Stuff you didn’t know about Lenses

Prof. Hank Dietz

University of Kentucky
Electrical & Computer Engineering
I Have Over 250 Lenses.
I Barely Know How They Work.
Some References...

http://www.handprint.com/ASTRO/ae4.html

http://petapixel.com/2012/04/19/how-optical-lenses-are-manufactured/

http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/aberration.html

Things You Already Know

- Focal length
- Aperture
- Focus
  (with the extra note that closer than infinity focus changes focal length & f/number)
- DoF
- Lenses tend to be expensive
What Is A **Lens**?

- Glass or other transparent substance
- One or more sides is curved
- Concentrates or disperses light rays
- A lens **may contain multiple simple lenses as elements**
  - To correct optical defects
  - To change projection characteristics
Types Of Simple Lenses

- Shaped surfaces:
  - **Refractive** – conventional lenses
  - **Reflective** – mirror lenses
  - Usually *spherical*, can be *aspherical* (radical aspherical may be dimpled!)
  - **Diffractive** – pinholes, wave plates, etc.
- A lens may combine simple types (e.g., reflective+refractive = *catadioptric*)
Point Spread Function (PSF)

- PSF – point of light image (e.g., airy disc)
- Line Pairs Per mm – resolution measure
- Modulation Transfer Function (MTF) – lppmm at a given contrast % for black/white
- Sharpness – usually MTF50
Resolution Measurements

- MTF measures resolved line pairs/mm
- Visual extinction of converging lines
- Slanted edge % contrast measurements:
  - https://www.imatest.com/docs/getting-started/
  - https://sourceforge.net/projects/mtfmapper/
- Siemens star shows aliasing/touching rays at resolution limit
Comparing Lenses

- Computed charts: which lens is sharper?
  Sigma 150-600mm f/5.6-6.3 DG OS HSM
  Tamron 150-500mm f/5.6-6.7 Di III VC VXD
- DxO publishes a lot of lens test data:
  https://www.dxomark.com/Lenses/
What does Out Of Focus PSF look like?

- It’s a Gaussian blur, right?
What does OOF PSF look like?

- Nope. It’s actually an evenly-shaded disc shaped like the lens aperture...
Mirror Lens OOF PSF
Correcting Aberrations

- Main reason we don't use simple lenses... elements can compensate for each other
- Doublets and symmetric designs help
- Bending/aspherics/high-index glass help SA (radioactive rare earths were common)
- Smaller aperture helps most aspects
Did he say **RADIACTIVE**?

- Calm down... **they don't make 'em anymore**
- Then again, I have some and use 'em:

![Image of a lens with readings 2075 CPM 13.4uSv/h]
Correcting What Wavelengths?

- Single wavelength, e.g., for laser lenses
- Achromat: 2 wavelength correction
- Apochromat: 3+ corrected wavelengths
- Wavelengths commonly used:
  - 485.1nm – blue line of hydrogen
  - 589.67nm – yellow line of helium
  - 656.3nm – red line of hydrogen
Some Lens Aberrations

- **Spherical Aberration (SA)** – marginal rays have a different focus plane
- **Coma** – off-axis point becomes “comet like”
- **Oblique Astigmatism** – radial/tangential lines have different focus planes
Undercorrected / Overcorrected
Spherical Aberration
Extreme Undercorrected SA, After / Before Focus
More Lens Aberrations

- **Curvature of Field** – focal plane is curved
- **Distortion** – pincushion or barrel
- **Chromatic Aberration (CA)**
  - Axial/Longitudinal – “bokeh CA”
  - Transverse/Lateral – color-dependent magnification (visible off-axis)
Axial CA After / Before Focus
Axial CA in a photo

[Image of a cardinal bird perched on a branch]
Purple Fringes (PF)

- Really didn't happen much on film...
- It's CA, but cause is highly controversial!
  - People claim it's violet or UV light
  - I claim it's mostly NIR
    (I'm right, although wikipedia disagrees)
Lens Flare

- Flare can look like:
  - The patterns we all know & love/hate
  - A drop in overall contrast (that all hate)
- How to reduce flare?
  - Don't point lens at anything contrasty (composition & shading/hoods)
  - Reduce the number of lens surfaces
  - Anti-reflective coatings & multicoatings
Vignetting

- **Mechanical** – stuff in front blocks rays
- **Optical** – thickness makes the lens itself block rays (i.e., the photo above)
- **Natural** – $\cos^4$ falloff due to incident angle
- **Pixel** – due to microlenses, etc.
Vignetting
What's Wrong With This?
What's Wrong With This?
What's Wrong With This?
How Lenses Are Made

- Various **refractive index**, low/high dispersion
- Ground/molded/pressed & polished
- Plastic can be shaped more aggressively, but glass is more stable for large lenses
- Elements can be cemented together
Diffractive Optics (Lenses)

- Diffraction exposes interference pattern
- Limits resolution of refractive/reflective lens
- **Pinhole** – fixed focal length, no distortion
- **Zone Plate** – like pinhole, but brighter
- Binary array diffractive elements (rare!)
- Can have great properties, but often dark
Lensmaker's Equation

\[ \frac{1}{f} = (n - 1) \left[ \frac{1}{R_1} - \frac{1}{R_2} + \frac{t(n - 1)}{nR_1R_2} \right] \]

- \( f \) = focal length
- \( t \) = center thickness
- \( n \) = refractive index
- \( R_1, R_2 \) = radii of curvature
Thin Lens Equations

\[ \frac{1}{f} = (n - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right). \]

\[ \phi = (n - 1)(c_1 - c_2) = (n - 1)c, \]

- \((t << f)\) is a thin lens
- \(\phi = 1/f\), the optical power of the lens
- \(c = 1/R\), curvature of the lens
- For a plano-convex lens:

\[ \phi = (n - 1)c_1; \quad f = R_1/(n - 1). \]
Lens Designs

- **Meniscus** – bent simple lens, less SA
- **Achromatic doublet** – less CA
  (high dispersion concave, low convex)
- **Petzval** – portrait lens (fast, sharp center)
Lens Designs

- **Rapid rectilinear** – landscape lens, not fast
- **Double Gauss** – symmetric meniscus lenses, very fast, used by most “normal lenses” (“normal” means focal length = diagonal)
Some Double Gauss Lenses...
Lens Designs

- **Telephoto** – shorter than focal length
- **Retrofocus** (reverse telephoto) – longer rear focus than focal length
Lens Designs

- **Cooke Triplet** – good correction, expensive, and not very fast nor wide view... but focal length can change: **Zoom**
- Modern zooms are complex, don't change focus as focal length is changed, etc.
Tilt & Shift (NOT decentering!)

- **Tilt** – Scheimpflug principle – focus plane rotates by more than you tilted
  - Fake miniature
  - Extended DoF
- **Shift** – avoids tilt while shifting view
Conclusion

- Now you know what to expect from lenses
- You have no clue how to design a good one (neither do I)
- Bill Claff certainly knows lens designs:
  
  https://www.photonstophotos.net/GeneralTopics/Lenses/OpticalBench/OpticalBench.htm