Lecture 3:

Colors: Human Vision & Computer Vision

COMP 590/776: Computer Vision
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Etymology

PHOTOGRAPHY

light

drawing / writing
Simple models of a camera assume an image is a “quantitative measurement” of scene radiance.
This assumption is made often in computer vision

- Shape from shading
- HDR imaging
- Image matching
- Color constancy
- Applications relying on color
- Image delubrriing
- Etc ...

From Lu et al, CVPR'10

From Jon Mooser, CGIT Lab, USC

From O'Reilly's digital media forum
Camera = light-measuring device?
Camera pipeline photo-finishing routines

“Secret recipe” of a camera

Photographs taken from three different cameras with the same aperture, shutter speed, white-balance, ISO, and picture style.
Modern photography pipeline

Starting point: reality (in radiance)

Pre-Camera
Lens Filter
Lens
Shutter
Aperture

In-Camera
CMOS response (raw-RGB)
raw-RGB processing +
“Photo-finishing Processing”

Scene Radiance

This Week

End of Pipeline

Post-Processing
Touch-up Hist
equalization Spatial
warping
Etc ...

Ending point: better than reality (in sRGB)

Camera Output: sRGB

Even if we stopped here, the original CMOS response potentially has had many levels of processing.

Next Week
Digital cameras

- Digital cameras are *not designed to be* light-measuring devices
- They are designed to produce visually pleasing photographs
- There is a great deal of processing (photo-finishing) applied in the camera hardware
Today’s class

• Eye & Human Vision
• Pinhole Camera
• Perception of Color
• Quantifying Color
• Commonly Used Color Spaces
• Color Constancy
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The Eye

• 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
Saccadic eye movement
Saccadic eye movement

Micro-saccadic movements

Large-saccadic movements
Biology of color sensations

- Our eye has three receptors (cone cells) that respond to visible light and give the sensation of color.
Retina up-close
Cones and rods

- We have additional light sensitive cells called *rods* that are not responsible for color.
- Rods are used in low-light vision.
- Cone cells are most concentrated around the fovea of the eye.

Fovea = region of retina where visual activity is the highest, responsible for central vision.
Night Sky: why are there more stars off-center?
Rod / Cone sensitivity

Intensity of light reflected from objects (lamberts)

10
1
10^{-2}
10^{-5}
10^{-9}

Dazzling light; bright sun on snow
Outdoors in full sunlight
Outdoors under a tree on a sunny day
Comfortable indoor illumination; night sports events
Threshold for perception of color; bright moonlight
Threshold when dark-adapted

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Projection

Steve Seitz
Image formation

Let’s design a camera

• Idea 1: put a piece of film in front of an object
• Do we get a reasonable image?
• No. This is a bad camera.
Pinhole camera

Add a barrier to block off most of the rays
- This reduces blurring
- The opening known as the aperture
- How does this transform the image?
Camera Obscura

• Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
• Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Source: A. Efros
Camera Obscura
Home-made pinhole camera

Why so blurry?

http://www.debevec.org/Pinhole/
Pinhole photography


6-month exposure
https://petapixel.com/2019/07/17/this-is-the-worlds-first-solargraphy-timelapse/
Shrinking the aperture

- Why not make the aperture as small as possible?
  - Less light gets through
  - *Diffraction* effects...
Shrinking the aperture
Adding a lens

A lens focuses light onto the film

- There is a specific distance at which objects are “in focus”
  - other points project to a “circle of confusion” in the image
- Changing the shape of the lens changes this distance
Eye vs Camera

<table>
<thead>
<tr>
<th></th>
<th>Human Eye</th>
<th>Camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does light enter?</td>
<td>Pupil</td>
<td>Aperture</td>
</tr>
<tr>
<td>What controls the amount of light?</td>
<td>Iris</td>
<td>Diaphragm</td>
</tr>
<tr>
<td>What interprets the image?</td>
<td>Retina</td>
<td>Film</td>
</tr>
<tr>
<td>How is the light focused?</td>
<td>Lens</td>
<td>Lens</td>
</tr>
</tbody>
</table>

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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
Color

Def Color (noun): The property possessed by an object of producing different sensations on the eye as a result of the way it reflects or emits light.

Oxford Dictionary
Color is perceptual

• **Color is not** a primary *physical* property on an object
• Red, Green, Blue, Pink, Orange, Atomic Tangerine, Baby Pink, etc., are just words we assign to human color sensations

Which is the "true blue"?

Where do “color sensations” come from?

A very small range of electromagnetic radiation

Generally wavelengths from 380 to 720nm are visible to most individuals.
Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.
White light through a prism

Light is separated into “monochromatic” light at different wave lengths.
Light-material interaction

$$\ell(\lambda) = r(\lambda)e(\lambda)$$

spectral radiance

$$r(\lambda)$$

spectral reflectance

$$e(\lambda)$$

illuminant spectrum
Light-material interaction

\[ \ell(\lambda) = r(\lambda)e(\lambda) \]

- spectral radiance

- illuminant spectrum

- spectral reflectance
Illuminant Spectral Power Distribution (SPD)

- Most types of light “contain” more than one wavelengths.
- We can describe light based on the distribution of power over different wavelengths.

We call our sensation of all of these distributions “white”.
Light-material interaction

\[ \ell(\lambda) = r(\lambda)e(\lambda) \]

spectral radiance

\[ e(\lambda) \]

illuminant spectrum

\[ r(\lambda) \]

spectral reflectance
Spectral reflectance

- Most materials absorb and reflect light differently at different wavelengths.
- We can describe this as a ratio of reflected vs incident light over different wavelengths.
Light-material interaction

\[ \ell(\lambda) = r(\lambda)e(\lambda) \]

spectral radiance

\[ r(\lambda) \]

spectral reflectance

\[ e(\lambda) \]

illuminant spectrum
Three kinds of cones:

- S (short-wavelength-sensitive)
- M (middle-wavelength-sensitive)
- L (long-wavelength-sensitive)

Wavelengths: 440 nm, 530 nm, 560 nm

Relative Absorbance (%)

Wavelength (nm.)

Cone mosaic
Human color vision

**retinal color**

\[ \mathbf{c}(\ell(\lambda)) = (c_s, c_m, c_l) \]

\[ c_s = \int k_s(\lambda)\ell(\lambda)d\lambda \]

**perceived color**

**object color**

**color names**

**spectral radiance**
Retinal vs perceived color

This is known as Color Constancy: more later in this lecture
Perceived vs measured brightness by human eye

Human-eye response (measured brightness) is linear.

However, human-eye perception (perceived brightness) is non-linear:
• More sensitive to dark tones.
• Approximately a Gamma function.
Not everyone is trichromat

• Types of color blindness:
  • Deuteranopia: missing M cones
  • Protanopia: missing L cones
  • Tritanopia: missing S cones

• “M” and “L” on the X-chromosome
  • Why men are more likely to be color blind
  • “L” has high variation, so some women are tetrachromatic

• Some animals have
  • 1 (night animals)
  • 2 (e.g., dogs)
  • 4 (fish, birds)
  • 5 (pigeons, some reptiles/amphibians)
  • 12 (mantis shrimp)

http://en.wikipedia.org/wiki/Color_vision
Trichromacy

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

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

Cone primaries = L, M, S
Image primaries = R, G, B
Tristimulus color theory

Grassman’s Law states that a source color can be matched by a linear combination of three independent “primaries”. 

\[
\begin{align*}
\text{Source light #1} & \quad = \quad R_1^* + G_1^* + B_1^* \\
\text{Source light #2} & \quad = \quad R_2^* + G_2^* + B_2^*
\end{align*}
\]

Three lights (shown as lightbulbs) serve as primaries. Each light has intensity, or weights, \(R_1, G_1, B_1\) to match the source light #1 perceived color.

Same three primaries and the weights \((R_2, G_2, B_2)\) of each primary needed to match the source light #2 perceived color.

If we combined source lights 1 & 2 to get a new source light 3

\[
\begin{align*}
\text{Source light #3} & \quad = \quad (R_1 + R_2)^* + (G_1 + G_2)^* + (B_1 + B_2)^*
\end{align*}
\]

The amount of each primary needed to match the new source light #3 is the sum of the weights that matched lights sources #1 & #2.

This may seem obvious now, but discovering that light obeys the laws of linear algebra was a huge and useful discovery.
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Radiometry vs. photometry

- **Radiometry**
  - Quantitative measurements of radiant energy
  - Often shown as spectral power distributions (SPD)
  - Measures either light coming from a source (radiance) or light falling on a surface (irradiance)

- **Photometry/ colorimetry**
  - Quantitative measurement of **perceived** radiant energy based on human’s sensitivity to light
  - Perceived in terms of “brightness” (photometry) and color (colorimetry)
Quantifying color

• We still need a way to quantify color & brightness
• SPDs go through a “black box” (human visual system) and are perceived as color
• The only way to quantify the “black box” is to perform a human study
CIE RGB color matching

Human subjects matched test colors by add or subtracting three primaries.

Field of view was 2-degrees (where color cones are most concentrated)

"Standard Observer" (Willing participant with no eye disease)

Experiments carried out by W. David Wright (Imperial College) and John Guild (National Physical Laboratory, London) – Late 1920s
For some test colors, no mix of the primaries could give a match! For these cases, the subjects were asked to add primaries to the test color to make the match.

This was treated as a negative value of the primary added to the test color.

“Standard Observer”
(Willing participant with no eye disease)
Plots are of the mixing coefficients of each primary needed to produce the corresponding monochromatic light at that wavelength.

Note that these functions have been scaled such that area of each curve is equal.
Negative values – the three primaries used did not span the full range of perceptual colors.
CIE 1931 XYZ

• In 1931, the CIE met and approved defining a new canonical basis, termed XYZ that would be derived from Wright-Guild’s CIE RGB data

• Properties desired in this conversion:
  • White point defined at X=1/3,Y=1/3,Z=1/3
  • Y would be the luminosity function (V(\(\lambda\)))
  • Quite a bit of freedom in selecting these XYZ basis
  • In the end, the adopted transform was:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
0.4887180 & 0.3106803 & 0.2006017 \\
0.1762044 & 0.8129847 & 0.0108109 \\
0.0000000 & 0.0102048 & 0.9897952
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

CIE 1931 RGB

Nice article see: Fairman et al “How the CIE 1931 Color-Matching Functions Were Derived from Wright–Guild Data”, Color Research & Application, 1997
CIE xy (chromaticity)

Hue changes as one moves around the spectral locus

Saturation increases as one moves out radially from white

Green
Yellow
Orange
White
Red
Blue
Indigo
Violet

\[ x = \frac{X}{X + Y + Z} \]
\[ y = \frac{Y}{X + Y + Z} \]

\((X, Y, Z) \leftrightarrow (x, y, Y)\)

chromaticity

luminance/brightness

Perspective projection of 3D retinal color space to two dimensions.
This gives us the familiar horseshoe shape of visible colors as a 2D plot. Note the axis are x & y.

Point “E” represents where X = Y = Z have equal energy (X = 0.33, Y = 0.33, Z = 0.33)

CIE XYZ “white point”

In the 1930s, CIE had a bad habit of over using the variables X, Y. Note that x, y are chromaticity coordinates, x, y (with the bar above) are the matching functions, and X, Y are the imaginary SPDs of CIE XYZ.
Fast forward 80+ years

- CIE 1931 XYZ, CIE 1931 xyY (2-degree standard observer) color spaces have stood the test of time

- Many other studies have followed (most notably - CIE 1965 XYZ 10- degree standard observer), ...

- But in the literature (and in this tutorial) you’ll find CIE 1931 XYZ color space remains the preferred standard
What is perhaps most amazing?

• 80+ years of CIE XYZ and it is all based on the experiments by the “standard observers”

• How many standard observers were used? 100, 500, 1000?

A Standard Observer
CIE XYZ is based on 17 standard observers

10 by Wright, 7 by Guild

“The Standard Observers”
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CIE XYZ and RGB

• While CIE XYZ is a canonical color space, images/devices rarely work directly with XYZ
• XYZ are not real primaries
• RGB primaries dominate the industry
• We are all familiar with the RGB color cube

But by now, you should realize that Red, Green, Blue have no quantitative meaning. We need to know their corresponding SPDs or CIE XYZ values.
Color spaces: RGB

Default color space

RGB cube
- Easy for devices
- But not perceptual

Color gamuts

The RGB values span a subspace of CIE-XYZ to define the devices gamut.
Color gamuts

Gamuts of various common industrial RGB spaces

If you have RGB values, they are specific to a particular device.
The problem with RGBs visualized in chromaticity space

RGB values have no meaning if the primaries between devices are not the same!
HSV: Perceptual Color Space

Hue
Name of the color
(yellow, red, blue, green, ...)

Value/Lightness/Brightness
How light or dark a color is.

Saturation/Chroma/Color Purity
How “strong” or “pure” a color is.
• Perceptual dimensions of color:
  • **Hue**: the “kind” of color, regardless of its attributes
  • **Saturation**: Purity, “colorfulness”
  • **Value** (or lightness): total amount of light

• Use rgb2hsv() and hsv2rgb() in Matlab, in Python w/skimage

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Slide from Steve Seitz / Ren Ng
Color spaces: HSV
Intuitive color space

- **H**
  - \((S=1,V=1)\)

- **S**
  - \((H=1,V=1)\)

- **V**
  - \((H=1,S=0)\)
Color spaces: L*a*b*

“Perceptually uniform”* color space

L = Luma (Lightness)
a = Red to Green
b = Blue to yellow

\[ L = L \]
\[ a = a \]
\[ b = b \]
CIE LAB space

- CIE LAB space (also written as CIE \(L^{*}a^{*}b^{*}\)) was introduced as a perceptually uniform color space.

- Why?
  - CIE XYZ provides a means to map between a physical SPD (radiometric measurement) to a colorimetric measurement (perceptual).
  - However, a uniform change in CIE XYZ space does result in an uniform change in perceived color difference (see diagram).

- CIE Lab transforms CIE to a new space where color (and brightness) differences are more uniform.

The ellipses shows the range of colors (around the center of the ellipse) that would be perceived as the same. We can see that CIE XYZ this is not uniform.

David MacAdam performed experiments into color perception. This plot is known as the MacAdam ellipses.
Chromaticity comparison's between CIE LAB and CIE XYY

Image from Bagdasar et al ICSTCC'17
I want to train Deep Learning algorithms, why should I care beyond RGB color spaces?

- If you are training ML systems to do object recognition, detection, etc, you shouldn’t care.

- But if you are solving different Image Processing & Computational Photography tasks, you should!

- CIE Lab color space is commonly used for tasks like:
  - Image Colorization
  - Intrinsic Image Decomposition
  - Reflectance Estimation

- Many papers often use other color spaces instead of RGB. It can help in easier learning.
Color error metric – CIE 2000 Delta E (ΔE)

• The CIE defined a color error metric in 2000 based on the CIE LAB space. This returns a color error between 0-100.

• You will see this referred to as CIEDE2000, CIEDE, ΔE, Delta E, DE, ...

• Delta E 2000 interpretation:

<table>
<thead>
<tr>
<th>Delta E</th>
<th>Perception</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;= 1.0</td>
<td>Not perceptible by human eyes.</td>
</tr>
<tr>
<td>1 - 2</td>
<td>Perceptible through close observation.</td>
</tr>
<tr>
<td>2 - 10</td>
<td>Perceptible at a glance.</td>
</tr>
<tr>
<td>11 - 49</td>
<td>Colors are more similar than opposite</td>
</tr>
<tr>
<td>100</td>
<td>Colors are exact opposite</td>
</tr>
</tbody>
</table>

In general, DE of 2 or less is considered to be very good. It means a standard observer could not tell that two colors are different unless they observed them very closely.

Table from https://zschuessler.github.io/DeltaE/learn/
Color error metric – CIE 2000 Delta E (ΔE)

• How do you use this in practice?
  • As a metric or loss function to measure color/chromaticity of the reconstructed image w.r.t. GT image.

“Measure Albedo in the Wild: Filling the Gap in Albedo Evaluation”, ongoing work in my group which uses this metric to evaluate a Deep Learning algorithm’s ability to estimate ‘true’ color of an object.
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An object’s SPD

- In a real scene, an object’s SPD is a combination of its reflectance properties and scene illumination.

Our earlier example ignored illumination (we could assume it was pure white light).

Instead, think of this of how the object reflects different wavelengths.

Tomato SPD

Wavelength (\(\lambda\))

Illuminant 1 SPD

Illuminant 2 SPD

Illuminant 3 SPD

\(\lambda\)
Color constancy

• Our visual system is able to compensate for the illumination

Looks the same!
Chromatic adaptation example
Chromatic adaptation example
What color is the “The Dress”?

https://en.wikipedia.org/wiki/The_dress
Two Scene Interpretations of #thedress

Warm illumination

![Blue & black dress](image1)

Cool illumination

![White & gold dress](image2)

Same image

![Same dress](image3)

Blue & black material

White & gold material

Brainard and Hurlbert, 2015
Color constancy/chromatic adaptation

• Color constancy (also called chromatic adaptation) is the ability of the human visual system to adapt to scene illumination
• This ability is not perfect, but it works fairly well
• Image sensors do not have this ability (it must be performed as a processing step, i.e. “white balance”)

Note: Our eyes do not adjust to the illumination in the photograph -- we adjust to the viewing conditions of the scene we are viewing the photograph!
Color temperature

- Illuminants are often described by their "color temperature"
- This mapping is based on theoretical “blackbody radiators” that produce SPDs for a given temperature -- expressed in Kelvin (K)
- We map light sources (both real and synthetic) to their closest color temperature (esp in Photography/Video production)

\[ B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \]

Plank's law
Spectral density of electromagnetic radiation emitted by a blackbody radiator at a given temperature T.
Color temperature

Kelvin Color Temperature Scale

10,000K

10,000K+: Blue Sky

9,000K

7,000K-7,500K: Cool White Seesmart LED

7,000K

6,000K: Cloudy Sky
6,000K-6,000K: Day White Seesmart LED

6,000K

5,000K

4,800K: Direct Sunlight
4,800K-4,5000K: Natural White Seesmart LED
4,000K: Clear Metal Halide

4,000K

3,000K

3,000K: 100W Halogen
2,800K: 100W Incandescent
2,700K-3,200K: Warm White Seesmart LED

2,000K

2,000K: High Pressure

1,900K: Candle

Typical description of color temperature used in photography & lighting sources.
Usage of color temperature in these ads relate to the perceived color of the bulb's light. The heat output of a typical LED bulb is between 60°C-100°C (~333-373K).
White point

• A white point is a CIE XYZ or CIE xyY value of an ideal “white target” or “white reference”

• The idea of chromatic adaptation is to make white points the same between scenes.
Color constancy (at its simplest)

• (Johannes) Von Kries transform
• Compensate for each channel corresponding to the L,M,S cone response

\[
\begin{bmatrix}
L_2 \\
M_2 \\
S_2
\end{bmatrix} =
\begin{bmatrix}
1/L_{1w} & 0 & 0 \\
0 & 1/M_{1w} & 0 \\
0 & 0 & 1/S_{1w}
\end{bmatrix}
\begin{bmatrix}
L_1 \\
M_1 \\
S_1
\end{bmatrix}
\]

\(L_2, M_2, S_2\) is the new LMS response with the illuminant divided “out”. In this case white is equal to [1,1,1]

\(L_{1w}, M_{1w}, S_{1w}\) is the LMS response to “white” under this illuminant

\(L_1, M_1, S_1\) are the input LMS space under an illuminant.
Illuminant to illuminant mapping

- More appropriate would be to map to another illuminant’s LMS response (e.g. in the desired viewing condition)

- \((LMS)_1\) under an illuminant with white-response \((L_{1w}, M_{1w}, S_{1w})\)
- \((LMS)_2\) under an illuminant with white-response \((L_{2w}, M_{2w}, S_{2w})\)

\[
\begin{bmatrix}
L_2 \\
M_2 \\
S_2
\end{bmatrix} = \begin{bmatrix}
L_{2w}/L_{1w} & 0 & 0 \\
0 & M_{2w}/M_{1w} & 0 \\
0 & 0 & S_{2w}/S_{1w}
\end{bmatrix} \begin{bmatrix}
L_1 \\
M_1 \\
S_1
\end{bmatrix}
\]

- \(L_2, M_2, S_2\) is the new LMS response with the illuminant divided “out” and scaled to LMS\(_{2}\) illuminant
- \(L_{1w}, M_{1w}, S_{1w}\) is the LMS response to “white” the input illuminant, \(L_{2w}, M_{2w}, S_{2w}\) response to “white” of output illuminant
- \(L_1, M_1, S_1\) are the input LMS space under an illuminant.
Example

Simulation of different “white points” by photographing a “white” object under different illumination.

Images courtesy of Sharon Albert (Weizmann Institute)
Here, we have mapped the two input images to one below to mimic chromatic adaptation. The “white” part of the cup is shown before and after to help show that the illumination falling on white appears similar after the “chromatic adaptation”.

Example
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Next Class: A typical color imaging pipeline

NOTE: This diagram represents the steps applied on a typical consumer camera pipeline. ISPs may apply these steps in a different order or combine them in various ways. A modern camera ISP will undoubtedly be more complex, but will almost certainly implement these steps in some manner.
Watch these 5 min videos!

- Color in 5 min: https://youtu.be/6tTNgvAl1y4
- Displays in 5 min: https://youtu.be/1albYPL9Cfg
- Pinhole Camera in 5 min: https://youtu.be/F5WA26W4JaM

Additional Reading

Sec 3.1, 3.2, 3.3 from Forsyth & Ponce
Measure color & other aspects of perception in data visualization

Use models of perception to create tools for data science

Interested in Color & Perception of Color in Data Visualization?

UNC VisuaLab

danielle.szafir@cs.unc.edu  |  https://cu-visualab.org/

Modeling Color for Visualization
Slide Credits


• CS 194-26/294-26: Intro to Computer Vision and Computational Photography, UC Berkeley, by Alyosha Efros.

• CS 15-463, 663, 862, CMU, by Computational Photography, Ioannis Gkioulekas.