Lecture 14: Color

( unless otherwise stated slides are taken or adopted from Bob Woodham, Jim Little and Fred Tung )
Menu for Today (February 26, 2019)

Topics:
- Colour
- Colour Matching Experiments
- Trichromasity
- Colour Spaces

Redings:
- Today’s Lecture: Forsyth & Ponce (2nd ed.) 3.1-3.3
- Next Lecture: N/A

Reminders:
- Assignment 3: Texture Syntheis is due on March 1st (11:59pm)
- Grading for Midterm (by end of this week … hopefully)
Today’s “fun” Example: CVPR AC Meeting was *Yesterday*
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[ B. Zhao, L. Meng, W. Yin, L. Sigal, accepted to CVPR’19 ]
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Midterm Overview
Lecture 11: Re-cap — Laplacian vs. Gaussian Pyramids

Shown in opposite order for space

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)
Lecture 11: Re-cap — Oriented Pyramids

Oriental Filters

Laplacian Pyramid Layer

B_1

B_2

B_3

B_4

Oriented Pyramid Levels

Forsyth & Ponce (1st ed.) Figure 9.14
Lecture 11: Re-cap — Oriented Pyramids

Forsyth & Ponce (1st ed.) Figure 9.13
Lecture 11: Re-cap — Texture Representation

Steps:

1. Form a Laplacian and oriented pyramid (or equivalent set of responses to filters at different scales and orientations)

2. Square the output (makes values positive)

3. Average responses over a neighborhood by blurring with a Gaussian

4. Take statistics of responses
   — Mean of each filter output
   — Possibly standard deviation of each filter
The **image formation process** that produces a particular image depends on:

- **Lightening condition**
- **Scene geometry**
- **Surface properties**
- **Camera optics**

Sensor (or eye) **captures amount of light** reflected from the object.
Colour

— Light is produced in different amounts at different wavelengths by each light source

— Light is differentially reflected at each wavelength, which gives objects their natural colour (**surface albedo**)

— The sensation of colour is determined by the human visual system, based on the product of light and reflectance
Relative **Spectral Power** of Two Illuminants

Relative spectral power plotted against wavelength in nm

Forsyth & Ponce (2nd ed.) Figure 3.4
Surface reflection depends on both the viewing \((\theta_v, \phi_v)\) and illumination \((\theta_i, \phi_i)\) direction, with Bidirectional Reflection Distribution Function: \(\text{BRDF}(\theta_i, \phi_i, \theta_v, \phi_v)\)

Lambertian surface:

\[
\text{BRDF}(\theta_i, \phi_i, \theta_v, \phi_v) = \frac{\rho d}{\pi}
\]

constant, called albedo
Spectral **Albedo** of Natural Surfaces

Forsyth & Ponce (2nd ed.) Figure 3.6
Reflected light **at each wavelength** is the product of illumination and surface reflectance at that wavelength.

Surface reflectance often is modeled as having two components:

- **Lambertian** reflectance: equal in all directions (diffuse)
- **Specular** reflectance: mirror reflectance (shiny spots)
(small) Graphics Review

Surface reflection depends on both the viewing \((\theta_v, \phi_v)\) and illumination \((\theta_i, \phi_i)\) direction, with Bidirectional Reflection Distribution Function: \(\text{BRDF}(\theta_i, \phi_i, \theta_v, \phi_v)\)

**Lambertian surface:**

\[
\text{BRDF}(\theta_i, \phi_i, \theta_v, \phi_v) = \frac{\rho d}{\pi}
\]

\[
L = \frac{\rho d}{\pi} I(\hat{i} \cdot \hat{n})
\]

*Slide adopted from: Ioannis (Yannis) Gkioulekas (CMU)*
Surface reflection depends on both the viewing \((\theta_v, \phi_v)\) and illumination \((\theta_i, \phi_i)\) direction, with Bidirectional Reflection Distribution Function: \(\text{BRDF}(\theta_i, \phi_i, \theta_v, \phi_v)\)

**Lambertian** surface:

\[
\text{BRDF}(\theta_i, \phi_i, \theta_v, \phi_v) = \frac{\rho d}{\pi}
\]

**Mirror** surface: all incident light reflected in one directions \((\theta_v, \phi_v) = (\theta_r, \phi_r)\)
Show a split field to subjects. One side shows the light whose colour one wants to match. The other a weighted mixture of three primaries (fixed lights)

\[ T = w_1 P_1 + w_2 P_2 + w_3 P_3 \]
Recall: Color is an Artifact of Human Perception

“Color” is **not** an objective physical property of light (electromagnetic radiation). Instead, light is characterized by its wavelength.

What we call “color” is how we subjectively perceive a very small range of these wavelengths.
Color Matching Experiments

Show a split field to subjects. One side shows the light whose colour one wants to match. The other a weighted mixture of three primaries (fixed lights)

\[ T = w_1 P_1 + w_2 P_2 + w_3 P_3 \]
Color Matching Experiments

Figure Credit: Brian Wandell, Foundations of Vision, Sinauer Associates, 1995
Example 1: Color Matching Experiment

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\[ T = w_1 P_1 + w_2 P_2 + w_3 P_3 \]

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Example 2: Color Matching Experiment

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We say a “negative” amount of $P_2$ was needed to make a match, because we added it to the test color side.
Example 2: Color Matching Experiment

We say a “negative” amount of $P_2$ was needed to make a match, because we added it to the test color side.

The primary color amount needed to match:

Example Credit: Bill Freeman
Many colours can be represented as a positive weighted sum of $A$, $B$, $C$

Write

$$M = aA + bB + cC$$

where the = sign should be read as “matches”

This is **additive** matching

Defines a colour description system

— two people who agree on $A$, $B$, $C$ need only supply $(a, b, c)$
Color Matching Experiments

— Some colours can’t be matched this way
— Instead, we must write

\[ M + aA = bB + cC \]

where, again, the = sign should be read as “matches”

— This is **subtractive** matching
— Interpret this as \((-a, b, c)\)
Color Matching Experiments

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— This is **subtractive** matching

— Interpret this as \((-a, b, c)\)

Problem for **designing displays**: Choose phosphors R, G, B so that **positive linear combinations** match a large set of colours
Principles of **Trichromacy**

**Experimental facts:**

Three primaries work for most people, provided we allow subtractive matching
- Exceptional people can match with two or only one primary
- This likely is caused by biological deficiencies

Most people make the same matches
- There are some anomalous trichromats, who use three primaries but match with different combinations
Human **Cone Sensitivity**

http://hyperphysics.phy-astr.gsu.edu/hbase/vision/colcon.html
Metameric Lights

Two lights whose spectral power distributions appear identical to most observers are called metamers.

(A) A tungsten bulb     (B) TV monitor set to match (A)

Figure credit: Brian Wandell, Foundations of Vision, Sinauer Associates, 1995
Grassman’s Laws

For colour matches:

- **symmetry**: \( U = V \Leftrightarrow V = U \)
- **transitivity**: \( U = V \) and \( V = W \) \( \Rightarrow U = W \)
- **proportionality**: \( U = V \Leftrightarrow tU = tV \)
- **additivity**: if any two of the statements are true, then so is the third

\[
U = V, \\
W = X, \\
(U + W) = (V + X)
\]

These statements mean that colour matching is, to an accurate approximation, linear.
— Describing colours accurately is of practical importance (e.g. Manufacturers are willing to go to a great deal of trouble to ensure that different batches of their product have the same colour)

— This requires a standard system for representing colour.
Linear Color Spaces

A choice of primaries yields a linear colour space — the coordinates of a colour are given by the weights of the primaries used to match it

Choice of primaries is equivalent to choice of colour space

— **RGB**: Primaries are monochromatic energies, say 645.2 nm, 526.3 nm, 444.4 nm

— **CIE XYZ**: Primaries are imaginary, but have other convenient properties. Colour coordinates are \((X, Y, Z)\), where \(X\) is the amount of the \(X\) primary, etc.
RGB Colour Matching Functions

- Primaries monochromatic
- Wavelengths 645.2, 526.3 and 444.4 nm
- Negative parts means some colours can be matched only subtractively

Forsyth & Ponce (2nd ed.) Figure 3.9
RGB Color Space
RGB Colour Matching Functions

- Primaries monochromatic
- Wavelengths 645.2, 526.3 and 444.4 nm
- Negative parts mean some colours can be matched only subtractively

Forsyth & Ponce (2nd ed.) Figure 3.9
CIE XYZ: Colour matching functions are positive everywhere, but primaries are imaginary. Usually draw $x$, $y$, where

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

Overall brightness is ignored

Forsyth & Ponce (2nd ed.) Figure 3.8
— White is in the center, with saturation increasing towards the boundary

— Mixing two coloured lights creates colours on a straight line

— Mixing 3 colours creates colours within a triangle

— Curved edge means there are no 3 actual lights that can create all colours that humans perceive!
— White is in the center, with saturation increasing towards the boundary

— Mixing two coloured lights creates colours on a straight line

— Mixing 3 colours creates colours within a triangle

— Curved edge means there are no 3 actual lights that can create all colours that humans perceive!
The sub-space of CIE colours that can be displayed on a typical computer monitor (phosphor limitations keep the space quite small)
Adding **red** to the green color outside of the region brings it back to where it can be matched by **green** and **blue** RGB primaries.
Usually one cannot reproduce colours exactly

This means it is important to know whether a colour difference would be noticeable to a human viewer
Uniform Colour Spaces

McAdam Ellipses: Each ellipse shows colours perceived to be the same

10 times actual size

Actual Size

Forsyth & Ponce (2nd ed.) Figure 3.14
McAdam ellipses demonstrate that differences in \( x, y \) are a poor guide to differences in perceived colour.

A **uniform colour space** is one in which differences in coordinates are a good guide to differences in perceived colour.

— example: CIE LAB
HSV Colour Space

The coordinates of a colour in a linear space like RGB or CIE XYZ may not necessarily...

— encode properties that are common in language or important in applications

— capture human intuitions about the topology of colours, e.g. hue relations are naturally expressed in a circle
HSV Colour Space

More natural description of colour for human interpretation

**Hue**: attribute that describes a pure colour
— e.g. ’red’, ’blue’

**Saturation**: measure of the degree to which a pure colour is diluted by white light
— pure spectrum colours are fully saturated

**Value**: intensity or brightness

Hue + saturation also referred to as *chromaticity*. 
HSV Colour Space

Gonzalez and Woods, 2008
Image colour depends on both light colour and surface colour

**Colour constancy**: determine hue and saturation under different colours of lighting

It is surprisingly difficult to predict what colours a human will perceive in a complex scene
- depends on context, other scene information

Humans can usually perceive
- the colour a surface would have under white light
Colour *Constancy*

A classic experiment by Land and McCann
Environmental Effects

**Chromatic adaptation:** If the human visual system is exposed to a certain colour light for a while, colour perception starts to skew

**Contrast effects:** Nearby colours affect what is perceived
Summary

- Approaches to texture exploit pyramid (i.e. scaled) and oriented representations
- Human colour perception
  - colour matching experiments
  - additive and subtractive matching
  - principle of trichromacy
- RGB and CIE XYZ are linear colour spaces
- Uniform colour space: differences in coordinates are a good guide to differences in perceived colour
- HSV colour space: more intuitive description of colour for human interpretation
- (Human) colour constancy: perception of intrinsic surface colour under different colours of lighting