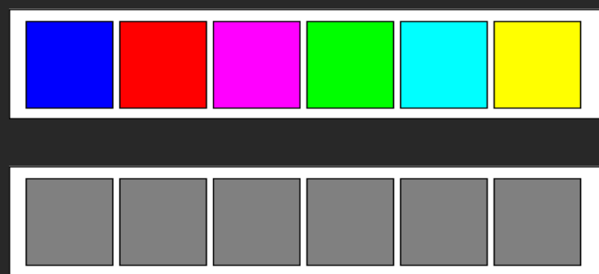


41

Perceptual brightness

Color palette

HSL Lightness
(Photoshop)

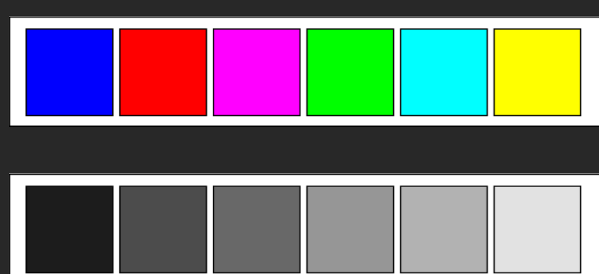


42

Perceptual brightness

Color palette

Luminance Y
(CIE XYZ)

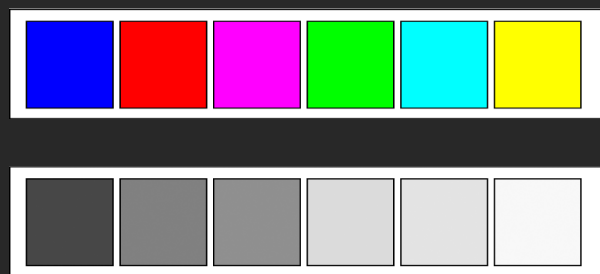


43

Perceptual brightness

Color palette

Munsell Value
L* (CIE LAB)



44

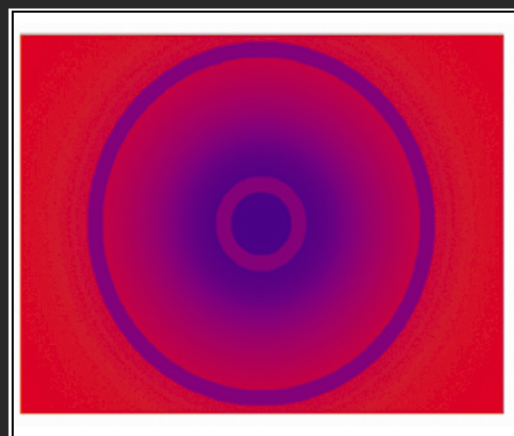
"In order to use color effectively it is necessary to recognize that it deceives continually."

- Josef Albers, *Interaction of Color*

49

Simultaneous Contrast

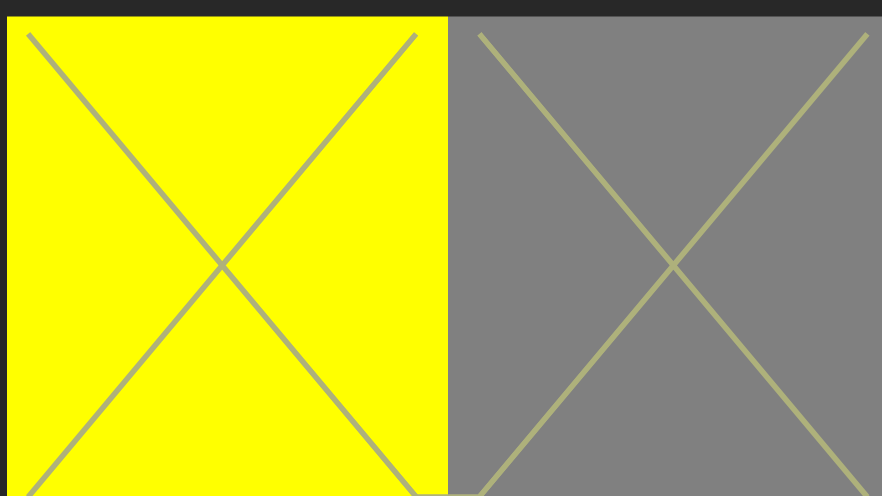
The inner and outer thin rings are the physical purple



Donald MacLeod

50

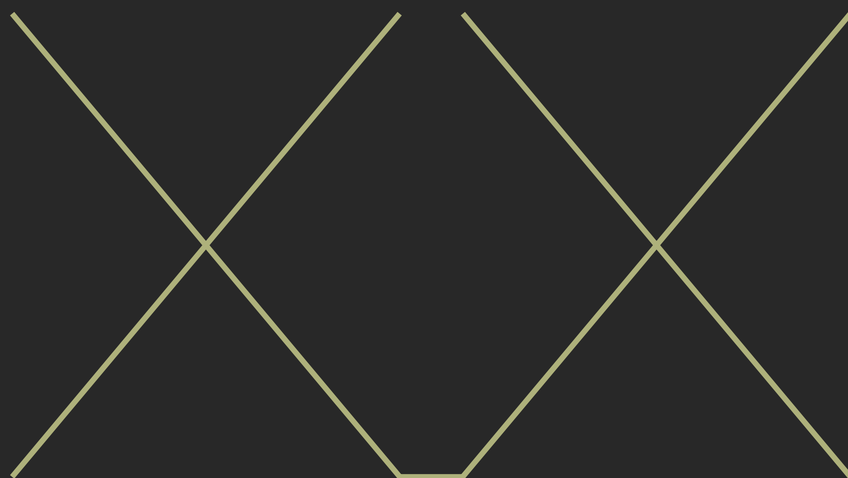
Simultaneous Contrast



Josef Albers

53

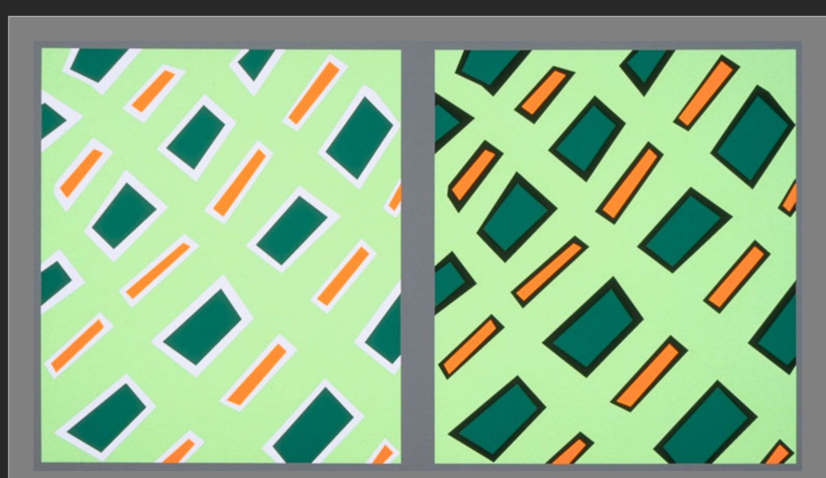
Simultaneous Contrast



Josef Albers

54

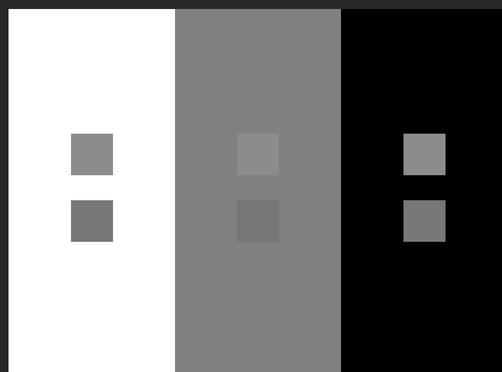
Bezold Effect



62

Crispening

Perceived difference depends on background



From Fairchild, *Color Appearance Models*

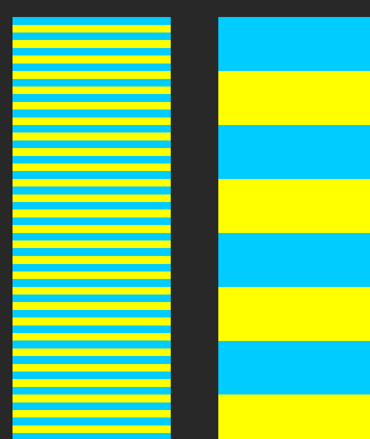
63

Spreading

Adjacent colors blend

Spatial frequency

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



Redrawn from *Foundations of Vision*
© Brian Wandell, Stanford University

64

Announcements

70

Final project

New visualization research or data analysis project
- **Research**: Pose problem, Implement creative solution
- **Data analysis**: Analyze dataset in depth & make a visual explainer

Deliverables
- **Research**: Implementation of solution
- **Data analysis/explainer**: Article with multiple interactive visualizations
- 6-8 page paper

Schedule
- Project proposal: Wed 2/19
- Design review and feedback: 3/9 and 3/11
- Final presentation: 3/16 (7-9pm) Location: TBD
- Final code and writeup: 3/18 11:59pm

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

71

THE BROWN INSTITUTE FOR MEDIA INNOVATION

Join us for a talk and conversation with Brown Institute Director, Professor Maneesh Agrawala, featuring

Sean Rameswaram

Host of Vox's *Today, Explained*

Tuesday, February 18 – 5pm
Allen 101x, Cypress Auditorium
Paul G. Allen Building
330 Jane Stanford Way

RSVP: http://bit.ly/bimi_Rameswaram

The Brown Institute is excited to welcome Sean Rameswaram, host of Today, Explained, Vox's daily explainer podcast. As advertised by Vox, *Today, Explained is your all killer, no filler, Monday to Friday news*. Sean, a veteran of the podcast space, will discuss Vox's novel approach to their daily show and will join Brown Institute Director Maneesh Agrawala in conversation about the state of podcasts. Before joining Vox to host its daily news podcast, Sean was a correspondent for Radiolab's More Perfect. He has also made radio for the CBC, NPR, and WNYC, where he hosted the fondly remembered Sideshow podcast for Studio 360.

72

Color Naming

73

What color is this?

74

What color is this?

75

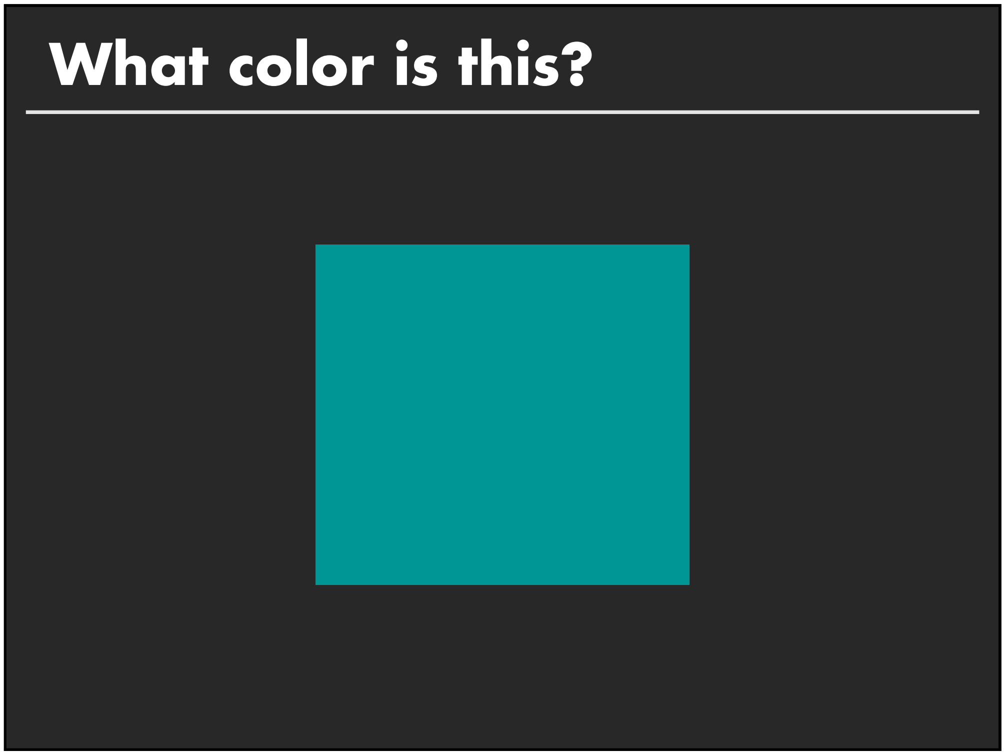
What color is this?

76

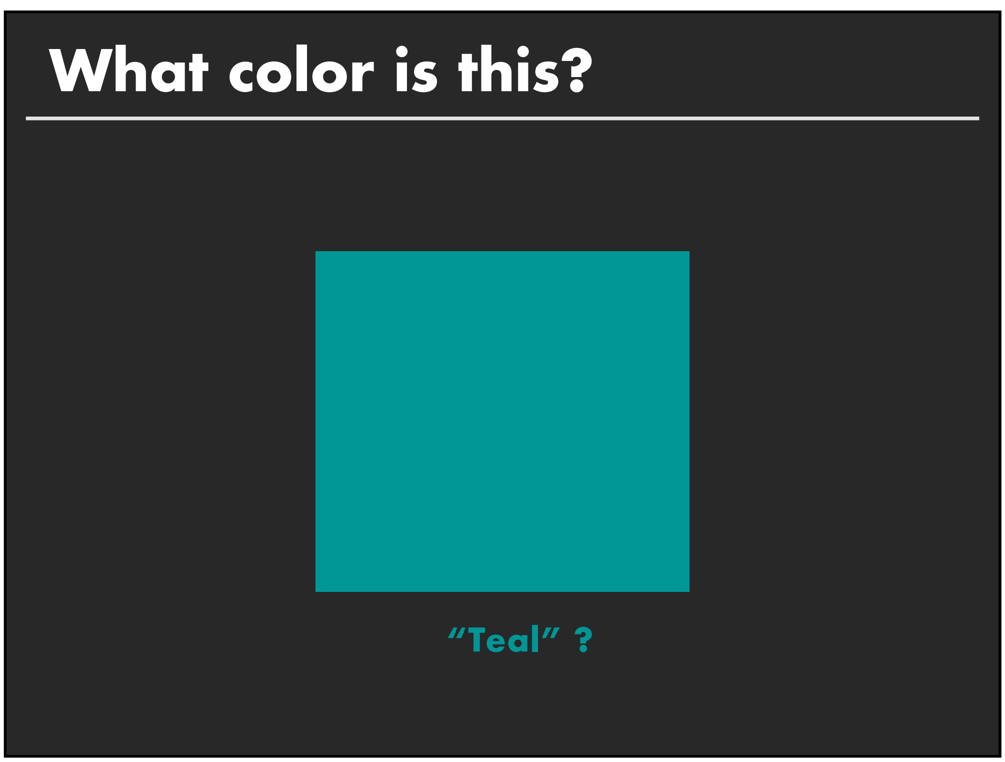
What color is this?

"Blue"

77



78



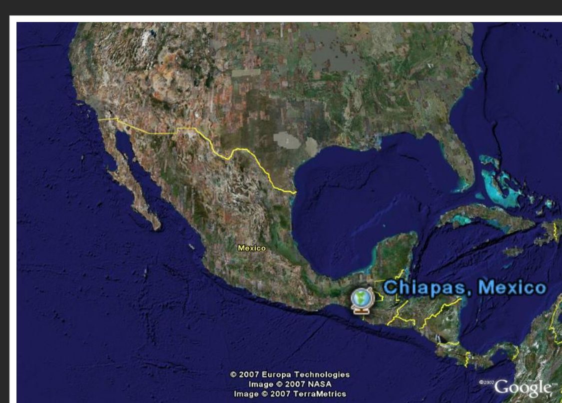
79

Colors according to XKCD…

80

Basic color terms

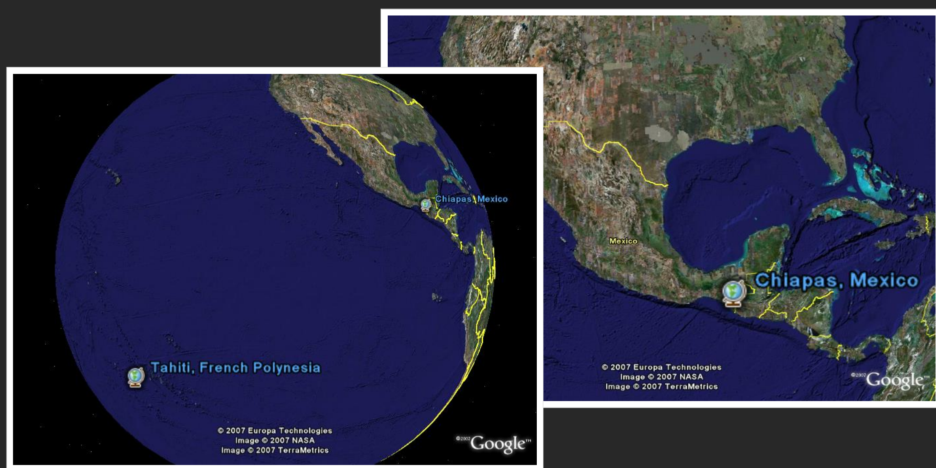
Chance discovery by Brent Berlin and Paul Kay



81

Basic color terms

Chance discovery by Brent Berlin and Paul Kay



82

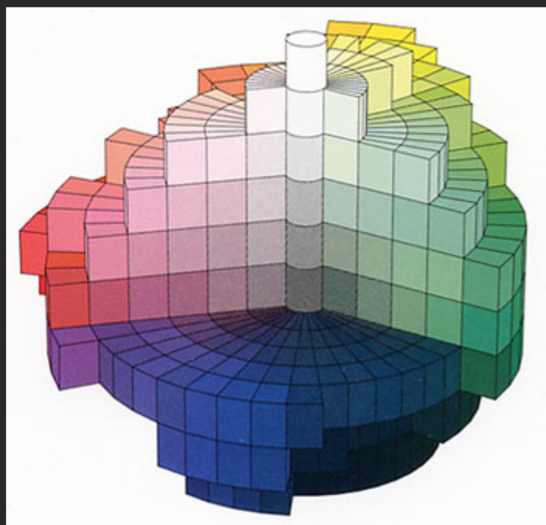
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay

Initial study in 1969
Surveyed speakers from 20 languages
Literature from 69 languages

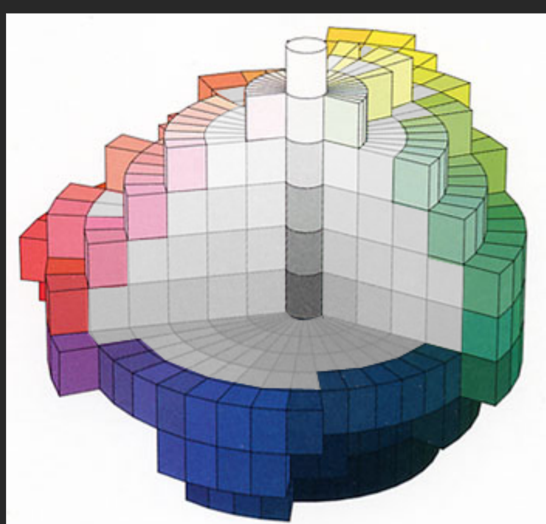
83

World color survey



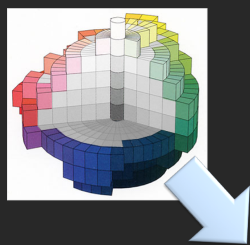
84

World color survey

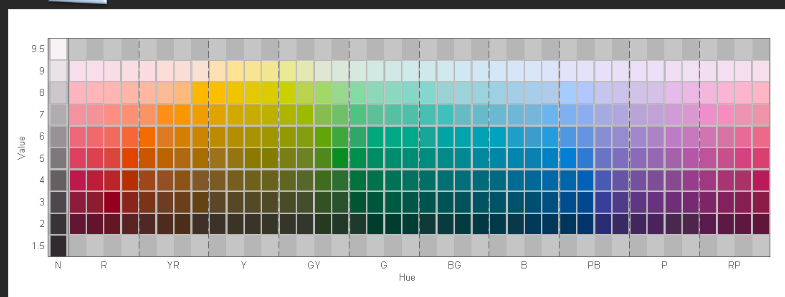


85

World color survey

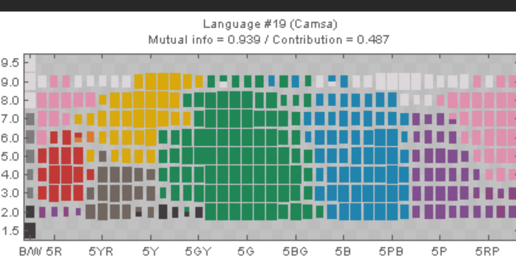


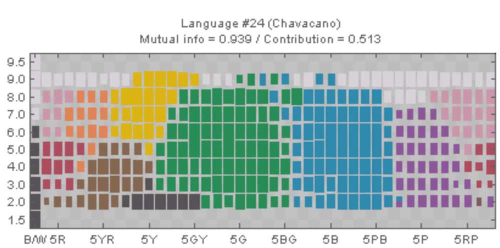
Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



86

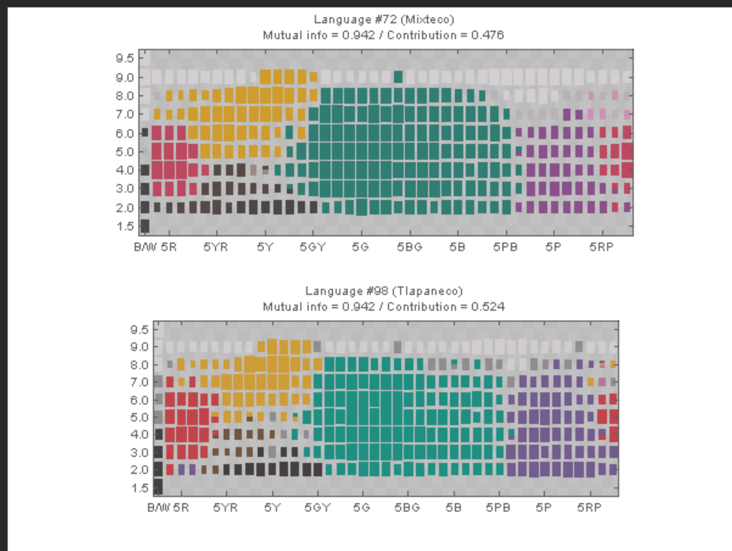
Results from WCS (South Pacific)





87

Results from WCS (Mexico)



88

Universal (?) Basic Color Terms

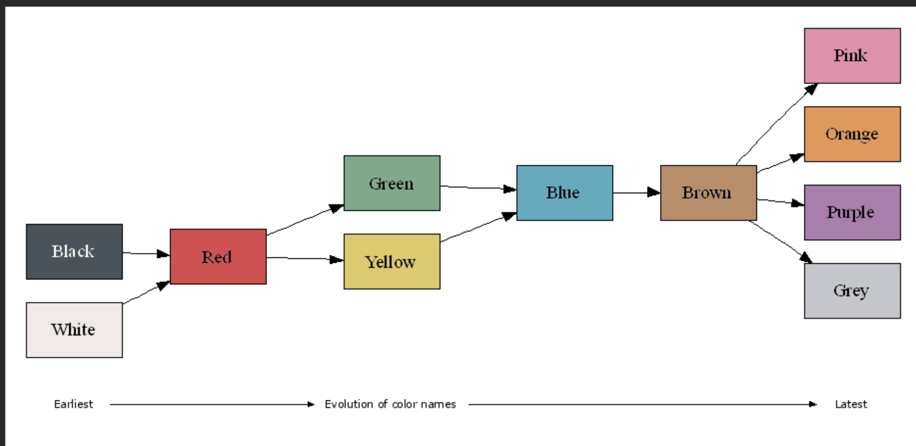
Basic color terms recur across languages

White	Red	Pink
Grey	Yellow	Brown
Black	Green	Orange
	Blue	Purple

89

Evolution of Basic Color Terms

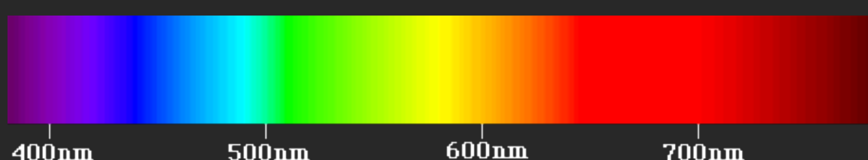
Proposed universal evolution across languages



90

Rainbow color ramp

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



91

Rainbow color ramp

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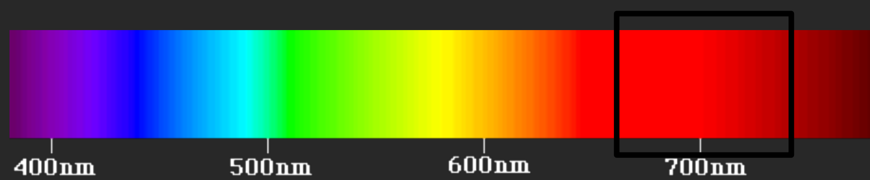

92

Rainbow color ramp

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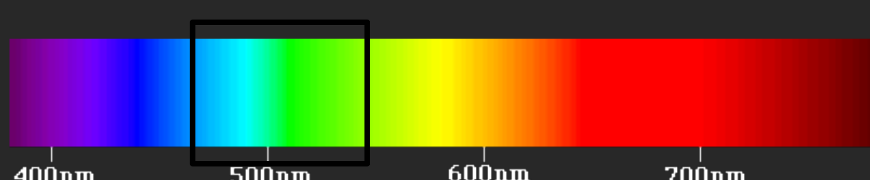
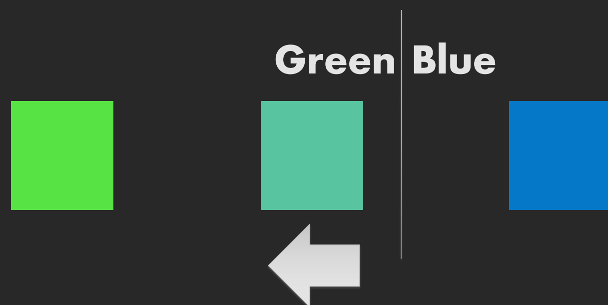


93

Naming affects color perception

Color name boundaries



94

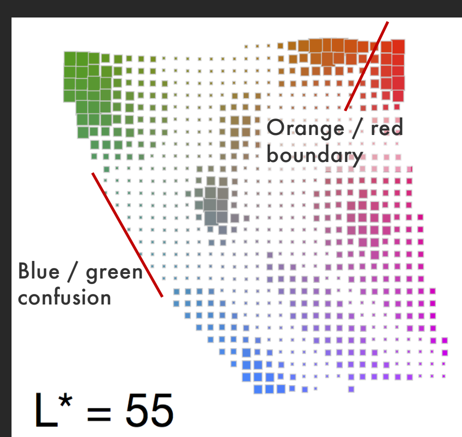
Color naming models

[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)*



95

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

96

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*	

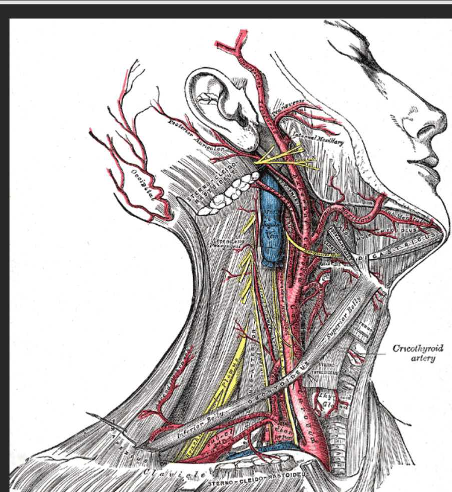
http://vis.stanford.edu/color-names

97

Using Color in Visualization

99

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

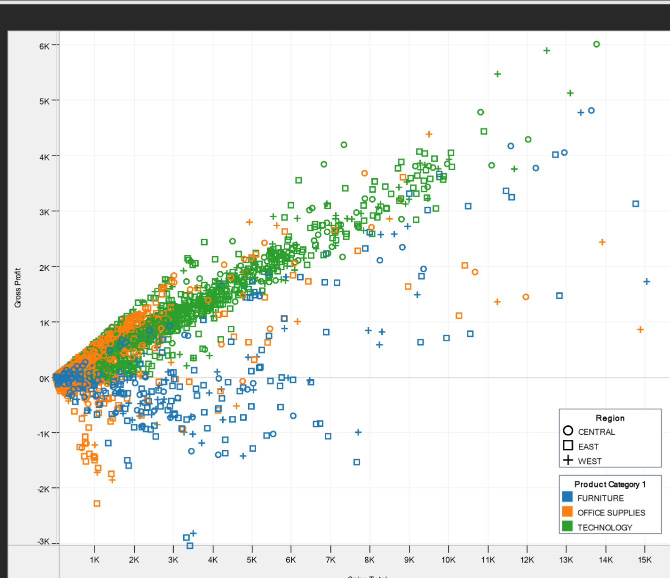
101

Molecular Models

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

102

Product Categories



Created by Tableau - Visual Analysis for Databases™

103

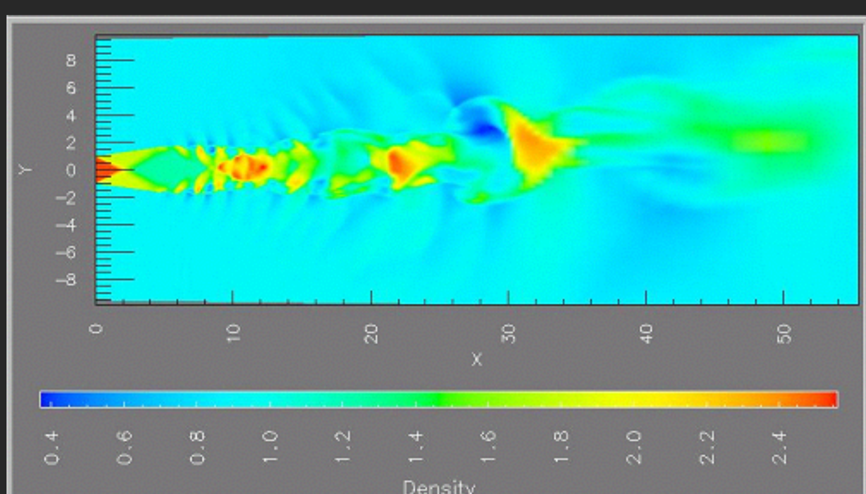
Grouping, Highlighting

	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

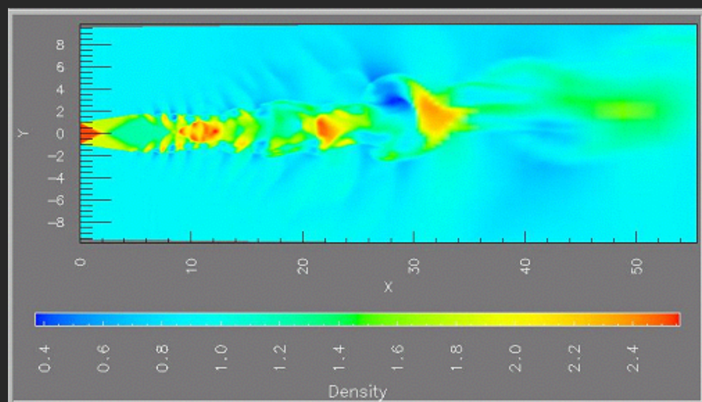
104

Mapping Data to Color (Rainbows)



123

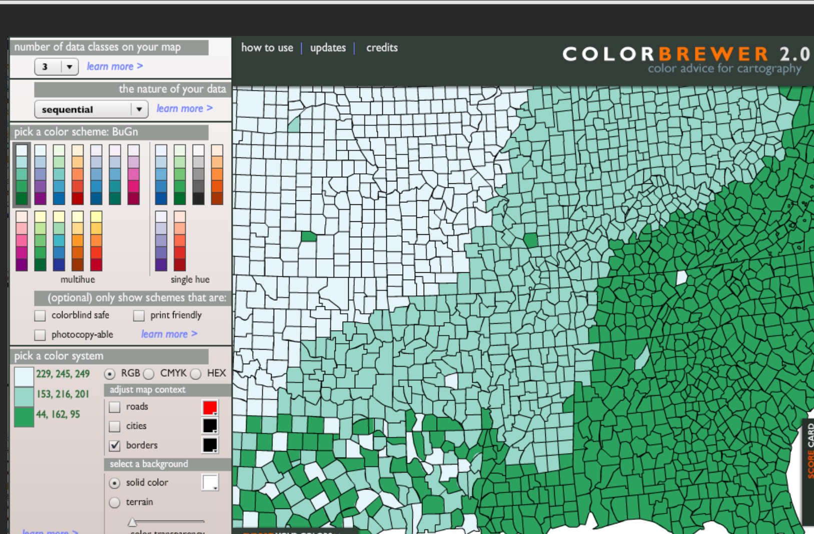
Avoid rainbow color maps!



1. Hues are not naturally ordered
2. People segment colors into classes, perceptual banding
3. Naïve rainbows unfriendly to color blind viewers
4. Low luminance colors (blue) hide high frequencies

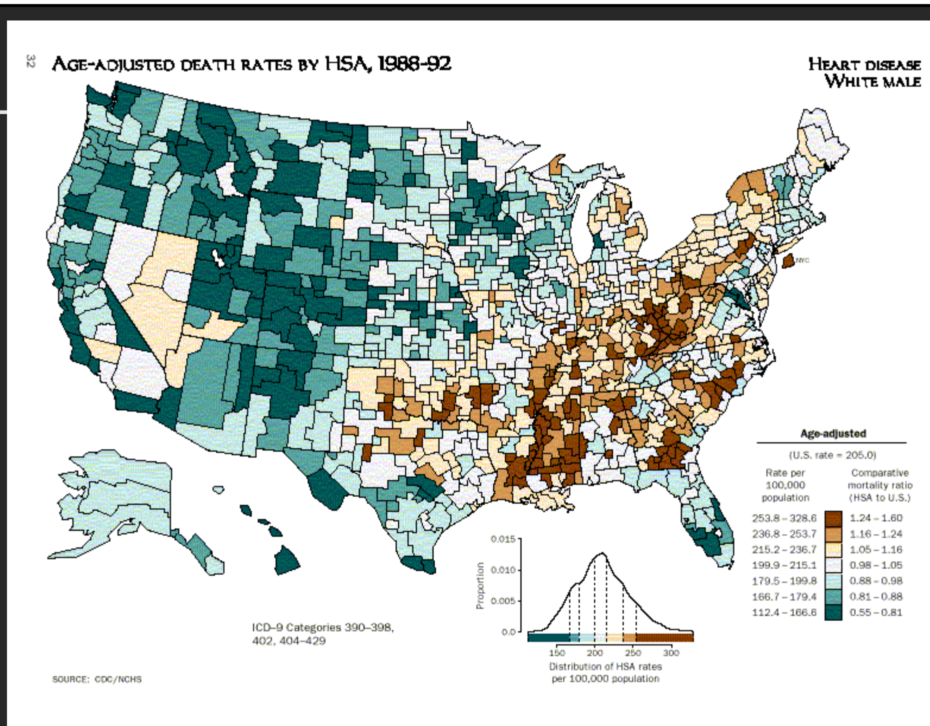
124

Color Brewer



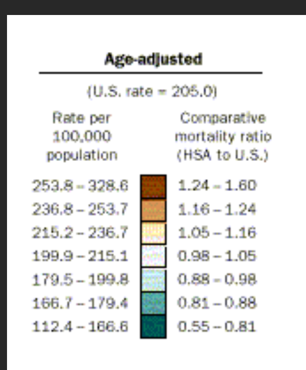
www.colorbrewer.org

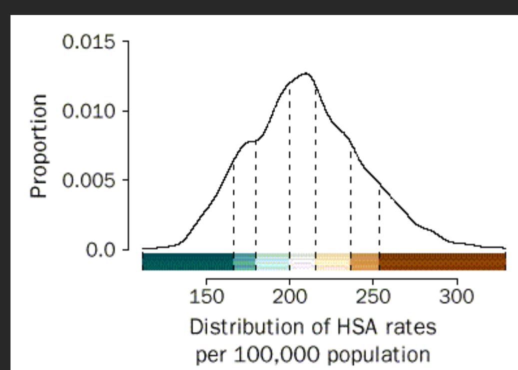
130



131

Classing quantitative data





Age-adjusted mortality rates for the United States

Common option: break into 5 or 7 quantiles

132

Classing Quantitative Data

Equal interval (arithmetic progression)

Quantiles *(recommended)*

Standard deviations

Clustering (Jenks' natural breaks / 1D K-Means)

- Minimize within group variance
- Maximize between group variance

133

Quantitative color encoding

Sequential color scale

- Ramp in luminance, possibly also hue
- Typically higher values map to darker colors

Diverging color scale

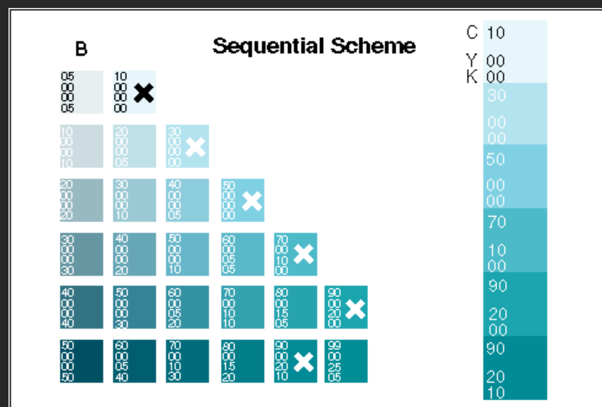
- Useful when data has a meaningful "midpoint"
- Use neutral color (e.g., grey) for midpoint
- Use saturated colors for endpoints

Limit number of steps in color to 3-9

134

Sequential Scale Single Hue

Ramp primarily in luminance, subtle hue difference

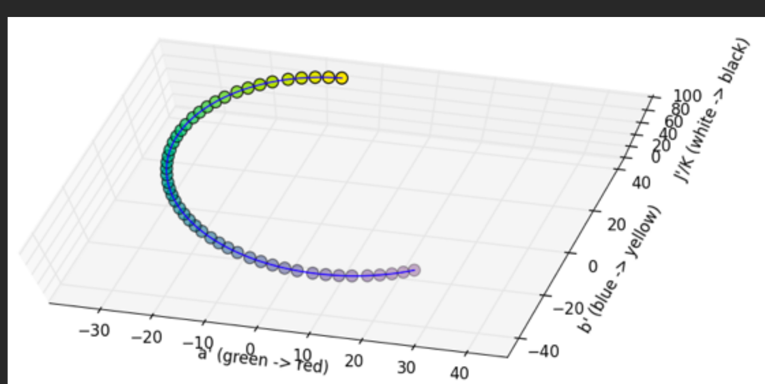


http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes

138

Sequential Scale Multi Hue

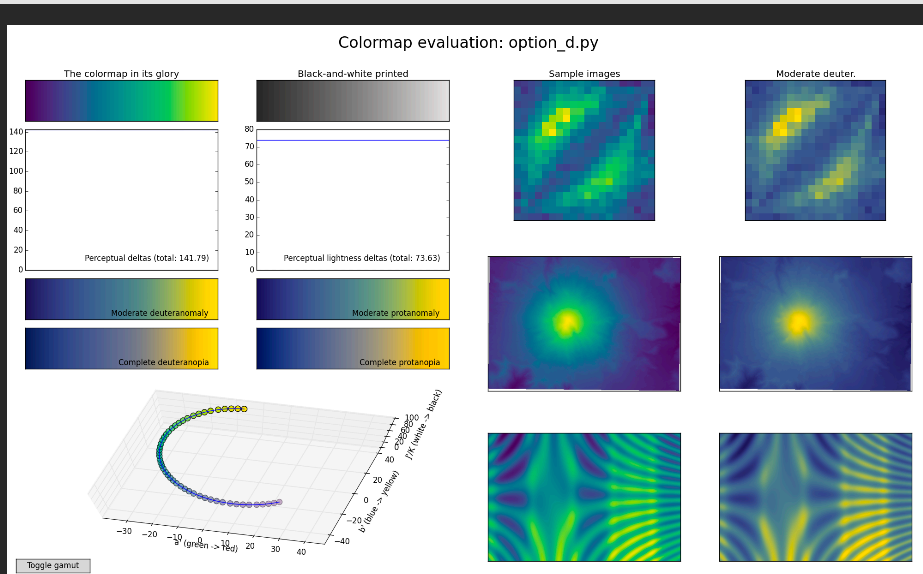
Ramp luminance & hue in perceptual color space
Avoid contrasts subject to color blindness!



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

139

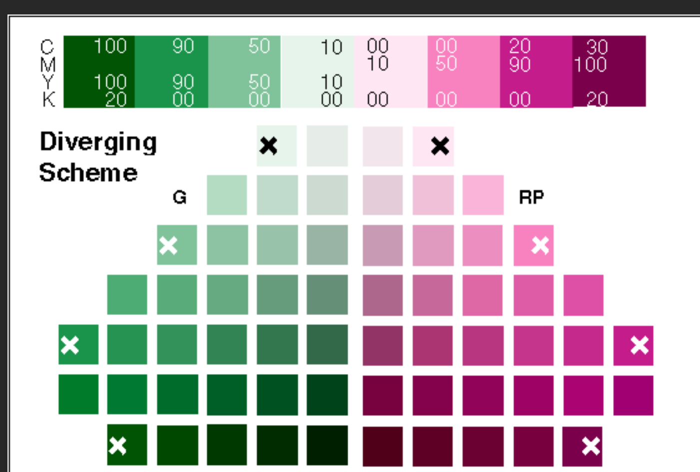
Sequential Scale Multi Hue



Viridis, https://bids.github.io/colormap/

140

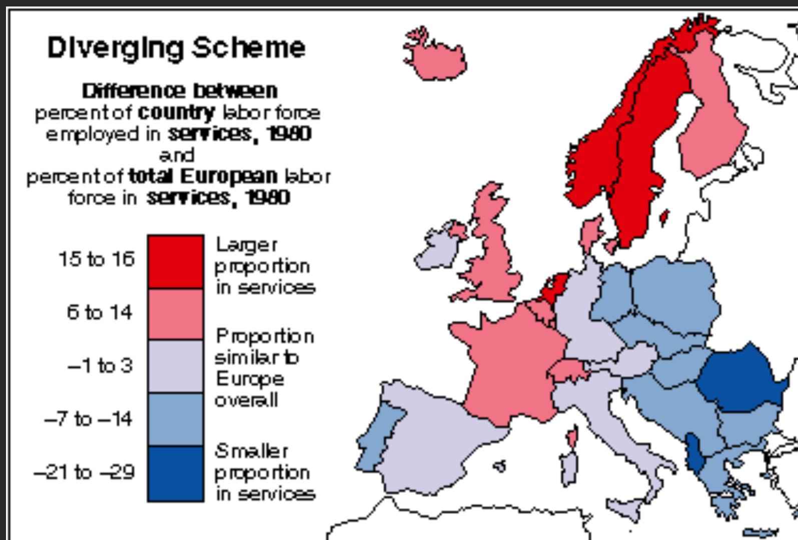
Diverging color scheme



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

141

Diverging color scheme



143

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

144

Summary: Color Design Principles

Control value (darkness/lightness)

- Ensure legibility
- Avoid unwanted emphasis

Use a limited hue palette (~6 colors)

- Control color "pop out"
- Be aware of perceptual color grouping
- Avoid clutter from too many competing colors

Use neutral backgrounds

- Control impact of color
- Minimize simultaneous contrast

147