# Light and color

#### Subhransu Maji

**CMPSCI 670: Computer Vision** 

September 15, 2016

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GREEN BLUE YELLOW PURPLE ORANGE RED WHITE PURPLE ORANGE BLUE RED GREEN WHITE YELLOW PURPLE RED GREEN BLUE

GREEN BLUE YELLOW PURPLE ORANGE RED WHITE PURPLE ORANGE BLUE RED GREEN WHITE YELLOW PURPLE RED GREEN BLUE

#### **Overview**

#### Light and color

- Spectral basis of light
- Color perception in the human eye
- Tristimulus theory and color spaces
- Color phenomena
- Applications
- Photometry
  - Light transport
  - Interaction of light with surfaces
  - Shape from shading

### What is color?

- "Color is the result of interaction between light in the environment and our visual system"
- "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



Stephen E. Palmer

### Newton's theory of light



Newton's sketch of his crucial experiment in which light from the sun is refracted through a prism. One color is then refracted through a second prism to show that it undergoes no further change. Light is then shown to be composed of the colors refracted in the second prisms.

Image credit: Warden and Fellows



### The electromagnetic spectrum



#### **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.

> Relative spectral power



#### Some examples of the spectra of light sources



400

500

600

700

B. Gallium Phosphide Crystal







#### Some examples of the reflectance spectra of surfaces



### Interaction of light and surfaces



 Reflected color is the result of interaction between the light source spectrum and the reflection surface reflectance



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#### Interaction of light and surfaces

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



#### Room for one color, Olafur Eliasson

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### The eye

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



### Rods and cones, fovea



- Rods are responsible for intensity, cones for color perception
- Rods and cones are non-uniformly distributed on the retina
  - Fovea Small region (1 or 2°) at the center of the visual field containing the highest density of cones - and no rods
- There are about 5 million cones and 100 million rods in each eye

#### Demonstration of visual acuity



#### Blind spot

With left eye shut, look at the cross on the left. At the right distance, the circle on the right should disappear (Glassner, 1.8).

### Rod/cone sensitivity



Why can't we read in the dark?

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Slide by A. Efros 16

#### **Physiology of Color Vision**

#### Three kinds of cones:





WAVELENGTH (nm.)

- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

© Stephen E. Palmer, 2002

# Physiology of color vision: fun facts

- "M" and "L" pigments are encoded on the X-chromosome
  - That's why men are more likely to be color blind
  - "L" gene has high variation, so some women may be *tetra-chromatic*
- Color blindness
  - Red-green color blindness mutation in L or M photoreceptors; difficulty in discriminating red and green hues
  - Blue-yellow color blindness mutation in S photoreceptors; difficulty in discriminating bluish and greenish hues, yellowish and reddish hues
- Some animals have one (night animals), two (e.g. dogs), four (fish, birds), five (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp) types of cones

#### Mantis Shrimp: Extraordinary Eyes







### **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
- How can we represent an entire spectrum with 3 numbers?
- We can't! A lot 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



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#### How insects see



http://fieldguidetohummingbirds.wordpress.com/2008/11/11/do-we-see-what-bees-see/





visible light image simulated bee vision <u>http://photographyoftheinvisibleworld.blogspot.de/</u> CMPSCI 670 Subhransu Maji (UMass, Fall 16) Copyright Dr. Klaus Schmitt<sub>22</sub>

### Standardizing color experience

- We would like to understand which spectra produce the same color sensation in people under similar viewing conditions
- Color matching experiments







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**p**<sub>3</sub>



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:



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## 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 18<sup>th</sup> century (Thomas Young)

#### Grassman's Laws (1853)

- Color matching appears to be linear
- 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 mix two test lights, then mixing the matches will match the result:
  - 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  $A + B = (u_1 + v_1) P_1 + (u_2 + v_2) P_2 + (u_3 + v_3) P_3$ .
- 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  $kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3$ .

#### 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

#### Linear color spaces

How to compute the weights of the primaries to match any spectral signal?

**Given:** a choice of three primaries and a target color signal

# **Find:** weights of the primaries needed to match the color signal







## Color matching function: primary color

We know that a monochromatic light  $\lambda_i$ of wavelength will be matched by the amounts  $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.



And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

$$\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$



Source: W. Freeman
# Color matching functions: any color

Store the color matching functions in the rows of the matrix, C

	$(c_1(\lambda_1))$	•••	$c_1(\lambda_N)$
<i>C</i> =	$c_2(\lambda_1)$	•••	$c_2(\lambda_N)$
	$c_3(\lambda_1)$	•••	$c_{3}(\lambda_{N})$



Let the new spectral signal be described by the vector *t*.

 $\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$  Then the amounts of each primary needed to match t are:  $\vec{e} = C\vec{t}$ 

The components  $e_1$ ,  $e_2$ ,  $e_3$  describe the color of t. If you have some other spectral signal, s, and s matches t perceptually, then  $e_1$ ,  $e_2$ ,  $e_3$ , will also match s (by Grassman's Laws)

# **RGB** space

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



#### Cone responses to RGB signals

#### Comparison of RGB matching functions with best linear transformation of cone responses

4.20 COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS. The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the Stiles and Burch (1959) colormatching functions. The symbols show the matches predicted from the photocurrents of the three types of macaque cones. The predictions included a correction for absorption by the lens and other inert pigments in the eye. Source: Baylor, 1987.



#### Linear color spaces: CIE XYZ

- Primaries are "imaginary", but matching functions are positive everywhere
- Y parameter corresponds to brightness or *luminance* of a color
- Z corresponds to blue simulation



## **Uniform color spaces**

- Unfortunately, differences in x,y coordinates do not reflect perceptual color differences
- CIE u'v' is a transform of x,y to make the ellipses more uniform



#### Nonlinear color spaces: HSV

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



### Some early attempts in color spaces



Philipp Otto Runge's Farbenkugel (color sphere), 1810



A BALANCED COLOR SPHERE

Munsell's balanced color sphere, 1900, from A Color Notation, 1905

# Light and color

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September 20, 2016

### Administrivia

- No office hours today
  - New office hours: Tuesdays 10am-11am
  - Email me if you want to meet this week
- Homework 2 posted
  - Due on Friday
- In general, I'll try to post a homework each Friday which will be due the following Friday

### Recap of the last lecture

#### ◆ Last lecture:

- Physics of light
  - Light can be described by its spectrum
- Color perception in the human eye
  - Rods and cones
- Tristimulus theory
  - Three primary colors are sufficient to match light of any color
  - Linearity of light
- Today
  - Color phenomena
  - Photometry
    - Interaction of light with surfaces
    - Shape from shading

 The ability of the human visual system to perceive color relatively constant despite changes in illumination conditions





We perceive the same color both in shadow and sunlight

Color constancy causes A and B to look different although the pixel values are the same

http://en.wikipedia.org/wiki/Color constancy

#### Recap: interaction of light and surfaces



 Reflected color is the result of interaction between the light source spectrum and the reflection surface reflectance



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white and gold *or* blue and black

light is blue so white is tinted blue and gold doesn't really change

light is yellow, so black reflects the yellow and the blue is unaffected

#### http://xkcd.com/1492/



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#### http://xkcd.com/1492/



## **Chromatic adaptation**

- The visual system changes its sensitivity depending on the luminances prevailing in the visual field
  - The exact mechanism is poorly understood
- Adapting to different brightness levels
  - Changing the size of the iris opening (i.e., the aperture) changes the amount of light that can enter the eye
  - Think of walking into a building from full sunshine
- Adapting to different color temperature
  - The receptive cells on the retina change their sensitivity
  - For example: if there is an increased amount of red light, the cells receptive to red decrease their sensitivity until the scene looks white again
  - We actually adapt better in brighter scenes: This is why candlelit scenes still look yellow

#### http://www.schorsch.com/kbase/glossary/adaptation.html

- When looking at a picture on screen or print, our eyes are adapted 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

- 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

- Von Kries adaptation
  - Multiply each channel by a gain factor
- **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  $1/r_w$ ,  $1/g_w$ ,  $1/b_w$



- Without gray cards: we need to "guess" which pixels correspond to white objects
- Gray world assumption
  - The image average  $r_{ave}$ ,  $g_{ave}$ ,  $b_{ave}$  is gray
  - Use weights 1/r<sub>ave</sub>, 1/g<sub>ave</sub>, 1/b<sub>ave</sub>
- Brightest pixel assumption
  - 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

# **Color and language**



Evolution of color terms across ~20 diverse languages

B. Berlin and P. Kay, Basic Color Terms: Their Universality and Evolution (1969)

### Grayscale to color

#### **Colorful Image Colorization** [Project Page]

Richard Zhang, Phillip Isola, Alexei A. Efros. In ECCV, 2016.



https://github.com/richzhang/colorization

## Further readings and thoughts ...

- Color matching applet
  - http://graphics.stanford.edu/courses/cs178/applets/ colormatching.html
- B. Berlin and P. Kay, Basic Color Terms: Their Universality and Evolution (1969)
  - It is a book. The library has some copies.
- D.A. Forsyth, A novel algorithm for color constancy
  - Gamut based approach
  - http://luthuli.cs.uiuc.edu/~daf/papers/colorconst.pdf
- Lots of recent work on grayscale to color using CNNs

# Radiometry

#### • Questions:

- how "bright" will surfaces be?
- what is "brightness"?
  - measuring light
  - interactions between light and surfaces
- Core idea think about light arriving at a surface around any point is a hemisphere of directions
- Simplest problems can be dealt with by reasoning about this hemisphere



Computer Vision - A Modern Approach Set: Radiometry Slides by D.A. Forsyth

#### Lambert's wall



# What is the distribution of brightness on the ground?

Computer Vision - A Modern Approach Set: Radiometry Slides by D.A. Forsyth

# More complex wall



Computer Vision - A Modern Approach Set: Radiometry Slides by D.A. Forsyth

#### More complex wall





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## Light at 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

#### Fluorescence







## Modeling surface reflectance

Bidirectional reflectance distribution function (BRDF)

- How bright a surface appears when viewed from one direction when light falls on it from another
- **Definition**: ratio of the radiance in the emitted direction to irradiance in the incident direction



$$\frac{L_o(\underline{x},\vartheta_o,\varphi_o)}{L_i(\underline{x},\vartheta_i,\varphi_i)\cos\vartheta_id\omega}$$

#### **Simplifying assumptions** locality, no fluorescence,

does not generate light

#### Gonioreflectometer



The University of Virginia spherical gantry, an example of a modern image-based gonioreflectometer

#### BRDFs can be incredibly complicated...



# Suppressing the angles in the BRDF

#### BRDF is a very general notion

- some surfaces need it (underside of a CD; tiger eye; etc)
- very hard to measure
  - illuminate from one direction, view from another, repeat
- very unstable
  - minor surface damage can change the BRDF
  - e.g. ridges of oil left by contact with the skin can act as lenses
- for many surfaces, light leaving the surface is largely independent of exit angle
  - surface roughness is one source of this property

# **Special cases: Diffuse reflection**

- Light is reflected equally in all directions
  - Dull, matte surfaces like chalk or cotton cloth
  - Microfacets scatter incoming light randomly
  - Effect is that light is reflected (approximately) equally in all directions
- Brightness of the surface depends on the incidence of illumination







#### Diffuse reflection: Lambert's law





 $B = \rho(\mathbf{N} \cdot \mathbf{S})$  $= \rho \|\mathbf{S}\| \cos \theta$ 

B: radiosity (total power leaving the surface per unit area)
ρ: albedo (fraction of incident irradiance reflected by the surface)
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 of with  $\cos^{n}(\delta\theta)$
- Lambertian + specular model: sum of diffuse and specular term
  - a reasonable approximation to lot of surfaces we see


#### **Specular reflection**



#### Moving the light source



#### Changing the exponent

### Role of specularity in computer vision





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#### Photometric stereo (shape from shading)

• Can we reconstruct the shape of an object based on shading cues?



Luca della Robbia, *Cantoria*, 1438

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### Photometric stereo

#### Assume:

- A Lambertian object
- A *local shading model* (each point on a surface receives light only from sources visible at that point)
- A set of *known* light source directions
- A set of pictures of an object, obtained in exactly the same camera/ object configuration but using different sources
- Orthographic projection

Goal: reconstruct object shape and albedo



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## Surface model: Monge patch



## Image model

- Known: source vectors  $S_j$  and pixel values  $I_j(x,y)$
- **Unknown:** surface normal N(x,y) and albedo  $\rho(x,y)$
- Assume that the response function of the camera is a linear scaling by a factor of k
- Lambert's law:

$$I_{j}(x, y) = k \rho(x, y) (\mathbf{N}(x, y) \cdot \mathbf{S}_{j})$$
$$= (\rho(x, y) \mathbf{N}(x, y)) \cdot (k\mathbf{S}_{j})$$
$$= \mathbf{g}(x, y) \cdot \mathbf{V}_{j}$$

#### Least squares problem

• For each pixel, set up a linear system:

- Obtain least-squares solution for g(x,y) (which we defined as N(x,y) $\rho(x,y)$ )
- Since N(x,y) is the unit normal, ρ(x,y) is given by the magnitude of g(x,y)

• Finally, 
$$N(x,y) = g(x,y) / \rho(x,y)$$

#### Example



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Subhransu โงเลม (บางเลจร, กลม 10)

#### Recovering a surface from normals

Recall the surface is written as

$$(x, y, f(x, y))$$

This means the normal has the form:

$$\mathbf{g}(x, y) = \begin{pmatrix} g_1(x, y) \\ g_2(x, y) \\ g_3(x, y) \end{pmatrix}$$

$$\mathbf{N}(x, y) = \frac{1}{\sqrt{f_x^2 + f_y^2 + 1}} \begin{pmatrix} f_x \\ f_y \\ 1 \end{pmatrix}$$

Then we obtain values for the partial derivatives of the surface:

$$f_x(x, y) = g_1(x, y) / g_3(x, y)$$
  
$$f_y(x, y) = g_2(x, y) / g_3(x, y)$$

## Recovering a surface from normals

*Integrability*: for the surface *f* to exist, the mixed second partial derivatives must be equal:

$$\frac{\partial}{\partial y}(g_1(x,y)/g_3(x,y)) =$$

$$\frac{\partial}{\partial x}(g_2(x,y)/g_3(x,y))$$

(in practice, they should at least be similar) We can now recover the surface height at any point by integration along some path, e.g.

$$f(x, y) = \int_{0}^{x} f_{x}(s, y) ds + \int_{0}^{y} f_{y}(x, t) dt + C$$

(for robustness, should take integrals over many different paths and average the results)

## Surface recovered by integration



F&P 2<sup>nd</sup> ed., sec. 2.2.4 84

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## Works for more complicated surfaces

#### Input



Estimated albedo



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Integrated

х

## Limitations

- Orthographic camera model
- Simplistic reflectance and lighting model
- No shadows
- No inter-reflections
- No missing data
- Integration is tricky

## **Application**

# GELSIGHT



#### https://www.youtube.com/watch?v=S7gXih4XS7A

### Finding the direction of the light source

$$I(x,y) = \mathbf{N}(x,y) \cdot \mathbf{S}(x,y) + A$$

Full 3D case:



$$\begin{pmatrix} N_{x}(x_{1}, y_{1}) & N_{y}(x_{1}, y_{1}) & N_{z}(x_{1}, y_{1}) & 1 \\ N_{x}(x_{2}, y_{2}) & N_{y}(x_{2}, y_{2}) & N_{z}(x_{2}, y_{2}) & 1 \\ \vdots & \vdots & \vdots & \vdots \\ N_{x}(x_{n}, y_{n}) & N_{y}(x_{n}, y_{n}) & N_{z}(x_{n}, y_{n}) & 1 \end{pmatrix} \begin{pmatrix} S_{x} \\ S_{y} \\ S_{z} \\ A \end{pmatrix} = \begin{pmatrix} I(x_{1}, y_{1}) \\ I(x_{2}, y_{2}) \\ \vdots \\ I(x_{n}, y_{n}) \end{pmatrix}$$

For points on the *occluding contour*:

$$\begin{pmatrix} N_x(x_1, y_1) & N_y(x_1, y_1) & 1 \\ N_x(x_2, y_2) & N_y(x_2, y_2) & 1 \\ \vdots & \vdots & \vdots \\ N_x(x_n, y_n) & N_y(x_n, y_n) & 1 \end{pmatrix} \begin{pmatrix} S_x \\ S_y \\ A \end{pmatrix} = \begin{pmatrix} I(x_1, y_1) \\ I(x_2, y_2) \\ \vdots \\ I(x_n, y_n) \end{pmatrix}$$

P. Nillius and J.-O. Eklundh, "Automatic estimation of the projected light source direction," CVPR 2001 CMPSCI 670 Subhransu Maji (UMass, Fall 16) 88

## Finding the direction of the light source



P. Nillius and J.-O. Eklundh, "Automatic estimation of the projected light source direction," CVPR 2001

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### Application: Detecting composite photos

#### Real photo

#### Fake photo





M. K. Johnson and H. Farid, Exposing Digital Forgeries by Detecting Inconsistencies in Lighting, ACM Multimedia and Security Workshop, 2005. CMPSCI 670 Subhransu Maji (UMass, Fall 16) 90

# More readings and thoughts ...

- People can perceive reflectance
  - <u>Surface reflectance estimation and natural illumination statistics</u>, R.O. Dror, E.H. Adelson, and A.S. Willsky, Workshop on Statistical and Computational Theories of Vision 2001
- HDR photography
  - <u>Recovering High Dynamic Range Radiance Maps from Photographs</u>, Paul E. Devebec and Jitendra Malik, SIGGRAPH 1997