Information Visualization and Visual Analytics (M1522.000500)

Map Color and Other Channels

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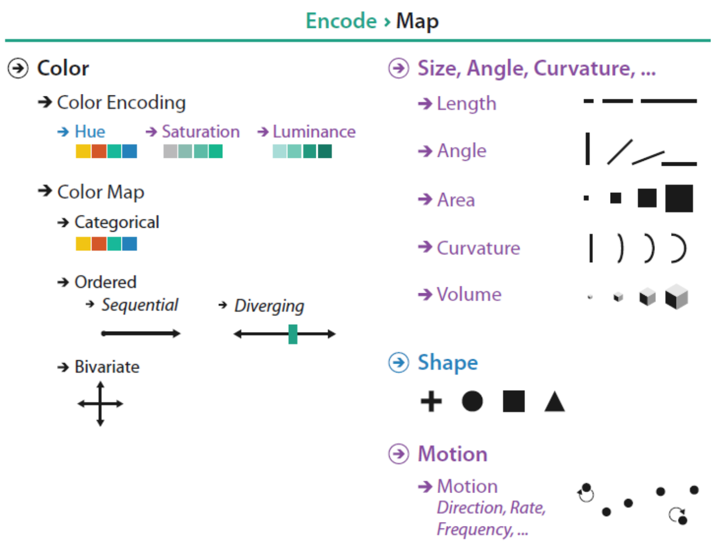
Introduction

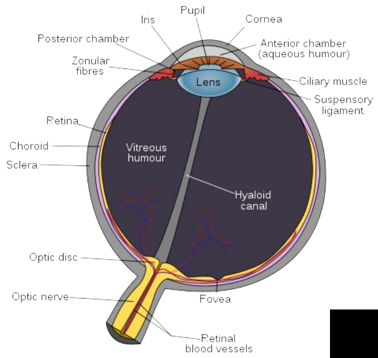
The Big Picture

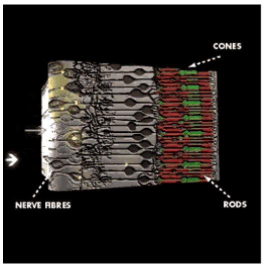
- Design choices for mapping
  - Color
  - Others



Rods and Cones

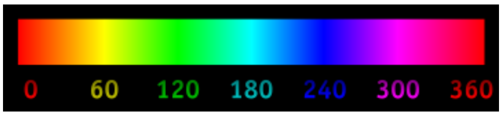
- Rods (or Rod Cells)
  - active at low light levels
    - night vision
  - only one wavelength sensitivity function
  - 100 million rod receptors
- Cones (or Cone Cells) for Color
  - convert spectra to 3 cone response signals
  - active at normal light levels
  - three types: sensitivity functions peaks at different wavelengths
    - red(Long), green(Medium), blue(Short)
  - 6 million cone receptors
  - Focused in the center of vision (fovea)

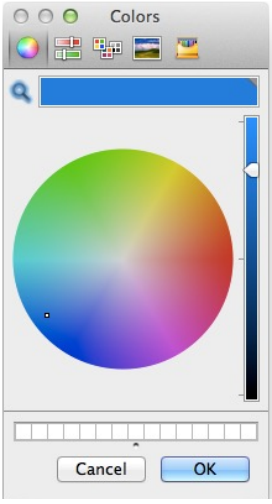




Terms

- Luminance
  - physically measured amount of light
- Brightness
  - perceived (relative, not absolute) amount of light
  - brightness is nonlinear
- Lightness
  - perceived reflectance of a surface
  - lightness depends on a reference white
  - a white surface is **light**, but a black surface is **dark**
  - amount of BLACK mixed with a pure color (≠ perceived luminance)
- Hue
  - (pure) color
- Saturation (colorfulness)
  - perceived intensity of a specific color
  - strength or vividness
  - amount of WHITE mixed with a pure color





Luminance is not Brightness

We are change meters!

- Eye sensitive over 9 orders of magnitude
- 5 orders of magnitude (room – sunlight)

- Receptors bleach and become less sensitive with more light
- Takes up to ***half an hour*** to recover sensitivity

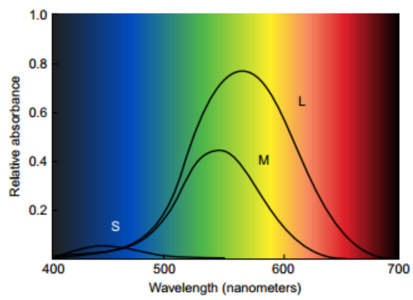
- We are not light meters, but **change** meters
  - Nervous system works by computing **difference** in signals
  - precise absolute numerical values ☹
  - patterns of differences or changes over time ☺
    - the eye and brain are extremely sensitive to

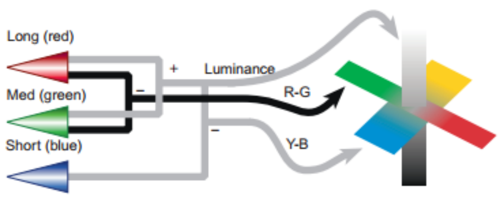
Color Theory

Color Vision

- Rods: Low light settings, black-white
- Cones: Normal light settings, color
- 3 Opponent channels
  - Red-Green, Blue-Yellow, Black-White

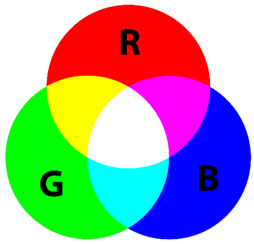
  *Related to colorblind
- Luminance and chromaticity
  - Luminance: High resolution
  - Chromaticity: Lower resolution

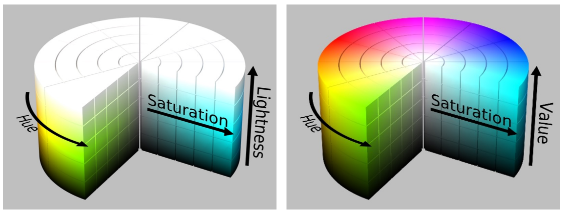




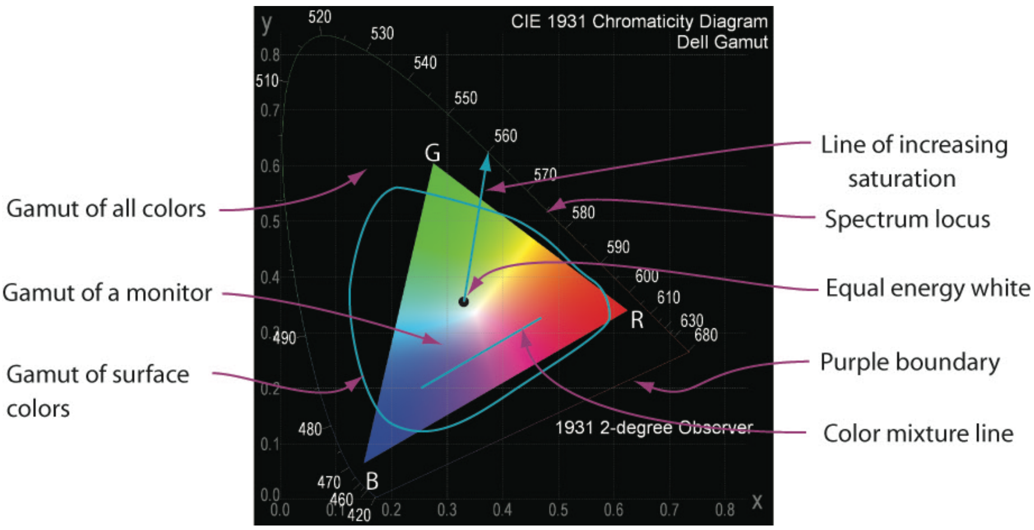
Color Space

- Mathematical ways to describe color w/ 3 parameters
- RGB: computationally easy, poor match with real mechanics of how we see
- HSL: Hue, Saturation, Lightness
  - Pseudo-perceptual (not really perceptual)
- HSV: Hue, Saturation, Value(for grayscale)
- CIEXYZ
- …





International Standards



The colored triangle represents the gamut of a computer monitor. Colors as shown are only approximate.

Three Independent Channels

- The quality of having **three** independent channels for conveying color information in the eye.

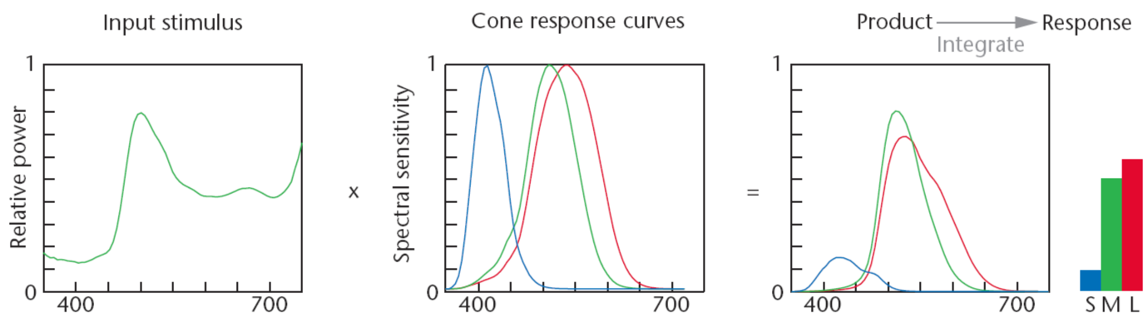
- Condition of possessing three independent channels for conveying color information, derived from the three different cone types,

  - *A Glossary of Color Science*

- Retina contains three types of color receptors (called cone cells in vertebrates) with different absorption spectra.

Input x Con response curve → Three Values

- All spectra can be reduced to precisely three values without loss of information with re spect to the visual system

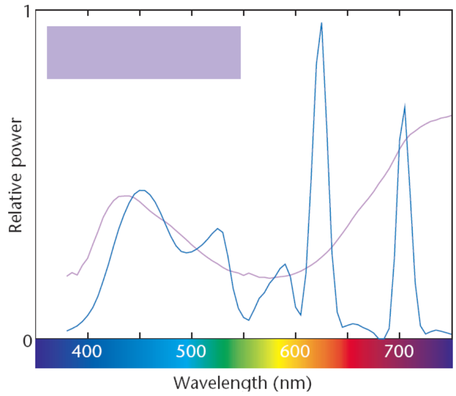


2 Multiplying a spectrum times the cone response curves and integrating the result creates the basic color signal to the brain. The height of the bars reflects the strength of the three signals. (Reprinted by permission from A K Peters Ltd.)

Metamerism

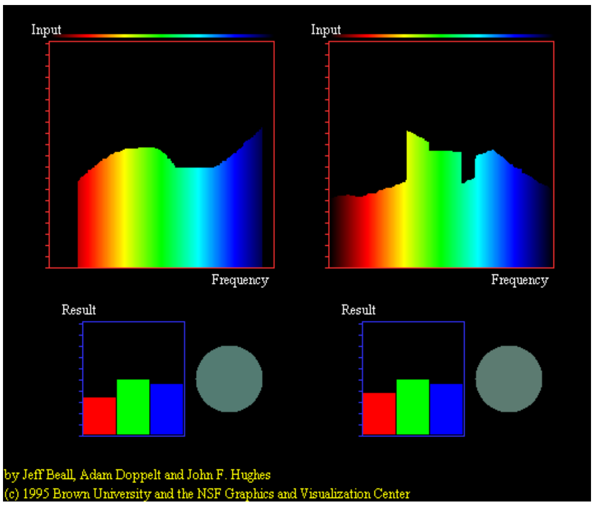
Ambiguity in trichromacy

- Any spectra that create the same trichromatic response are indistinguishable
- Different spectral distributions that are perceived as identical colors if they stimulate the same cone response.



Metamerism

Metamers Demo



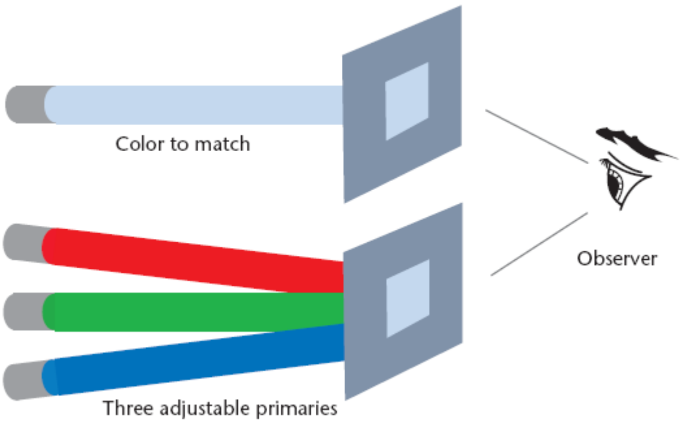
http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/spectrum/metamers_java_browser.html

Model of Standard Observer

- Color-matching experiments in the 1920s and 1930s
- a large percentage of test subjects created color matches
- similar enough to establish a model of a statistically derived standard observer

Color Matching Functions

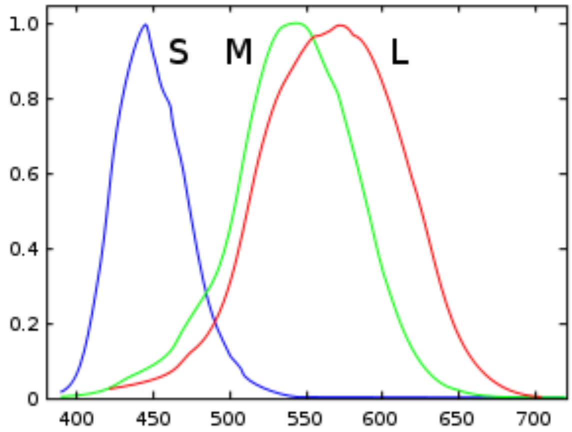
- Color Matching Experiment
  - An observer adjust three primary lights to match each smaple color



Stone, Representing Color As Three Numbers, CG&A 25(4):78-85

Primary Colors of Light

- Red, Green, Blue
- Why we choose these three
- Among 6-7 million cone cells of our eye,
  - 65% is sensitive to red (630 nm): L cones
  - 33% is sensitive to green (530 nm): M cones
  - 2% is sensitive to blue (450 nm): S cones

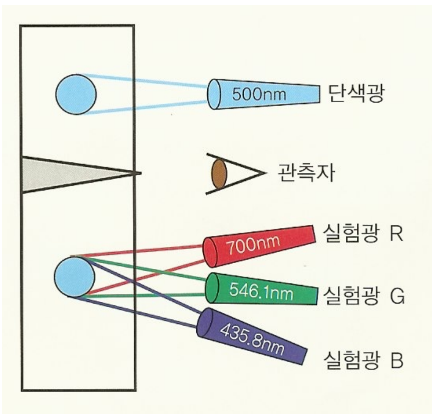


Color Matching Functions

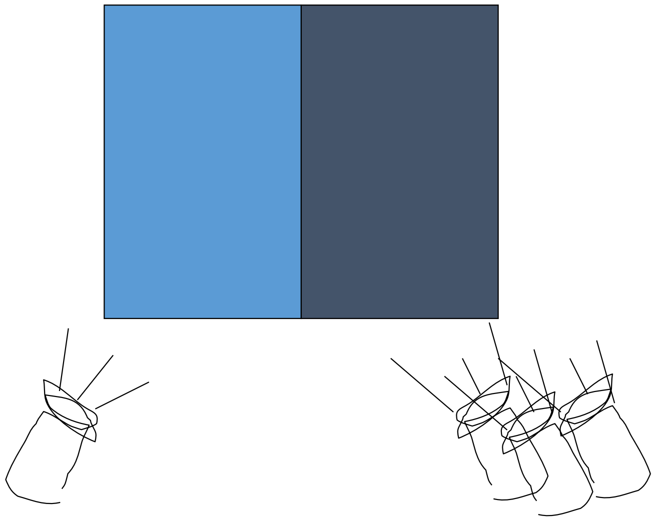
- Tri-stimulus ➔ the amount of R, G, B lights to form a certain color

$$C(\lambda) = r(\lambda)\mathrm{R} + g(\lambda)\mathrm{G} + b(\lambda)\mathrm{B}$$

- From the *color matching experiment*
  - Conducted by W. David Wright and John Guild in the 1920s



Experiment 1



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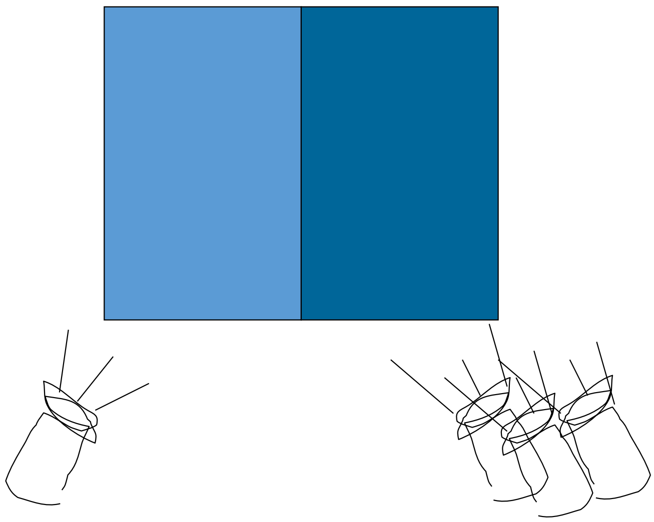
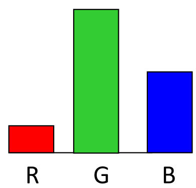


R: 700.0 nm
G: 546.1 nm
B: 435.8 nm



Color Matching Experiment

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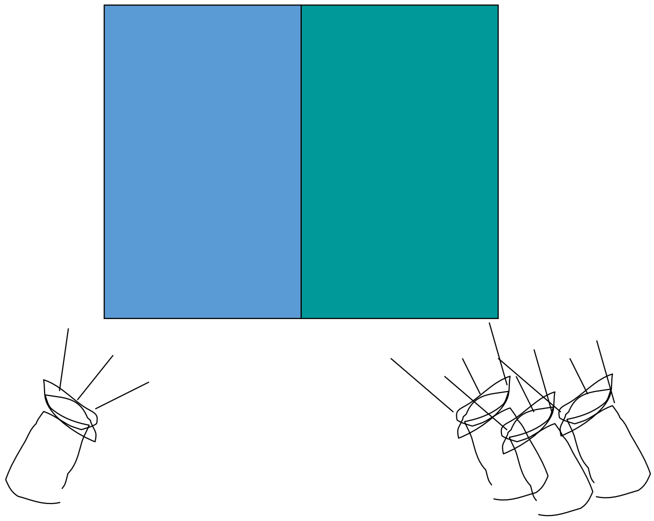

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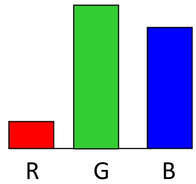
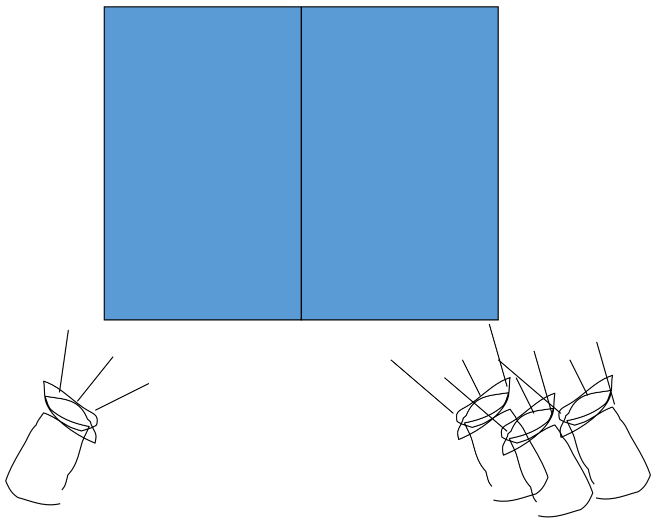
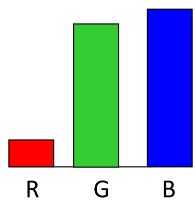


Color Matching Experiment

Experiment 1

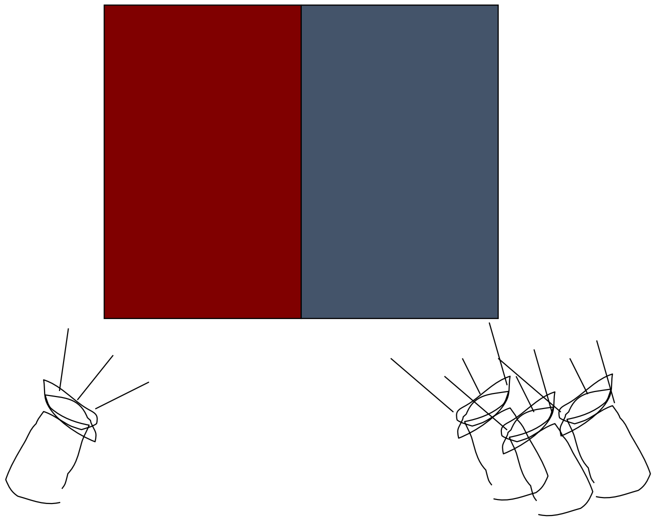


The primary color amounts needed for a match

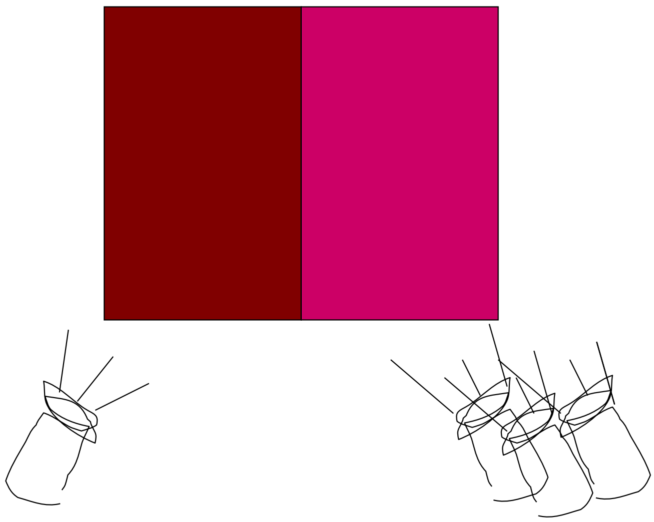


Information Visualization and Visual Analytics – Map Color & Other Channels

Experiment 2



Experiment 2



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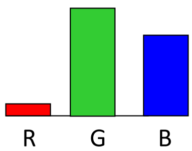

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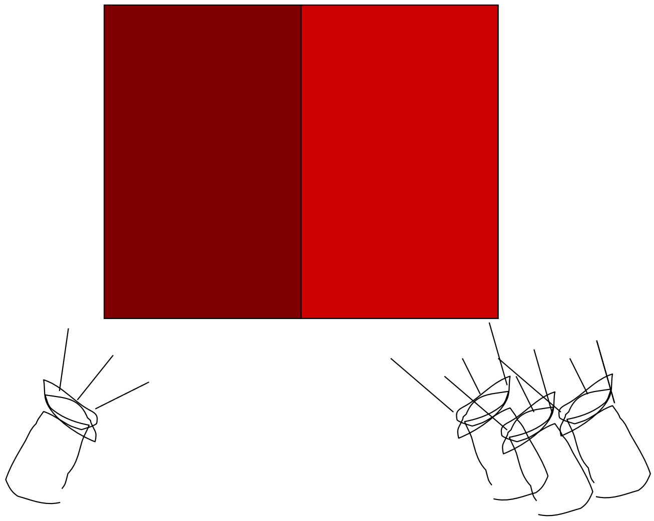

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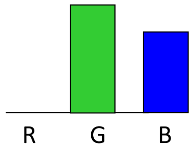
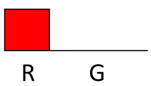
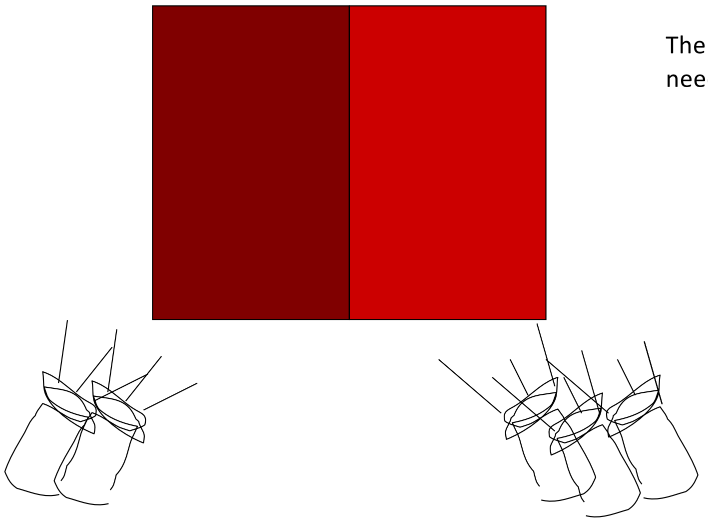


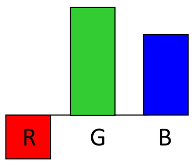
Experiment 2

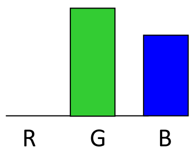
We say a "negative" amount of R was needed to make the match, because we added it to the test color's side.





The primary color amounts needed for a match:



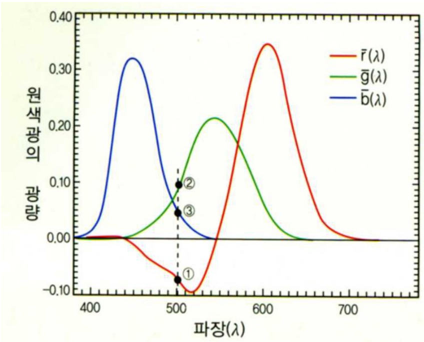


CIERGB Color System

- A color system published in 1931 by CIE (International Commission on Illumination)
- Based on experimental results
- When we use R,G,B color, we have negative primaries

[표 3-1] 컬러 매칭 함수 $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$ [CIE, No.15.2]

파장 (λ nm)	컬러 매칭 함수		
	$\bar{r}(\lambda)$	$\bar{g}(\lambda)$	$\bar{b}(\lambda)$
380	0.00003	−0.00001	0.00117
400	0.00030	−0.00014	0.01214
420	0.00211	−0.00110	0.11541
440	−0.00261	0.00149	0.31228
460	−0.02608	0.01485	0.29821
480	−0.04939	0.03914	0.14494
500	−0.07173	0.08536	0.04776
…	…	…	…
760	0.00006	0.00000	0.00000
780	0.00000	0.00000	0.00000



CIERGB Color Matching Functions

CIERGB Color System

- Normalize:

$$r(\lambda)=\frac{\bar{r}(\lambda)}{\bar{r}(\lambda)+\bar{g}(\lambda)+\bar{b}(\lambda)}$$

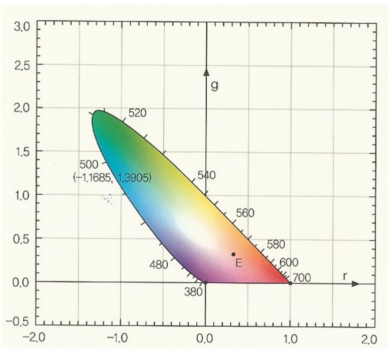
$$g(\lambda)=\frac{\bar{g}(\lambda)}{\bar{r}(\lambda)+\bar{g}(\lambda)+\bar{b}(\lambda)}$$

$$b(\lambda)=\frac{\bar{b}(\lambda)}{\bar{r}(\lambda)+\bar{g}(\lambda)+\bar{b}(\lambda)}$$

[표 3-2] 컬러 매칭 함수와 색도 좌표 [CIE, No. 15.2]

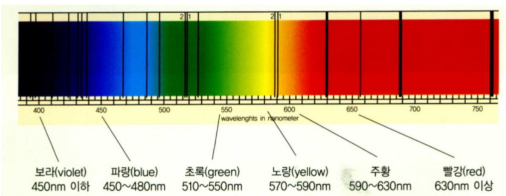
(시야각 : 2°)

파장 (λ nm)	컬러 매칭 함수			색도 좌표		
	$\bar{r}(\lambda)$	$\bar{g}(\lambda)$	$\bar{b}(\lambda)$	$r(\lambda)$	$g(\lambda)$	$b(\lambda)$
380	0.00003	−0.00001	0.00117	0.0272	−0.0115	0.9843
400	0.00030	−0.00014	0.01214	0.0247	−0.0112	0.9865
420	0.00211	−0.00110	0.11541	0.0181	−0.0094	0.9913
440	−0.00261	0.00149	0.31228	−0.0084	0.0048	1.0036
460	−0.02608	0.01485	0.29821	−0.0909	0.0517	1.0392
480	−0.04939	0.03914	0.14494	−0.3667	0.2906	1.0761
500	−0.07173	0.08536	0.04776	−1.1685	1.3905	0.7780
…	…	…	…	…	…	…
760	0.00006	0.00000	0.00000	1.0000	0.0000	0.0000
780	0.00000	0.00000	0.00000	1.0000	0.0000	0.0000



All real colors can be represented as combinations of *r, g* since *r+g+b*=1

rg Chromaticity Diagram



CIEXYZ Color System

- The **dominant international standard** for color specification (1931, by CIE)
- Use three imaginary primary colors, X, Y, and Z
- The following transformation [Dean B. Judd] makes color matching functions positive everywhere

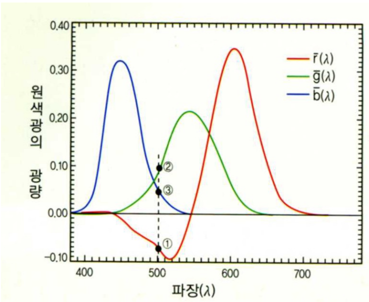
$$\bar{x}(\lambda) = 2.7689\bar{r}(\lambda) + 1.7517\bar{g}(\lambda) + 1.1302\bar{b}(\lambda)$$
$$\bar{y}(\lambda) = 1.0000\bar{r}(\lambda) + 4.5907\bar{g}(\lambda) + 0.0601\bar{b}(\lambda)$$
$$\bar{z}(\lambda) = 0.0000\bar{r}(\lambda) + 0.0565\bar{g}(\lambda) + 5.5943\bar{b}(\lambda)$$

CIEXYZ Color System

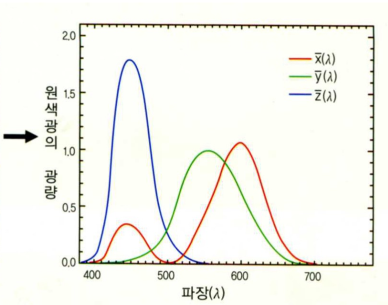
[표 3-3] 컬러 매칭 함수와 비교 표[CIE, No. 15.2]

(시야각 : 2°)

파장 (λ nm)	컬러 매칭 함수			컬러 매칭 함수		
	$\bar{r}(\lambda)$	$\bar{g}(\lambda)$	$\bar{b}(\lambda)$	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$
380	0.00003	−0.00001	0.00117	0.0014	0.0000	0.0065
400	0.00030	−0.00014	0.01214	0.0143	0.0004	0.0679
420	0.00211	−0.00110	0.11541	0.1344	0.0040	0.6456
440	−0.00261	0.00149	0.31228	0.3483	0.0230	1.7471
460	−0.02608	0.01485	0.29821	0.2908	0.0600	1.6692
480	−0.04939	0.03914	0.14494	0.0956	0.1390	0.8130
500	−0.07173	0.08536	0.04776	0.0049	0.3230	0.2720
…	…	…	…	…	…	…
760	0.00006	0.00000	0.00000	0.0002	0.0001	0.0000
780	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000



The CIE RGB color matching functions



The CIE XYZ standard observer color matching functions

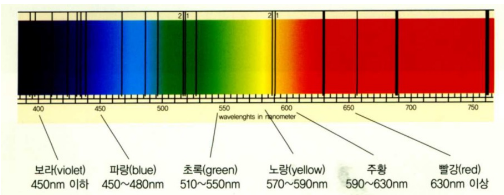
CIEXYZ Color System

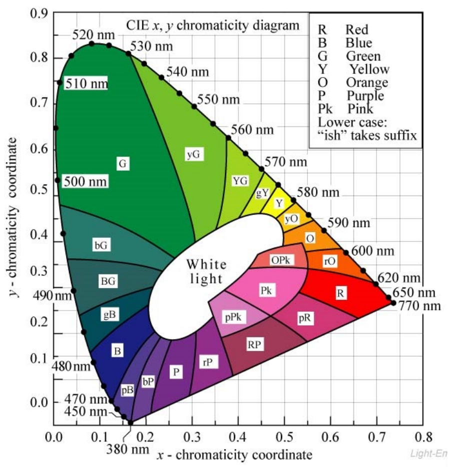
- Normalize:
$$x(\lambda)=\frac{\bar{x}(\lambda)}{\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)}$$
$$y(\lambda)=\frac{\bar{y}(\lambda)}{\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)}$$
$$z(\lambda)=\frac{\bar{z}(\lambda)}{\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)}$$

All real colors can be represented as positive combinations of *x*, *y* since *x*+*y*+*z*=1

CIEXYZ Color System

- **CIE chromaticity diagram** encompasses all the perceivable colors in 2D space (x,y)





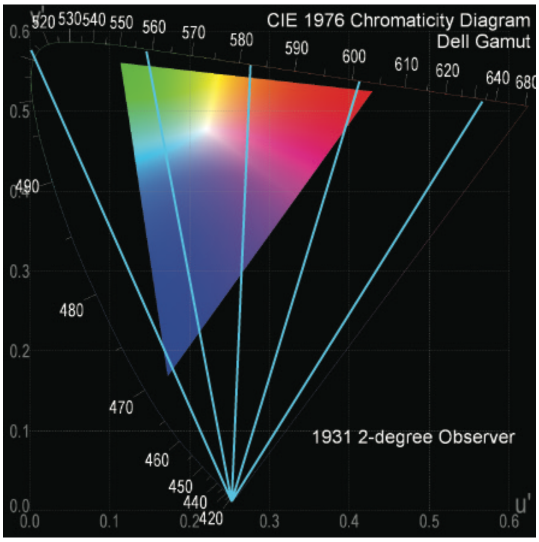
Perceptually Uniform Color Spaces

- CIE XYZ color space is very far from being perceptually uniform

- Two uniform color spaces (by transformations of XYZ)
  - CIElab
  - CIEluv → CIE *Lu'v'* UCS diagram

  - **equally sized steps** appear **equal to our visual systems**

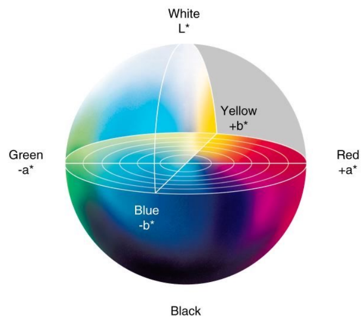
CIEluv Uniform Color Space

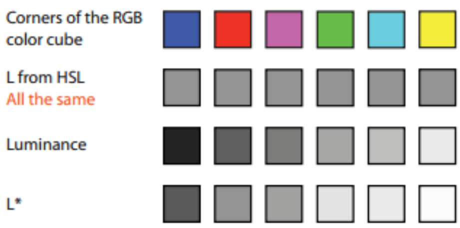


The colored triangle represents the gamut of a computer monitor. Colors as shown are only approximate.

Color Space

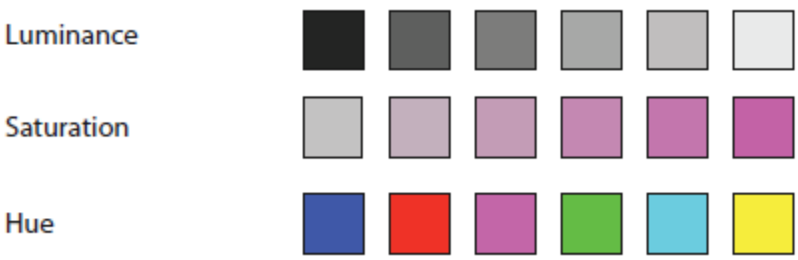
- HSL: popular color space
  - still only pseudo-perceptual
  - Lightness(L) very different from true luminance
- L*a*b*
  - Calibrates the issues on HSL
- Each model can be mathematically converted to each other





Luminance, Saturation and Hue

- Luminance: Amount of physical light
  - *Brightness: Amount of perceived light
- Saturation: Perceived intensity of a specific color
- Hue: Wavelength of light



Luminance as magnitude channel

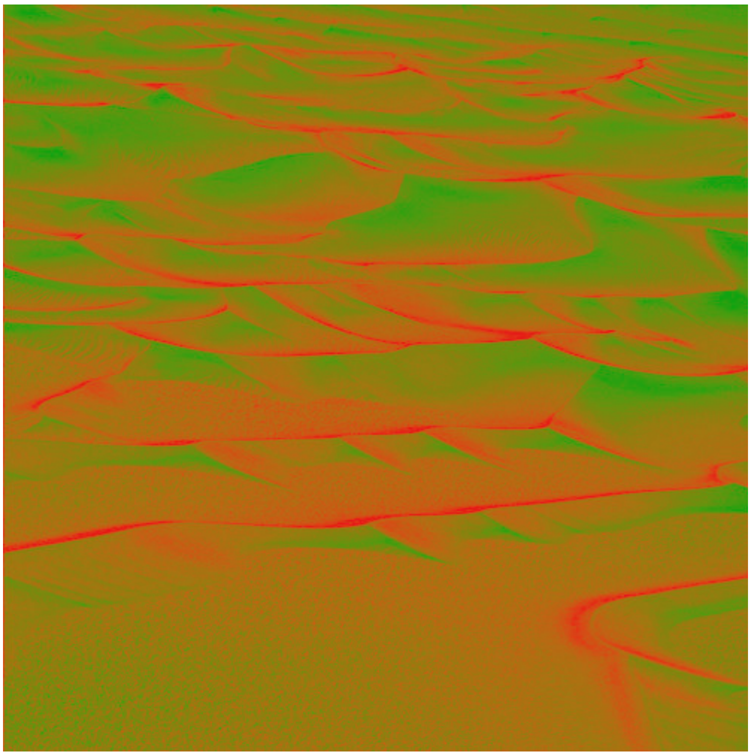
- Magnitude channel of luminance
  - Suitable for ordered data types
  - But, *not accurate* and has many issues
  - Fundamentally, **at most 5 levels** can be used
- Luminance contrast is used for resolving details
  - Resolve fine detail and see crisp edges
  - Fundamentally, minimum 3:1 contrast for text, 10:1 recommended

Luminance Contrast for Details

- Luminance contrast needed to see **detail**
  - 3:1 recommended
  - 10:1 ideal for small text
- Equal luminance makes it hard to read despite a large chromatic difference
- Purely chromatic differences are not suitable for displaying fine detail

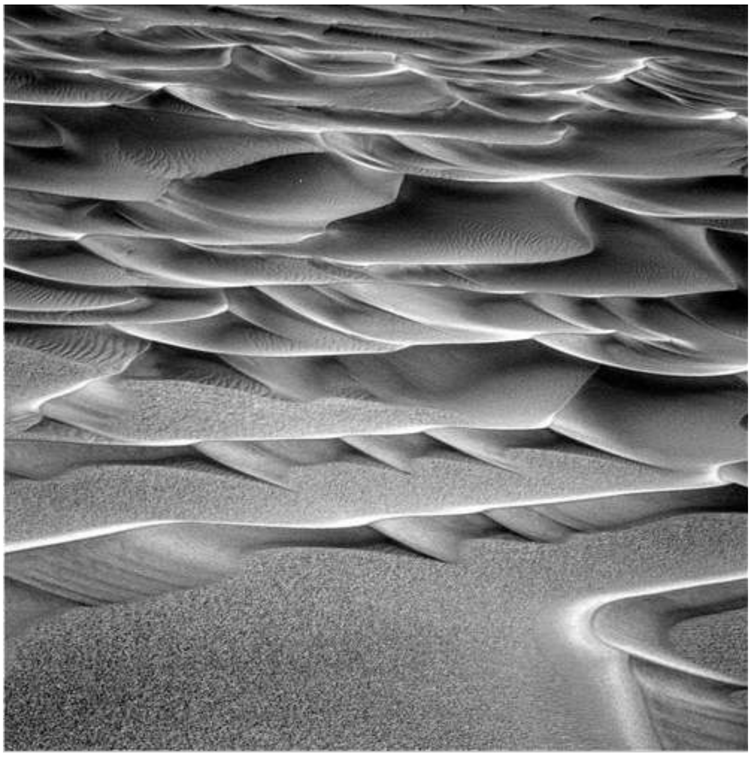
Some Natural philosophers
suppose that these colors arise
from accidental vapours diffused
in the air, which communicate
their own hues to the shadows;

Shape-from-hue



Colin Ware

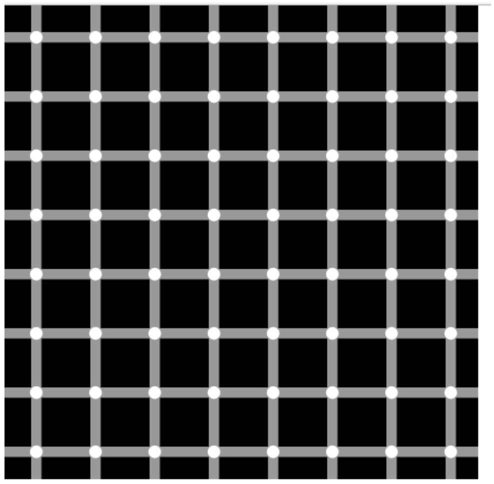
Shape-from-shading



Colin Ware

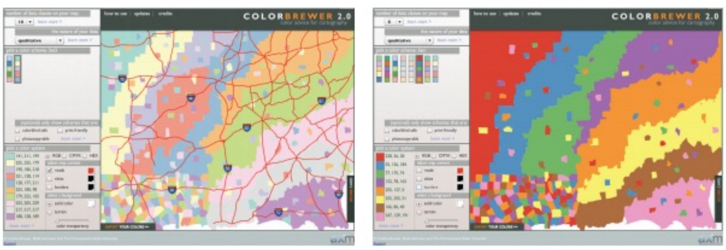
Issues of Luminance

- Luminance is different from brightness
- Brightness is heavily related to the **context** of the environment, and this causes various illusions
  - ex) Hermann Grid Illusion
- For more details, check Ware's book
  - Ware. *Information visualization: perception for design*. Elsevier, 2013



Saturation

- Magnitude of saturation
  - Low accuracy for noncontiguous regions (around 3 levels)
- Related to the size channel
  - More difficult to perceive **when size is small**
  - **bright, highly saturated colors for small regions**
  - **low-saturation (pastel) colors for large regions**



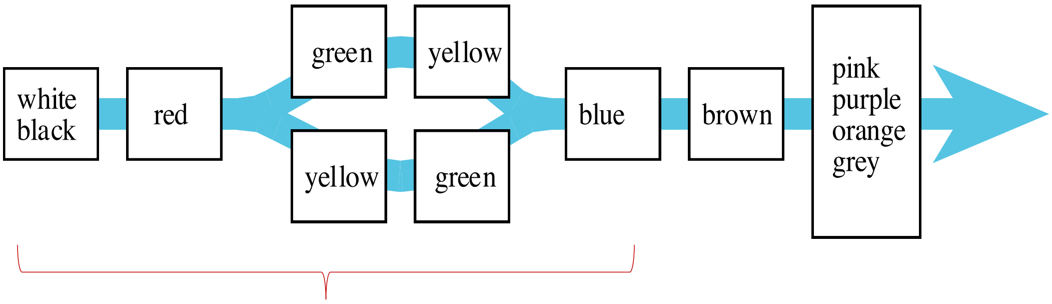
(a) (b)

Hue as identity Channel

- Effective for categorical data / groupings
  - After spatial position
  - No particular order
- Interaction with size channel
  - Harder to perceive in smaller regions
- Make fine distinctions for contiguous regions
- Lower accuracy on discontinuous regions
  - About 6~7 levels can be distinguished

Cross-Cultural Color Naming

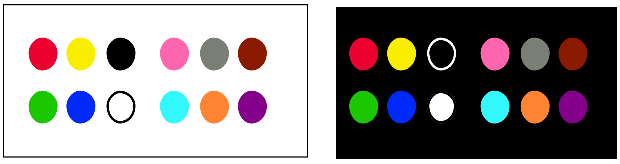
- Berlin and Kay, 1969
  - basic color terms in >100 languages
- Primary color terms are consistent across cultures
- Neural basis for primary color names is innate

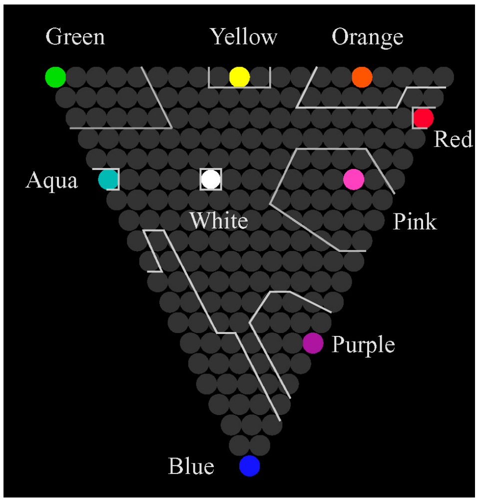


Primary Axes of Opponent Color Model

Color Categories

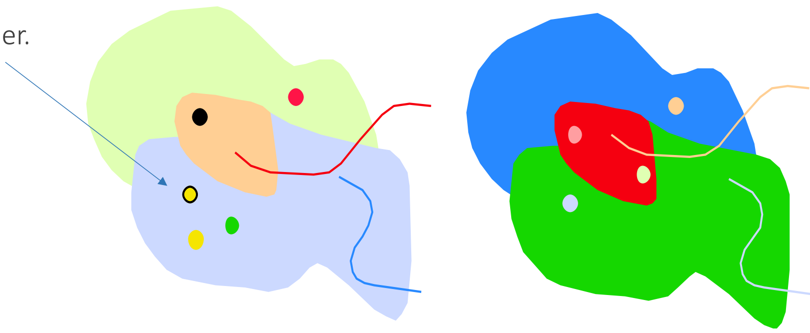
- Task: Name the colors
- Regions same > 75%
- Nonuniform sizes
- Only 8 hues named
  - out of 210 colors
  - → small number of labels





Color Coding

- Large areas: low saturation (is enough)
- Small areas: high saturation (is needed)
- Break isoluminance with borders
  - Always make a distinct luminance border.
- Must have luminance contrast with background to see details



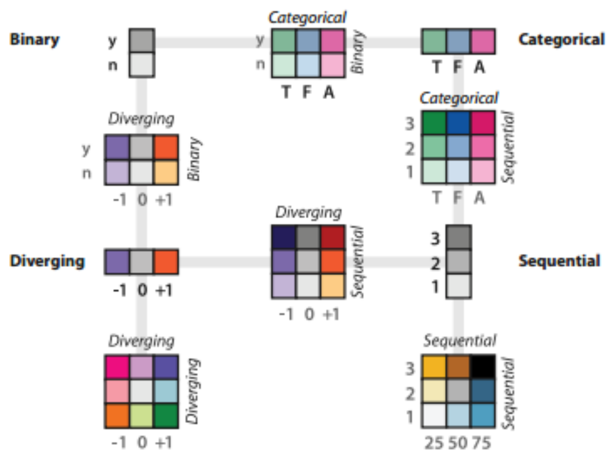
Which is better?

Transparency

- Interacts with other three channels
  - Especially with luminance and saturation
- Small number of steps can be used
  - About 2
- Mostly used at superimposed layers

Colormaps

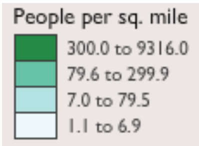
- specifies a mapping between colors and data values
  - Categorical
  - Ordered : Sequential / Diverging
  - Continuous (range of values)
  - Segmented (into discrete bins)

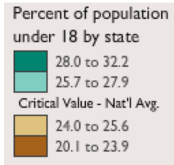


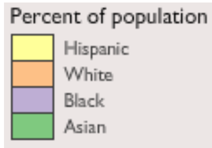
Color Brewer

- http://colorbrewer2.org/

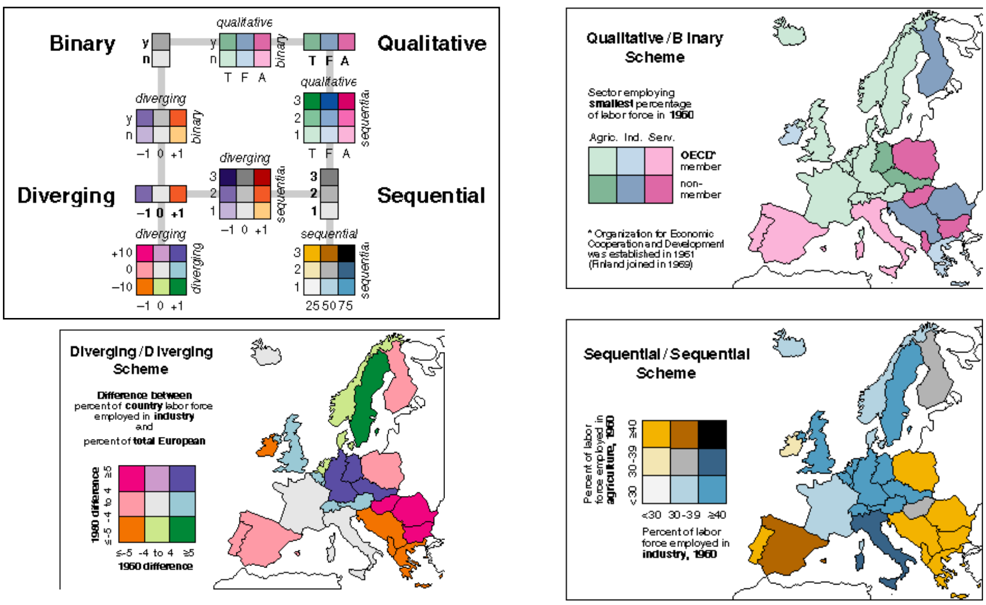
- sequential scheme
  - light colors for low data values
  - dark colors for high data values
- diverging scheme
  - put equal emphasis on mid-range critical values and extremes at both ends of the data range.
- qualitative scheme
  - hues are used to create the primary visual differences between classes







Color Advice for Cartography



Categorical Colormaps

- Encode categories as colors
- # of discriminable colors for coding small separated regions
  - 6~12, including background color and default color
- Guidelines
  - bright, highly saturated colors for small regions
  - low-saturation (pastel) colors for large regions
  - Luminance contrast
  - Colorbrewer2.org

(a) (b)

Categorical Colormaps – why it is difficult to design a color map

- colors should be close in luminance
  - to avoid major difference in salience
  - to ensure that all can be seen against the same background

vs.

- colors should be sufficiently different in luminance
  - distinguished even in black and white

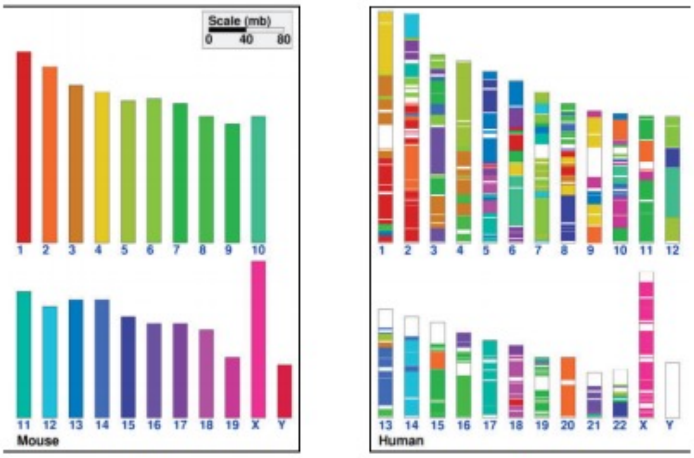
Colormaps

Resolving Issues of Categorical Colormaps

- distinguish bars in large regions next to each other

  vs.

- distinguish noncontiguous small regions



(a) (b)

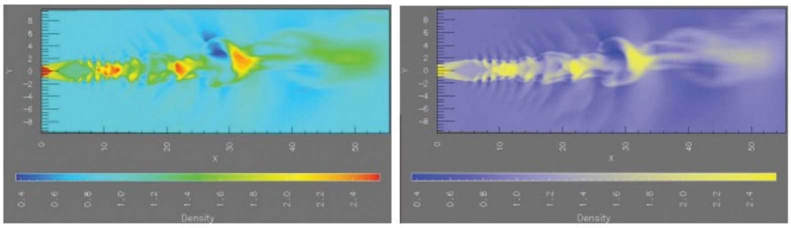
Colomaps

Resolving Issues of Categorical Colormaps

- When there aren't enough colors to distinguish items
  1. Reduce number of bins
     - **derive a new and smaller set of attributes** (cf. inadvertent segmentation into bins that arises from the user's perceptual system)
     - **derive meaningful aggregate groups** (by using a hierarchy)
  2. Use additional visual channels

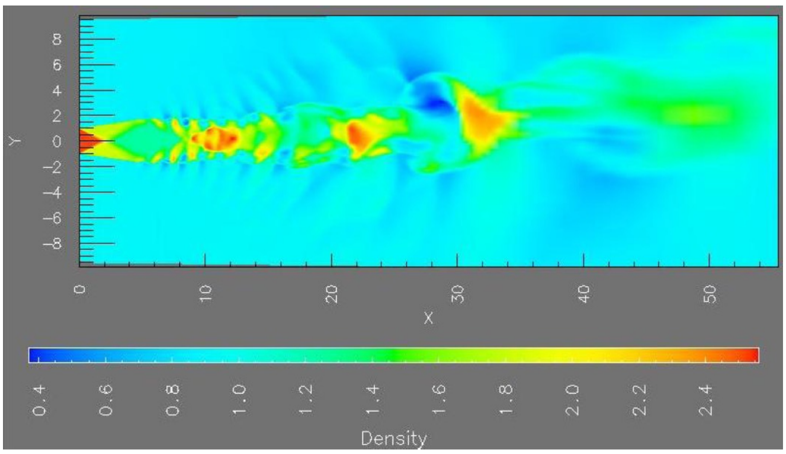
Ordered Colormaps

- Rainbow
- Diverging
  - Two hues at endpoints with neutral color as midpoint
- Sequential
  - Grayscale / Control saturation and brightness of single hue
- # of hues → level of structure hoped to be emphasized
  - Fine-grained/Mid-level/High-level (neighborhood) structures



Mid-level neighborhood structure

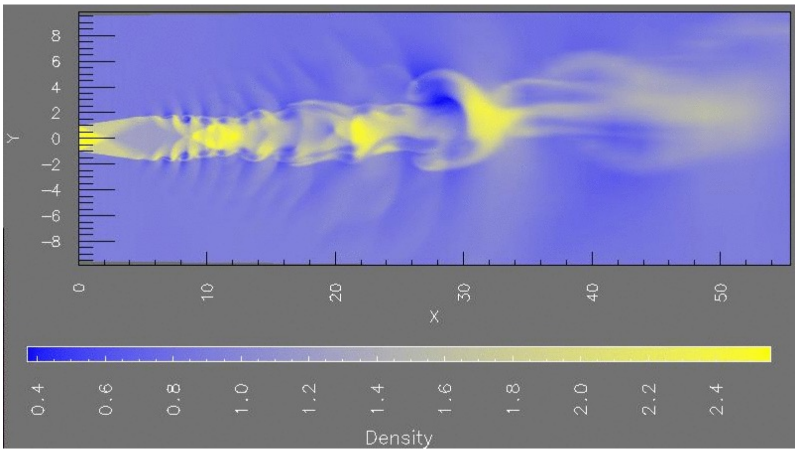
- Low-frequency → segmentation
  - people can easily discuss specific subranges
  - the red part, the orange part, the green part, ...



Non-Rainbow (Diverging) Colormap Advantages

Large-scale (High-level) structure

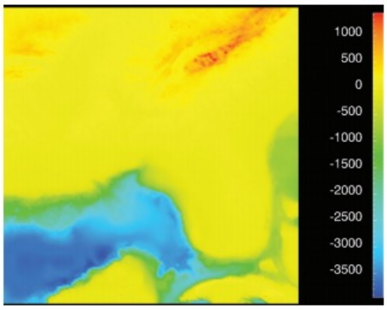
- High-frequency → continuity
  - diverging color map: interpolating between just two hues
  - not easy to verbally distinguish between smaller neighborhoods

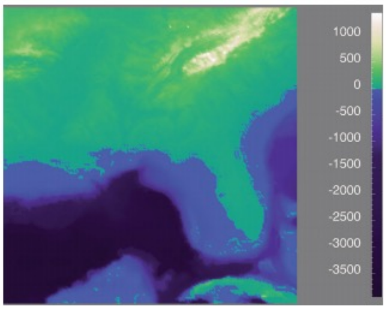


Colormaps

Using Rainbow Colormaps

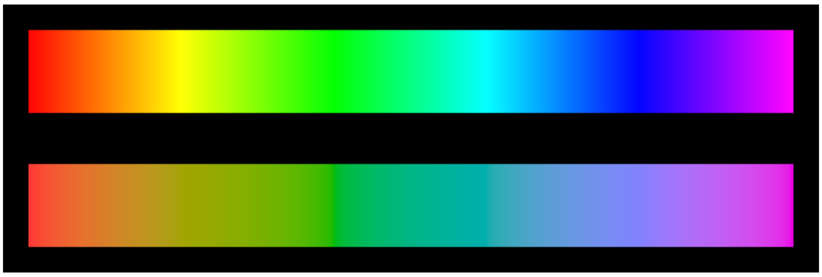
- Easily namable colors, but there are three problems:
  - Hues don't have implicit perceptual order
  - Scale is not perceptually linear (same interval in different ranges of colormap is not perceptually same)
  - *Fine detail* cannot be perceived w/ only hues
- **Monotonically increasing luminance** colormaps
  - Multiple hues ordered according to luminance





Rainbow Colormap Disadvantages

- Segmentation artifacts
  - popular interpolation perceptually nonlinear!
- One solution: create perceptually linear colormap
  - but lose vibrancy → not commonly used



Kindlmann, Reinhard, and Creem. Face-based Luminance Matching for Perceptual Colormap Generation. Proc. Vis 02 www.cs.utah.edu/ gk/lumFace

Using Rainbow Colormaps

- Segmented Rainbow colormaps are good categorical data
  - with a small number of categories
- **deliberately bin the data explicitly**
  - to match meaningful semantic divisions in the data

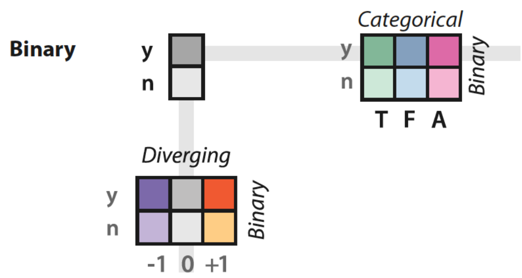
vs.

- just relying on eyes to create bins of unequal size
  - by just using continuous rainbow colormap

(c)

Bivariate Colormaps

- Encode one attribute - univariate
- Encode two separate attributes w/ different colors - bivariate
  - Comprehensible when one attribute has only two levels (i.e. binary)

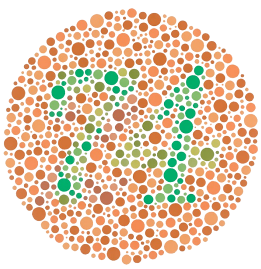


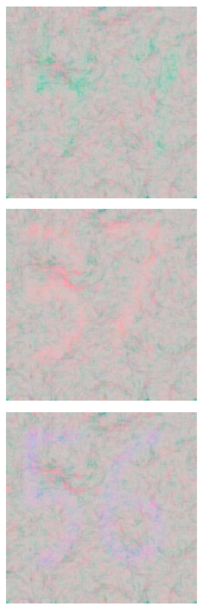
- Poor result when both attributes have categorical multiple levels

Color Deficiency

- deuteranope (medium-wavelength)
  - has green deficit
- protanope (long-wavelength)
  - has red/green deficit
  - 8~10% of males!
- tritanope
  - has yellow/blue deficit (very rare)

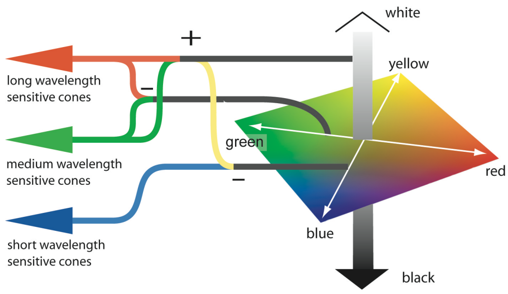
- http://www.vischeck.com/vischeck
  - test your images
  - use this with your final projects!





Color Blindness

- 3D to 2D space
- 10 % of male
- 1% of female
- R-G color blindness

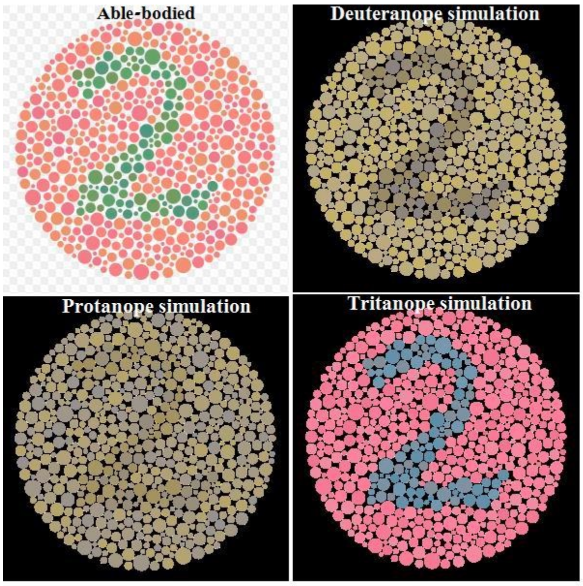


- Can generate color blind acceptable palette
- Yellow blue variation OK

Colorblind Safe Colormap Design

- Most colorblinds are red-green
  - Male>>Female
  - Colorblind affects perceiving not only r-g, but other colors
- Avoid using only hue channel to encode information
  - Also control luminance and saturation
- Avoid using red-green color scheme
- Utilize programs that shows how colorblind perceives

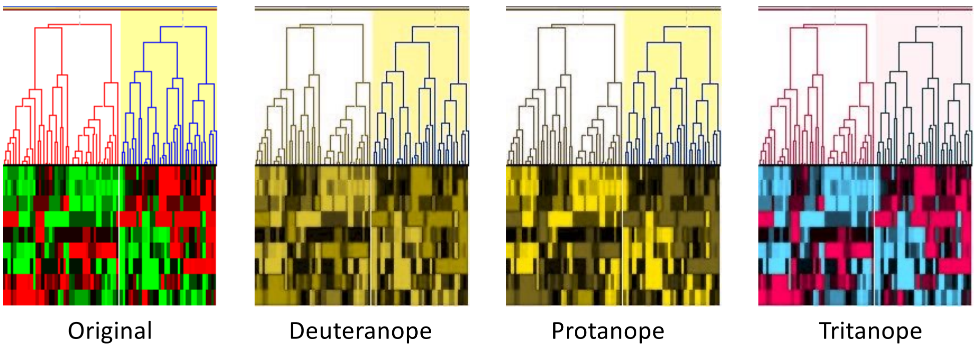
Color-deficiency Simulation



Perception by Color Deficiency

Color-deficiency Simulation

- vischeck results (https://www.vischeck.com/)

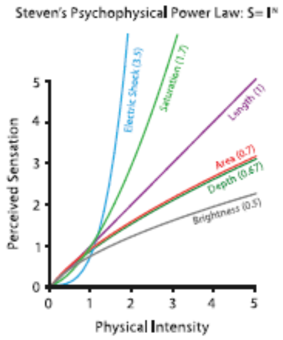


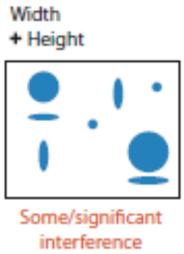
- How to get around?
  - distinquish by more than hue alone
  - redundantly encode with saturation, brightness

Information Visualization and Visual Analytics – Map Color & Other Channels

Size Channel

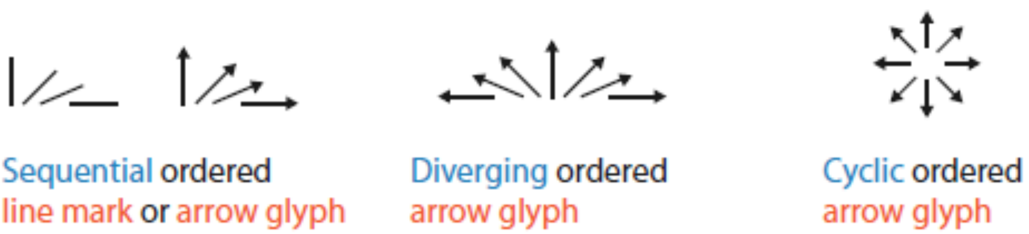
- Effective for ordered data
- Affects most channels
  - Shape, orientation, color hue/saturation
- Length: Very precise
- Size / Volume: Inaccurate
- Larger dimension subsumes a smaller one
  - Acts integrally
- area judgements -> length judgements





Angle Channel

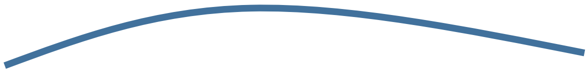
- Orientation of a mark
  - Angle / Tilt
- Sequential, Diverging, Cyclic
- Accuracy of perception is not uniform
  - Very accurate at vertical, horizontal, diagonal (45 degree)
  - Not accurate at others



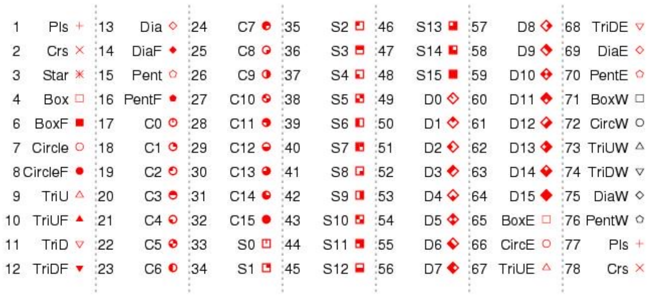
Other Channels

Curvature/Shape Channel

- Curvature
  - Not accurate, only on lines, same as 3D (Don't use it)



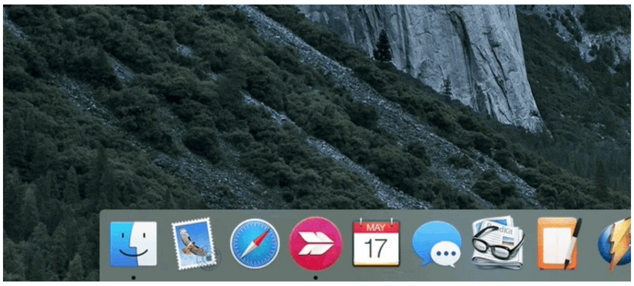
- Shape
  - Closure, Curvature, Termination, Intersection...
  - Identity channel used on point and line
  - Strong interaction between size and shape



Other Channels

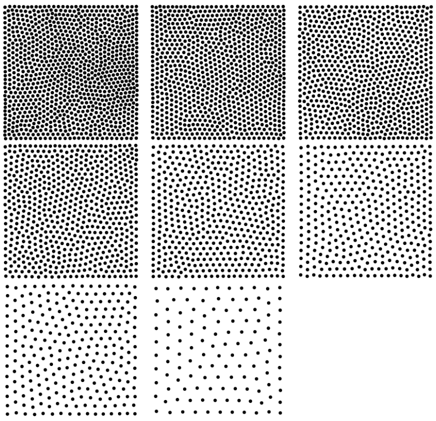
Motion Channel

- Direction / Velocity / Frequency
  - Oscillation frequently used
- Salient, separable from other states
  - Draws (too much) attention
  - different motion channels are separable from each other?
  - how many discriminable bins exist in each?
    - Mostly used as bi-state(move, not move)
- Used for highlighting
  - transitory vs. ongoing
  - blinking



Texture and Stippling Channel

- Texture
  - Very small-scale patterns
  - (Orientation + Scale) [Angle + Size] + Contrast [Density]
  - Categorical attributes / Ordered attributes
- Stippling
  - Fill in regions of drawing with small strokes
  - Used at older printing technology



Credits and Resources

- Many slides from Tamara Munzner's slide deck
- Many slides from John Stasko's slide deck
- Many figures from Main Textbook by Tamara Munzner

- ColorBrewer, Brewer.
  - http://www.colorbrewer2.org/
- Color In Information Display. Stone. SIGGRAPH Course Notes, 2004.
  - https://dl.acm.org/doi/pdf/10.1145/1103900.1103921
  - https://courses.cs.washington.edu/courses/cse442/18au/lectures/CSE442-Color.pdf

Note

- Questions?