Image Formation

Frédo Durand
MIT - EECS
Administtrivia

- PSet 0 is out
- Due Tuesday February 12
Plan

• Pinhole optics
• Lenses
• Exposure
Why not use sensors without optics?

- It receives light from all directions
- It gets all possible images from all possible viewpoints
- We need to be more selective

From Photography, London et al.
Pinhole

From Photography, London et al.
Demo!
Focal length

![Diagram of a pinhole camera with labels for focal length (f), distance (s), film/sensor, and scene.]
Demo!
Focal length: pinhole optics

• What happens when the focal length is doubled?
  – Projected object size is doubled
  – Amount of light gathered is divided by 4
Questions?
Pinhole size?

Photograph made with small pinhole

From Photography, London et al.
2.18 **DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS.** These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechardt, 1958.

From Wandell
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
Recap: Problem with pinhole?

- Not enough light!
- Diffraction limits sharpness
Solution: refraction!

From Photography, London et al.
Lenses

- Gather more light!
- But need to be focused

To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.

This time, using a simple convex lens with an f/16 aperture, the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.

The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

From Photography, London et al.
Lenses

- Essentially add multiple pinhole images
- Shift them to align (refraction)
- Alignment works only for one distance

From Photography, London et al.
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
How lenses focus

• Let’s look at an object at distance D
How to trace rays

- Start by rays through the center
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
• You get the focus plane for a given scene plane
  – All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens
Focusing

- To focus closer than infinity
  - Move the sensor/film *further* than the focal length
Thin lens formula

\[ f \]

\[ D' \]

\[ D \]
Thin lens formula

Similar triangles everywhere!
Thin lens formula

Similar triangles everywhere!

\[ \frac{y'}{y} = \frac{D'}{D} \]
Thin lens formula

\[ \frac{y'}{y} = \frac{D'}{D} \]

\[ \frac{y'}{y} = \frac{(D' - f)}{f} \]
Thin lens formula

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

• By symmetry, an object at the focal length requires the film to be at infinity.
Extensions tubes

- Allow us to put sensor/film farther
  → focus closer
Question?
Field of view & focusing

- What happens to the field of view when one focuses closer?
  - It's reduced
Field of view & focusing

- What happens to the field of view when one focuses closer?
  - It's reduced
Questions?

Focal length in practice

- 24mm
- 50mm
- 135mm
Focal length vs. viewpoint

- Telephoto makes it easier to select background (a small change in viewpoint is a big change in background.)
Focal length vs. viewpoint

- Martin Scorcese, Good Fellas
- Moves camera as you zoom in
- Better known as the Hitchcock Vertigo effect
Focal length & sensor

- 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
  - Conversion factor on the 20D?
  - On the SD500, it is 1/1.8 " (7.18 x 5.32 mm)
  - What is the 7.7-23.1mm zoom on the SD500?
36x24mm (35mm format)

28.7x19.1mm (EOS 1D) = 1.26x magnification factor

APS-C sized sensors (EOS 10D, Nikon D100, Pentax *ist D, etc) = 1.5x - 1.6x

18x13.5mm (4/3" system - Olympus E-1)

8.8x6.6mm (2/3" P&S)

8.8x6.6mm (2/3")

7.2x5.3mm (1/1.8")

5.3x4mm (1/2.7")
Recap

• **Pinhole is the simplest model of image formation**
  – but dark
  – diffraction limited

• **Lenses gather more light**
  – But get only one plane focused
  – Focus by moving sensor/film
  – Cannot focus infinitely close

• **Focal length determines field of view**
  – From wide angle to telephoto
  – Depends on sensor size

*More in the lens lecture*
Questions?
Exposure

• Get the right amount of light to sensor/film
• Two main parameters:
  – Shutter speed
  – Aperture (area of lens)

+ sensor/film sensitivity (ISO)
Shutter speed

• Controls how long the film/sensor is exposed
• Pretty much linear effect on exposure
• Usually in fraction of a second:
  – 1/30, 1/60, 1/125, 1/250, 1/500
  – Get the 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. 1/500 for a 500mm
Main effect of shutter speed

- Motion blur

From Photography, London et al.
Effect of shutter speed

- Freezing motion

Walking people: 1/125
Running people: 1/250
Car: 1/500
Fast train: 1/1000
Aperture

- Diameter of the lens opening (controlled by diaphragm)
- Expressed as a fraction of focal length, in f-number
  - $f/2.0$ on a 50mm means that the aperture is 25mm
  - $f/2.0$ on a 100mm means that the aperture is 50mm
- 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 the pattern?
Main effect of aperture

• Depth of field

From Photography, London et al.
Depth of field

sensor  lens  Point in focus  Object with texture
Depth of field

- We allow for some tolerance

```plaintext
Max acceptable circle of confusion
```

```plaintext
Depth of field
```

```plaintext
Point in focus
```

```plaintext
Object with texture
```

```plaintext
Sensor
```

```plaintext
Lens
```

```plaintext
Depth of focus
```
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

Smaller aperture

More depth of field

From Photography, London et al.
Questions?
Exposure

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

• Reciprocity

  The same exposure is obtained with an exposure twice as long and an aperture area half as big

  – Hence square root of two progression of f stops vs. power of two progression of shutter speed
  – Reciprocity can fail for very long exposures

From Photography, London et al.
Reciprocity

- Assume we know how much light we need
- We have the choice of an infinity 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

- Often we must compromise
  - Open more to enable faster speed (but shallow DoF)
Small aperture (deep depth of field), slow shutter speed (motion blurred). In this scene, a small aperture (f/16) produced great depth of field; the nearest paving stones as well as the farthest trees are sharp. But to admit enough light, a slow shutter speed (1/8 sec) was needed; it was too slow to show moving pigeons and it also meant that a tripod had to be used to hold the camera steady.

From Photography, London et al.
Medium aperture (moderate depth of field), medium shutter speed (some motion sharp). A medium aperture (f/4) and shutter speed (1/125 sec) sacrifice some background detail to produce recognizable images of the birds. But the exposure is still too long to show the motion of the birds’ wings sharply.

From Photography, London et al.
Large aperture (shallow depth of field), fast shutter speed (motion sharp). A fast shutter speed (1/500 sec) stops the motion of the pigeons so completely that the flapping wings are frozen. But the wide aperture (f/2) needed gives so little depth of field that the background is now out of focus.
Questions?
Sensitivity (ISO)

- Third variable for exposure
- Linear effect (200 ISO needs half the light as 100 ISO)
- Film photography: trade sensitivity for grain

- Digital photography: trade sensitivity for noise

 Gain

<table>
<thead>
<tr>
<th>Camera Model</th>
<th>ISO 100</th>
<th>ISO 200</th>
<th>ISO 400</th>
<th>ISO 800</th>
<th>ISO 1600</th>
<th>ISO 3200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nikon D2X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kodachrome 25 ASA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ektachrome 64 ASA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fujichrome 100 ASA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ektachrome 200 ASA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From dpreview.com
Questions?
Equipment

- Do get an SLR, compacts are way too limited
- Don't worry about brand
- Don't worry about the body, get the cheapest one
- Worry about lenses
  - Zooms are convenient but quality can be a problem
    - avoid the basic zoom, but the one above is usually great
    - Maximum aperture matters (the smaller the number, the better)
  - Get a prime in the 35-85mm range
    (cheap, high quality, wide aperture)
    50mm f/1.8
- Get a tripod
- Get an external flash if you want to take “event” pictures
  - And orient towards (white) wall/ceiling
  - Good flash photography is very difficult
- Count ~1k for camera+standard zoom+50mm
Nikon

Tends to be a tad cheaper

- D40 is a great body. D80 is a little better.
- 18-70
- 55-200 is surprisingly not so bad and super cheap
- Get the 50mm f/1.8
Canon

- Rebel Xsi
- 17-85
- 70-200 f/4.0 (amazing lens)
- 50mm f/1.8
- 100mm f/2.8 macro (great also for portraits)
Other brands

Not as big a range, future not always clear (see Minolta), have been slower to get to digital SLR

• Olympus
  – Good system, but smaller sensor

• Pentax
  – Good entry camera

• Sigma
  – Intriguing sensor (Foveon), limited system

• Fuji
  – One-trick pony (the sensor)
  – Nikon body

• Sony
  – Interesting hybrid, the R1
  – Very silent, good images, crappy viewfinder, no interchangeable lenses
  – New SLR, alpha. Pretty good.
  – Lens selection not as good as Nikon/Canon
Shooting

- Use aperture priority, work on depth of field
- Change your viewpoint
- Don't center things
- Learn to adjust ISO

- Shoot raw
- Check your histogram
Software

- Photo management + lightweight editing
  - Lightroom, Aperture, Lightzone

- Crop to improve composition
- Manage contrast using curve and adjustment layers
- Add light to dark areas
- Sharpen a bit
- Convert to black and white

- Use Photoshop only if you really need to
Questions?
Reference

- [http://courses.csail.mit.edu/6.869/lectnotes/lect1](http://courses.csail.mit.edu/6.869/lectnotes/lect1)

- The slides use illustrations from these books
More references
Next time: exposure, color
Metering

• Photosensitive sensors measure scene luminance
• Usually TTL (through the lens)
• Simple version: center-weighted average

• Assumption? Failure cases?
  – Usually assumes that a scene is 18% gray
  – Problem with dark and bright scenes
White polar bear given exposure suggested by meter

White polar bear given 2 stops more exposure

Gray elephant given exposure suggested by meter

Black gorilla given exposure suggested by meter

Black gorilla given 2 stops less exposure

From Photography, London et al.
Metering

• Centered average

• Spot

• Smart metering
  – Nikon 3D matrix
  – Canon evaluative

• Incident
  – Measure incoming light
Nikon 3D Color Matrix


- Learning from database of 30,000 photos
- Multiple captors (segments)
- Exposure depends on
  - Brightness from each segments
  - Color
  - Contrast
  - Distance
  - Focus (where is the subject)
Exposure & metering

• The camera metering system measures how bright the scene is
• In Aperture priority mode, the photographer sets the aperture, the camera sets the shutter speed
• In Shutter-speed priority mode, the photographers sets the shutter speed and the camera deduces the aperture
  – In both cases, reciprocity is exploited
• In Program mode, the camera decides both exposure and shutter speed (middle value more or less)
• In Manual, the user decides everything (but can get feedback)
Pros and cons of various modes

• Aperture priority (My favorite, I use it 90% of the time)
  – Direct depth of field control
  – Cons: can require impossible shutter speed (e.g. with f/1.4 for a bright scene)

• Shutter speed priority
  – Direct motion blur control
  – Cons: can require impossible aperture (e.g. when requesting a 1/1000 speed for a dark scene)
    – Note that aperture is somewhat more restricted

• Program
  – Almost no control, but no need for neurons

• Manual
  – Full control, but takes more time and thinking
Recap: Metering

• Measure scene brightness
• Some advanced modes that take multiple sources of information
• Still an open problem