Lenses

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Final project
Overview

• So far, we have mostly taken the input image for granted
• Today, we focus on the optics side & image formation
Important question

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

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

• Why is it so complicated?

• What do these buzzwords and acronyms mean?
Lens 101

review
• Focal length (in mm)
  – Determines the field of view.
    wide angle (<30mm) to telephoto (>100mm)
• Focusing distance
  – Which distance in the scene is sharp
• Depth of field
  – Given tolerance, zone around the focus distance that is sharp
• Aperture (in f number)
  – Ratio of used diameter and focal lens.
    Number under the divider $\Rightarrow$ small number = large aperture
    (e.g. f/2.8 is a large aperture, f/16 is a small aperture)
• Shutter speed (in fraction of a second)
  – Reciprocity relates shutter speed and aperture
• Sensitivity (in ISO)
Quantities

- focal length
- focus distance
- field of view
- depth of field
- lens size
- sensor size
Focal length

<30mm: wide angle
50mm: standard
>100mm telephoto

Affected by sensor size (crop factor)
Lenses

- In a photo system, the lens is most critical
- Lenses are characterized by
  - Prime vs. zoom
  - Focal length (field of view)
  - Maximum aperture (the f number like f/2.8)
  - Various gizmos (e.g. image stabilization, faster autofocus)
  - More complex quality issues
  - Minimum focusing distance
- Max aperture is usually correlated with quality
- Warning: lenses are addictive
• Yes, you can get a cheap & razor sharp high-quality lens: look for a prime in the 35-100mm range
  – e.g. Canon 50mm f/1.8, 85mm f/1.8, Nikon 50mm f/1.8

• See also

  http://www.photozone.de/3Technology/lens_tec4.htm
Lens quality varies!

source: the luminous landscape
<table>
<thead>
<tr>
<th>Camera Configuration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Canon 100-400mm f/3.5-f/5.6L zoom</td>
<td>Canon 400mm f/5.6L</td>
</tr>
<tr>
<td>@ f/5.6</td>
<td>@ f/5.6</td>
</tr>
</tbody>
</table>

source: the luminous landscape
Center is usually OK

- [http://www.photo.net/equipment/canon/70-300do_2/](http://www.photo.net/equipment/canon/70-300do_2/)
Image corners are often sacrificed

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

- http://www.photo.net/equipment/canon/70-300do_2/
Again, better when stopped down

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

Even when combined with a digital camera, an EF lens has high potential. In this photo of a harbor crowded with yachts, high resolution reveals the fine detail in individual boats. Photographing images with detailed subject matter, such as landscapes, is possible without having to differentiate between a digital camera and a 35mm film camera.

source: canon red book
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.

From Ray's Applied Photographic Optics
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
View #1 of lenses: Geometrical

- Snell’s law bends geometrical rays
- Most aberrations can be expressed in this framework
View #2 of lenses (Fermat/wave)

- 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

From Optical System Design by Fisher and Tadic
Diffraction
Geeky joke

At first God said

\[ \nabla \cdot \mathbf{E} \quad = \quad 4\pi \rho \]
\[ \nabla \times \mathbf{E} \quad = \quad -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} \]
\[ \nabla \cdot \mathbf{B} \quad = \quad 0 \]
\[ \nabla \times \mathbf{B} \quad = \quad \frac{4\pi}{c} \mathbf{J} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}, \]

and there was light

(interestingly, the joke has a higher Google rating than the actual book of Genesis)

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. Flugge, 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.)
Fraunhofer diffraction

- Far from aperture (ideally at infinity)
  "Lots of things get linearized"
- Incoming coherent plane wave, aperture
- Diffraction = Fourier transform of aperture
- Works because
  - wave in time & space
  - coherent
Airy patterns

- Absolute limit on lens resolution
- Important at small aperture

Airy rings using (a) a 0.5-mm hole diameter and (b) a 1.0-mm hole diameter. (Photo by E. H.)

From Hecht's Optics
Lens diffraction

Lens diffraction


- See also [http://www.cambridgeeincolour.com/tutorial;diffraction-photography.htm](http://www.cambridgeeincolour.com/tutorial;diffraction-photography.htm)
Diffraction & Fourier

• Aperture Fourier transform
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
Why spherical lenses?

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

From Optical System Design by Fisher and Tadic
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

source: canon red book
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

Optical axis

Inward coma

Outward coma

source: canon red book
Comatic aberration

From Hecht's Optics
Astigmatism

Figure-21 Astigmatism

This is the phenomenon where there is no point image

Principle ray

Lens

Optical axis

Sagittal image

Meridional 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

source: canon red book

Photo-5 Example of curvature of field

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

Photo-6 Example of curvature of field

Focus on corners of screen causes center to go out of focus.
Curvilinear 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
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

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

APO" elements (UD, SUD, CaF2, LD, SLD, ED etc.) improve contrast and sharpness by reducing chromatic aberration (color defects) that usually occur in tele lenses. These elements are able to focus different wave lengths of one light ray in one point (see picture below). These elements are quite expensive and usually not used for cheaper lenses. The problem is however that the quality of these special elements varies heavily so the effect is often downgraded to a marketing gag - this is especially true for some third-party manufacturers! As a rule-of-thumbs a good long tele lens will always feature two or more of these special elements. Recently the first ultra-wide and wide-angle lenses emerged using APO elements besides aspericals in order to reduce problems with lateral color shifts.

http://www.photozone.de/3Technology/lengstece.htm
Fluorite

- Low dispersion

**Figure-22** Comparison of Color Aberration Correction

**Figure-21** Secondary Spectrum

**Photo-12** Artificial Fluorite Crystals and Fluorite Lenses

source: canon red book
Diffractive optics (DO)

Figure-58 Diffraction
- Slit (small aperture, etc.)
- Light entering through slit
- Entering light
- Wavelength
- Light blocking area (aperture blade, etc.)

Figure-59 Principle of diffracted light generation
- Entering light
- Lattice interval
- Angle of diffraction
- Wavelength of light
- Light blocking area
- Primary diffracted light

Photo-23 Multi-Layered Diffractive Optical Element (DO lens)
- Refractive only
- Diffractive only
- Refractive / diffractive hybrid
- B G R
- R G B
- G R B

Source: Canon Red Book
From Optical System Design by Fisher and Tadic
Diffractive optics

- Enables smaller lenses

Figure-64 Compact and Lightweight Lenses Thanks to Multi-layered Diffractive Optical Element

source: canon red book
Purple fringing

- [http://www.dpreview.com/learn/?/key=chromatic+aberration](http://www.dpreview.com/learn/?/key=chromatic+aberration)

"Purple Fringing" and Microlenses

Although the above chromatic aberrations can be purple in color under certain circumstances, "Purple Fringing" usually refers to a typical digital camera phenomenon that is caused by the microlenses. In simplified terms purple fringing is "chromatic aberration at microlens level". As a consequence, purple fringing is visible throughout the image frame, unlike normal chromatic aberration. Edges of contrasty subjects suffer most, especially if the light comes from behind them, as shown in the example below. Blooming tends to increase the visibility of purple fringing.
Software post-processing
Recall Radial distortion

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

\[
\hat{r}^2 = \hat{x}^2 + \hat{y}^2 \\
\hat{x}' = \hat{x}/(1 + \kappa_1 \hat{r}^2 + \kappa_2 \hat{r}^4) \\
\hat{y}' = \hat{y}/(1 + \kappa_1 \hat{r}^2 + \kappa_2 \hat{r}^4) \\
x = f \hat{x}'/\hat{z} + x_c \\
y = f \hat{y}'/\hat{z} + y_c
\]

Use this instead of normal projection
source digital outback
General principle

• Calibrate lens
• Perform image warp
• Perform different warps for various color channels
Software

- [http://www.tawbaware.com/maxlyons/pano12ml.htm](http://www.tawbaware.com/maxlyons/pano12ml.htm)

From DXO:
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:

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

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.
Example of flare "bug"

• Some of the first copies of the Canon 24-105 L had big flare problems

Coating

- Use destructive interferences
- Optimized for one wavelength

Figure 5.7  An anti-reflection coating on glass using the principle of destructive interference of light between reflections $R_1$ and $R_2$

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
Coating

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
Flare and Ghosting

Figure-29 Flare and Ghosting

source: canon red book
Use a hood! (and a good one)

Hood is too short

Good hood

Adapted from Ray's Applied Photographic Optics
Anti-Reflection Coating Techniques
This method employs a special paint on angled surfaces and joining surfaces where the lens elements are held in place by the lens barrel to stop light entering the lens from reflecting from these parts. If a standard coating is used, reflections

source: canon red book
Flare/ghosting special to digital

For flat protective glass

In lenses employing flat protective glass, a reflection occurs between the image sensor and the protective glass, which causes the subject to be photographed in a position different from the actual position.

Source: canon red book

For a meniscus lens

In lenses employing a meniscus lens, no reflection like that seen to the left occurs.
Coating for digital

Lens for which the lens shape and coating have not been optimized

Flaring and ghosting occurs with lens for which the lens shape and coating have not been optimized.

Entracing light ray

Light ray reflected by the image sensor surface

The power of lenses only visible in extreme enlargement

Lens

source: canon red book

Lens for which the lens shape and coating have been optimized

Flaring and ghosting are suppressed with lens for which the lens shape and coating have been optimized.

Entracing light ray

Light ray reflected by the image sensor surface

Reflection by the lens surface has been suppressed by optimizing the coating.
Vignetting

- The periphery does not get as much light

Figure-28 Vignetting

source: canon red book
Vignetting

- http://www.photozone.de/3Technology/lensotec3.htm
Quality evaluation
LPIs

- Line pair per inch

Input

After lens

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

*Figure 11.50* An example of the kind of lens design information available via computer techniques. (Photos courtesy Optical Research Associates.)

From Hecht's Optics
Lens design, ray tracing

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)
Floating elements

- Move with focus to optimize response (but are not responsible for focusing)

Figure-32  EF85mm f/1.2L USM Floating System

Figure-33  Floating Effect (at 0.95m)

source: canon red book
Image stabilization
Image stabilization

1. Lens when still
   - To subject
   - IS lens group
   - Focal plane

2. Camera shaken
   - Camera shake

3. Camera shaking corrected
   - Corrected light rays
   - IS lens group shifts downward

Photo-21  Shake-detecting gyro sensor

source: canon red book
Image stabilization

Figure-54  EF70-200mm f/2.8L IS USM Image Stabilizer System

source: canon red book
Image stabilization

source: canon red book
1000mm, 1/100s, monopod, IS
Different versions

- Canon, Nikon: in the lens
- Panasonic, Konica/Minolta: move sensor
Special lenses
Some special lenses

- Mirror lenses
- Tilt-shift lenses
- Macro lenses
  - Why sharpness is always great (thanks Gauss)
  - Why you lose light
catadioptric (mirror)

500mm vivitar ($100)
500mm Canon (5k)
Mirror lens
References

- Optics
  - Eugene Hecht

- Optical System Design
  - Robert E. Fischer / Biljana Tadic-Galeh

- Applied Photographic Optics
  - Sidney E. Ray

- Photography
  - Eighth Edition

- EF LENS WORK III
  - The Eyes of EOS