Color in Information Display

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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

Why Color?

Physical World		Visual System		Mental Models
Lights, surfaces, objects	→	Eye, optic nerve, visual cortex	→	Red, green, brown
				Apple, leaf, bark
				Ripe, fresh, eatable
				…and then to action.

Color in Information Display

Physical World → Visual System → Mental Models

Lines, patches, shaded regions → Eye, optic nerve, visual cortex → Roads, lakes

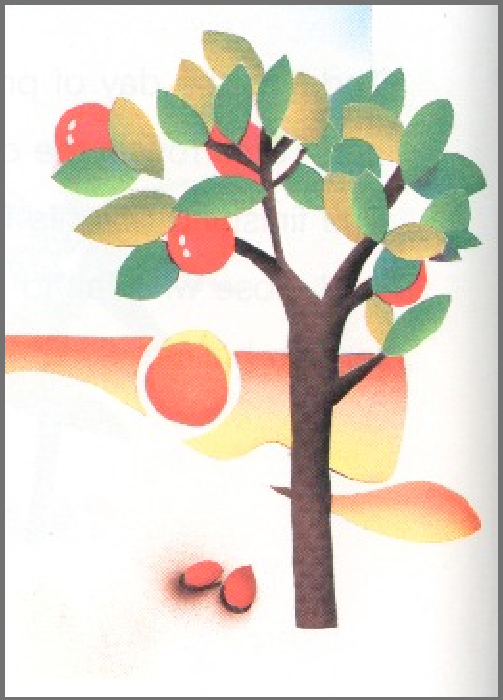
Profit, loss, trends

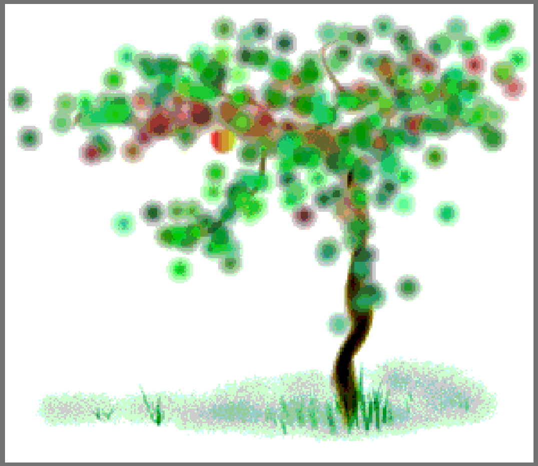
Failures, threats

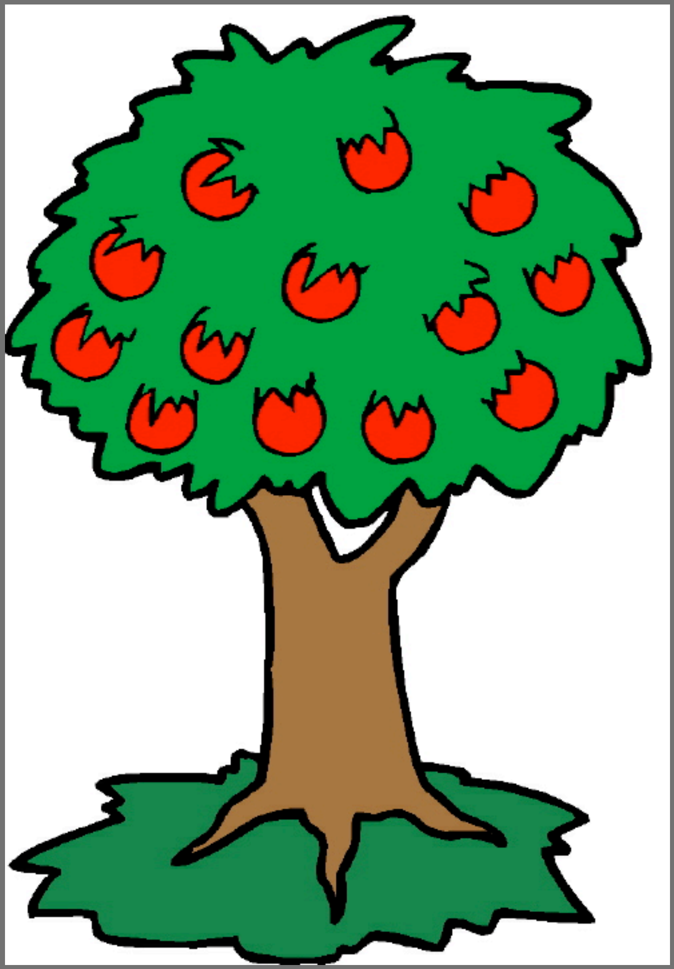
…and then to action

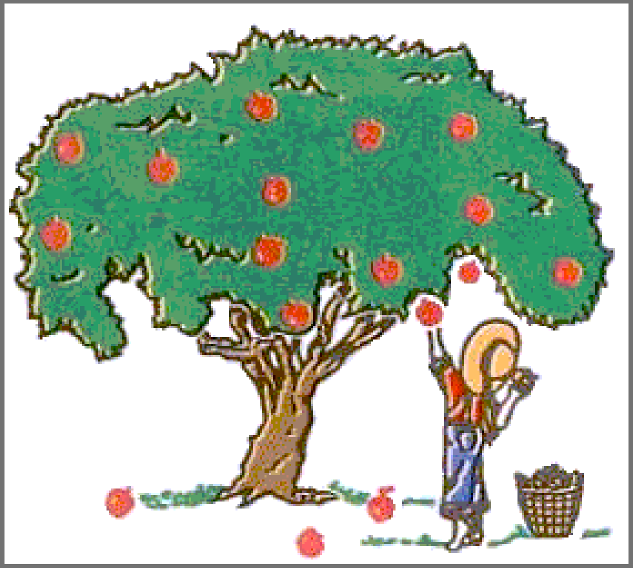
Illustrators, graph makers
Artists, designers
A few scientific principles









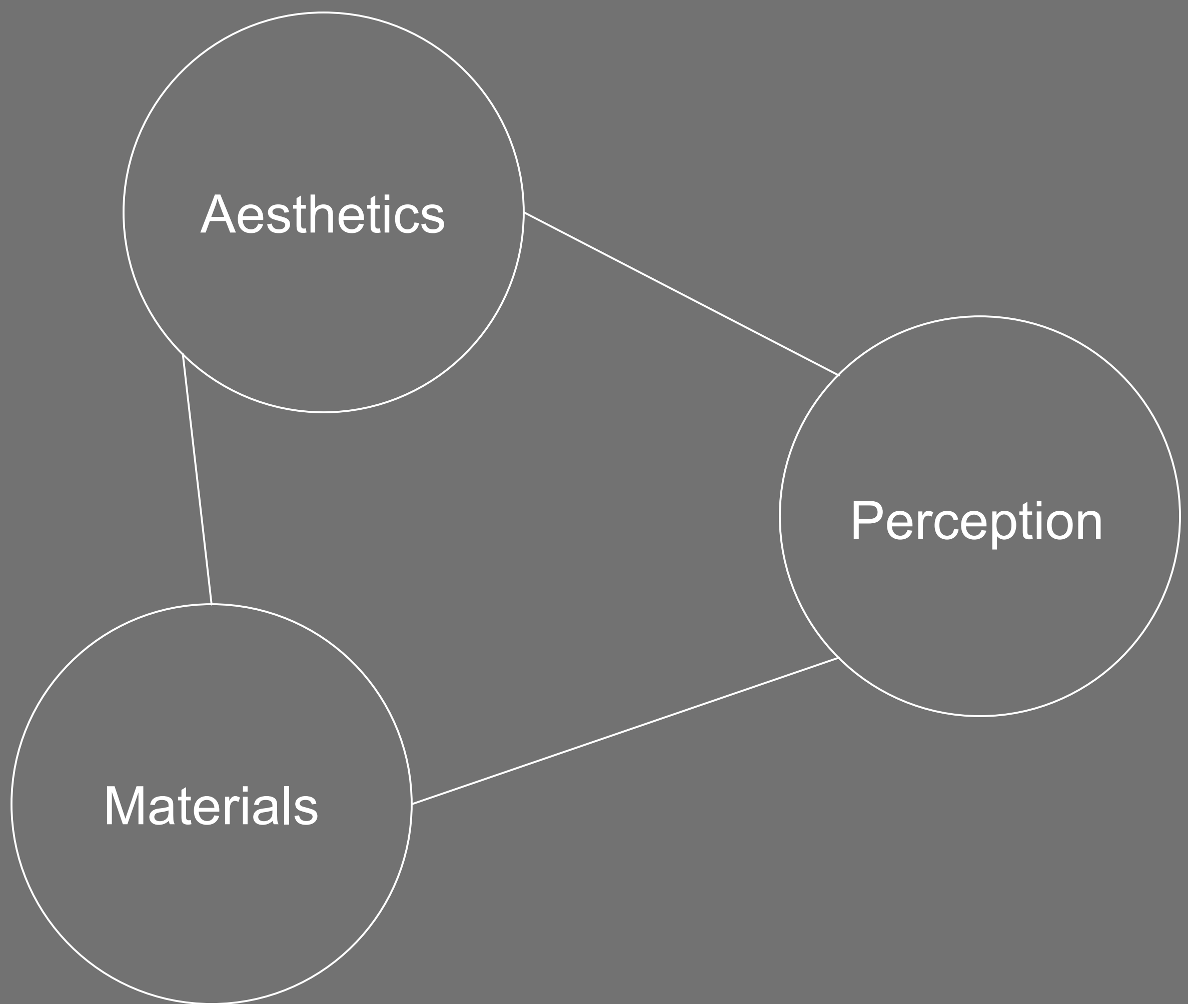


Why Should We Care?

- Poorly designed color is confusing
  - Creates visual clutter
  - Misdirects attention
- Poor design devalues the information
  - Visual sophistication
  - Evolution of document and web design
- “Attractive things work better”

– Don Norman

Effective Color



Color Models

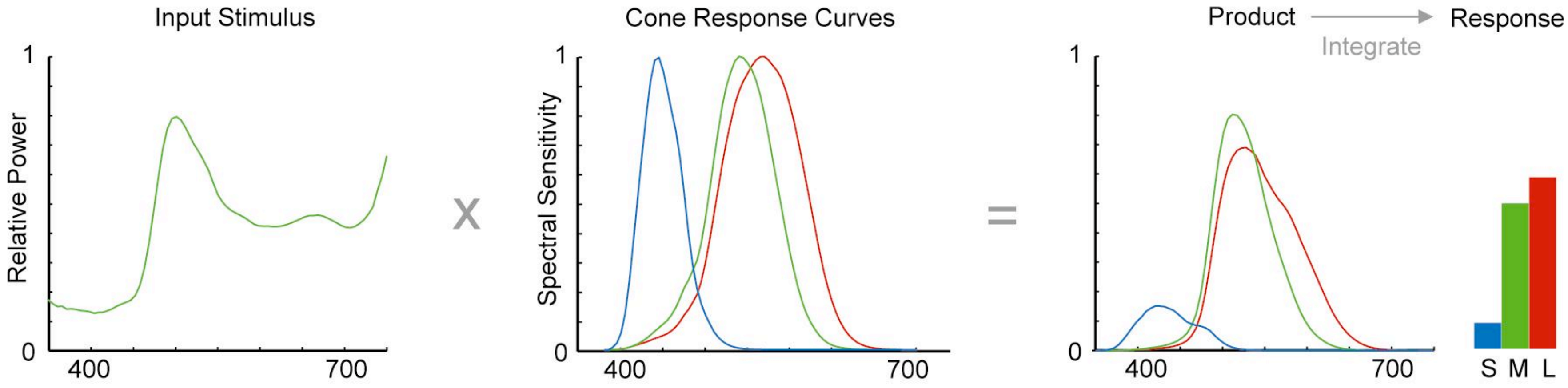
Physical World	Visual System		Mental Models	
Light Energy →	Cone Response →	Opponent Encoding →	Perceptual Models →	Appearance Models
Spectral distribution functions F(λ)	Reduce to three values (LMS) CIE tristimulus values (XYZ)	Separate Lightness, Chroma (A,R-G,Y-B)	Unique White CIELAB Munsell (HVC)	*Hue, chroma, saturation, colorfulness lightness, brightness* CIECAM02

Visual System

- Light path
  - Cornea, pupil, lens, retina, optic nerve, brain
- Retinal cells
  - Rods and cones
  - Unevenly distributed
- Cones
  - Three “color receptors”
  - Concentrated in fovea

Cone Response

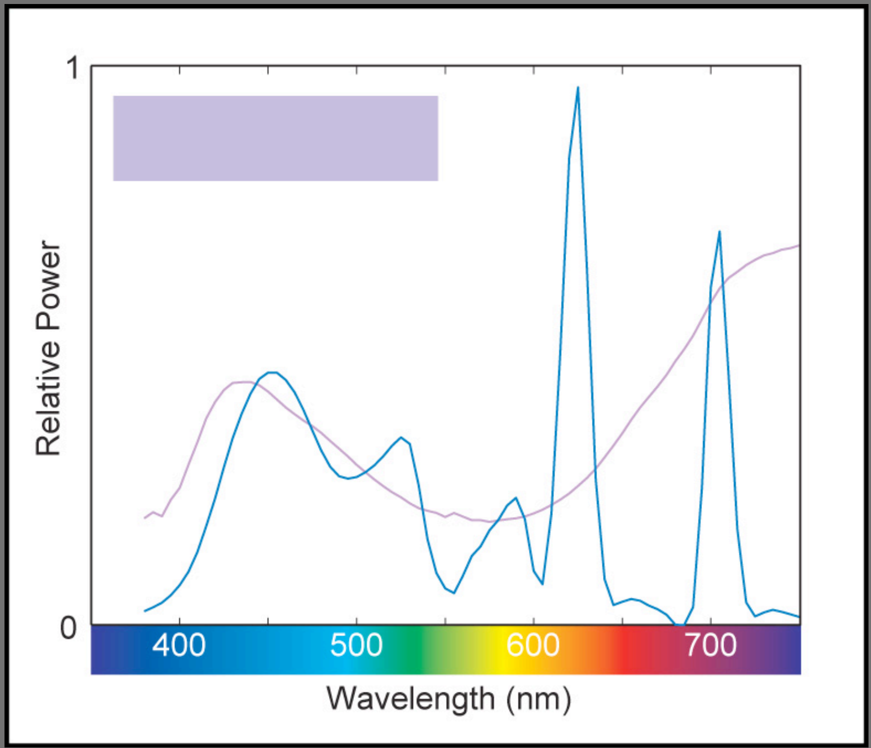
- Encode spectra as three values
- Long, medium and short (LMS)
- *Trichromacy*



From *A Field Guide to Digital Color*, © A.K. Peters, 2003

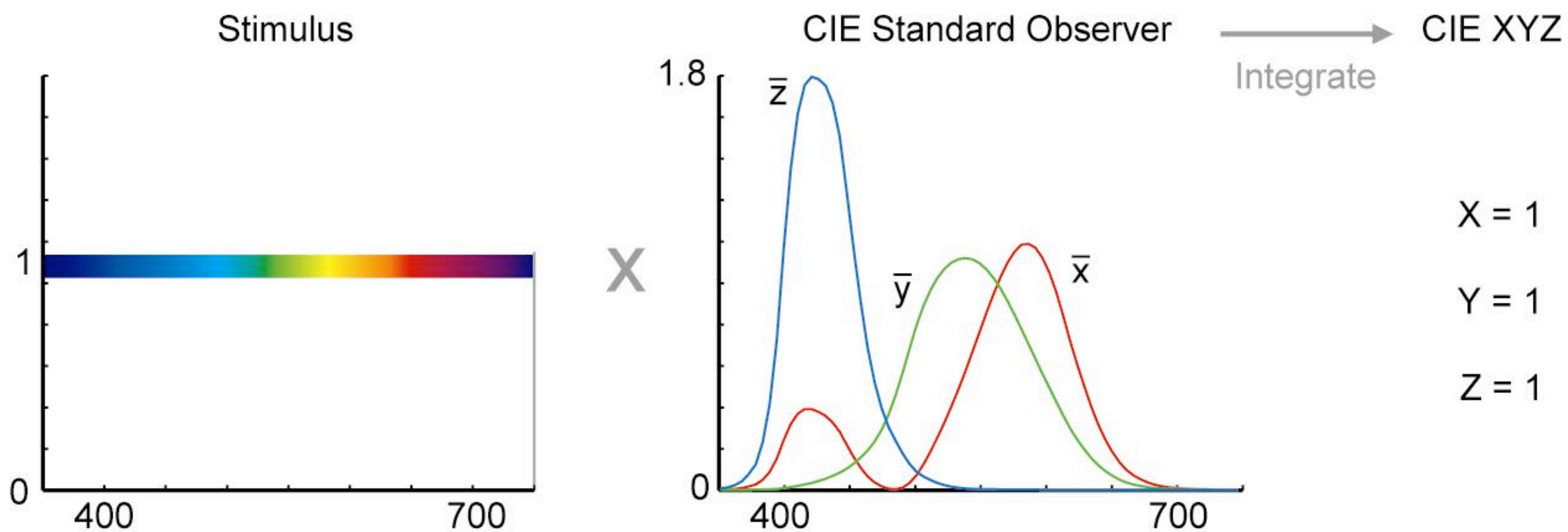
Effects of Retinal Encoding

- All spectra that stimulate the same cone response are indistinguishable
- *Metameric match*



CIE Standard "Cones"

- CIE Color Matching Functions (CMF)
- CIE tristimulus values (XYZ)
- Foundation for color measurement



From *A Field Guide to Digital Color*, © A.K. Peters, 2003

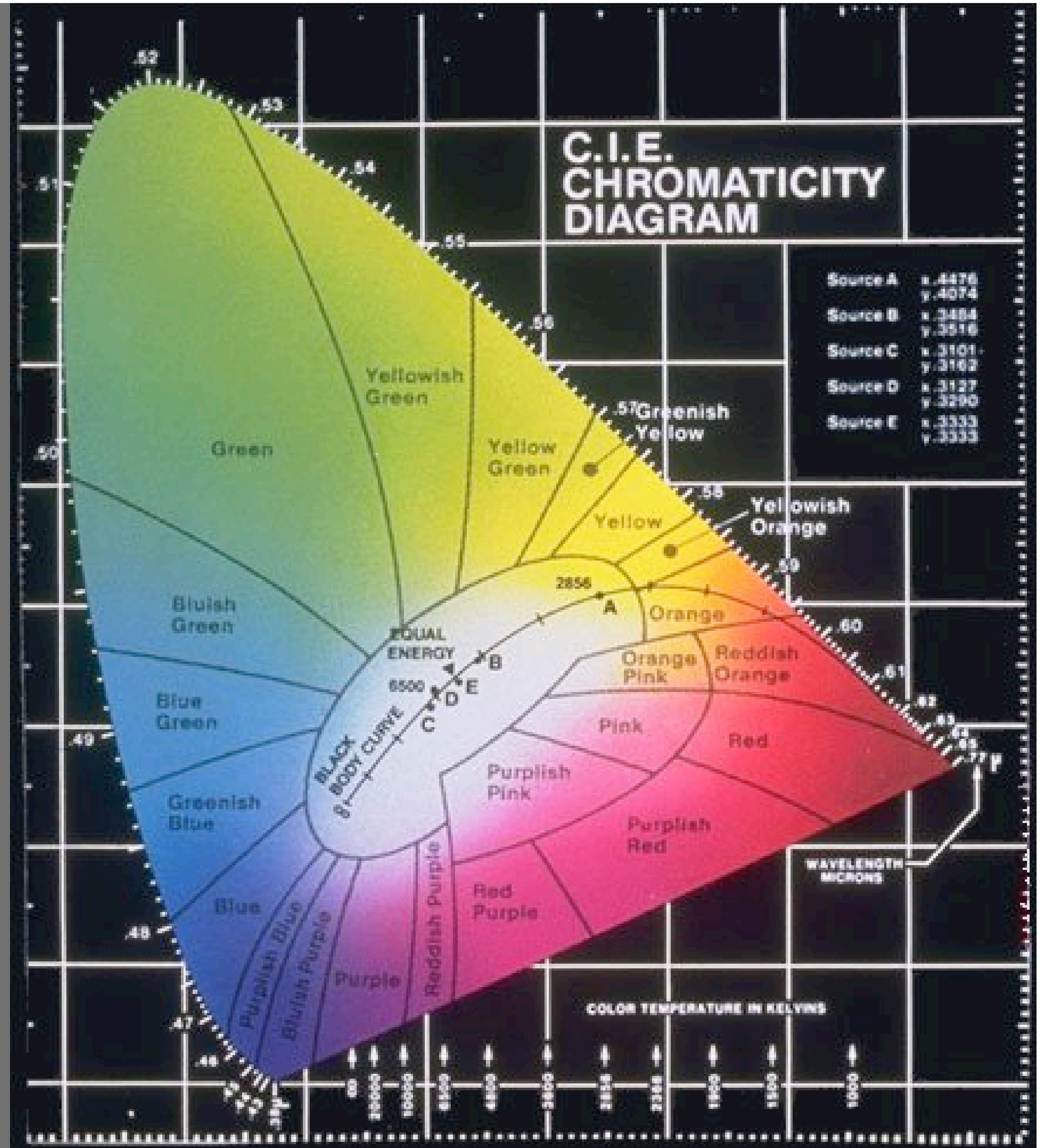
CIE Chromaticity Coordinates

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

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

$$1 = x+y+z$$

XYZ = xyY



Courtesy of PhotoResearch, Inc.

Tristimulus models (CIE XYZ)

- Absolute specification, based on cone response to a spectral stimulus
- Single colors, neutral background, constant adaptation
- Many different values for “white” and “black”
- Do two colors match exactly?*

*

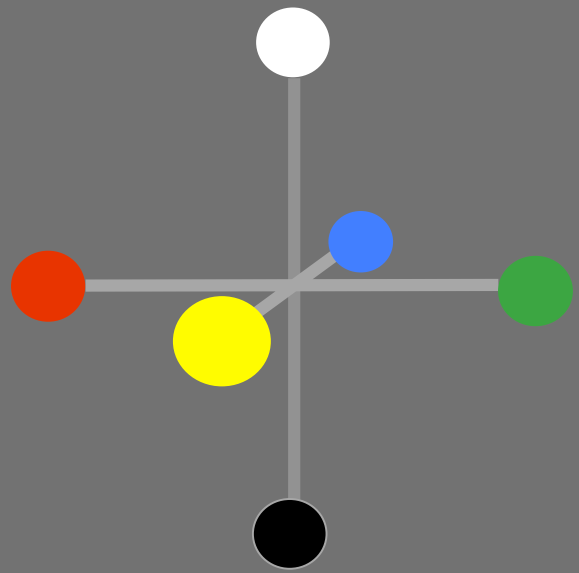
Color Models

Physical World	Visual System		Mental Models	
Light Energy →	Cone Response →	Opponent Encoding →	Perceptual Models →	Appearance Models
Spectral distribution functions F(λ)	Three numbers (LMS) CIE tristimulus values (XYZ)	Separate Lightness, Chroma (A,R-G,Y-B)	Unique White CIELAB Munsell	*Hue, chroma, saturation, colorfulness lightness, brightness* CIECAM02

Trichromacy
Metamerism
Color matching

Opponent Color

- Definition
  - Achromatic axis
  - R-G and Y-B axis
  - Separate lightness from chroma channels
- Occurs in retina



Effects of Opponent Color

- Unique hues
  - —No reddish-green
- Afterimages
  - – Red-green, blue-yellow, black-white
- Color vision deficiencies
  - – Red-green anomalies *
  - – Blue-yellow anomalies
- Foundation for perceptual color spaces

Model “Color blindness”

- Flaw in opponent processing
  - Red-green common (deuteranope, protanope)
  - Blue-yellow possible (tritanope)
  - Luminance channel almost “normal”
- Effect is 2D color vision model
  - Flatten color space
  - Can be simulated (Brettel et. al.)
  - Vischeck (www.vischeck.com)

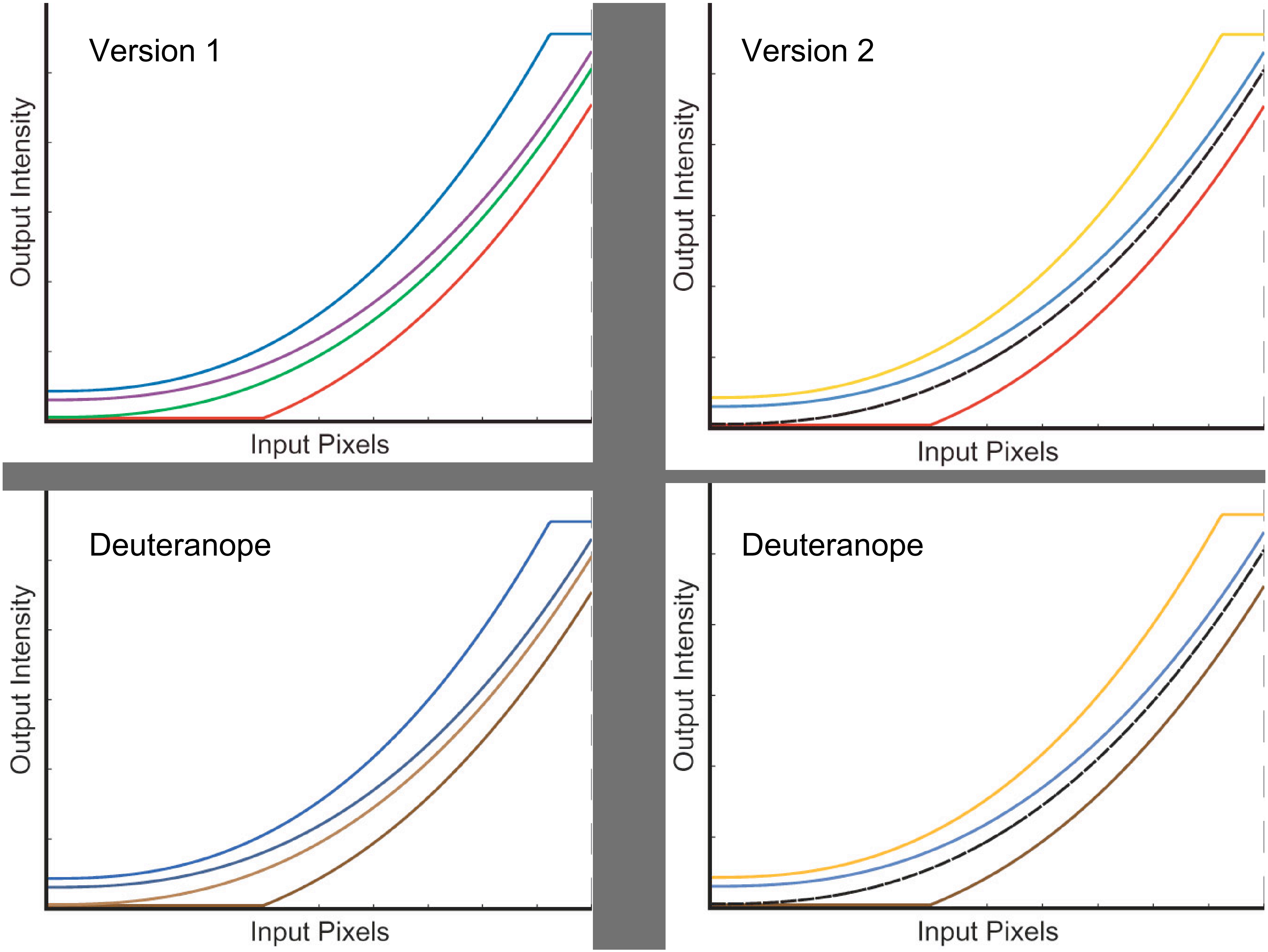
Vischeck (www.vischeck.com)

- Simulates color vision deficiencies
- Web service or Photoshop plug-in
- Robert Dougherty and Alex Wade

Deuteranope

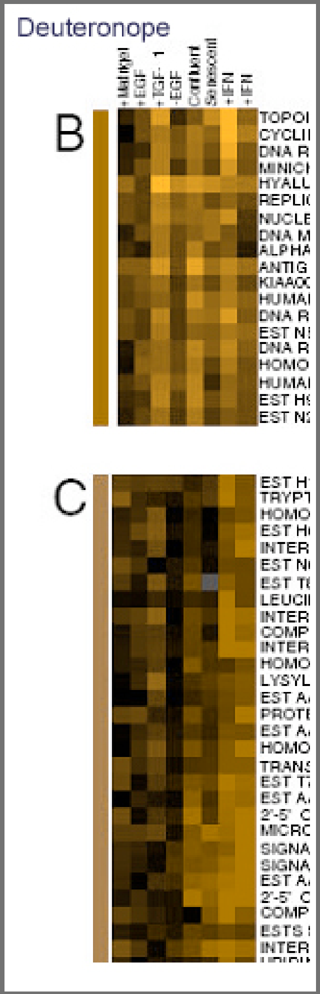
Protanope

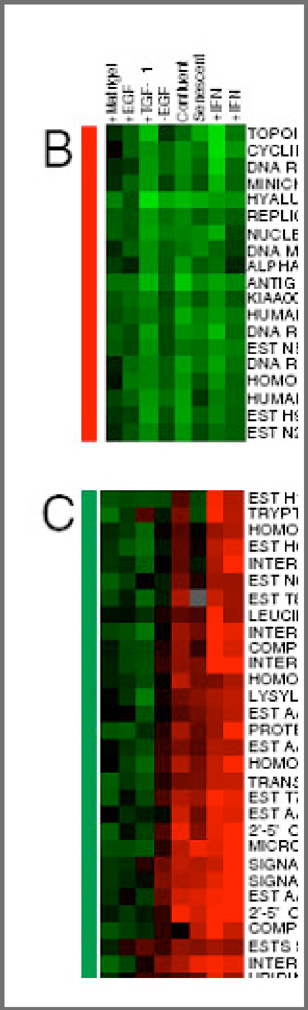
Tritanope

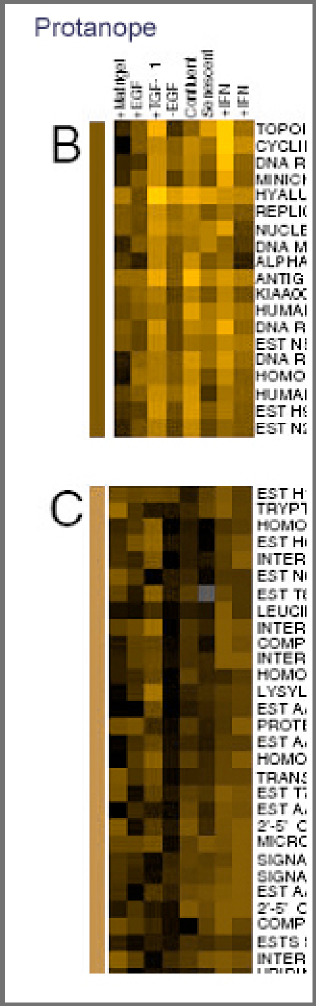


Version 1
Output Intensity
Input Pixels
Version 2
Output Intensity
Input Pixels
Deuteranope
Output Intensity
Input Pixels
Deuteranope
Output Intensity
Input Pixels

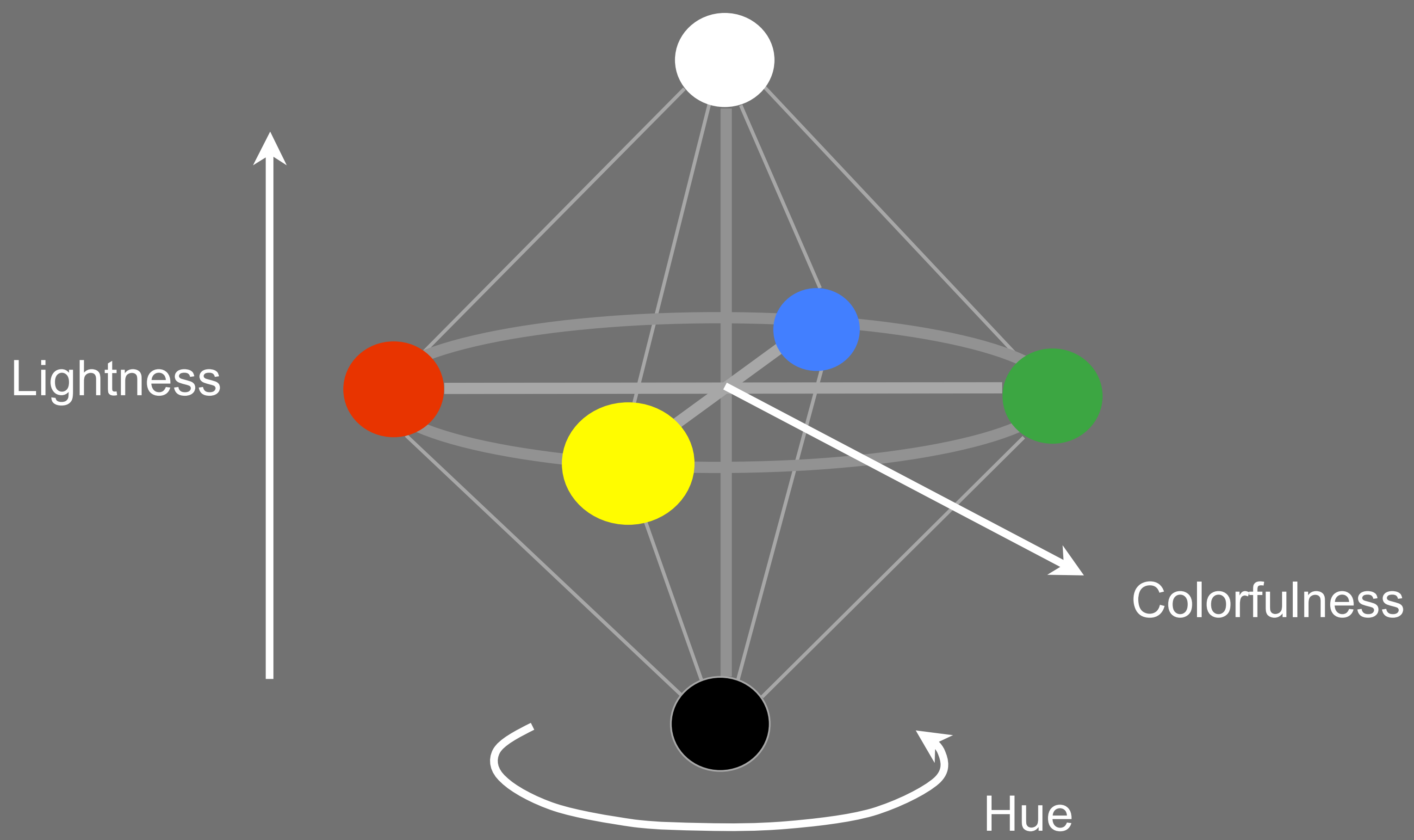
Genes in Vischeck







Perceptual Color Spaces



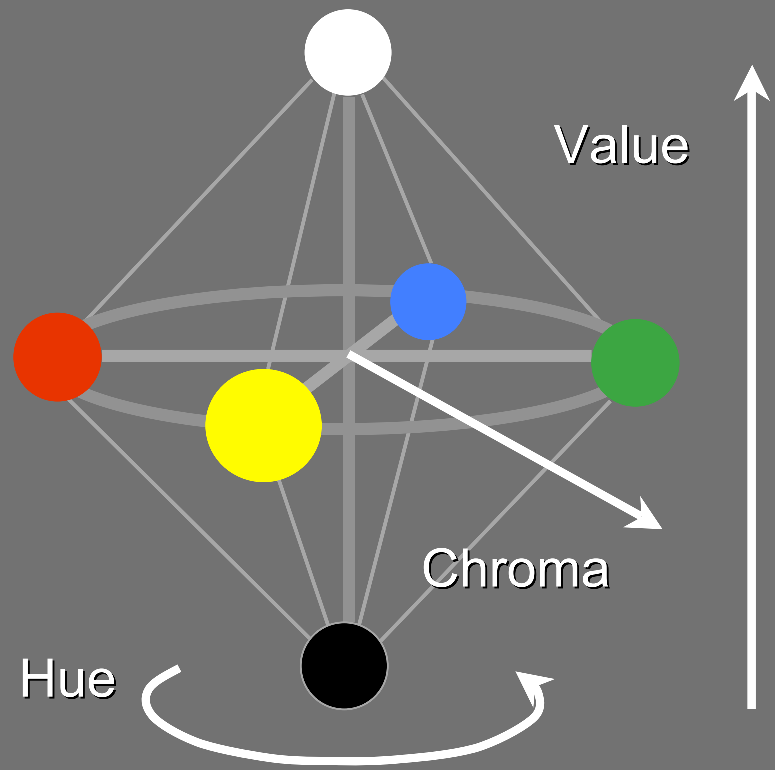
Unique black and white

Perceptual models

- Relative specification
- Unique values for “white” and “black”
- How similar are two colors?

Munsell Color

- Hue, Value, Chroma
  - 5 R 5/10 (bright red)
  - N 8 (light gray)
- Perceptually uniform



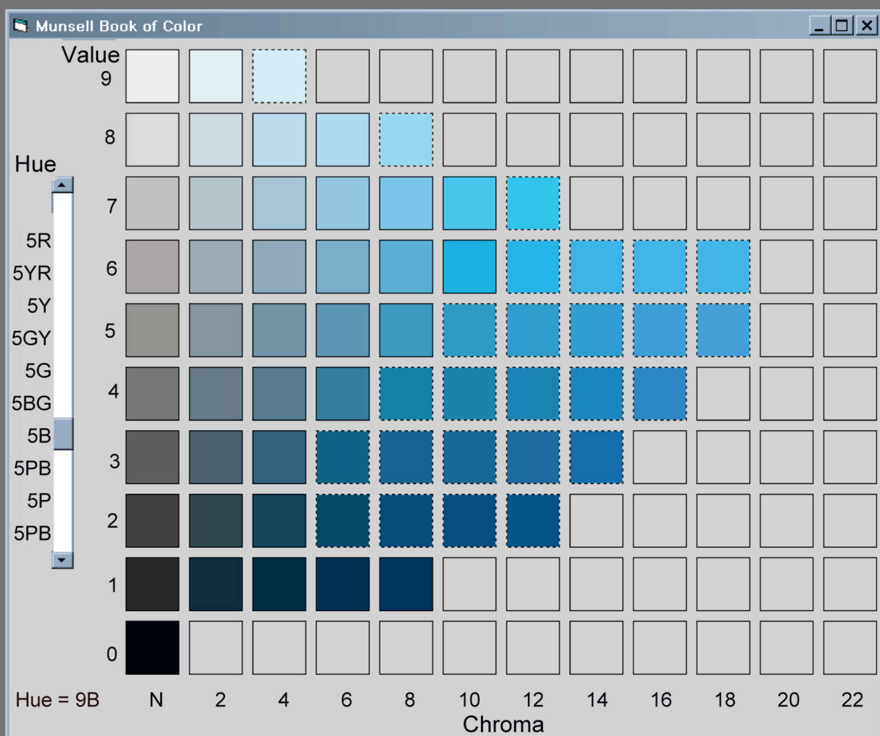
Munsell Renotation System maps between HVC and XYZ

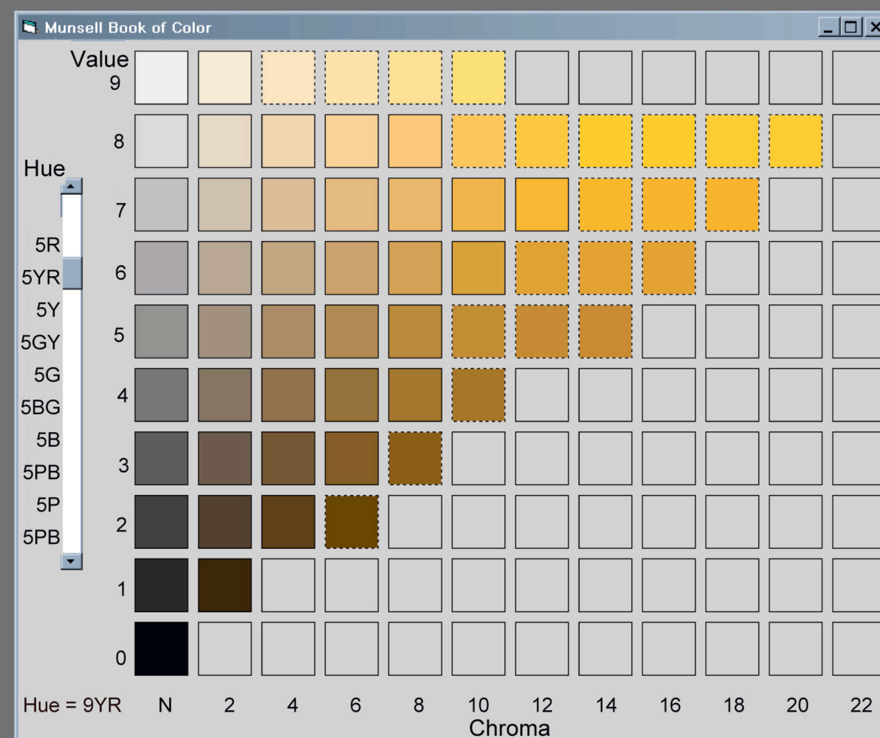
Munsell Atlas

Courtesy Gretag-Macbeth

Interactive Munsell Tool

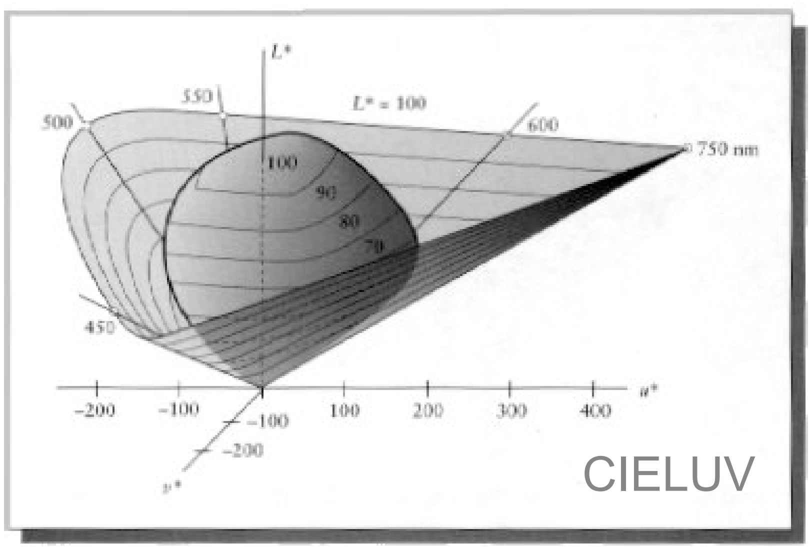
- From www.munsell.com



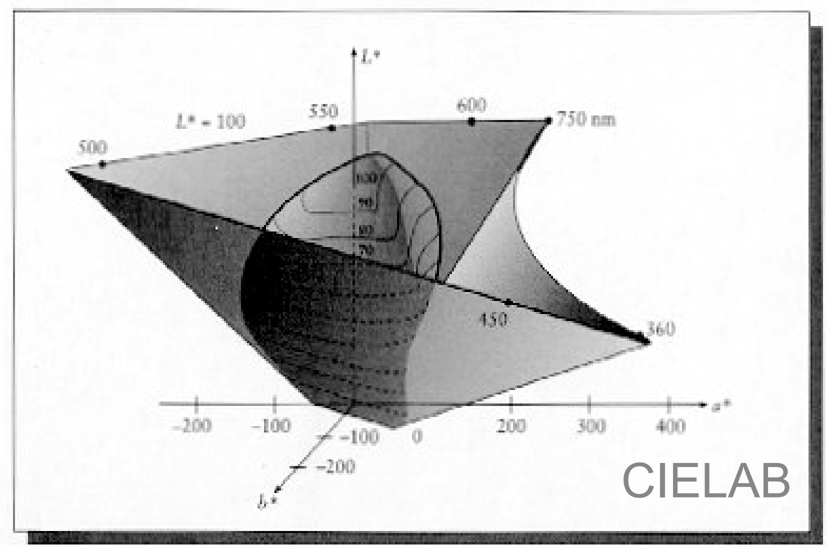


CIELUV and CIELAB

- Lightness (L*), two color axis (u*, v*) or (a*,b*)
- Non-linear function of CIE XYZ
- Defined for computing color differences



CIELUV

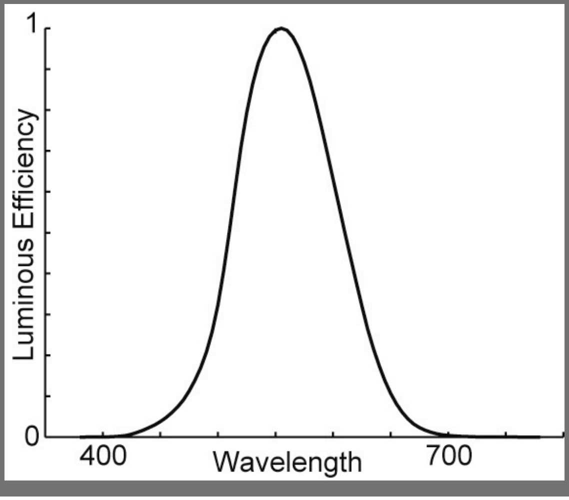


CIELAB

From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64

Lightness Scales

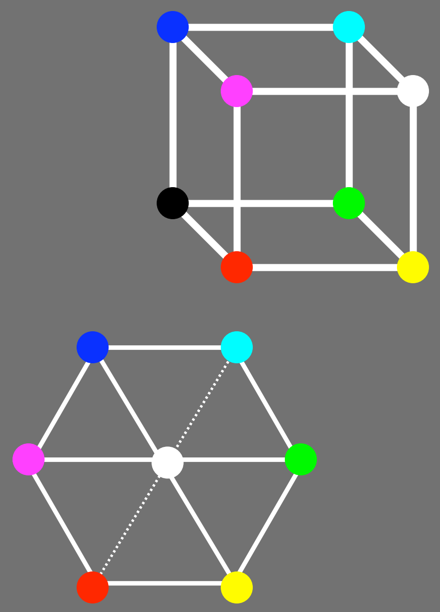
- Lightness, brightness, luminance, and L*
  - Lightness is relative, brightness absolute
  - Absolute intensity is light power (cd/m^2)
- Luminance is perceived intensity
  - Luminance varies with wavelength
  - Luminous efficiency function
  - Equivalent to CIE Y



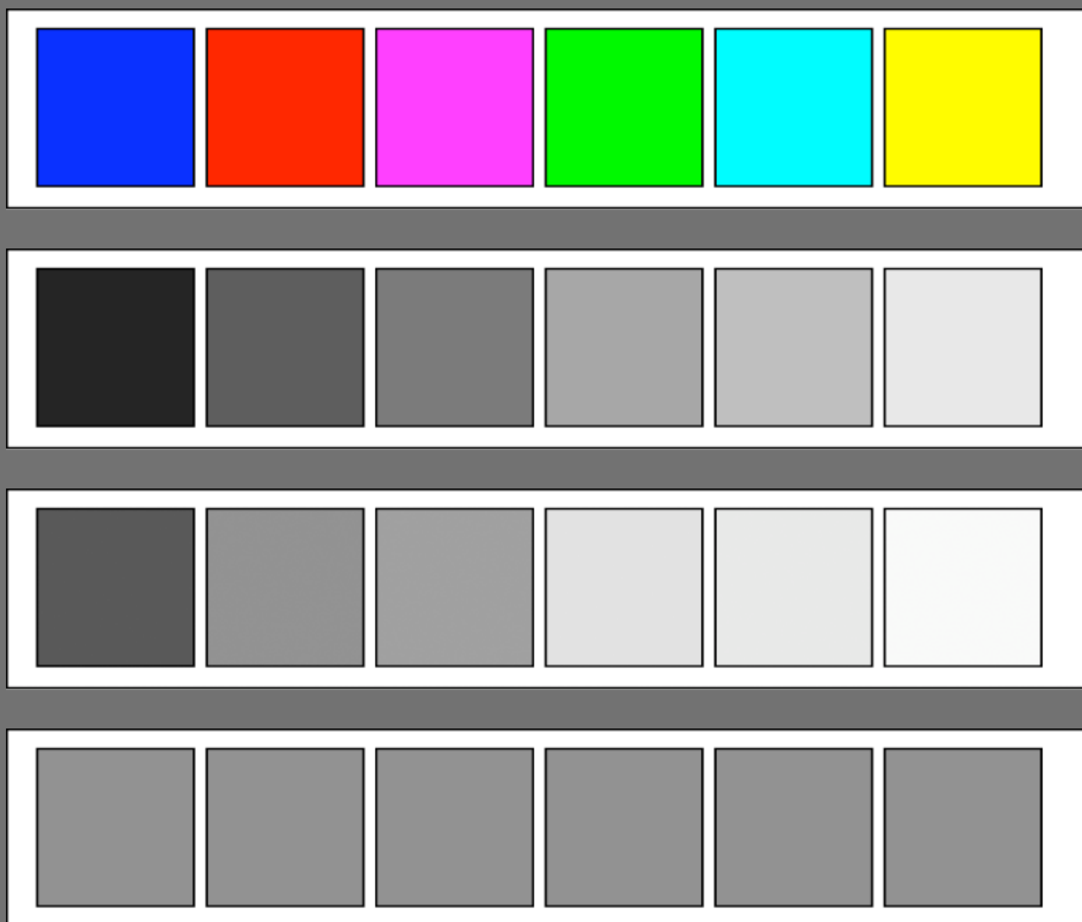
Green and blue lights of equal intensity have different luminance values

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



L vs. Luminance, L*



Corners of the RGB color cube

Luminance of these colors

L* for these colors

L from HLS
All the same

Color Models

Physical World | **Visual System** | **Mental Models**

Light Energy → Cone Response → Opponent Encoding → Perceptual Models → Appearance Models

Light Energy

Spectral distribution functions $F(\lambda)$

Cone Response

Three numbers (LMS)

CIE tristimulus values (XYZ)

Opponent Encoding

Separate Lightness, Chroma

(A,R-G,Y-B)

Perceptual Models

Unique White

CIELAB Munsell (HVC)

Appearance Models

Hue, chroma, saturation, colorfulness lightness, brightness

CIECAM02

Trichromacy
Metamerism
Color matching

Color differences
"Intuitive" color spaces
Image encoding
Color scales

2. Color Appearance

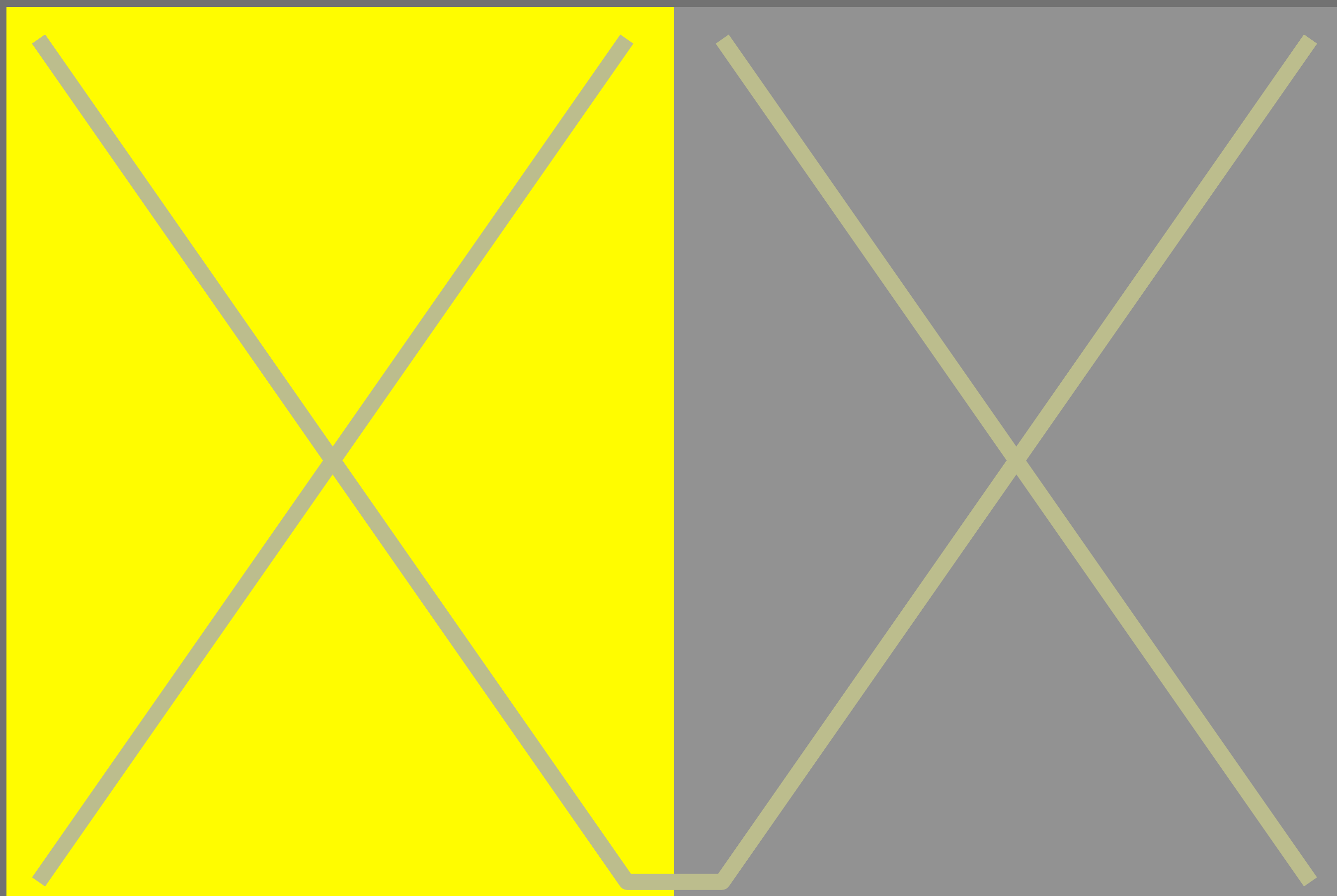


Image courtesy of John MCann

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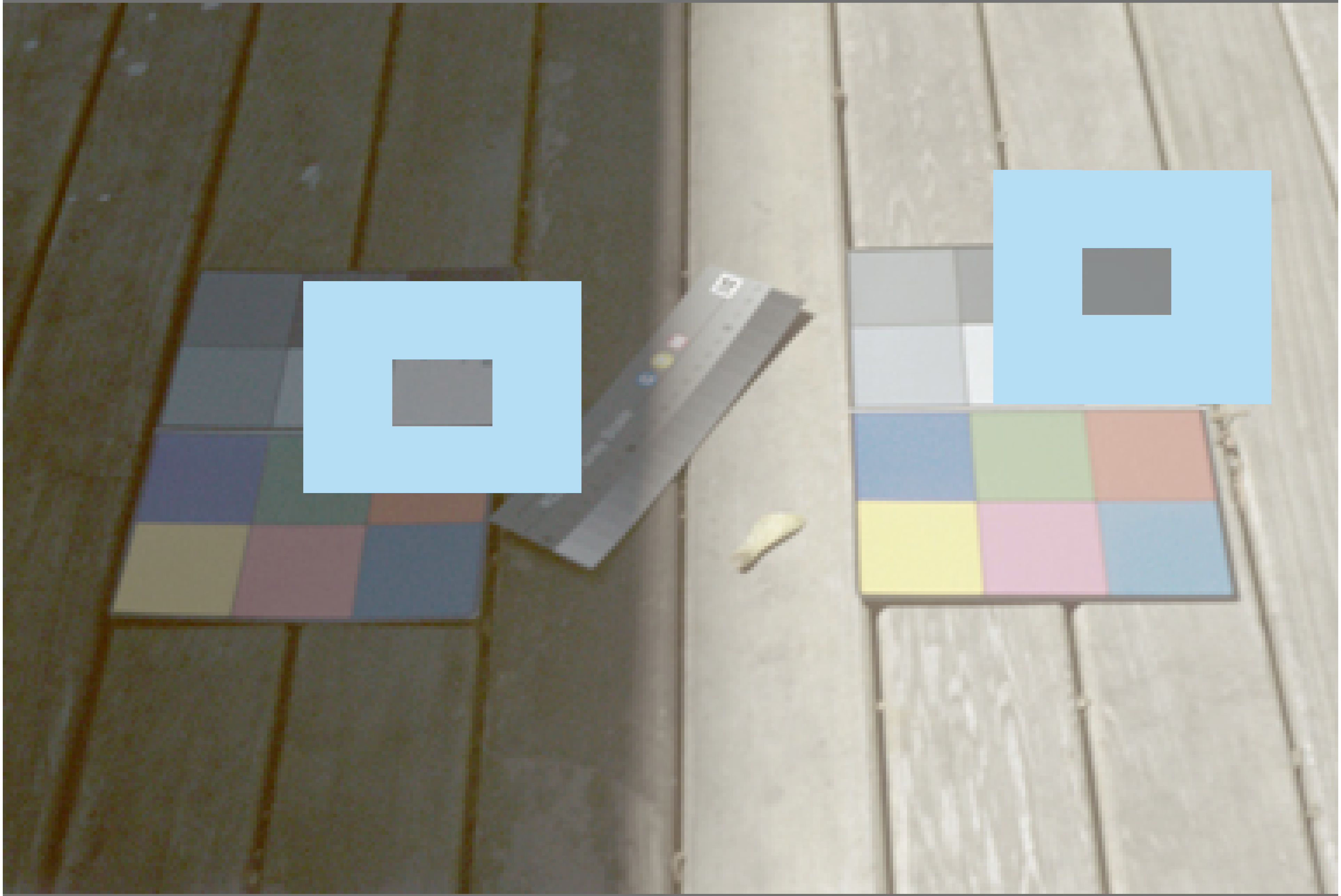
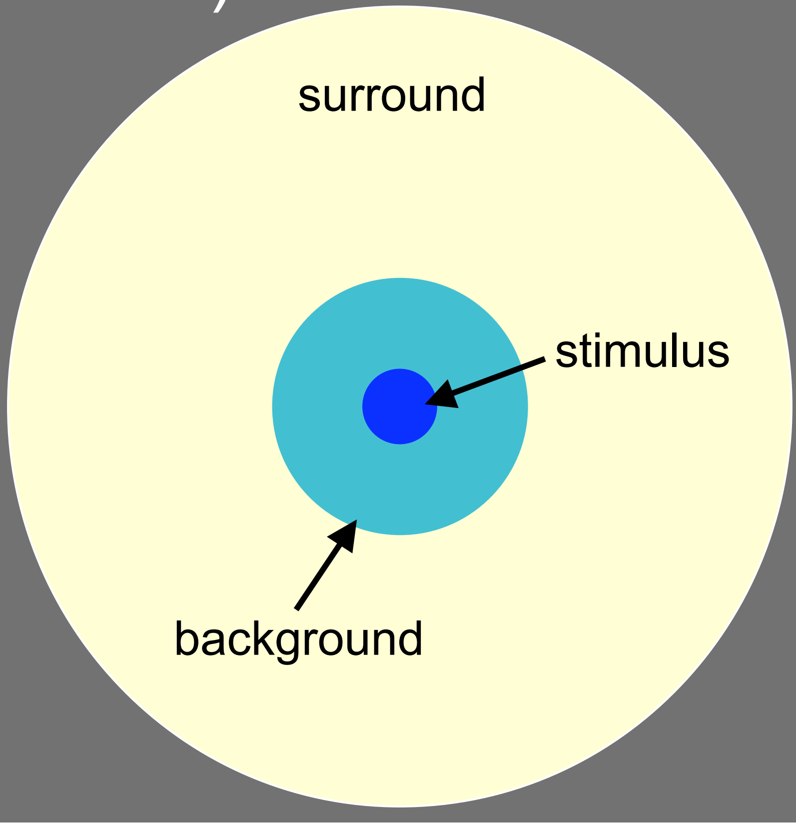


Color Appearance

- More than a single color
  - Adjacent colors (background)
  - Viewing environment (surround)
- Appearance effects
  - Adaptation
  - Simultaneous contrast
  - Spatial effects



Color Appearance Models
Mark Fairchild

Light/Dark Adaptation

- Adjust to overall brightness
  - 7 decades of dynamic range
  - 100:1 at any particular time
- Absolute illumination effects
  - Hunt effect

    Higher brightness increases colorfulness
  - Stevens effect

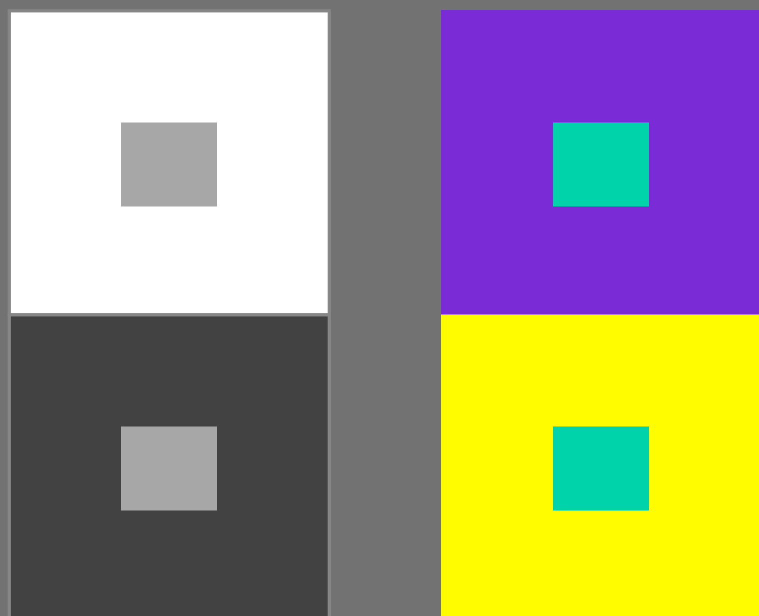
    Higher brightness increases contrast

Chromatic Adaptation

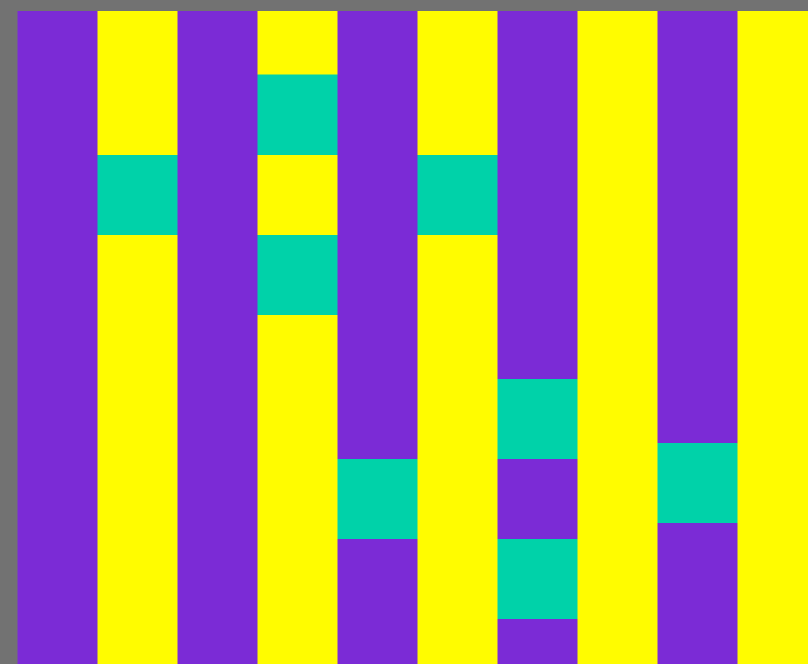
- Change in illumination
- Cones "white balance"
  - Scale cone sensitivities
  - von Kries
  - Also cognitive effects
- Creates unique white

From *Color Appearance Models*, fig 8-1

Simultaneous Contrast

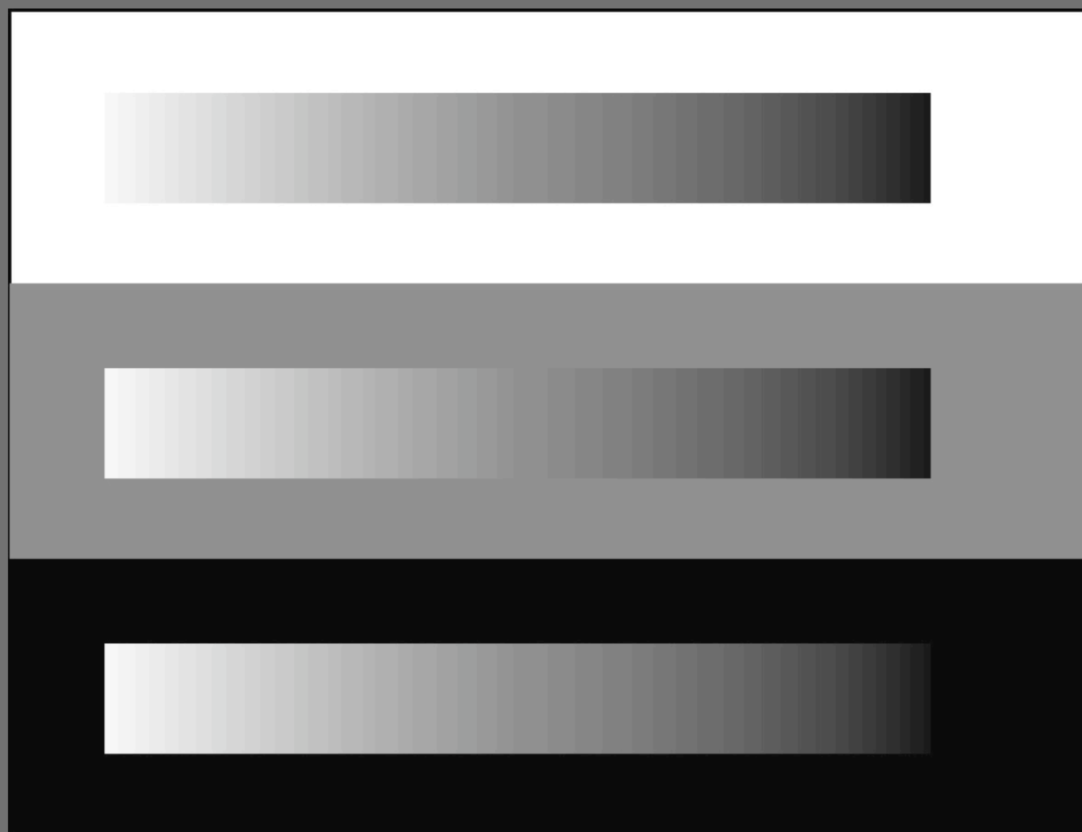


"After image" of background
adds to the color



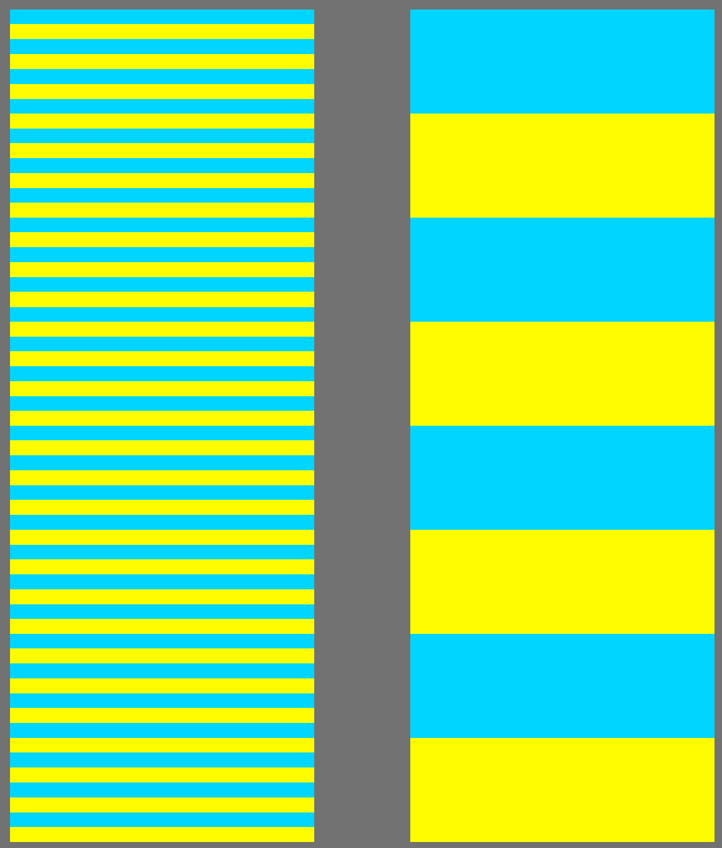
Reality is more complex

Affects Lightness Scale

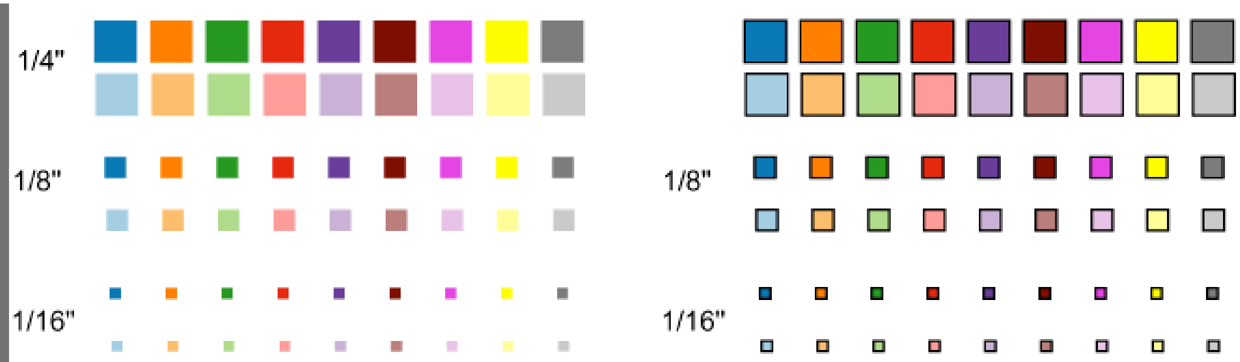


Effect of Spatial Frequency

- Smaller = less saturated
- The paint chip problem
- Color image perception
- S-CIELAB



Redrawn from *Foundations of Vision*, fig 6
© Brian Wandell, Stanford University



18 palette colors, 2pt outline, mimics shape

abc abc abc abc
abc abc abc abc
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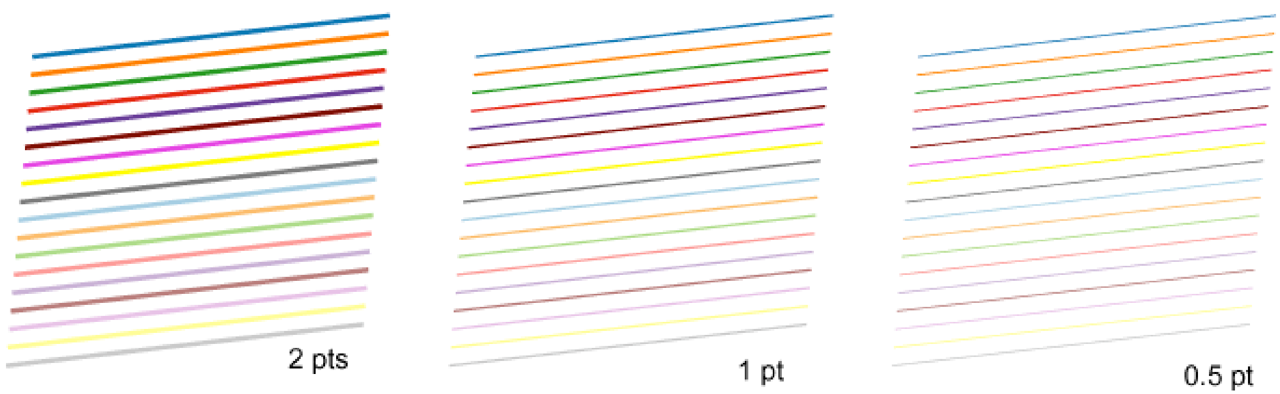
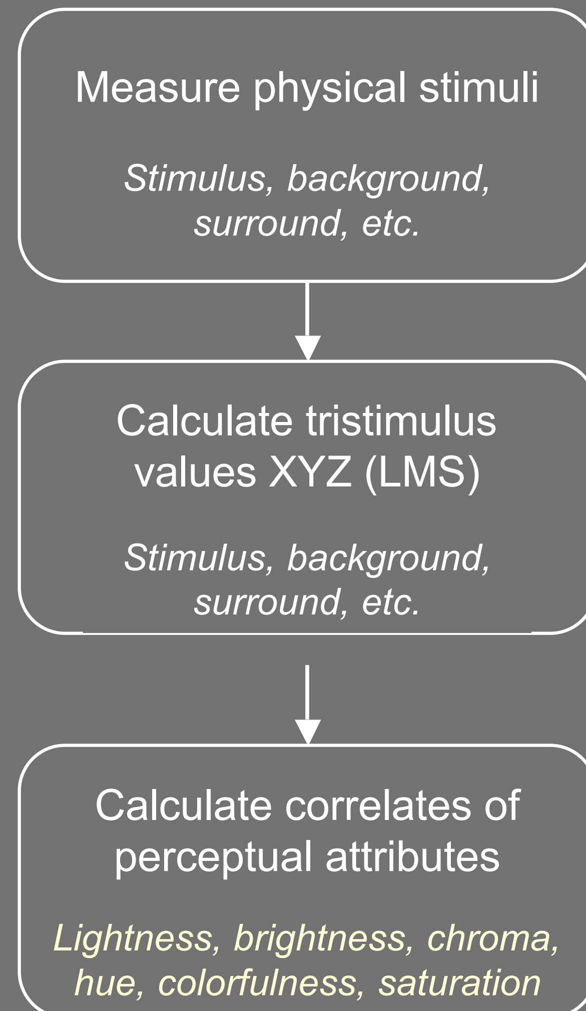
Colored lines



Color Appearance Models

- From measurements to color appearance
- Models
  - CIELAB, RLAB, LLAB
  - S-CIELAB
  - CIECAM97s, CIECAM02
  - Hunt
  - Nayatani, Guth, ATG



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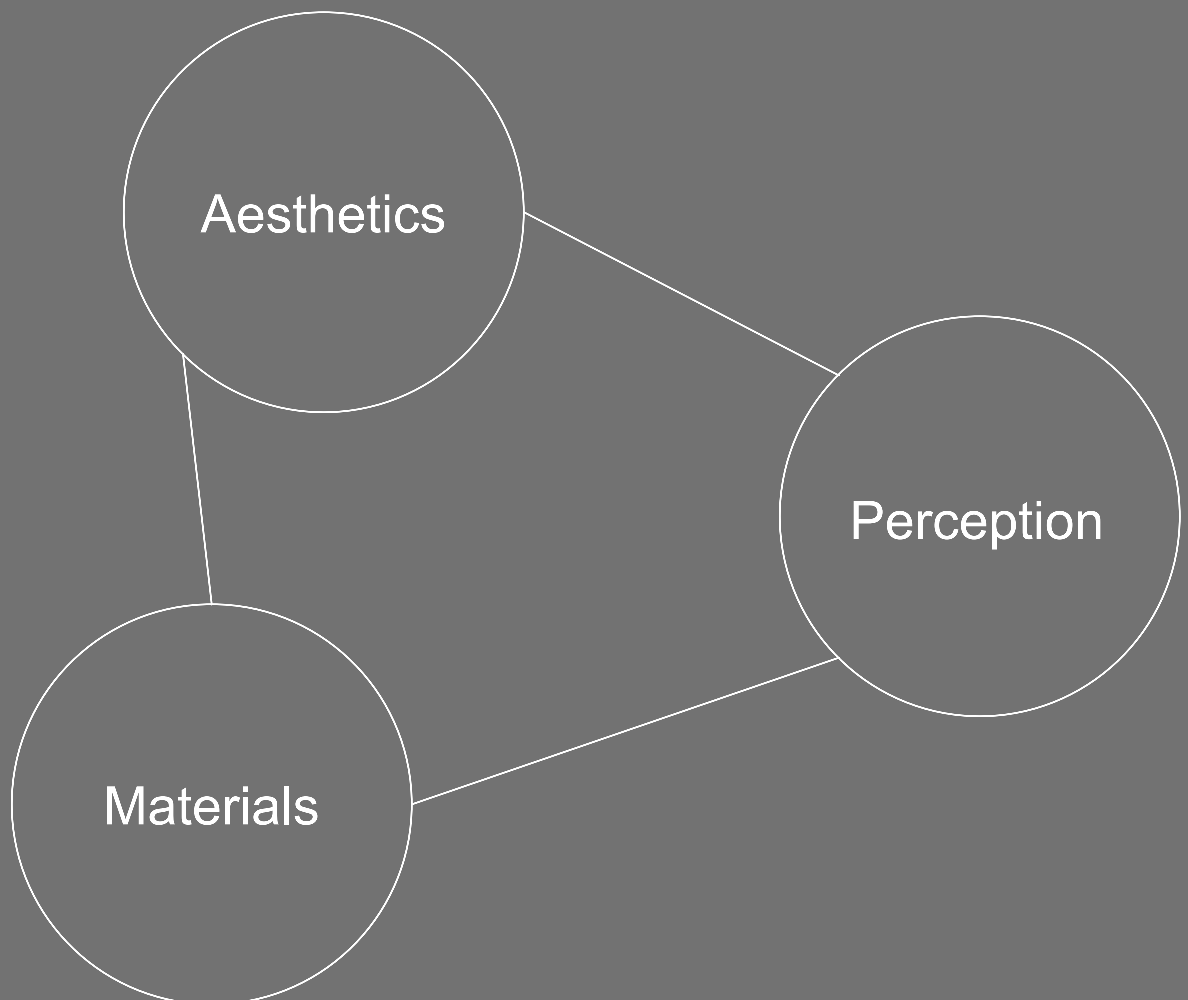
Trichromacy
Metamerism
Color matching

Color differences
"Intuitive" color spaces
Image encoding
Color scales

Adaptation
simultaneous contrast
Image appearance
Complex matching

Effective Color



Design Basics

- Four basic principles
  - Proximity: Related items should be close
  - Alignment: Create visual connections
  - Repetition: Unify by reusing elements
  - Contrast: Identical, or very different
- Practice
  - Visual literacy
  - Design experience

Non-designer's Design Book
Robin Williams

Color Design Basics

- Basic principles
  - Contrast & analogy (contrast, proximity)
  - Color schemes & palettes (repetition, alignment)
  - “Get it right in black and white”
- Practice
  - Visual literacy
  - Design experience

Color "Space"

Munsell Color Space

- Value
  - Perceived lightness
- Hue
  - Color's "name"
  - Color wheel
- Chroma
  - Intensity or purity with respect to gray
  - Similar to saturation

Principles of Color Design
Wucius Wong

Value

- Perceived lightness/darkness of a color
- Scale from black to white
  - Power scale
  - Munsell value, L*
- Single most important factor in color design

Get it right in black and white

- Value alone defines shape
  - No edge without lightness change
  - No shading with out lightness variation
- Value difference defines contrast
  - Defines legibility
  - Controls attention

Controls Legibility

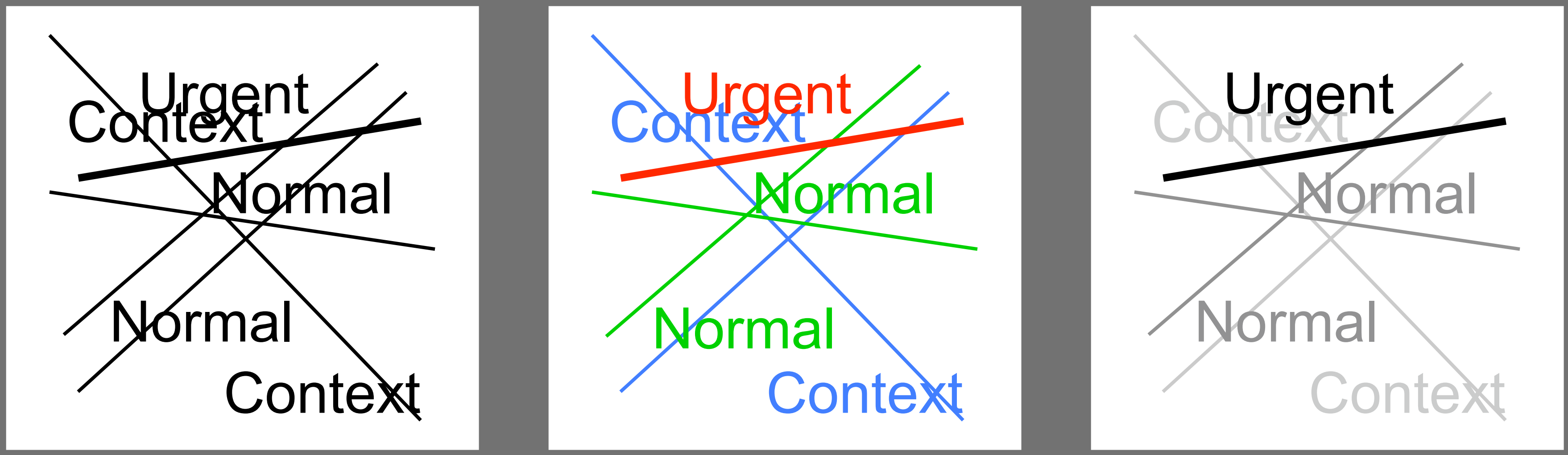
Larry Arend, colorusage.arc.nasa.gov

Drop Shadows

Drop Shadow

Need an edge

Controls Attention, Clutter



A Brief Plug