Today

• Measuring color
  – Spectral power distributions
  – Color mixing
  – Color matching experiments
  – Color spaces
    • Uniform color spaces

• Perception of color
  – Human photoreceptors
  – Environmental effects, adaptation

• Using color in machine vision systems

What is color?

• The result of interaction between physical light in the environment and our visual system.

• A psychological property of our visual experiences when we look at objects and lights, not a physical property of those objects or lights.

Color and light

• Color of light arriving at camera depends on
  – Spectral reflectance of the surface light is leaving
  – Spectral radiance of light falling on that patch

• Color perceived depends on
  – Physics of light
  – Visual system receptors
  – Brain processing, environment

Color and light

White light: composed of about equal energy in all wavelengths of the visible spectrum

Newton 1665

Electromagnetic spectrum

Human Luminance Sensitivity Function
Measuring spectra

**Spectroradiometer**: separate input light into its different wavelengths, and measure the energy at each.

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The Physics of Light

Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 – 700 nm.

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Spectral power distributions

Some examples of the spectra of light sources

A. Ruby Laser
B. Gallium Phosphide Crystal
C. Tungsten Lightbulb
D. Normal Daylight

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Surface reflectance spectra

Some examples of the reflectance spectra of surfaces

Red
Yellow
Blue
Purple

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Color mixing

Cartoon spectra for color names:

- Red
- Green
- Blue
- Yellow
- Cyan

Additive color mixing

Colors combine by *adding* color spectra

Light adds to black.
Examples of additive color systems

Superposition

Additive color mixing:
The spectral power
distribution of the
mixture is the sum of the
spectral power
distributions of the
components.

Examples of subtractive color systems

Subtractive color mixing

Colors combine by multiplying color spectra.

Pigments remove color from incident light (white).

Examples of subtractive color systems

• Printing on paper
• Crayons
• Photographic film

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How to know if people perceive the same color?

• Important to reproduce color reliably
  – Commercial products, digital imaging/art
• Only a few color names recognized widely
  – English ~11: black, blue, brown, grey, green, orange, pink, purple, red, white, and yellow
• We need to specify numerically.
• Question: What spectral radiances produce the same response from people under simple viewing conditions?
Color matching experiments

- **Goal:** find out what spectral radiances produce same response in human observers.

- **Assumption:** simple viewing conditions, where we say test light alone affects perception
  - Ignoring additional factors for now like adaptation, complex surrounding scenes, etc.

Color matching experiment 1

The primary color amounts needed for a match.

\[
\begin{array}{ccc}
p_1 & p_2 & p_3 \\
\end{array}
\]

Color matching 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.

\[
\begin{array}{ccc}
p_1 & p_2 & p_3 \\
\end{array}
\]

Color matching experiment 2

The primary color amounts needed for a match:

\[
\begin{array}{ccc}
p_1 & p_2 & p_3 \\
\end{array}
\]

Color matching experiment 2

\[
\begin{array}{ccc}
p_1 & p_2 & p_3 \\
\end{array}
\]

Color matching

- What must we require of the primary lights chosen?
- How are three numbers enough to represent entire spectrum?
Metamers

- If observer says a mixture is a match → receptor excitations of both stimuli must be equal.
- But lights forming a perceptual match still 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

Grassman’s laws

- If two test lights can be matched with the same set of weights, then they match each other:
  - Suppose \( A = u_1 P_1 + u_2 P_2 + u_3 P_3 \) and \( B = u_1 P_1 + u_2 P_2 + u_3 P_3 \).
  Then \( A = B \).
- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose \( A = u_1 P_1 + u_2 P_2 + u_3 P_3 \).
  Then \( kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3 \).
- If we mix two test lights, then mixing the matches will match the result (superposition):
  - Suppose \( A = u_1 P_1 + u_2 P_2 + u_3 P_3 \) and \( B = v_1 P_1 + v_2 P_2 + v_3 P_3 \).
  Then \( A + B = (u_1+v_1) P_1 + (u_2+v_2) P_2 + (u_3+v_3) P_3 \).

\( \text{Here } "=\text{ matches}" \).
Computing color matches

Arbitrary new spectral signal is linear combination of the monochromatic sources.

\[
\mathbf{t} = \begin{pmatrix}
  t(\lambda_1) \\
  \vdots \\
  t(\lambda_n)
\end{pmatrix}
\]

Color matching functions specify how to match a unit of each wavelength, so:

\[
\begin{pmatrix}
  e_1 \\
  e_2 \\
  \vdots \\
  e_n
\end{pmatrix} = \begin{pmatrix}
  c_1(\lambda_1) & \cdots & c_1(\lambda_n) \\
  \vdots & \ddots & \vdots \\
  c_n(\lambda_1) & \cdots & c_n(\lambda_n)
\end{pmatrix}
\begin{pmatrix}
  n(\lambda_1) \\
  \vdots \\
  n(\lambda_n)
\end{pmatrix}
\]

\[ e = \mathbf{C} \mathbf{t} \]

Kristen Grauman

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Standard color spaces

- Use a common set of primaries/color matching functions

- Linear color space examples
  - RGB
  - CIE XYZ

- Non-linear color space
  - HSV

RGB color space

- Single wavelength primaries
- Good for devices (e.g., phosphors for monitor), but not for perception

CIE XYZ color space

- Established by the commission international d’eclairage (CIE), 1931
- Y value approximates brightness
- Usually projected to display:

\[
(x,y) = \left( \frac{X}{X+Y+Z}, \frac{Y}{X+Y+Z} \right)
\]

- CIE XYZ Color matching functions

Kristen Grauman

Adapted from W. Freeman

Image credit: pbs.org
HSV color space

- Hue, Saturation, Value
- Nonlinear – reflects topology of colors by coding hue as an angle
- Matlab: hsv2rgb, rgb2hsv.

Distances in color space

- Not necessarily: CIE XYZ is **not** a uniform color space, so magnitude of differences in coordinates are poor indicator of color "distance".

McAdam ellipses: Just noticeable differences in color

Uniform color spaces

- Attempt to correct this limitation by remapping color space so that just-noticeable differences are contained by circles \( \rightarrow \) distances more perceptually meaningful.

Examples:
- CIE \( u'v' \)
- CIE Lab

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The Eye

- Iris: colored annulus with radial muscles
- Pupil: the hole (aperture) whose size is controlled by the iris
- Lens: changes shape by using ciliary muscles (to focus on objects at different distances)
- Retina: photoreceptor cells

Types of cones

- React only to some wavelengths, with different sensitivity (light fraction absorbed)
- Brain fuses responses from local neighborhood of several cones for perceived color
- Sensitivities vary per person, and with age
- Color blindness: deficiency in at least one type of cone

Trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching; “trichromatic” nature of the human visual system
  - Most people make the same matches for a given set of primaries (i.e., select the same mixtures)

Environnmental effects & adaptation

- Chromatic adaptation:
  - We adapt to a particular illuminant
- Assimilation, contrast effects, chromatic induction:
  - Nearby colors affect what is perceived; receptor excitations interact across image and time
- Afterimages

  Color matching \(\neq\) color appearance
  Physics of light \(\neq\) perception of light

Cones
- cone-shaped
- less sensitive
- operate in high light color vision

Rods
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision
Chromatic adaptation

• If the visual system is exposed to a certain illuminant for a while, color system starts to adapt / skew.


Brightness perception

Edward Adelson

http://web.mit.edu/persci/people/adelson/illusions_demos.html

Edward Adelson

http://web.mit.edu/persci/people/adelson/illusions_demos.html

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http://web.mit.edu/persci/people/adelson/illusions_demos.html

Look at blue squares  Look at yellow squares

• Content © 2008 R.Bea Lotto
• http://www.lottolab.org/articles/illusionsoflight.asp
Contrast effects
After images
• Tired photoreceptors send out negative response after a strong stimulus

http://www.sandlotscience.com/Aftereffects/Andrus_Spiral.htm
http://www.michaelbach.de/ot/mot_adaptSpiral/index.html
Source: Steve Seitz

Name that color
Blue Red Green Cyan
Magenta Black Pink
Yellow Orange Violet
Brown Purple Cyan
Indigo Red Green Blue
High level interactions affect perception and processing.

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Color as a low-level cue for CBIR

Color-based image retrieval
• Given collection (database) of images:
  – Extract and store one color histogram per image
• Given new query image:
  – Extract its color histogram
  – For each database image:
    • Compute intersection between query histogram and database histogram
  – Sort intersection values (highest score = most similar)
  – Rank database items relative to query based on this sorted order

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Color-based image retrieval

Example database

Example retrievals

Color-based skin detection


Color-based segmentation for robot soccer


http://www.cs.utexas.edu/users/AustinVilla/?p=research/auto_vsi