1

CS-184: Computer Graphics

Lecture #2: Color

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University of California, Berkeley

Slides revised using additional materials from Maneesh Agrawala

2

Announcements

- Sign up for Piazza
- Assignment 0: due September 12th, 11:59pm
  - Class accounts given out in Section Tuesday
- Homework 1: due September 10th, 5:00pm
- Waitlist...

3

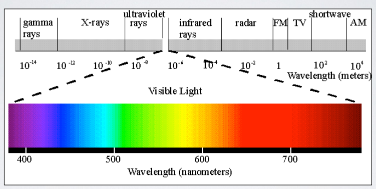
Today

- Color, Light, and Perceptions
  - The basics

4

What is Light?

- Radiation in a particular frequency range



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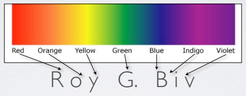
Spectral Colors

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



- Bright and distinct in appearance

Reproduction only, not a real spectral color!

6

Other Colors

- Most colors seen are a mix light of several frequencies

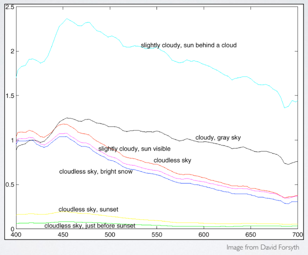


Image from David Forsyth

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

Other Colors

7

- Most colors seen are a mix light of several frequencies

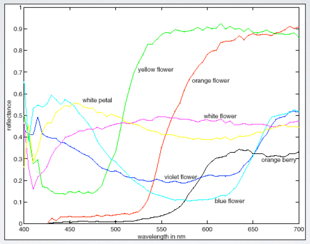


Image from David Forsyth

Other Colors

8

- Most colors seen are a mix light of several frequencies

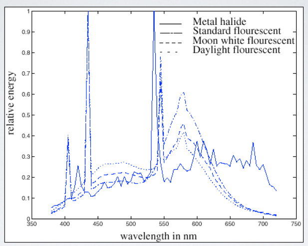


Image from David Forsyth

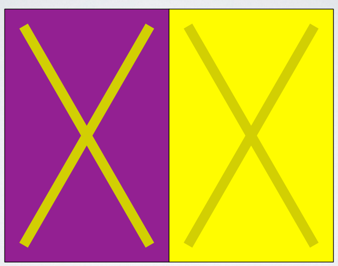
Perception -vs- Measurement

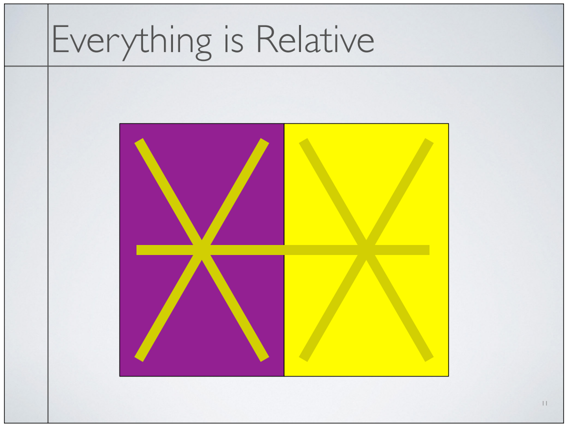
9

- 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

10





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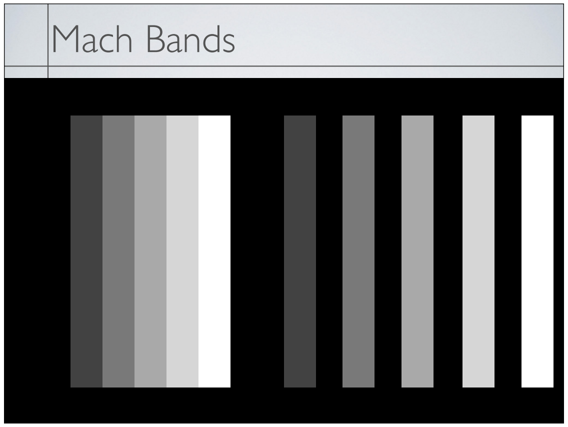
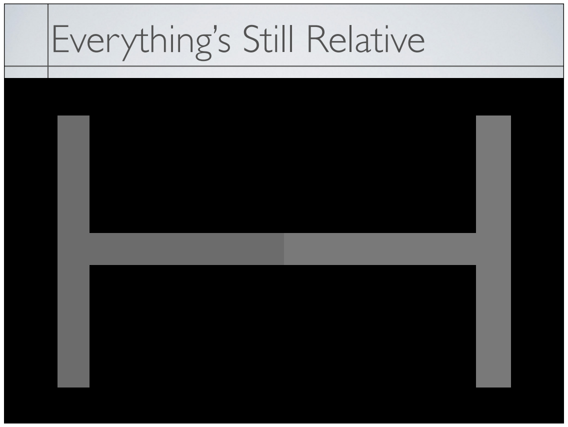
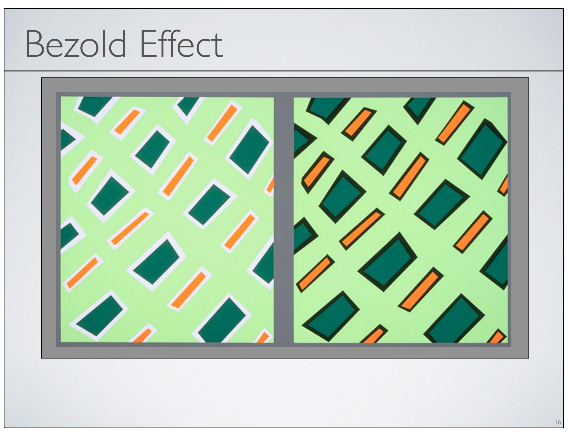
13



14



15

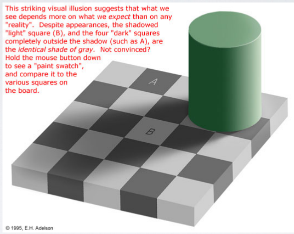


16

17

Perception

The eye does not see intensity values...



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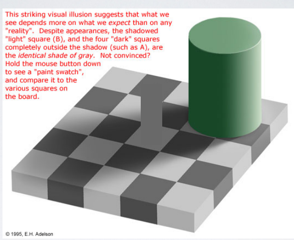
18

Perception

The eye does not see intensity values...



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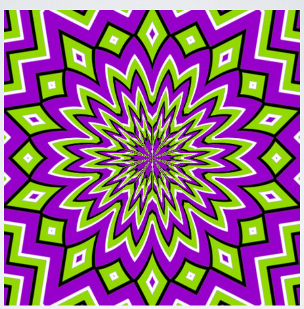
19

Perception

The eye does not see intensity values...

20

Perception



21

Eyes as Sensors

- The human eye contains cells that sense light
  - Rods
    - No color (sort of)
    - Spread over the retina
    - More sensitive

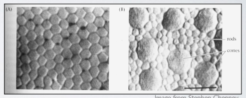


Image from Stephen Chenney

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

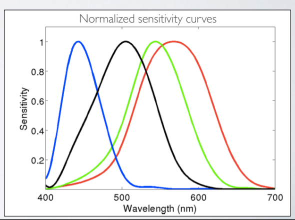
21

22

Cones

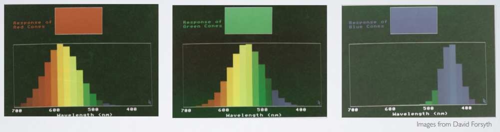
- Each type of cone responds to different range of frequencies/wavelengths
  - Long, medium, short
- Also called by color
  - Red, green, blue
  - Misleading:

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



Cones

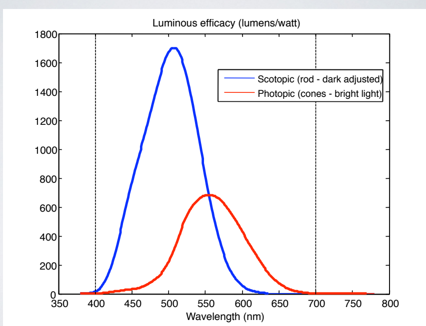
23



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

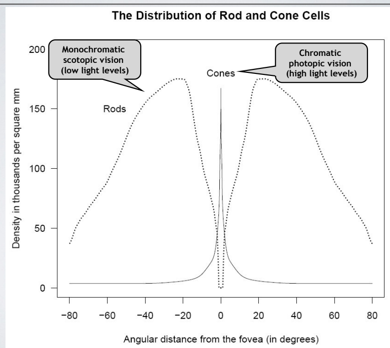
Rods vs Cones

24



Eyes as Sensors

25



Cones

26

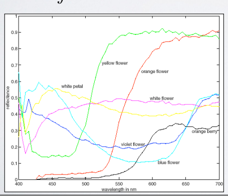
- Response of a cone is given by a convolution integral :

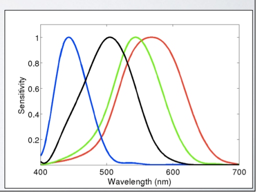
continuous version of a dot product

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

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

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





27

28

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

29

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)

30

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

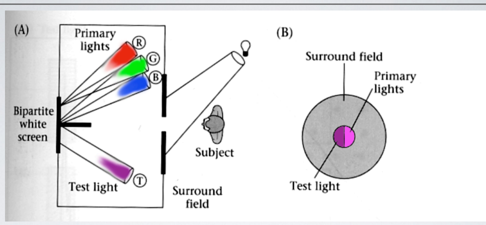
31

- 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

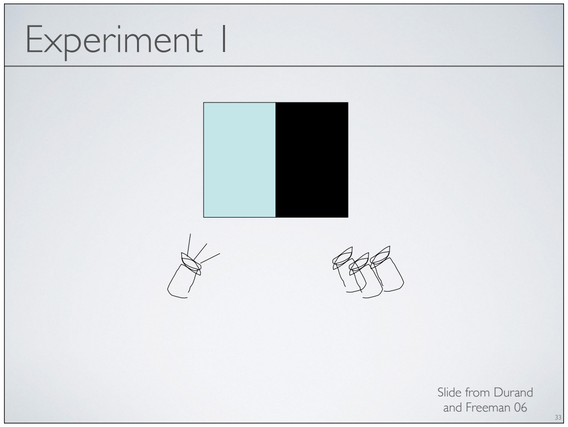
32



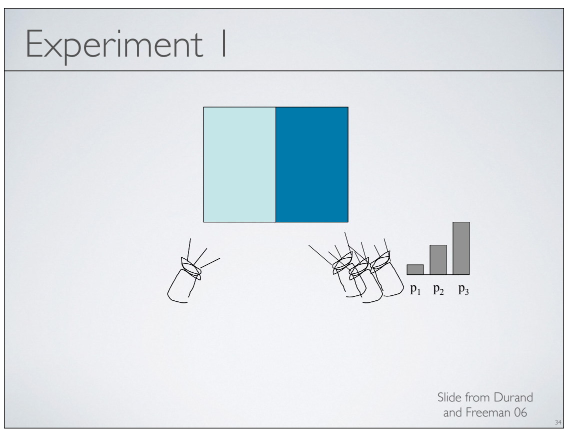
Show test light spectrum on left

Mix "primaries" on right until they match

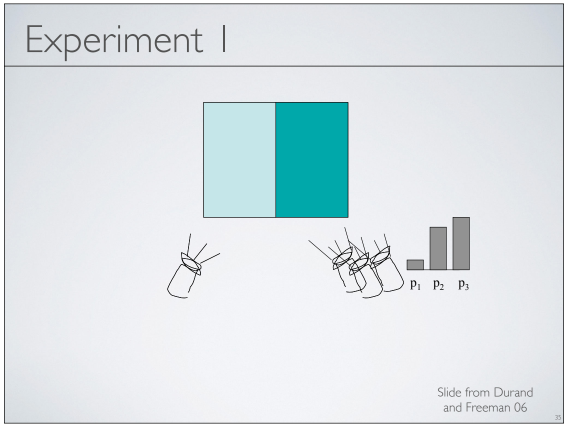
The primaries need not be RGB


Experiment 1
Slide from Durand and Freeman 06

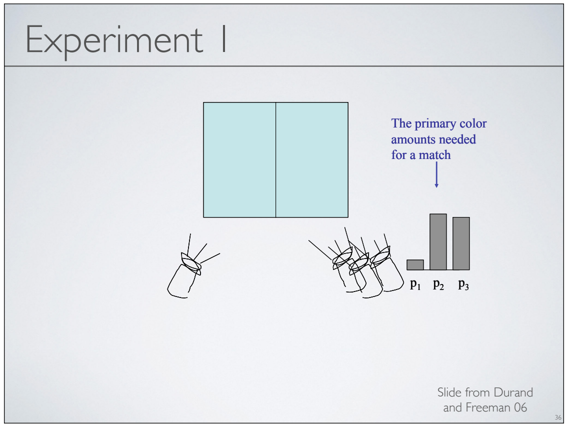
33


Experiment 1
p_1 p_2 p_3
Slide from Durand and Freeman 06

34

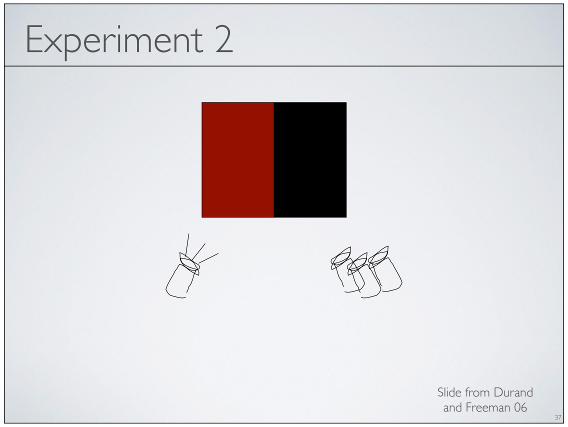

Experiment I
p1 p2 p3
Slide from Durand and Freeman 06

35

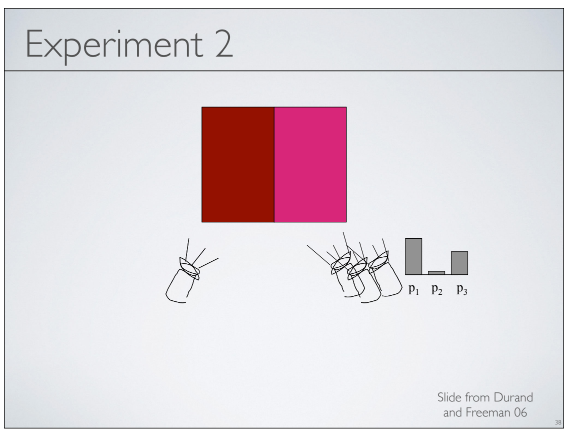

Experiment I
The primary color amounts needed for a match
p1 p2 p3
Slide from Durand and Freeman 06

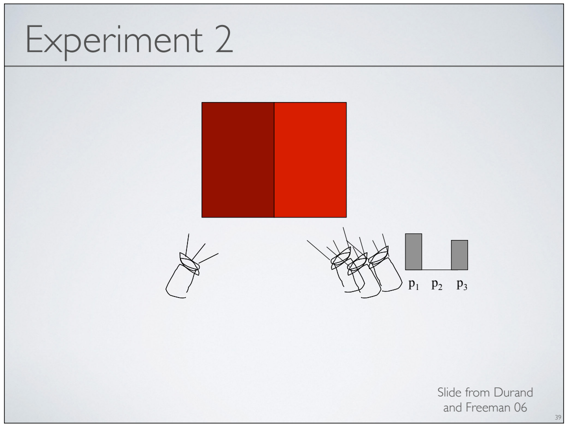
36

37

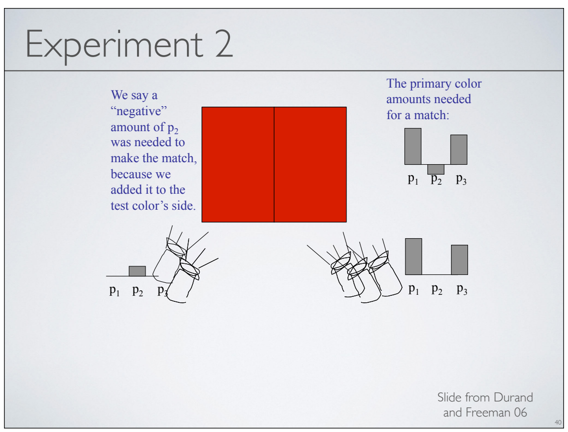

Experiment 2
Slide from Durand and Freeman 06

38


Experiment 2
p1 p2 p3
Slide from Durand and Freeman 06


Experiment 2
p1 p2 p3
Slide from Durand and Freeman 06

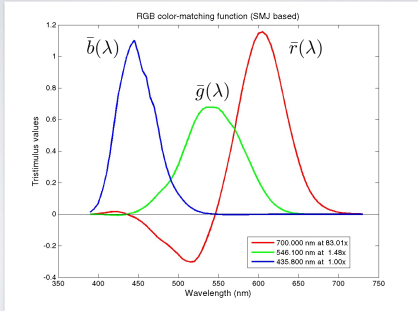
39


Experiment 2
We say a "negative" amount of p2 was needed to make the match, because we added it to the test color's side.
The primary color amounts needed for a match:
p1 p2 p3
p1 p2 p3
p1 p2 p3
Slide from Durand and Freeman 06

40

Color Matching Functions

41



Input wavelengths are CIE 1931 monochromatic primaries

Using Color Matching Functions

42

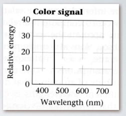
- For a monochromatic light of wavelength λ_i we know the amount of each primary necessary to match it:

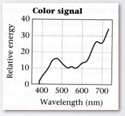
$$\bar{r}(\lambda_i), \bar{g}(\lambda_i), \bar{b}(\lambda_i)$$

- 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





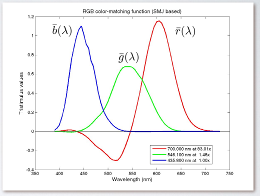
43

Using Color Matching Functions

- Given color matching functions in matrix form and new light

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

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

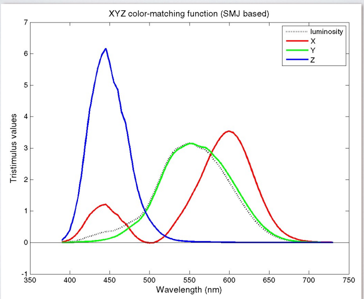


- amount of each primary necessary to match is given by $C\Phi$

44

CIE XYZ

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



45

Rescaled XYZ to xyz

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

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

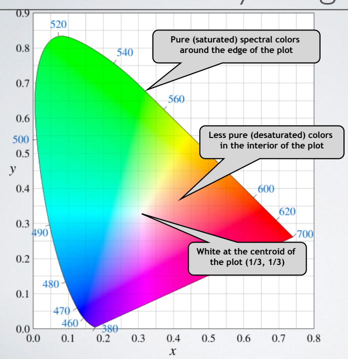
$x+y+z = 1$

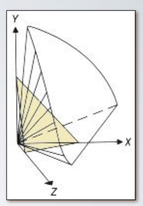
Because the sum of the chromaticity values x, y, and z is always 1.0, a plot of any two of them loses no information

Such a plot is a chromaticity diagram

46

CIE Chromaticity Diagram





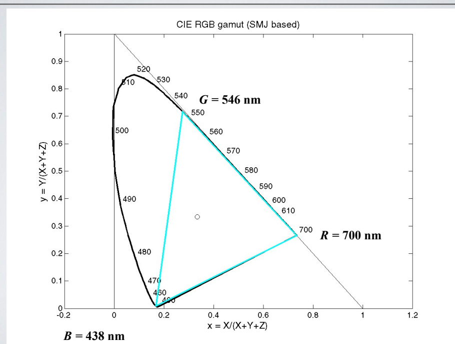
Gamut

47

- 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?

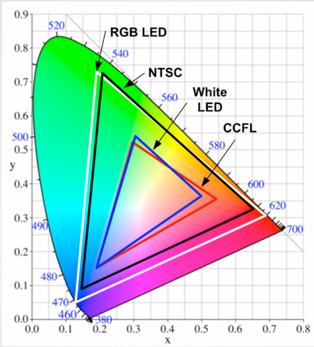
CIE 1931 RGB Gamut

48



49

Other Gamuts (LCDs and NTSC)



50

Subtractive Mixing

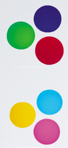
- Given three primaries we agree on p_1, p_2, p_3
- Make generic color with $\Phi = W - (\alpha p_1 + \beta p_2 + \gamma p_3)$
- Max limited by W
- Color now described by α, β, γ

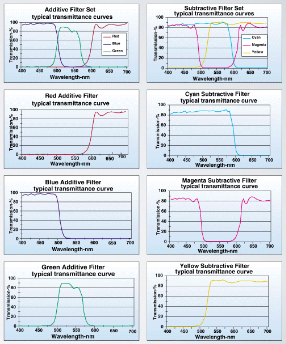
- Example: ink [CMYK]

Why 4th ink for black?

51

Additive & Subtractive Primaries





51

52

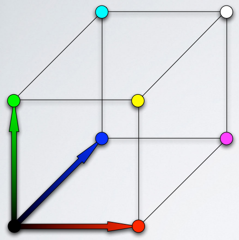
Additive & Subtractive Primaries

- Incorrect to say "the additive primaries are red, green, and blue"
  - Any set of three non-collinear primaries yields a gamut
  - Primaries that appear red, green, and blue are a good choice, but not the only choice
  - Are additional (non-collinear) 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

52

53

Color Spaces



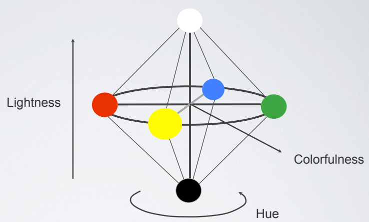
RGB color cube

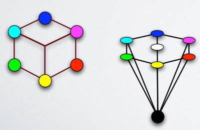
- Does not correspond very well to perception (e.g. distance between two points has little meaning)

54

Color Spaces

HSV color cone

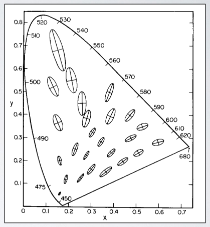




55

Color Spaces

- RGB color cube
- HSV color cone
- CIE (x,y)



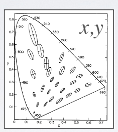
MacAdam Ellipses (10x)

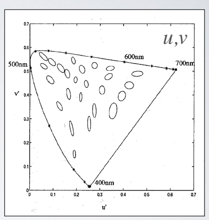
Colors in ellipses indistinguishable from center.

56

Color Spaces

- RGB color cube
- HSV color cone
- CIE (x,y)
- CIE (u,v)





Scaled to be closer to circles.

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

57

Color Spaces

RGB color cube

HSV color cone

CIE (x,y)

CIE (u,v)

CMYK

Many others...

57

58

Monitor Intensity and Gamma

- Monitors convert **pixel value into intensity level**
  - 0.0 maps to zero intensity = black (well not quite)
  - 1.0 maps to full intensity = white
- Monitors are not linear
  - 0.5 does not map to "halfway" gray, (e.g. 0.5 might map to 0.217)
  - Nonlinearity characterized by exponential function $I = a^\gamma$ where I = displayed intensity and a = pixel value (between 0 and 1)
  - For many monitors γ is near 2 (often between 1.8 and 2.2)

58

59

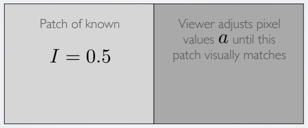
Determining Gamma $I = a^\gamma$

- Suppose I know displayed intensity of a patch $I = 0.5$

$$0.5 = a^\gamma$$

- Let viewer adjust pixel value a of nearby patch until match

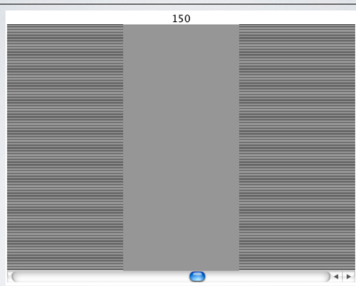
$$\gamma = \frac{\ln 0.5}{\ln a}$$



- How do we make a patch of known intensity?

60

Determining Gamma

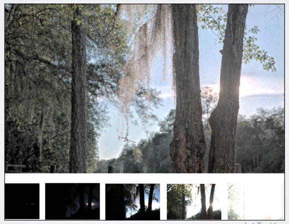


http://www.cs.cornell.edu/Courses/cs4620/2008fa/homeworks/gamma.htm

61

Dynamic Range

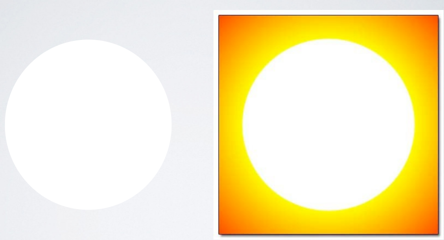
- Max/min values also limited on devices
  - "blackest black"
  - "brightest white"



Jack Tumblin

62

Fake High Dynamic Range



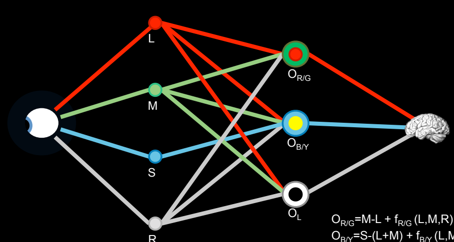
Tone Mapping

63

Kirk and O'Brien 2011

Rods Contribute to Color

64



Color Phenomena

65

- 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

66

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

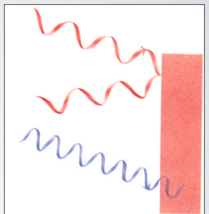


Fig. 1.18 Reflection: red light bounces off an opaque red object, while light of other colours is absorbed.

Unknown!

67

Transmission

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

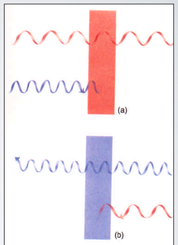


Fig. 1.17 Absorption: a red transparent medium absorbs all wavelengths of light except red (a); a blue transparent medium absorbs all wavelengths except blue (b)

Unknown!

67

68

Scattering

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

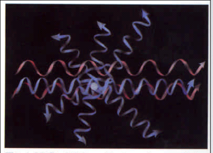


Fig. 1.25 Rayleigh scattering: when particles in air or water are small relative to light wavelength they scatter blue light preferentially.

Unknown!

68

69

Interference

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

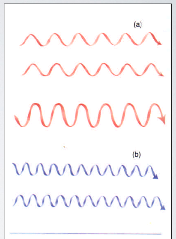


Fig. 1.20 Interference: when two light waves are in phase, they interfere positively to reinforce each other and produce a wave with double the intensity of colour (a). When two waves are out of phase they cancel each other and no colour is seen (b).

Unknown?

69

70

Iridescence

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

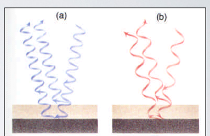


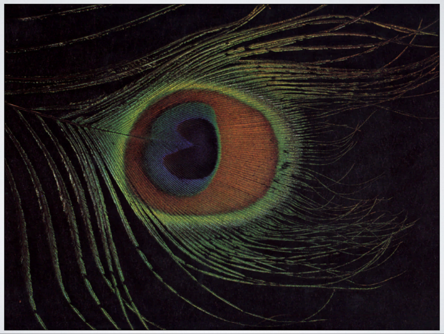
Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at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

70

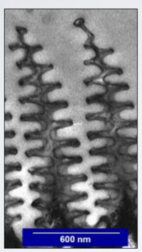
Iridescence

71



Iridescence

72



73

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

74

Fluorescence / Phosphorescence

75

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"

76

Black Body Radiation