Announcement

• Room Change
  – 304 Educational Sciences

• A total of 5 (five) late days are allowed for projects.

• Office hours
  – Me: 11am-12pm Thursday (or by appointment)
  – Yu-Chi: 12:00-1:00PM Monday and Wednesday
Image Formation

Film

Digital Camera

The Eye

Alexei Efros’ slide
• Let’s design a camera
  – Idea 1: put a piece of film in front of an object
  – Do we get a reasonable image?

Steve Seitz's slide
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

- The first camera
  - 5th B.C. Aristotle, Mozi (Chinese: 墨子)
  - How does the aperture size affect the image?

http://en.wikipedia.org/wiki/Pinhole_camera
Shrinking the aperture

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

2 mm

1 mm

0.6 mm

0.35 mm

0.15 mm

0.07 mm
Sharpest image is obtained when:

\[ d = 2 \sqrt{f \lambda} \]

d is diameter,
f is distance from hole to film
\( \lambda \) is the wavelength of light, all given in metres.

Example: If \( f = 50mm \),

\[ \lambda = 600nm \text{ (red)}, \]

\[ d = 0.36mm \]
Pinhole cameras are popular

Jerry Vincent's Pinhole Camera
Impressive Images

Jerry Vincent's Pinhole Photos
What’s wrong with Pinhole Cameras?

- Low incoming light => Long exposure time => Tripod

<table>
<thead>
<tr>
<th>KODAK Film or Paper</th>
<th>Bright Sun</th>
<th>Cloudy Bright</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRI-X Pan</td>
<td>1 or 2 seconds</td>
<td>4 to 8 seconds</td>
</tr>
<tr>
<td>T-MAX 100 Film</td>
<td>2 to 4 seconds</td>
<td>8 to 16 seconds</td>
</tr>
<tr>
<td>KODABROMIDEx Paper, F2</td>
<td>2 minutes</td>
<td>8 minutes</td>
</tr>
</tbody>
</table>

What’s wrong with Pinhole Cameras

People are ghosted
What’s wrong with Pinhole Cameras

People become ghosts!
Pinhole Camera Recap

- Pinhole size (aperture) must be “very small” to obtain a clear image.

- However, as pinhole size is made smaller, less light is received by image plane.

- If pinhole is comparable to wavelength of incoming light, **DIFFRACTION** effects blur the image!
What’s the solution?

• 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

Steve Seitz’s slide
**Thin lens optics**

- Simplification of geometrical optics for well-behaved lenses
- All parallel rays converge to one point on a plane located at the focal length $f$
- All rays going through the center are not deviated
  - Hence same perspective as pinhole

Frédo Durand’s slide
Demo!

–http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html (by Fu-Kwun Hwang)
Thin lens formula
Thin lens formula

Similar triangles everywhere!
Thin lens formula

Similar triangles everywhere! \( \frac{y'}{y} = \frac{D'}{D} \)
Thin lens formula

Similar triangles everywhere!

\[
y'/y = D'/D
\]

\[
y'/y = (D' - f)/D
\]
Thin lens formula

\[ \frac{1}{D'} + \frac{1}{D} = \frac{1}{f} \]

The focal length \( f \) determines the lens’s ability to bend (refract) light. It is a function of the shape and index of refraction of the lens.
Film camera

scene

lens & motor

aperture & shutter

film

YungYu Chuang's slide
Film camera

*Still Life*, Louis Jaques Mande Daguerre, 1837

Srinivasa Narasimhan's slide
Before Film was invented

Lens Based Camera Obscura, 1568

Srinivasa Narasimhan's slide
Silicon Image Detector, 1970

Shree Nayar's slide
A digital camera replaces film with a sensor array.
Each cell in the array is a light-sensitive diode that converts photons to electrons.
SLR (Single-Lens Reflex)

- Reflex (R in SLR) means that we see through the same lens used to take the image.
- Not the case for compact cameras

YungYu Chuang's slide
SLR view finder

Prism

Mirror (flipped for exposure)

Mirror (when viewing)

Film/sensor

Light from scene

Your eye

YungYu Chuang's slide
Compound Lens System

- Rule: Image formed by first lens is the object for the second lens.
- If $d \approx 0$, the combined focal length $f$ is

$$f = \frac{f_1 f_2}{f_1 + f_2}$$
Field of View (FoV) vs Focal Length

Canon EF-S
60mm f/2.8

Canon EF
100mm f/2.8

Canon EF
180mm f/3.5
Field of View (FoV) vs Focal Length

Frédo Durand’s slide
Field of View (FoV) vs Focal Length

Gaussian Lens Formula: \[
\frac{1}{i} + \frac{1}{o} = \frac{1}{f}
\]

Field of View: \[\alpha = 2\arctan\left(\frac{w}{2i}\right) \approx 2\arctan\left(\frac{w}{2f}\right)\]

Example: \[w = 30\text{mm}, f = 50\text{mm} \Rightarrow \alpha \approx 33.4^\circ\]

Question: How does FoV change when we focus on closer objects?
Changing the aperture size affects depth of field. A smaller aperture increases the range in which the object is approximately in focus.
Aperture

- Aperture is the diameter of the lens opening, usually specified by f-stop, f/D, a fraction of the focal length.
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm

- When a change in f-stop occurs, the light is either doubled or cut in half.
- Lower f-stop, more light (larger lens opening)
- Higher f-stop, less light (smaller lens opening)
F-stop

Gaussian Law: \[ \frac{1}{i} + \frac{1}{o} = \frac{1}{f} \quad \frac{1}{i'} + \frac{1}{o'} = \frac{1}{f} \quad \Longleftrightarrow \quad (i'-i) = \frac{f}{(o'-f)} \frac{f}{(o-f)} (o-o') \]

Blur Circle Diameter: \[ b = \frac{d}{i''} (i' - i) \approx \frac{d}{f} (i' - i) \]

\[ f\text{-stop: } \# = \frac{f}{d} \]
F-stop

Canon EF-S 60mm f/2.8
Canon EF 100mm f/2.8
Canon EF 180mm f/3.5
Exposure

• Two main parameters:
  – Aperture (in f stop)
  – shutter speed (in fraction of a second)

See http://www.photonhead.com/simcam/
Effects of shutter speeds

- Slower shutter speed => more light, but more motion blur
- Faster shutter speed freezes motion
So far, we’ve only talked about monochrome sensors. Color imaging has been implemented in a number of ways:

• Field sequential
• Multi-chip
• Color filter array
• X3 sensor
Field sequential
Field sequential
Field sequential
Prokudin-Gorskii (early 1900’s)

Lantern projector

http://www.loc.gov/exhibits/empire/

YungYu Chuang's slide
Prokudin-Gorskiii (early 1990’s)
Multi-chip

wavelength dependent

YungYu Chuang's slide
Embedded color filters

Color filters can be manufactured directly onto the photodetectors.
Color filter array

Color filter arrays (CFAs)/color filter mosaics

Bayer pattern

YungYu Chuang's slide
Color filter array

Color filter arrays (CFAs)/color filter mosaics
Why CMY CFA might be better

Kodak 13um Pixel CMY & RGB Response

Quantum Efficiency (%) vs Wavelength (nm)
Bayer’s pattern
Demosaicking CFA’s

<table>
<thead>
<tr>
<th>R 11</th>
<th>G 12</th>
<th>R 13</th>
<th>G 14</th>
<th>R 15</th>
<th>G 16</th>
<th>R 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>G 21</td>
<td>B 22</td>
<td>G 23</td>
<td>B 24</td>
<td>G 25</td>
<td>B 26</td>
<td>G 27</td>
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<tr>
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<td>G 32</td>
<td>R 33</td>
<td>G 34</td>
<td>R 35</td>
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<td>R 51</td>
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<td>R 53</td>
<td>G 54</td>
<td>R 55</td>
<td>G 56</td>
<td>R 57</td>
</tr>
</tbody>
</table>

bilinear interpolation

\[ G_{44} = (G_{34} + G_{43} + G_{45} + G_{54})/4 \]
\[ R_{44} = (R_{33} + R_{35} + R_{53} + R_{55})/4 \]

original  
input  
linear interpolation

YungYu Chuang's slide
Demosaicking CFA’s

<table>
<thead>
<tr>
<th>R</th>
<th>G</th>
<th>R</th>
<th>G</th>
<th>R</th>
<th>G</th>
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<td>G</td>
<td>32</td>
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<td>33</td>
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<td>B</td>
<td>42</td>
<td>G</td>
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<td>B</td>
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<td>72</td>
<td>R</td>
<td>73</td>
<td>G</td>
<td>74</td>
</tr>
</tbody>
</table>

Median-based interpolation (Freeman)

1. Linear interpolation
2. Median filter on color differences

YungYu Chuang's slide
Demosaicking CFA’s

Median-based interpolation (Freeman)

original

input

linear interpolation

color difference (e.g. G-R)

median filter (kernel size 5)

Reconstruction (G=R+filtered difference)

YungYu Chuang’s slide
Demosaicking CFA’s

*Input*  
*Bilinear*  
*Cok*  
*Freeman*  
*LaRoche*

Generally, Freeman’s is the best, especially for natural images.

YungYu Chuang's slide
Foveon X3 sensor

• light penetrates to different depths for different wavelengths
• multilayer CMOS sensor gets 3 different spectral sensitivities
Color filter array

In conventional systems, color filters are applied to a single layer of photodetectors in a tiled mosaic pattern. The filters let only one wavelength of light-red, green or blue - pass through to any given pixel, allowing it to record only one color. As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.

YungYu Chuang's slide
X3 technology

A Foveon® X3™ image sensor features three separate layers of photodetectors embedded in silicon. Since silicon absorbs different colors of light at different depths, each layer captures a different color. Stacked together, they create full-color pixels.

As a result, only Foveon X3 image sensors capture red, green and blue light at every pixel location.

red  green  blue  output

YungYu Chuang's slide
Foveon X3 sensor

Bayer CFA

X3 sensor
Cameras with X3

Sigma SD10, SD9

Polaroid X530

YungYu Chuang's slide
Sigma SD9 vs Canon D30

YungYu Chuang's slide
Color processing

• After color values are recorded, more color processing usually happens:
  – White balance
  – Non-linearity to approximate film response or match TV monitor gamma
Auto White Balance

warmer

automatic white balance

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = \begin{bmatrix}
\frac{255}{R'_w} & 0 & 0 \\
0 & \frac{255}{G'_w} & 0 \\
0 & 0 & \frac{255}{B'_w}
\end{bmatrix} \begin{bmatrix}
R' \\
G' \\
B'
\end{bmatrix}
\]

YungYu Chuang's slide
Auto White Balance

The auto white balance was unable to find a white reference, resulting in dull and artificial colors.

The auto white balance got it right this time in a very similar scene because it could use the clouds as its white reference.

Manual white balance

white balance with the white book

white balance with the red book

YungYu Chuang's slide
Lens related issues: Compound Thick Lens

principal planes

nodal points

thickness
Lens related issues: Vignetting

Vignetting

$L_3 \ L_2 \ L_1$

more light from A than B!
Lens related issues: Vignetting

more light from A than B!

Goldman & Seitz ICCV 2005
Lens related issues: Chromatic Abberation

Lens has different refractive indices for different wavelengths.

Special lens systems using two or more pieces of glass with different refractive indexes can reduce or eliminate this problem.

http://www.dpreview.com/learn/?/Glossary/Optical/chromatic_aberration_01.htm
Lens related issues: Distortion

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

from Helmut Dersch

Steve Seitz’s slide
Digital camera review website

- Demonstration of digital cameras
- http://www.dpreview.com/
- A cool video of digital camera illustration