BBM 444 – Week 2

Image Formation and Cameras

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Image Formation
A photon’s life choices

• Absorption
• Diffusion
• Reflection
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• Phosphorescence
• Interreflection

Slide credit: James Hays
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The incident ray might be fully absorbed by the material.

Slide credit: James Hays
A photon’s life choices

- Absorption
- **Diffuse Reflection**
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The incident ray might be reflected from the material at many angles.
A photon’s life choices

- Absorption
- Diffusion
- **Specular Reflection**
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The incident ray might be reflected from the material only at a single direction.

Slide credit: James Hays
A photon’s life choices

• Absorption
• Diffusion
• Reflection
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• Phosphorescence
• Interreflection

The material might allow the ray to pass through it without being scattered.
A photon’s life choices

• Absorption
• Diffusion
• Reflection
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• Phosphorescence
• Interreflection

The incident ray might be bended as it passes from a material.

Slide credit: James Hays
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- *Fluorescence*
- Subsurface scattering
- Phosphorescence
- Interreflection

The material might absorb the light and then emit the light.

Slide credit: James Hays
A photon’s life choices

• Absorption
• Diffusion
• Reflection
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• Phosphorescence
• Interreflection

The light might penetrate the surface of a translucent material, and be scattered by interacting with the material.

Slide credit: James Hays
A photon’s life choices

• Absorption
• Diffusion
• Reflection
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• **Phosphorescence**
• Interreflection

The light might be absorbed by a phosphorescent material but (unlike fluorescence), the material does not immediately re-emit the light it absorbs.
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- **Interreflection**

The light might be reflected from an object, strike other surrounding objects, …

(Specular Interreflection)
Image formation

• What determines the brightness of an image pixel?
White light: composed of about equal energy in all wavelengths of the visible spectrum

Color

4.1 NEWTON’S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Slide credit: B. Freeman and A. Torralba
Interaction of light and surfaces

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

Slide credit: Alyosha Efros
What is color?

- Color is the result of interaction between physical 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*
Brightness Perception

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

Edward H. Adelson
Brightness Perception

http://web.mit.edu/persci/people/adelson/illusions_demos.html
Why does a visual system need color? (an incomplete list...)

- To tell what food is edible.
- To distinguish material changes from shading changes.
- To group parts of one object together in a scene.
- To find people’s skin.
- Check whether a person’s appearance looks normal/healthy.
The Eye

• The human eye is a camera

Figures: Francis Crick, The Astonishing Hypothesis, 1995
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


Slide credit: Alyosha Efros
Receptors Density - Fovea
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

Images by Shimon Ullman
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).
3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.
Human eye photoreceptor spectral sensitivities

- 3 different types, denoted L, M, and S, for whether they are sensitive to the long, middle, or short wavelengths of the visible spectrum.
Rod / Cone sensitivity

The famous sock-matching problem…

Slide credit: Alyosha Efros
Electromagnetic Spectrum

Human Luminance Sensitivity Function

Slide credit: Alyosha Efros

http://www.yorku.ca/eye/photopik.htm
Visible Light

Why do we see light of these wavelengths?

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

© Stephen E. Palmer, 2002

Slide credit: Alyosha Efros
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.
Some examples of the spectra of light sources

A. Ruby Laser
B. Gallium Phosphide Crystal
C. Tungsten Lightbulb
D. Normal Daylight
Some examples of the reflectance spectra of surfaces

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>% Photons Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>Red</td>
</tr>
<tr>
<td>700</td>
<td>Yellow</td>
</tr>
<tr>
<td>400</td>
<td>Blue</td>
</tr>
<tr>
<td>700</td>
<td>Purple</td>
</tr>
</tbody>
</table>
More Spectra

Metamers: different spectral distributions that are perceived as identical colors

Slide credit: Derek Hoiem
Physiology of Color Vision

Three kinds of cones:

- Why are M and L cones so close?
- Why are there 3?
3 is better than 2...

- “M” and “L” on the X-chromosome
  - Why men are more likely to be color blind (see what it’s like: http://www.vischeck.com/vischeck/vischeckURL.php)

- “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), or even 12 (mantis shrimp)

Slide credit: Derek Hoiem

http://en.wikipedia.org/wiki/Color_vision
We don’t perceive a spectrum

- We perceive
  - Hue: mean wavelength, color
  - Saturation: variance, vividness
  - Intensity: total amount of light

- Same perceived color can be recreated with combinations of three primary colors ("trichromacy")
Trichromacy and CIE-XYZ

Perceptual equivalents with RGB

Perceptual equivalents with CIE-XYZ

\[
\begin{bmatrix}
X \\
Y \\
Z \\
\end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix}
0.49 & 0.31 & 0.20 \\
0.17697 & 0.81240 & 0.01063 \\
0.00 & 0.01 & 0.99 \\
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B \\
\end{bmatrix}
\]

Slide credit: Derek Hoiem
CIE-XYZ

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

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

Slide credit: Derek Hoiem
Color Sensing in Camera (RGB)

- 3-chip vs. 1-chip: quality vs. cost
- Why more green?

Why 3 colors?

Slide credit: Steve Seitz
Practical Color Sensing: Bayer Grid

• Estimate RGB at ‘G’ cells from neighboring values

Slide credit: Steve Seitz
RGB color space

- RGB cube
  - Easy for devices
  - But not perceptual
  - Where do the grays live?
  - Where is hue and saturation?

*Figure 6.8* RGB 24-bit color cube.
• Hue, Saturation, Value (Intensity)  
  – RGB cube on its vertex  
• Decouples the three components (a bit)  
• Use rgb2hsv() and hsv2rgb() in Matlab

Slide credit: Steve Seitz
White balance & Chromatic adaptation

- Different illuminants have different color temperature
- Our eyes adapt to this: Chromatic adaptation
  - We actually adapt better in brighter scenes
  - This is why candlelit scenes still look yellow

Slide credit: Fredo Durand

White balance Problem

• When watching a picture on screen or print, we adapt to the illuminant of the room, not that of the scene in the picture
• The eye cares more about objects’ intrinsic color, not the color of the light leaving the objects
• We need to discount the color of the light source
Image Formation

Digital Camera

The Eye

Slide credit: Alyosha Efros
A digital camera replaces film with a sensor array

- Each cell in the array is light-sensitive diode that converts photons to electrons

*FIGURE 2.17* (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.
Digital images

- **Sample** the 2D space on a regular grid
- **Quantize** each sample (round to nearest integer)

- Image thus represented as a matrix of integer values.

Slide credit: K. Grauman, S. Seitz
Cameras

The film records the image transmitted by the lens.

The lens elements rotate forward and back to bring objects at different distances into sharp focus.

The aperture adjusts the amount of light reaching the film. A large opening allows the most light to pass through the lens to the film. The smallest opening lets in the least amount of light.

The viewfinder shows the picture that the lens focuses on the film.

The shutter opens and closes to control the length of time that light strikes the film.
How do we see the world?

- Let’s design a camera
  - Idea 1: put a piece of film in front of an object
  - Why is there no picture appearing on the paper?
Light rays from many different parts of the scene strike the same point on the paper.
Pinhole Camera

- Light from a scene passes through the pinhole (a single point) and projects an inverted image on the image plane.
The pinhole camera only allows rays from one point in the scene to strike each point of the paper.
Dimensionality Reduction Machine (3D to 2D)

What have we lost?
- Angles
- Distances (lengths)
Funny things happen...

- Parallel lines in the world intersect in the image at a vanishing point.
Parallel lines aren’t...

The images of parallel lines intersect at the *horizon*.
Vanishing points and lines

Photo from online Tate collection

Slide credit: J. Hays
Vanishing points and lines
Lengths can’t be trusted...
Lengths can’t be trusted...
...but humans adopt!

Müller-Lyer Illusion

We don’t make measurements in the image plane

Slide credit: Alyosha Efros

http://www.michaelbach.de/ot/sze_muelue/index.html
Modeling projection

- **The coordinate system**
  - We will use the pin-hole model as an approximation
  - Put the optical center (Center Of Projection) at the origin
  - Put the image plane (Projection Plane) *in front* of the COP
    - Why?
  - The camera looks down the *negative* z axis
    - we need this if we want right-handed-coordinates

Slide credit: Steve Seitz
Modeling projection

- **Projection equations**
  - Compute intersection with PP of ray from \((x,y,z)\) to COP
  - Derived using similar triangles

\[
(x, y, z) \rightarrow \left(-d\frac{x}{z}, -d\frac{y}{z}, -d\right)
\]

- We get the projection by throwing out the last coordinate:

\[
(x, y, z) \rightarrow \left(-d\frac{x}{z}, -d\frac{y}{z}\right)
\]
Homogeneous coordinates

Is this a linear transformation?
- no—division by $z$ is nonlinear

Trick: add one more coordinate:

\[
(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}
\]

homogeneous image coordinates

\[
(x, y, z) \Rightarrow \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}
\]

homogeneous scene coordinates

Converting from homogeneous coordinates

\[
\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow \frac{x}{w}, \frac{y}{w}
\]

\[
\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \Rightarrow \frac{x}{w}, \frac{y}{w}, \frac{z}{w}
\]
Perspective Projection

Projection is a matrix multiply using homogeneous coordinates:

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1/d & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix}
= 
\begin{bmatrix}
x \\
y \\
-z/d \\
1
\end{bmatrix}
\Rightarrow (-d\frac{x}{z}, -d\frac{y}{z})
\]

divide by third coordinate

This is known as **perspective projection**

- The matrix is the projection matrix
- Can also formulate as a 4x4

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & -1/d & 0
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix}
= 
\begin{bmatrix}
x \\
y \\
z \\
-z/d
\end{bmatrix}
\Rightarrow (-d\frac{x}{z}, -d\frac{y}{z})
\]

divide by fourth coordinate
Orthographic Projection

- Special case of perspective projection
  - Distance from the COP to the PP is infinite
  - Also called “parallel projection”
  - What’s the projection matrix?

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1 \\
\end{bmatrix}
= 
\begin{bmatrix}
x \\
y \\
z \\
1 \\
\end{bmatrix}
\Rightarrow (x, y)
\]
Spherical Projection

- What if PP is spherical with center at COP?
- In spherical coordinates, projection is trivial: \((q,f) = (q,f,d)\)
- Note: doesn’t depend on focal length \(f\)!
Building a real camera
Camera Obscura (darkened room)

Camera Obscura, Gemma Frisius, 1558

- The first camera
  - known to Aristotle
  - Depth of the room is the effective focal length

Slide credit: Alyosha Efros
Camera Obscura used for Tracing

Lens Based Camera Obscure, 1568
Vermeer and The Camera Obscura

Officer and Laughing Girl, 1657

http://www.essentialvermeer.com/camera_obscura/co_one.html
Camera Obscura

from BBC's Genius of Photography
Pinhole Size

Photograph made with small pinhole

Photograph made with larger pinhole

From Photography, London et al.
Due to the Sun?
Shadows?

Slide credit: Antonio Torralba
Accidental Pinhole Camera

Window turned into a pinhole

View outside

Slide credit: Antonio Torralba
Mixed accidental pinhole and anti-pinhole cameras
Mixed accidental pinhole and anti-pinhole cameras

Cameras and Lenses

Shrinking aperture size

– Rays are mixed up

– Why the aperture cannot be too small?
  • Less light passes through (dark images)
  • Diffraction effect

Slide credit: Fei-Fei Li
The reason for lenses

- We need light, but big pinholes cause blur.
- Lenses gather more light but needs to be *focused*. 
Focus and Defocus

- 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

Slide credit: Steve Seitz
Thin lenses

- Thin lens equation: \( \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \)

  - Any object point satisfying this equation is in focus
  - What is the shape of the focus region?
  - How can we change the focus region?
  - Thin lens applet: [http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html](http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html) (by Fu-Kwun Hwang)
The depth of field is the range of distance that appears acceptably sharp.

- does not abruptly change from sharp to unsharp but instead occurs as a gradual transition
Aperture controls Depth of Field

- Changing the aperture size affects depth of field
  - A smaller aperture increases the range in which the object is approximately in focus
  - But small aperture reduces amount of light – need to increase exposure
Varying the aperture

Large aperture = small DOF

Small aperture = large DOF

from Photography, London et al.
Nice Depth of Field effect
Light Field / Plenoptic Cameras

- Lytro ($399, Sept 2012)
- Multiple, “synthetic apertures”
- Allows focusing after capture
Field of View (Zoom)

From London and Upton
Field of View (Zoom) = Cropping

From London and Upton

Slide credit: Alyosha Efros
FOV depends on Focal Length

Size of field of view governed by size of the camera retina:

$$\varphi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Smaller FOV = larger Focal Length

Slide credit: Alyosha Efros
Field of View / Focal Length

Large FOV, small $f$
Camera close to car

Small FOV, large $f$
Camera far from the car

Slide credit: Alyosha Efros
Changing FOV – magnification constant

• Hitchcock zoom ("Vertigo effect")

• moving back while changing the focal length lets you keep objects at one depth the same size

Slide credit: Fredo Durand
Changing FOV – magnification constant

• Hitchcock zoom (“Vertigo effect”)

See:
http://www.petapixel.com/2012/05/03/trippy-example-of-hitchcock-zoom-shot-on-a-beach/

Slide credit: Fredo Durand
Lens Flaws: Chromatic Aberration

- Dispersion: wavelength-dependent refractive index
  - (enables prism to spread white light beam into rainbow)
- Modifies ray-bending and lens focal length: \( f(\lambda) \)

- color fringes near edges of image
- Corrections: add ‘doublet’ lens of flint glass, etc.
Chromatic Aberration

Near Lens Center

Near Lens Outer Edge

Slide credit: Alyosha Efros
Radial Distortion (e.g. ‘Barrel’ and ‘pin-cushion’)

straight lines curve around the image center
Radial Distortion

- Radial distortion of the image
  - Caused by imperfect lenses
  - Deviations are most noticeable for rays that pass through the edge of the lens

Slide credit: Alyosha Efros
Reading Assignment

• How Digital Cameras Work (HowStuffWorks).
  

• A. Torralba and W. T. Freeman, Accidental pinhole and pinspeck cameras: revealing the scene outside the picture, In CVPR (2012).
  
  http://people.csail.mit.edu/torralba/research/accidentalcameras/
Programming Assignment #1 – Part I

- Big Spanish Castle Illusion (John Sadowski)*

  Stare at the dot for 30 seconds. Then, without moving your eyes, move the mouse over the image.
  - The image will look like it's in color until you move your eyes.

*Adopted from the assignment developed by Fredo Durand
Programming Assignment #1 – Part II

• Build your own pinhole screen from household items

- Empty soup can
- Scissors
- Hammer and small nail
- Wax Paper
- Elastic Bands / Tape
- Black Spray Paint

http://darkpinesmedia.wordpress.com/constructing-pinhole-can-screens-and-boxes/
Programming Assignment #1 - Bonus

Accidental pinhole and pinspeck cameras