Focal length in practice

24mm

50mm

135mm

For a 24x36mm sensor
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
Perspective vs. viewpoint

- Portrait: distortion with wide angle
- Why?

Wide angle | Standard | Telephoto

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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?
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
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
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 the 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.

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.
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
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

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 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).

http://www.karbosguide.com/books/photobook/chapter22.htm
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

http://www.zazzle.com/canon_camera_mode_dial_tshirt-235252453011181628
Recap: Metering

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

• Why is this toy so expensive
  – EF 70-200mm f/2.8L IS USM
  – $1700

• Why is it better than this toy?
  – EF 70-300mm f/4-5.6 IS USM
  – $550

• Why is it so complicated?

• What do these buzzwords and acronyms mean?

Tuesday, April 12, 2011
Lens quality varies!

source: the luminous landscape

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Center is usually OK

- http://www.photo.net/equipment/canon/70-300do_2/

250x500 pixel crops, centre of frame f5.6
Image corners are often sacrificed

- [Link to image](http://www.photo.net/equipment/canon/70-300do_2/)

250x500 pixel crops, corner of frame f5.6
Max aperture is tough

- [http://www.photo.net/equipment/canon/70-300do_2/](http://www.photo.net/equipment/canon/70-300do_2/)

250x500 pixel crops, centre of frame f5.6
Gets better when stopped down

- [http://www.photo.net/equipment/canon/70-300do_2/](http://www.photo.net/equipment/canon/70-300do_2/)

250x500 pixel crops, centre of frame f11
Copy variation

- Left: Addy's 100-400; Right: Frédo's
- (full aperture, 135mm)
Why are lenses so complex?

- It’s not so easy to send light where it should go

source: canon red book
Simple lenses are not so good

Plate 11.2  Aberrated imagery from a simple biconvex lens
The image of simple regular patterned subject shows increasingly poor quality off axis and the two uncoated surfaces of the lens both reflect the light source.
Complex lenses are better!

Plate 11.1 Imaging by simple and compound lenses
(a) Simple biconvex one element lens of focal length 100 mm and diameter 50 mm giving f/2. Note poor edge detail and low overall contrast. (b) Same lens stopped down to f/11. Quality and contrast have improved. (c) A well-corrected five-element 105 mm lens used at f/11.

From Ray’s Applied Photographic Optics
Lens 101 review
Thin lens optics

• Simplification of geometrical optics 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

TODAY WE GO BEYOND THESE SIMPLIFICATIONS
View #1 of lenses: Geometrical

• Snell’s law bends geometrical rays
  – I mean, Descartes’ law
• Most aberrations can be expressed in this framework
View #2 of lenses (Wave/Fermat)

• Light is focused because all paths have same length
  – Higher index of refraction (speed of light) compensates for length
  – Constructive interference
Consequences on image quality

- Geometrical optics: hard to focus all rays
- Wave optics: diffraction problems
Geometrical perspective
• Snell’s law bends geometrical rays
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
Simplification of first-order optics

- Snell’s law: \( \eta_1 \sin \theta_1 = \eta_2 \sin \theta_2 \)
- First order/thin lens optics: use \( \sin \theta = \theta \)
Third-order optics

- \( \sin \theta = \theta - \theta^3/6 \)
- The extra term leads to third-order aberrations
Third-order aberrations
Spherical aberration

- Rays don’t focus at same position

source: Hecht Optics
Comatic aberration

Figure-20 Comatic Aberration

This is the phenomenon where the diagonal light rays do not focus on one point on the image surface.

This is the phenomenon where there is a tail like that of a comet.

Off-axis parallel pencil of rays

Inward coma

Outward coma

Optical axis

source: canon red book
Comatic aberration
Astigmatism

This is the phenomenon where there is no point image.

source: canon red book
Defects

Photo-2 The photographs are magnifications of the subject and surrounding area from part of a test chart photographed with a 24mm x 36mm film frame and printed on quarter size paper.

Almost ideal image formation

Peripheral □ part magnified

① Example of spherical aberration

②-1 Example of inward coma

③ Example of astigmatism

②-2 Example of outward coma

source: canon red book
Curvature of field

Figure-22 Curvature of field

This is the phenomenon where a good image focus surface is bent.

○ This is an ideal lens with no image bending.

Subject surface

Focus surface

Subject

○ Occurrence of image bending

Photo-5 Example of curvature of field

Focusing on center of screen causes corners to go out of focus.

Photo-6 Example of curvature of field

Focusing on corners of screen causes center to go out of focus.

source: canon red book

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Curvilinear/radial distortion

Figure 6.10  The effects of curvilinear distortion. (a) The selection of a geometrically incorrect ray bundle by asymmetric location of the aperture stop. (b) Image shape changes caused by barrel and pincushion distortion.

From "The Manual of Photography" Jacobson et al

http://www.dxo.com/us/photo/dxo_optics_pro/optics_geometry_corrections/distortion
Radial distortion

• Correct for “bending” in wide field of view lenses

e.g. parametric warp, specified by two lens-dependent parameters $k_1$ and $k_2$

$$\tilde{r}^2 = \tilde{x}^2 + \tilde{y}^2$$

$$\tilde{x}' = \tilde{x}/(1 + \kappa_1 \tilde{r}^2 + \kappa_2 \tilde{r}^4)$$

$$\tilde{y}' = \tilde{y}/(1 + \kappa_1 \tilde{r}^2 + \kappa_2 \tilde{r}^4)$$

$$x = f \tilde{x}'/\tilde{z} + x_c$$

$$y = f \tilde{y}'/\tilde{z} + y_c$$

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Why spherical lenses?

• Because they are easy to manufacture
• (Start from whatever shape, if you grind enough, it will become spherical)
Aspherical lenses

Spherical aberration of spherical lens

Focal point alignment with aspherical lens

Photo-9 Spherical Lens Example

Photo-10 Aspherical Lens Example

source: canon red book
Aspherical lenses

- Harder to manufacture ➞ used with parsimony
Chromatic aberrations
Chromatic aberration

- The previous aberrations depend on wavelength (because of varying index of refraction)

source: canon red book
Achromatic doublet

Figure 6.38 An achromatic doublet. The paths of the rays are much exaggerated.
Apochromatic & others

• Optimize for multiple wavelengths
  • http://www.vanwalree.com/optics/chromatic.html

Figure 5. Principles of color correction. The colored faces are known as the secondary spectrum.
Fluorite

• Low dispersion

source: canon red book
Bottomline

• Fighting chromatic aberrations is the main cause of lens complexity
Diffraction
(a) The shadow of Mary's hand holding a dime, cast directly on 4 x 5 Polaroid A.S.A. 3000 film using a He–Ne beam and no lenses. (Photo by E. H.) (b) Fresnel diffraction of electrons by zinc oxide crystals. (After H. Boersch from Handbuch der Physik, edited by S. Flügge, Springer-Verlag, Heidelberg.)

Diffraction through an aperture with varying \( \lambda \) as seen in a ripple tank. (Photo courtesy PSSC Physics, D. C. Heath, Boston, 1960.)
Airy patterns

- Image of an infinitesimal point
  - for disk aperture
- Absolute limit on lens resolution
- Important at small aperture
- Critical for microscope & telescope

- Formally:
  Bessel function
  - Fourier transform of disk
  - Equivalent of sinc for the box

From Hecht's Optics
Diffraction & Fourier

• Aperture Fourier transform

Photo by Eric Chan
Fraunhofer diffraction

- Incoming coherent plane wave
  - e.g. light coming from a star
  - should image into perfectly sharp point
Converge at focal length $\iff$ same path duration (aka optical length)

- peripheral paths spend more time in air
- but less in lens (lens is thinner at periphery)
- light is slower in glass

**Fermat principle**

![Diagram showing converged light path through a lens.](image)
Refraction and the Lifeguard Problem

- Running is faster than swimming
Fermat principle

- Converge at focal length $\iff$ same path duration (aka optical length)
- Wave contributions remain coherent $\Rightarrow$ interfere positively

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Fermat principle

- Converge at focal length $\iff$ same path duration (aka optical length)
- Wave contributions remain coherent $\implies$ interfere positively
- Same for any direction, just different point

mono-chromatic plane wave

Lens

same optical path length in blue

focal plane

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Huygens-Fresnel principle

- Each point of the aperture is equivalent to a source of spherical “wavelets”
  - kind of superposition principle
  - All “synchronized” (coherent)

- When no obstacle, their superposition is still a plane wave
• Contribution at a point on sensor
  – same Fermat minimal paths as before
  – Contribution: integral over paths

Diffraction with lens
Integral at a point on sensor

- Wavelets lower in aperture have longer path
  - $\text{path}(A, P) = \text{path}(B', P)$
  - $\text{phase}(A) = \text{phase}(B)$
  - $\|BB'\| = \|AB\| \sin \theta$
    (where $\theta$ is deviation from optical axis)
  - $dt = \|BB'\|/c$
    where $c$ is the speed of light
Integral at a point on sensor

- point at z from A:
- \( dt(z) = z \sin \theta / c = kz \)
Integral at a point on sensor

- point at z from A:
- $dt(z) = z \sin \theta / c = kz$
- wave: $x(A,t) = x(z,t) = X(t) = e^{i\omega t}$
- $x(z',t) = x(z, t-dt(z)) = X(t) e^{-i\omega dt}$
Integral at a point on sensor

- $x(z', t) = x(z, t - dt(z)) = X(t) \ e^{-i\omega dt}$

- contribution at $P$:

$$\int_X X(t - \text{path}(A, P)) \ e^{-i\omega k z}$$
Integral at a point on sensor

- average power contribution at P: \( \| \int_{z} e^{-i \omega k z} \|^{2} \)

- Looks a lot like Fourier power spectrum for frequency \( k \omega \)

- Note that \( k \) increases when \( P \) moves up
  - (linearly if the sine is linearized)
Summary

- Diffraction => power spectrum
- Huygens Fresnel: point waves at aperture
- Integrate those little waves, offset by path length => integrate sine waves
  => Fourier
Effect of aperture size

- When we scale down a function
- Scale up power spectrum
- smaller aperture $\Rightarrow$ More diffraction
Lens diffraction

Lens diffraction

- See also [http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm](http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm)
The idiocy of Megapixels

Questions?
Other quality issues
Flare

Figure 5.6 Formation of flare spots by a simple lens. Images of the source are formed at distances $A$ and $B$, where:

$$A = \left( \frac{n - 1}{an - 1} \right) f \quad B = \left( \frac{n - 1}{bn - 1} \right) f$$

and $a = 2, 4, 6 \ldots$, $b = 3, 5, 7, \ldots$ For $n = 1.5$, $A = f/4, f/10, f/16$ etc. and $B = f/7, f/13, f/19$ etc.

From "The Manual of Photography" Jacobson et al
Example of flare "bug"

- Some of the first copies of the Canon 24-105 L had big flare problems
Use a hood! (and a good one)

Adapted from Ray's Applied Photographic Optics

Flare ray Hood is to short

Good hood

Adapted from Ray's Applied Photographic Optics

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Plate 15.1  Lens flare with an uncoated lens
(a) Flare effects. (b) Reduction of flare by use of a lens-hood.

From Ray's Applied Photographic Optics
Coating

- Apply thin layer with different index of refraction
- Use destructive interferences
- One of the most important advances in optics

From "The Manual of Photography" Jacobson et al  
Coating

• Image taken with an uncoated lens
• Note the muted color

http://www.alliedforum.net/viewtopic.php?f=106&t=2093
Coating

- Optimized for one wavelength

Figure 5.8  The effects on surface reflection of various types of anti-reflection coatings as compared with uncoated glass (for a single lens surface at normal incidence)

From "The Manual of Photography" Jacobson et al
Vignetting

- http://www.photozone.de/3Technology/lensotec3.htm
Vignetting

- The periphery does not get as much light

source: canon red book
Quality evaluation
LPIs

- Line pair per inch

Input

After lens

http://www.imatest.com/docs/sharpness.html


http://www.imatest.com/docs/tour.html
Sharpness
MTF

- Modulation Transfer Function
- Pretty much Fourier transform of lens response
- Complex because needs to be measured at multiple location

source: canon red book

Here the x axis is image location
Blur index based on Photoshop!

- Lens sharpness (or lack thereof) expressed as the amount of Photoshop blur that would blur the image similarly

- 50mm f/1.4 [http://www.slrgear.com/reviews/showproduct.php/product/140/sort/2/cat/10/page/2](http://www.slrgear.com/reviews/showproduct.php/product/140/sort/2/cat/10/page/2)
Lens design
Optimization software

- Has revolutionized lens design
- E.g. zooms are good now

From Hecht's Optics
Lens design, ray tracing

Figure-5

Figure-6

Figure-7

Figure-8

Figure-9

Figure-10

source: canon red book
Optimization

• Free parameters
  – Lens curvature, width, position, type of glass
  – Some can be fixed, other vary with focal length, focus (e.g. floating elements)
  – Multiplied by number of lens elements

• Energy/merit function
  – MTF, etc.
  – Black art of massaging the merit function

• Optimize for
  – All image locations
  – All wavelengths
  – All apertures
  – All focusing distances
  – All focal lengths (zoom only)

• Usually uses simulated annealing
References

- *Optics*, fourth edition, Eugene Hecht
- *Optical Engineering: Optical System Design*, Robert E. Fischer and Biljana Tadic-Galek
- *EF Lens Work III: The Eyes of EOS*, Canon
Links

- [http://www.dpreview.com/learn/?/key=chromatic+aberration](http://www.dpreview.com/learn/?/key=chromatic+aberration)
- [http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/aberrcon.html#c1](http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/aberrcon.html#c1)