



Lenses

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Final project



Overview

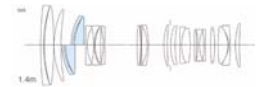


- So far, we have mostly taken the input image for granted
- Today, we focus on the optics side & image formation

Important question



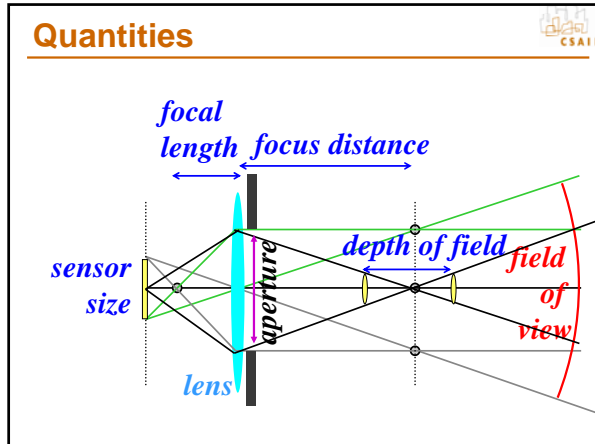
- Why is this toy so expensive
 - EF 70-200mm f/2.8L IS USM
- Why is it better than this toy?
 - EF 70-300mm f/4-5.6 IS USM
- Why is it so complicated?



- 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 → 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)**



Focal length

<30mm: wide angle
50mm: standard
>100mm telephoto
 Affected by sensor size (crop factor)

The diagram shows a person holding a camera with different focal lengths, illustrating how the field of view changes. A 7.5mm lens provides a very wide field of view (180°), while a 500mm lens provides a very narrow field of view (9°). Three example photos are shown: a 24mm wide-angle shot of a landscape, a 50mm standard shot, and a 135mm telephoto shot of a cliff.

- ### 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

- ### 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>



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



- 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/



250x500 pixel crops, centre of frame f5.6

Gets better when stopped down



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

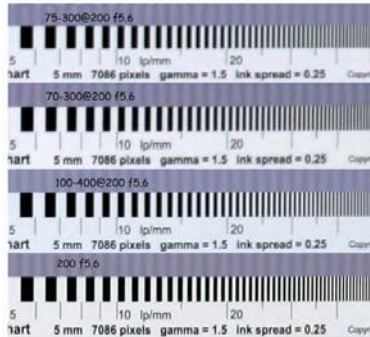


250x500 pixel crops, centre of frame f11

Typical test pattern



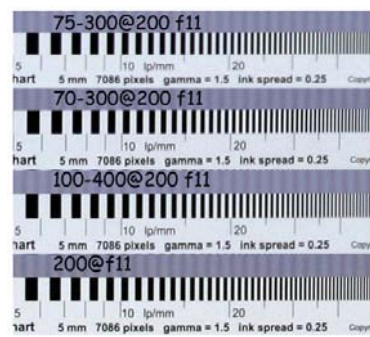
- http://www.photo.net/equipment/canon/70-300do_2/



Again, better when stopped down



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



Power of lenses

When the lens has high resolution

When the lens has low resolution

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 lines. 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

Figure-11
Cross-Section of the EF24-70mm 1:2.8L USM

Photo: 4 Photo: Zeiss Carl Lens Book

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

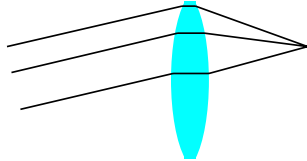
View #1 of lenses: Geometrical

- 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

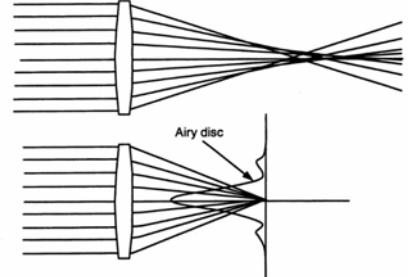


Consequences on image quality



- Geometrical optics: hard to focus all rays
- Wave optics: diffraction problems

Figure 3.1
Image Quality: Geometrical Aberrations (Top) and Diffraction Limited (Bottom)



From Optical System Design by Fisher and Tadic

Diffraction

Geeky joke



At first God said

$$\begin{aligned}\nabla \cdot \mathbf{E} &= 4\pi\rho \\ \nabla \times \mathbf{E} &= -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{B} &= \frac{4\pi}{c} \mathbf{J} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t},\end{aligned}$$

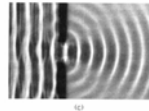
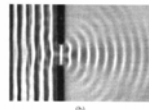
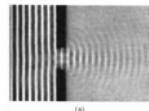
and there was light

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



Equations from <http://scienceworld.wolfram.com/physics/MaxwellEquations.html>

Diffraction



(a) The shadow of Mary's hand holding a dime, cast directly on a 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. Borchers from Handbuch der Physik, edited by S. Flügge, Springer Verlag, Heidelberg.)

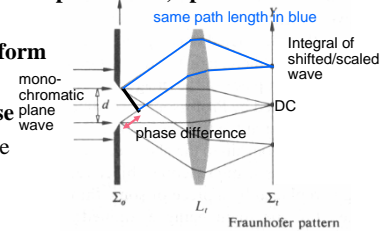
(c) Diffraction through an aperture with varying λ , as seen in a ripple tank. (Re courtesy PSC, Physics, D. C. Heath, Boston, 1962.)

From Hecht's Optics

Fraunhofer diffraction

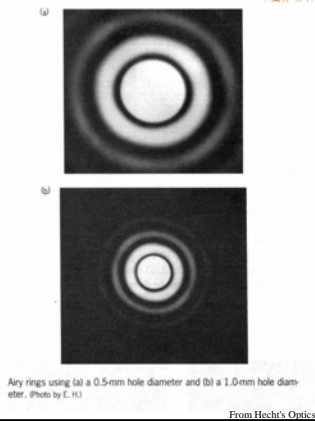


- Far from aperture (ideally at infinity)
 - Lots of things get linearized
- Incoming coherent plane wave, aperture
- Diffraction = Fourier transform of aperture
- Works because
 - wave in time & space
 - coherent



Airy patterns

- Absolute limit on lens resolution
- Important at small aperture



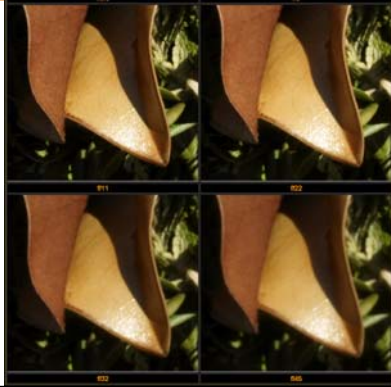
Lens diffraction

- <http://luminous-landscape.com/tutorials/understanding-series/understanding-series/understanding-series/understanding-series/diffraction.shtml> (heavily cropped)



Lens diffraction

- <http://luminous-landscape.com/tutorials/understanding-series/understanding-series/understanding-series/understanding-series/diffraction.shtml> (heavily cropped)
- See also <http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm>



Diffraction & Fourier

- Aperture Fourier transform

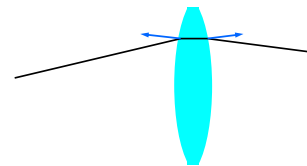


Photo by Eric Chan

Geometrical perspective

Back to View #1 of thin lenses

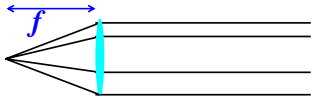
- Snell's law bends geometrical rays



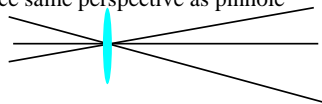
Thin lens optics



- Simplification of geometrical optics for well-behaved lenses
- All parallel rays converge to one point on a plane located at the focal length f



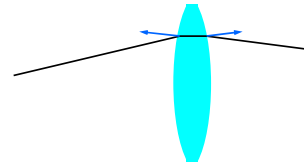
- All rays going through the center are not deviated
 - Hence same perspective as pinhole



Simplification of first-order optics



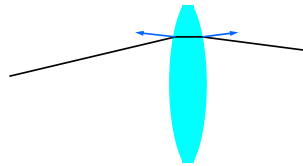
- Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$
- First order/thin lens optics: use $\sin \theta = \theta$



Third-order optics



- $\sin \theta = \theta - \theta^3/6$
- The extra term leads to third-order aberrations

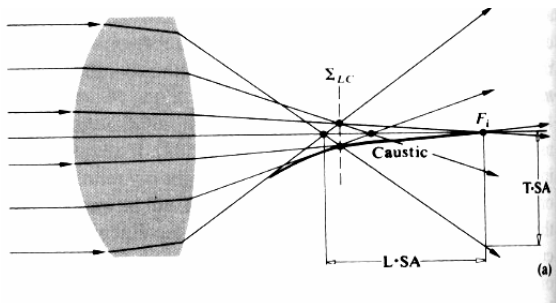


Third-order aberrations

Spherical aberration



- Rays don't focus at same position



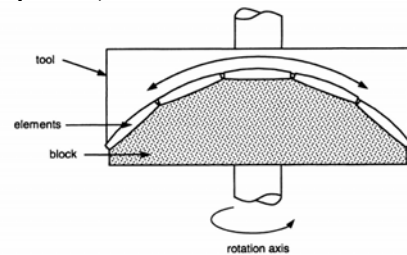
source: Hecht Optics

Why spherical lenses?



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

Figure 3.2
Manufacture of
Spherical
Surfaces



From Optical System Design by Fisher and Tadic

Aspherical lenses

Photo-9 Spherical Lens Example

Spherical aberration of spherical lens

Photo-10 Aspherical Lens Example

Focal point alignment with aspherical lens

source: canon red book

Aspherical lenses

- Harder to manufacture → used with parsimony

Figure-14 EF85mm f1.2L USM Optical System - Ray Tracing Diagram

Figure-15 EF14mm f2.8L USM Optical System - Ray Tracing Diagram

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.

- Inward coma
- Outward coma

Off-axis parallel pencil of rays

Optical axis

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

Po

P1

P2

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 Zeiss 35mm f/3.5 lens 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

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

Photo-6 Example of curvature of field

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

Curvilinear distortion

Barrel distortion

Pincushion distortion

(a)

Object

Images

Barrel distortion

Pincushion distortion

(b)

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)

Figure-18 Chromatic Aberration

- This phenomenon occurs because the prism's index of refraction varies depending on the wavelength (color).

Parallel light rays

Optical axis

Off-axis object point

Axial chromatic aberration (longitudinal chromatic aberration)

Photo-3 Axial chromatic aberration

Photo-4 Transverse chromatic aberration

source: canon red book

Achromatic doublet

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

From Hecht's Optics

Apochromatic & others

- Optimize for multiple wavelengths
- <http://www.vanwalree.com/optics/chromatic.html>

chromatic

achromatic

apochromatic

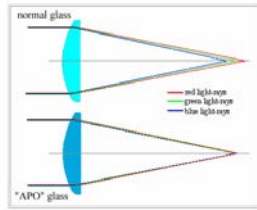
superachromatic

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

Apochromatic glass

APO^o 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-thumb 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 asphericals in order to reduce problems with lateral color shifts.

<http://www.photozone.de/3Technology/lenstec8.htm>



Fluorite

- Low dispersion

Figure-22 Comparison of Color Aberration Correction

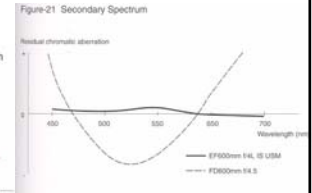
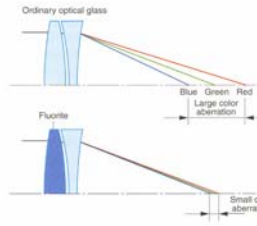


Photo-12 Artificial Fluorite Crystals and Fluorite Lenses



source: canon red book

Diffractive optics (DO)

Figure-56 Diffraction

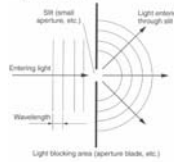
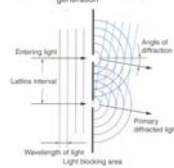


Figure-59 Principle of diffracted light generation

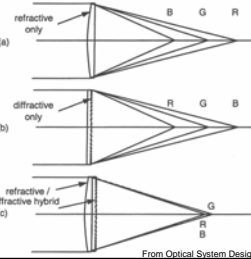


source: canon red book

Photo-13 Multi-Layered Diffractive Optical Element (DO lens)



source: canon red book

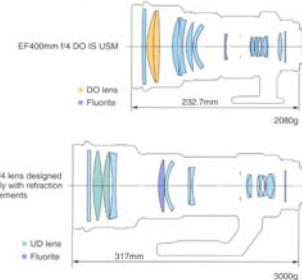


From Optical System Design, by Fisher and Tadic

Diffractive optics

- Enables smaller lenses

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



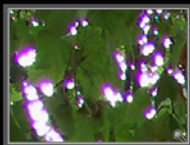
source: canon red book

Purple fringing

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

"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. Booming tends to increase the visibility of purple fringing.



Example of purple fringing

Software post-processing

Recall Radial distortion



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



$$\begin{aligned} \hat{r}^2 &= \hat{x}^2 + \hat{y}^2 \\ \hat{x}' &= \hat{x} / (1 + \kappa_1 \hat{r}^2 + \kappa_2 \hat{r}^4) \\ \hat{y}' &= \hat{y} / (1 + \kappa_1 \hat{r}^2 + \kappa_2 \hat{r}^4) \\ x &= f \hat{x}' / \hat{z} + x_c \\ y &= f \hat{y}' / \hat{z} + y_c \end{aligned}$$

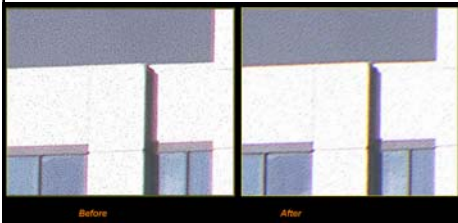
Use this instead of normal projection



General principle



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



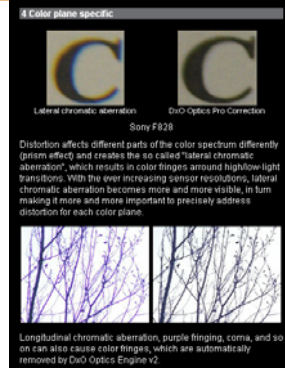
Corrected with Picture Window 3.1

From the luminous landscape <http://www.luminous-landscape.com/reviews/chromatic.shtml>

Software



- http://www.dxo.com/en/photo/dxo_optics_pro/technology_distortion.php
- <http://www.dl-c.com/Temp/>
- <http://www.tawbaware.com/maxlyons/pano12m1.htm>



From DXO

Other quality issues

Flare

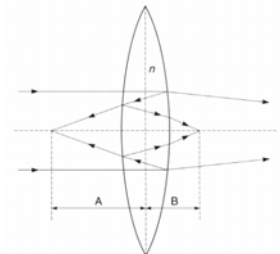


Figure 5.6 Formation of flare spots by a simple lens. Images of the source are formed at distances A and B, where:

$$A = \frac{n-1}{n-1} f \quad B = \frac{n-1}{n-1} f$$

and $a = 2, 4, 6 \dots, b = 3, 5, 7 \dots$ 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
- <http://www.the-digital-picture.com/Reviews/Canon-EF-24-105mm-f-4-L-IS-USM-Lens-Review.aspx>



Coating

- Use destructive interferences
- Optimized for one wavelength

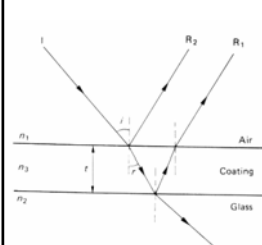


Figure 5.7 An anti-reflection coating on glass using the principle of destructive interference of light between the reflections R_1 and R_2

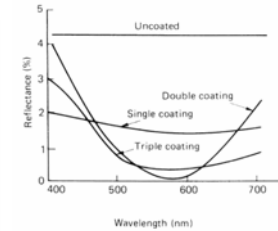


Figure 5.8 The effects on surface reflection of various types of anti-reflection coatings as compared with uncoated glass (for a single lens surface at normal incidence)

From "The Manual of Photography" Jacobson et al

Coating

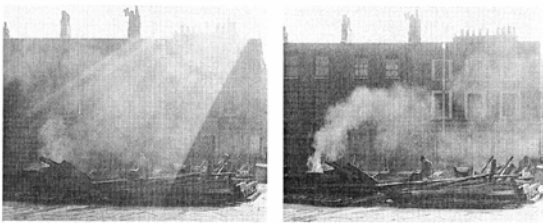
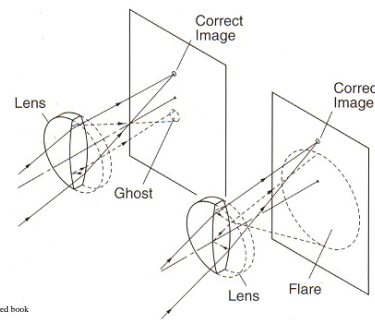


Plate 15.1 Lens flare with an uncoated lens
(a) Flare effects, (b) Reduction of flare by use of a lens-hood.

From Ray's Applied Photographic Optics

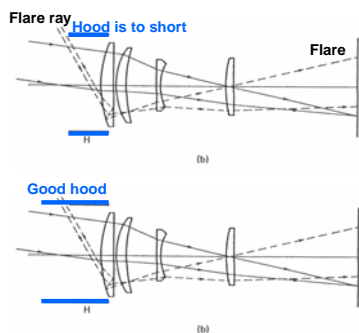
Flare and Ghosting

Figure-29 Flare and Ghosting



source: canon red book

Use a hood! (and a good one)



Adapted from Ray's Applied Photographic Optics

Fighting reflections

Figure-35 EF28-135mm f/4.5-5.6 IS USM flare cut moving aperture diaphragm

Flare cut aperture diaphragm

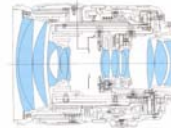
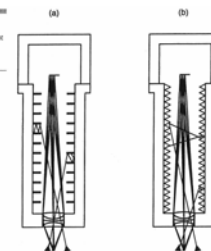


Photo-35 EF28-135mm f/4.5-5.6 IS USM Flare Cut Moving Aperture Diaphragm



Figure-36 EF24mm f/2.8 Internal Light Blocking Grooves

Figure 30.7 Use of Threads and Beads for Stray-Light Attenuation in Machine Vision System




① 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 barrels to stop light entering the lens from reflecting from these parts. If a standard coating is used, reflections

source: canon red book

From Optical System Design by Fisher and Tadic


Flare/ghosting special to digital

For flat protective glass

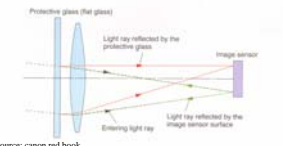


In lenses employing flat protective glass, a reflection occurs between the image sensor and the protective glass, which causes the subject to be photographed in a position different from the actual position.

For a meniscus lens



In lenses employing a meniscus lens, no reflection like that seen to the left occurs from the actual position.



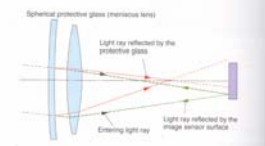
Protective glass (flat glass)

Light ray reflected by the protective glass

Image sensor

Entering light ray

Light ray reflected by the image sensor surface



Spherical protective glass (meniscus lens)

Light ray reflected by the protective glass

Image sensor


Entering light ray

Light ray reflected by the image sensor surface

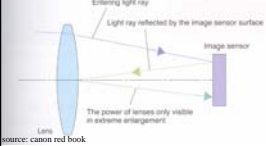
source: canon red book

Coating for digital

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



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



Entering light ray

Light ray reflected by the image sensor surface

Image sensor


Light ray reflected by the lens surface

The power of lenses only visible in extreme enlargement

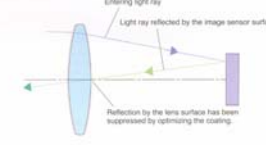
Lens

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

Lens for which the lens shape and coating have been optimized



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



Entering light ray

Light ray reflected by the image sensor surface

Image sensor

Light ray reflected by the lens surface

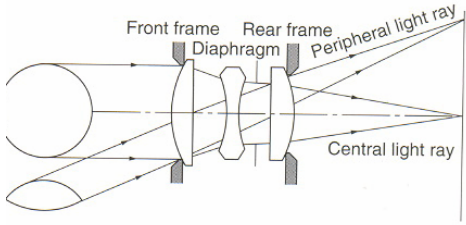
Reflection by the lens surface has been suppressed by optimizing the coating.

source: canon red book

Vignetting

- The periphery does not get as much light

Figure-28 Vignetting



Front frame

Rear frame

Diaphragm

Peripheral light ray

Central light ray

source: canon red book

Vignetting

- <http://www.photozone.de/3Technology/lenstec3.htm>

vignetting



no vignetting




Quality evaluation


LPIs

- Line pair per inch

Input

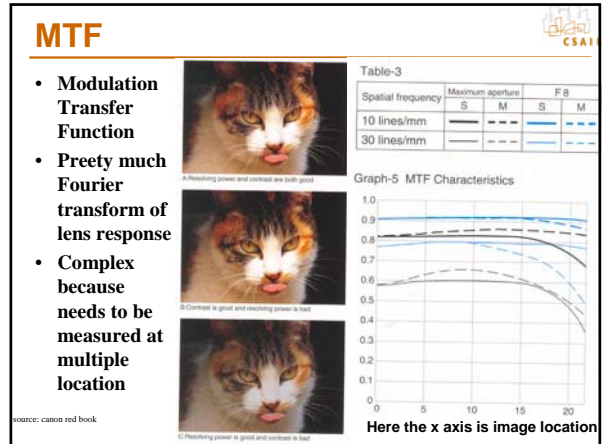
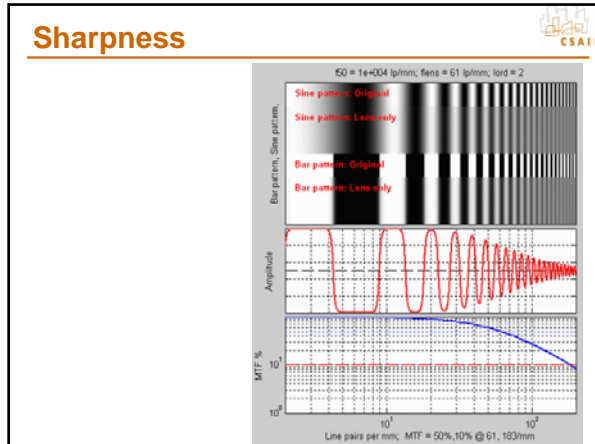


After lens



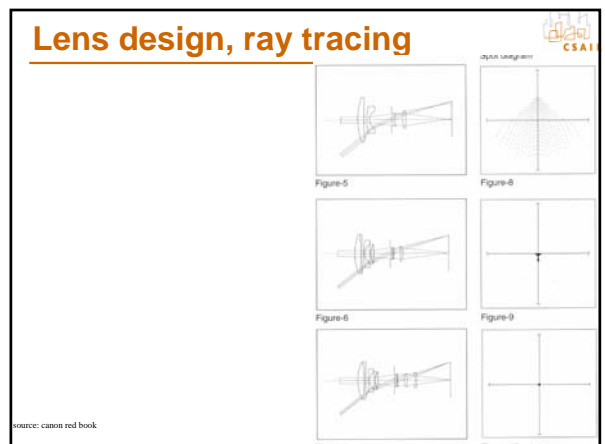
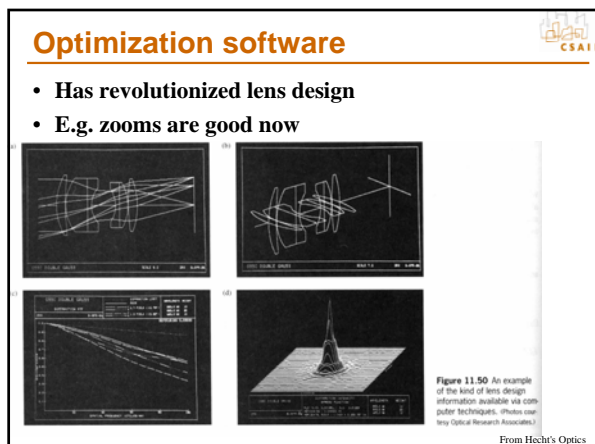
<http://www.imatest.com/docs/sharpness.html>

- http://www.optikos.com/Pdf_files/how_to_measure_mtf.pdf
- <http://www.imatest.com/docs/tour.html>



- ## Blur index based on Photoshop!
- CSAI
- Lens sharpness (or lack thereof) expressed as the amount of Photoshop blur that would blur the image similarly
 - <http://www.imatest.com/>
 - http://www.dxo.com/en/measure/dxo_analyser/default.php
 - Cool vis at <http://www.slrgear.com/reviews/index.php>
- 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>
 - 16-35mm <http://www.slrgear.com/reviews/showproduct.php/product/142/sort/2/cat/11/page/1>
 - 55-200 <http://www.slrgear.com/reviews/showproduct.php/product/141/sort/2/cat/11/page/1>
 - 28-135 <http://www.slrgear.com/reviews/showproduct.php/product/139/sort/2/cat/11/page/1>
 - 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



Optimization

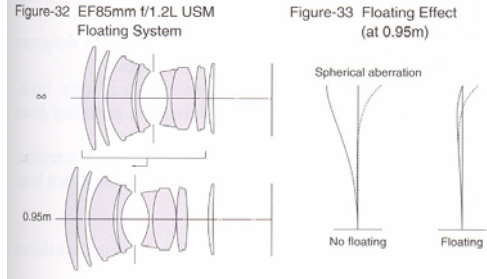


- **Free parameters**
 - Lens curvature, width, position, type of glass
 - Some can be fixed, other vary with focal length, focus (e.g. floating elements)
 - Multiplied by number of lens elements
- **Energy/merit function**
 - MTF, etc.
 - Black art of massaging the merit function
- **Optimize for**
 - All image locations
 - All wavelengths
 - All apertures
 - All focusing distances
 - All focal lengths (zoom only)

Floating elements



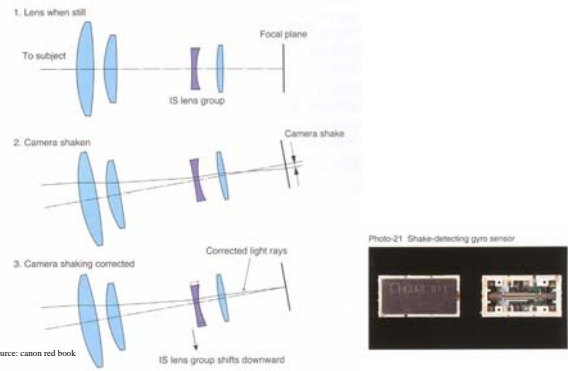
- **Move with focus to optimize response (but are not responsible for focusing)**



source: canon red book

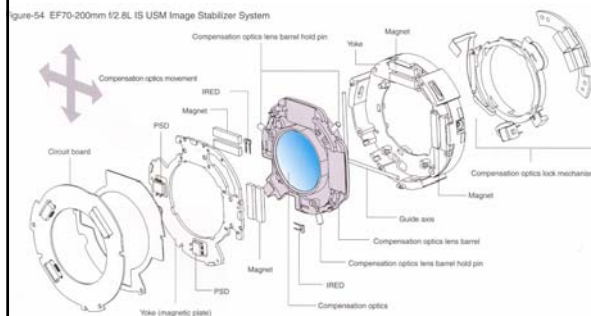
Image stabilization

Image stabilization



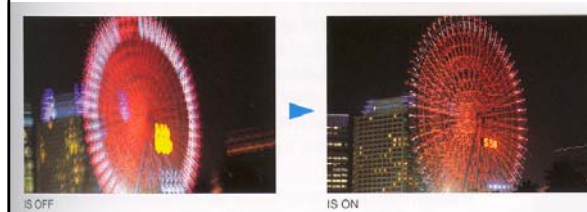
source: canon red book

Image stabilization



source: canon red book

Image stabilization



source: canon red book

1000mm, 1/100s, monopod, IS



Different versions



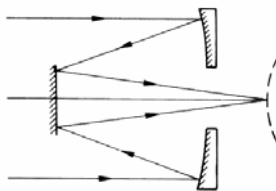
- Canon, Nikon: in the lens
- Panasonic, Konica/Minolta: move sensor

Special lenses

Some special lenses



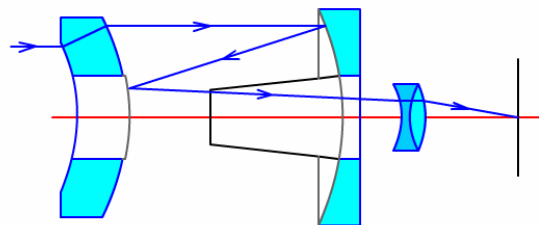
- Mirror lenses
- Tilt-shift lenses
- Macro lenses
 - Why sharpness is always great (thanks Gauss)
 - Why you lose light



catadioptric (mirror)



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



From "The Manual of Photography" Jacobson et al

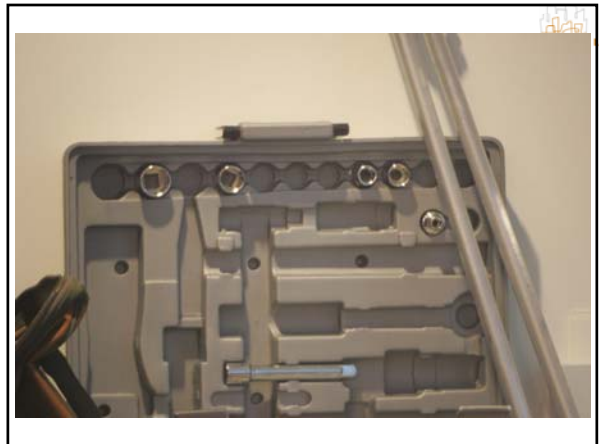
500mm vivitar (\$100)

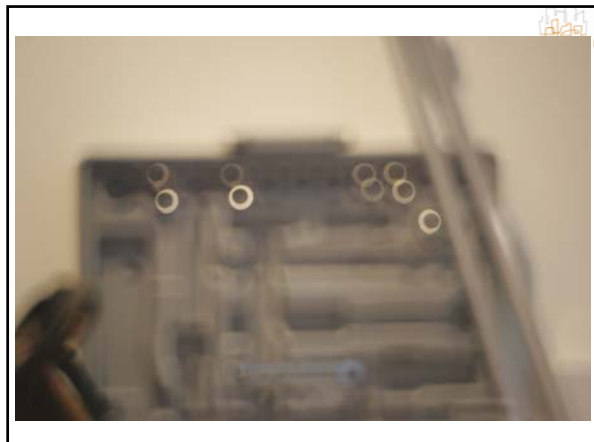


500mm Canon (5k)



Mirror lens



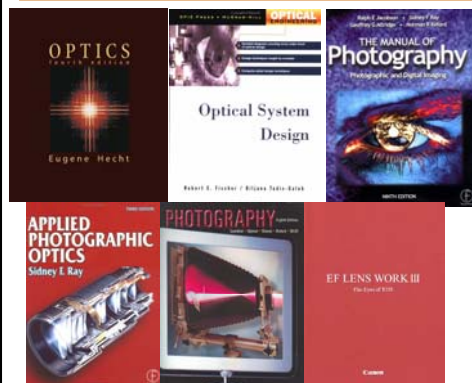


<http://www.digit-life.com/articles2/rubinar/>



Canon D60 + ME Rubinar - R/500

References



Links

- http://en.wikipedia.org/wiki/Chromatic_aberration
- <http://www.dpreview.com/learn/?/key=chromatic+aberration>
- <http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/aberrcon.html#c1>
- http://en.wikipedia.org/wiki/Spherical_aberration
- [http://en.wikipedia.org/wiki/Lens_\(optics\)](http://en.wikipedia.org/wiki/Lens_(optics))
- http://en.wikipedia.org/wiki/Optical_coating
- <http://www.vanwalree.com/optics.html>
- http://en.wikipedia.org/wiki/Aberration_in_optical_systems
- <http://www.imatest.com/docs/iqf.html>
- <http://www.luminous-landscape.com/tutorials/understanding-series/understanding-mtf.shtml>