Image Formation

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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

\[ f \]

\[ s \]

Film/sensor

pinhole

scene
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?
Cool demo

- [http://www.youtube.com/watch?v=gvzpu0Q9RTU&feature=player_embedded#at=53](http://www.youtube.com/watch?v=gvzpu0Q9RTU&feature=player_embedded#at=53)
• http://www.petapixel.com/2011/05/25/university-mistakes-pinhole-camera-for-a-bomb-ruins-photo-project/
Pinhole size?

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.
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.
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

http://www.mashpedia.com/Ripple_tank
Recap: Problem with pinhole?

- Not enough light!
- Diffraction limits sharpness
Questions?

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

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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

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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

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Thin lens formula

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

Similar triangles everywhere!
Thin lens formula

Similar triangles everywhere! \[ \frac{y'}{y} = \frac{D'}{D} \]
Thin lens formula

Similar triangles everywhere!

\[ \frac{y'}{y} = \frac{D'}{D} \]
\[ \frac{y'}{y} = \frac{(D' - f)}{f} \]
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 = cropping

- 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 Scorsese, Good Fellas
- Moves camera as you zoom in
- Better known as the Hitchcock Vertigo effect
Perspective vs. viewpoint

- Portrait: distortion with wide angle
- Why?

Wide angle  Standard  Telephoto
• [http://stepheneastwood.com/tutorials/lensdistortion/strippage.htm](http://stepheneastwood.com/tutorials/lensdistortion/strippage.htm)
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

Running people

Car

Fast train

1/125

1/250

1/500

1/1000

Note: it doesn’t mean that shutter speed is proportional to the speed of the object. A photographer usually tracks the subject.
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?
Youtube tutorial

• http://www.youtube.com/watch?feature=player_embedded&v=KmNIouLByJQ
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

![Diagram of depth of field]

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

Max acceptable circle of confusion

- Depth of focus
- Sensor
- Lens
- Object with texture
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

From Photography, London et al.
Very large aperture

• Kubrick used an f/0.7 lens for Barry Lyndon!
• http://www.visual-memory.co.uk/sk/ac/len/page1.htm
• http://www.youtube.com/watch?v=gqkBzaFqcuE
•

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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 sharply. It also meant that a tripod had to be used to hold the camera steady.
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.
Analog

- http://www.nzeldes.com/HOC/Posographe.htm

see also http://meters.barrylevinson.org/
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

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From dpreview.com

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Questions?
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
Challenge: high or low key scenes

• This photo is not 18% grey on average
• I had to tell the camera to make it 4 times brighter
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
Metering

- Centered average
- Spot
- Smart metering
  - Nikon 3D matrix
  - Canon evaluative
- Incident
  - Measure incoming light

Choice on Nikon

http://www.mir.com.my//

From the luminous landscape

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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 photographer 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
Reference

• http://courses.csail.mit.edu/6.869/lectnotes/lect1
• http://en.wikipedia.org/wiki/Lens_(optics)

• The slides use illustrations from these books
More references

Ansel Adams
The Camera

Ansel Adams
The Negative

Ansel Adams
The Print

The Ansel Adams Photography Series 1

The Ansel Adams Photography Series 2

The Ansel Adams Photography Series 1

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