Lecture 4:

Light & Color

Prof. Rob Fergus

Slides: S. Lazebnik, S. Seitz, W. Freeman, F. Durand, D. Forsyth, D. Lowe, B. Wandell, S. Palmer, K. Grauman
Image formation
From light rays to pixel values

\[ X = E \cdot \Delta t \]

- Camera response function: the mapping \( f \) from irradiance to pixel values
  - Useful if we want to estimate material properties
  - Enables us to create high dynamic range images

Source: S. Seitz, P. Debevec
Image formation
The interaction of light and surfaces

- What happens when a light ray hits a point on an object?
  - Some of the light gets **absorbed**
    - converted to other forms of energy (e.g., heat)
  - Some gets **transmitted** through the object
    - possibly bent, through “refraction”
    - Or scattered inside the object (subsurface scattering)
  - Some gets **reflected**
    - possibly in multiple directions at once
  - Really complicated things can happen
    - fluorescence

- Let’s consider the case of reflection in detail
  - Light coming from a single direction could be reflected in all directions. How can we describe the amount of light reflected in each direction?
Bidirectional reflectance distribution function (BRDF)

- Model of local reflection that tells how bright a surface appears when viewed from one direction when light falls on it from another

- Definition: ratio of the *radiance* \( L \) in the emitted direction to *irradiance* \( E \) in the incident direction

\[
\rho(\theta_i, \phi_i, \theta_e, \phi_e) = \frac{L_e(\theta_e, \phi_e)}{E_i(\theta_i, \phi_i)} = \frac{L_e(\theta_e, \phi_e)}{L_i(\theta_i, \phi_i) \cos \theta_i \, d\omega}
\]
BRDFs can be incredibly complicated...
Diffuse reflection

- Light is reflected equally in all directions
  - Dull, matte surfaces like chalk or latex paint
  - Microfacets scatter incoming light randomly

- **BRDF is constant**
  - *Albedo*: fraction of incident irradiance reflected by the surface
**Diffuse reflection: Lambert’s law**

- Viewed brightness does not depend on viewing direction, but it *does* depend on direction of illumination

\[
B(x) = \rho(x)(N(x) \cdot S(x))
\]

- **B**: radiosity
- **\(\rho\)**: albedo
- **\(N\)**: unit normal
- **\(S\)**: source vector (magnitude proportional to intensity of the source)
Specular reflection

- Radiation arriving along a source direction leaves along the specular direction (source direction reflected about normal)
- Some fraction is absorbed, some reflected
- On real surfaces, energy usually goes into a lobe of directions
- Phong model: reflected energy falls off with $\cos^n(\delta \theta)$
- Lambertian + specular model: sum of diffuse and specular term
Specular reflection

Moving the light source

Changing the exponent
Color
What is color?

• Color is a psychological property of our visual experiences when we look at objects and lights, not a physical property of those objects or lights (S. Palmer, Vision Science: Photons to Phenomenology)

• Color is the result of interaction between physical light in the environment and our visual system
Overview of Color

- Physics of color
- Human encoding of color
- Color spaces
- White balancing
Electromagnetic Spectrum

Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm
Why do we see light of these wavelengths?

...because that’s where the Sun radiates EM energy

Visible Light

Plank’s law for Blackbody radiation
Surface of the sun: ~5800K
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.
The Physics of Light

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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The Physics of Light

Some examples of the reflectance spectra of surfaces

- **Red**
  - Wavelength (nm): 400 to 700
- **Yellow**
  - Wavelength (nm): 400 to 700
- **Blue**
  - Wavelength (nm): 400 to 700
- **Purple**
  - Wavelength (nm): 400 to 700

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Interaction of light and surfaces

• Reflected color is the result of interaction of light source spectrum with surface reflectance

• Spectral radiometry
  – All definitions and units are now “per unit wavelength”
  – All terms are now “spectral”

From Foundation of Vision by Brian Wandell, Sinauer Associates, 1995
Interaction of light and surfaces

• What is the observed color of any surface under monochromatic light?

Olafur Eliasson, *Room for one color*
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The human eye is a camera!

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What’s the “film”?
  - photoreceptor cells (rods and cones) in the **retina**
The Retina

Cross-section of eye

Cross section of retina

Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
Pigmented epithelium

Retina up-close
Two types of light-sensitive receptors

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

**Rods**
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision
The famous sock-matching problem...
Three kinds of cones:

- Why are M and L cones so close?
- Are there 3?
Color perception

Rods and cones act as filters on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

- Q: How can we represent an entire spectrum with 3 numbers?
- A: We can’t! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable
    » such spectra are known as metamers
Spectra of some real-world surfaces

metamers

yellow flower
white petal
orange flower
white flower
violet flower
orange berry
blue flower

reflectance

wavelength in nm
Standardizing color experience

• We would like to understand which spectra produce the same color sensation in people under similar viewing conditions

• Color matching experiments

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995
Color matching experiment 1
Color matching experiment 1

Source: W. Freeman
Color matching experiment 1

Source: W. Freeman
Color matching experiment 1

The primary color amounts needed for a match

Source: W. Freeman
Color matching experiment 2

Source: W. Freeman
Color matching experiment 2

Source: W. Freeman
Color matching experiment 2

Source: W. Freeman
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:

Source: W. Freeman
Trichromacy

• In color matching experiments, most people can match any given light with three primaries
  – Primaries must be independent
• For the same light and same primaries, most people select the same weights
  – Exception: color blindness
• Trichromatic color theory
  – Three numbers seem to be sufficient for encoding color
  – Dates back to 18th century (Thomas Young)
Lightness constancy

http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html
Lightness constancy

- Possible explanations
  - Simultaneous contrast
  - Reflectance edges vs. illumination edges

http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html
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Linear color spaces

• Defined by a choice of three *primaries*
• The coordinates of a color are given by the weights of the primaries used to match it

mixing two lights produces colors that lie along a straight line in color space

mixing three lights produces colors that lie within the triangle they define in color space
How to compute the weights of the primaries to match any spectral signal

- **Matching functions**: the amount of each primary needed to match a monochromatic light source at each wavelength

Source: W. Freeman
RGB space

• Primaries are monochromatic lights (for monitors, they correspond to the three types of phosphors)
• *Subtractive matching* required for some wavelengths

RGB matching functions

- $p_1 = 645.2 \text{ nm}$
- $p_2 = 525.3 \text{ nm}$
- $p_3 = 444.4 \text{ nm}$
How to compute the weights of the primaries to match any spectral signal

- Let $c(\lambda)$ be one of the matching functions, and let $t(\lambda)$ be the spectrum of the signal. Then the weight of the corresponding primary needed to match $t$ is

$$w = \int c(\lambda)t(\lambda) d\lambda$$
Linear color spaces: CIE XYZ

- Primaries are imaginary, but matching functions are everywhere positive
- The Y parameter corresponds to brightness or *luminance* of a color
- 2D visualization: draw \((x, y)\), where
  \[ x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z} \]

Matching functions

http://en.wikipedia.org/wiki/CIE_1931_color_space
Nonlinear color spaces: HSV

- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)
- RGB cube on its vertex
Useful reference

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White balance

• When looking at a picture on screen or print, we adapt to the illuminant of the room, not to that of the scene in the picture
• When the white balance is not correct, the picture will have an unnatural color “cast”

http://www.cambridgeincolour.com/tutorials/white-balance.htm
White balance

• Film cameras:
  • Different types of film or different filters for different illumination conditions

• Digital cameras:
  • Automatic white balance
  • White balance settings corresponding to several common illuminants
  • Custom white balance using a reference object

http://www.cambridgeincolour.com/tutorials/white-balance.htm
White balance

- Von Kries adaptation
  - Multiply each channel by a gain factor
  - A more general transformation would correspond to an arbitrary 3x3 matrix
White balance

• Von Kries adaptation
  • Multiply each channel by a gain factor
  • A more general transformation would correspond to an arbitrary 3x3 matrix

• Best way: gray card
  • Take a picture of a neutral object (white or gray)
  • Deduce the weight of each channel
    – If the object is recoded as \( r_w, g_w, b_w \)
      use weights \( 1/r_w, 1/g_w, 1/b_w \)
White balance

- Without gray cards: we need to “guess” which pixels correspond to white objects

- Gray world assumption
  - The image average $r_{\text{ave}}, g_{\text{ave}}, b_{\text{ave}}$ is gray
  - Use weights $1/r_{\text{ave}}, 1/g_{\text{ave}}, 1/b_{\text{ave}}$

- Brightest pixel assumption (non-staurated)
  - Highlights usually have the color of the light source
  - Use weights inversely proportional to the values of the brightest pixels

- Gamut mapping
  - Gamut: convex hull of all pixel colors in an image
  - Find the transformation that matches the gamut of the image to the gamut of a “typical” image under white light

- Use image statistics, learning techniques
Uses of color in computer vision

Color histograms for indexing and retrieval

Uses of color in computer vision

Skin detection

M. Jones and J. Rehg, Statistical Color Models with Application to Skin Detection, IJCV 2002.

Source: S. Lazebnik
Uses of color in computer vision

Nude people detection

Uses of color in computer vision

Image segmentation and retrieval


Source: S. Lazebnik
Uses of color in computer vision

Robot soccer

M. Sridharan and P. Stone,
_Towards Eliminating Manual Color Calibration at RoboCup_. RoboCup-2005: Robot Soccer World Cup IX, Springer Verlag, 2006
Uses of color in computer vision

Building appearance models for tracking

D. Ramanan, D. Forsyth, and A. Zisserman.
Tracking People by Learning their Appearance. PAMI 2007.

Source: S. Lazebnik