Bioinformatics II
Winter Term 2016/17

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Chapter 2:
Color and Perception

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Section 2.1:
Quantifying Color

Radiometric Units

Units used when measuring electromagnetic radiation:

Name	Symbol	Unit
Radiant Energy	Q_e	J
Radiant Flux	Φ_e	$W = J/s$
Irradiance	E_e	W/m^2
Radiosity	M_e	W/m^2
Radiance	L_e	$W/(m^2 sr)$
Radiant Intensity	I_e	W/sr

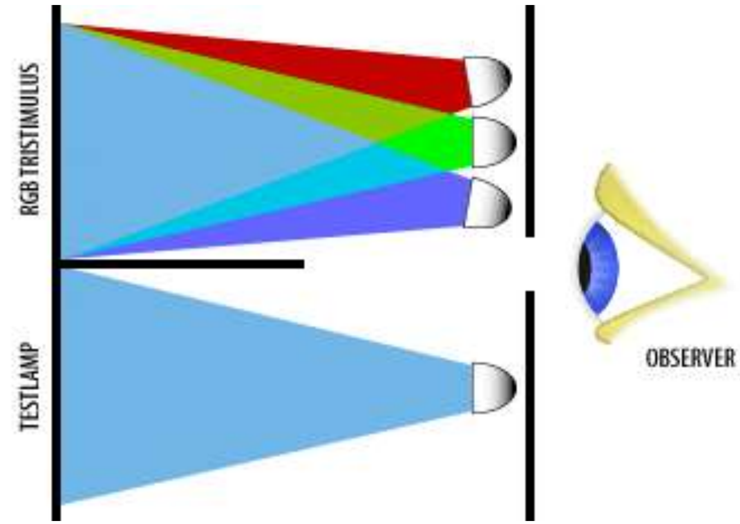
Photometric Units

Units used when measuring lights in terms of *perceived intensity* (weighted by luminous efficiency function)

Name	Symbol	Unit
Luminant Energy	Q_v	$lm \cdot s$
Luminant Flux	Φ_v	lm
Illuminance	E_v	$lux = lm/m^2$
Luminosity	M_v	$lux = lm/m^2$
Luminance	L_v	$lm/(m^2 sr)$
Luminant Intensity	I_v	$cd = lm/sr$

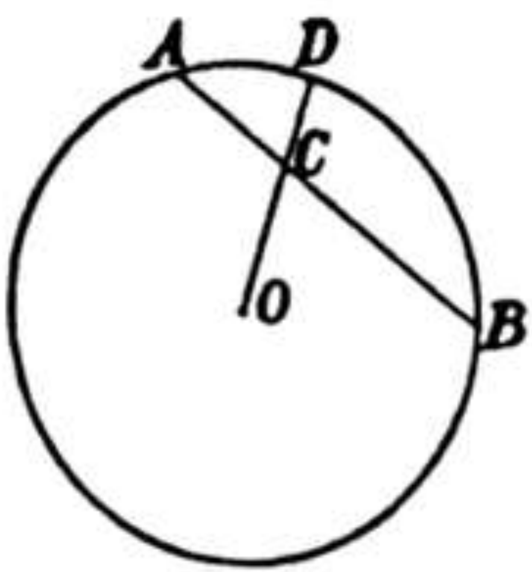
Primary Colors

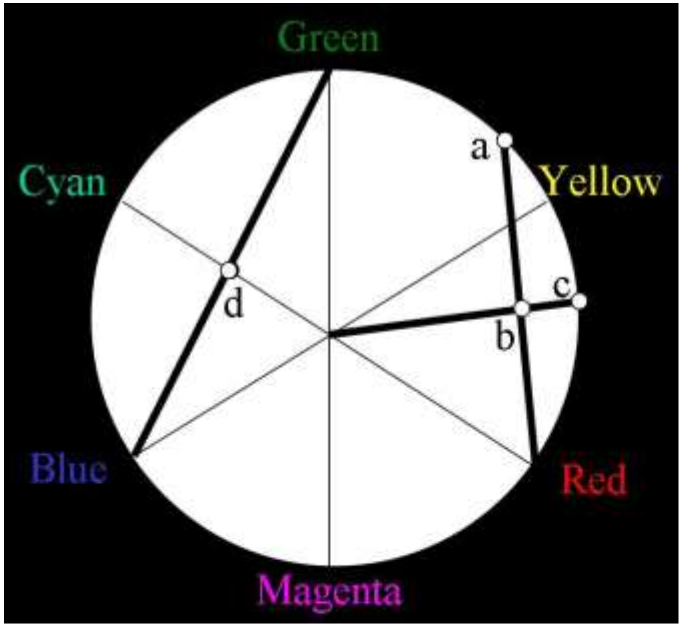
- It’s possible to match any color by mixing three **primary colors**
  - Might require “negative light”, i.e., adding one of the primaries to the reference
  - **Metamers** = physically different spectral distributions perceived as the same color
  - Typical primary colors (digital cameras, computer screens):
    - Red, Green, Blue



Grassman’s Law

- Hermann Günther Graßmann (1809–1877):
  - “If two simple but non-complementary spectral colors be mixed with each other, they give rise to the color sensation which may be represented by a color in the spectrum lying between both and mixed with a certain quantity of white.”



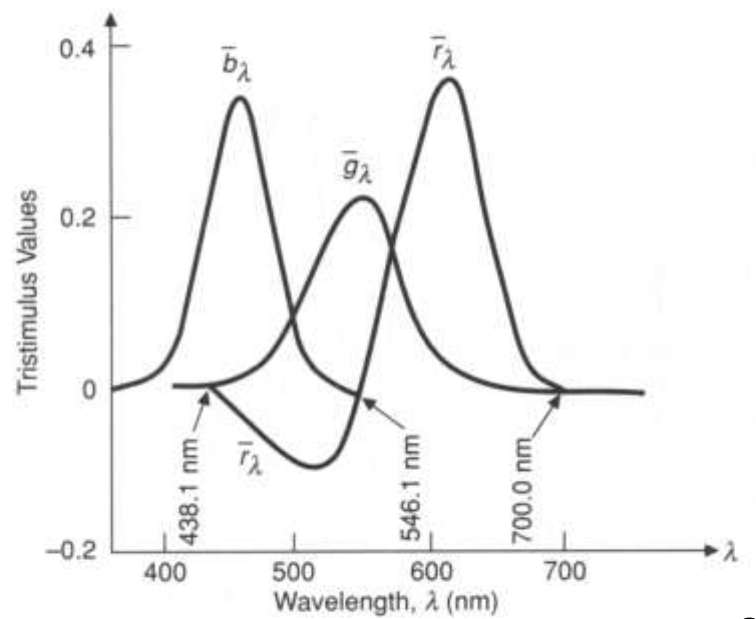


Changing Primaries

- Due to projection of the continuous spectrum onto three types of cones, color can be described as a **3D vector space**
  - Representing the same color using a **different set of primaries** amounts to **changing the basis**
  - Row *i* of M_{CB} given by coefficients needed to match new primary *i* using the old primaries

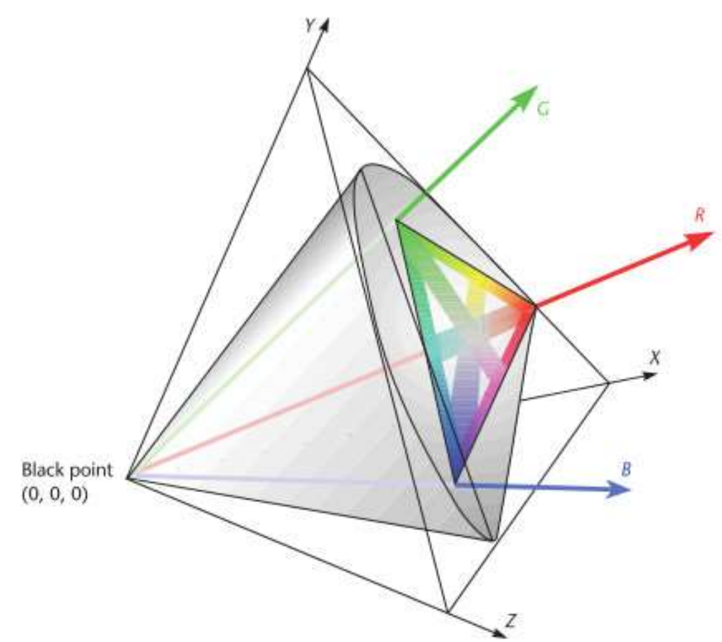
CIE 1931 Standard Observer

- In 1931, the CIE provided the **first mathematical definition** of a color space
  - Based on matching pure spectral colors with primaries using a **“standard observer”**
    - Group of 15-20 trained individuals
  - **Primaries:** R = 700 nm, G = 546 nm, B = 436 nm
  - Wavelengths around 500 nm require **negative contribution** of red
    - No triple of physically feasible primary colors lead to non-negative weights



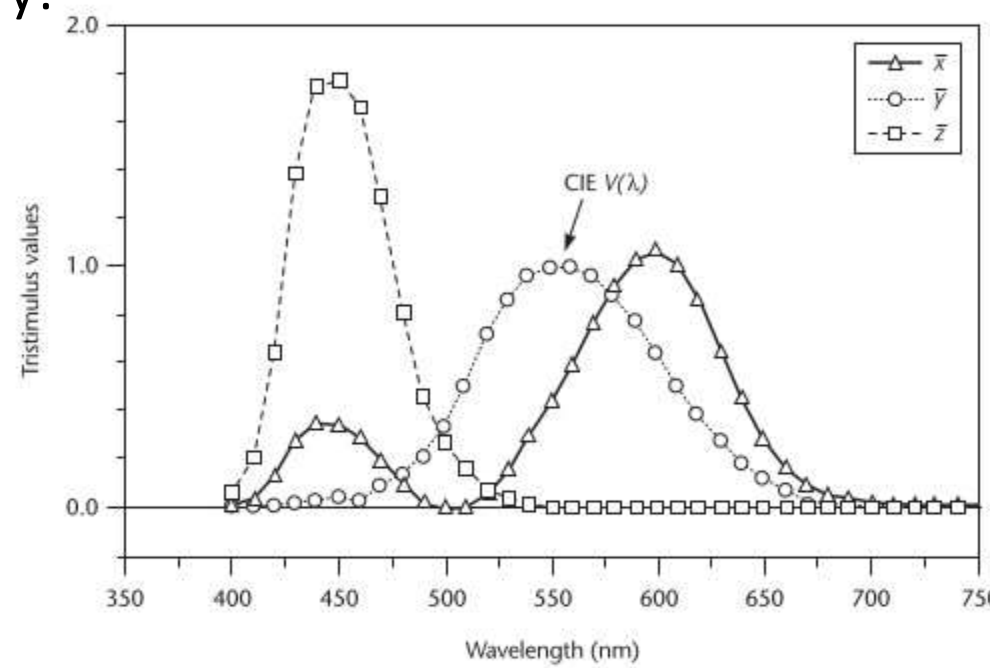
CIE XYZ Color Space

- For the color space established by the 1931 standard, the CIE defined basis vectors which can reproduce any visible wavelength **without negative contributions**
  - "Virtual" **XYZ primaries**
  - Do not correspond to any physically possible colors



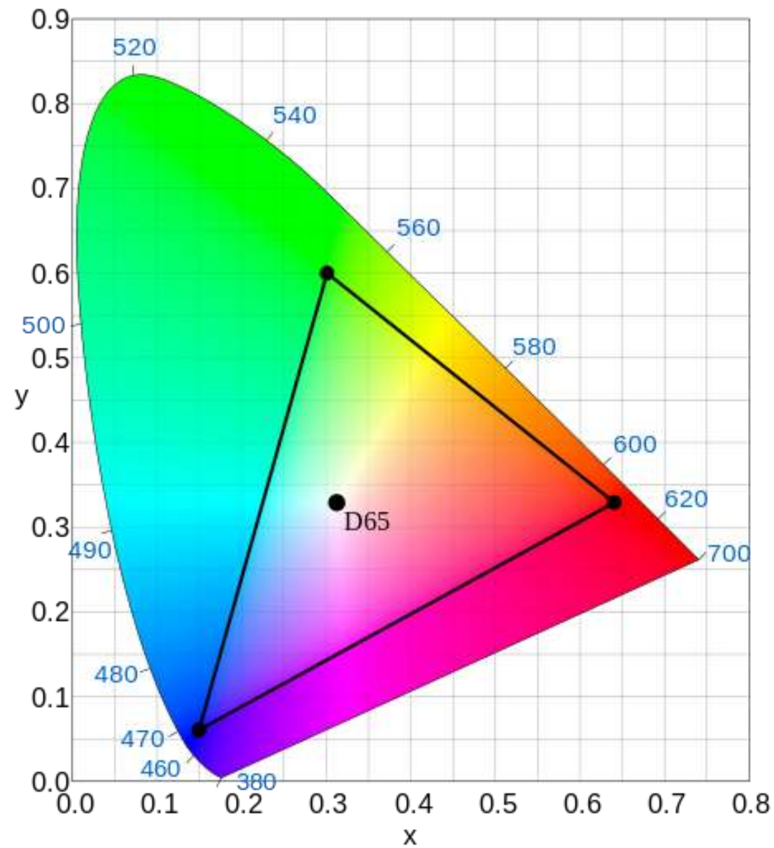
Properties of XYZ Color Space

- **CIE XYZ** is a widely used standard for exact specification of colors
  - XYZ values obtained by integrating intensity against three matching functions
  - X/Z have zero luminance
    - Primaries are imaginary!
  - Y = luminance $V(\lambda)$



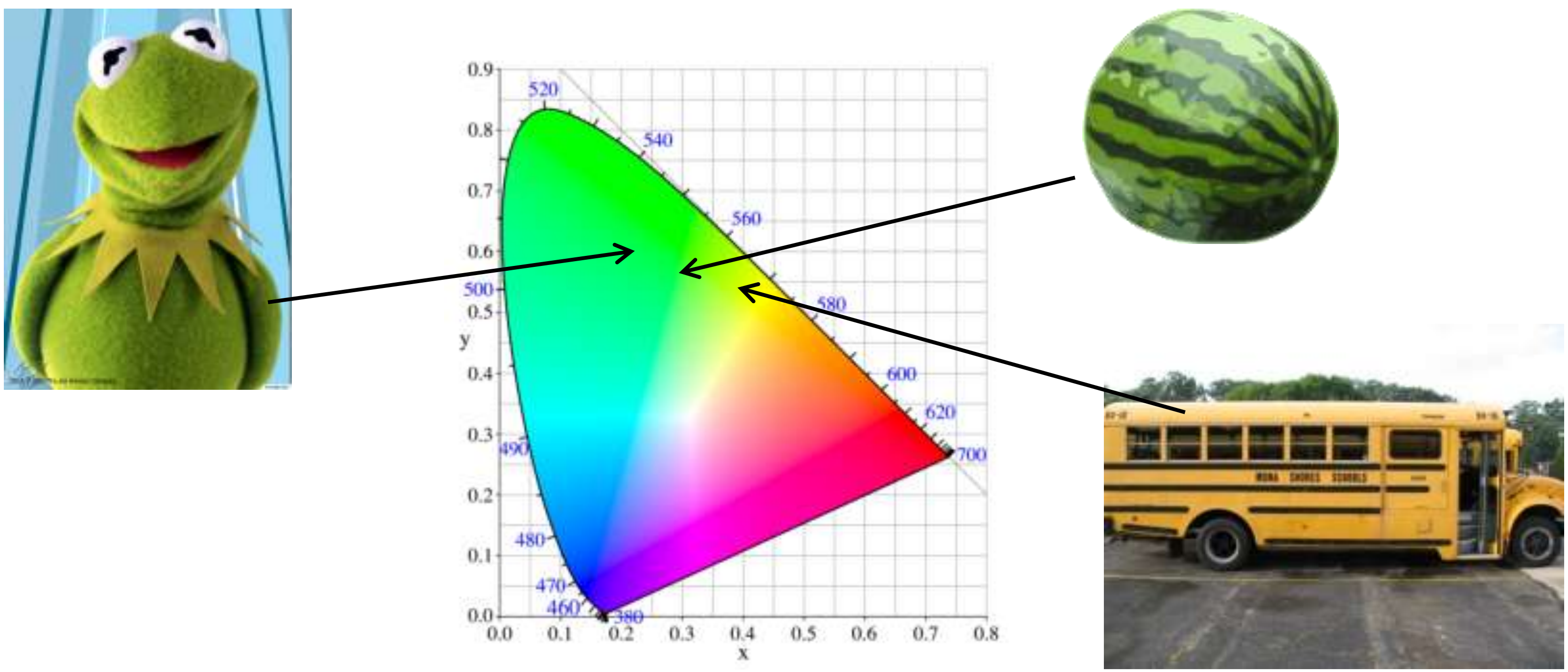
Chromaticity Coordinates

- **Chroma** is defined by normalizing by the overall amount of light (X+Y+Z)
  - $x = \frac{X}{X+Y+Z}, y = \frac{Y}{X+Y+Z}$
  - Unaffected by changes in luminance
  - Leads to **CIE chromaticity diagrams**
    - Spectral locus
    - Purple boundary
    - sRGB gamut
    - Complementary color: Reflect at whitepoint



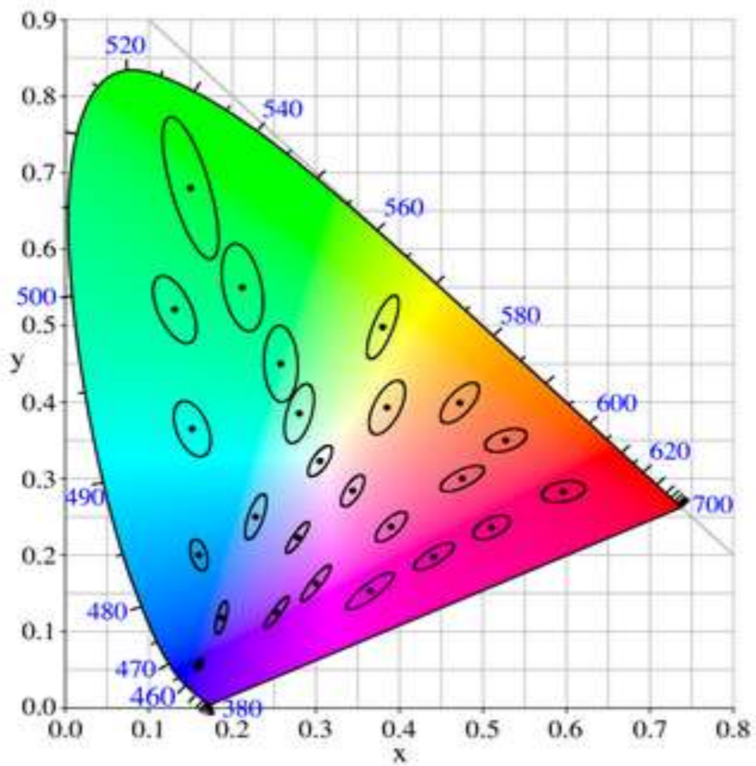
Perceptual Uniformity?

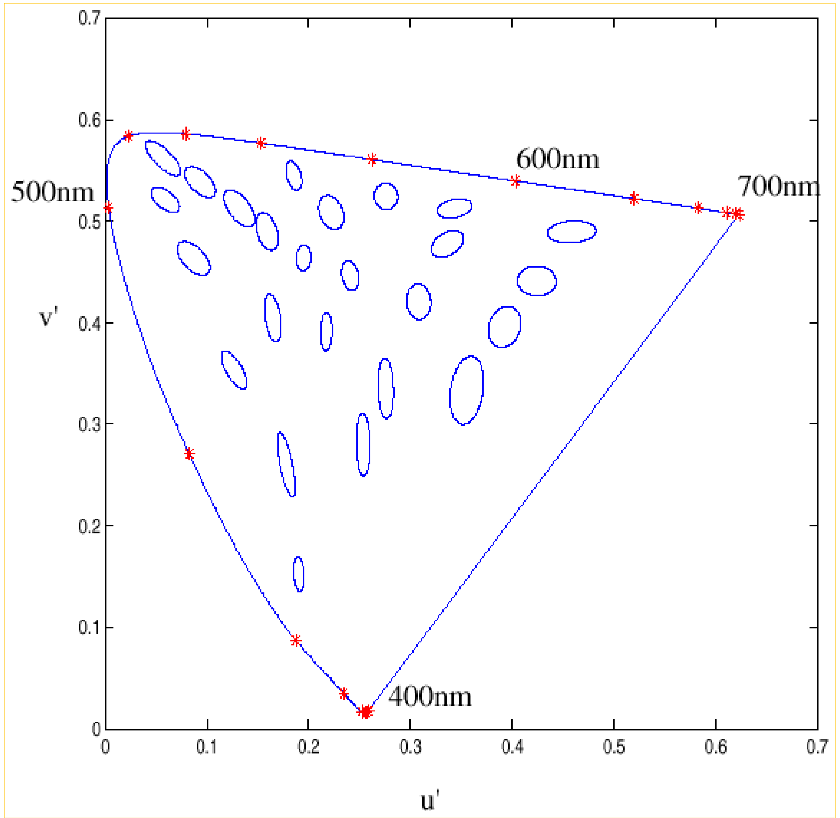
- Distances in chroma do not reflect perceptual differences
  - Problematic for quantization



Uniform Color Spaces

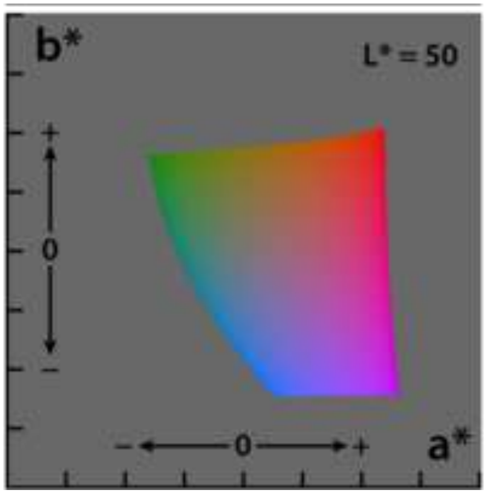
- **McAdam ellipses** illustrate just noticable differences in color
- **Uniform color spaces** attempt to warp them to circles





CIElab

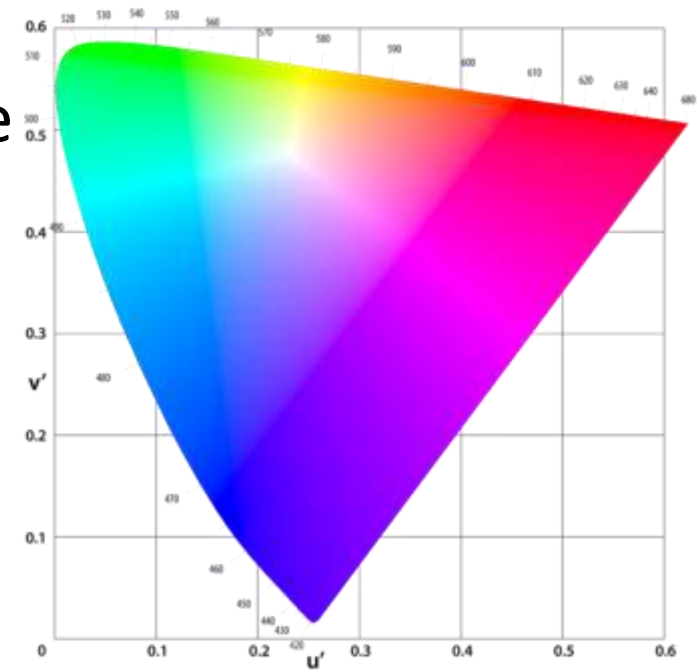
- In 1978, CIE proposed two perceptually more uniform color spaces, CIElab and CIEluv
  - Require reference white X_n, Y_n, Z_n
  - Lab: Axes roughly aligned with lightness (L*), red/green (a*), yellow/blue (b*) channels
    - $L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$
    - $a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right]$
    - $b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$
    - $f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{else} \end{cases}$



CIEluv

- In CIEluv color space, blending between two colors still leads to a line (unlike CIElab)
  - $u' = \frac{4X}{X+15Y+3Z} \quad v' = \frac{9Y}{X+15Y+3Z}$
  - To account for the fact that it becomes harder to perceive differences in color at lower lightness:

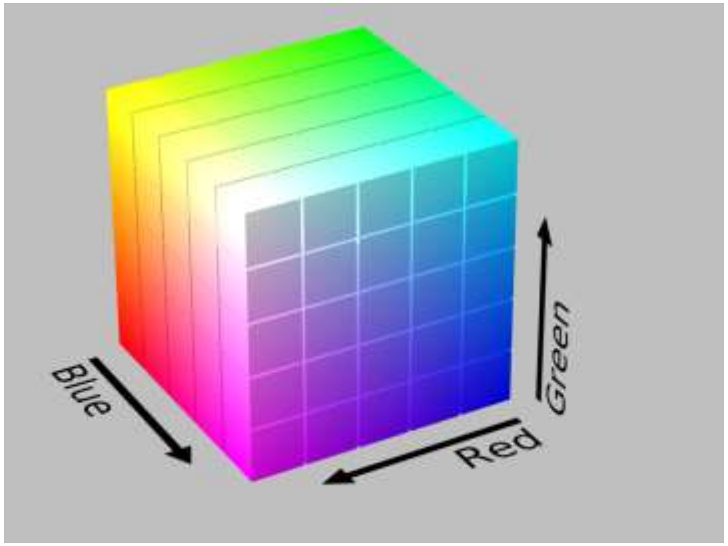
    L^* as before
    $u^* = 13L^*(u' - u'_n)$
    $v^* = 13L^*(v' - v'_n)$
  - Unit distance in CIEluv approximates JND

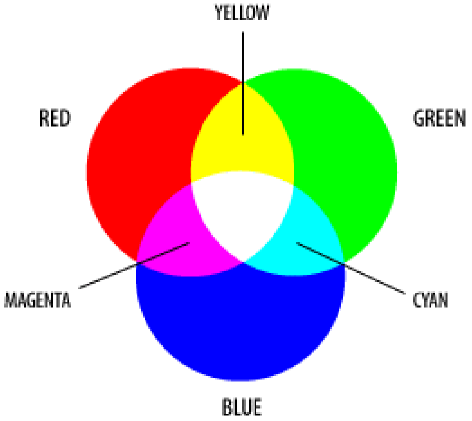


Uniform Chromaticity Scale

RGB Color Space

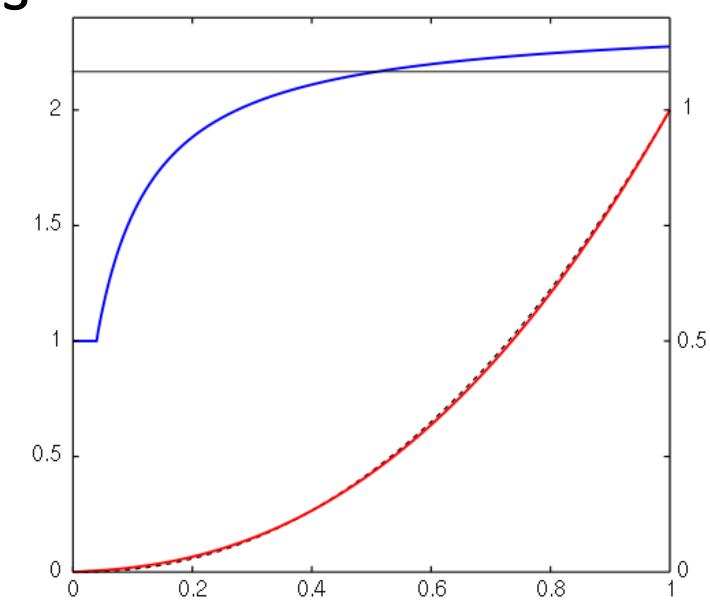
- **RGB:** Natural color space for devices that additively mix red, green, blue primary colors
  - Coefficients denote intensities of three primaries
    - Often either scaled to [0,1] or to [0,255]
  - Axes not aligned with perception
  - Not perceptually uniform
  - Device-specific





sRGB Color Space

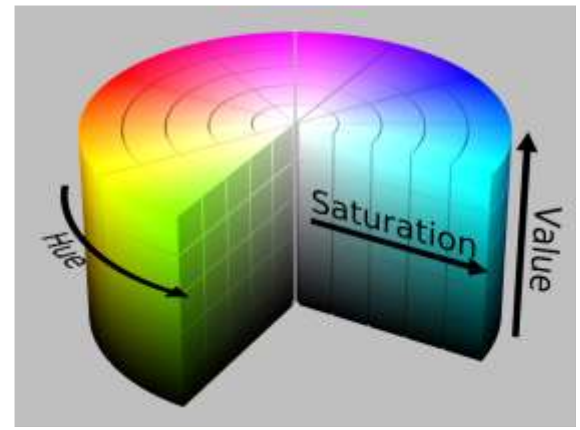
- **sRGB:** Device-independent color space
  - Created by HP and Microsoft in 1996
  - Optimized for monitors, printers, internet
  - Fixes primary colors and a non-linear mapping from coordinates to intensities
    - Efficient use of quantized coefficients
    - Red line: Intensity vs. values
    - Blue line: Effective gamma
  - Many modern devices map sRGB to device-specific RGB

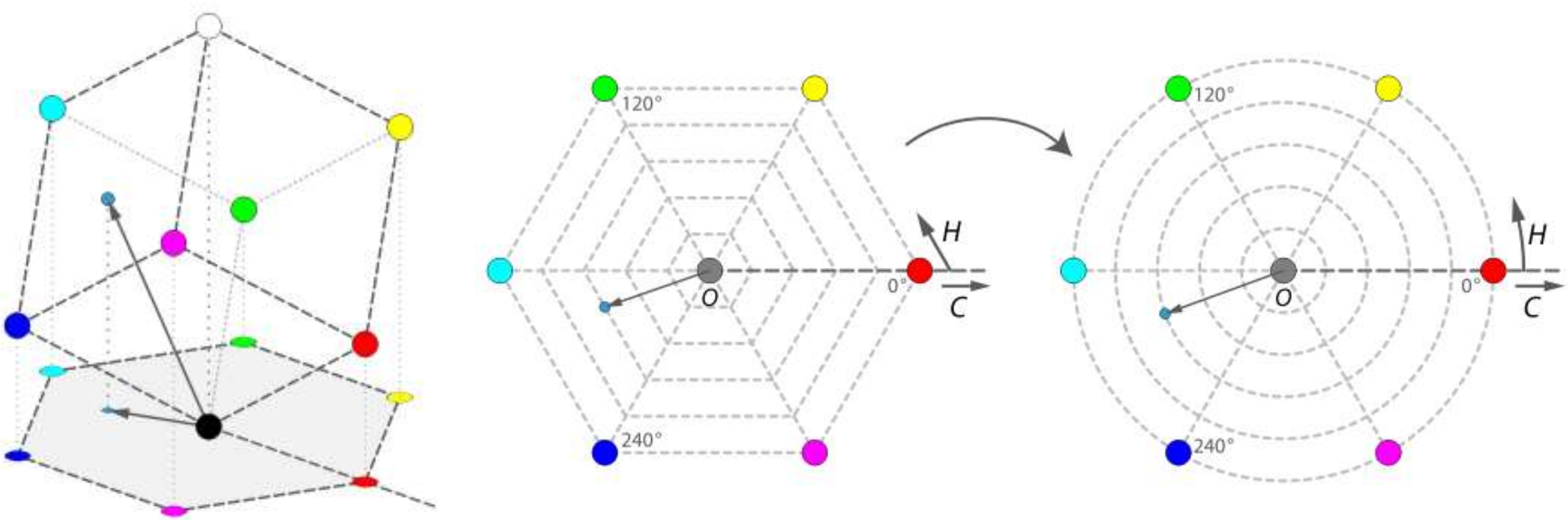


HSV Color Space

- **HSV:** Perceptually more natural, more intuitive for color specification
  - Hue 

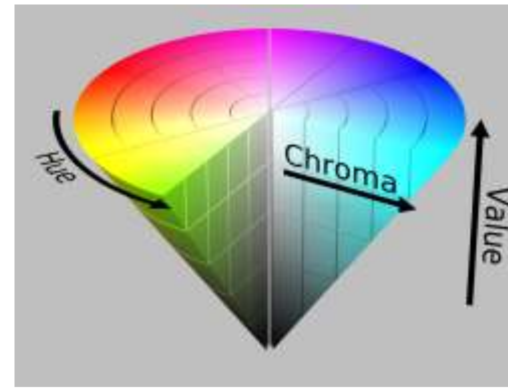
  - Saturation (colorful vs. gray)
  - Value (dark vs. bright)

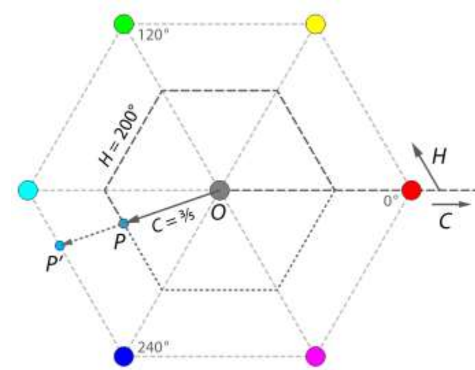




RGB to HSV

- How to convert RGB ∈ [0,1] to HSV:
  - Let M=max(R,G,B); m=min(R,G,B)
  - V=M
    - puts primary and secondary colors into plane with white
  - $S = 1 - \frac{m}{M} = \frac{C}{V}$ with C=M-m
  - $H = 60° \times \begin{cases} 0 & \text{if } C = 0 \\ \frac{G-B}{C} \bmod 6 & \text{if M} = \text{R} \\ \frac{B-R}{C} + 2 & \text{if M} = \text{G} \\ \frac{R-G}{C} + 4 & \text{if M} = \text{B} \end{cases}$





Perceptual Incorrectness of HSV

- Holding S in HSV constant only provides a **rough approximation** to perceptually exact equi-saturation

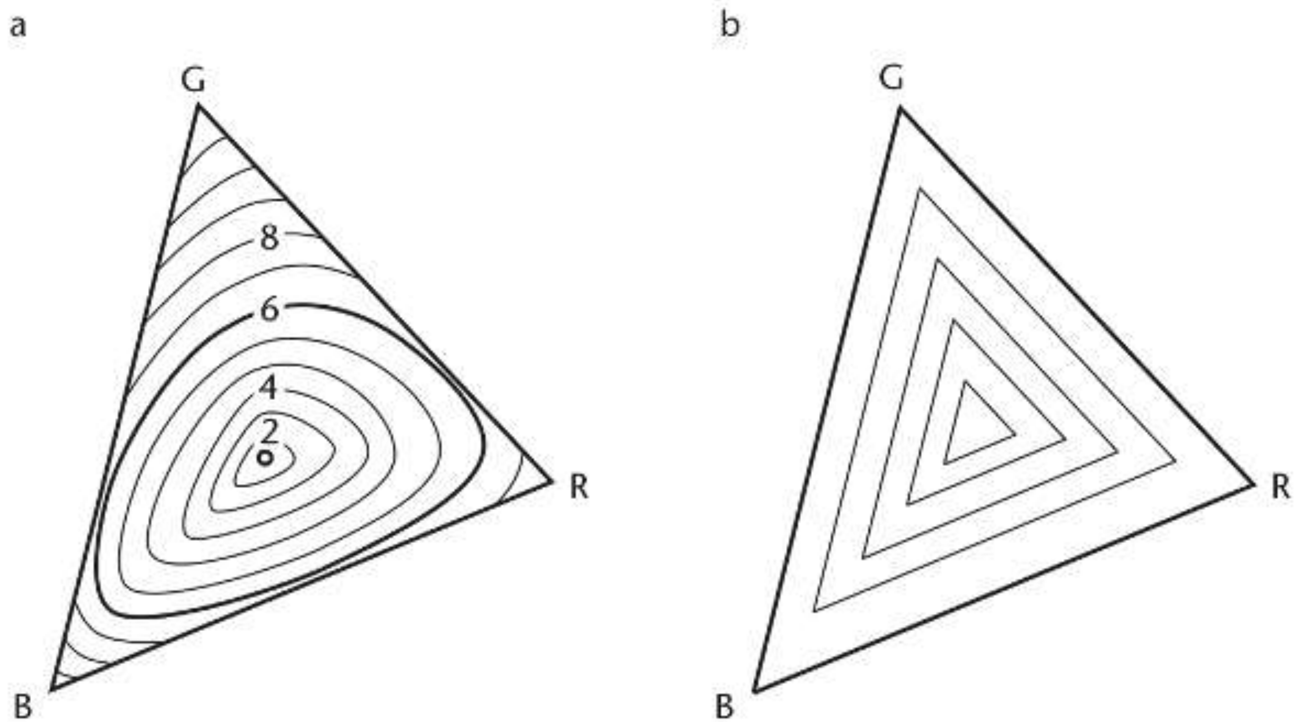
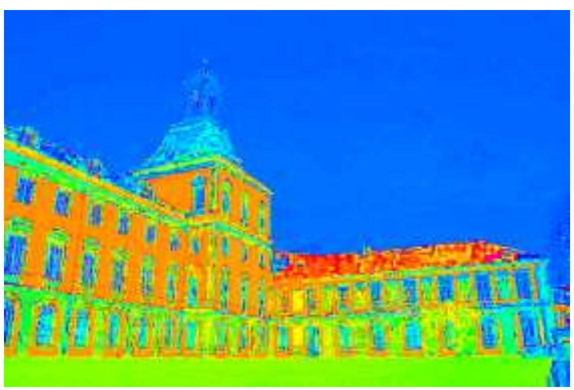


Illustration: RGB vs. HSV

Red

Green

Blue



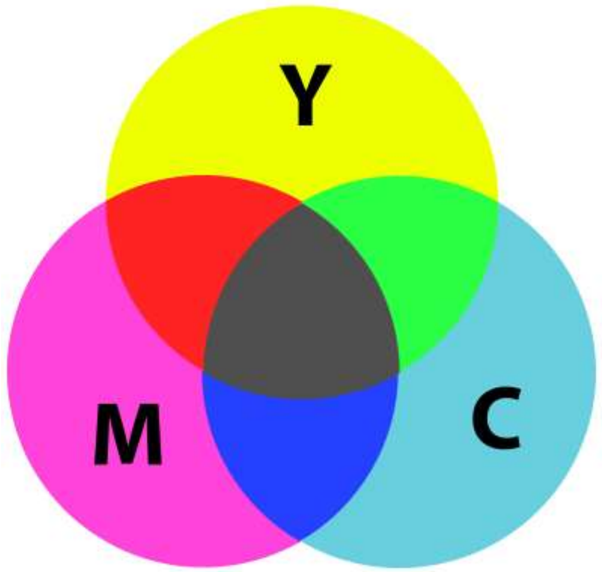
Hue

Saturation

Value

CMYK

- Primaries for subtractive color mixing (e.g., printing) are cyan, magenta, yellow
  - Red/green/blue obtained as secondary colors
  - Interactions between pigments make results of subtractive mixing much harder to predict than for additive mixing on computer screens
  - Black (K) added, since C+M+Y often does not produce a perfect black



Summary: Quantifying Color

- When measuring light, have to distinguish between **radiometric** and **photometric units**
- Any color can be matched using three **primary colors**
  - Can treat color as a vector space
- Common **color spaces:**
  - CIE XYZ, CIElab, CIEluv
  - RGB, sRGB, HSV
  - CMYK

Section 2.2:
Color for Visualization

Impact of Color Maps on Interpretation

All these examples show exactly the same data:

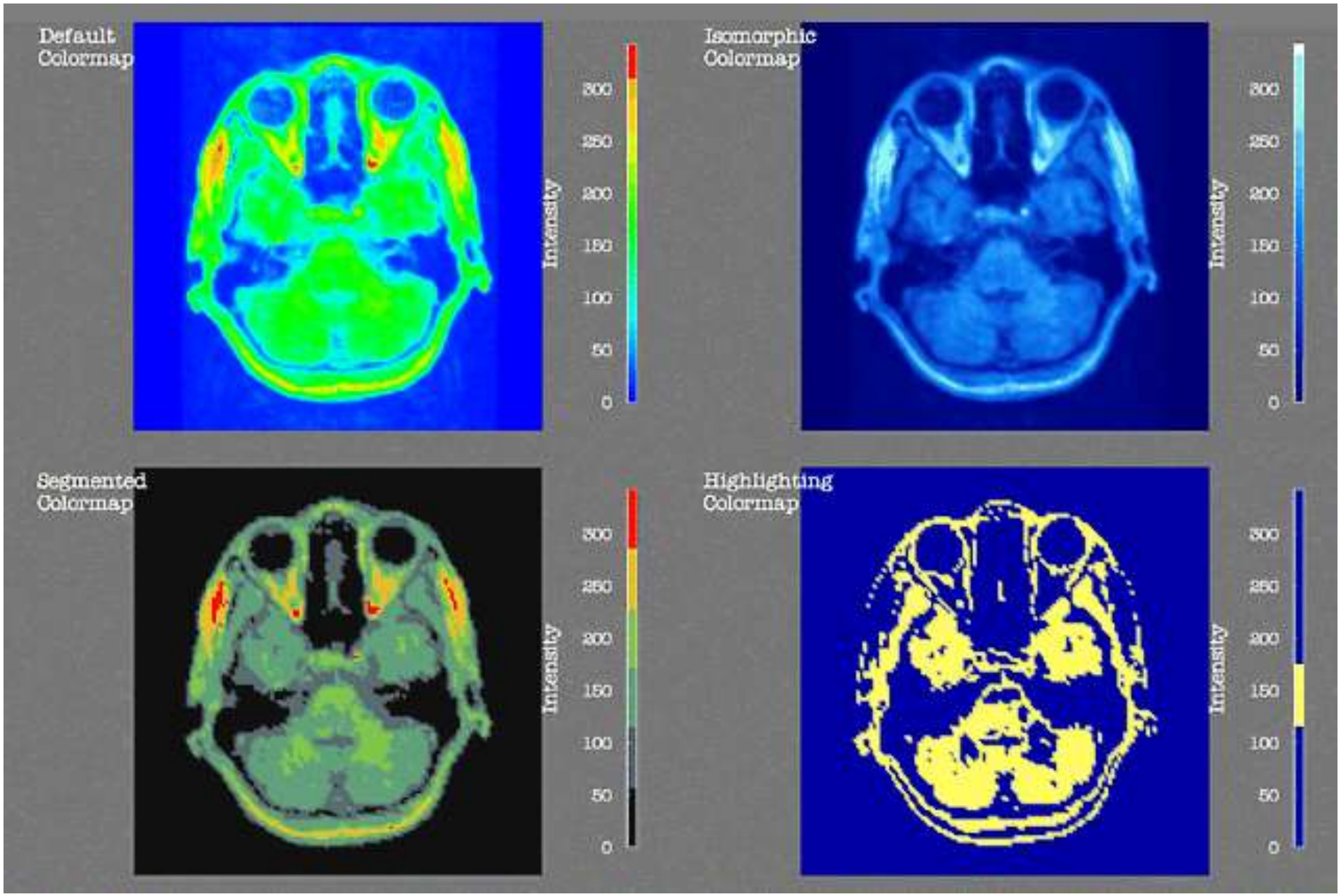


Image Source: Rogowitz et al.

Pick Your Colors Wisely!

In this case, unnecessary surgery was performed based on a poorly adjusted color map:

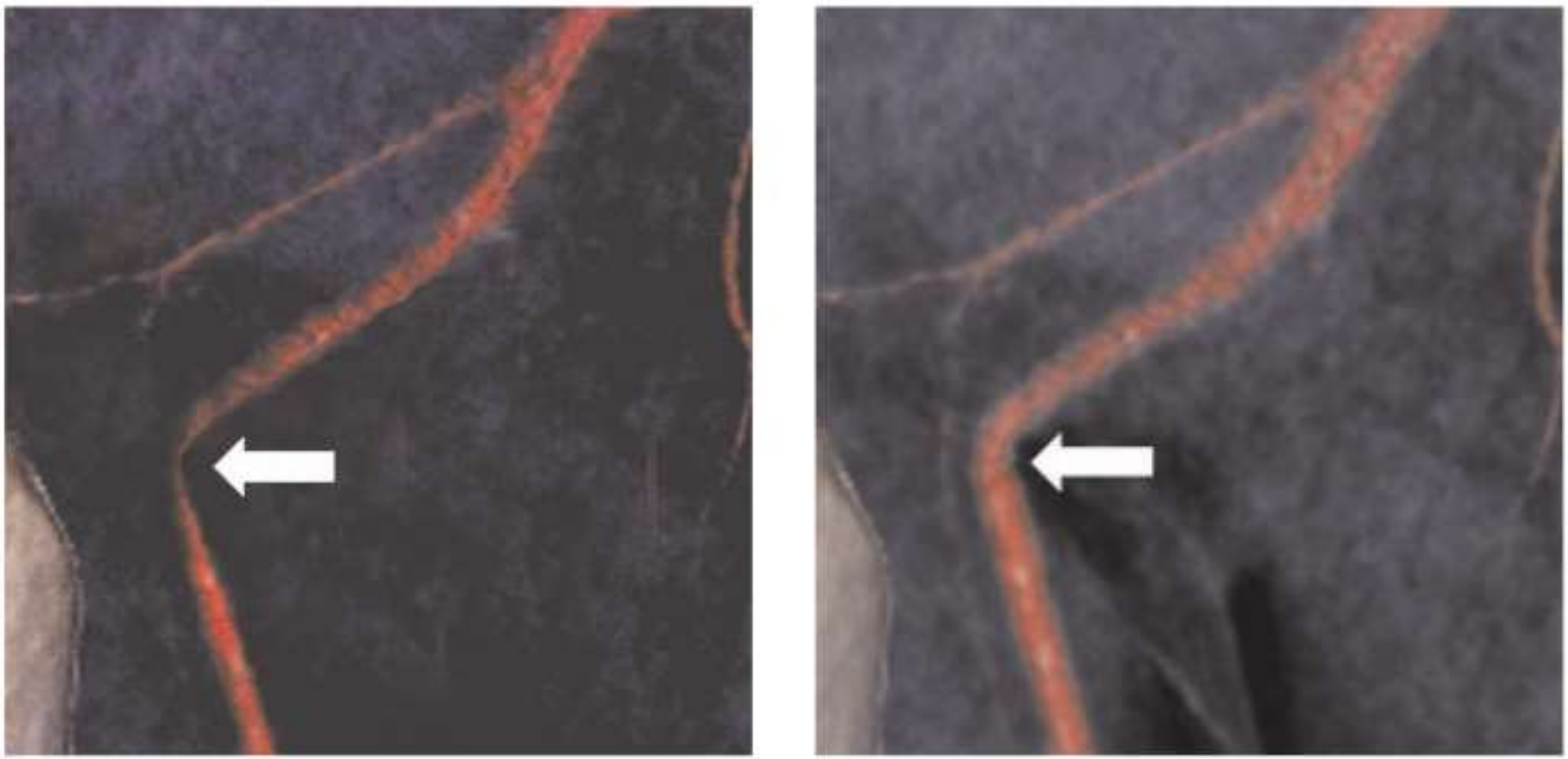


Image Source: Lundström et al.

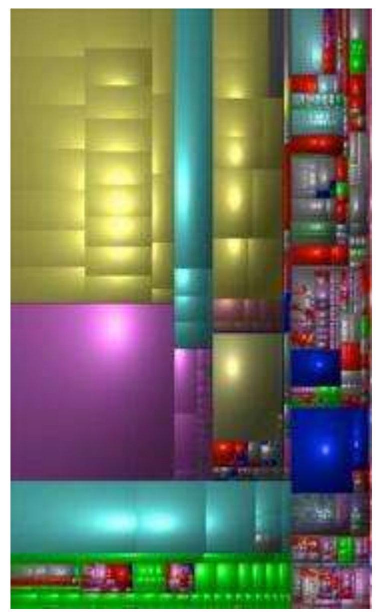
Scales of Measurement

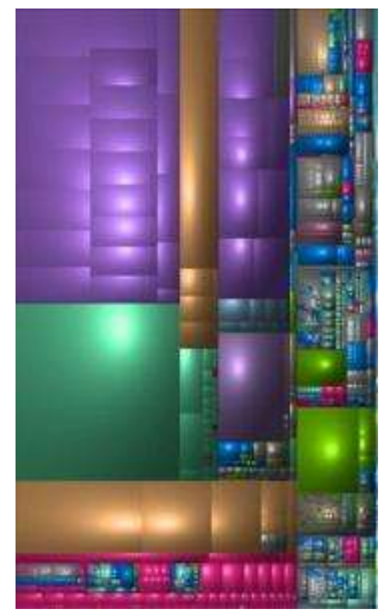
- Four **scales of measurement** according to Stanley Smith Stevens

Operation	Nominal	Ordinal	Interval	Ratio
$=$ / $\neq$	Yes	Yes	Yes	Yes
$>$ / $<$	No	Yes	Yes	Yes
$+$ / $-$	No	No	Yes	Yes
$\times$ / $\div$	No	No	No	Yes

Scales of Measurement and Color

- **Principle:** Visualization *V(D)* of data *D* should reflect intrinsic symmetries of *D*
  - *Example:* Color coding nominal values should be symmetric under permutation



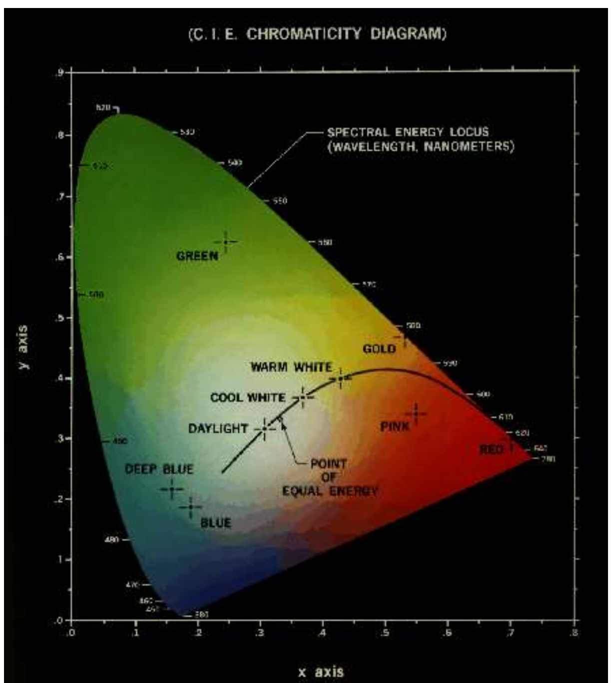


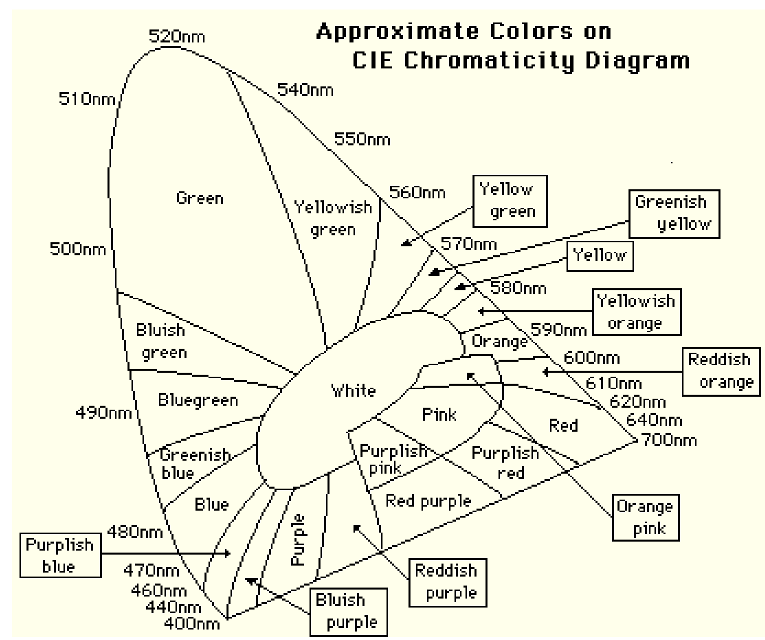
Example by Gordon Kindlmann

Color Mapping Nominal Data

Around 9 basic colors are reliably distinguished:

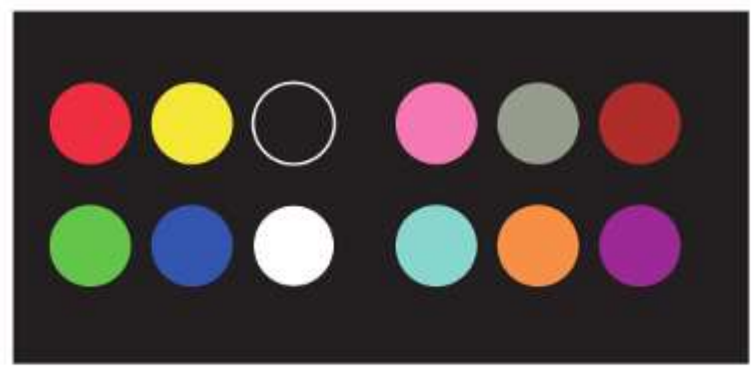
- Magenta (430 nm)
- Blue (476 nm)
- Blue-green (504 nm)
- Green (515 nm)
- Yellow green (556 nm)
- Yellow (582 nm)
- Orange (596 nm)
- Reddish orange (610 nm)
- Red (642 nm)





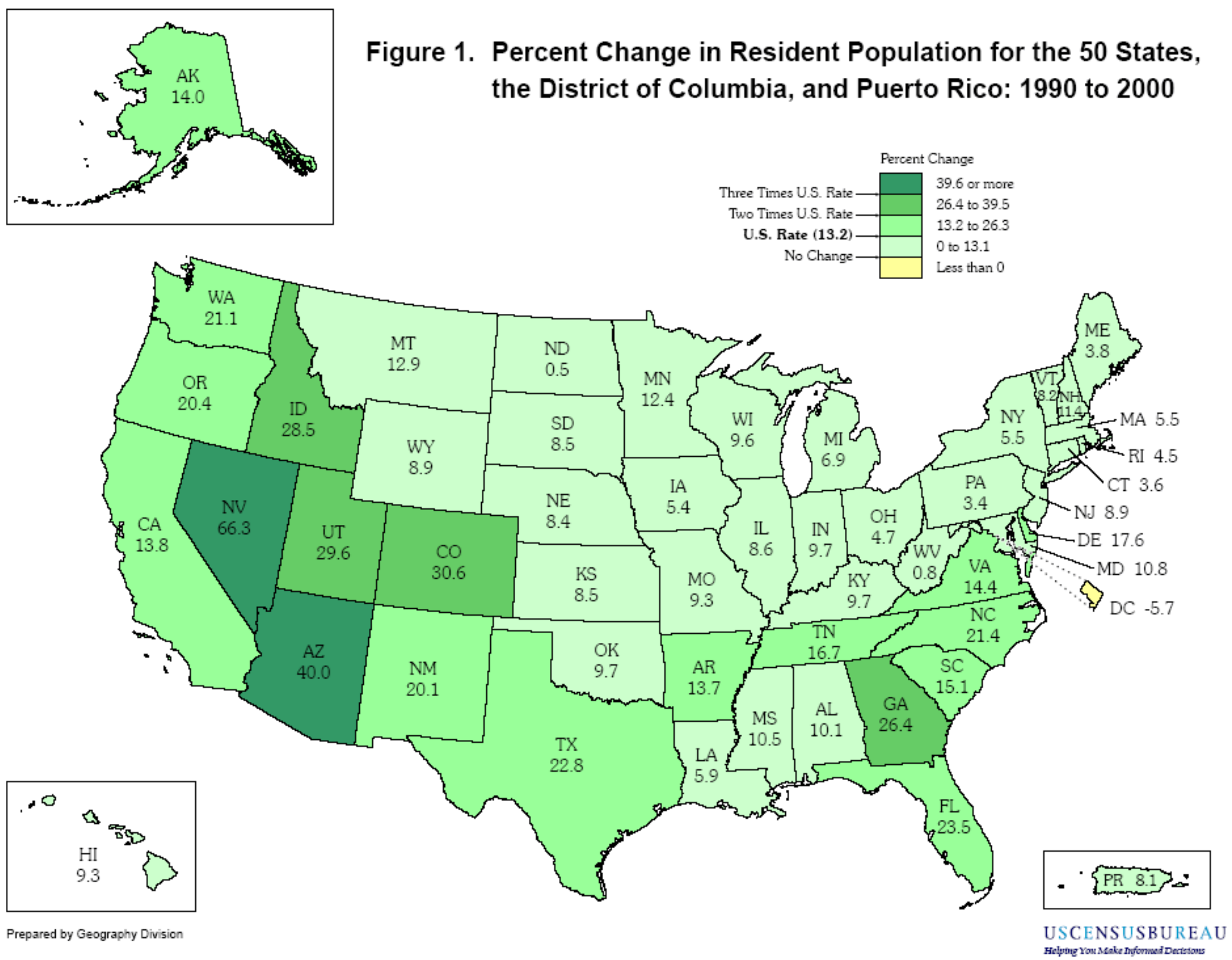
Use Opponent Colors First

- For labeling nominal data, the six **opponent colors** are a natural choice
  - Pink / cyan / gray / orange / brown / purple are recommended by Ware in case more than six colors are needed



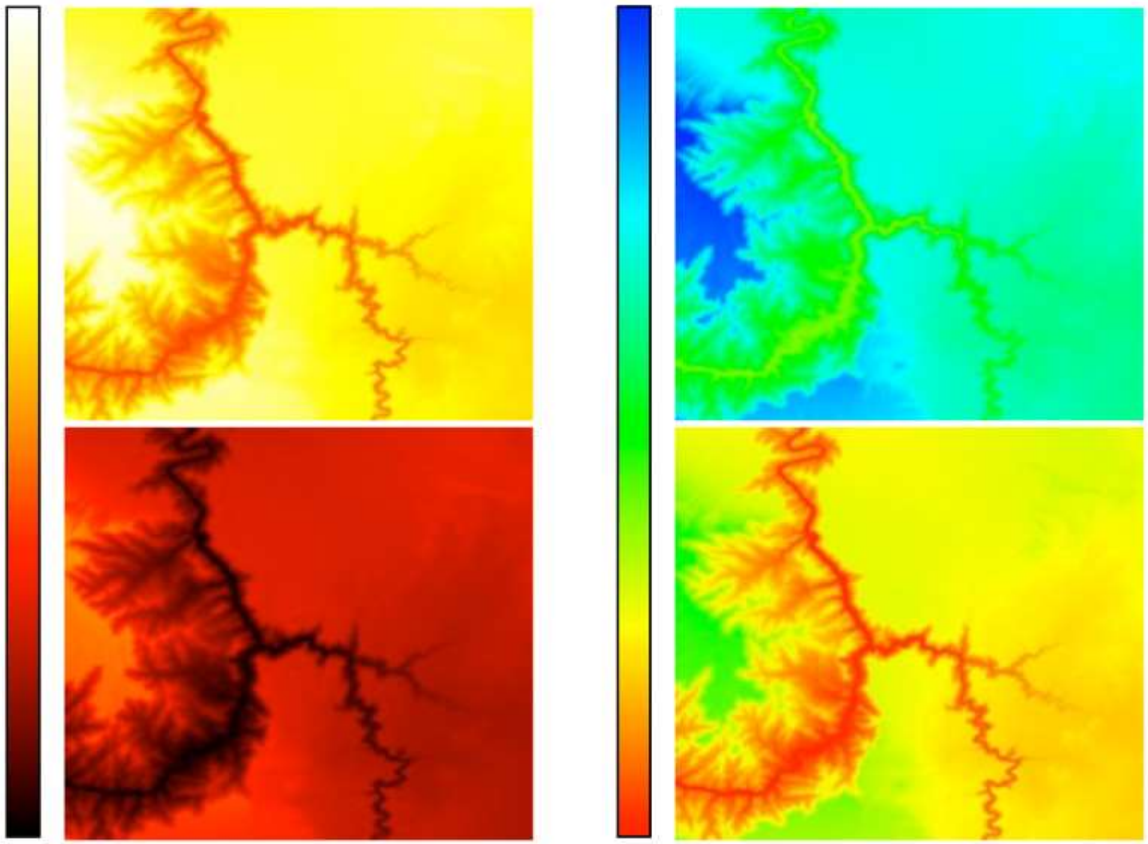
Color Mapping Ordinal Data

- Color Map needs to clearly suggest ordering



Color Mapping Interval Data

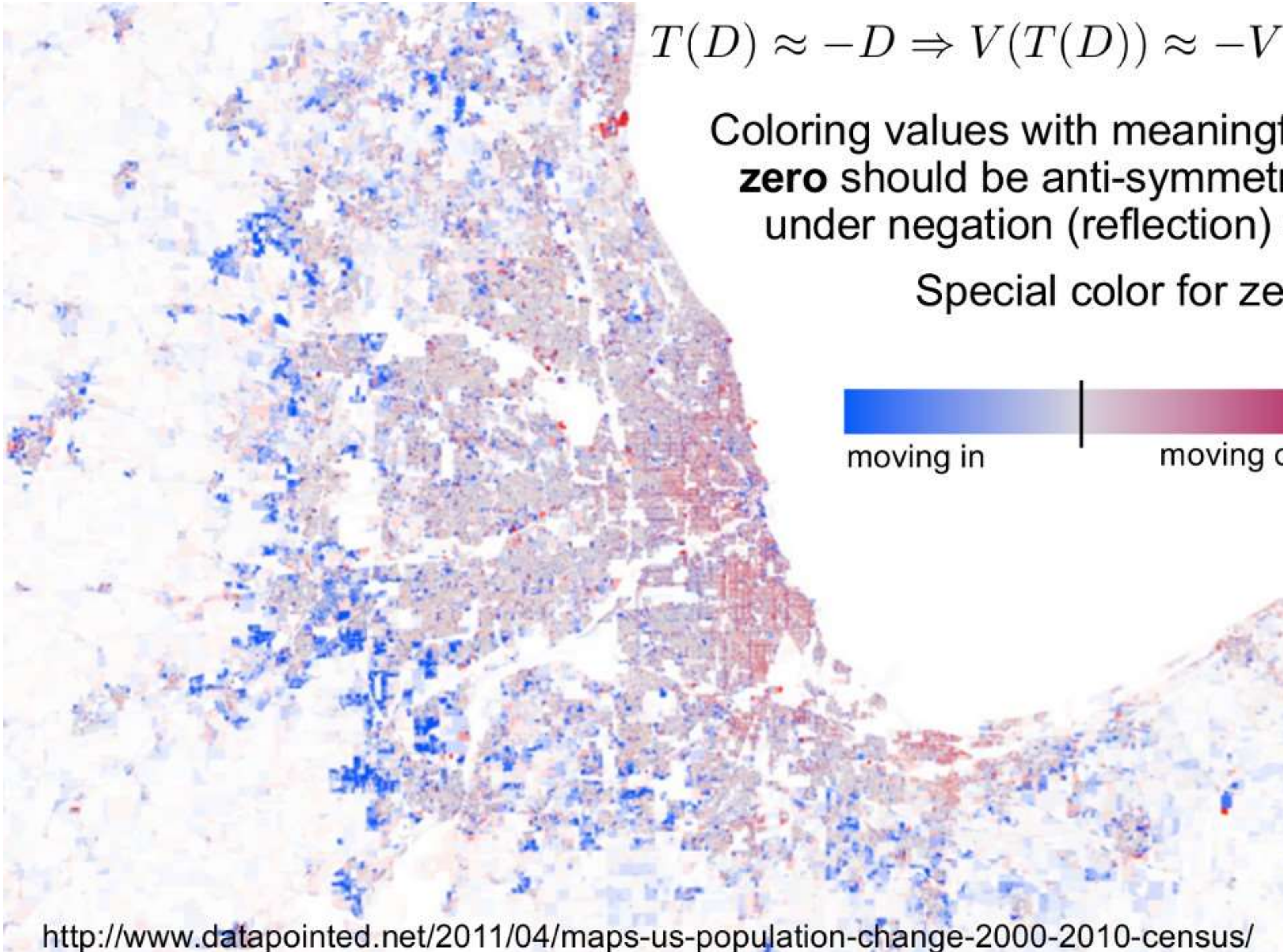
- Coloring of values on an interval scale should be symmetric to addition of a constant



$$V(D+c) \approx V(D) \quad V(D+c) \neq V(D)$$

Example by Gordon Kindlmann

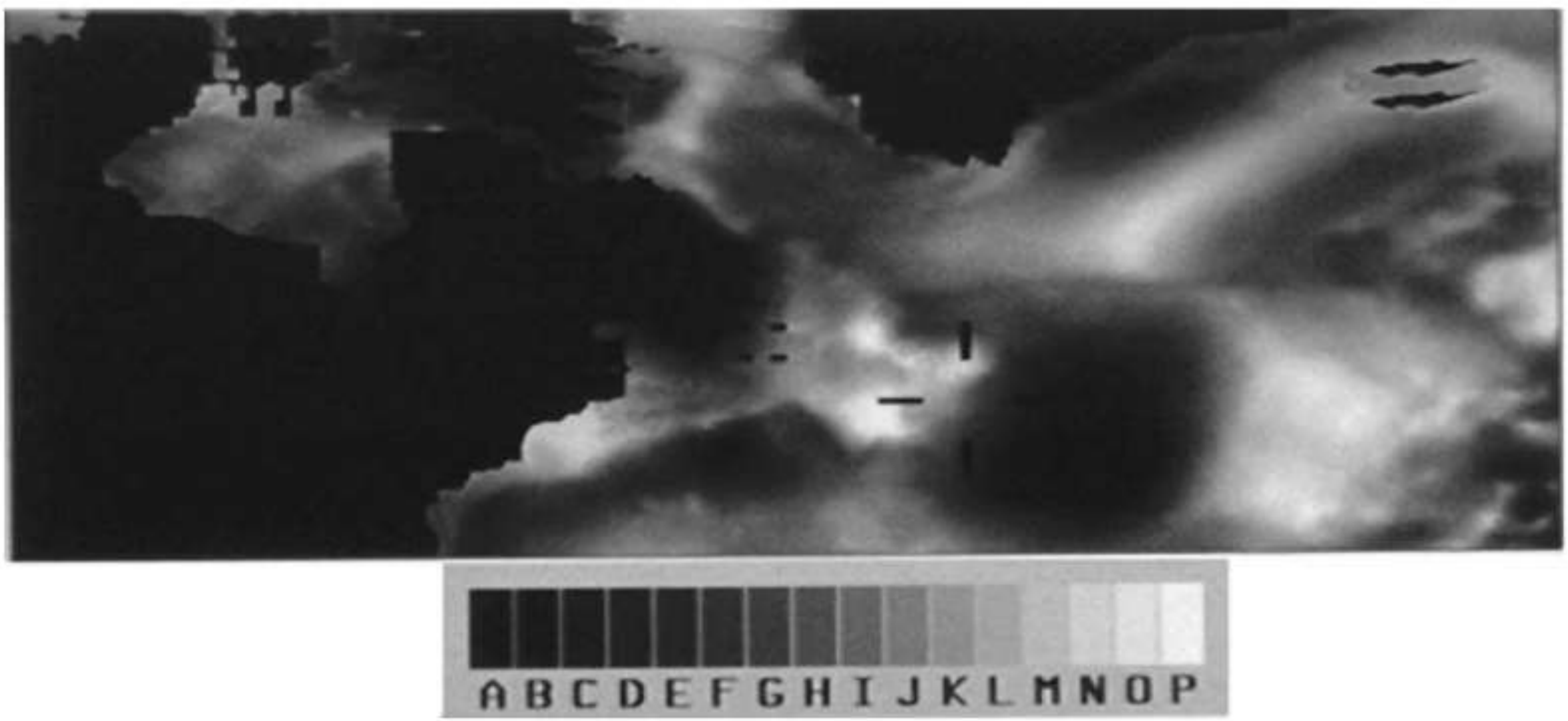
Color Mapping Ratio Data



Example by Gordon Kindlmann

Caveat: Grayscale for Color Coding

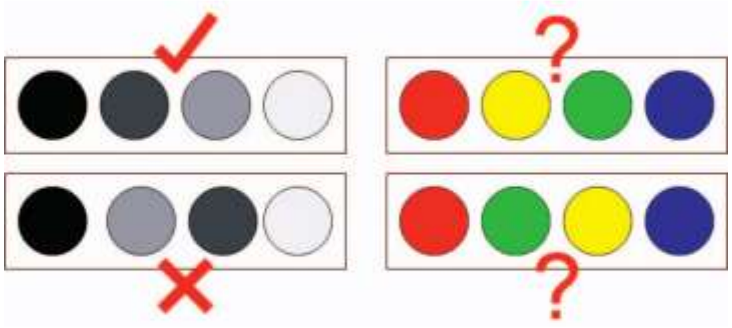
- Due to **contrast effects,** large readoff errors (20% of range) occur when using grayscale to encode continuous quantities



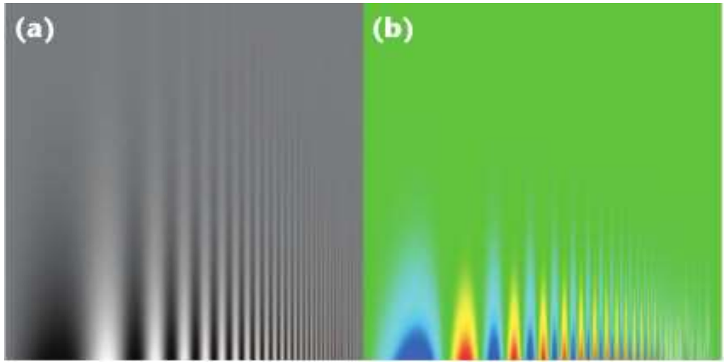
Issues with Rainbow Color Map

Default color map in many visualization systems, improves readoff accuracy, **but...**

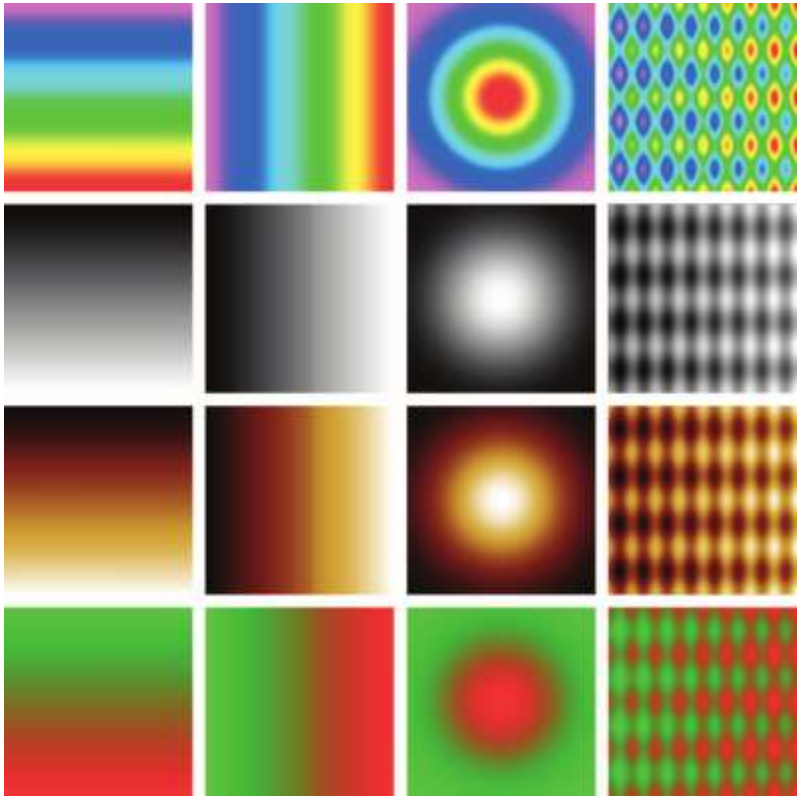
1. No intuitive ordering:



2. Can reduce sensivity:



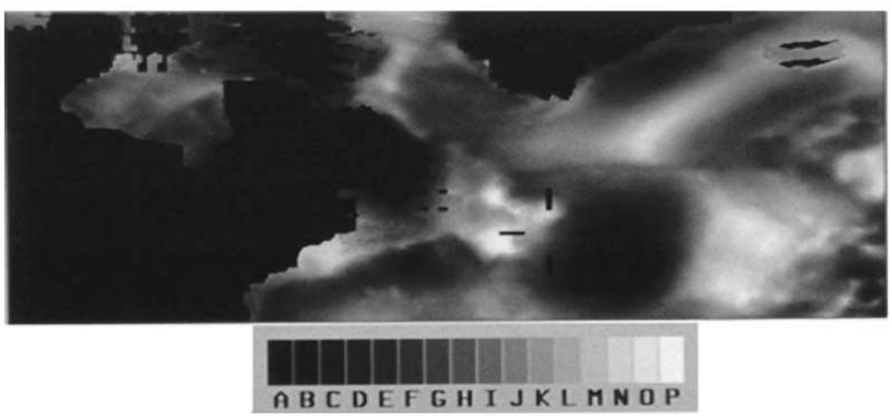
3. Artifactual gradients:

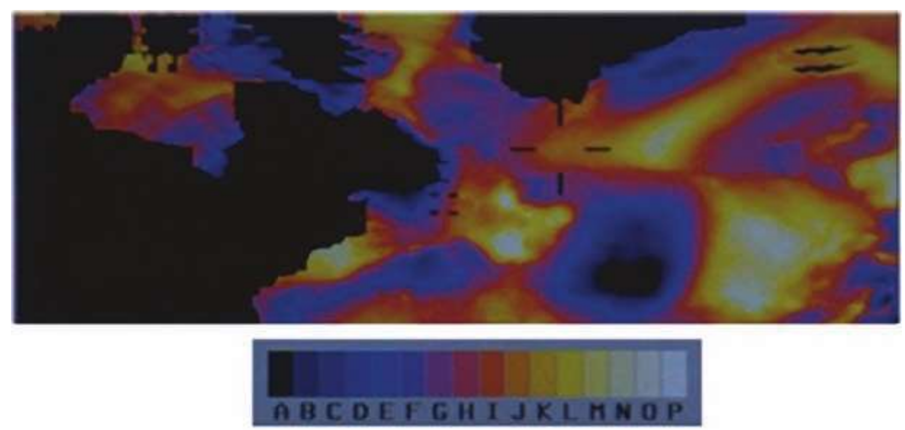


Reference: Borland/Taylor, Rainbow Color Map (Still) Considered Harmful, CG&A 2007

Spiral Color Maps

- Combine changes in hue with monotonically increasing (“upwards spiraling”) luminance
  - Supports reading off values precisely
  - Still maintains an intuitive impression of high and low values

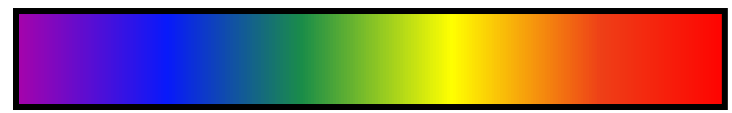




Some Classic Color Maps

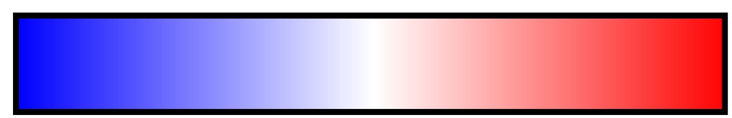
- Gray scale color table
  - Intuitive ordering

- Rainbow color table
  - Based on HSV color space



- “Black body radiation”

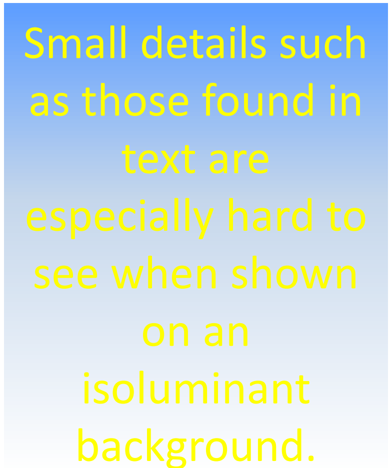
- Cool-to-warm

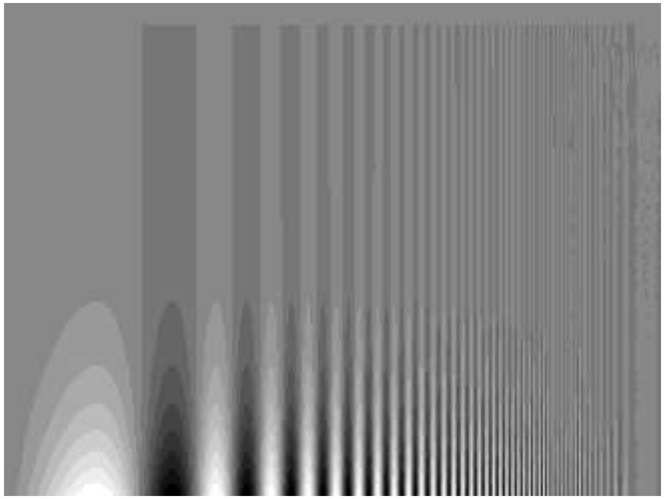


- Blue-to-yellow

Fine Detail

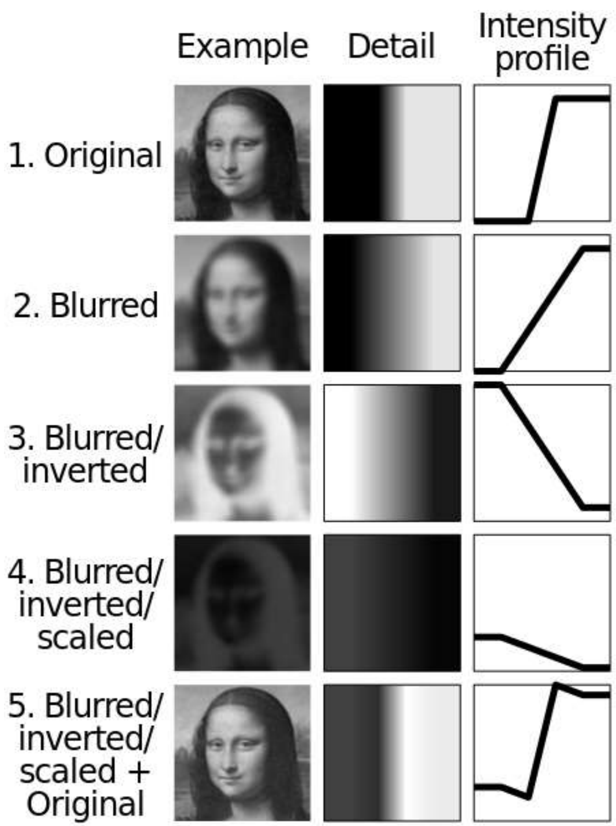
- For visualizations that include fine detail (such as text), use enough **luminance contrast**
  - At least 3:1, better 10:1
  - If that's not an option, add a strong border (or a Cornsweet edge)

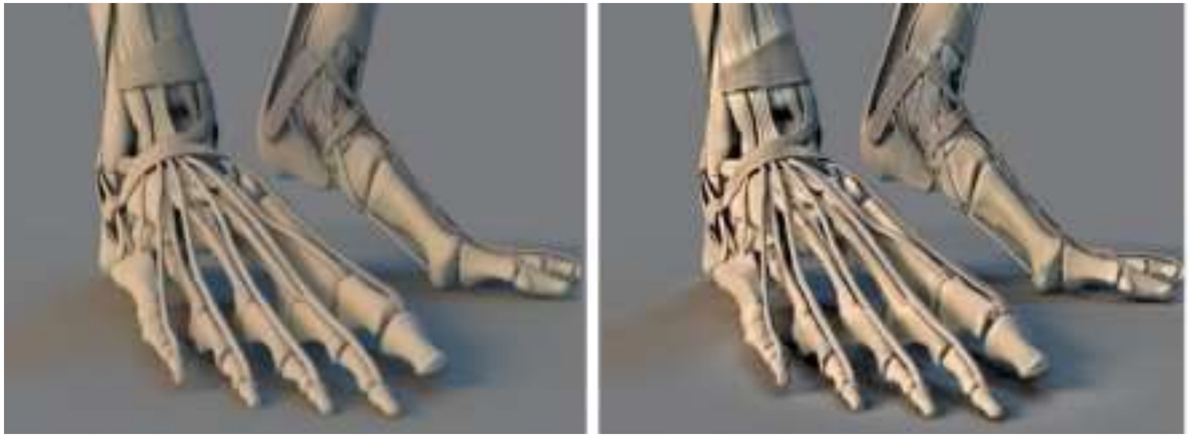




Consider Using Cornsweet Effect

- **Cornsweet edges** can increase apparent contrast in an image (e.g., unsharp masking)





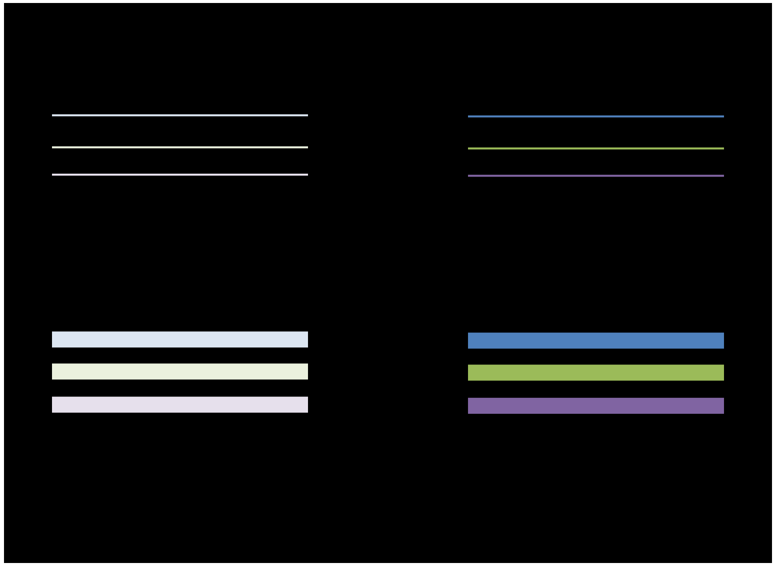
[Ritschel et al., SIGGRAPH 2008]

Cornsweet Effect in Art

- Georges-Pierre Seurat (1859 – 1891): Bathers at Asnières

Saturation

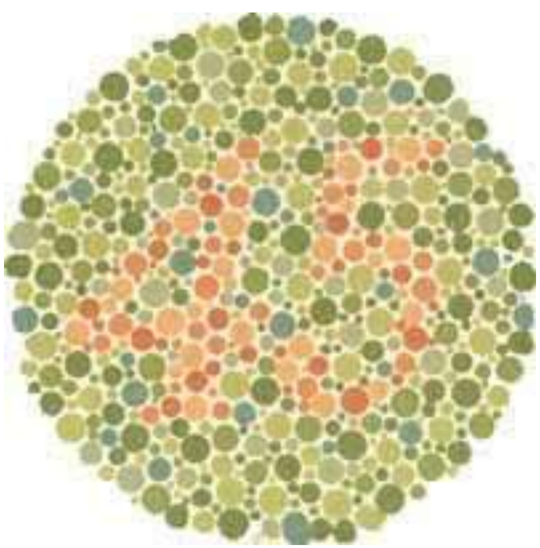
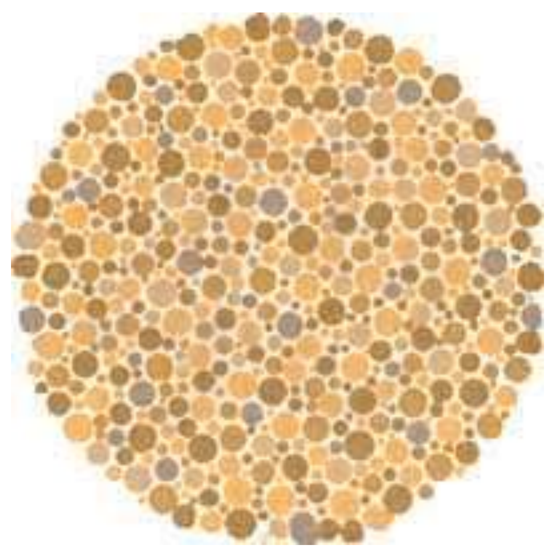
- Colors on **small shapes** or **fine details** need to be strong in order to be distinguishable
- Soft (pastel) colors should be used for **backgrounds** or for **segmenting larger areas**
- Do not use saturation levels to encode >3-4 values



What will a dark background change?

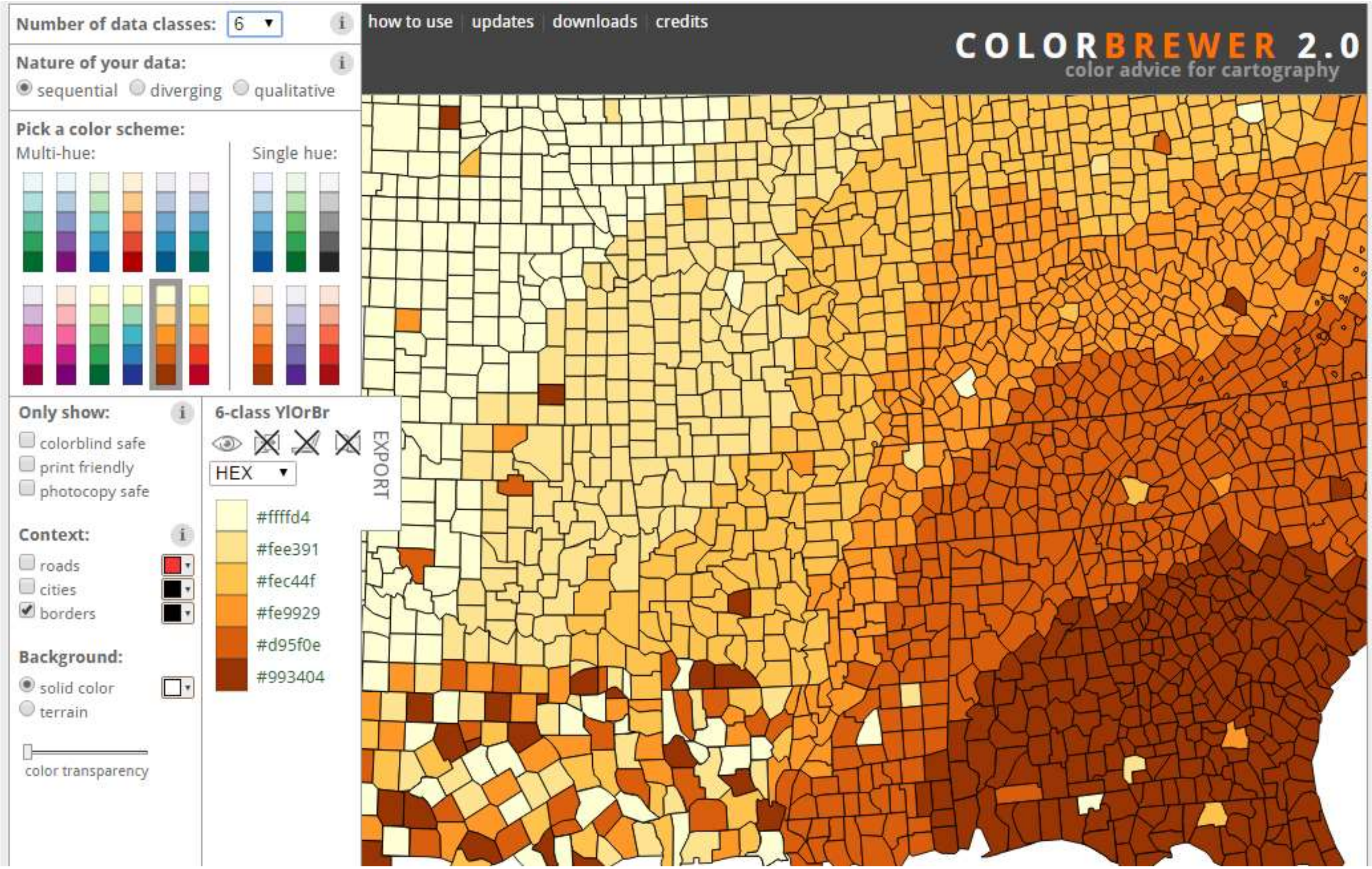
Keep Color Impairment in Mind

- **Color impairment** (especially red-green weakness) affects a substantial part of the population!
  - Can check pictures using: http://www.vischeck.com/vischeck/
  - Algorithm for image improvement: http://www.vischeck.com/daltonize/


Practical Advise

- Visit colorbrewer2.org



Section 2.3:
Attention

Preattentive Processing

- A limited set of visual properties are processed *preattentively*
  - quickly, without need for focusing attention
- This is important for design of visualizations
  - what can be perceived immediately
  - what properties are good discriminators
  - what can mislead viewers

Example: Preattentive Processing

- Count the number of 3s:

1281768756138976546984506985604982826762

9809858458224509856458945098450980943585

9091030209905959595772564675050678904567

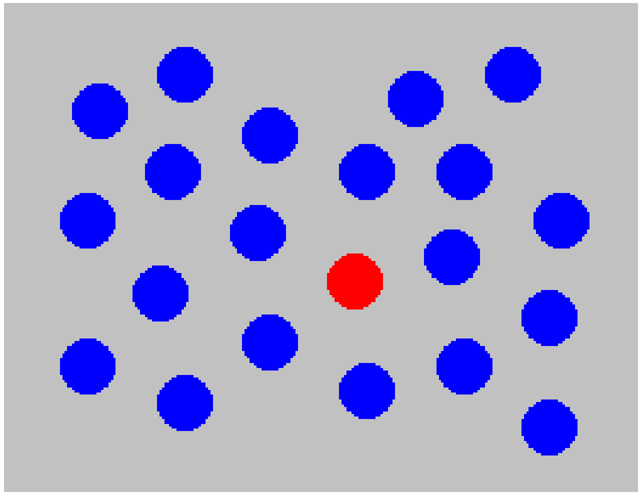
8845789809821677654876364908560912949686

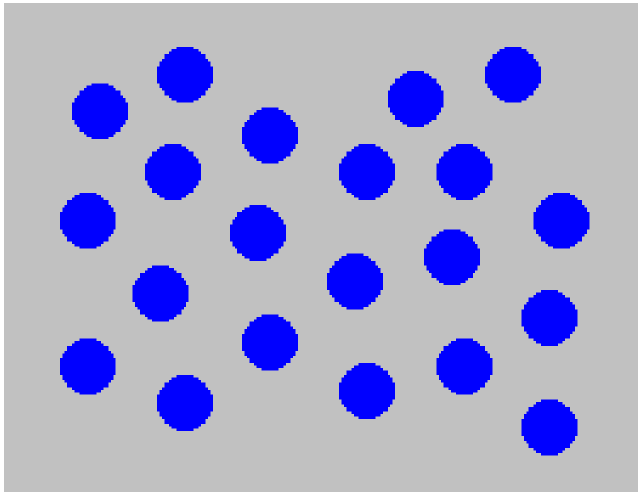
Example: Preattentive Processing

- Count the number of 3s:

1281768756138976546984506985604982826762
9809858458224509856458945098450980943585
9091030209905959595772564675050678904567
8845789809821677654876364908560912949686

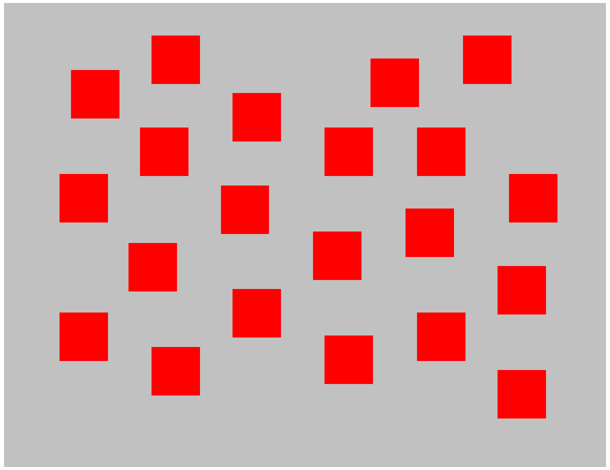
Example: Color Selection

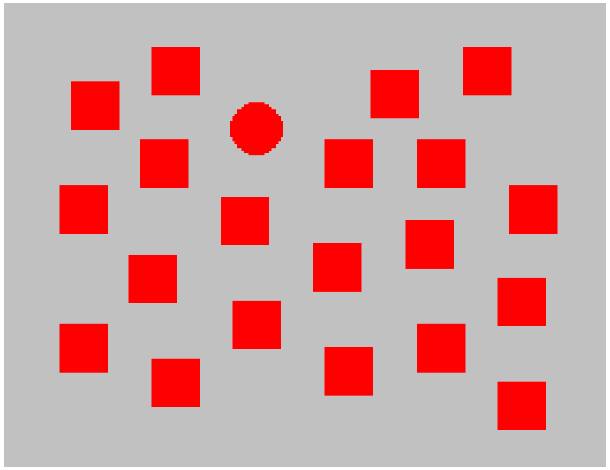




Viewer can rapidly and accurately determine whether the target (red circle) is present or absent. Difference detected in color.

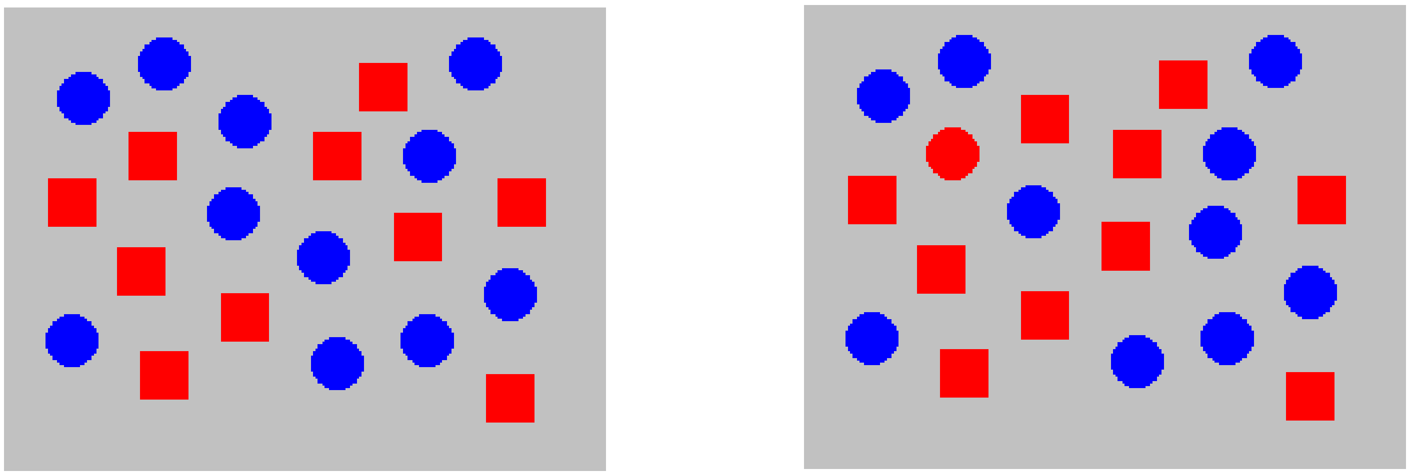
Example: Shape Selection





Viewer can rapidly and accurately determine whether the target (red circle) is present or absent. Difference detected in form (curvature)

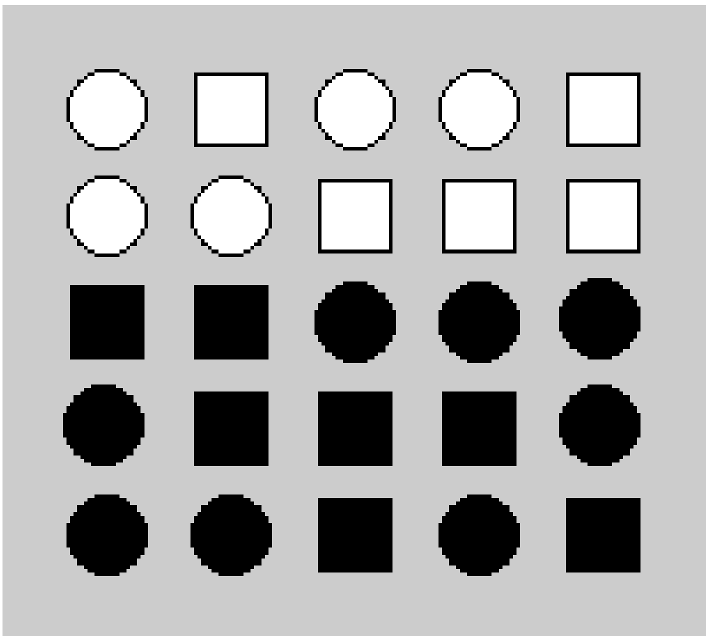
Example: Conjunction of Features

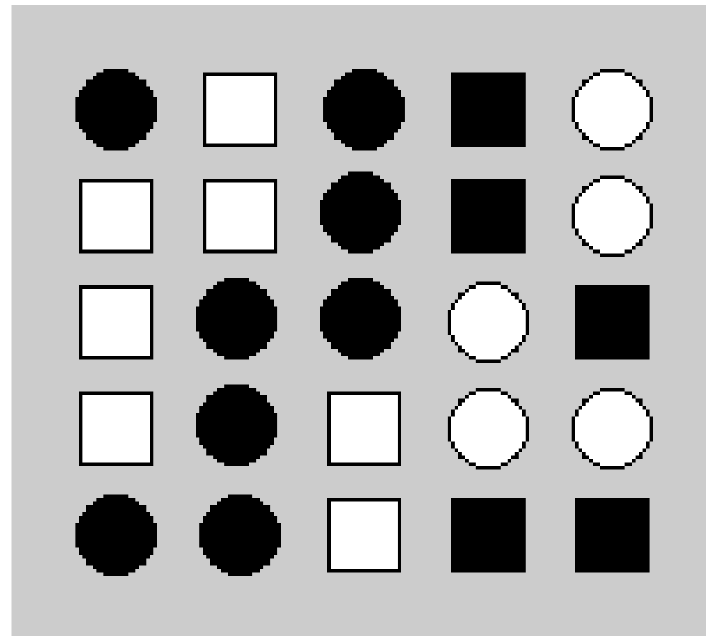


Viewer can *no longer* rapidly and accurately determine whether the target (red circle) is present or absent when target has two or more features, each of which are present in the distractors. Viewer must search sequentially.

Example: Shape vs. Fill

- **Question:** Is there a boundary?



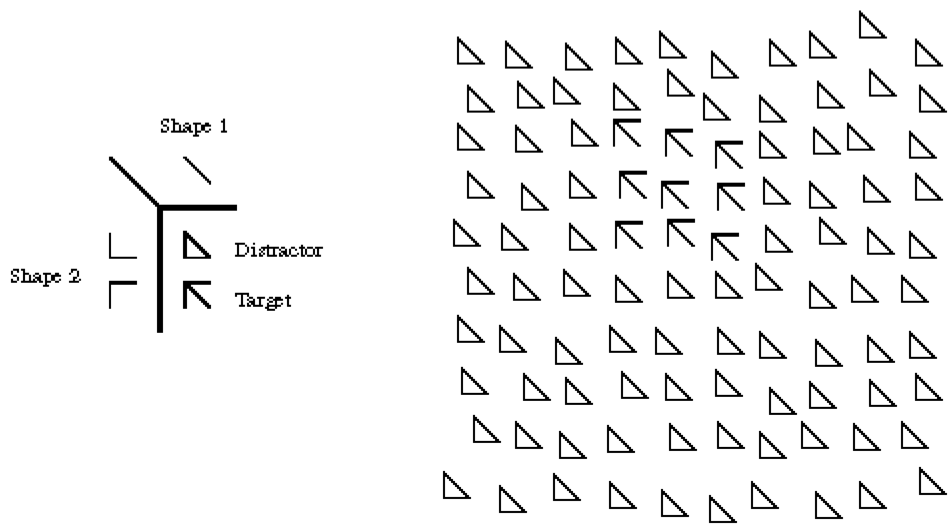


Cannot be done preattentively if both features change at the same time.

Pre-attentive Processing

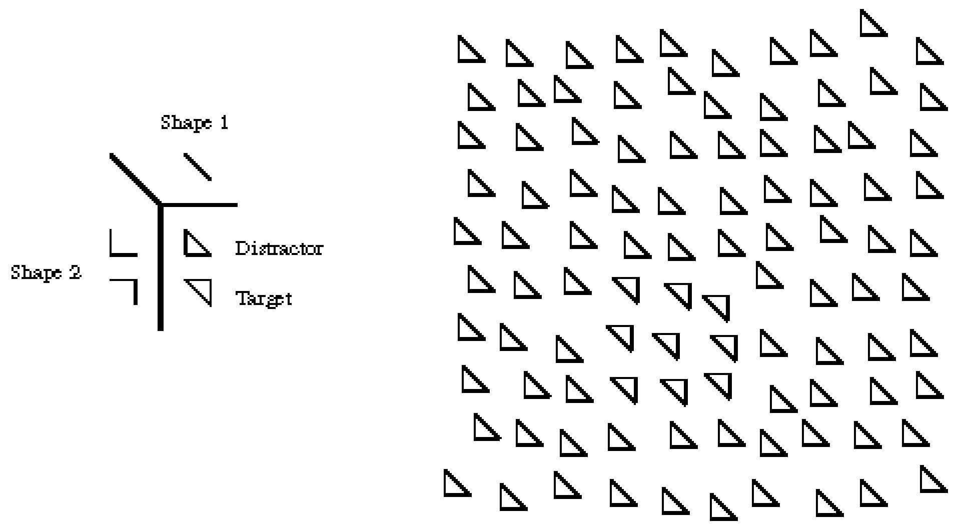
- < 200 - 250ms qualifies as pre-attentive
  - eye movements alone take at least 200ms
  - yet certain processing can be done very quickly, implying low-level processing in parallel
- If a decision takes a fixed amount of time regardless of the number of distractors, it is considered to be preattentive.

Example: Emergent Features



Target has a unique feature with respect to distractors (open sides) and so the group can be detected preattentively.

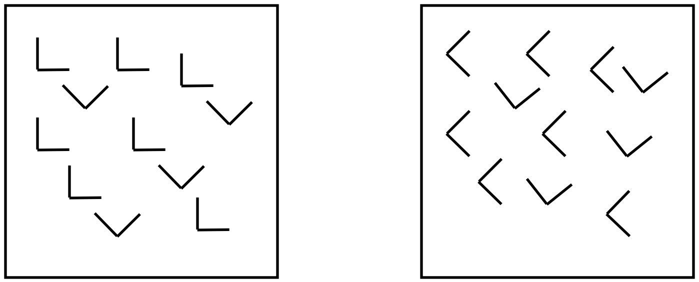
Example: Emergent Features



Target does not have a unique feature with respect to distractors and so the group cannot be detected preattentively.

Asymmetric Preattentive Properties

- Some properties are asymmetric
  - a sloped line among vertical lines is preattentive
  - a vertical line among sloped ones is not



Text NOT Preattentive

SUBJECT PUNCHED QUICKLY OXIDIZED TCEJBUS DEHCNUP YLKCIUQ DEZIDIXO
CERTAIN QUICKLY PUNCHED METHODS NIATREC YLKCIUQ DEHCNUP SDOHTEM
SCIENCE ENGLISH RECORDS COLUMNS ECNEICS HSILGNE SDROCER SNMULOC
GOVERNS PRECISE EXAMPLE MERCURY SNREVOG ESICERP ELPMAXE YRUCREM
CERTAIN QUICKLY PUNCHED METHODS NIATREC YLKCIUQ DEHCNUP SDOHTEM
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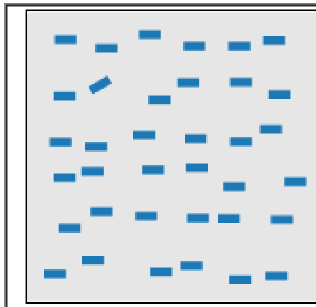
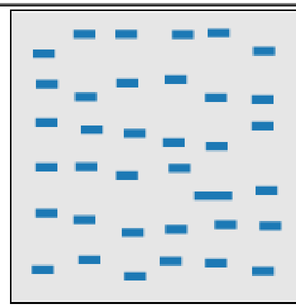
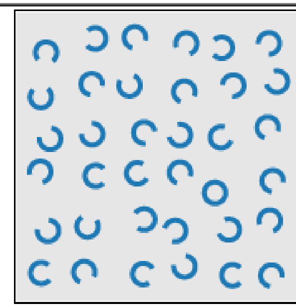
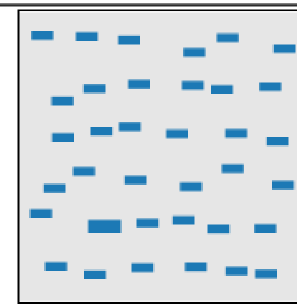
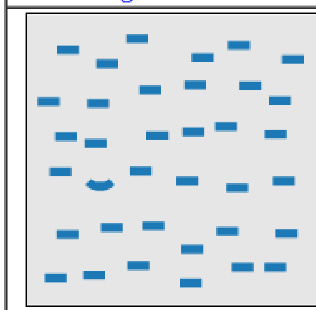
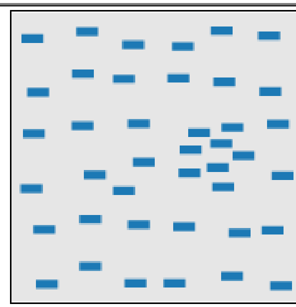
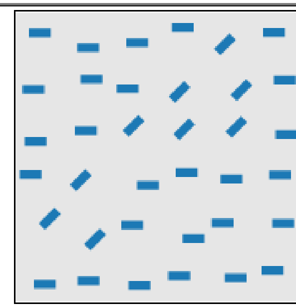
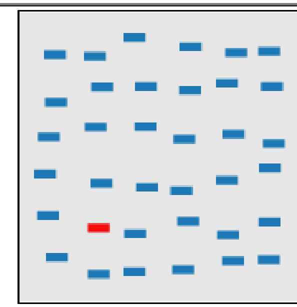
List of Preattentive Visual Properties

See Christopher Healey's page for examples:

http://www.csc.ncsu.edu/faculty/healey/PP/index.html

			
line (blob) orientation Julész & Bergen 83; Sagi & Julész 85a, Wolfe et al. 92; Weigle et al. 2000	length, width Sagi & Julész 85b; Treisman & Gormican 88	closure Julész & Bergen 83	size Treisman & Gelade 80; Healey & Enns 98; Healey & Enns 99
			
curvature Treisman & Gormican 88	density, contrast Healey & Enns 98; Healey & Enns 99	number, estimation Sagi & Julész 85b; Healey et al. 93; Trick & Pylyshyn 94	colour (hue) Nagy & Sanchez 90; Nagy et al. 90; D'Zmura 91; Kawai et al. 95; Bauer et al. 96; Healey 96; Bauer et al. 98; Healey & Enns 99

Change Blindness

- Perceiving change requires **attention,** which requires guidance
  - Motion strongly draws our attention
  - Masking out motion makes us **blind to changes** in images

- Sequences courtesy of Ron Rensink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Change Blindness: Explanations

- **Theories of change blindness** include:
  - **Not stored:** Visual impression may be lost, only abstraction is preserved
  - **Stored, but not accessible:** Sometimes able to realize change in hindsight (and provide additional information) if pointed to it
  - **First impression:** Only first impression is stored (exchange main actor in short movie)
  - **Combination:** Images are merged into a single impression

Acknowledgement

- Sources of this lecture include slides by:
  - Robert Winningham, Western Oregon University
  - Christopher Healey, North Carolina State University
  - Liz Marai, University of Illinois at Chicago
  - Gordon Kindlmann, University of Chicago
  - Kristen Grauman, UT-Austin
- …as well as much material from Colin Ware's *Information Visualization* book

Further Reading

- Colin Ware: *Information Visualization: Perception for Design.* Morgan Kaufmann, 2013
- Gunter Wyszecki, W. S. Stiles: *Color Science: Concepts and Methods, Quantitative Data and Formulae.* Second edition, Wiley, 2000
- Matthew Ward, Georges Grinstein, Daniel Keim: *Interactive Data Visualization: Foundations, Techniques, and Applications.* A. K. Peters, 2010