CS 89.15/189.5, Fall 2015

**Computational Aspects of Digital Photography**

Image Formation & Camera Basics

Wojciech Jarosz
wojciech.k.jarosz@dartmouth.edu
Administrivia

Make sure to sign onto Piazza (some of you haven’t)
- I’ll be posting announcements there

Video introduction was due last night!
- If you haven’t submitted, you can submit by tonight

Programming Assignment 0 is due tonight

“Programming” Assignment 1 is now available (start early!)

Schedule fix: no x-hour nor Saturday class this week
- We’ll make up Saturday class during another x-hour this term
Today’s agenda

How do we see the world, and how can we replicate that to create a camera?

Pinhole optics

(Simplified) Lenses

Exposure
  - shutter speed
  - aperture
  - ISO
Emission theory of vision

“For every complex problem there is an answer that is clear, simple, and wrong.”
-- H. L. Mencken

Supported by:
- Empedocles
- Plato
- Euclid (kinda)
- Ptolemy
- 50% of US college students*

Eyes send out “feeling rays” into the world

Exciting New Study!

Study: People Far Away From You Not Actually Smaller

Researchers say that, contrary to prior assertions, the subject above stands at equal height at left and at right, and does not grow smaller as he walks away from the camera.
Dimensionality reduction machine (3D to 2D)

3D world

2D image

What do we lose?

After a slide by Alyosha Efros

Figures © Stephen E. Palmer, 2002
Exciting New Study!

Study: People Far Away From You Not Actually Smaller

Researchers say that, contrary to prior assertions, the subject above stands at equal height at left and at right, and does not grow smaller as he walks away from the camera.

Lengths can’t be trusted...

Angles also...
...but humans adapt!

We don’t make measurements in the image plane

After a slide by Alyosha Efros
...but humans adapt!

We don’t make measurements in the image plane

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

Müller-Lyer Illusion

After a slide by Alyosha Efros
Fooling the eye
Fooling the eye

Making of 3D sidewalk art: http://www.youtube.com/watch?v=3SNYtd0Ayto
How do we see the world?

Let’s design a camera

- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?
How do we see the world?

- Receives light from all directions
- Gets all possible images from all possible viewpoints
- Need to be more selective. How?
How do we see the world?

Add a barrier to block off most of the rays.
How do we see the world?

Add a barrier to block off most of the rays

- Opening known as the aperture
- Reduces blurring
Pinhole camera

From *Photography*, London et al.
Pinhole camera (aka camera obscura)

First idea: Mo-Ti, China (470-390 BC)

First built: Alhazen, Iraq/Egypt (965-1039 AD)

Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Gemma Frisius, 1558

http://en.wikipedia.org/wiki/Pinhole_camera
8-hour exposure (Abelardo Morell)

http://www.abelardomorell.net/books/books_m02.html
Pinhole cameras everywhere

Tree shadow during solar eclipse

After a slide by Steve Seitz
Other pinholes

Another way to make a pinhole camera

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

After a slide by Alyosha Efros
Pinhole optics: “focal length”

What happens when the “focal length” is doubled?

- Projected object size is doubled
- Amount of light gathered is divided by 4
Field of view

Determines how much of scene is in frame

Traditionally specified by focal length

- But interpreting this number requires considering the “format,” or size of the film or sensor

After decades of 35mm, we are stuck with that standard

- Fields of view are usually discussed using the numbers that would be written on a lens for the 35mm format
FOV depends on focal length

\[ FOV = 2 \arctan \left( \frac{s}{2f} \right) \]
Questions?
Another way to make a pinhole camera

Why so blurry?

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

After a slide by Alyosha Efros
Pinhole size?

Small pinhole:
- sharper image

Larger pinhole:
- blurrier image
Shrinking the aperture

Why not make aperture as small as possible?
- Less light gets through
- Why does it get blurrier?
Diffraction

Wave nature of light

Smaller aperture means more diffraction

For Fourier fans:

- diffraction pattern = Fourier transform of the aperture

- smaller aperture means bigger Fourier spectrum

diffraction of water waves
Youtube demos

http://www.youtube.com/watch?v=kH57Di7Sj0c
http://www.youtube.com/watch?v=lIn-BLJNXpY
http://www.youtube.com/watch?v=KSIg_EaIFrw
http://www.youtube.com/watch?v=sjmBcm84iA4
Bottom line

The smaller the hole, the more diffraction

Depends on wavelength of wave (~500 nm for green)

Where is the sweet spot between blurring and diffraction?

\[ A \approx 2\sqrt{f\lambda} \]

https://en.wikipedia.org/wiki/Pinhole_camera#Selection_of_pinhole_size

http://www.mashpedia.com/Ripple_tank
Camera, version 0: Box with hole

Pinhole recap:

- Large pinholes produce blurry images
- Small pinholes produce dim images
- Diffraction limits sharpness for tiny pinholes
Questions?

Assignment 1: Shoe-box Camera Obscura

Due next week. Start early! Can work with a partner.
Be careful…

http://www.petapixel.com/2011/05/25/university-mistakes-pinhole-camera-for-a-bomb-ruins-photo-project/

University Mistakes Pinhole Camera for a Bomb, Ruins Photo Project

Michael Zhang • May 25, 2011
Replacing pinholes with lenses

From *Photography*, London et al.
Lenses

Gather more light!

But need to be focused

From Photography, London et al.

After a slide by Frédo Durand
Lenses

Essentially add multiple pinhole images

~ shift them to align (refraction)

Alignment works only for one distance

From *Photography*, London et al.

After a slide by Frédo Durand
Camera, v. 1: Box with lens & shutter

First practical cameras had
- film (roll film or glass plate)
- lens (small aperture)
- mechanism for winding film
- mechanism for triggering shutter

Limitations
- cannot control exposure
- focus is fixed (like an inexpensive phone camera today)
- want to be outdoors in strong light

George Eastman
Kodak Camera
1888

After a slide by Steve Marschner
More ingredients

Timed shutter
- with a UI for setting duration of exposure ("exposure time")

Variable aperture
- effective size of hole through which light enters can be changed
- with a UI for setting the size ("aperture")

Viewfinder
- to frame what you are photographing
- some way better than guessing
Camera, v. 2: 3 variables, 5 controls

- Turn to focus
- Turn to adjust aperture
- Pull to wind film
- Turn to adjust shutter speed
- Press to take picture

After a slide by Steve Marschner
Basic camera controls

Focus

Shutter speed

Aperture size

Adjustments that must be set for each image

- by you or by the camera’s software

- modern consumers cameras hide these, but they are still there
Thin lens optics

Simplification of geometrical optics for well-behaved lenses

Parallel rays converge to a point on a plane located at the focal length $f$ from lens

Rays going through the center are not deviated
  - hence, same perspective as pinhole
How lenses focus

Let’s look at an object at distance $D_o$
How to trace rays

Start by rays through the center

Choose focal length, trace parallels
How to trace rays

Start by rays through the center

Choose focal length, trace parallels

All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens

After a slide by Frédo Durand
Demo!

http://graphics.stanford.edu/courses/cs178/applets/thinlens.swf
Focusing

Focus closer than infinity?

- Move the sensor/film *further* than the focal length
Thin lens formula

Similar triangles everywhere!

After a slide by Frédo Durand
Thin lens formula

Similar triangles everywhere!

\[ \frac{y_i}{y_o} = \frac{D_i}{D_o} \]
Thin lens formula

Similar triangles everywhere!

$$\frac{y_i}{y_o} = \frac{D_i}{D_o}$$

$$\frac{y_i}{y_o} = \frac{D_i - f}{f}$$
Thin lens formula

All rays passing through a single point $y_o$ on a plane at distance $D_o$ in front of the lens will pass through a single point $y_i$ at distance $D_i$ behind the lens.

\[
\frac{1}{D_i} + \frac{1}{D_o} = \frac{1}{f}
\]
To focus objects at different distances, move sensor relative to lens.

At $D_o = D_i = 2f$ we have 1:1 imaging, because

$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$

In 1:1 imaging, if the sensor is 36mm wide, an object 36mm wide will fill the frame.

After a slide by Marc Levoy
To focus objects at different distances, move sensor relative to lens.

At $D_0 = D_i = 2f$ we have 1:1 imaging, because

$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$

Can’t focus on objects closer than its focal length $f$

- requires sensor at infinity
Demo

http://graphics.stanford.edu/courses/cs178/applets/gaussian.html
Virtual optical bench

By Andrew Adams

- http://graphics.stanford.edu/~abadams/lentstoy.swf

Also

Extensions tubes

Allow us to put sensor/film farther
- focus closer
Properties of real lenses

Mostly undesired!

Aberrations

- Spherical aberration
- Chromatic aberration

Distortion

- Barrel distortion
- Pincushion distortion

Etc.
Questions?
Field of view & focusing

What happens to the field of view when one focuses closer?

- It's reduced
- “breathing”
Question

What’s the advantage of a lens with a short focal length? In what situation would this be useful?

What’s the advantage of a lens with a long focal length? In what situation would this be useful?
Recall: Focal length impacts FOV

\[ \text{FOV} = 2 \arctan \left( \frac{s}{2f} \right) \]
Focal length & field of view

From *Photography*, London et al.

After a slide by Marc Levoy
Focal length & field of view

From Photography, London et al.

After a slide by Marc Levoy
Focal length = cropping

From Photography, London et al.
Focal length = cropping

From Photography, London et al.

After a slide by Marc Levoy
Focal length = cropping

From *Photography*, London et al.
Focal length = cropping

After a slide by Marc Levoy
Changing focal length vs. viewpoint

changing the focal length lets us move back from a subject, while maintaining its size in the image

but moving back changes perspective relationships

After a slide by Marc Levoy
Changing focal length vs. viewpoint

Moving forward while shortening focal length lets you keep objects at one depth the same size.

In cinematography, this is called the dolly-zoom, or “Vertigo effect” after Hitchcock’s movie.
Changing FOV, magnification constant

“Hitchcock zoom”

“Vertigo effect”

“Dolly-zoom”

Photos: Micaël Reynaud
Perspective vs. viewpoint

Portrait: distortion with wide angle. Why?
Portrait distortion

http://stepheneastwood.com/tutorials/lensdistortion/strippage.htm
Focal length & sensor size

What happens when the film is half the size?

Application:
- Real film is 36x24mm
- On the 10D, the sensor is 22.5 x 15.0 mm
- Crop/conversion factor on the 10D?
<table>
<thead>
<tr>
<th>Sensor Name</th>
<th>Medium Format</th>
<th>Full Frame</th>
<th>APS-H</th>
<th>APS-C</th>
<th>4/3</th>
<th>1&quot;</th>
<th>1/1.63&quot;</th>
<th>1/2.3&quot;</th>
<th>1/3.2&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Size</td>
<td>53.7 x 40.2mm</td>
<td>35 x 23.9mm</td>
<td>27.9 x 18.6mm</td>
<td>23.6 x 15.8mm</td>
<td>17.3 x 13mm</td>
<td>13.2 x 8.8mm</td>
<td>8.38 x 5.59mm</td>
<td>6.16 x 4.62mm</td>
<td>4.54 x 3.42mm</td>
</tr>
<tr>
<td>Sensor Area</td>
<td>21.59 cm²</td>
<td>8.6 cm²</td>
<td>5.19 cm²</td>
<td>3.73 cm²</td>
<td>2.25 cm²</td>
<td>1.16 cm²</td>
<td>0.47 cm²</td>
<td>0.28 cm²</td>
<td>0.15 cm²</td>
</tr>
<tr>
<td>Crop Factor</td>
<td>0.64</td>
<td>1.0</td>
<td>1.29</td>
<td>1.52</td>
<td>2.0</td>
<td>2.7</td>
<td>4.3</td>
<td>5.62</td>
<td>7.61</td>
</tr>
</tbody>
</table>

### Image

<table>
<thead>
<tr>
<th>Medium Format</th>
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<th>4/3</th>
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<th>1/2.3&quot;</th>
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<tr>
<td><strong>Example</strong></td>
<td>[Image]</td>
<td>[Image]</td>
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<td>[Image]</td>
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</tr>
</tbody>
</table>

Recap

Pinhole is the simplest model of image formation
- But dark
- Diffraction limited

Lenses gather more light
- But get only one plane focused
- Distance from lens to this plane is called focus distance
- Focus by moving sensor/film
- Cannot focus infinitely close

Focal length determines field of view
- From wide angle to telephoto
- Depends on sensor size
Exposure

Get the right amount of light to sensor/film

Two main parameters:

- Shutter speed
- Aperture (area of lens)
+ sensor/film sensitivity (ISO)
Exposure

Exposure = Irradiance x Time

Exposure time
- in seconds
- controlled by shutter

Irradiance
- amount of light falling on a unit area of sensor per second
- controlled by aperture
Shutter speed

Controls how long the film/sensor is exposed

Pretty much linear effect on exposure (until sensor saturates)

Denoted in fractions of a second:

- 1/30 s, 1/60 s, 1/125 s, 1/250 s, 1/500 s

- See a pattern?

On a normal lens, normal humans can hand-hold down to 1/60

- In general, the rule of thumb says that the limit is the inverse of focal length, e.g. 1/500s for 500mm
Main effect of shutter speed

Motion blur

Doubling exposure time doubles motion blur (const. velocity)
Shutter

Various technologies

Goal: achieve uniform exposure across image

Fig. 2.8 Two-blade guillotine shutter.

From Camera Technology, Goldberg
Figure 6-6. Jacques Henri Lartigue, *Grand Prix of the Automobile Club of France, 1912*. This classic photograph provides an exaggerated example of the distortion that can be caused by a focal-plane shutter. The oval shape of the automobile tire is caused by the motion of the car between the time the bottom of the tire was exposed and the top. (Remember—the image is upside-down on the negative.) The same principle caused the leaning appearance of the spectators. Lartigue turned the camera to follow the automobile (panning), and thus the image of the spectators moved at the film plane during the exposure. (Courtesy International Museum of Photography at George Eastman House.)
Camera movement

The solution:

- (yes, it’s a pain to carry)
Exposure

Exposure = Irradiance x Time

Exposure time
- in seconds
- controlled by shutter

Irradiance
- amount of light falling on a unit area of sensor per second
- controlled by aperture
Aperture

Diameter of the lens opening (controlled by diaphragm)

Irradiance on sensor is proportional to

- square of aperture diameter $A$
- inverse square of distance to sensor ($\sim$ focal length $f$)

As diameter $A$ of the aperture doubles, its area (hence the light that can get through it) increases by 4x. (circle area: $\pi A^2$)

If the distance to sensor is doubled, light projects onto an area 4x larger, so light falling per unit area decreases by 4x
F-number

So that aperture values give irradiance regardless of focal length, *aperture number N* is defined relative to focal length

\[ N = \frac{f}{A} \]

A relative aperture size (also F-number or just N) of N=2 is denoted “f/2” to reflect the above formula.

- f/2.0 on a 50mm means that the aperture is
- f/2.0 on a 100mm means that the aperture is
low F-number with long focal length

Sigma 200-500mm F2.8 EX DG lens

What does 1600mm lens look like?

http://www.digitalpixels.net/varia/the-web/sigma-200-500mm-f28-ex-dg-lens-on-the-field/


After a slide by Alyosha Efros
Disconcerting: **small f-number = big aperture**

What happens to the area of the aperture when going from f/2.0 to f/4.0? divided by 4 (square of f-number ratio)

Typical f numbers are

- f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32

- See a pattern?
  - aperture area gets halved in each step (1 f-stop)
  - f-number doubles every other step
Youtube tutorial

https://youtu.be/KmNIouLByJQ
Main effect of aperture

Depth of field

Doubling N (two f-stops) doubles depth of field

Large aperture opening

Small aperture opening

From Photography, London et al.
Depth of field

- Lens
- Sensor
- Point in focus
- Object with texture
Depth of field

We allow for some tolerance

Max acceptable circle of confusion
Circle of confusion

Also called “blur circle”

Calculation of radius $c$

- Lens focused at $S_1$
- Object at $S_2$
- Aperture $A$
- Focal length $f$

$$c = A \cdot \frac{|S_2 - S_1|}{S_2} \cdot \frac{f}{S_1 - f}$$

Proportional to $A$
Depth of field

What happens when we close the aperture by two stop?

- Aperture diameter is divided by two
- Depth of field is doubled
Depth of field

LESS DEPTH OF FIELD

Wider aperture  f/2

MORE DEPTH OF FIELD

Smaller aperture  f/16

From Photography, London et al.
F-number of the Human Eye

Questions?
Exposure

Two main parameters:

- Aperture (in f stop)
- Shutter speed (in fraction of a second)

Reciprocity

- Amount of light captured stays the same if exposure is doubled and aperture area is halved (or vice versa)

Hence square-root of two progression of f stops vs. power of two progression of shutter speeds

Reciprocity can fail for very long exposures
Reciprocity

Assume we know how much light we need

We have an infinite choice of shutter speed/aperture pairs

What will guide our choice of a shutter speed?
- Freeze motion vs. motion blur, camera shake

What will guide our choice of an aperture?
- Depth of field, diffraction limit
Analog

http://www.nzeldes.com/HOC/Posographe.htm
Sensitivity (ISO)

Third variable for exposure

Linear effect (200 ISO needs half the light as 100 ISO)

Film: trade sensitivity for grain

Digital: trade sensitivity for noise
Conclusions

Simple camera model
- Thin lens, aperture, shutter, sensor

Photographs often have undesired artifacts
- Distortions, color artifacts, blur, noise, under/overexposure

Goal: develop algorithms to remove artifacts after image is captured
Slide credits

Steve Marschner
Alyosha Efros
Frédo Durand
Marc Levoy
Matthias Zwicker