ECE 5470 Lecture 19

Color and Radiometry

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Topics

- Human perception of the spectral distribution of light (color)
  - Humans sense three different functions of light frequency distribution
- Computer representations of color
  - Color coding schemes
- Radiometry:
  - The physics of image intensity formation in illuminated scenes

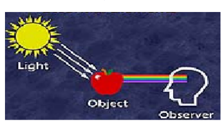
What is Color?

- Definition

  Color is a perceptual phenomenon, a product of our mental processing of electromagnetic radiation detected by our eyes. (Robinson, 1995)

- Photometry

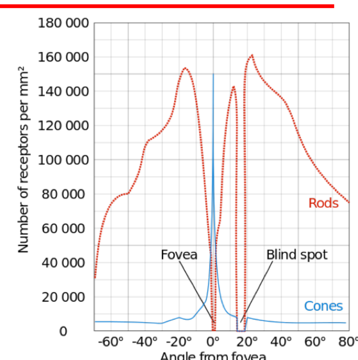
  Color Perception depends on
  - Light Source 
  - Object 
  - Observer 

  Complete Picture 

The Retina

Distribution of rods and cones along a line passing through the fovea and the blind spot of a human eye

Fovea 0.3 mm



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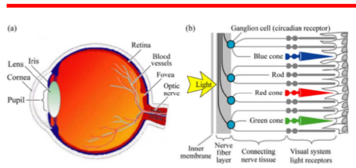
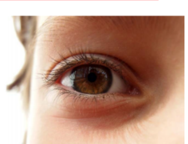
The Human Visual System (HVS)





The human eye contains two types of photosensors

Cones ⇒ Photopic vision (bright light)

Rods ⇒ Scotopic vision (dim light)

Color Sensors

- Color perception governing equation

Illumination

$$R_l(E) = \int h_l(\lambda) r(\lambda) f(\lambda) d\lambda$$

$$R_m(E) = \int h_m(\lambda) r(\lambda) f(\lambda) d\lambda$$

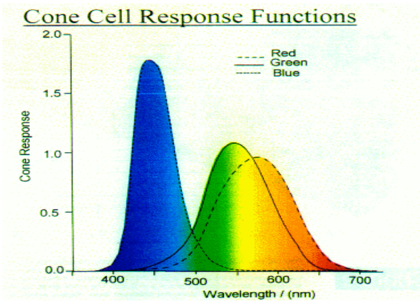
$$R_s(E) = \int h_s(\lambda) r(\lambda) f(\lambda) d\lambda$$

Three types of cone sensor:
long (l) red R
Medium (m) green G
Short (s) blue B

Sensor response

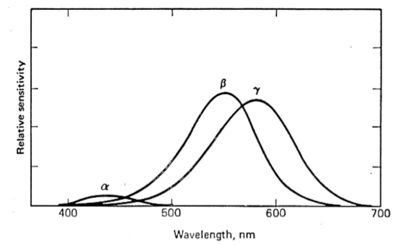
Reflecting surface

Cone Cell Frequency Response



Normalized sensitivity

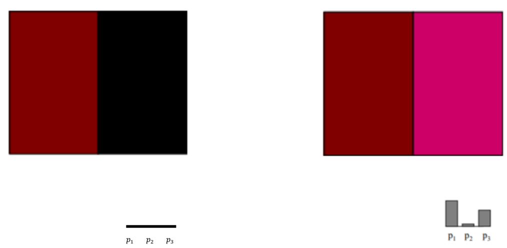
Cone Cell Relative Sensitivity



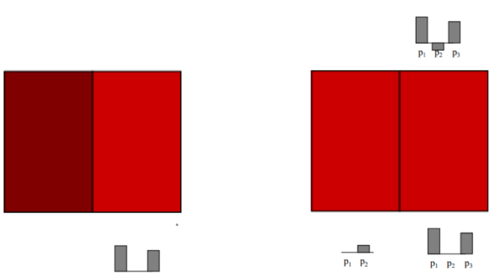
Color Matching

- Lights forming a perceptual match may be physically different
  - Match light: must be combination of primaries
  - Test light: any light
- **Metamers**: pairs of lights that match perceptually but not physically

Color Matching



Color Matching



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

Color Matching

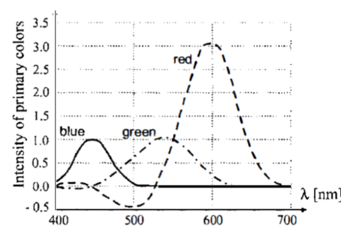
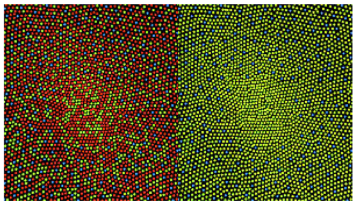


Fig : Color matching functions obtained in the color matching experiment. Intensities of the selected primary colors which perceptually match spectral color of given wavelength λ

The Retina

Illustration of the distribution of cone cells in the fovea of an individual with normal color vision (left), and a color blind (protanopic) retina. Note that the center of the fovea holds very few blue-sensitive cones.



Entire retina is approximately 72% of a sphere about 22 mm in diameter.
The entire retina contains about 7 million cones and 75 to 150 million rods.
Only 1 million optic nerve fibers
About 10% of axons in the optic nerve are devoted to the fovea.

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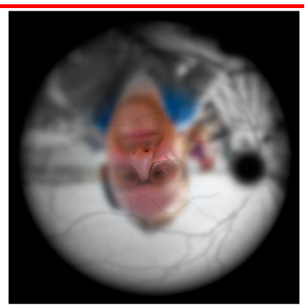
Photopic vision

- Fovea: a circular indentation in the retina of size 1.5mm (50,000 cones)
- Fewer s-cones (blue) 3 cpd
- M-cones and L-cones 60-100 cpd
- Possible cause: chromatic aberration of the lens blurs the short wavelength light

The Retina

Illustration of image as 'seen' by the retina independent of optic nerve and striate cortex processing.

The blood vessels in a normal human retina The optic disc is at left, and the macula lutea is near the center.



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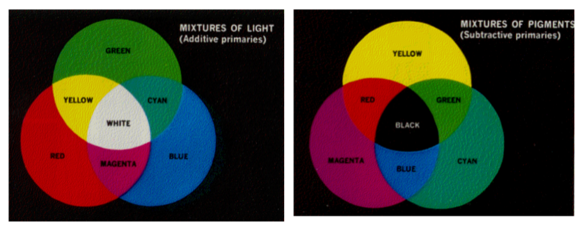
Primary and Secondary Colors



$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color Coding Schemes

A. Linear transforms: Intensity + 2D color space

Hardware implementations

CIE XYZ system

YIQ system → NTSC color television

RGB system → Color monitors and video cameras

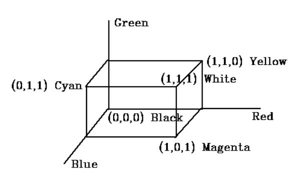
CMY system → Color Printers

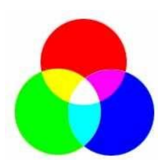
B.

HSI system → Of interest to painters

RGB space

- represented by cube model





YIQ Color Model

Used for Commercial Color TV broadcasting

Y → Illumination

I and Q → Color Information

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Other Linear Coding Schemes

CMY (used for printers)

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CMYK (used for printers)

Opponent Process (Modeled after the HVS?)

$$\begin{bmatrix} R-G \\ Bl-Y \\ W-Bk \end{bmatrix} = \begin{bmatrix} 1 & -2 & 1 \\ -1 & -1 & 2 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

HSI model

Basis of the HSI model → hue, saturation, Intensity

hue $\Rightarrow$ Dominant wavelength in a spectrum

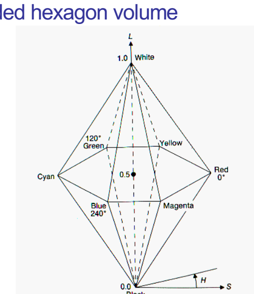
Saturation $\Rightarrow$ Purity of the color

Intensity $\Rightarrow$ Amount of light reflected

Illumination is decoupled from color information

HSI model

represented by double-sided hexagon volume



Transformation between RGB-HSI color models

$$I = \frac{1}{3}(R+G+B)$$

$$H = \cos^{-1}\left(\frac{2R-G-B}{2\sqrt{(R-G)^2+(R-B)(G-B)}}\right)$$

$$S = 1 - \frac{3}{R+G+B}\min(R,G,B)$$

What is H for grey?

RGB components

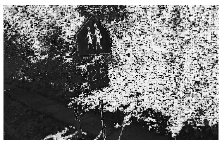
Green

Red

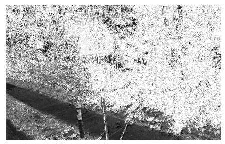
Blue

HSI components

Intensity



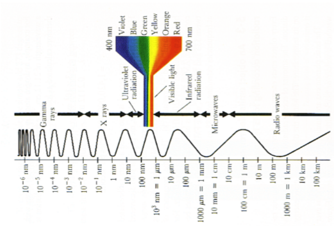
Hue



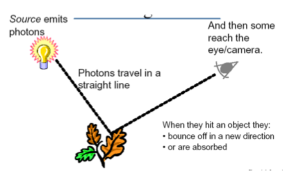
Saturation

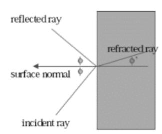
Radiometry

- Radiometry is the science of the measurement of electromagnetic radiation.
- Photometry deals only with the visible portion of the spectrum.



Radiometry





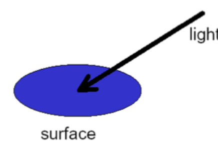
When a light ray hits a point on an object :
– Some of the light gets absorbed
  • converted to other forms of energy
  examples: heat, light of a lower energy (fluorescence)
– Some gets transmitted through the object
  • possibly bent, through "refraction"
– Some gets reflected

- Adapted from Michael Black, Brown University

Irradiance (E)

Irradiance: is the power per unit area of radiant energy falling on the image plane.

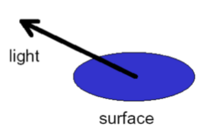
$$E = \frac{\delta P}{\delta A}$$



Radiance (L)

- Radiance is the power/unit area into a cone of directions having unit solid angle

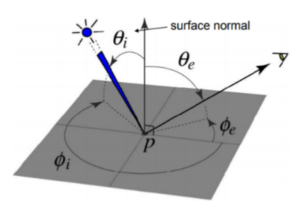
$$L = \frac{\delta^2 P}{\delta A \, \delta\omega}$$



- In general, radiance depends on the viewing angle

The BRDF

- The Bi-directional reflectance distribution function(BRDF) gives the ratio of the amount of energy radiated from the surface patch in some direction to the amount of energy arriving at the surface from some other direction.



$$L(\theta_e, \phi_e) = f(\theta_i, \phi_i, \theta_e, \phi_e) E(\theta_i, \phi_i)$$

Simple Reflectance Models

- A Lambertian surface is an ideal matte surface that reflects light uniformly in all directions.
- A Specular surface is a mirror like reflector of light.
- For most practical situations a surface may be modeled as either a Lambertian or a specular surface or a combination of the two.

Lambertian Surface

- (a) Lambertian Surface (ideal matte surface)
  - Radiance is independent of direction

$$f(\theta_i, \phi_i, \theta_e, \phi_e) = \text{constant}$$

  - For a distant light source I_0 (θ_s, ϕ_s)

$$L(\theta_e, \phi_e) = \text{constant} \cos\theta_s$$

  - The radiance is proportional to the cosine of the incident light

Specular Surface

- For a point light source I

$$L(\theta_e, \phi_e) = I(\theta_e, \phi_e - \pi)$$

Specular

Lambertian

Pictures @ Wikipedia

Summary Color

- The HVS has three different spectral (color) sensors
- Tristimulus values can be used to represent "color" as experienced by the HVS
- Several tristimulus coding schemes exist
- For machine vision RGB is most common input form, HSI is of interest but has issues.
- Some image sensors have more than three "color" detectors. (difficult for human visualization)

Summary Color applications

- Most computer vision systems do not rely on color.
- Color is useful for "natural" scenes (academic research):
  - Backgrounds: blue sky, green vegetation etc.
  - Color *may* be useful in image segmentation
- Many "color" spectral channels may be useful to characterize ground vegetation
- Color is used in microscopy through employment of stains that identify different biological materials
- Color may be used in constrained industrial applications (part of the scene may be "painted" in unique colors)