Color

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Jessica Hullman

CS 294-10: Visualization
Fall 2014

Assignment 3: Visualization Software

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

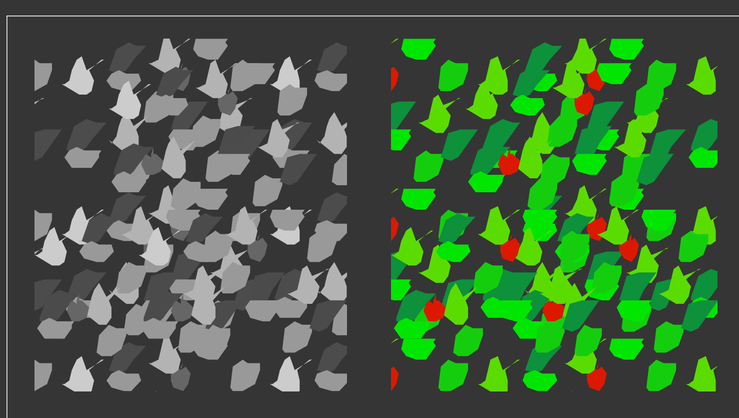
1. Describe data and storyboard interface
2. Implement interface and produce final writeup
3. Submit the application and a final writeup on the wiki

Can work alone or in pairs
Final write up due before class on **Oct 15, 2014**

Color

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

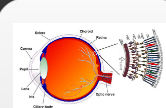
Color Perception
Color Naming
Using Color in Visualization

Color Perception

Physical World, Visual System, Mental Models

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



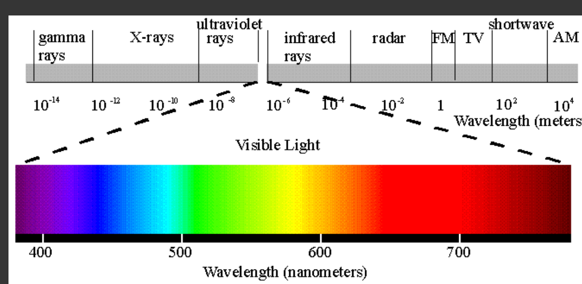
"Yellow"

Color Models

Physical World	Visual System		Mental Models	
Light Energy →	Cone Response →	Opponent Encoding →	Perceptual Models →	Appearance Models
Spectral distribution functions	Encode as three values (L,M,S)	Separate lightness, chroma	Color "Space"	Color in Context
F(λ)	CIE (X,Y,Z)	(A,R-G,Y-B)	Hue lightness saturation	Adaptation Background Size …
			CIELAB Munsell (HVC)	CIECAM02

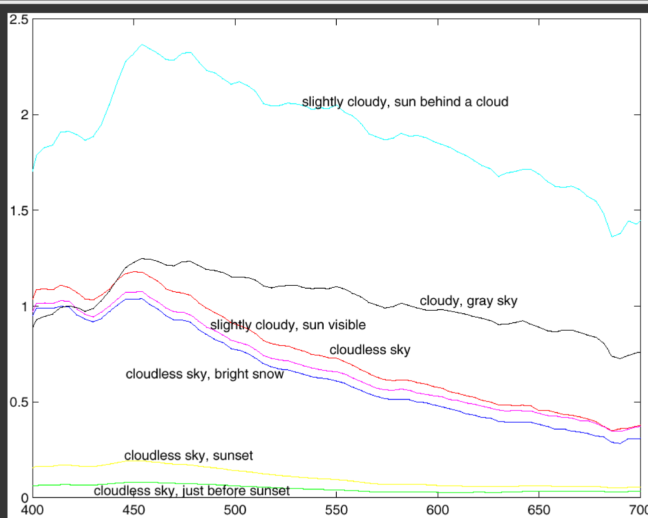
Physical World

Light is radiation in range of wavelengths



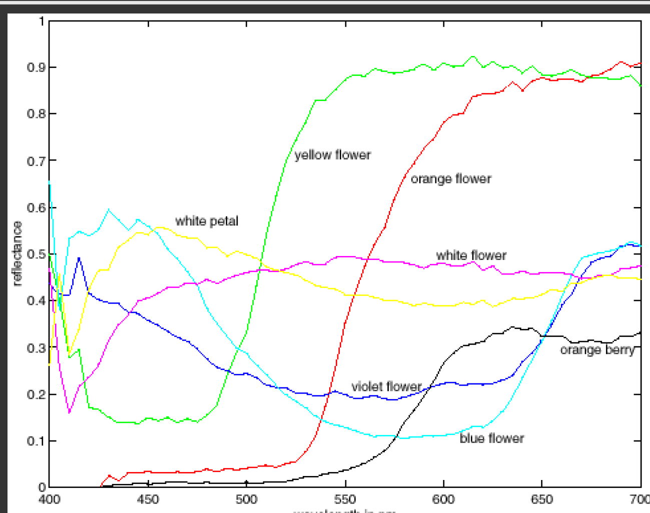
Light of single wavelength is *monochromatic*

Most Colors not Monochromatic



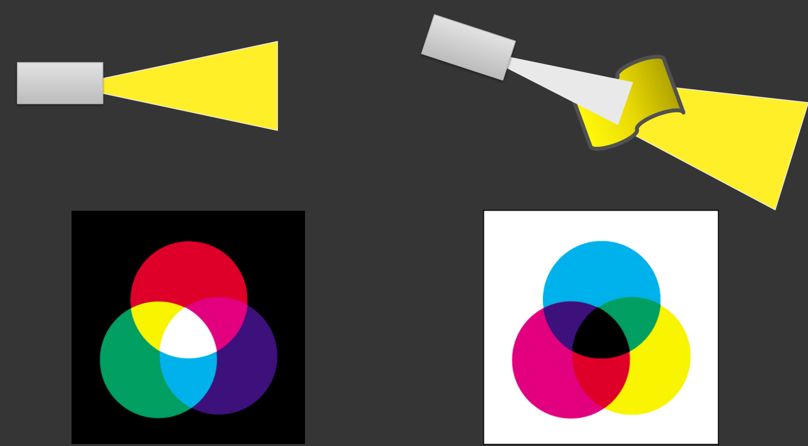
Curves describe spectral composition $\Phi(\lambda)$ of stimulus

Most Colors not Monochromatic



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

Emissive vs. reflective light



Additive
(digital displays)

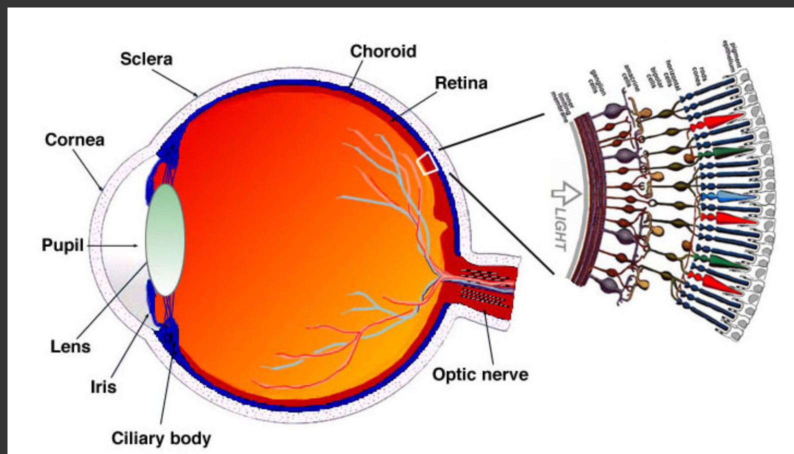
Subtractive
(print, e-paper)

Perception Vs. Measurement

You do not see the spectrum of light

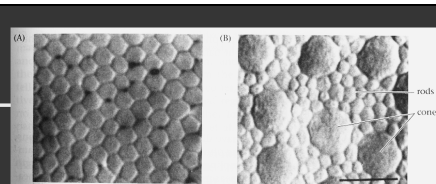
- Eyes make limited measurements
- Eyes physically adapt to circumstance
- You brain adapts in various ways
- Weird stuff also happens

Retina



Simple Anatomy of the Retina, Helga Kolb

Rods and Cones



Rods

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

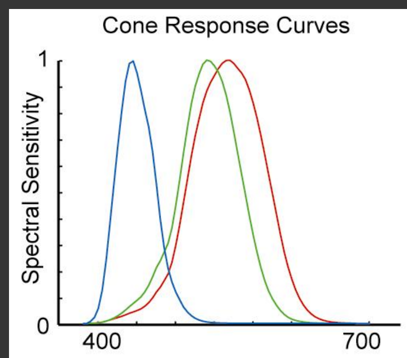
Cones

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

As light enters our cones…

LMS (Long, Middle, Short) Cones

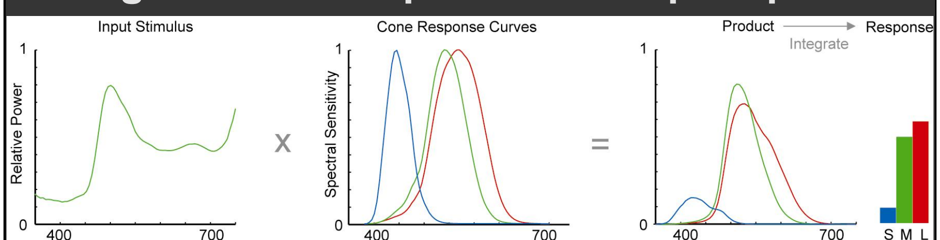
Sensitive to different wavelength



A Field Guide to Digital Color, Maureen Stone

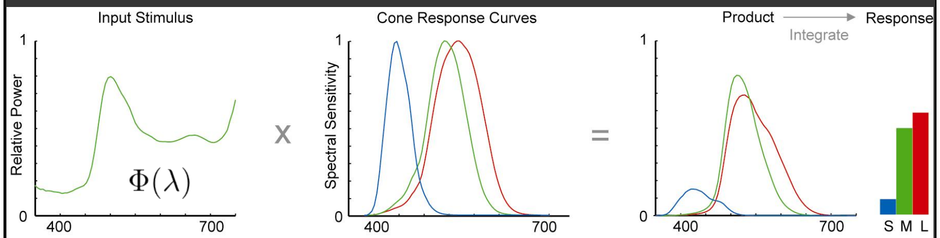
Cone Response

Integrate cone response with input spectra



Computing Cone Response

Integrate cone response with input spectra



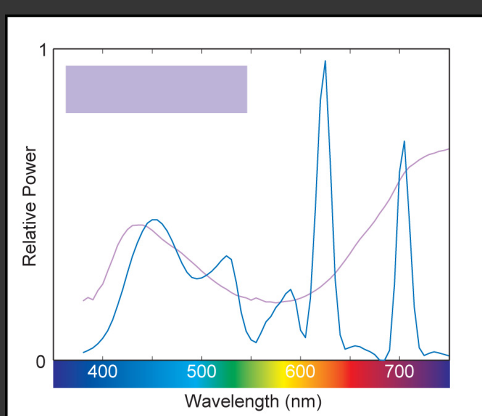
$$L = \int \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$

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

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

Metamers

All spectra that stimulate the same cone response are indistinguishable

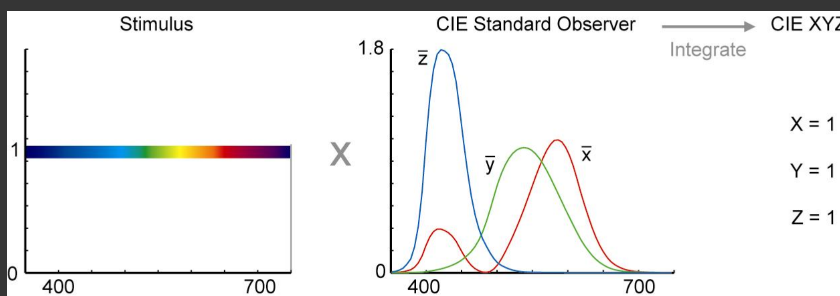


Two different spectra $\Phi_1(\lambda), \Phi_2(\lambda)$ produce same L,M,S response

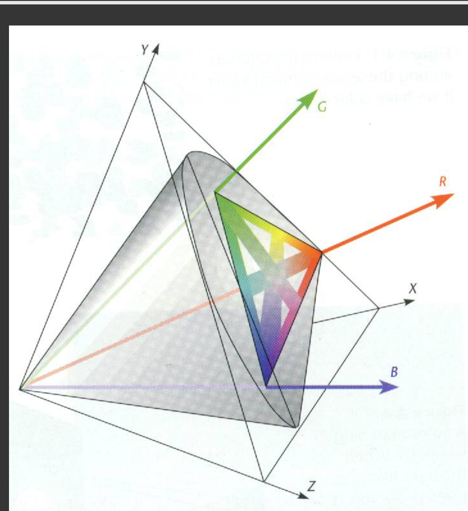
CIE XYZ Color Space

Standardized in 1931 to mathematically represent tri-stimulus response

"Standard observer" response curves



Chromaticity Diagram



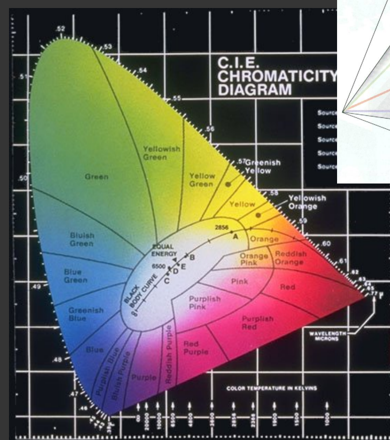
Colin Ware

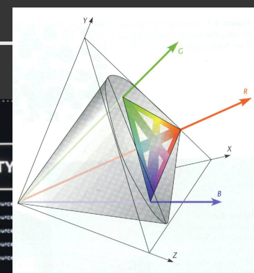
Chromaticity Diagram

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

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

$1 = x+y+z$

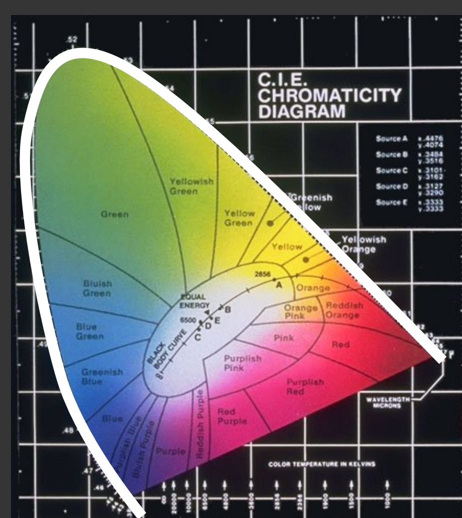




Courtesy of PhotoResearch, Inc.

CIE chromaticity diagram

Spectrum locus

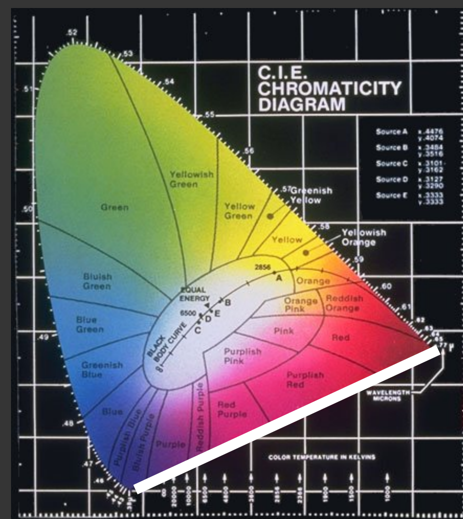


Courtesy of PhotoResearch, Inc.

CIE chromaticity diagram

Spectrum locus

Purple line



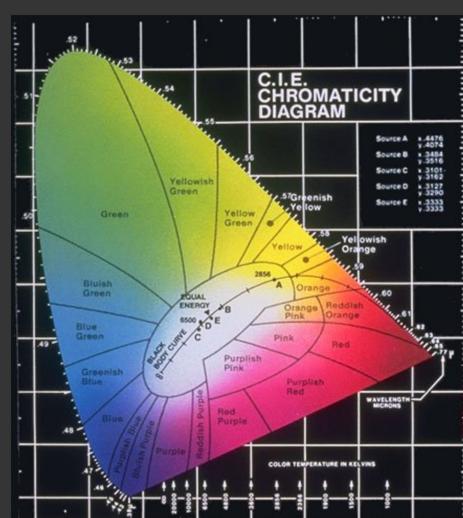
Courtesy of PhotoResearch, Inc.

CIE chromaticity diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line



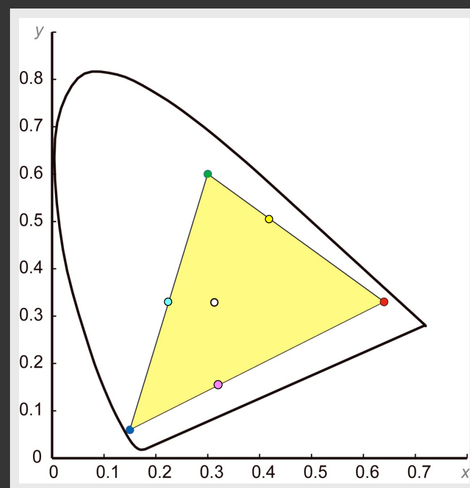
Courtesy of PhotoResearch, Inc.

Display Gamut

Typically defined by:

3 “Primaries”

Convex region



Other Gamuts

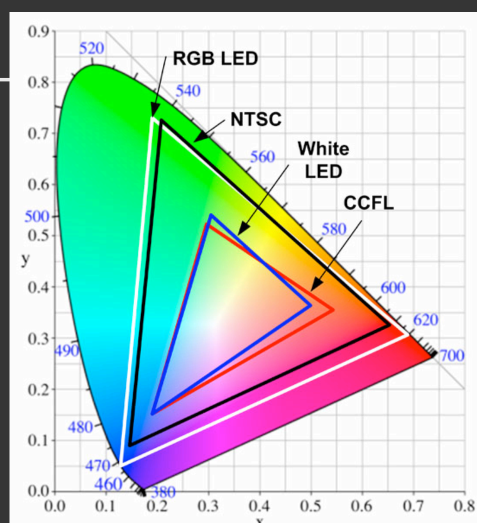
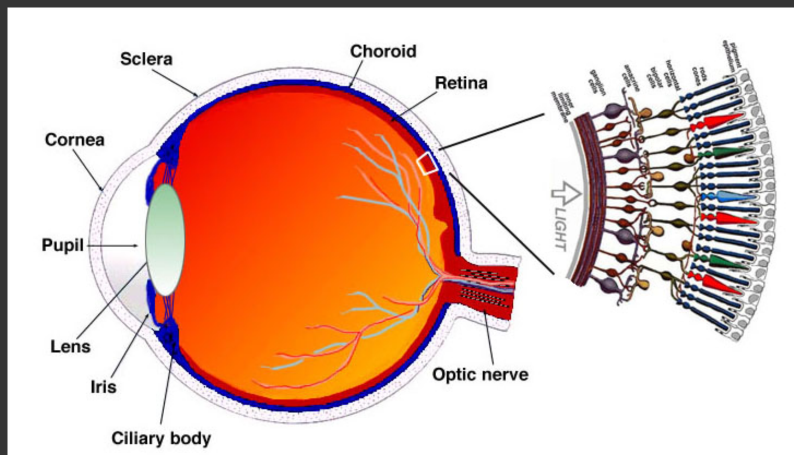


Fig. 3. The color gamut of LCDs with backlights employing CCFL, white LEDs and RGB LEDs are shown here along with the NTSC (television) color gamut.

Retina



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Color Models

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

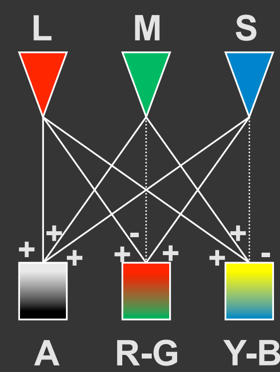
Opponent processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Fairchild

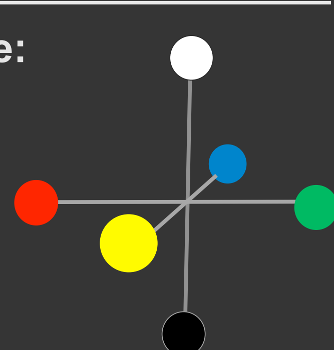
Opponent processing

LMS are combined to create:

Lightness

Red-green contrast

Yellow-blue contrast



Opponent processing

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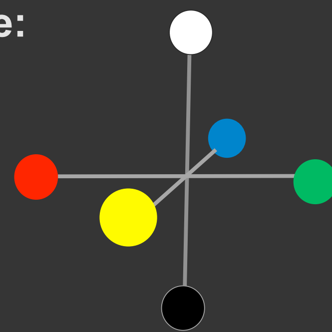


Experiments:

No reddish green, no bluish yellow

Color after images

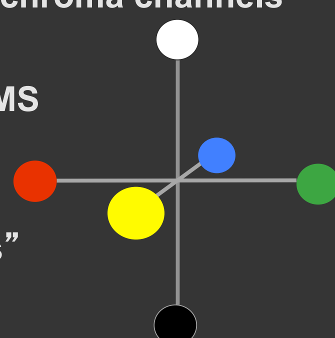
Opponent Color

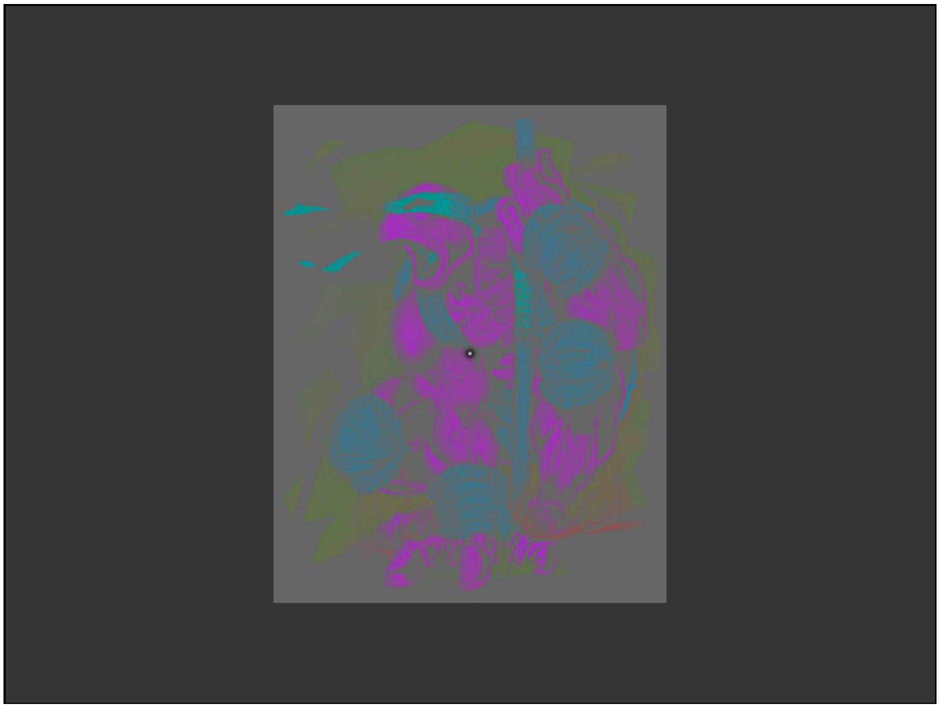
Definition

- Achromatic axis
- R-G and Y-B axis
- Separate lightness from chroma channels

First level encoding

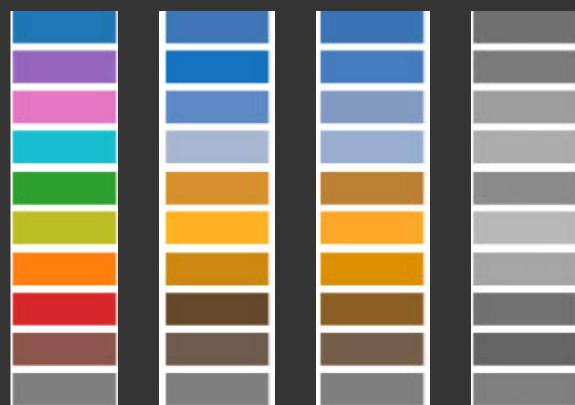
- Linear combination of LMS
- Before optic nerve
- Basis for perception
- Defines “color blindness”





Color blindness

Missing one or more retina cones or rods



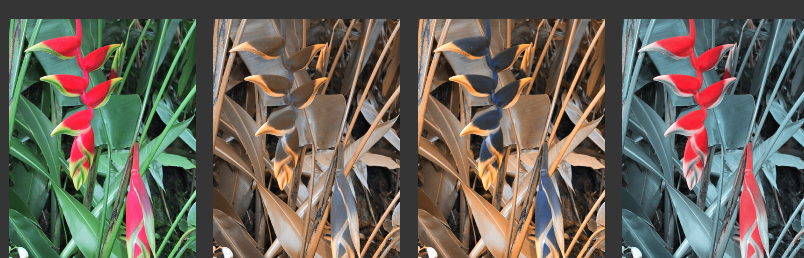
Protanope Deuteranope Luminance

Vischeck

Simulates color vision deficiencies

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

www.vischeck.com



Deuteranope Protanope Tritanope

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			CIELAB Munsell (HVC)	CIECAM02

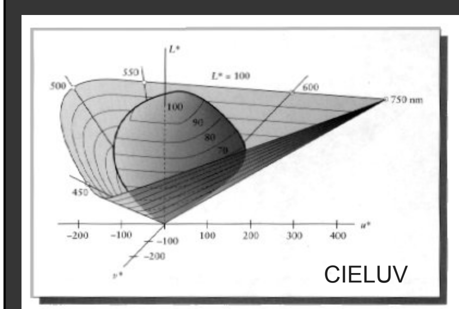
Color differences
"Intuitive" color spaces

Color scales

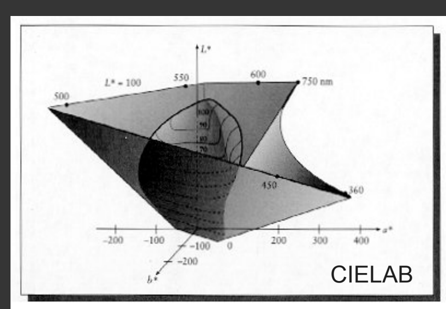
CIE LAB and LUV color spaces

Standardized in 1976 to mathematically represent opponent processing theory

Non-linear transformation of CIE XYZ



CIELUV



CIELAB

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"

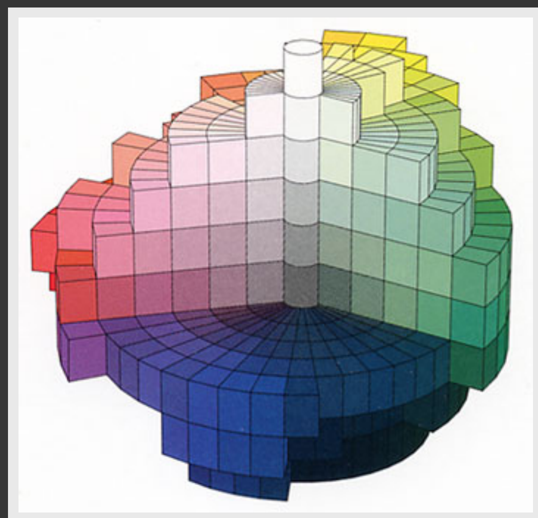
JND = Just noticeable difference (~2.3 units)

Munsell Atlas

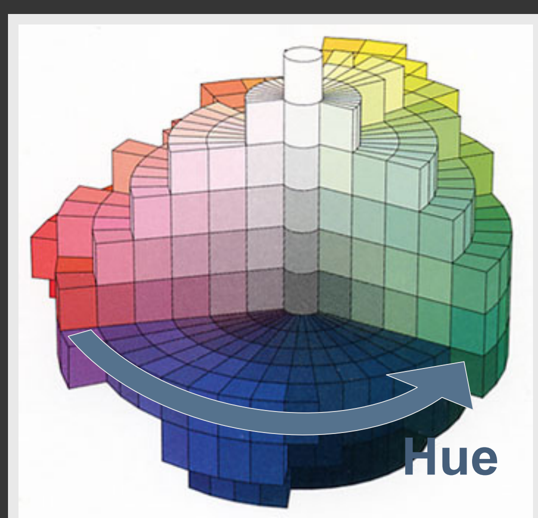
Developed the first perceptual color system based on his experience as an artist (1905)

Courtesy Gretag-Macbeth

Hue, Value, Chroma



Hue, Value, Chroma



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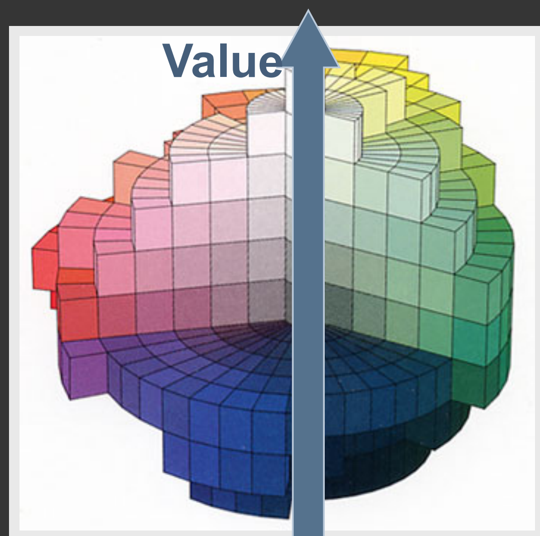

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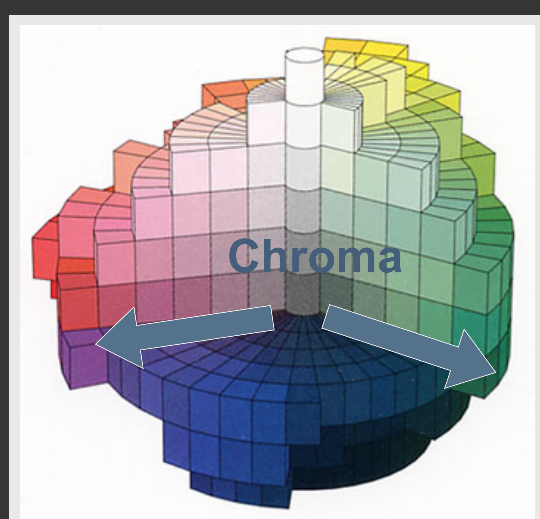


Psuedo-Perceptual Models

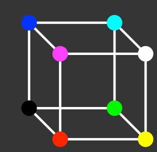
HLS, HSV, HSB

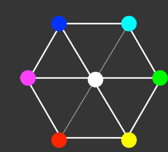
NOT perceptual models

Simple renotation of RGB

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

Cannot predict perceived lightness



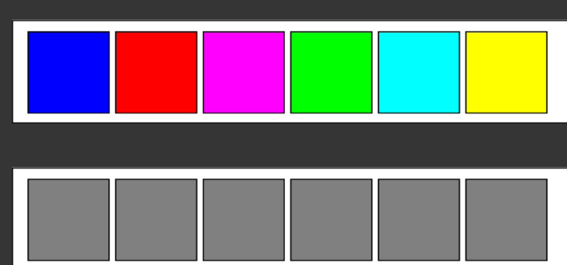


Perceptual brightness

Color palette

HSL Lightness

(Photoshop)

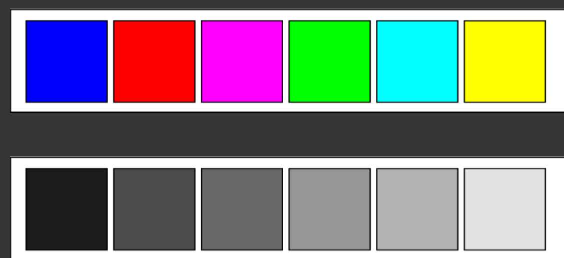


Perceptual brightness

Color palette

Luminance Y

(CIE XYZ)

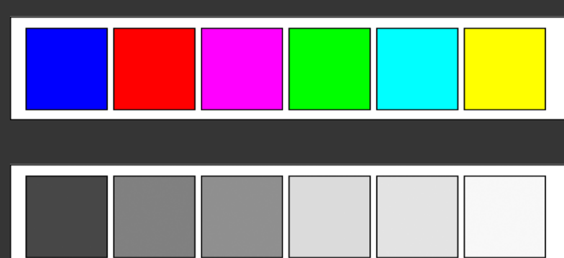


Perceptual brightness

Color palette

Munsell Value

L* (CIE LAB)



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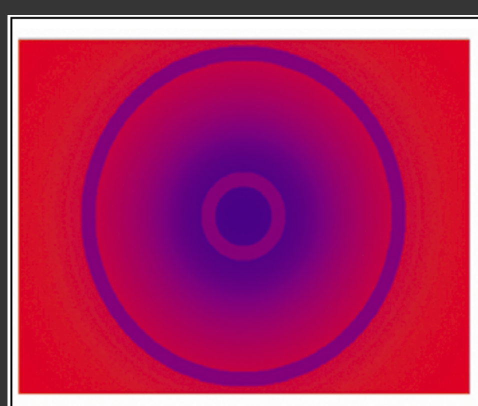
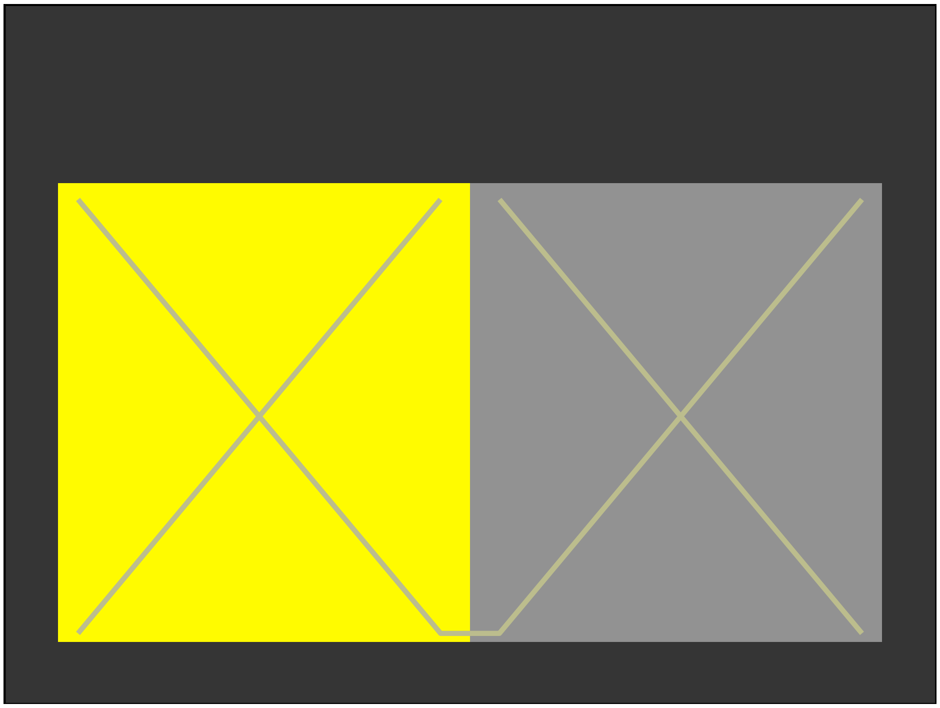
			CIELAB Munsell (HVC)	CIECAM02
				Adaptation Contrast effects Image appearance Complex matching

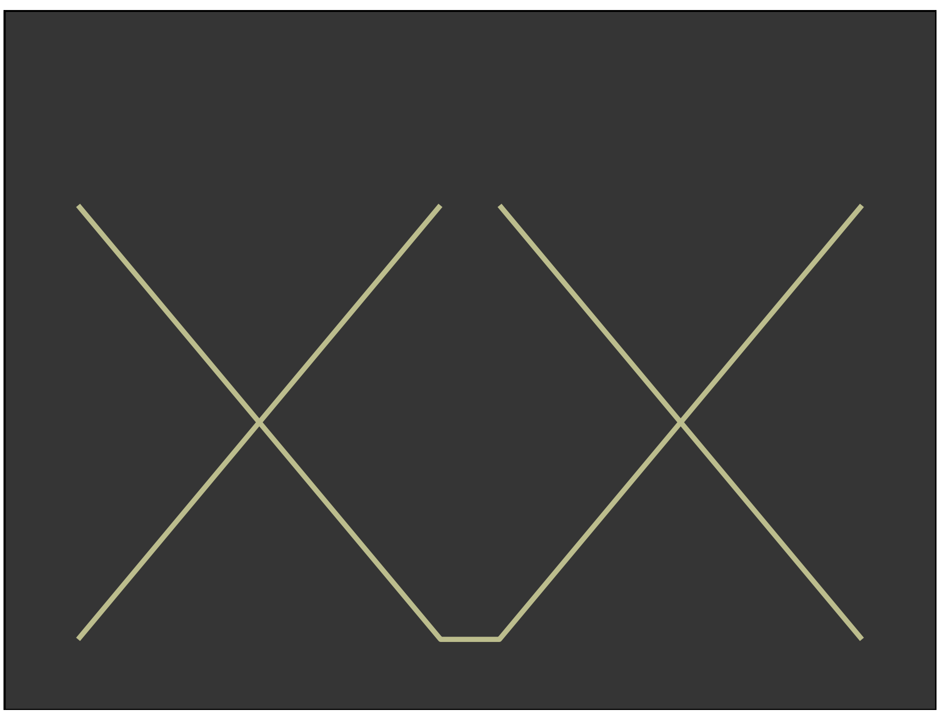
Simultaneous Contrast

The inner and outer thin rings are the physical purple

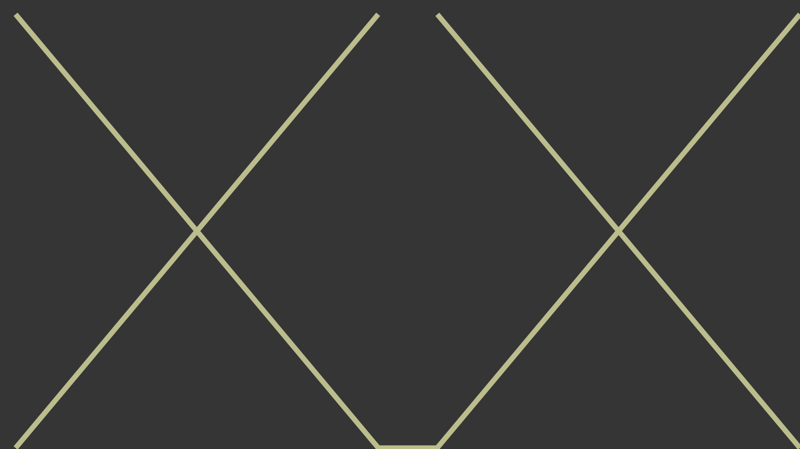


Donald MacLeod



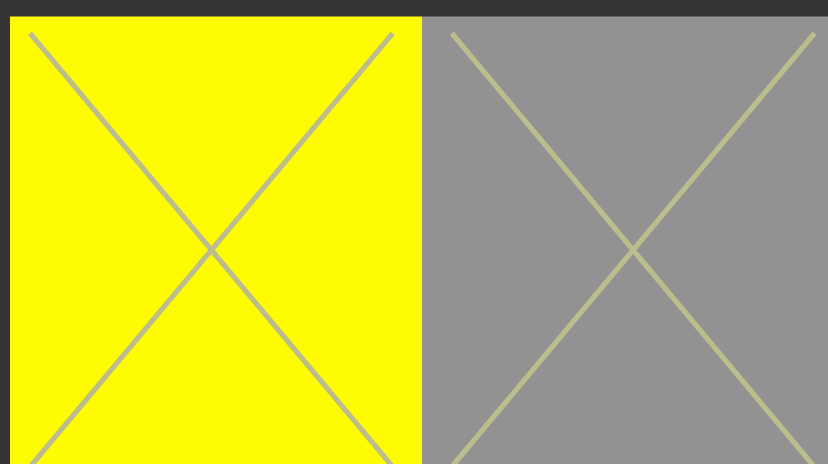


Simultaneous Contrast



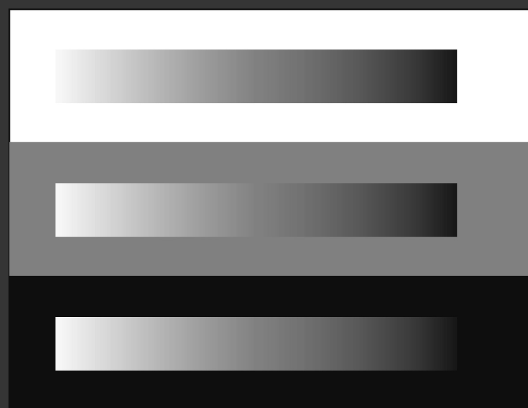
Josef Albers

Simultaneous Contrast

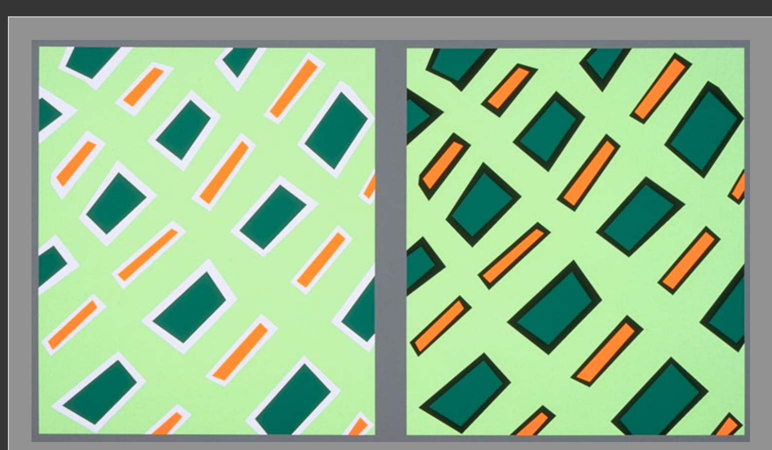


Josef Albers

Affects Lightness Scale

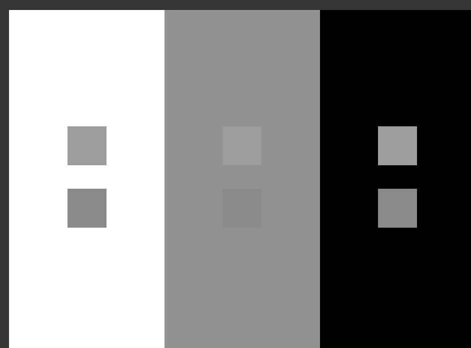


Bezold Effect



Crispening

Perceived difference depends on background



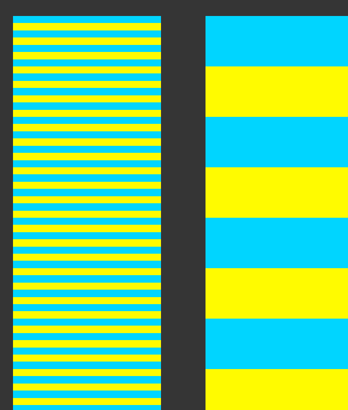
From Fairchild, *Color Appearance Models*

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

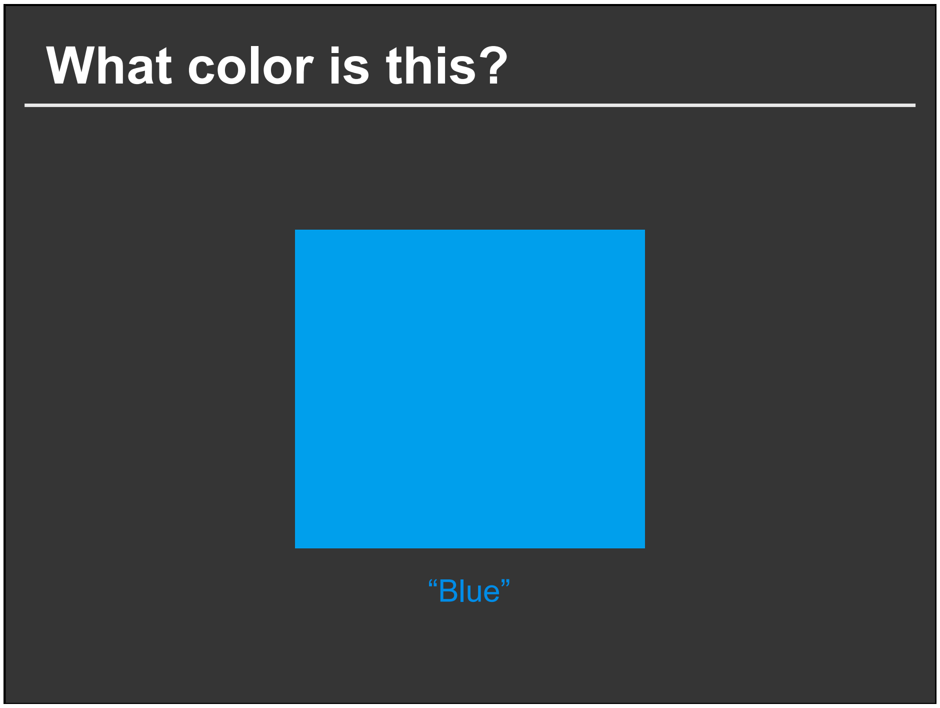
Color Naming

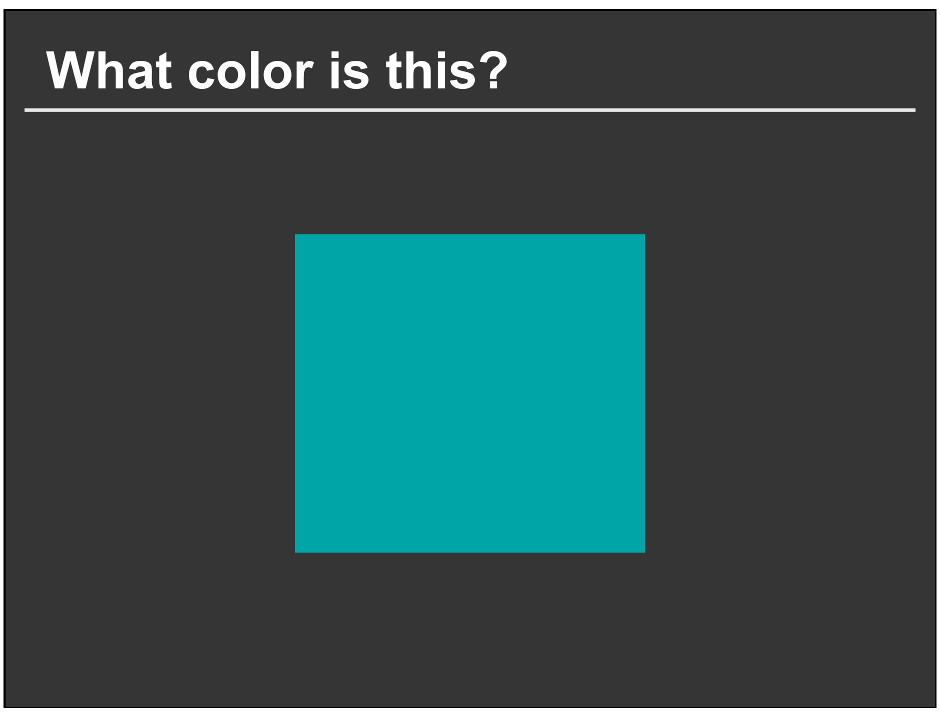
What color is this?

What color is this?

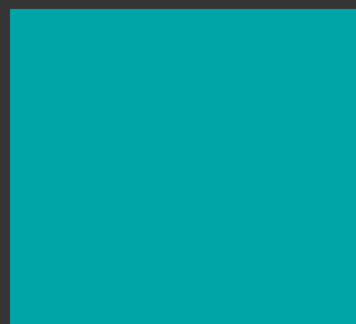
"Yellow"

What color is this?


What color is this?
“Blue”


What color is this?

What color is this?



"Teal" ?

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

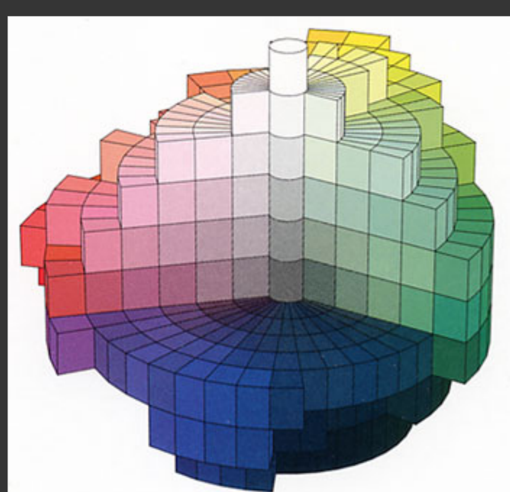
Chance discovery by Brent Berlin and Paul Kay

Initial study in 1969

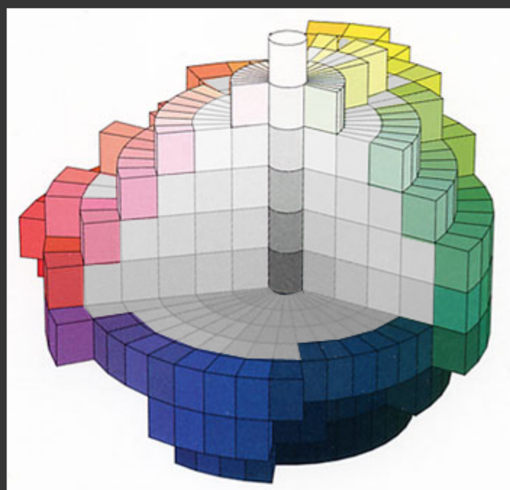
Surveyed speakers from 20 languages

Literature from 69 languages

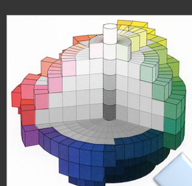
World color survey



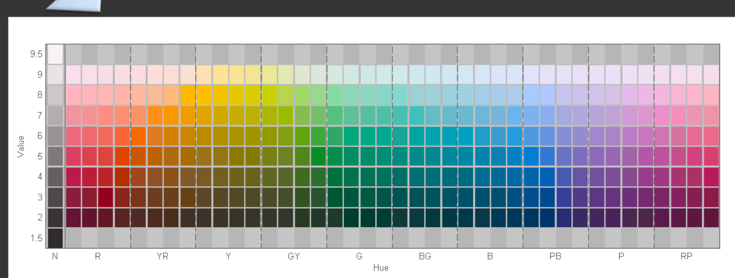
World color survey



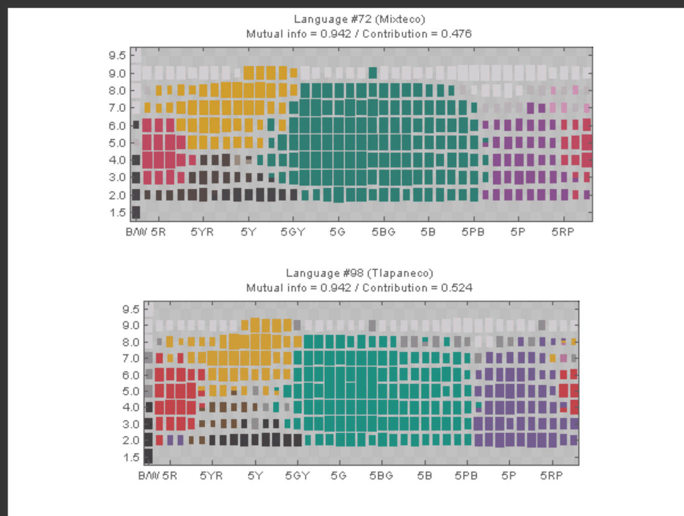
World color survey



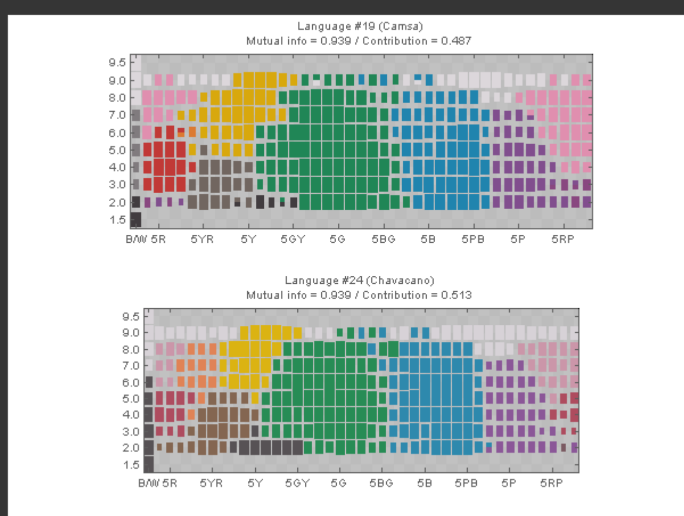
Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



Results from WCS (Mexico)



Results from WCS (South Pacific)



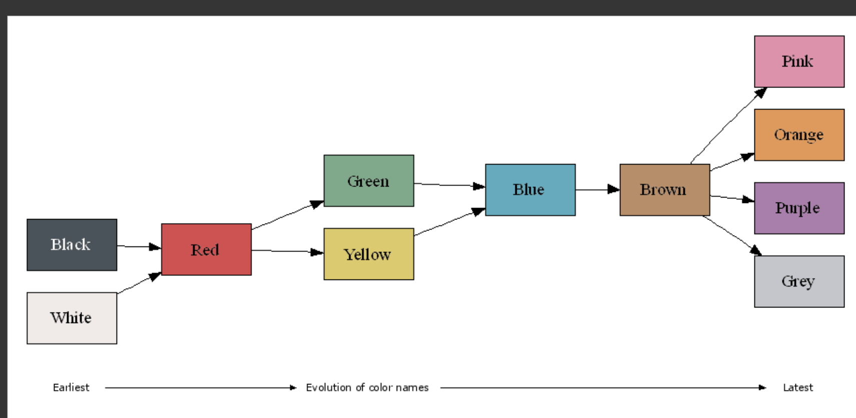
Universal (?) Basic Color Terms

Basic color terms recur across languages

White Red Pink
Grey Yellow Brown
Black Green Orange
Blue Purple

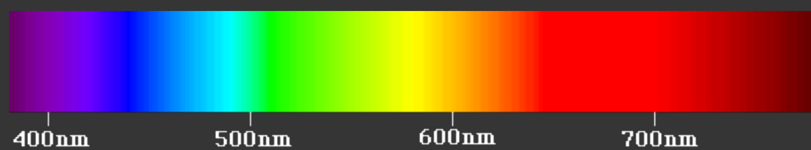
Evolution of Basic Color Terms

Proposed universal evolution across languages



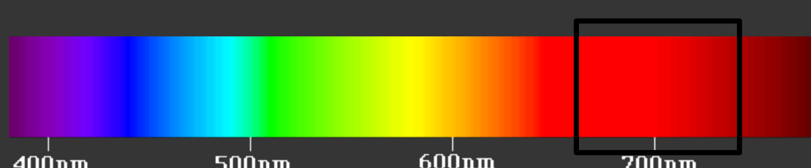
Rainbow color ramp

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



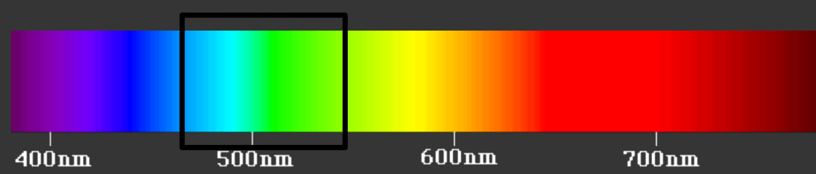
Rainbow color ramp

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



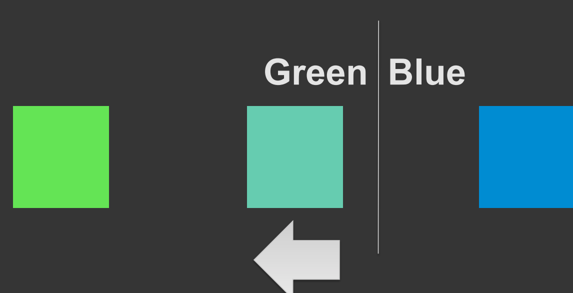
Rainbow color ramp

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



Naming affects color perception

Color name boundaries



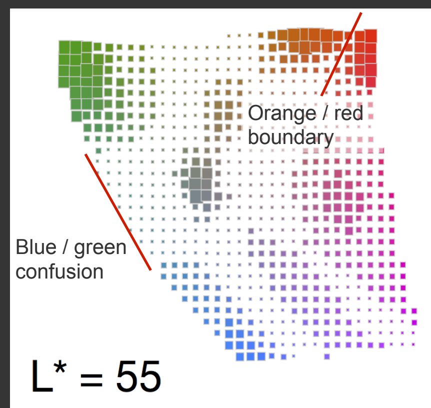
Color naming models

[Heer & Stone]

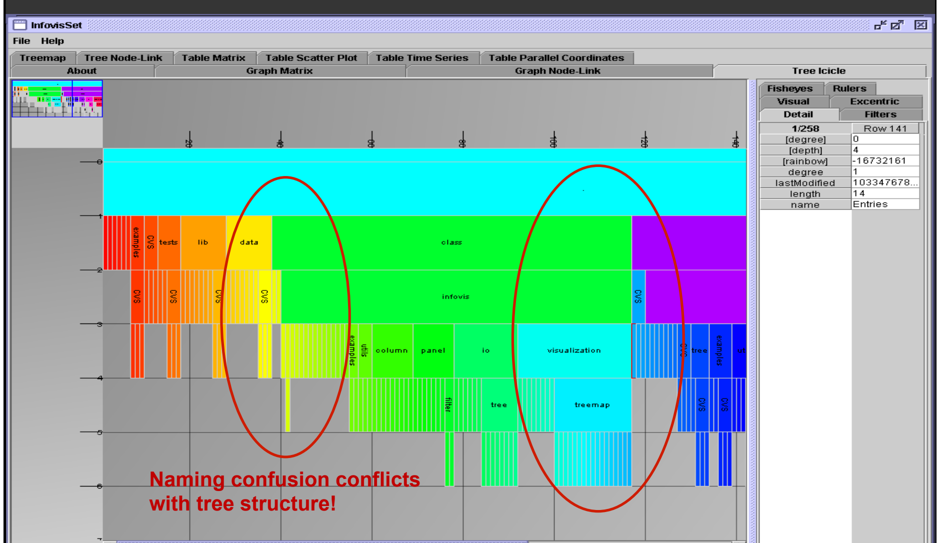
Model 3 million responses from XKCD survey

Bins in LAB space sized by *saliency*:
How much do people agree on color name?

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



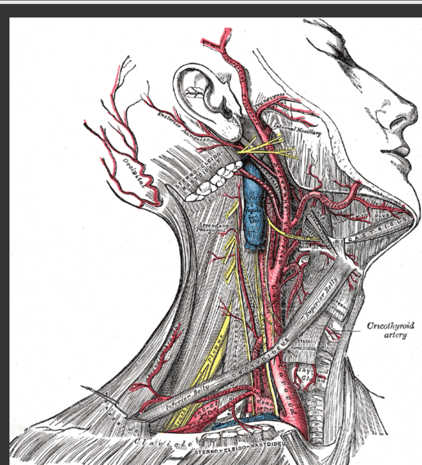
Icicle tree with colors



Using Color in Visualization

To Label

Gray's Anatomy



Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries

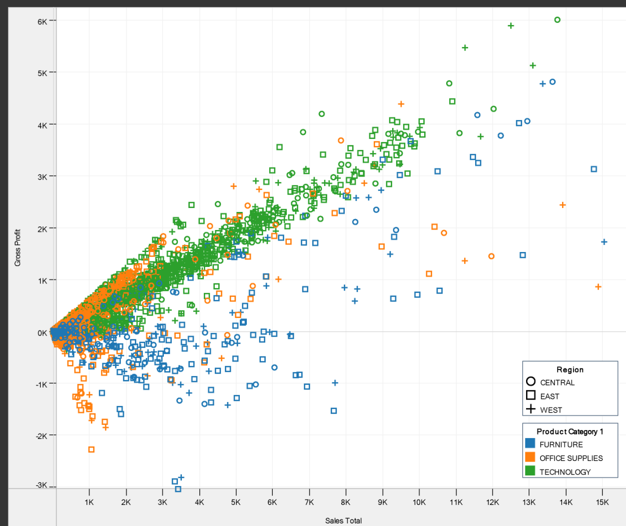
http://www.bartleby.com/107/illus520.html

Molecular Models

Organic Chemistry Molecular Model Set

http://www.indigo.com/models/gphmodel/62003.html

Product Categories



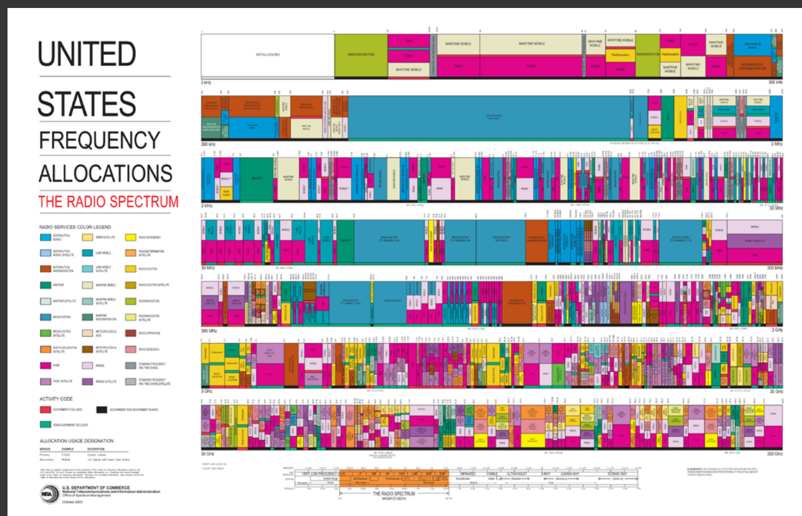
Created by Tableau - Visual Analysis for Databases™

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

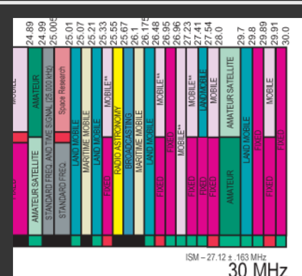
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
red	25.37	13.70	0.05	26.27	14.13	0.04	18.41	10.16	0.05	17.43	9.30	0.00
green	22.14	51.24	0.35	20.68	49.17	0.44	21.11	46.00	0.20	16.36	37.95	0.12
blue	13.17	3.71	74.89	15.38	5.20	86.83	11.55	3.37	65.53	9.96	3.44	56.14
gray	63.46	73.30	78.05	64.66	71.99	90.08	52.96	62.49	67.99	45.54	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

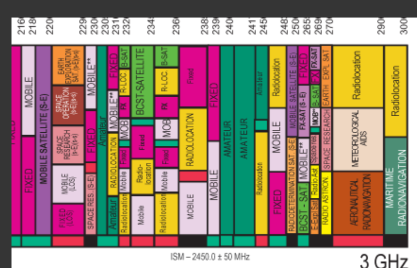
Radio Spectrum Map (33 colors)



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

Distinguishable on Inspection





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