Evaluation

• 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 length.
  Number under the divider ➔ small number = large aperture
  (e.g. f/2.8 is a large aperture, f/16 is a small aperture)

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**Focal length**

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

Affected by sensor size (crop factor)

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**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

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**Bottom line**

• 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/lenstec4.htm

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**Lens quality varies!**
Center is usually OK
• http://www.photo.net/equipment/canon/70-300do_2/

Image corners are often sacrificed
• http://www.photo.net/equipment/canon/70-300do_2/

Max aperture is tough
• http://www.photo.net/equipment/canon/70-300do_2/

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

Typical test pattern
• http://www.photo.net/equipment/canon/70-300do_2/
Again, better when stopped down:
- http://www.photo.net/equipment/canon/70-300d0_2/

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

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!

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 (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

**Diffraction**

**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

**Geeky joke**

At first God said

\[
\begin{align*}
V & = E \\
I & = \frac{E}{V} \\
B & = \frac{E}{V} \\
\end{align*}
\]

and there was light

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


**Diffraction**

From Hecht's Optics

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

Lens diffraction

- See also http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm

Diffraction & Fourier

- Aperture Fourier transform

Geometrical perspective

- Snell’s law bends geometrical rays

Back to View #1 of thin lenses

- 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

- Harder to manufacture ≥ used with parsimony

Comatic aberration

Astigmatism
**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.

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**Curvilinear distortion**


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**Chromatic aberrations**

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

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**Achromatic doublet**

Figure 6.38: An achromatic doublet. The paths of the rays are much exaggerated.

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**Apochromatic & others**

Optimize for multiple wavelengths.

http://www.vanwalree.com/optics/chromatic.html
**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 wavelengths 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/chemistry8.html

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**Fluorite**

- Low dispersion

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**Diffractive optics (DO)**

- Enables smaller lenses

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**Purple fringing**

- http://www.dpreview.com/learn/?/key=chromatic+aberration

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**Software post-processing**
Recall Radial distortion

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

\[
\begin{align*}
\tilde{z}^2 &= \tilde{z}^2 + \tilde{y}^2 \\
\tilde{z}' &= \frac{\tilde{z}}{1 + \kappa_1 \tilde{z}^2 + \kappa_2 \tilde{z}^4} \\
\tilde{y}' &= \frac{\tilde{y}}{1 + \kappa_1 \tilde{z}^2 + \kappa_2 \tilde{z}^4} \\
x &= f\tilde{x}'\tilde{z} + x_c \\
y &= f\tilde{y}'\tilde{z} + y_c
\end{align*}
\]

Use this instead of normal projection.

General principle

- Calibrate lens
- Perform image warp
- Perform different warps for various color channels

Software

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

Flare

Other quality issues
Example of flare "bug"

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

Flare and Ghosting

Flare/ghosting special to digital

Use a hood! (and a good one)

Lens hood

Fighting reflections
Coating

• Use destructive interferences
• Optimized for one wavelength

Vignetting

• The periphery does not get as much light

Quality evaluation

LPIs

• Line pair per inch
Sharpness

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

**Blur index based on Photoshop**

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

- [100 macro](http://www.slrgear.com/reviews/showproduct.php/product/157/sort/2/cat/10/page/1)
- [50mm f/1.4](http://www.slrgear.com/reviews/showproduct.php/product/140/sort/2/cat/10/page/2)
- [18-55](http://www.slrgear.com/reviews/showproduct.php/product/137/sort/2/cat/11/page/1)
- [17-85](http://www.slrgear.com/reviews/showproduct.php/product/136/sort/2/cat/11/page/1)
- [10-22](http://www.slrgear.com/reviews/showproduct.php/product/135/sort/2/cat/11/page/1)

**Lens design**

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

**Optimization software**

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

Floating elements

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

Image stabilization
1000mm, 1/100s, monopod, IS

Different versions
- Canon, Nikon: in the lens
- Panasonic, Konica/Minolta: move sensor

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


catadioptric (mirror)
References

References

http://www.digit-life.com/articles2/rubinar/

Links

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