Color II:
applications in photography

CS 178, Spring 2013

Began 5/16/13, finished 5/21.

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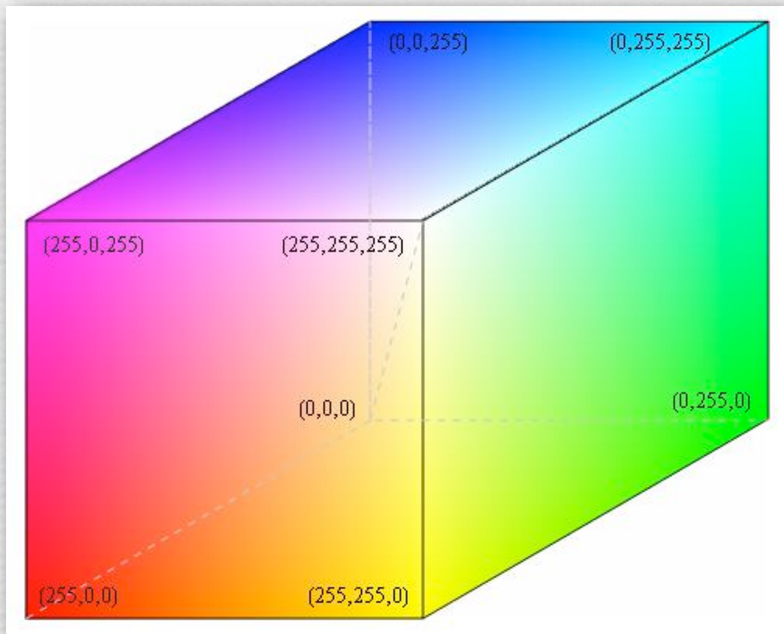
Outline

- spectral power distributions
- color response in animals and humans
- 3D colorspace of the human visual system
  - and color filter arrays in cameras
- reproducing colors using three primaries
- additive versus subtractive color mixing
- ☞ cylindrical color systems used by artists (and Photoshop)
- chromaticity diagrams
  - color temperature and white balancing
  - standardized color spaces and gamut mapping

The RGB cube

- choose three primaries R,G,B, pure wavelengths or not
- adjust scaling applied to (R,G,B) = (255,255,255) to obtain a desired *reference white*
- this yields an *RGB cube*



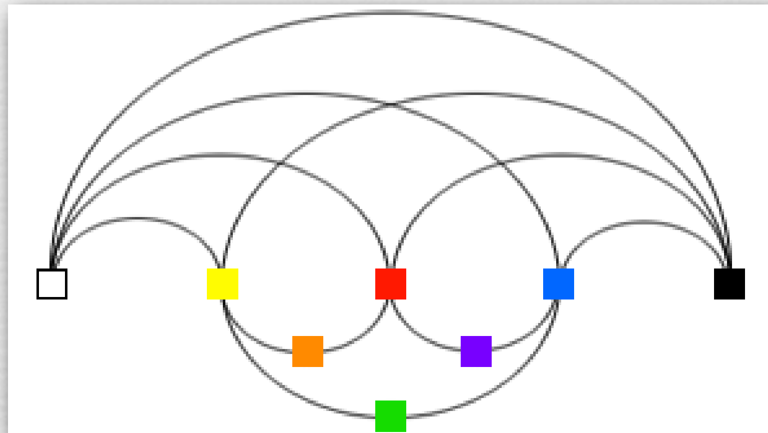
(FLASH DEMO)

http://graphics.stanford.edu/courses/cs178/applets/locus.html

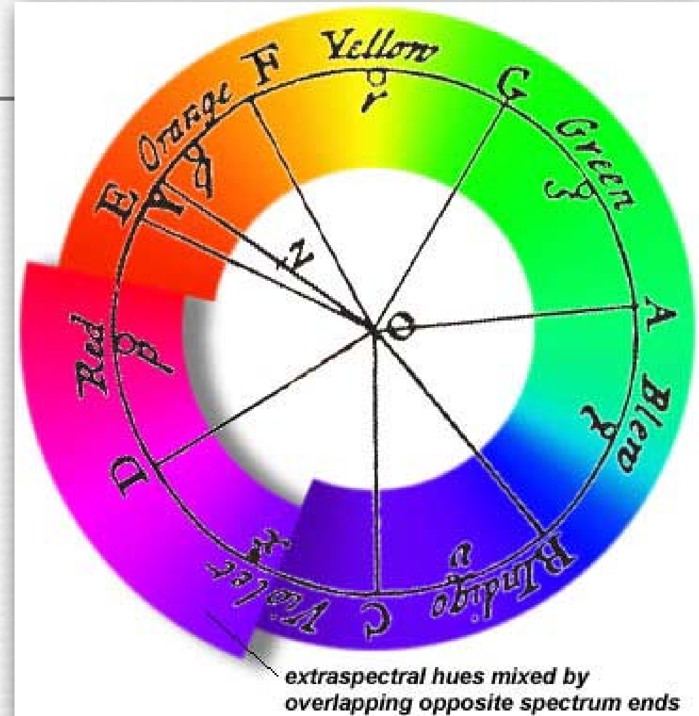
- programmers like RGB as a way of selecting colors
  - but artists don't

Newton's color circle

(http://www.handprint.com/HP/WCL/color6.html)



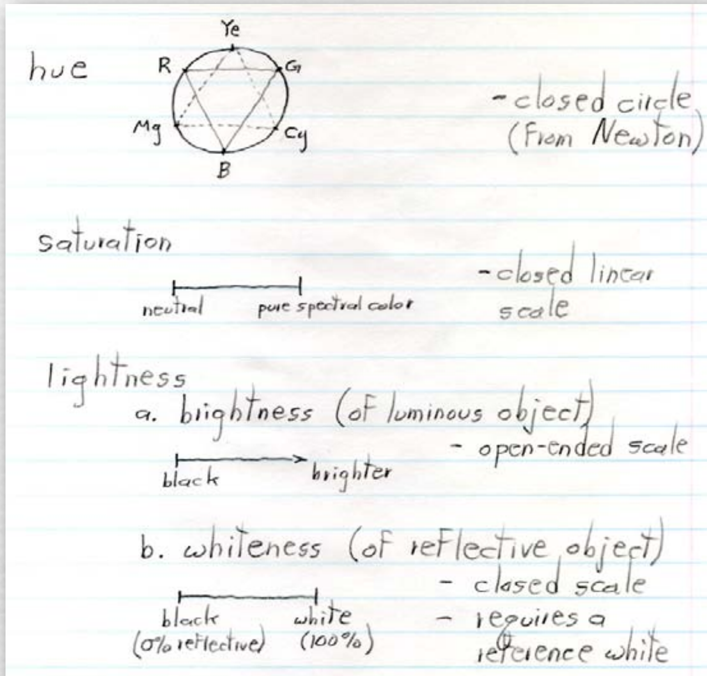
Peter Paul Rubens and François d'Aguilon (1613)

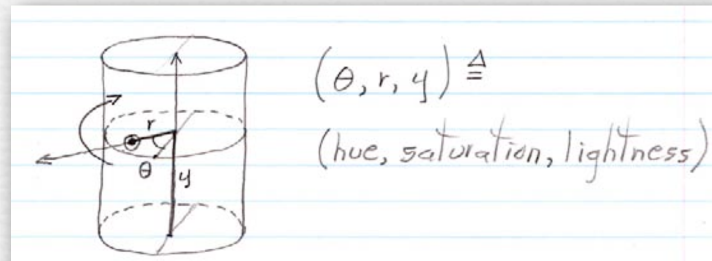


Isaac Newton (1708)

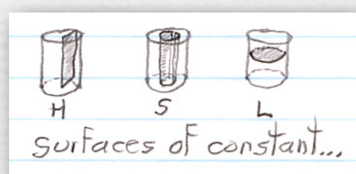
- previous authors could not move beyond linear scales, because they felt compelled to include black and white as endpoints
- Newton closed the circle by removing black and white, then added extra-spectral purples not found in the rainbow
  - by mixing red at one end with violet at the other end

Cylindrical color spaces (contents of whiteboard)



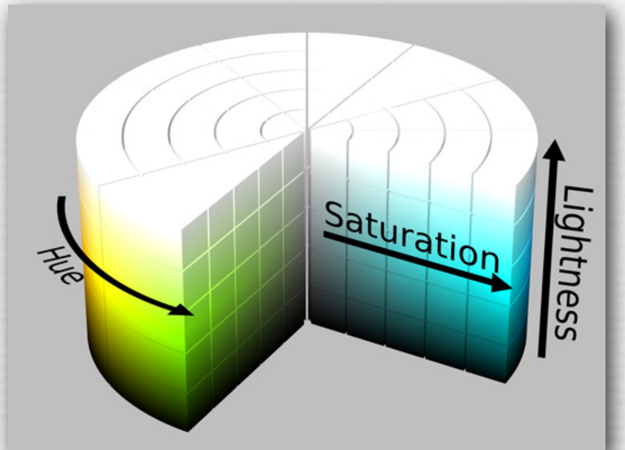


- given one circular scale and two linear scales, i.e. one angle and two lengths, the logical coordinate system is a cylindrical one
- selection of colors within such a system is easily done using 1D scales for H, S, and L, or 2D surfaces of constant H, S, or L

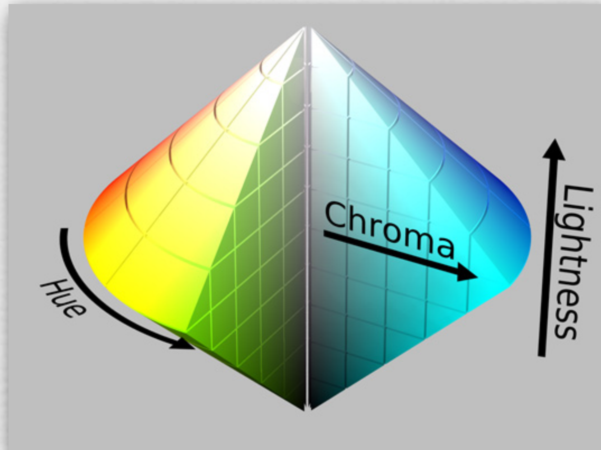


Cylindrical color spaces

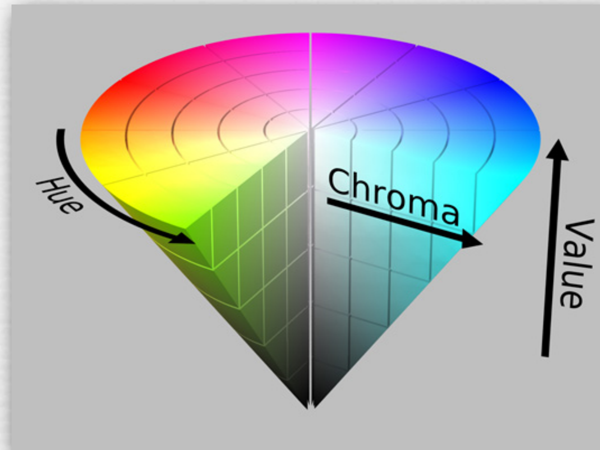
(wikipedia)



HSL cylinder



HSL double cone



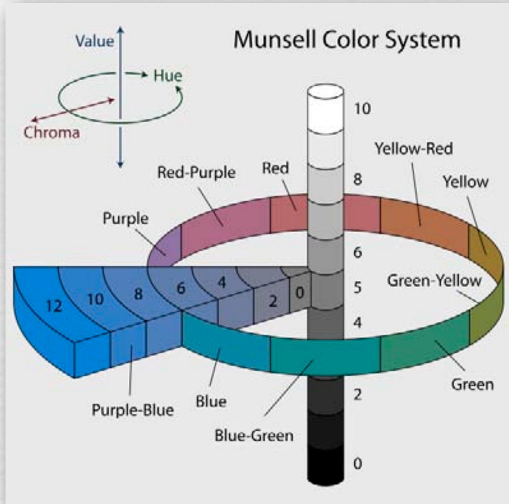
HSV single cone

- a cylinder is easy to understand, but colors near the top and bottom are indistinguishable
  - double cone solves this by compressing top & bottom to a point
- when artists mix RGB lights, they expect to get white, but the center of the L=0.5 disk in HSL space is gray
  - HSV single cone pushes the white point down to form a top plane
  - painters might prefer an inverted cone, with black on a base plane

Munsell color system

(wikipedia)

Albert Munsell
(1858-1918)



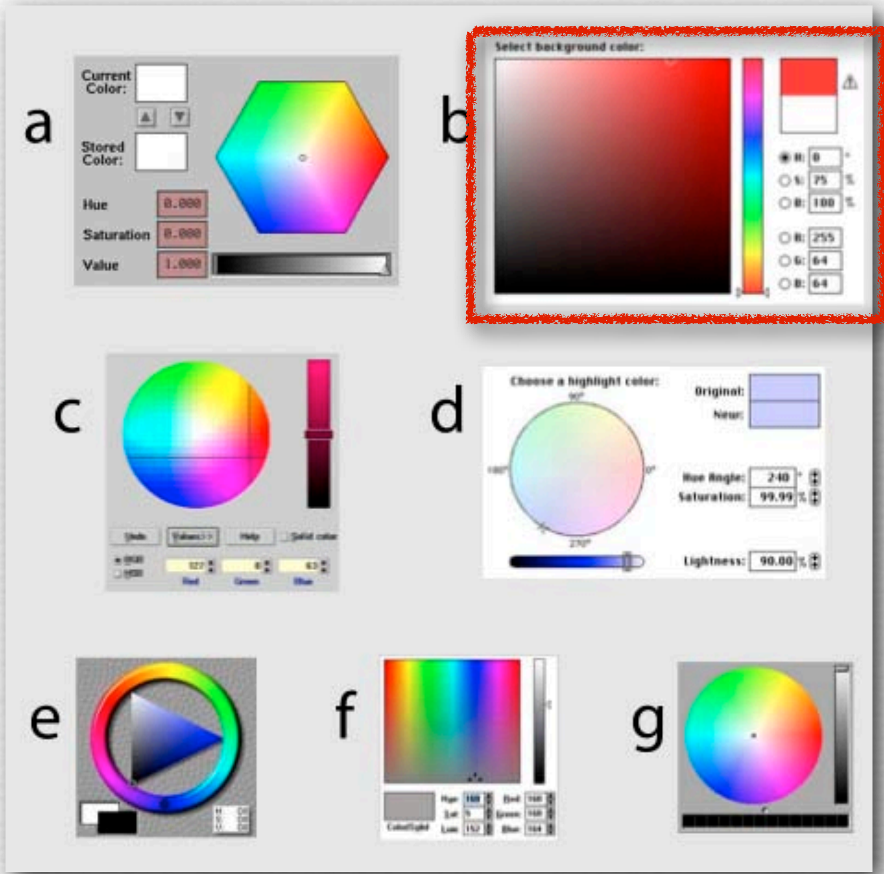
3-axis colorspace

1905 book

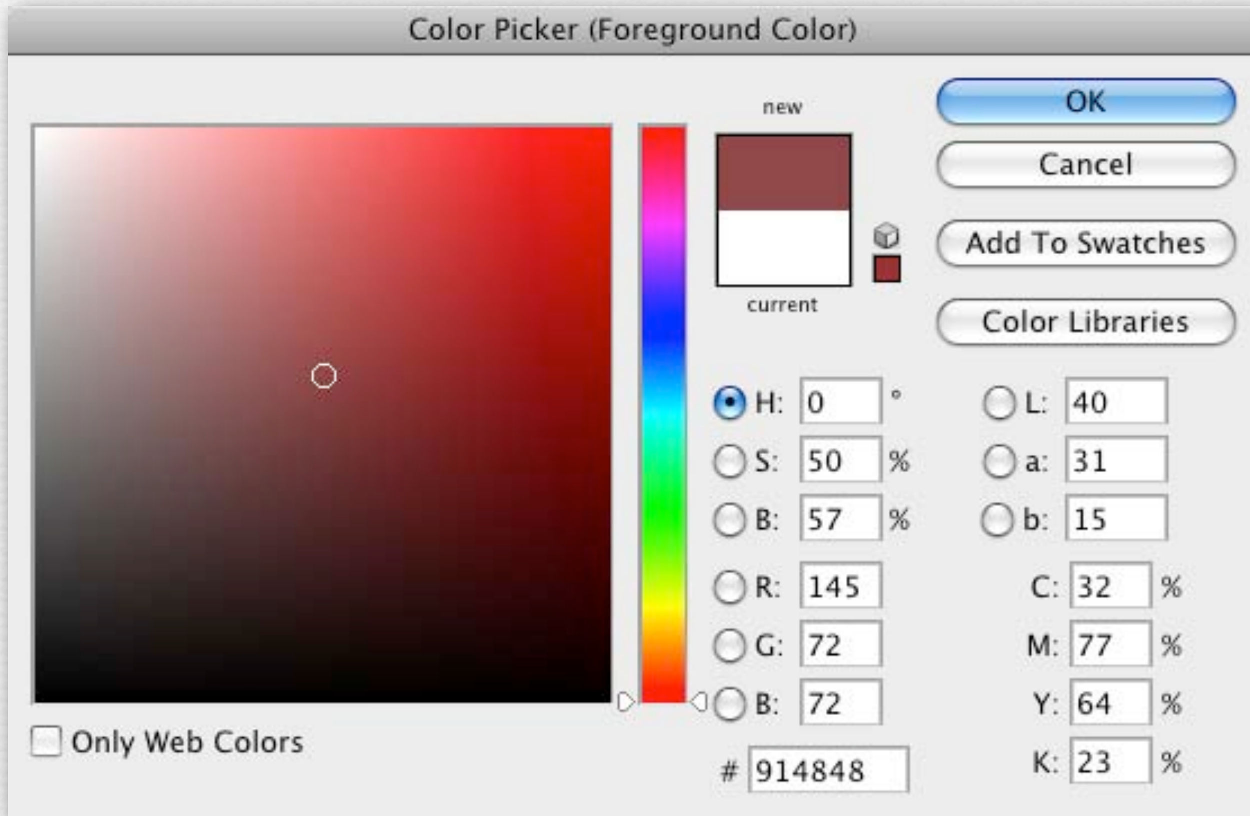
CG rendering of
1929 measurements

- spacing of colors is perceptually uniform (by experiment)
- outer envelope of solid determined by available inks

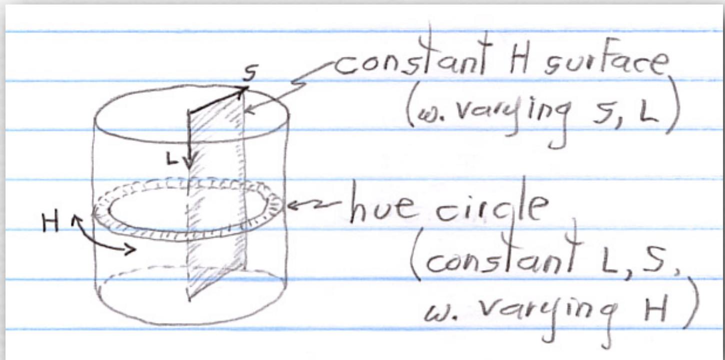
A menagerie of color selectors



Color selection in Photoshop

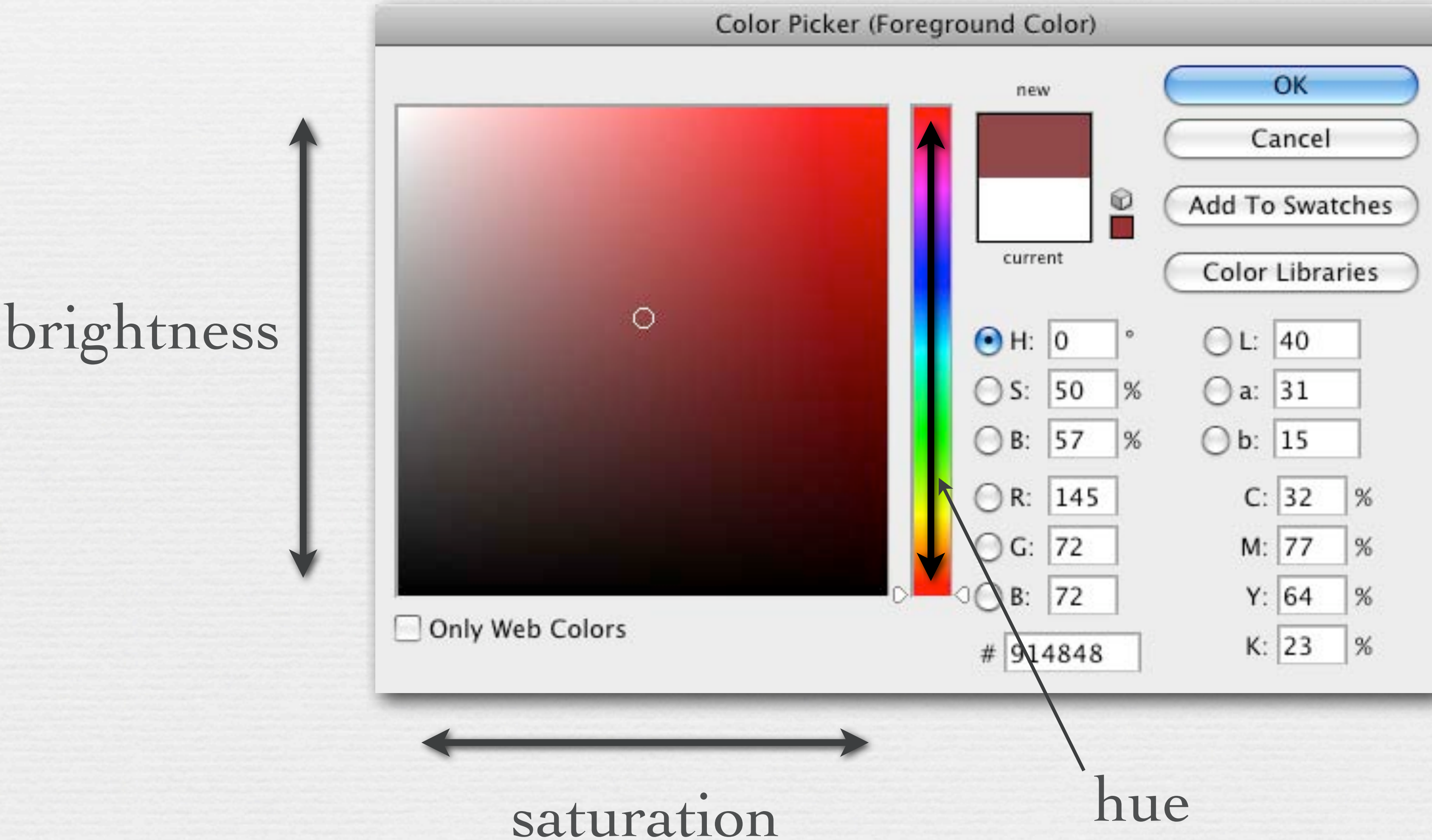


Photoshop's color selector in HSL space (contents of whiteboard)



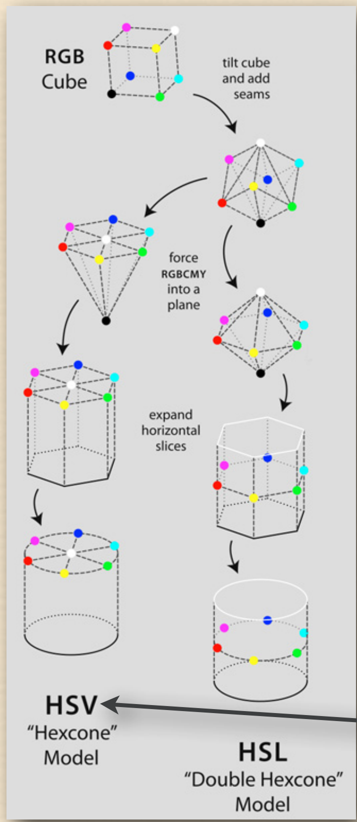
- the main rectangle in Photoshop's color selector is a 2D surface of constant hue in cylindrical color space, hence varying saturation and lightness
- the vertical rainbow to its right (in the dialog box) is a circumference along the outside surface of the cylinder, hence a 1D scale of varying hue and constant lightness and saturation

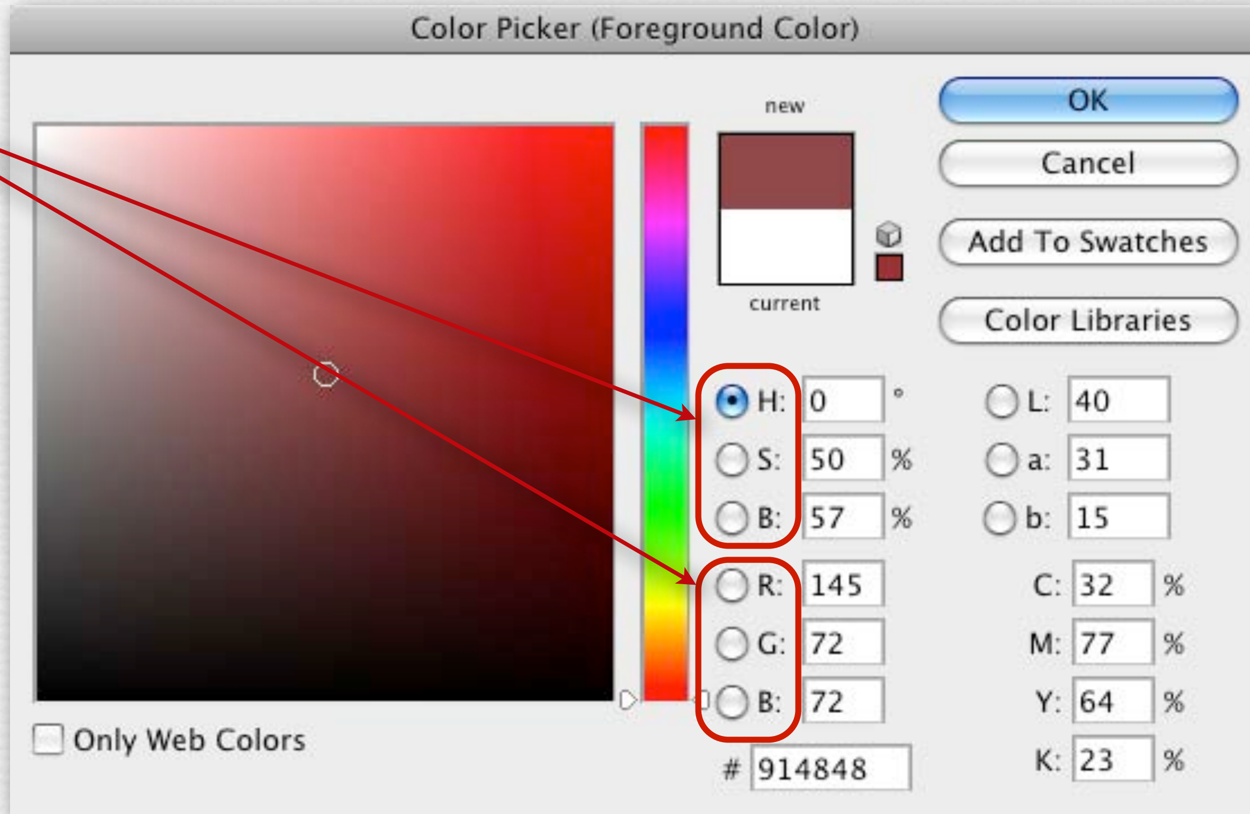
Color selection in Photoshop



Color selection in Photoshop

Cartesian to cylindrical coordinate conversion

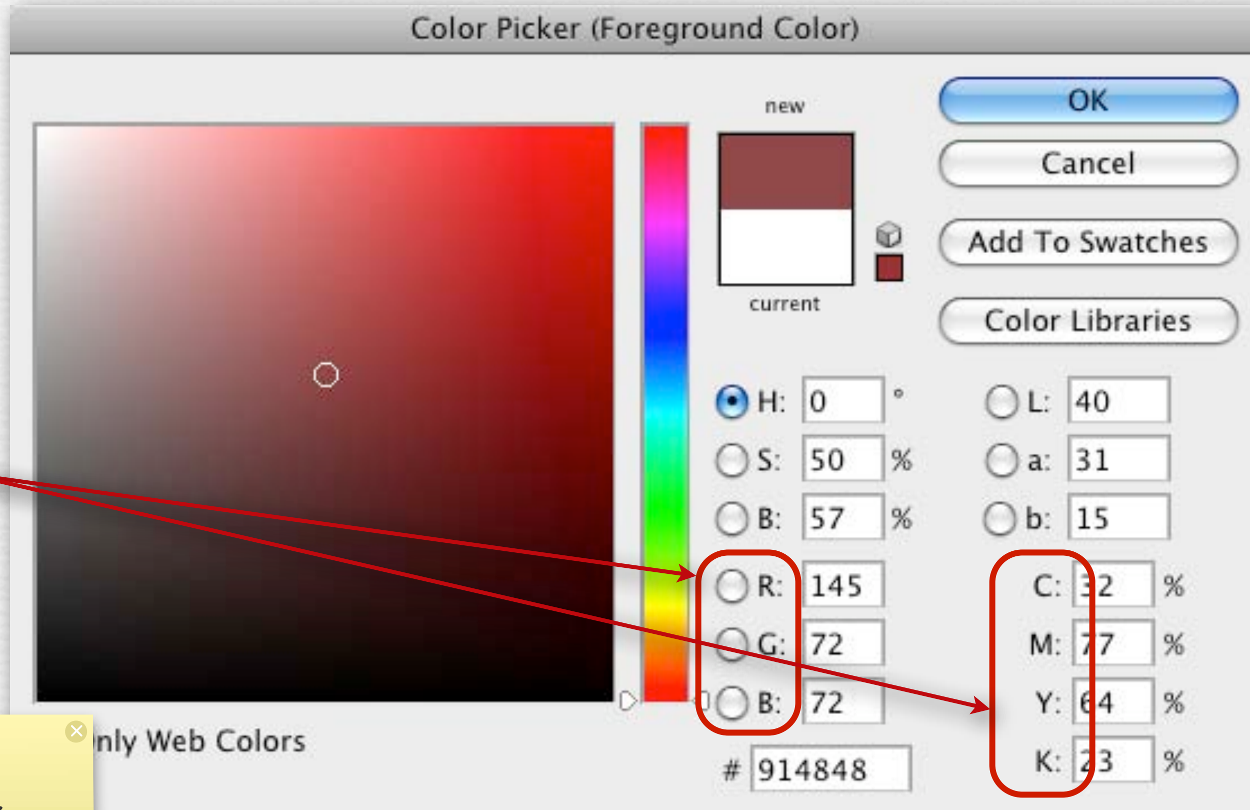




HSV ≈ Photoshop's HSB

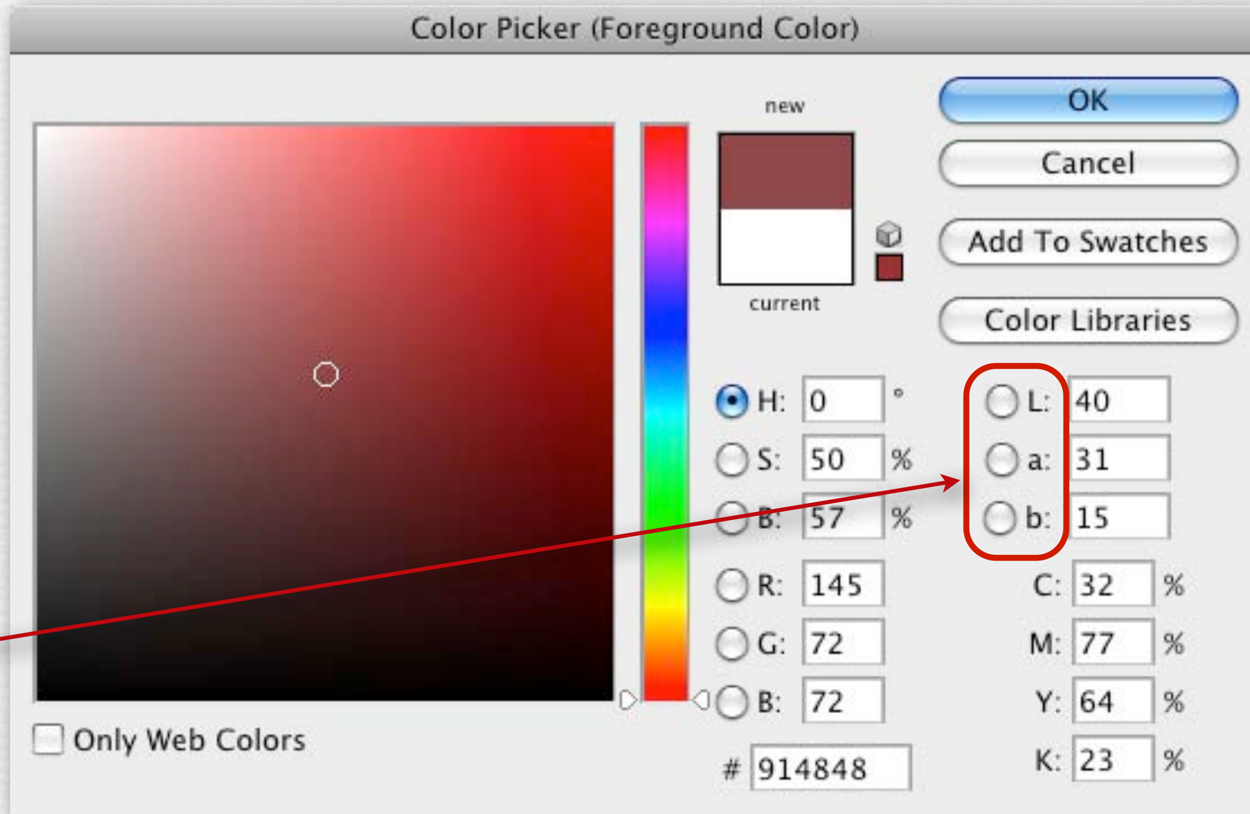
Color selection in Photoshop

conversion depends on color spaces selected for RGB and CMYK



As a student pointed out in class, this conversion cannot be done by a 3x3 matrix, because CMYK is a 4-vector. In fact, the conversion method depends on the color spaces selected for RGB versus CMYK, and could be arbitrarily complicated. Photoshop lets you choose each one separately. I will not hold you responsible for these conversion methods.

Color selection in Photoshop



we'll cover this later in the lecture

Recap

- *hue* is well represented by a color circle, formed from the rainbow plus mixtures of the two ends to form purples
- *saturation* is well represented by a linear scale, from neutral (black, gray, or white) to fully saturated (single wavelength)
- *lightness* is well represented by a linear scale, either open-ended if representing the brightness of luminous objects or closed-ended if representing the whiteness of reflective objects
- given one circular scale and two linear scales, the logical coordinate system is cylindrical where (H, S, L) = (θ, r, y)
- selection of colors within such a system is easily done using 1D scales for each of H, S, and L, or one such scale in combination with one 2D surface of constant H, S, or L

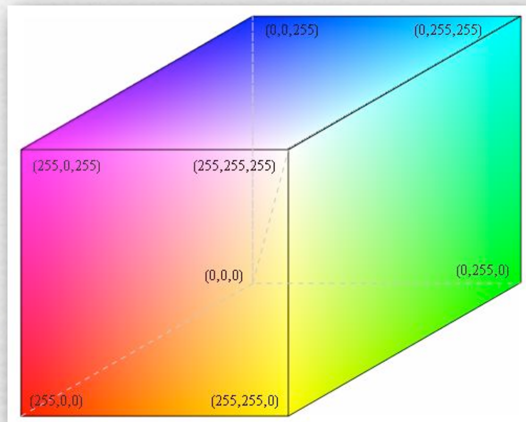
Questions?

Outline

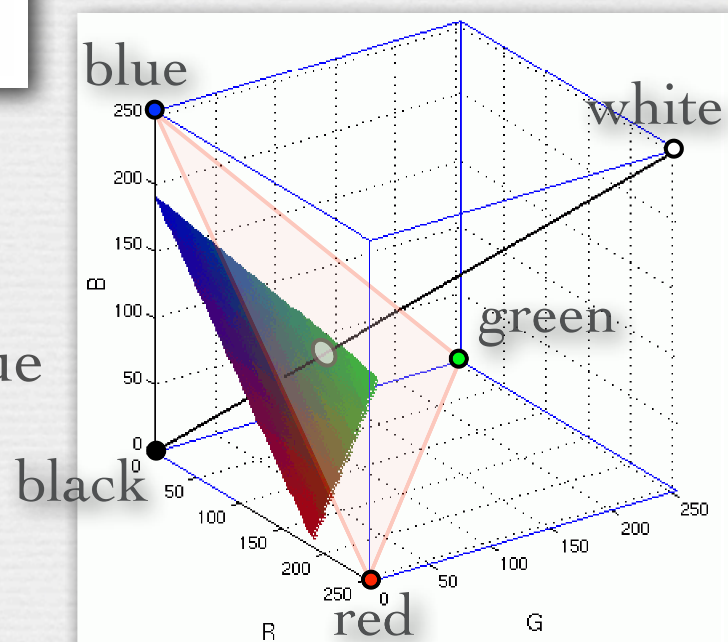
- spectral power distributions
- color response in animals and humans
- 3D colorspace of the human visual system
  - and color filter arrays in cameras
- reproducing colors using three primaries
- additive versus subtractive color mixing
- cylindrical color systems used by artists (and Photoshop)
- ☞ chromaticity diagrams
  - color temperature and white balancing
  - standardized color spaces and gamut mapping

Chromaticity diagrams

- choose three primaries R,G,B, pure wavelengths or not
- adjust R=1,G=1,B=1 to obtain a desired *reference white*
- this yields an *RGB cube*



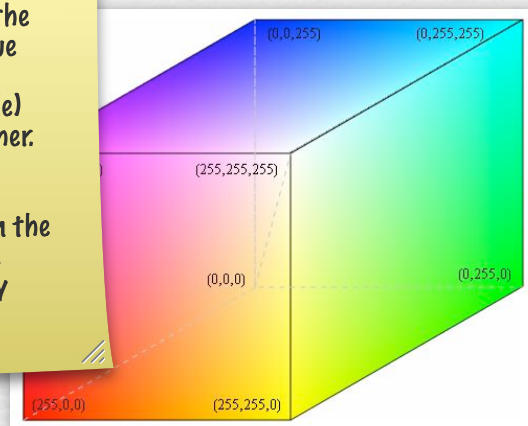
- one may factor the brightness out of any point in the cube by drawing a line to the origin and intersecting this line with the triangle made by corners Red, Green, Blue
- all points on this triangle, which are addressable by two coordinates, have the same brightness but differing *chromaticity*



Chromaticity diagrams

- choose three primaries R,G,B, pure wavelengths or not
- ad… ain a desired *reference white*
- thi…

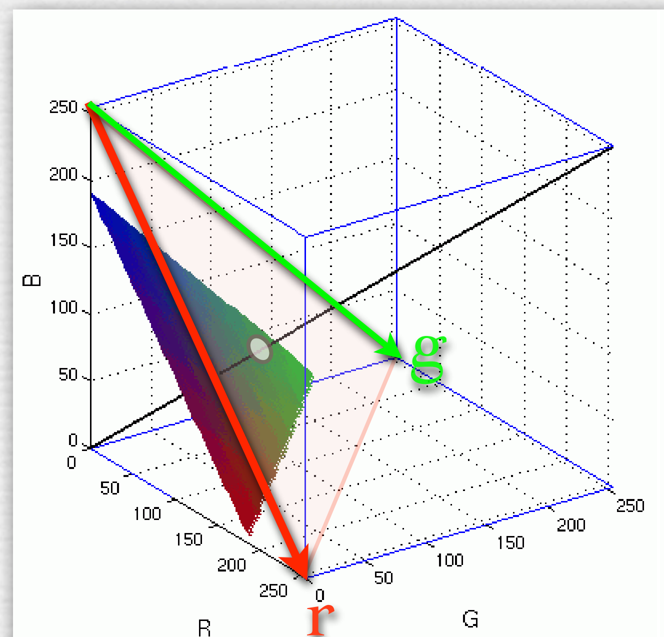
To reinforce a point that might not have been clear in class, projecting all points in the RGB cube onto the triangle connecting the cubes' red, green, and blue corners serves to factor out brightness, but it doesn't guarantee that all points (on this triangle) have the same (perceived) brightness as each other. It only guarantees that points having the same chromaticity (hue and saturation) but different brightnesses, i.e. points on lines emanating from the origin (at black), have been flattened onto single points (on the triangle). This is what is meant by factoring out brightness.



$$r = \frac{R}{R+G+B}$$

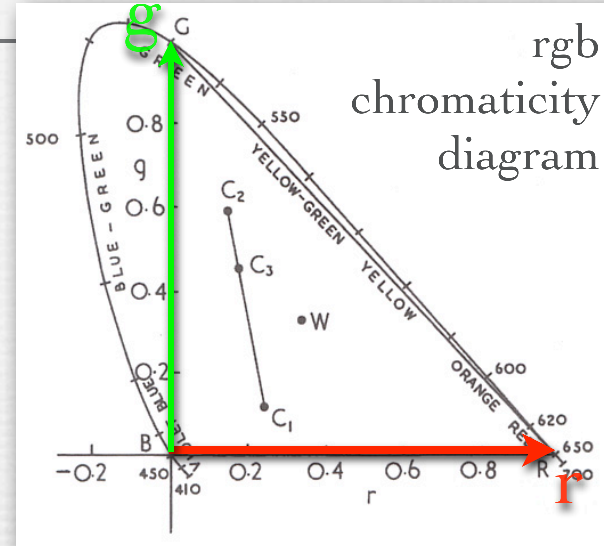
$$g = \frac{G}{R+G+B}$$

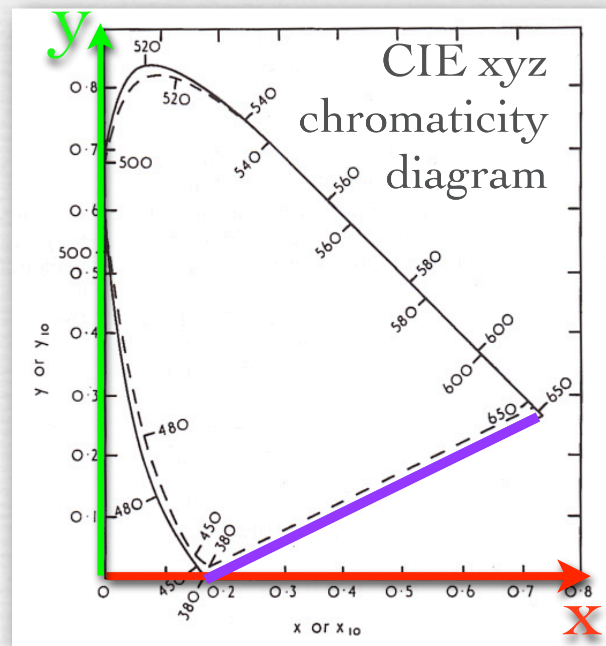
- one may factor the brightness out of any point in the cube by drawing a line to the origin and intersecting this line with the triangle made by corners Red, Green, Blue
- all points on this triangle, which are addressable by two coordinates, have the same brightness but differing *chromaticity*



Chromaticity diagrams

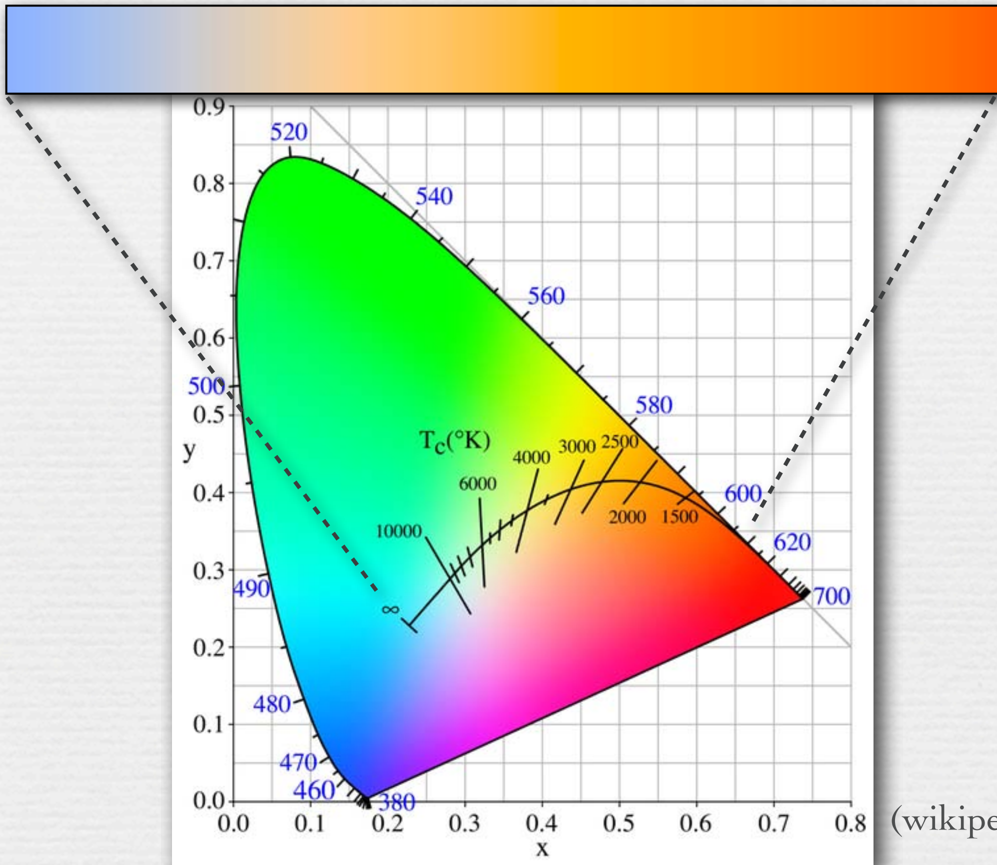
- this triangle is called the *rgb chromaticity diagram* for the chosen RGB primaries
  - mixtures of colors lie along straight lines
  - neutral (black to white) lies at (⅓, ⅓)
  - r>0, g>0 does not enclose spectral locus
- the same construction can be performed using <u>any</u> set of 3 vectors as primaries, even impossible ones (with $\rho < 0$ or $\gamma < 0$ or $\beta < 0$)
- the CIE has defined a set of primaries XYZ, and the associated *xyz chromaticity diagram*
  - x>0, y>0 <u>does</u> enclose spectral locus
  - one can connect red and blue on the locus with a *line of extra-spectral purples*
  - x,y is a standardized way to denote colors





(Hunt)

Application of chromaticity diagrams #1: color temperature and white balancing



(wikipedia)

<u>correlated color temperatures</u>

- 3200°K incandescent light
- 4000°K cool white fluorescent
- 5000°K equal energy white (D50, E)
- 6000°K midday sun, photo flash
- 6500°K overcast, television (D65)
- 7500°K northern blue sky

- ✦ the apparent colors emitted by a *black-body radiator* heated to different temperatures fall on a curve in the chromaticity diagram
- ✦ for non-blackbody sources, the nearest point on the curve is called the *correlated color temperature*

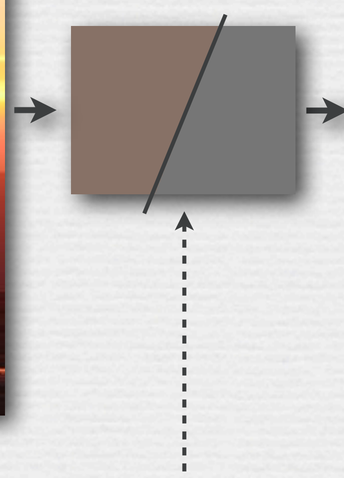
White balancing in digital photography

1. choose an object in the photograph you think is neutral (reflects all wavelengths equally) in the real world
2. compute scale factors (S_R,S_G,S_B) that force the object's (R,G,B) to be neutral (R=G=B), i.e. $S_R = ⅓ (R+G+B) / R$, etc.
3. apply the same scaling to all pixels in the sensed image

- your computer's interpretation of R=G=B, hence of your chosen object, depends on the color space of the camera
  - the color space of most digital cameras is sRGB
  - the reference white for sRGB is D65 (6500°K)
- thus, white balancing on an sRGB camera forces your chosen object to appear 6500°K (blueish white)
- if you trust your object to be neutral, this procedure is equivalent to finding the color temperature of the illumination

Finding the color temperature of the illumination

- Auto White Balance (AWB)
  - *gray world*: assume the average color of a scene is gray, so <u>force</u> the average color to be gray - often inappropriate



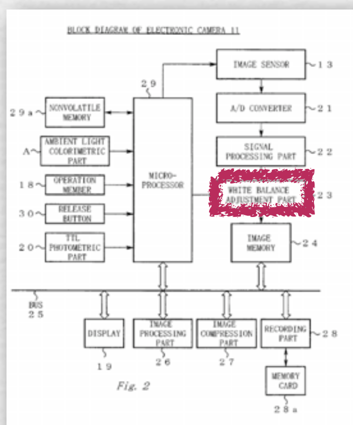
(Marc Levoy)

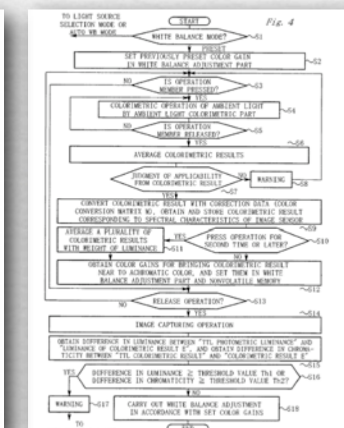
average (R, G, B) = (100%, 81%, 73%) ➔ (100%, 100% 100%)

(S_R, S_G, S_B) = (0.84, 1.04, 1.15)

Finding the color temperature of the illumination

- Auto White Balance (AWB)
  - *gray world*: assume the average color of a scene is gray, so force the average color to be gray - often inappropriate
  - assume the brightest pixel (after demosaicing) is a specular highlight, which usually reflects all wavelengths equally
    - fails if pixel is saturated
    - fails if object is metallic - gold has gold-colored highlights
    - fails if brightest pixel is not a specular highlight
  - find a neutral-colored object in the scene
    - but how??

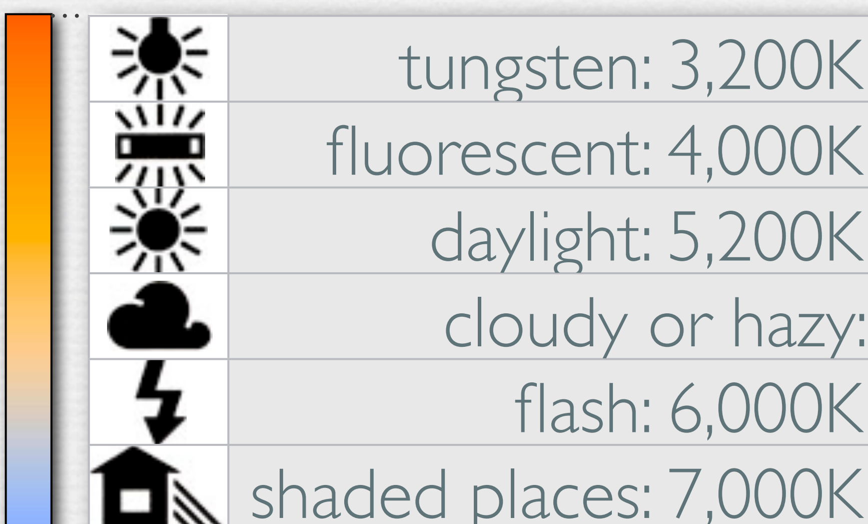


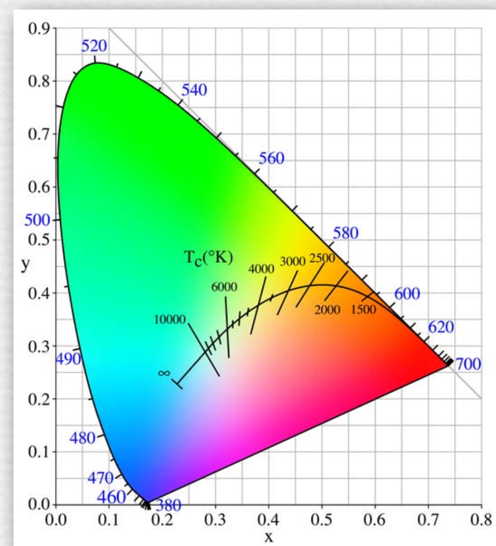


(Nikon patent)

Finding the color temperature of the illumination

- Auto White Balance (AWB)
- manually specify the illumination's color temperature
  - each color temperature corresponds to a unique (x,y)
  - for a given camera, one can measure the (R,G,B) values recorded when a neutral object is illuminated by this (x,y)
  - compute scale factors (S_R,S_G,S_B) that map this (R,G,B) to neutral (R=G=B); apply this scaling to all pixels as before





Incorrectly chosen white balance

(Eddy Talvala)

- scene was photographed in sunlight, then re-balanced as if it had been photographed under something warmer, like tungsten
  - re-balancer assumed illumination was very reddish, so it boosted blues
  - same thing would have happened if originally shot with tungsten WB

Recap

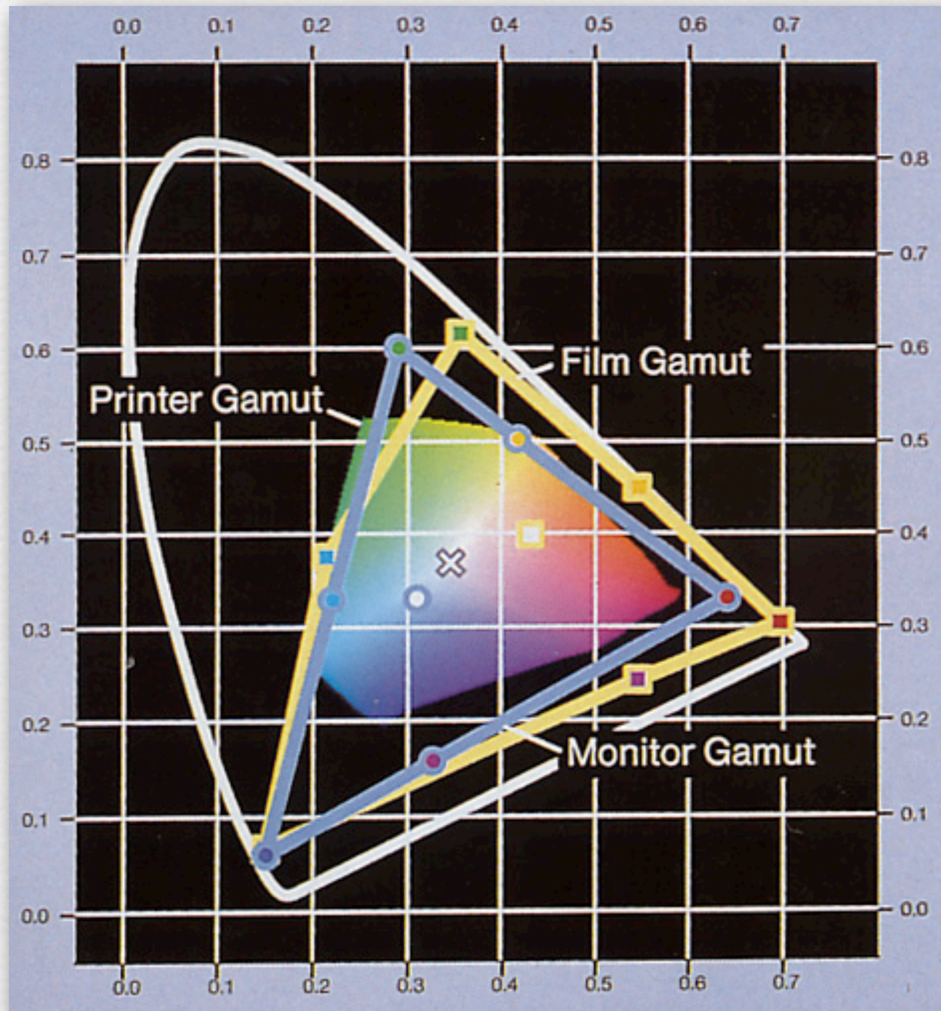
- by choosing three primaries (defined by three matching functions) and a *reference white* (defined by three "hidden scales"), one defines an *RGB cube*, with black at one corner and your reference white at the opposite corner
- by projecting points in an RGB cube towards the origin (black point) and intersecting them with the R+G+B=1 plane, one factors out brightness, yielding the 2D *rgb chromaticity diagram*
- repeating this for a standard but non-physical set of primaries called XYZ, one obtains the *xyz chromaticity diagram*; in this diagram the spectral locus falls into the all-positive octant
- by identifying a feature you believe is neutral (it reflects all wavelengths equally), to the extent its RGB values are not equal, you are identifying the color of the illumination; by rescaling all pixel values until that feature <u>is</u> neutral, you correct for the illumination, a process called *white balancing*
- a common scale for illumination color is *correlated color temperature*, which forms a curve in the xyz chromaticity diagram

Questions?

Application of chromaticity diagrams #2:
standardized color specifications and gamut mapping

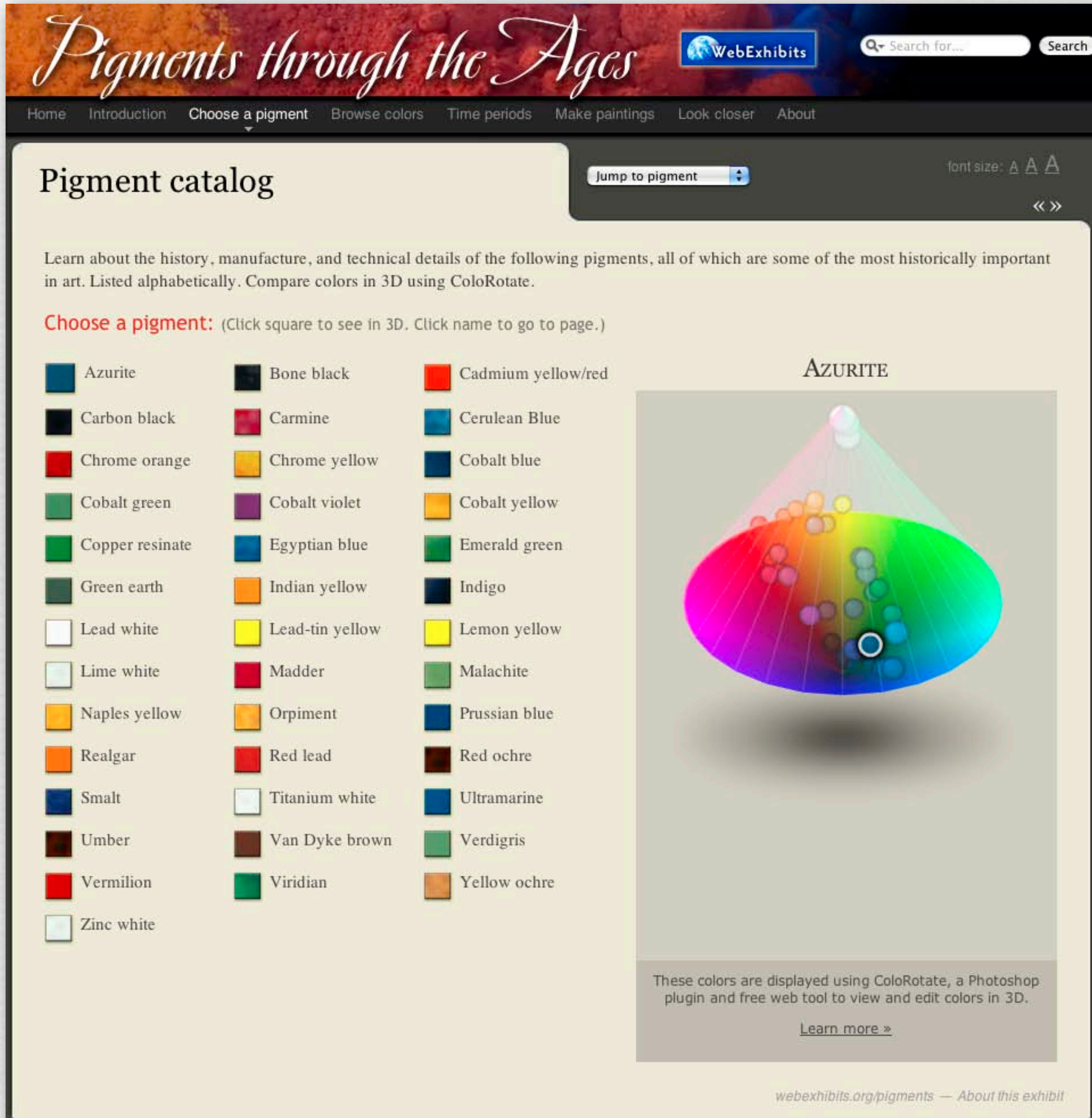
- the chromaticities reproducible using 3 primaries fill a triangle in the xyz chromaticity diagram, a different triangle for each choice of primaries; this is called the *device gamut* for those primaries

Q. Why is this diagram, scanned from a book, black outside the printer gamut?



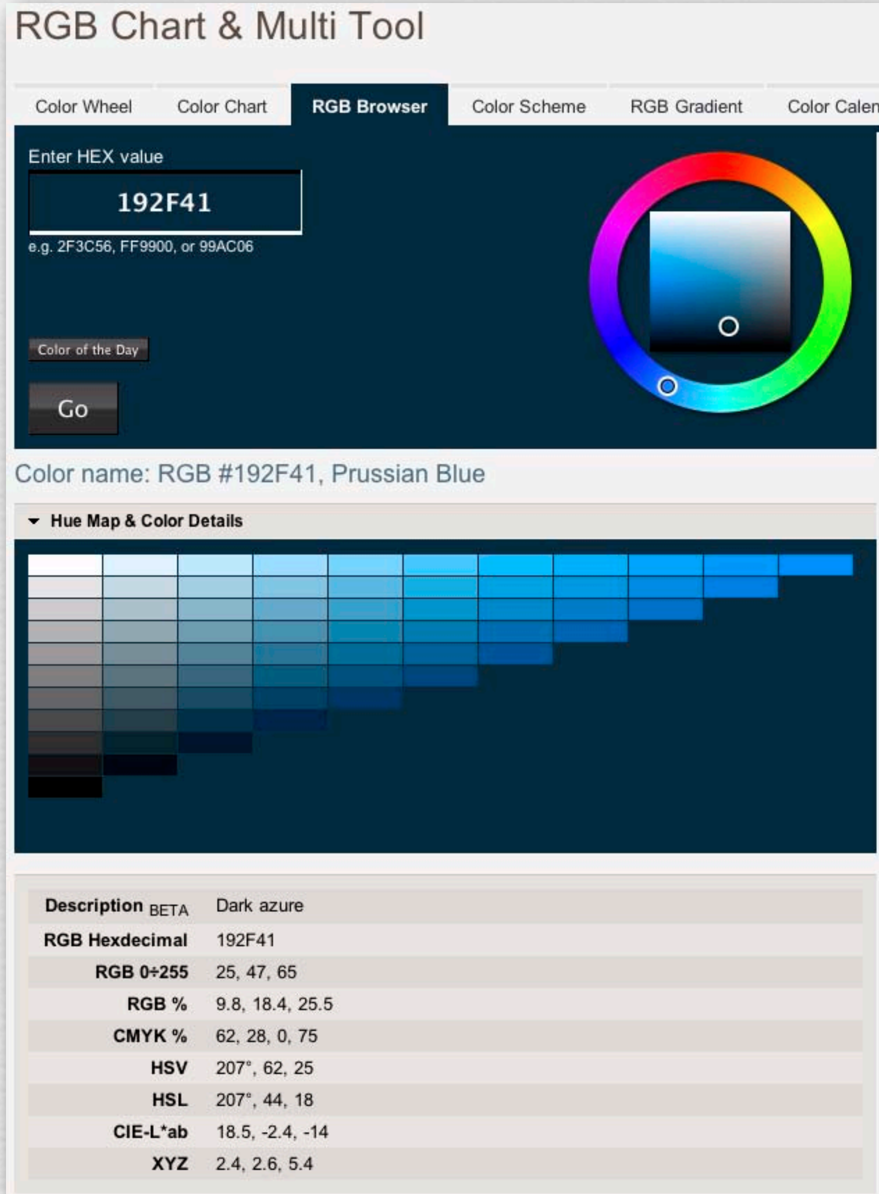
(Foley)

Pigment catalog



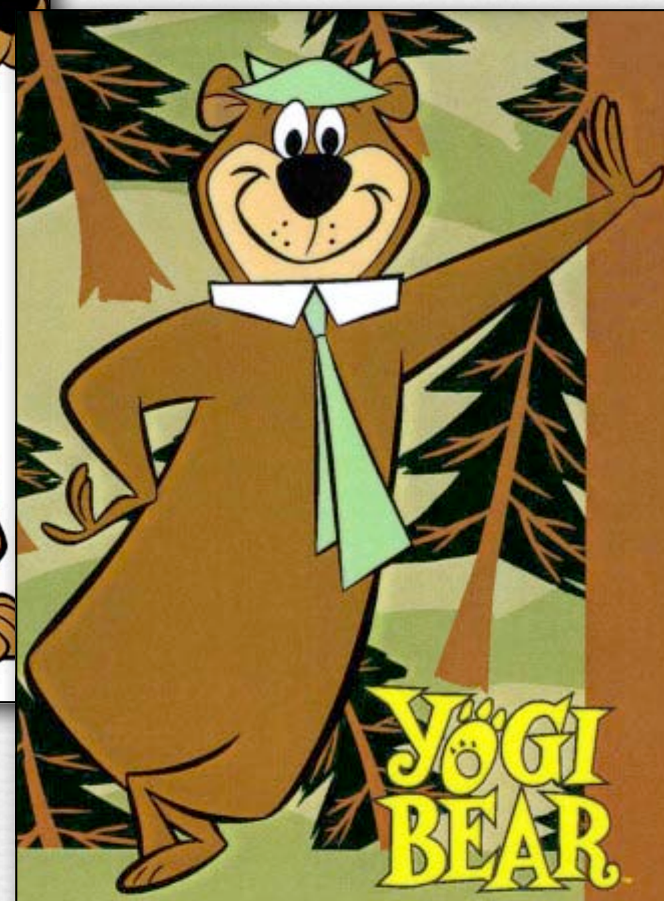
http://www.webexhibits.org/pigments/intro/pigments.html

XYZ values for Prussian Blue



http://www.perbang.dk/rgb/192F41/

Digitizing the paint colors at Hanna-Barbera Productions

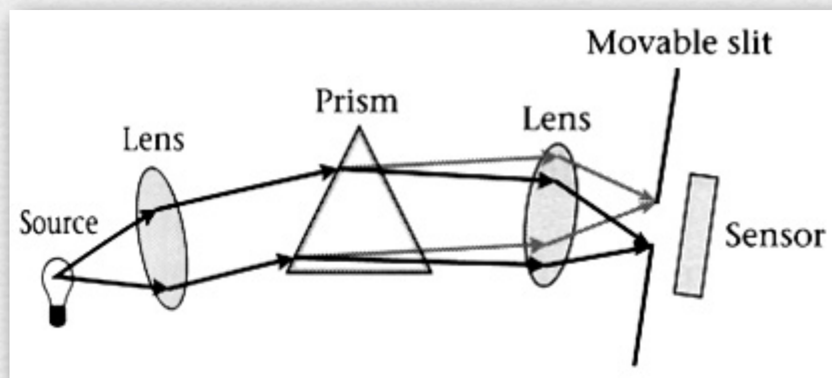


Digitizing the paint colors at Hanna-Barbera Productions

physical color samples

spectroreflectometer ↓

spectrum for each color



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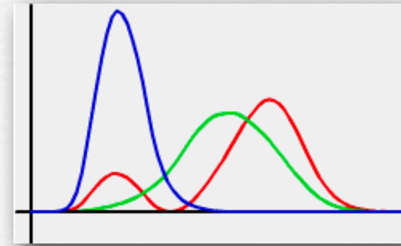


physical color samples

↓ spectroreflectometer

spectrum for each color

↓ CIE matching functions

XYZ coordinates

$$(X,Y,Z) = \left(\int_{400nm}^{700nm} L_e(\lambda)\,\bar{x}(\lambda)\,d\lambda,\ \int_{400nm}^{700nm} L_e(\lambda)\,\bar{y}(\lambda)\,d\lambda,\ \int_{400nm}^{700nm} L_e(\lambda)\,\bar{z}(\lambda)\,d\lambda \right)$$

Digitizing the paint colors at Hanna-Barbera Productions

physical color samples

↓ spectroreflectometer

spectrum for each color

↓ CIE matching functions

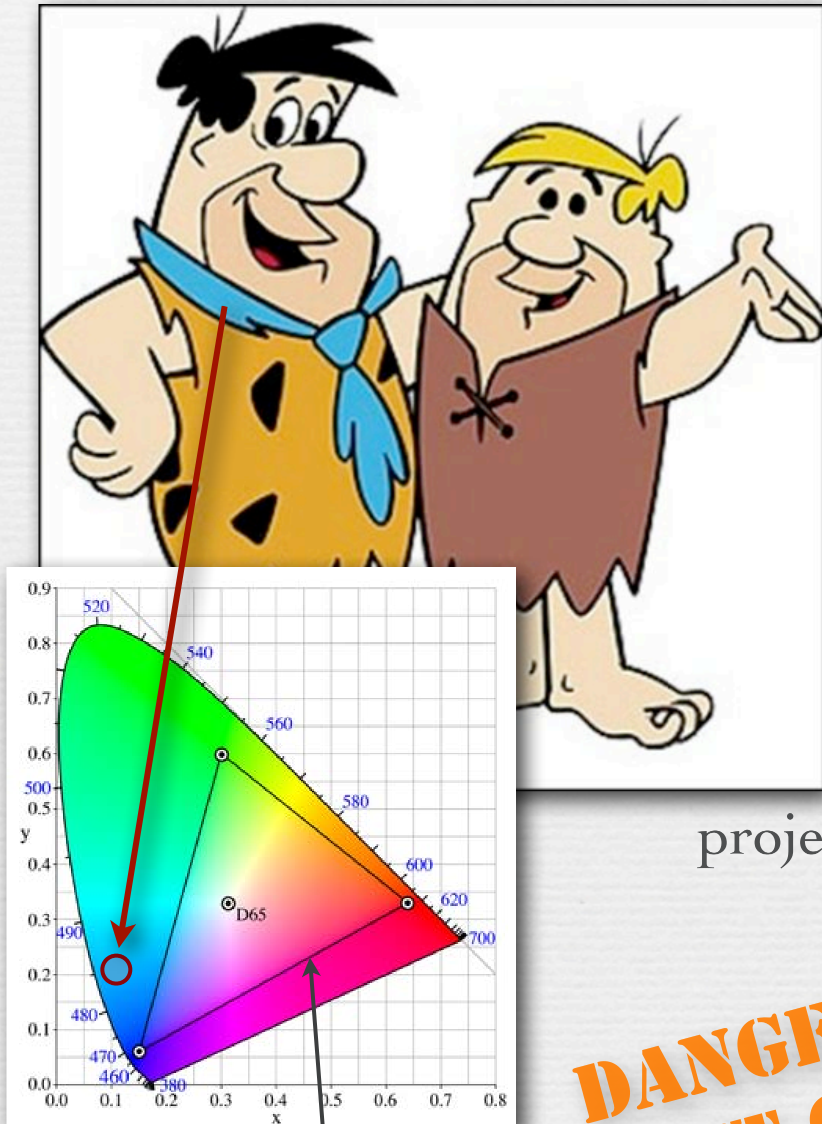
XYZ coordinates

↓ projection onto X=Y=Z=1 plane

xy chromaticity coordinates

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z}$$

Digitizing the paint colors at Hanna-Barbera Productions



NTSC gamut

physical color samples

spectroreflectometer ↓

spectrum for each color

CIE matching functions ↓

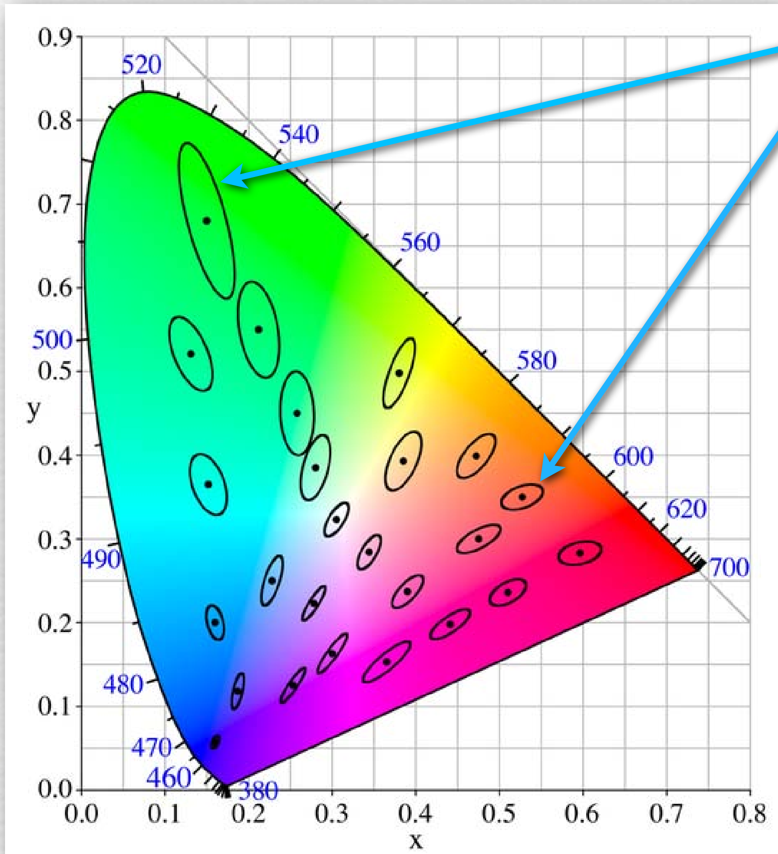
XYZ coordinates

projection onto X=Y=Z=1 plane ↓

xy chromaticity coordinates

DANGER: NECKTIE OUT OF GAMUT !!

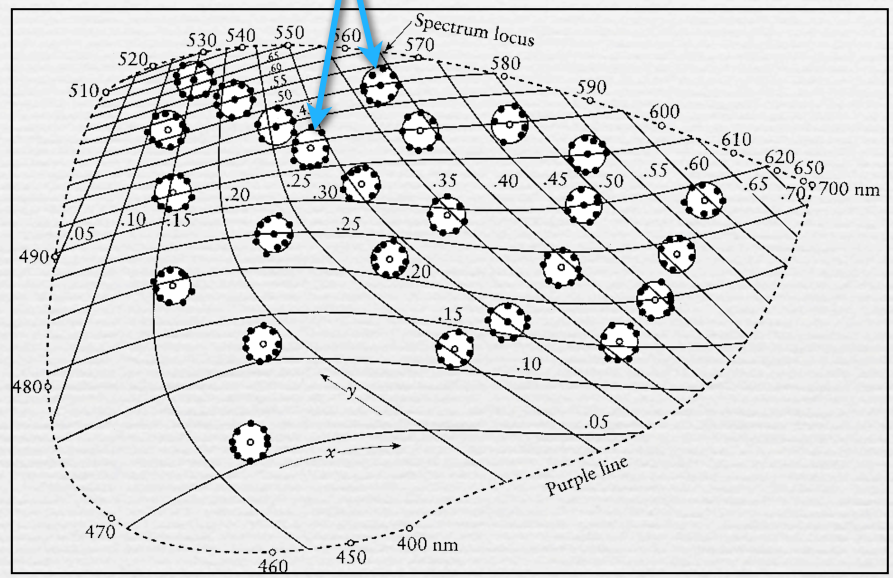
Uniform perceptual color spaces



(wikipedia)

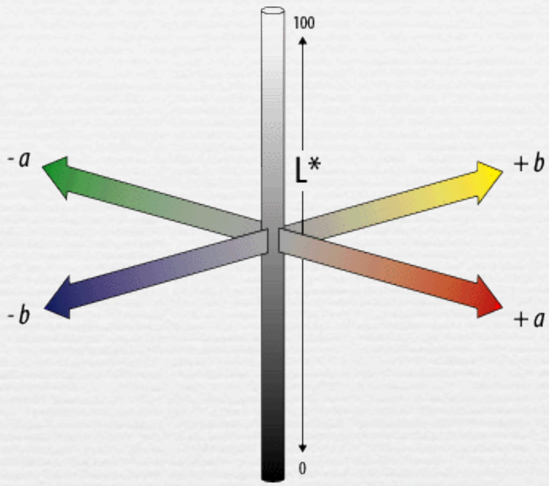
equally perceivable
“MacAdam ellipses”

(Wyszecki and Stiles)



- in the xyz chromaticity diagram, equal distances on the diagram are not equally perceivable to humans
- to create a space where they are equally perceivable, one must distort XYZ space (and the xy diagram) non-linearly

CIELAB space (a.k.a. L*a*b*)



$$L = 25\left(100\frac{Y}{Y_0}\right)^{1/3} - 16$$

$$a = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right]$$

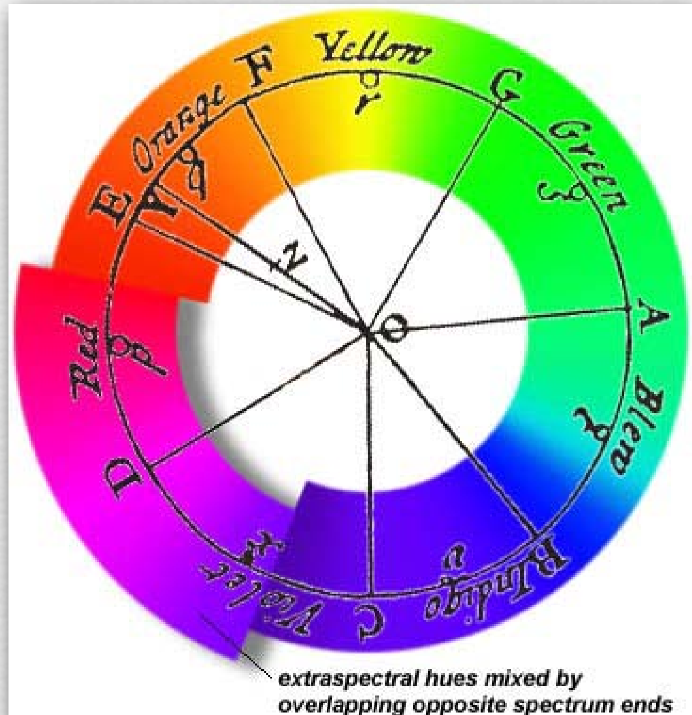
$$b = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

non-linear mapping (a gamma transform)

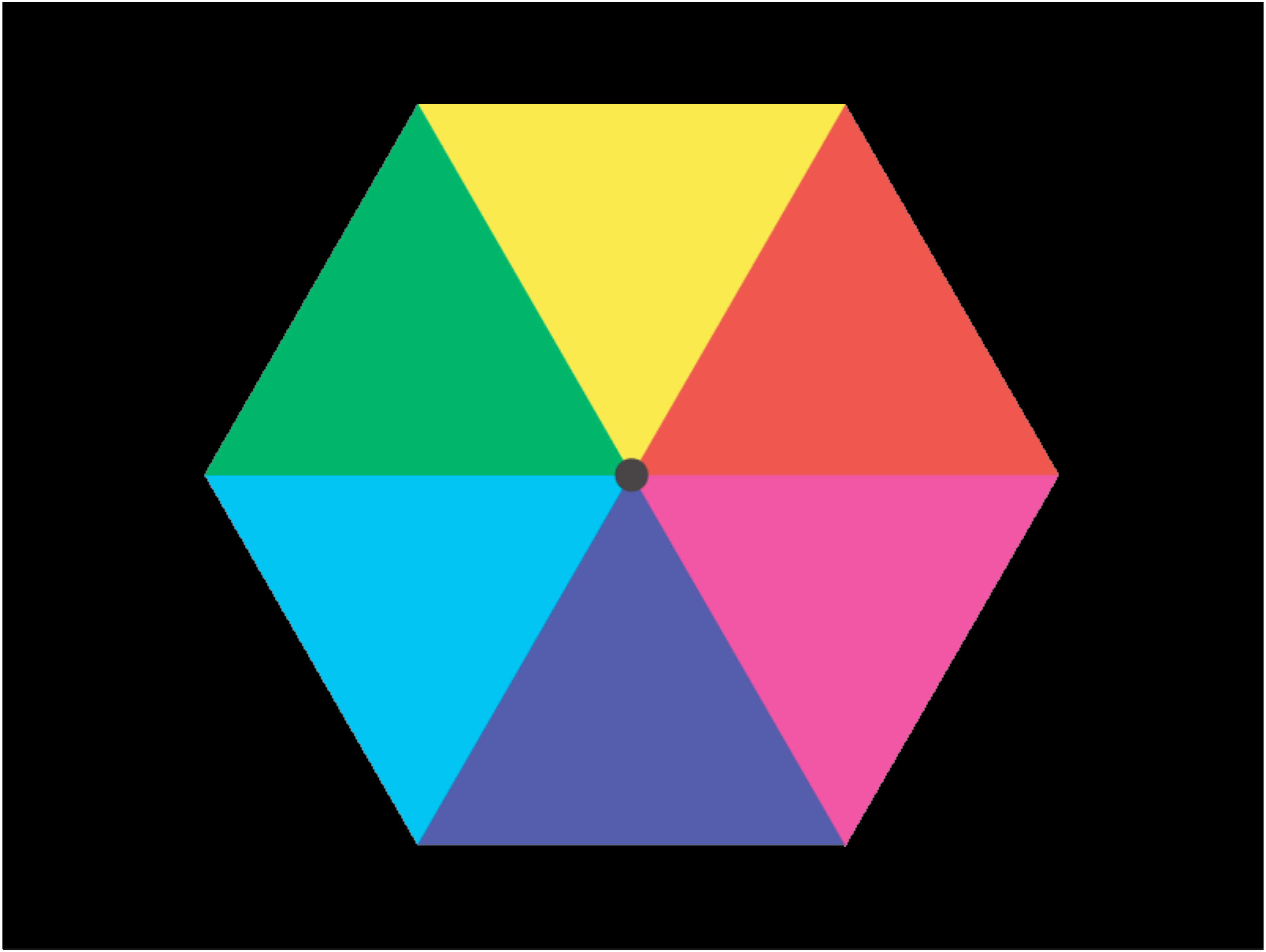
- L* is lightness
- a* and b* are color-opponent pairs
  - a* is red-green, and b* is blue-yellow
- gamma transform is because for humans, perceived brightness ∝ scene intensity$^{\gamma}$, where $\gamma \approx ⅓$

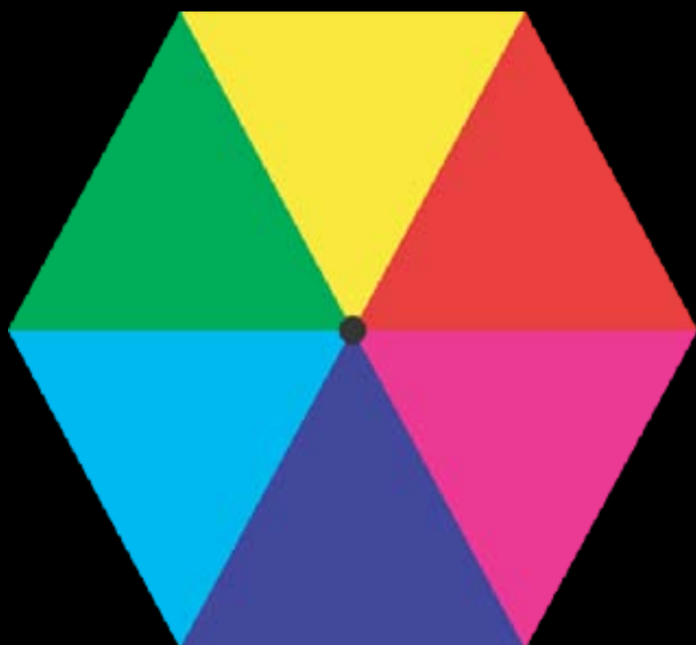
Complementary colors

(http://www.handprint.com/HP/WCL/color6.html)

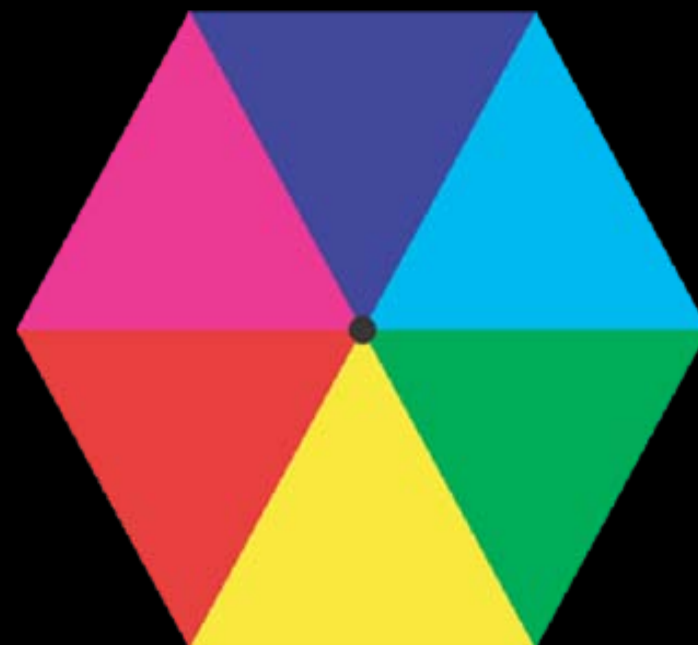


- Leonardo described complementarity of certain pairs of colors
- Newton arranged them opposite one another across his circle
- Comte de Buffon (1707-1788) observed that afterimage colors were exactly the complementary colors



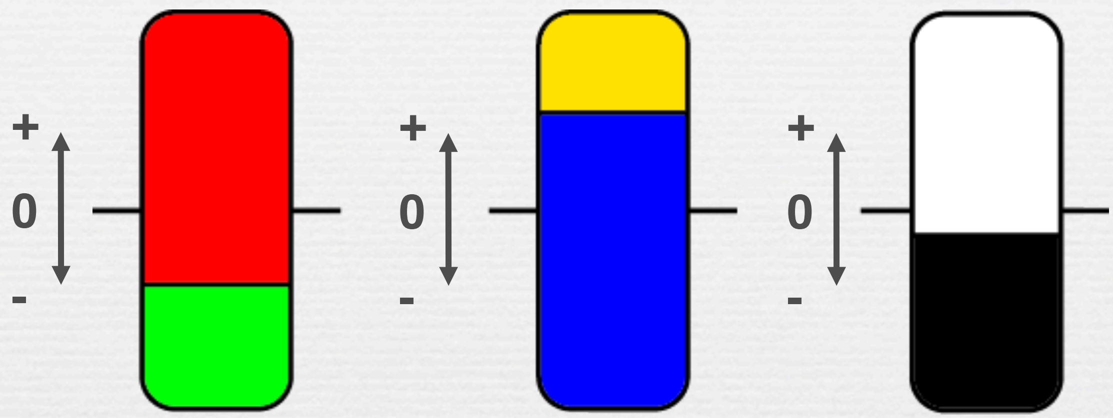


image



afterimage

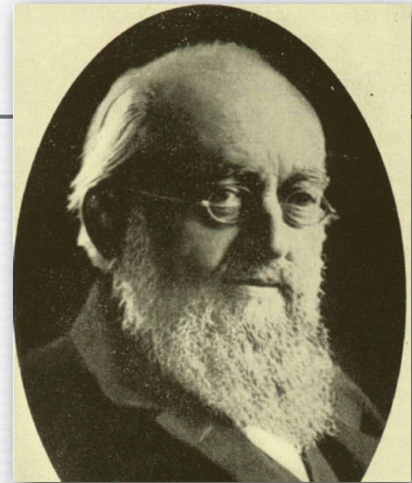
Opponent colors



red/green receptors

blue/yellow receptors

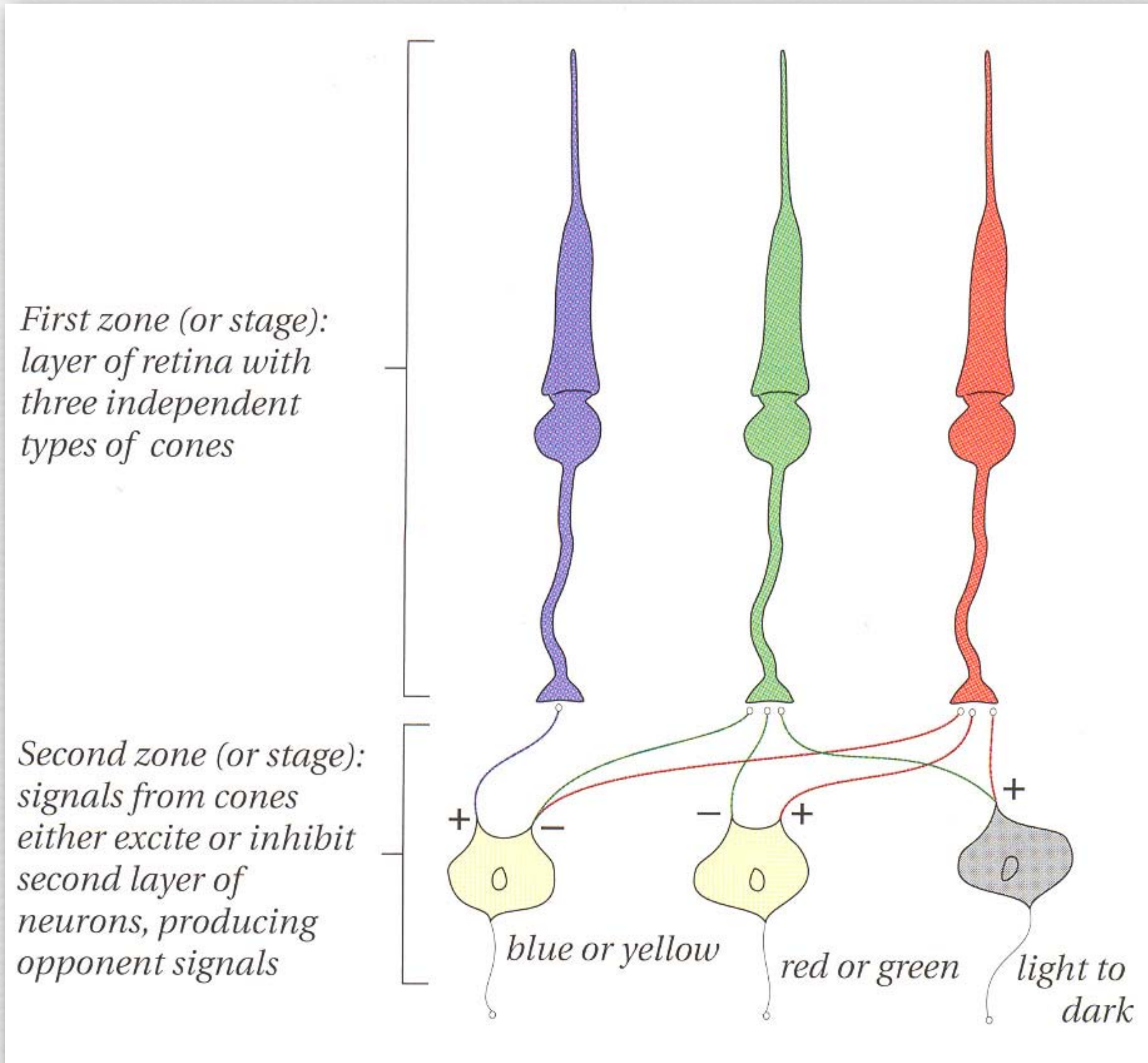
black/white receptors



Ewald Hering
(1834-1918)

- observed that humans don't see reddish-green colors or blueish-yellow colors
- hypothesized three receptors, as shown above

Opponent colors wiring



Practical use of opponent colors: NTSC color television

- ✦ color space is YIQ
  - Y = luminance
  - I = orange-blue axis
  - Q = purple-green axis

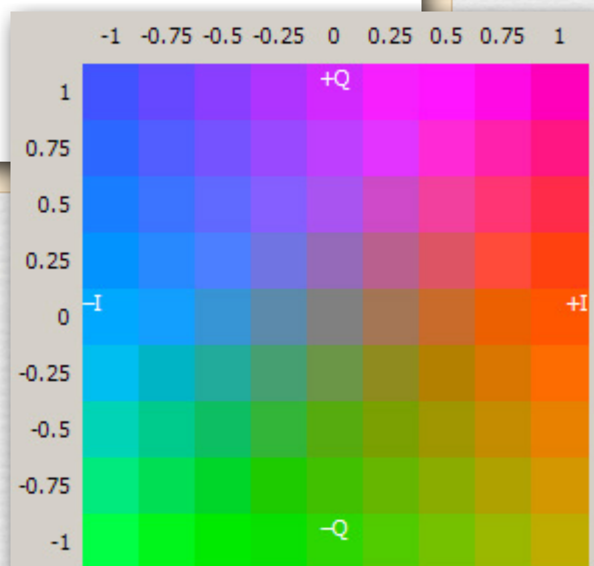
we are more sensitive to high frequencies in Y than I or Q, so devote more radio bandwidth to Y

$$R,G,B,Y \in [0,1], \quad I \in [-0.5957, 0.5957], \quad Q \in [-0.5226, 0.5226]$$

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.595716 & -0.274453 & -0.321263 \\ 0.211456 & -0.522591 & 0.311135 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0.9563 & 0.6210 \\ 1 & -0.2721 & -0.6474 \\ 1 & -1.1070 & +1.7046 \end{bmatrix} \begin{bmatrix} Y \\ I \\ Q \end{bmatrix}$$

RGB & YIQ are axes in (ρ, γ, β) space, hence these transforms are 3×3 matrix multiplications



(wikipedia)

Y

I

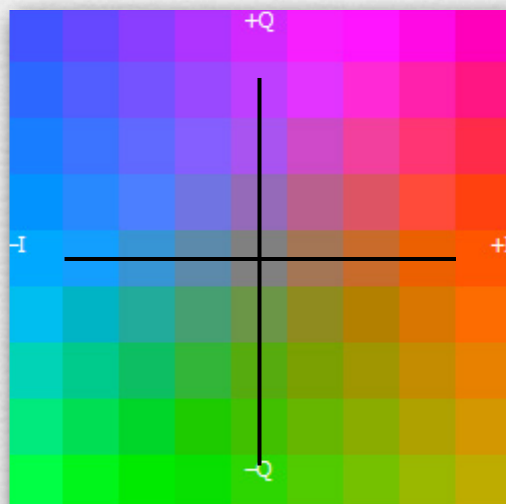
Q

Practical use of opponent colors: JPEG image compression

(wikipedia)

- color space is Y'CbCr
  - Y' = luminance
  - Cb = yellow-blue axis
  - Cr = red-green axis

$$\begin{aligned}
Y' &= 0 + (0.299 \cdot R'_D) + (0.587 \cdot G'_D) + (0.114 \cdot B'_D) \\
C_B &= 128 - (0.168736 \cdot R'_D) - (0.331264 \cdot G'_D) + (0.5 \cdot B'_D) \\
C_R &= 128 + (0.5 \cdot R'_D) - (0.418688 \cdot G'_D) - (0.081312 \cdot B'_D)
\end{aligned}$$



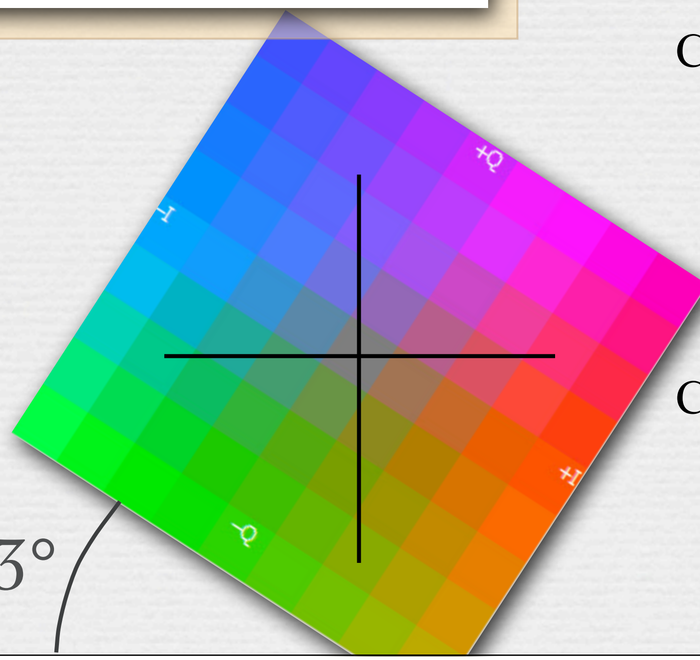
Practical use of opponent colors: JPEG image compr

- color space is Y'CbCr
  - Y' = luminance
  - Cb = yellow-blue axis
  - Cr = red-green axis

we are more sensitive to high frequencies in Y' than CbCr, so reduce CbCr resolution (~4×)

$$
\begin{aligned}
Y' &= \quad 0 + (0.299 \cdot R'_D) + (0.587 \cdot G'_D) + (0.114 \cdot B'_D) \\
C_B &= 128 - (0.168736 \cdot R'_D) - (0.331264 \cdot G'_D) + (0.5 \cdot B'_D) \\
C_R &= 128 + (0.5 \cdot R'_D) - (0.418688 \cdot G'_D) - (0.081312 \cdot B'_D)
\end{aligned}
$$

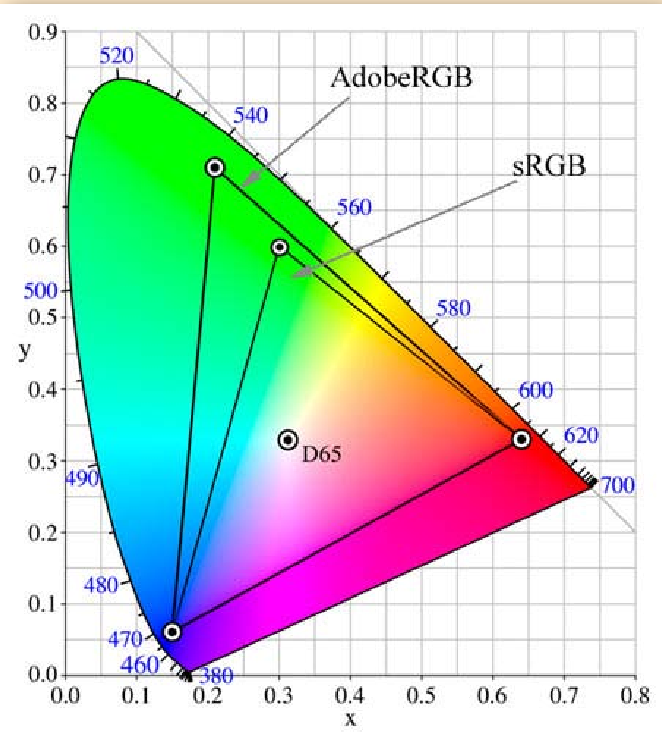
inputs R'_D, G'_D, B'_D are R^γ, G^γ, B^γ for some gamma $\gamma < 1$



(wikipedia)

The color spaces used in cameras

- to define an RGB color space, one needs
  - the location of the R,G,B axes in (ρ, γ, β) space, or equivalently in (x,y) space, i.e. what color are the 3 primaries?
  - the location of the R=G=B=1 point in (ρ, γ, β) space, i.e. what is the reference white?



- the mapping from the RGB space to (ρ, γ, β) may be
  - a linear transformation (i.e. 3 x 3 matrix) or a non-linear mapping (like L*a*b*)
  - sRGB and Adobe RGB use a non-linear mapping, but are not perceptually uniform

Not responsible on exams for orange-tinted material

Back to gamut mapping

(now in a perceptually uniform space)

input color space
(like sRGB)

non-linear mapping ↓

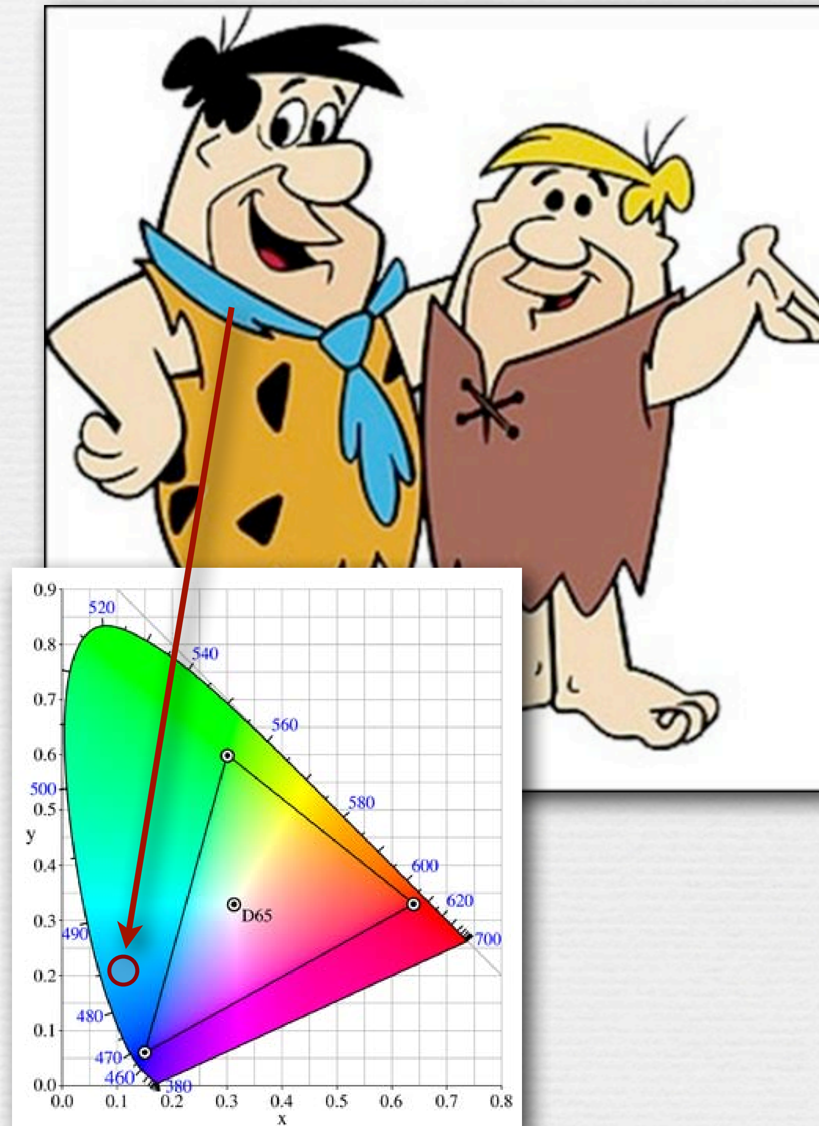
perceptually
uniform space
(like L*A*b*)

gamut mapping ↓

reduced gamut

non-linear mapping ↓

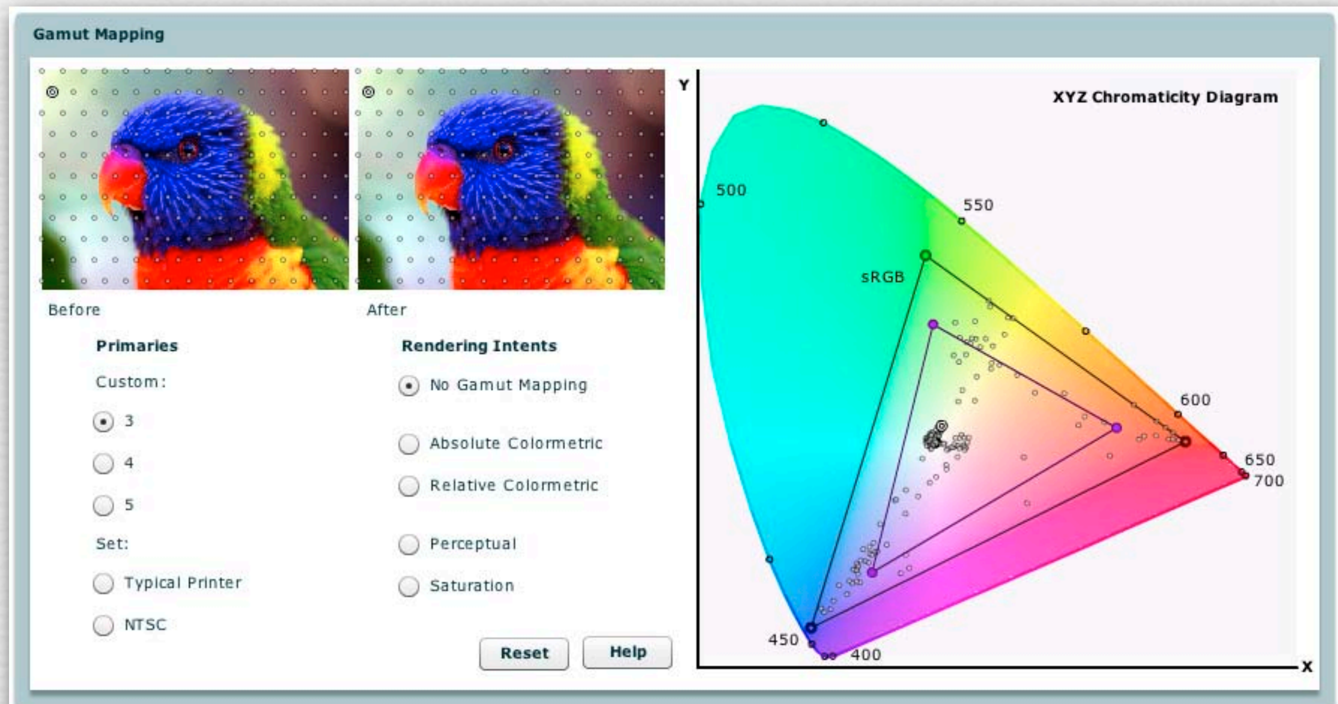
output color space
(like CMYK)



Rendering intents for gamut mapping

you can do this explicitly in Photoshop, or you can let the printer do it for you

- called "color space conversion options" in Photoshop
  - *relative colorimetric* - shrinks only out-of-gamut colors, towards N
  - *absolute colorimetric* - same but shrinks to nearest point on gamut
  - *perceptual* - smoothly shrinks all colors to fit in target gamut
  - *saturated* - sacrifices smoothness to maintain saturated colors



(FLASH DEMO)

http://graphics.stanford.edu/courses/cs178/applets/gamutmapping.html

Color spaces and color management

- Canon cameras
  - sRGB or Adobe RGB
- Nikon cameras
  - same, with additional options
- HP printers
  - ColorSmart/sRGB, ColorSync, Grayscale, Application Managed Color, Adobe RGB
- Canon desktop scanners
  - no color management (as of two years ago)
- operating systems' color management infrastructure
  - Apple ColorSync and Microsoft ICM
  - not used by all apps, disabled by default when printing

What a mess!

Recap

- the R+G+B=1 surface of a practical reproduction system (e.g. a display or printer) forms a triangle in the xyz chromaticity diagram, or more complicated figure if more than 3 primaries; the boundaries of this figure is the *gamut* for this system
- if a color to be reproduced falls outside the gamut of a target system, it must be replaced by a color lying inside the gamut, perhaps replacing other colors in the image at the same time to maintain color relationships; this is called *gamut mapping*
- gamut mapping can be performed manually (e.g. in Photoshop) or automatically by display or printer software, typically in a *perceptually uniform colorspace* like L*a*b*; how you perform the mapping is governed by a *rendering intent,* four of which are conventionally defined

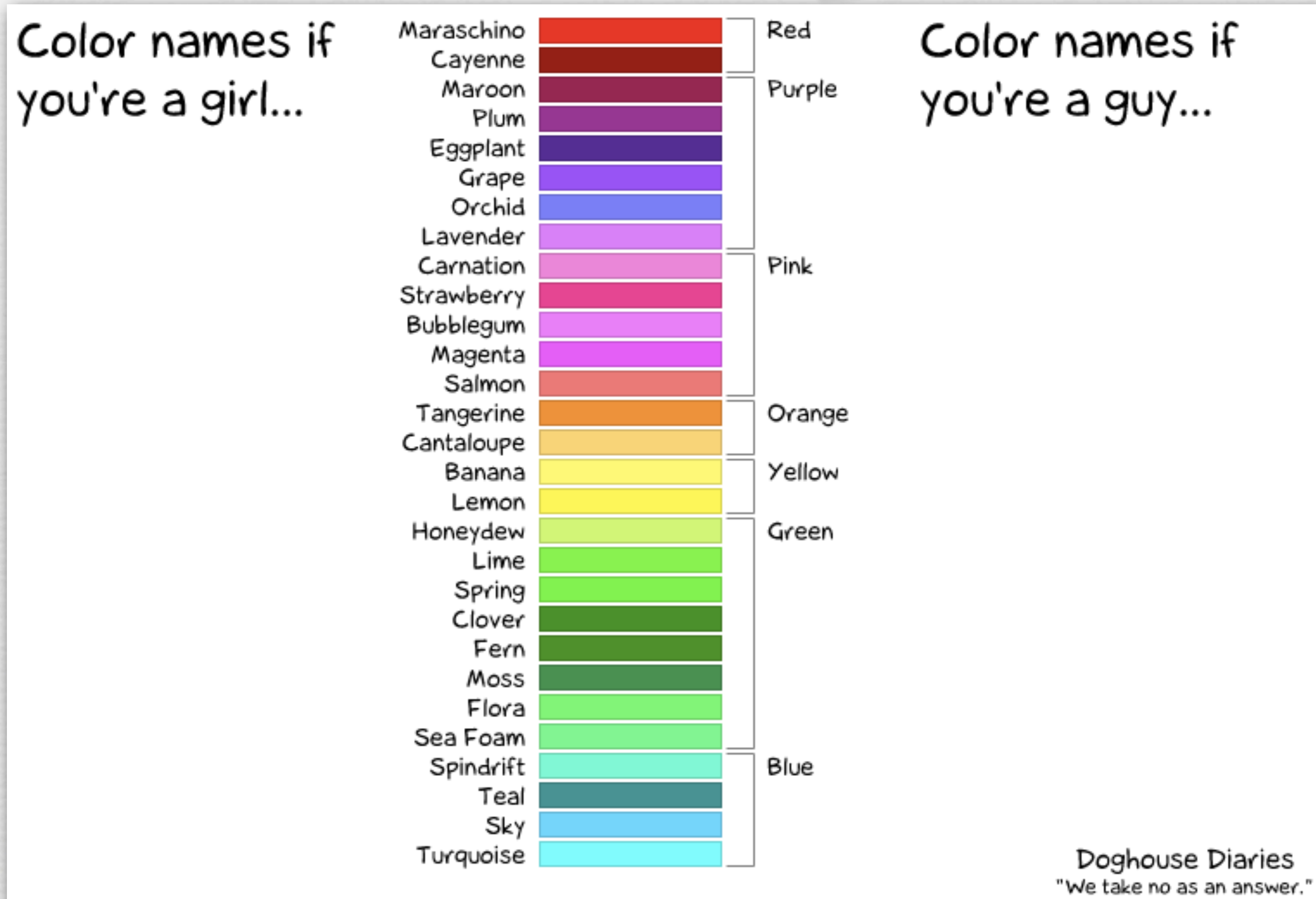
Questions?

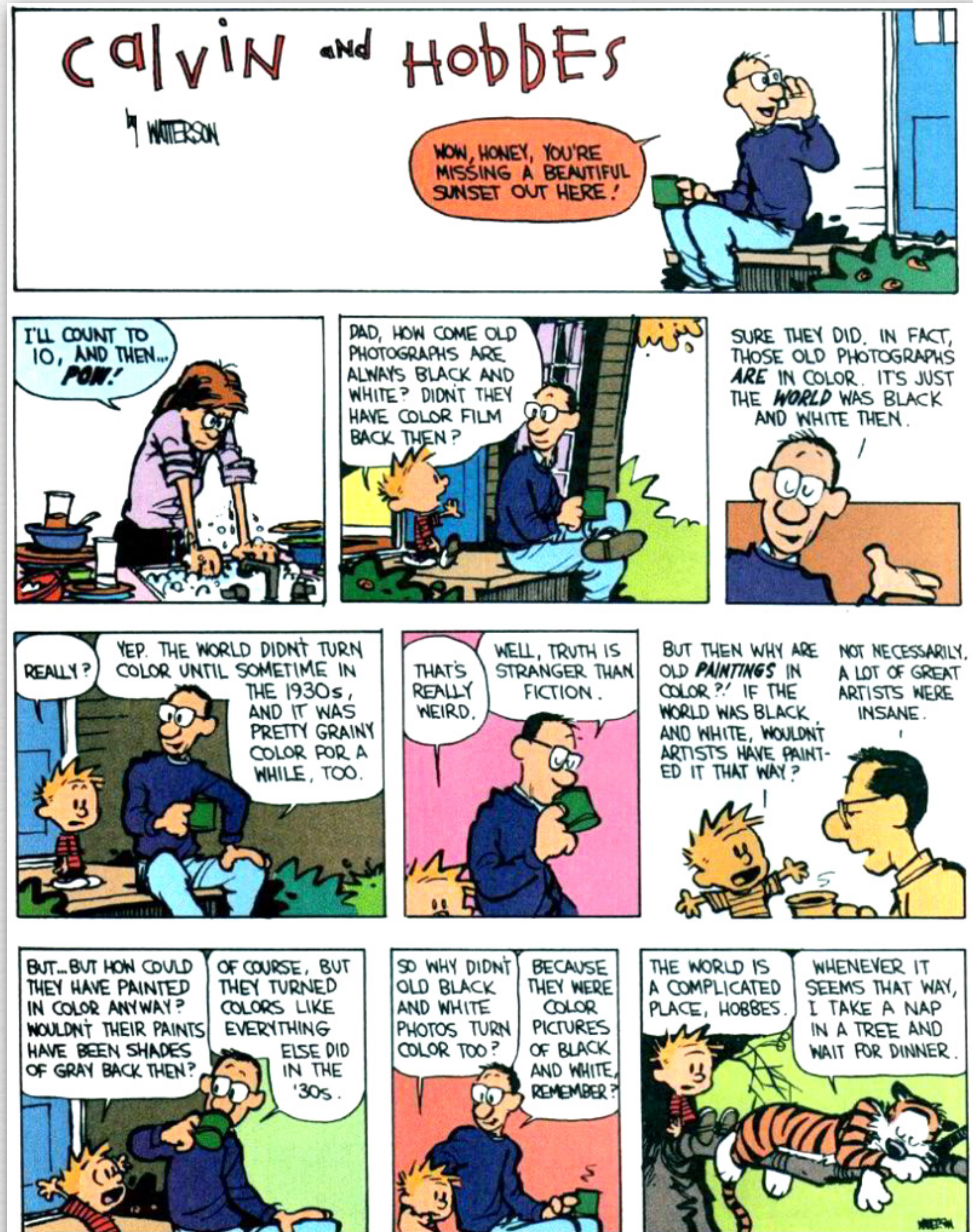
Slide credits

- Fredo Durand
- Bill Freeman
- Jennifer Dolson

- Robin, H., *The Scientific Image*, W.H. Freeman, 1993.
- Wandell, B., *Foundations of Vision*, Sinauer Associates, 1995.
- Hunt, R.W.G., *The Reproduction of Color* (6th ed.), John Wiley & Sons, 2004.
- Wyszecki, G. and Stiles, W.S., *Color Science* (2nd ed.), John Wiley & Sons, 1982.
- Foley, van Dam, et al., *Computer Graphics* (2nd ed.), Addison-Wesley, 1990.
- Berns, R.S., *Billmeyer and Saltzman's Principles of Color Technology* (3rd ed.), John Wiley, 2000.

Not responsible on exams for cantaloupe-tinted material




Calvin and Hobbes
by WATTERSON
WOW, HONEY, YOU'RE MISSING A BEAUTIFUL SUNSET OUT HERE!
I'LL COUNT TO 10, AND THEN... POW!
DAD, HOW COME OLD PHOTOGRAPHS ARE ALWAYS BLACK AND WHITE? DIDN'T THEY HAVE COLOR FILM BACK THEN?
SURE THEY DID. IN FACT, THOSE OLD PHOTOGRAPHS ARE IN COLOR. IT'S JUST THE WORLD WAS BLACK AND WHITE THEN.
REALLY?
YEP. THE WORLD DIDN'T TURN COLOR UNTIL SOMETIME IN THE 1930s, AND IT WAS PRETTY GRAINY COLOR FOR A WHILE, TOO.
THAT'S REALLY WEIRD.
WELL, TRUTH IS STRANGER THAN FICTION.
BUT THEN WHY ARE OLD PAINTINGS IN COLOR?! IF THE WORLD WAS BLACK AND WHITE, WOULDN'T ARTISTS HAVE PAINTED IT THAT WAY?
NOT NECESSARILY. A LOT OF GREAT ARTISTS WERE INSANE.
BUT... BUT HOW COULD THEY HAVE PAINTED IN COLOR ANYWAY? WOULDN'T THEIR PAINTS HAVE BEEN SHADES OF GRAY BACK THEN?
OF COURSE, BUT THEY TURNED COLORS LIKE EVERYTHING ELSE DID IN THE '30s.
SO WHY DIDN'T OLD BLACK AND WHITE PHOTOS TURN COLOR TOO?
BECAUSE THEY WERE COLOR PICTURES OF BLACK AND WHITE, REMEMBER?
THE WORLD IS A COMPLICATED PLACE, HOBBES.
WHENEVER IT SEEMS THAT WAY, I TAKE A NAP IN A TREE AND WAIT FOR DINNER.