CS-184: Computer Graphics

Lecture 2: Color

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University of California, Berkeley

Slides based on those of James O'Brien and Kurt Akeley

Announcements

Account sheets available after class

Sign up for Google Group

Maneesh's office hours:

- MW 12-12:30pm and T 5-6pm
- 635 Soda Hall

Assignment 1: due Sat Sep 4 by 11pm

Assignment 2: due Fri Sep 10 by 11pm

Announcements

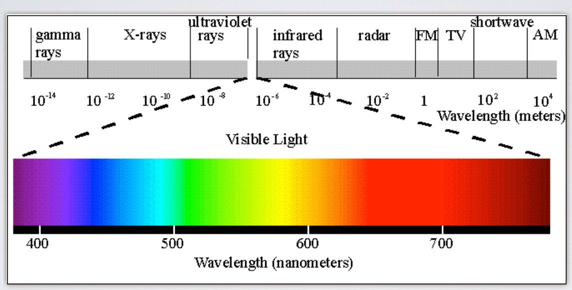
Suggestion: Best way to learn material is to print slides before class and take notes on them in class. Work through the math after class.

Today

Color and Light

What is Light?

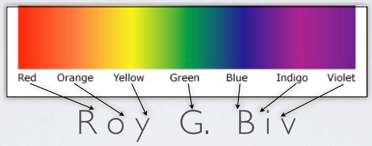
Radiation in a particular range of wavelengths



Light of a single wavelength is called **monochormatic**

Spectral Colors

Light at a single frequency



Bright and distinct in appearance

Reproduction only, not a real spectral color!

Other Colors

Most colors seen are a mix light of several wavelengths

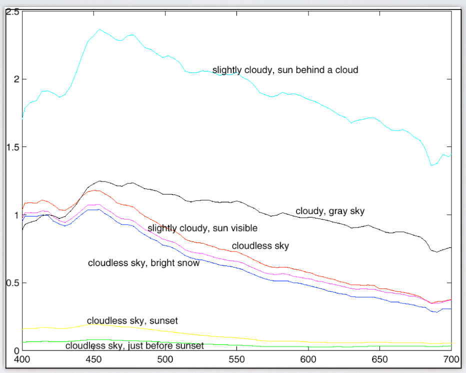
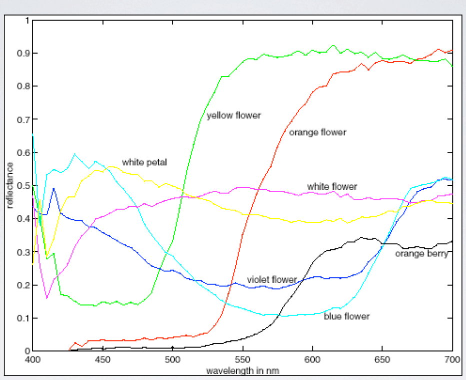


Image from David Forsyth

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

Other Colors

Most colors seen are a mix light of several wavelengths



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

Other Colors

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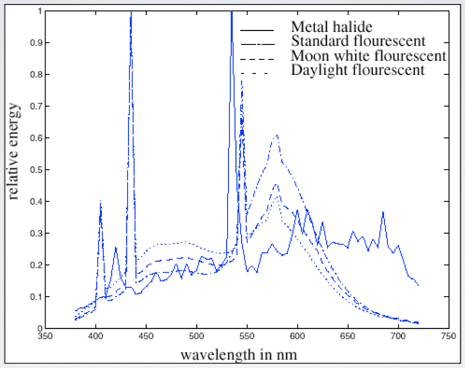


Image from David Forsyth

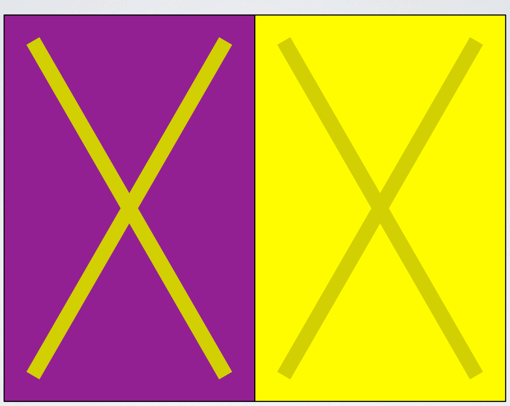
Curves describe spectral composition $\Phi(\lambda)$ of stimulus

Perception -vs- Measurement

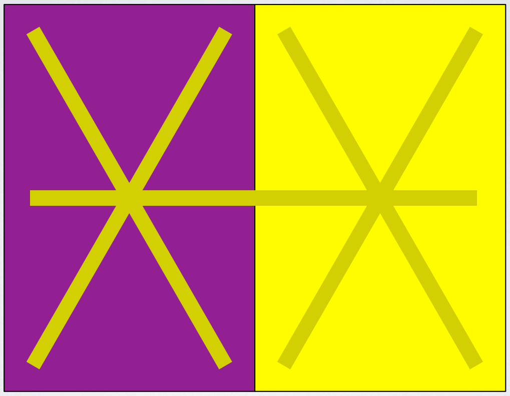
You do not "see" the spectrum of light

- Eyes make limited measurements
- Eyes physically adapt to circumstance
- You brain adapts in various ways also
- Weird stuff also happens

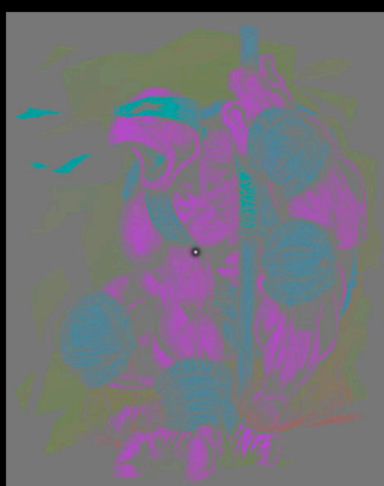
Everything is Relative



Everything is Relative

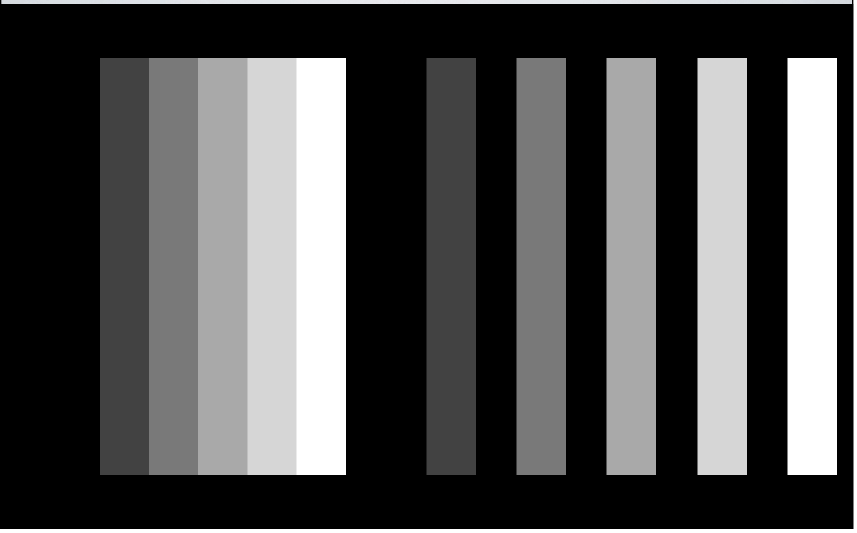


Adapt



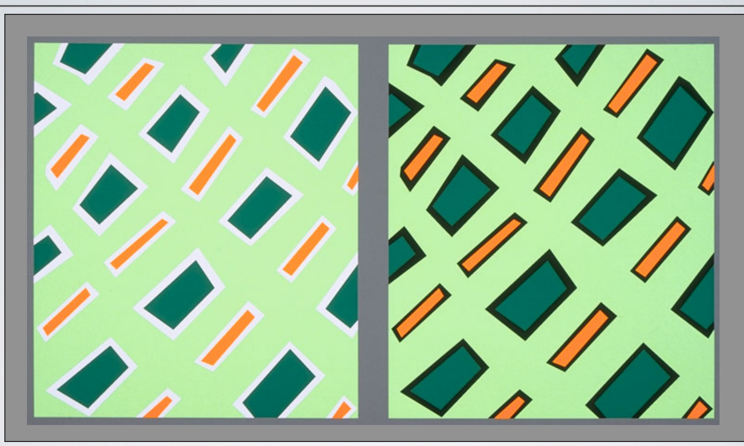
Adapt

Mach Bands



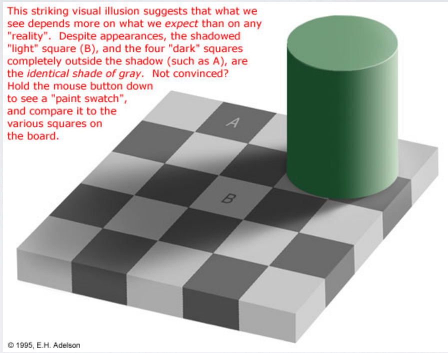
Everything's Still Relative

Bezold Effect



Perception

The eye does not see intensity values...



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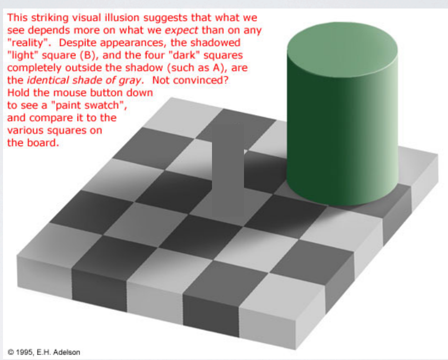

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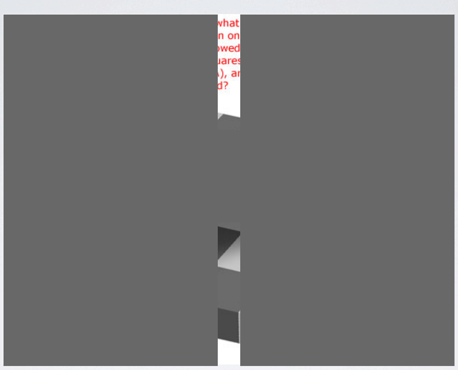
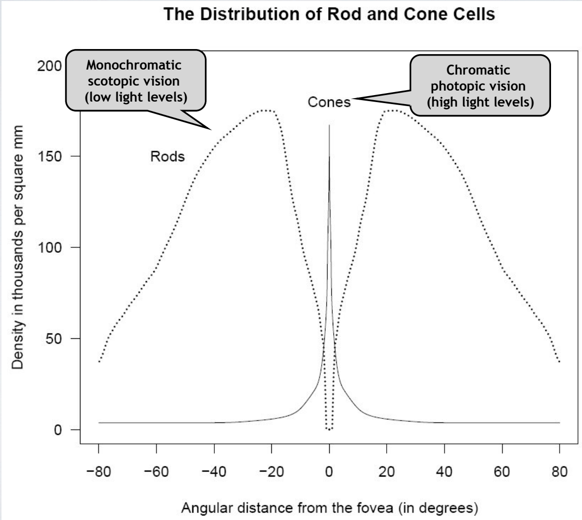


Eyes as Sensors



Rods and Cones

The human eye contains cells that sense light

- Rods
  - No color (sort of)
  - Spread over the retina
  - More sensitive

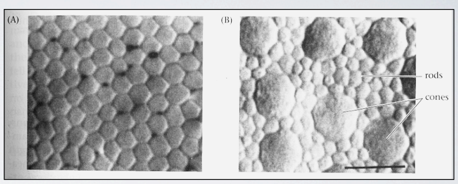


Image from Stephen Chenney

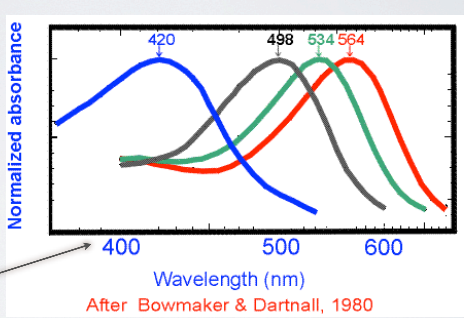
- Cones
  - Three types of cones
  - Each sensitive to different frequency distribution
  - Concentrated in fovea (center of the retina)
  - Less sensitive

Rods

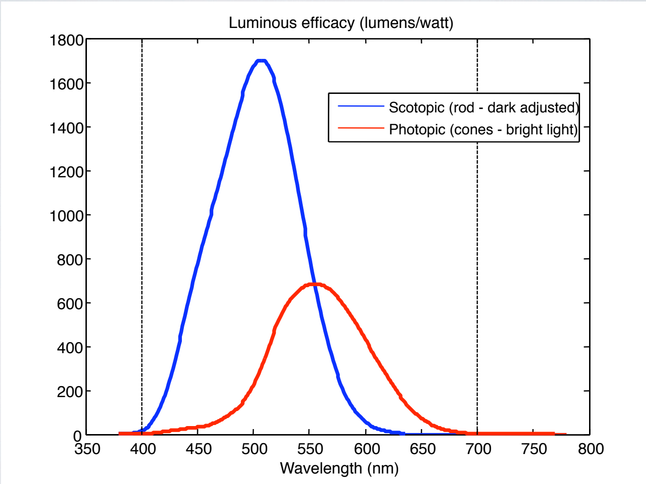
Rods are not uniform across visible spectrum

Explains why red light is good for night visions

Note the non-uniform scaling on axis!



Rods vs Cones

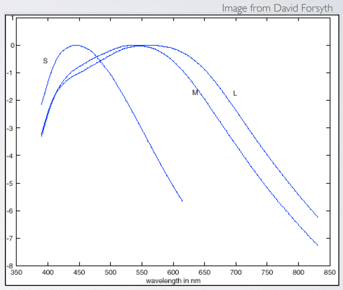


Cones

Each type of cone responds to different range of wavelengths

- Long, medium, short
- Ratio: L10/M40/S1

Image from David Forsyth



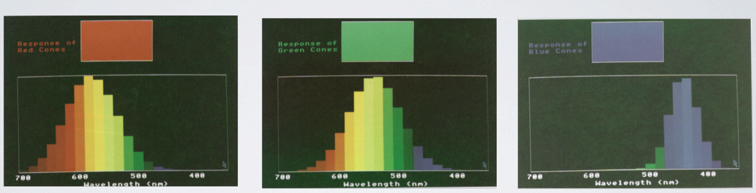
Note: Rod response peaks between S&M

Also called by color

- Red, green, blue
- Misleading:

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

Cones



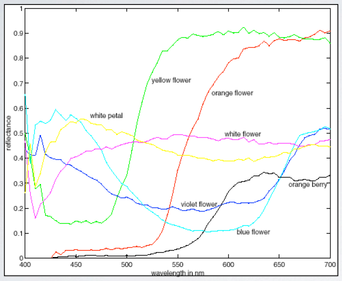
Images from David Forsyth

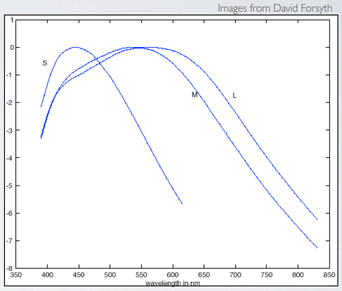
You can see that "red" and "green" cones respond to more than just red and green...

Cones

Response of a cone is given by a convolution integral :

Images from David Forsyth



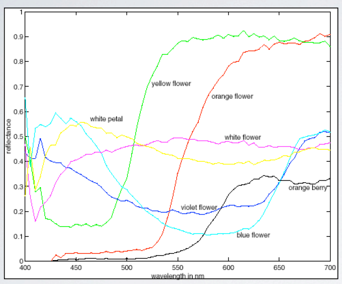


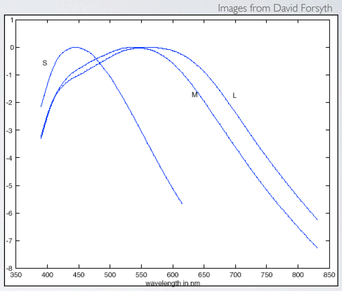
$$L = \int \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$
$$M = \int \Phi(\lambda) M(\lambda) \mathrm{d}\lambda$$
$$S = \int \Phi(\lambda) S(\lambda) \mathrm{d}\lambda$$

Cones

Response integral is a continuous version of a dot product

Images from David Forsyth





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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)

System that obeys **superposition** and **scaling** is called a **linear system**

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

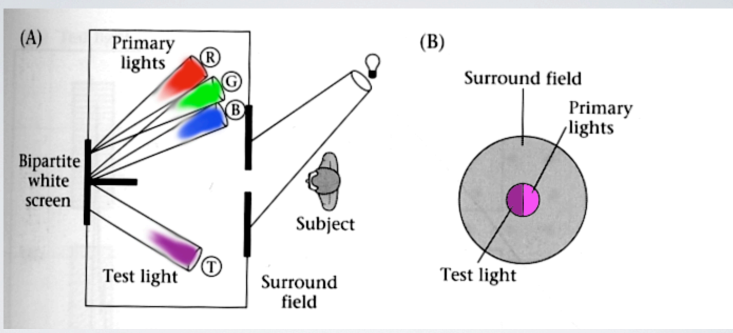
Match generic input light with $\Phi = \alpha p_1 + \beta p_2 + \gamma p_3$

Negative not realizable, but can add primary to test light

Color now described by α, β, γ

Example: computer monitor [RGB]

Additive Color Matching

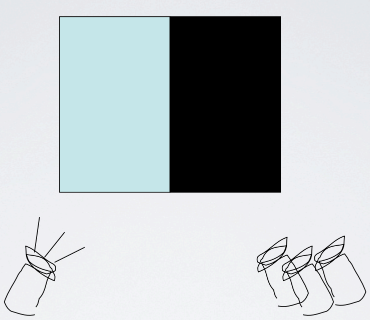


Show test light spectrum on left

Mix "primaries" on right until they match

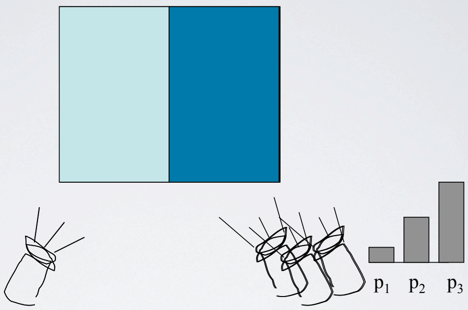
The primaries need not be RGB

Experiment 1



Slide from Durand and Freeman 06

Experiment 1



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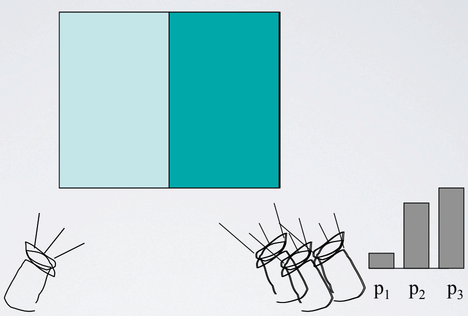

Slide from Durand and Freeman 06

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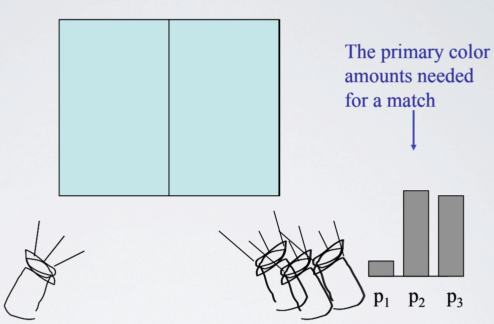
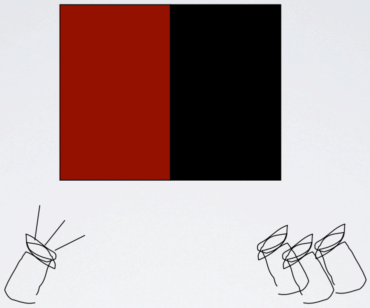


Slide from Durand and Freeman 06

Experiment 2



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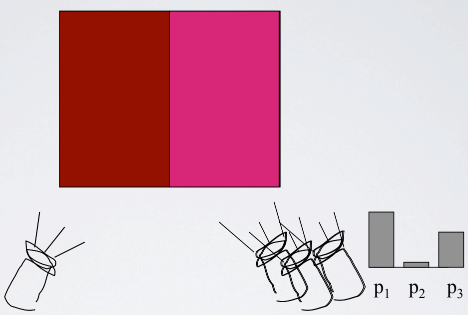

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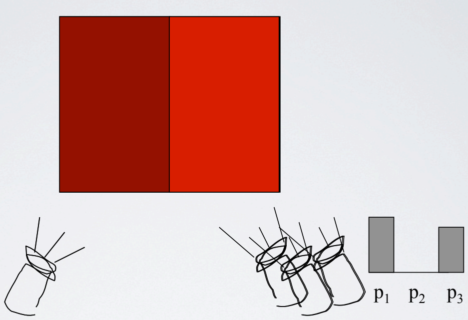
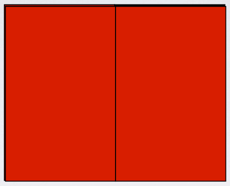


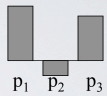
Slide from Durand and Freeman 06

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.

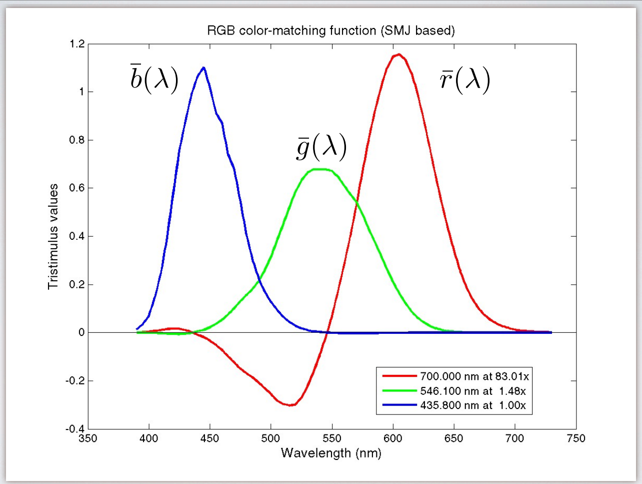


The primary color amounts needed for a match:



Slide from Durand and Freeman 06

Color Matching Functions

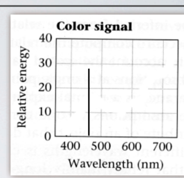


Input wavelengths are CIE 1931 monochromatic primaries

Using Color Matching Functions

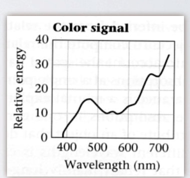
For a monochromatic light of wavelength λ_i we know the amount of each primary necessary to match it:

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



Given a new light input signal

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



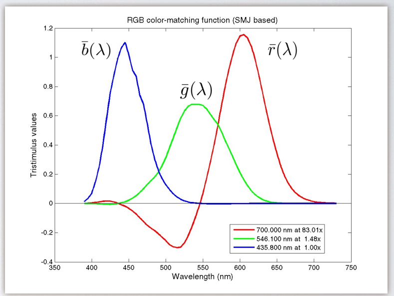
Compute the primaries necessary to match it

Using Color Matching Functions

Given color matching functions in matrix form and new light

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

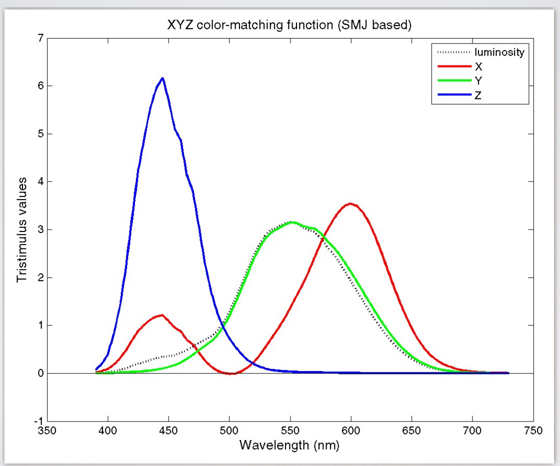
$$\Phi = \begin{pmatrix} \phi(\lambda_1) \\ \vdots \\ \phi(\lambda_N) \end{pmatrix}$$



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:

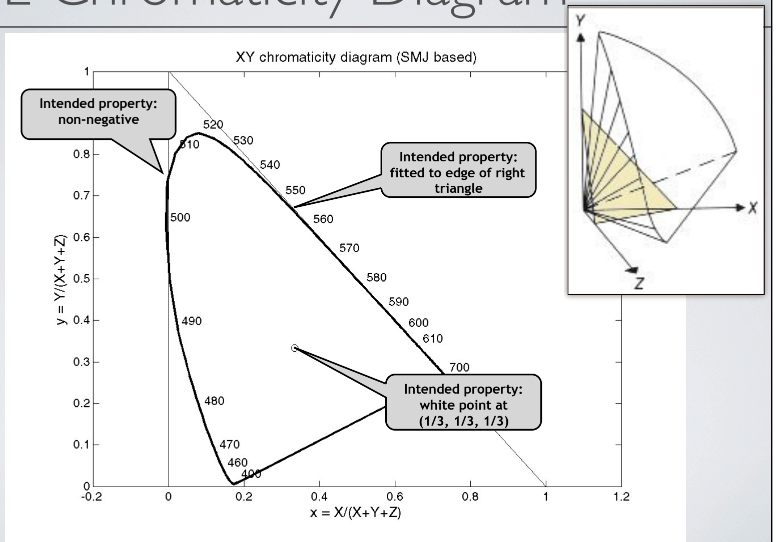
x = X / (X+Y+Z)
y = Y / (X+Y+Z)
z = Z / (X+Y+Z)

x+y+z = 1

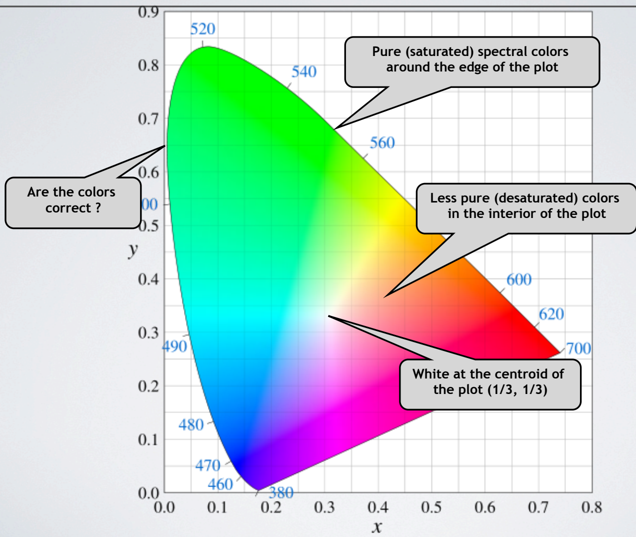
Because the sum of the chromaticity values x, y, and z is always 1.0, a plot of any two of them loses no information

Such a plot is a chromaticity diagram

CIE Chromaticity Diagram



CIE Chromaticity Diagram



Gamut

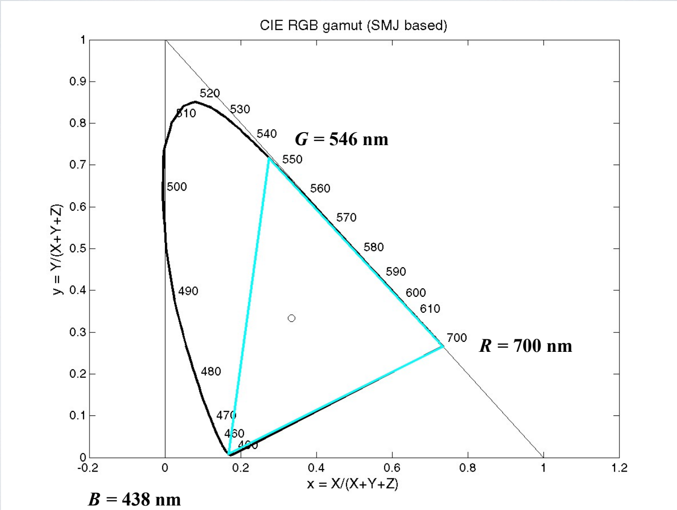
Gamut is the chromaticities generated by a set of primaries

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

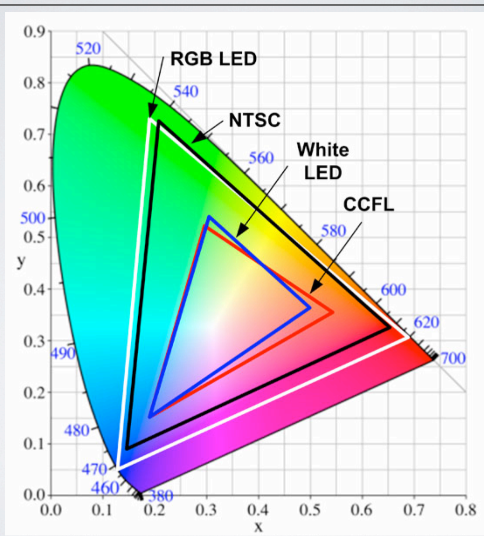
Thus the gamut is the convex hull of the primary chromaticities

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 $\Phi = W - (\alpha p_1 + \beta p_2 + \gamma p_3)$

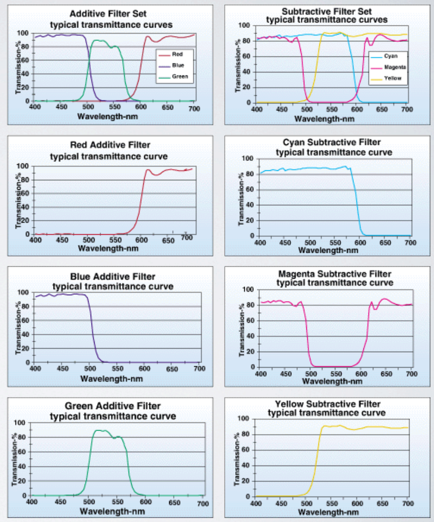
Max limited by W

Color now described by α, β, γ

Example: ink [CMYK]

Why 4th ink for black?

Additive & Subtractive Primaries



Additive & Subtractive Primaries

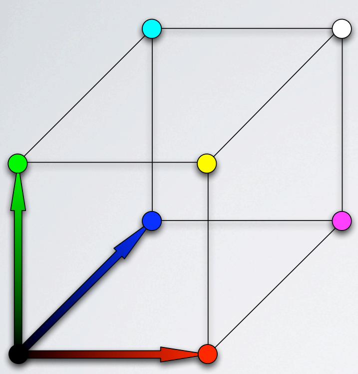
Incorrect to say "the additive primaries are red, green, and blue"

- 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

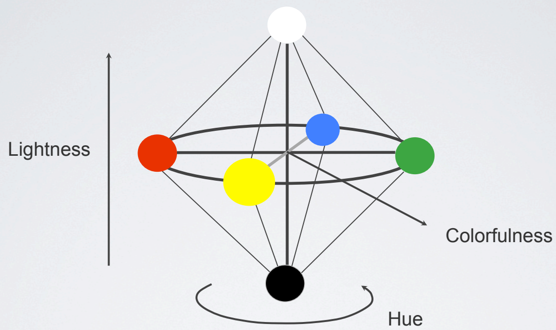


RGB color cube

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

Color Spaces

HSV color cone

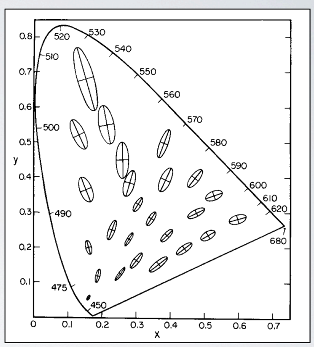


Color Spaces

RGB color cube

HSV color cone

CIE (x,y)



MacAdam Ellipses (10x)

Colors in ellipses indistinguishable from center.

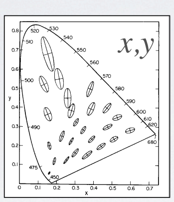
Color Spaces

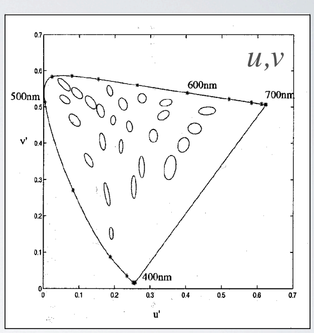
RGB color cube

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...

Color Phenomena

Light sources seldom shine directly in eye

Light follows some transport path, ***i.e.:***

- Source
- Air
- Object surface
- Air
- Eye

Color affected by interactions

Reflection

Light strikes object

Some frequencies reflect

Some adsorbed

Reflected spectrum is light times surface

Recall metamers...

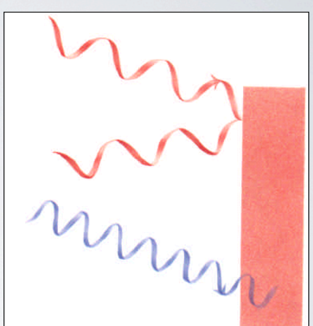


Fig. 1.18 Reflection: red light bounces off an opaque red object, while light of other colours is absorbed.

Unknown?

Transmission

Light strikes object

Some frequencies pass

Some absorbed (or reflected)

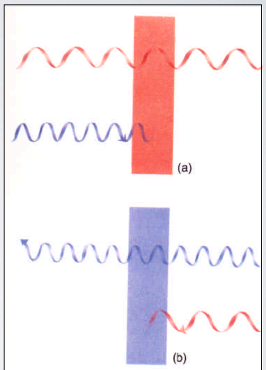


Fig. 1.17 Absorption: a red transparent medium absorbs all wavelengths of light except red (a); a blue transparent medium absorbs all wavelengths except blue (b)

Unknown?

Scattering

Interactions with small particles in medium

Long wavelengths ignore

Short ones scatter

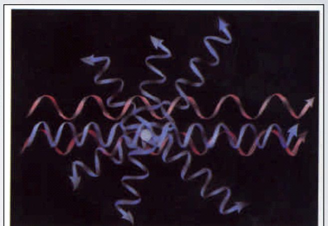


Fig. 1.25 Rayleigh scattering: when particles in air or water are small relative to light wavelength they scatter blue light preferentially.

Unknown?

Interference

Wave behavior of light

- Cancelation
- Reinforcement

Wavelength dependent

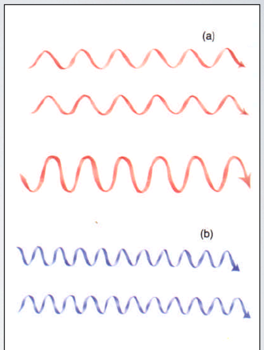


Fig. 1.20 Interference: when two light waves are in phase, they interfere positively to reinforce each other and produce a wave with double the intensity of colour (a). When two waves are out of phase they cancel each other and no colour is seen (b).

Unknown?

Iridescence

Interaction of light with

- Small structures
- Thin transparent surfaces

Light wave partially reflected and partially transmitted

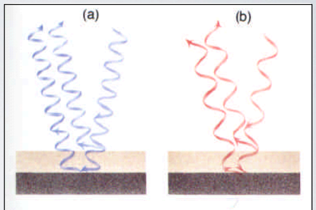
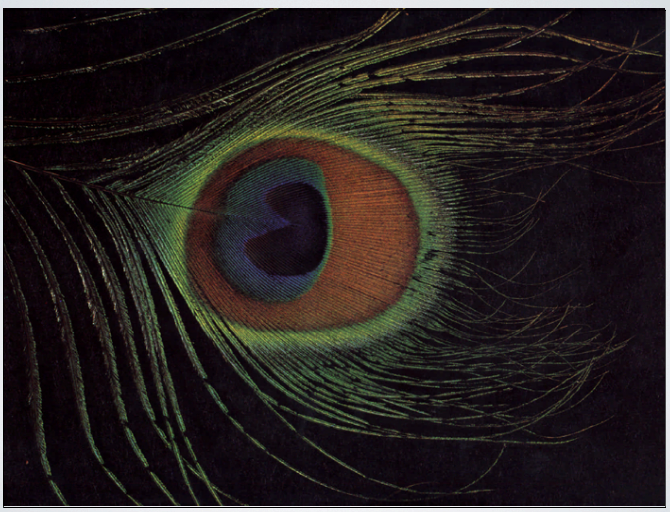


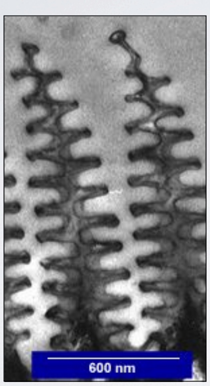
Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at 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

Summary

Spectrum entering eye and sensed by rods and cones

- Three types of cones
- Response is integral of incoming spectrum with cone response function
- Cones are linear
- Metamers and color matching
- Gamut - set of colors reproducible from small number (3) of primary spectra

Perception also influenced by nearby colors

Color spaces: RGB, HSV, CIE (x,y) ...

Color phenomena

- Physical interactions that generate and modify light spectra