CS-184: Computer Graphics

Lecture #2: Color

Prof. James O'Brien
University of California, Berkeley

V2011-F-02-1.0

Slides revised using additional materials from Maneesh Agrawala

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Announcments

- Account sheets available after class
- Sign up for Google Group

- Assignment 1: due Friday, Sept 2
- Assignment 2: due Tuesday, Sept 6

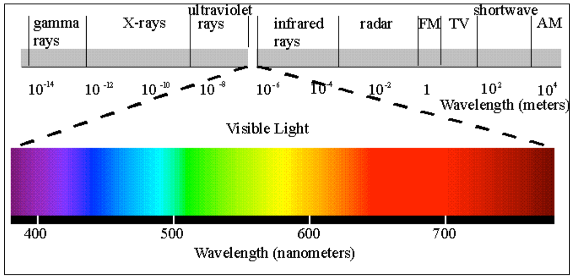
- New section: Wed 4:00-5:00 pm in 405 Soda
- Waitlist...

Today

- Color, Light, and Perceptions
  - The basics

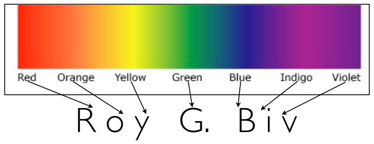
What is Light?

- Radiation in a particular frequency range

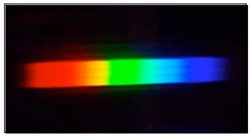


Spectral Colors

- Light at a single frequency
  - Also called **monochromatic** (an overloaded term)



- Bright and distinct in appearance



Reproduction only, not a real spectral color!

Other Colors

- Most colors seen are a mix light of several frequencies

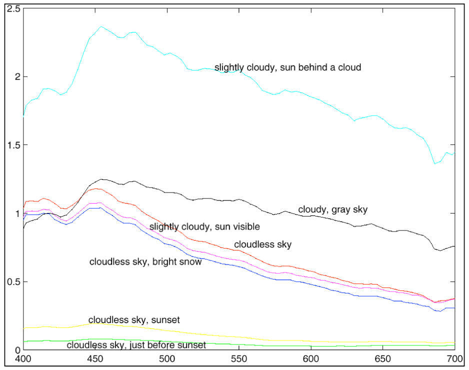


Image from David Forsyth

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

Other Colors

- Most colors seen are a mix light of several frequencies

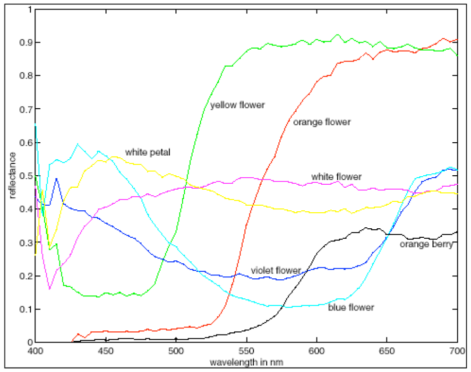


Image from David Forsyth

Other Colors

- Most colors seen are a mix light of several frequencies

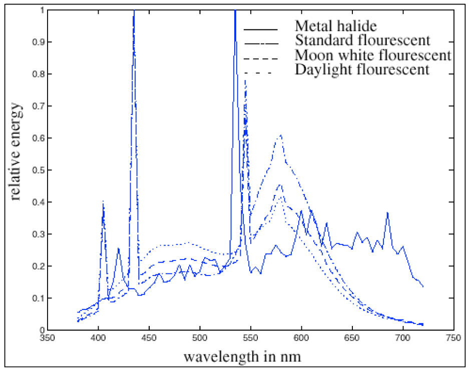
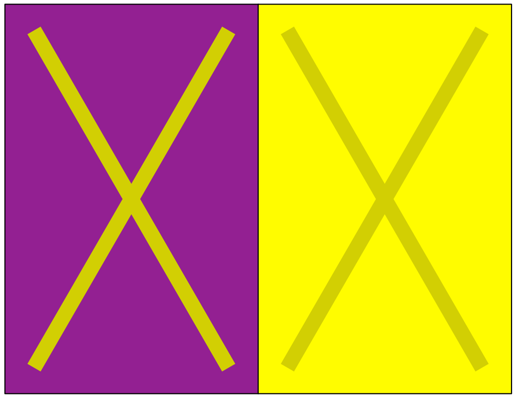


Image from David Forsyth

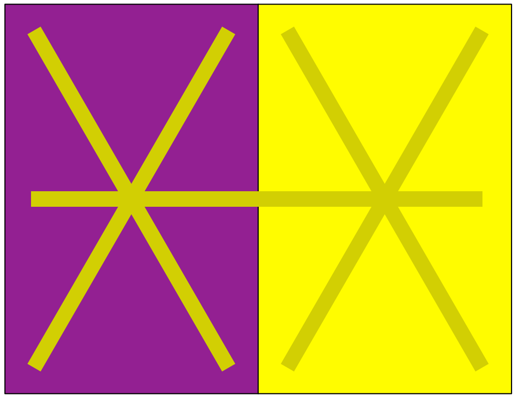
Perception -vs- Measurement

- You do not "see" the spectrum of light
  - Eyes make limited measurements
  - Eyes physically adapt to circumstance
  - You brain adapts in various ways also
  - Weird psychological/psychophysical stuff also happens

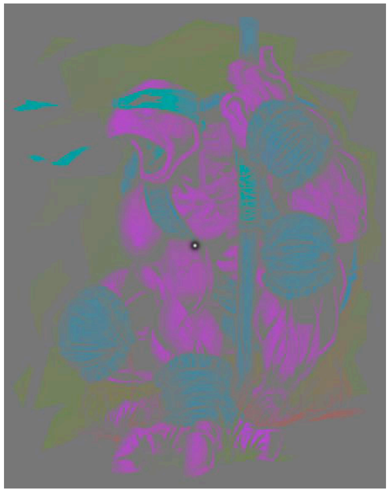
Everything is Relative



Everything is Relative



Adapt



Adapt

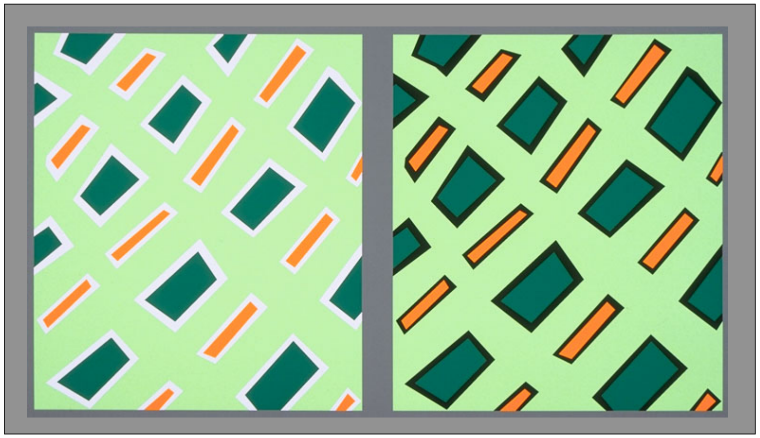
It’s all in your mind...

XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	RED	RED
XXXXXX	WHITE	WHITE
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	BLUE	BLUE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	WHITE	WHITE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE

Mach Bands

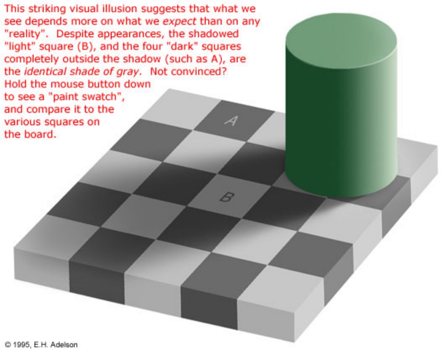
Everything's Still Relative

Bezold Effect



Perception

The eye does not see intensity values...

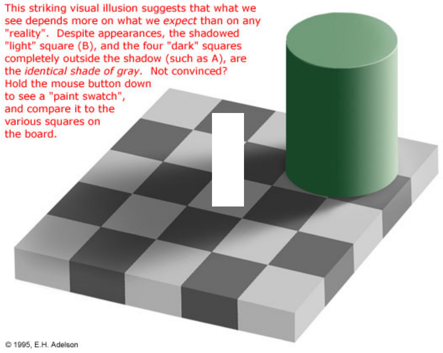


This striking visual illusion suggests that what we see depends more on what we *expect* than on any "reality". Despite appearances, the shadowed "light" square (B), and the four "dark" squares completely outside the shadow (such as A), are the *identical shade of gray*. Not convinced? Hold the mouse button down to see a "paint swatch", and compare it to the various squares on the board.

© 1995, E.H. Adelson

Perception

The eye does not see intensity values...



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© 1995, E.H. Adelson

Perception

The eye does not see intensity values...

Eyes as Sensors

- The human eye contains cells that sense light
  - Rods
    - No color (sort of)
    - Spread over the retina
    - More sensitive
  - Cones
    - Three types of cones
    - Each sensitive to different frequency distribution
    - Concentrated in fovea (center of the retina)
    - Less sensitive

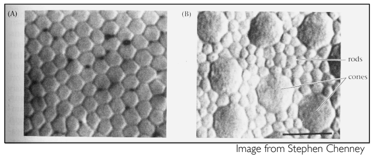
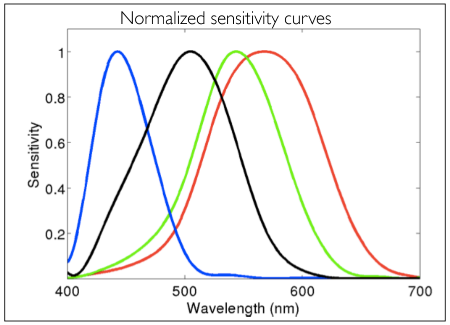


Image from Stephen Chenney

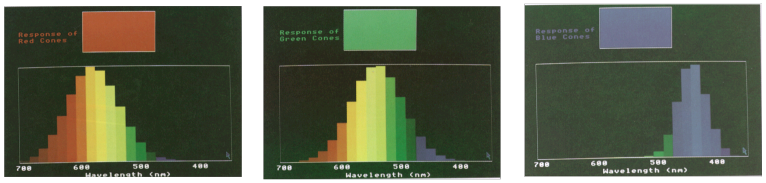
Cones

- Each type of cone responds to different range of frequencies/wavelengths
  - Long, medium, short
- Also called by color
  - Red, green, blue
  - Misleading:

    "Red" does not mean your red cones are firing...



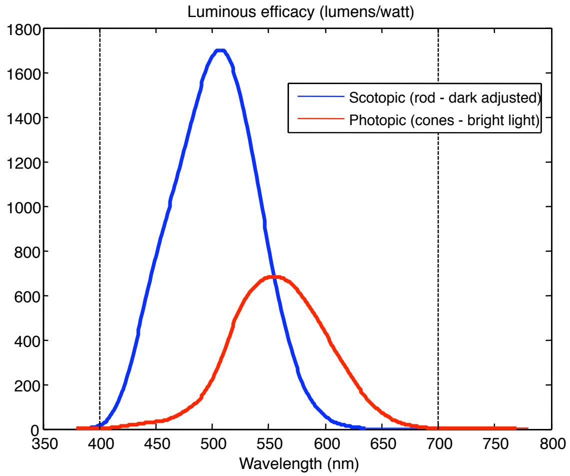
Cones



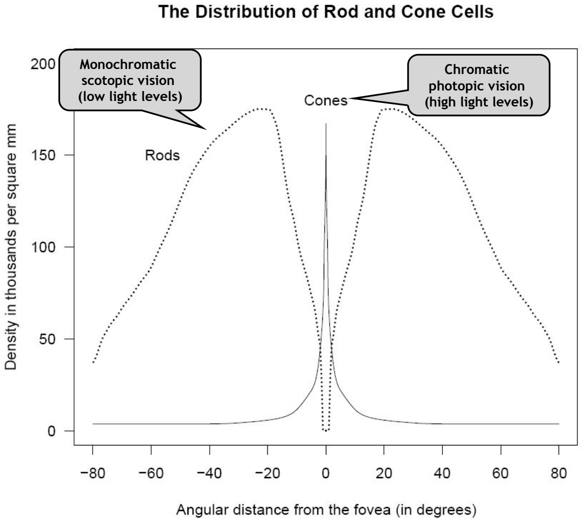
Images from David Forsyth

- You can see that "red" and "green" respond to more more than just red and green...

Rods vs Cones



Eyes as Sensors



Cones

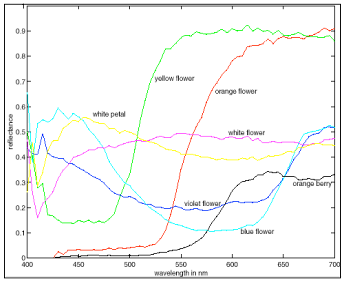
- Response of a cone is given by a convolution integral :

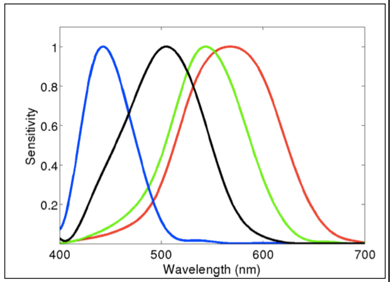
$$L = \int \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$

continuous version of a dot product

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

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





Trichromaticity

Eye records color by 3 measurements

We can "fool" it with combination of 3 signals

So display devices (monitors, printers, etc.) can generate perceivable colors as mix of 3 primaries

Cone Responses are Linear

Response to stimulus Φ_1 is (L_1, M_1, S_1)

Response to stimulus Φ_2 is (L_2, M_2, S_2)

Then response to $\Phi_1 + \Phi_2$ is $(L_1 + L_2, M_1 + M2, S_1 + S_2)$

Response to $n\Phi_1$ is (nL_1, nM_2, nS_1)

Cones and Metamers

Cone response is an integral

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

Metamers: Different light input $\Phi_1(\lambda), \Phi_2(\lambda)$ produce same L, M, S cone response

- Different spectra look the same
- Useful for measuring color

Additive Mixing

Given three primaries we agree on p_1, p_2, p_3

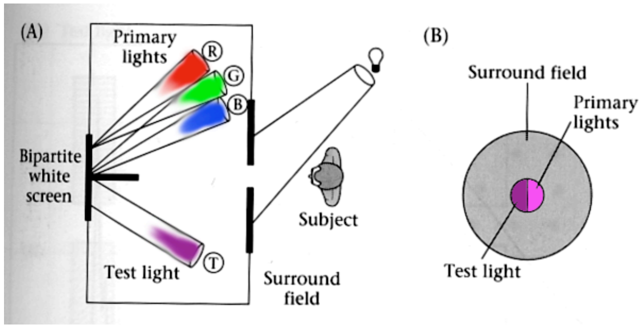
Match generic input light with $\Phi = \alpha p_1 + \beta p_2 + \gamma p_3$

Negative not realizable, but can add primary to test light

Color now described by α, β, γ

Example: computer monitor [RGB]

Additive Color Matching

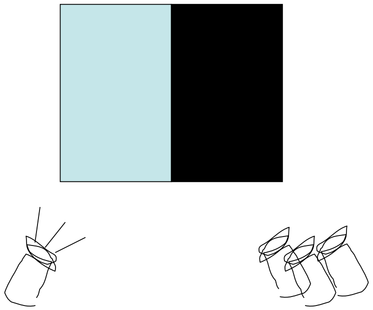


Show test light spectrum on left

Mix "primaries" on right until they match

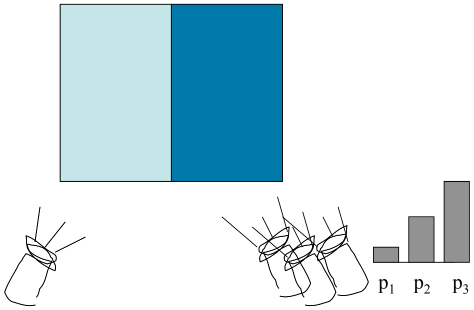
The primaries need not be RGB

Experiment 1



Slide from Durand
and Freeman 06

Experiment 1



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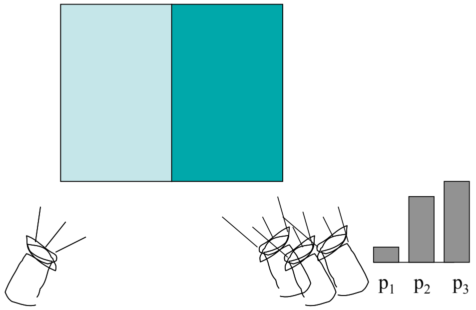

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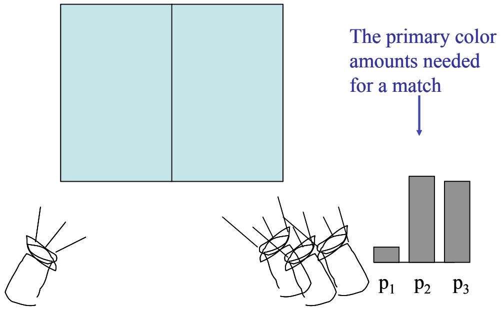
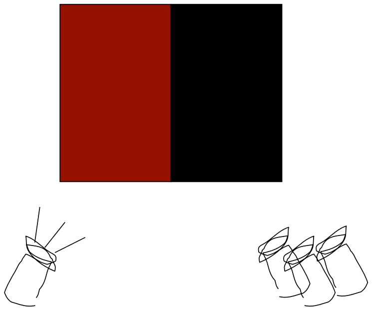
Experiment 1



The primary color
amounts needed
for a match

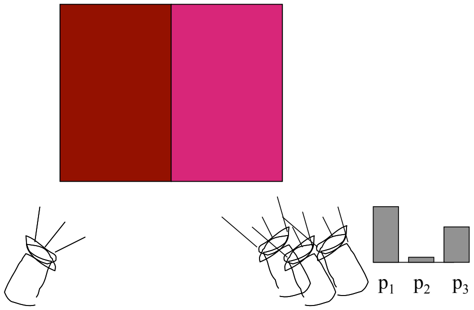
Slide from Durand
and Freeman 06

Experiment 2



Slide from Durand and Freeman 06

Experiment 2



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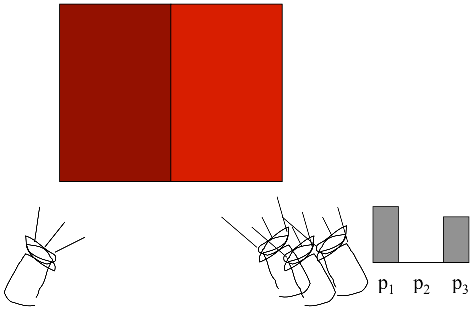
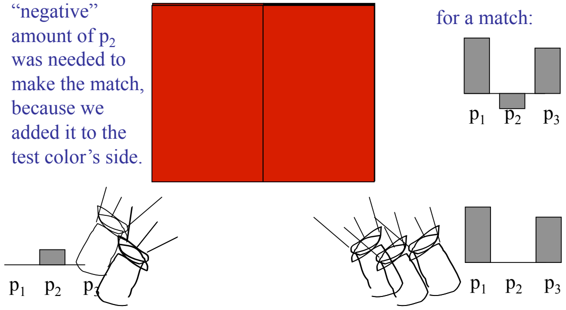


Slide from Durand and Freeman 06

Experiment 2

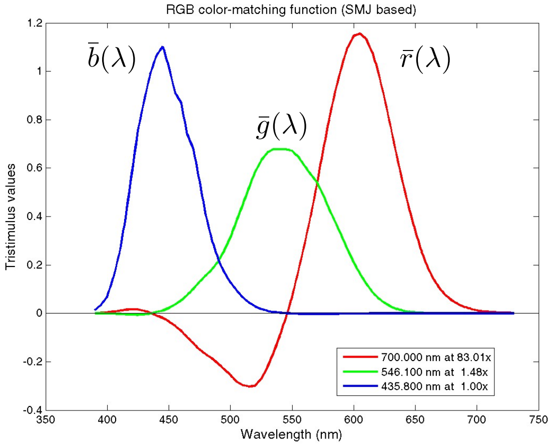


We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.

The primary color amounts needed for a match:

Slide from Durand and Freeman 06

Color Matching Functions

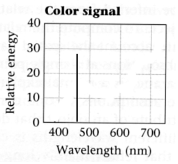


Input wavelengths are CIE 1931 monochromatic primaries

Using Color Matching Functions

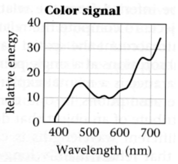
For a monochromatic light of wavelength λ_i we know the amount of each primary necessary to match it:

$$\bar{r}(\lambda_i), \bar{g}(\lambda_i), \bar{b}(\lambda_i)$$



Given a new light input signal

$$\Phi = \begin{pmatrix} \phi(\lambda_1) \\ \vdots \\ \phi(\lambda_N) \end{pmatrix}$$



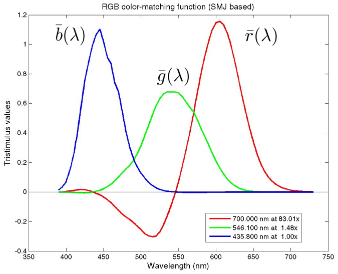
Compute the primaries necessary to match it

Using Color Matching Functions

Given color matching functions in matrix form and new light

$$C = \begin{pmatrix} \bar{r}(\lambda_1) & \dots & \bar{r}(\lambda_N) \\ \bar{g}(\lambda_1) & \dots & \bar{g}(\lambda_N) \\ \bar{b}(\lambda_1) & \dots & \bar{b}(\lambda_N) \end{pmatrix}$$

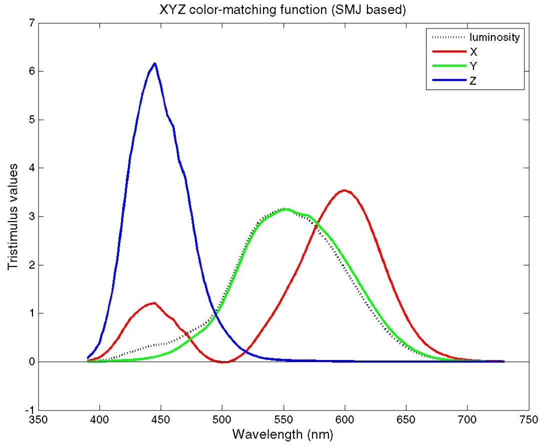
$$\Phi = \begin{pmatrix} \phi(\lambda_1) \\ \vdots \\ \phi(\lambda_N) \end{pmatrix}$$



amount of each primary necessary to match is given by $C\Phi$

CIE XYZ

Imaginary set of color primaries with positive values, X, Y, Z



Rescaled XYZ to xyz

Rescale X, Y, and Z to remove luminance, leaving chromaticity:

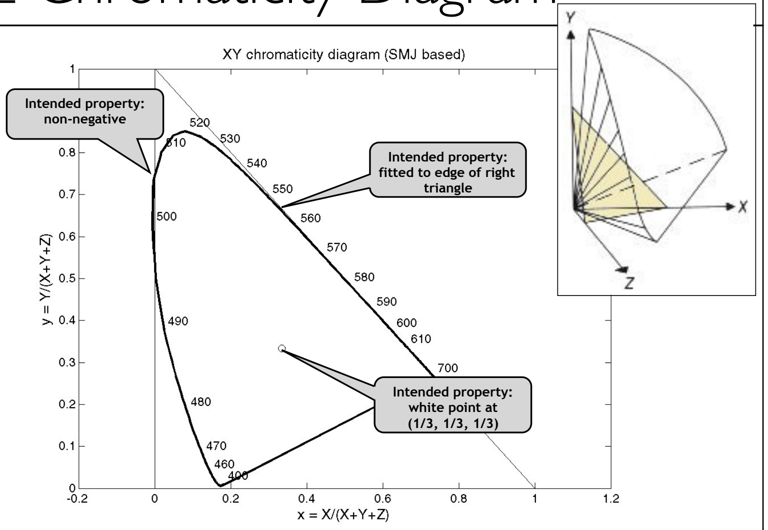
$$x = X / (X+Y+Z)$$
$$y = Y / (X+Y+Z)$$
$$z = Z / (X+Y+Z)$$

$$x+y+z = 1$$

Because the sum of the chromaticity values x, y, and z is always 1.0, a plot of any two of them loses no information

Such a plot is a chromaticity diagram

CIE Chromaticity Diagram

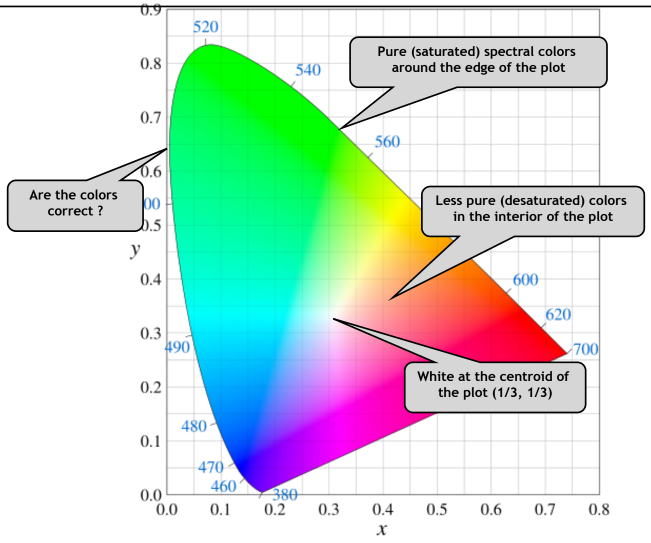


Intended property: non-negative

Intended property: fitted to edge of right triangle

Intended property: white point at (1/3, 1/3, 1/3)

CIE Chromaticity Diagram



Pure (saturated) spectral colors around the edge of the plot

Are the colors correct ?

Less pure (desaturated) colors in the interior of the plot

White at the centroid of the plot (1/3, 1/3)

Gamut

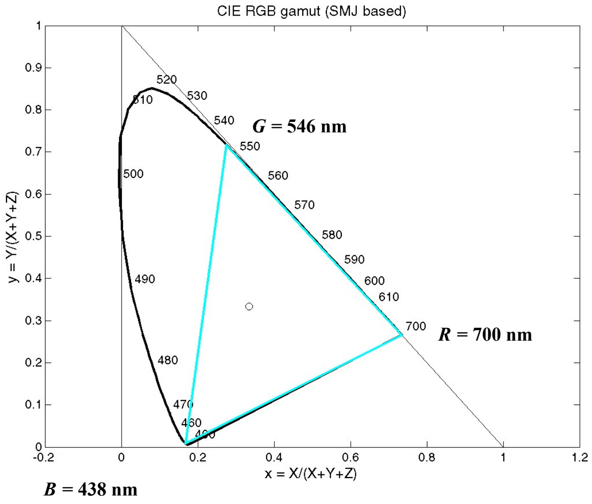
Gamut is the chromaticities generated by a set of primaries

Because everything we've done is linear, interpolation between chromaticities on a chromaticity plot is also linear

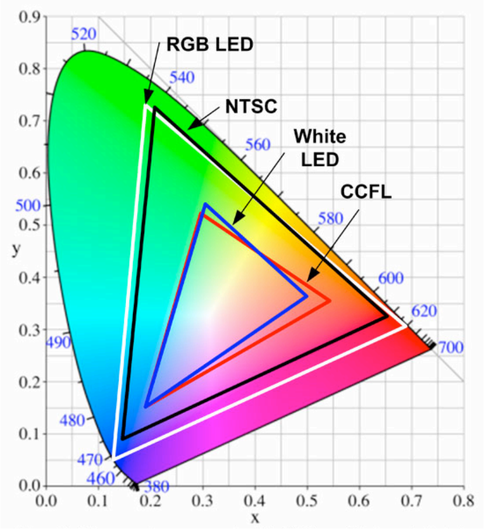
Thus the gamut is the convex hull of the primary chromaticities

What is the gamut of the CIE 1931 primaries?

CIE 1931 RGB Gamut



Other Gamuts (LCDs and NTSC)



Subtractive Mixing

Given three primaries we agree on p_1, p_2, p_3

Make generic color with $\Phi = W - (\alpha p_1 + \beta p_2 + \gamma p_3)$

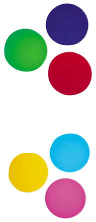
Max limited by W

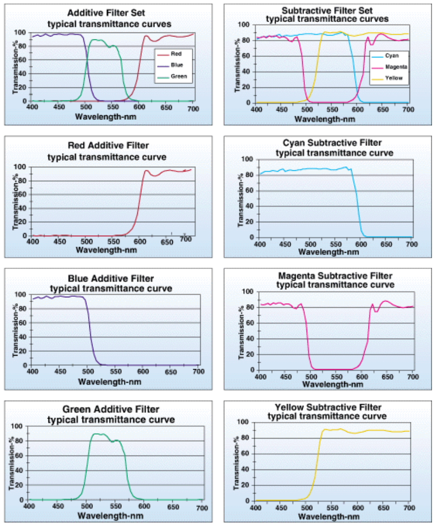
Color now described by α, β, γ

Example: ink [CMYK]

Why 4th ink for black?

Additive & Subtractive Primaries





Additive & Subtractive Primaries

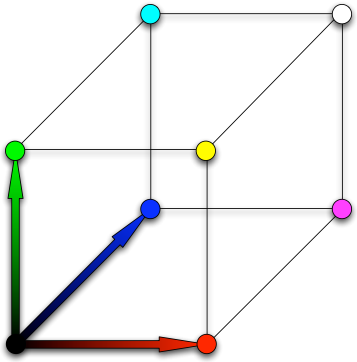
Incorrect to say "the additive primaries are red, green, and blue"

- Any set of three non-colinear primaries yields a gamut
- Primaries that appear red, green, and blue are a good choice, but not the only choice
- Are additional (non-colinear) primaries always better?

Similarly saying "the subtractive primaries are magenta, cyan, and yellow" is also incorrect, for the same reasons

- Subtractive primaries must collectively block the entire visible spectrum, but many sets of blockers that do so are acceptable "primaries"
- The use of black ink (the k in cmyk) is a good example
- Modern ink-jet printers often have 6 or more ink colors

Color Spaces

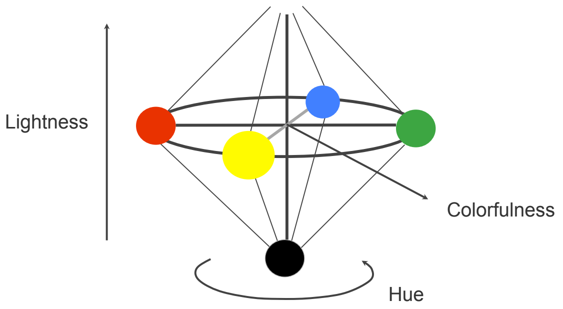


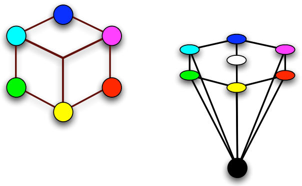
RGB color cube

- Does not correspond very well to perception (e.g. distance between two points has little meaning)

Color Spaces

HSV color cone



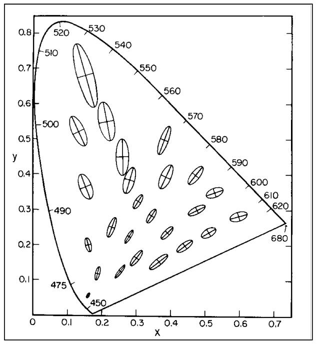


Color Spaces

RGB color cube

HSV color cone

CIE (x,y)



MacAdam Ellipses (10x)

Colors in ellipses indistinguishable from center.

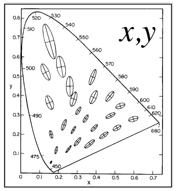
Color Spaces

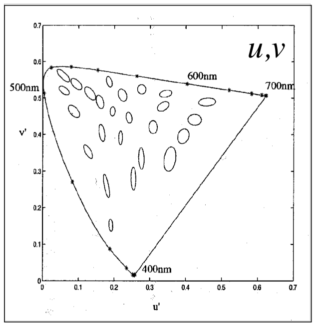
RGB color cube

HSV color cone

CIE (x,y)

CIE (u,v)





Scaled to be closer to circles.

$$\begin{bmatrix}u'\\v'\end{bmatrix}=\frac{1}{X+15Y+3Z}\begin{bmatrix}4X\\9Y\end{bmatrix}$$

Color Spaces

RGB color cube

HSV color cone

CIE (x,y)

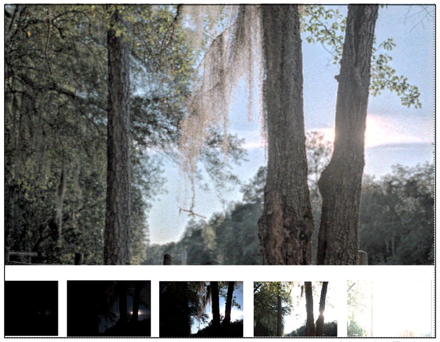
CIE (u,v)

CMYK

Many others...

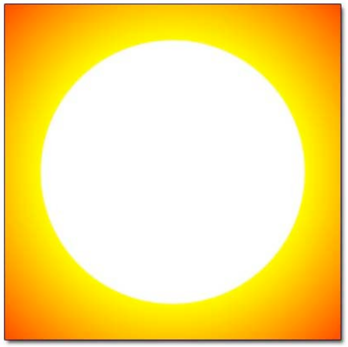
Dynamic Range

- Max/min values also limited on devices
  - "blackest black"
  - "brightest white"



Jack Tumblin

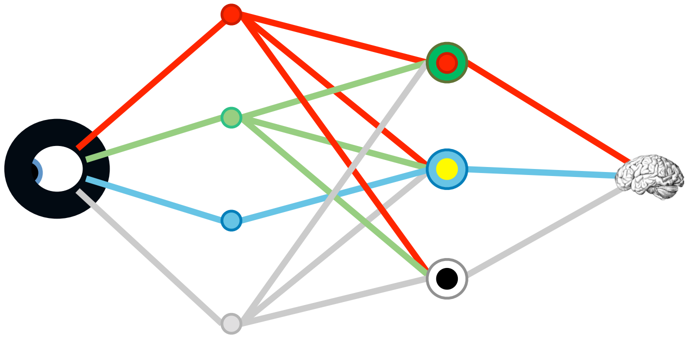
Fake High Dynamic Range



Tone Mapping

Kirk and O'Brien 2011

Rods Contribute to Color



Color Phenomena

- Light sources seldom shine directly in eye
- Light follows some transport path, ***i.e.*:**
  - Source
  - Air
  - Object surface
  - Air
  - Eye
- Color effected by interactions

Reflection

- Light strikes object
- Some frequencies reflect
- Some adsorbed
- Reflected spectrum is light times surface
- Recall metamers...

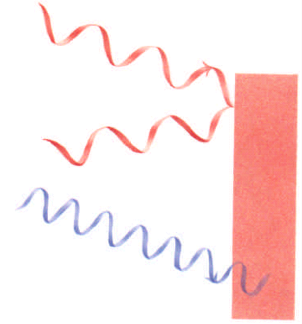


Fig. 1.18 Reflection: red light bounces off an opaque red object, while light of other colours is absorbed.

Unknown?

Transmission

- Light strikes object
- Some frequencies pass
- Some adsorbed (or reflected)

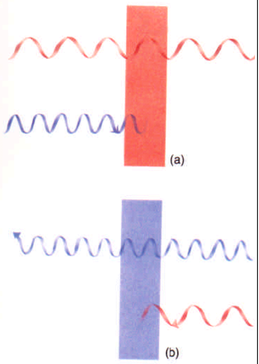


Fig. 1.17 Absorption: a red transparent medium absorbs all wavelengths of light except red (a); a blue transparent medium absorbs all wavelengths except blue (b)

Unknown?

Scattering

- Interactions with small particles in medium
- Long wavelengths ignore
- Short ones scatter

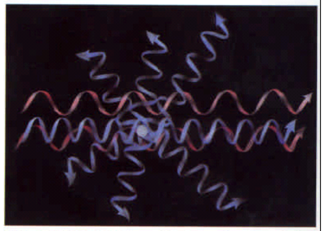


Fig. 1.25 Rayleigh scattering: when particles in air or water are small relative to light wavelength they scatter blue light preferentially.

Unknown?

Interference

- Wave behavior of light
  - Cancelation
  - Reinforcement
- Wavelength dependent

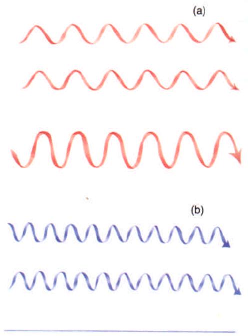


Fig. 1.20 Interference: when two light waves are in phase, they interfere positively to reinforce each other and produce a wave with double the intensity of colour (a). When two waves are out of phase they cancel each other and no colour is seen (b).

Unknown?

Iridescence

- Interaction of light with
  - Small structures
  - Thin transparent surfaces

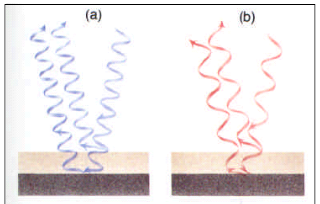
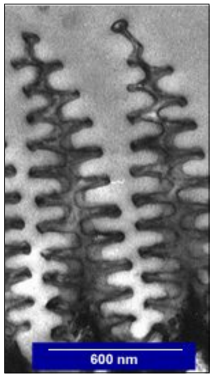


Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at the surface. In this case the blue waves are in phase and their colour is reinforced (a) but the red waves are out of phase and their colour is cancelled (b).

Unknown?

Iridescence

Iridescence



Fluorescence / Phosphorescence

- Photon come in, knocks up electron
- Electron drops and emits photon at other frequency
- May be some latency

- Radio active decay can also emit visible photons

Fluorescence / Phosphorescence

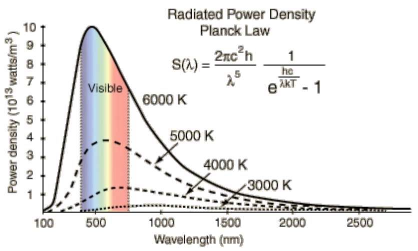
Black Body Radiation

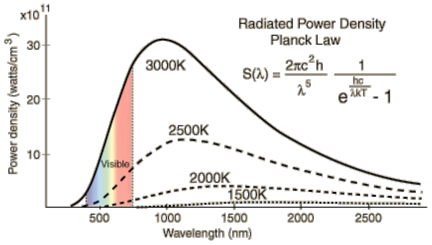
- Hot objects radiate energy
- Frequency is temperature dependent
- Moderately hot objects get into visible range
- Spectral distribution is given by

$$E(\lambda) \propto \left(\frac{1}{\lambda^5}\right)\left(\frac{1}{\exp(hc/k\lambda T)-1}\right)$$

- Leads to notion of "color temperature"

Black Body Radiation





HyperPhysics