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Cameras As Computing Systems

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Stuff You Didn't Know About Lenses

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I Have Over 125 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/aberrcon.ht

http://www.lensrentals.com/blog/2011/08/lens-geneology-part-1
http://www.lensrentals.com/blog/2011/09/lens-genealogy-part-2

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

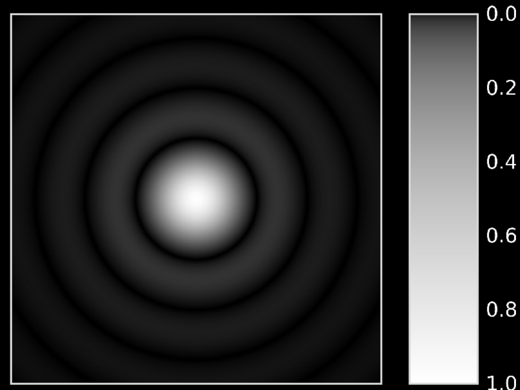
What Is A Lens?

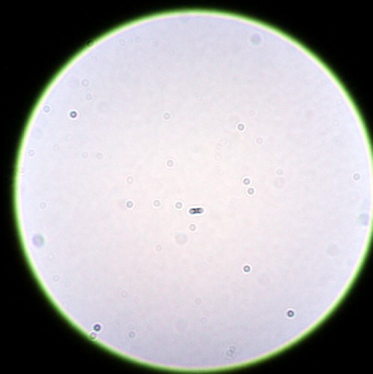
- Glass or other transparent substance
- One or more sides is curved
- Concentrates or disperses light rays
- A lens may contain multiple simple lenses as elements
  - To correct optical defects
  - To change projection characteristics

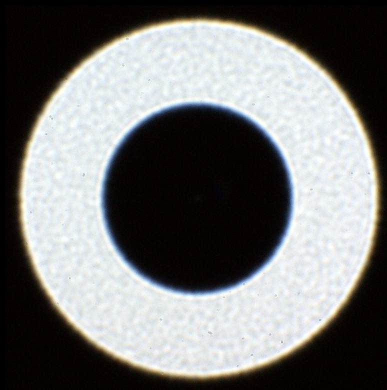
Types Of Simple Lenses

- 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)
- Out-Of-Focus (OOF) PSF shape is aperture
- Line Pairs Per mm – resolution measure
- Modulation Transfer Function (MTF) – lppmm at a given contrast % for black/white
- Sharpness – usually MTF50

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

Correcting What Wavelengths?

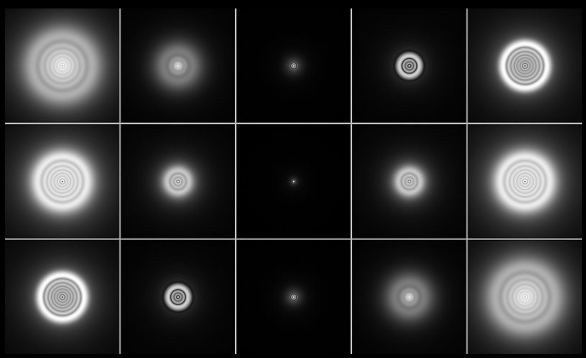
- Single wavelength, e.g., for laser lenses
- Achromat: 2 wavelength correction
- Apochromat: 3+ corrected wavelengths
- Wavelengths commonly used:

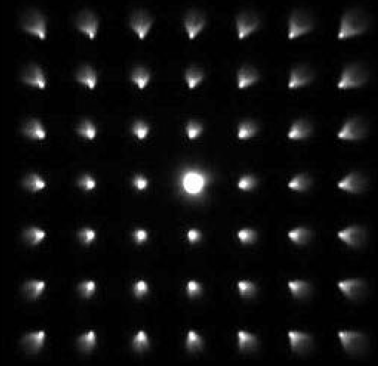
485.1nm – blue line of hydrogen
589.67nm – yellow line of helium
656.3nm – red line of hydrogen

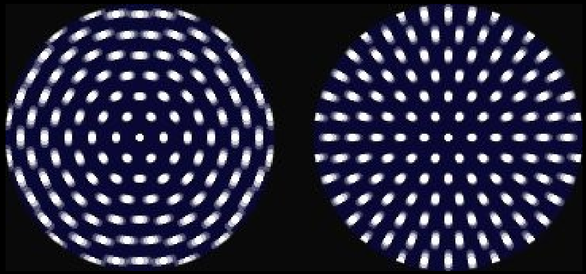
Did he say RADIOACTIVE?

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

Some Lens Aberrations

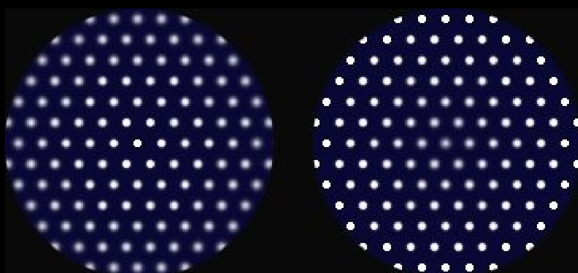


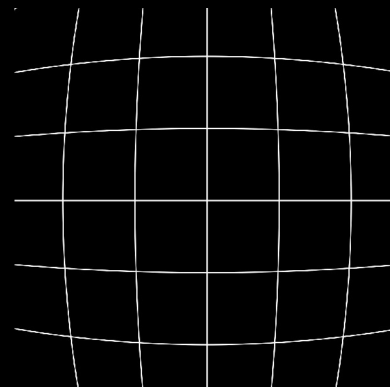


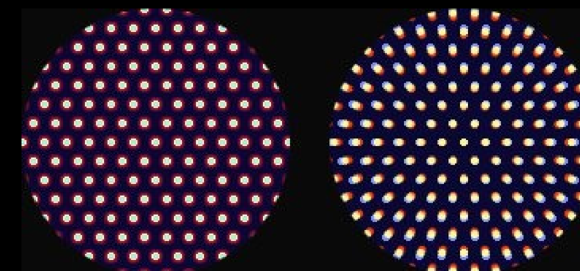


- Spherical Aberration (SA) – marginal rays have a different focus plane
- Coma – off-axis point becomes "comet like"
- Oblique Astigmatism – radial/tangential lines have different focus planes

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)

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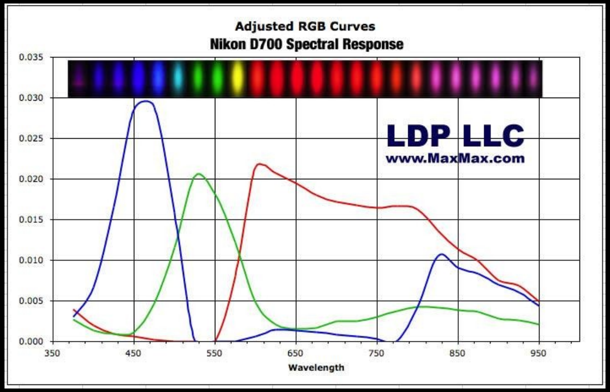
Purple Fringing (PF)



- 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)

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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.

What's Wrong With This?

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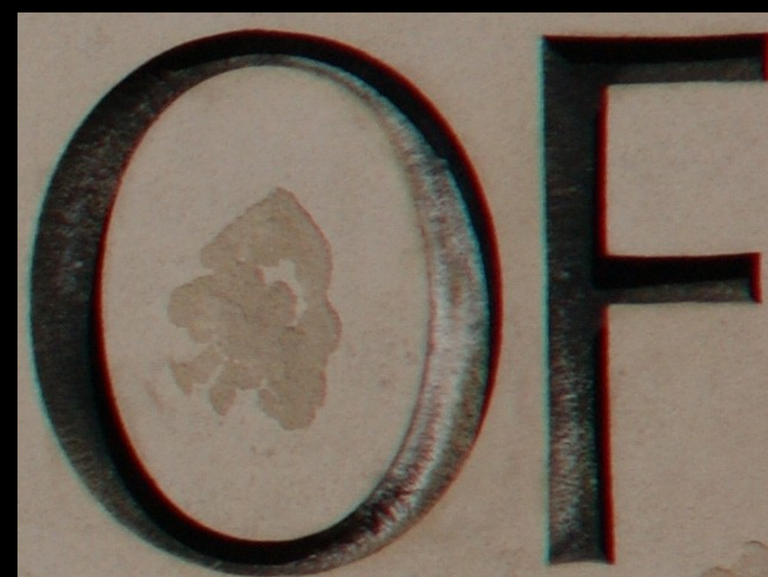
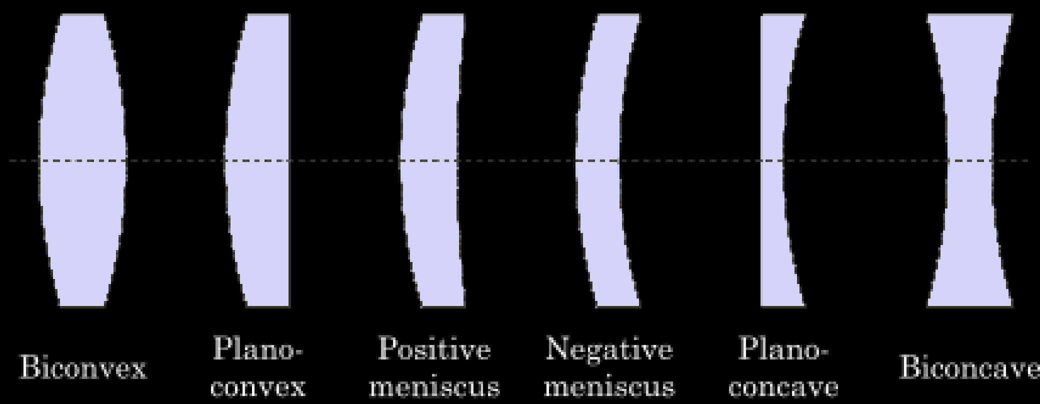


What's Wrong With This?


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

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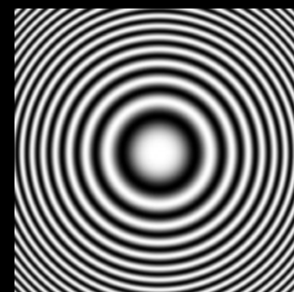
Diffractive Optics (Lenses)



- 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

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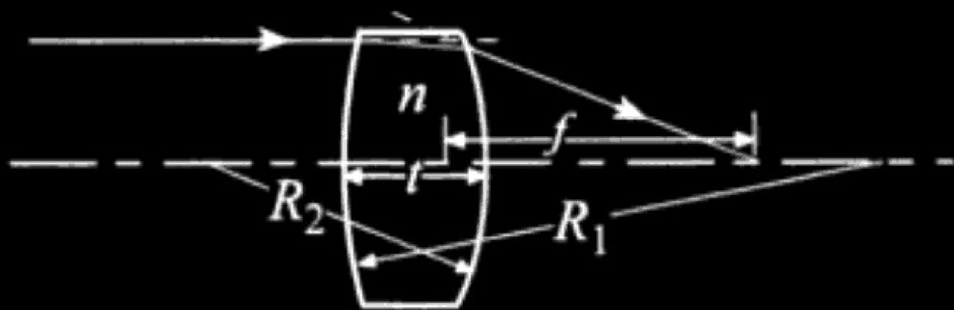
Lensmaker's Equation



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

- f = focal length
- t = center thickness
- n = refractive index
- R1, R2 = radii of curvature

Thin Lens Equations

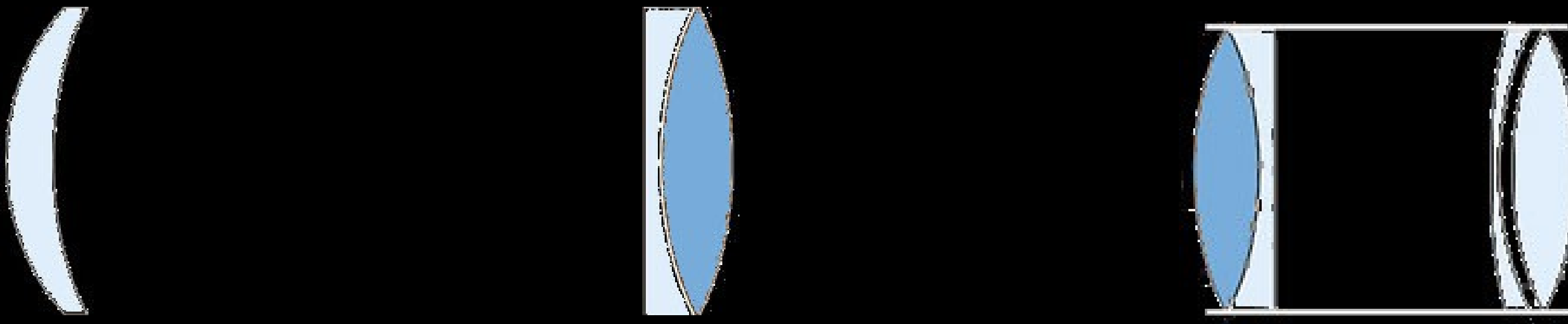
$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

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

- ($t \ll f$) 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:

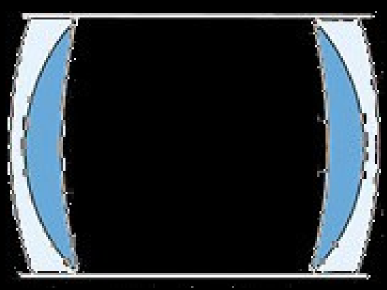
$$\phi = (n-1)c_1; \quad f = R_1/(n-1).$$

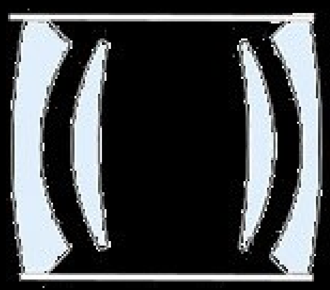
Lens Designs



- 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)

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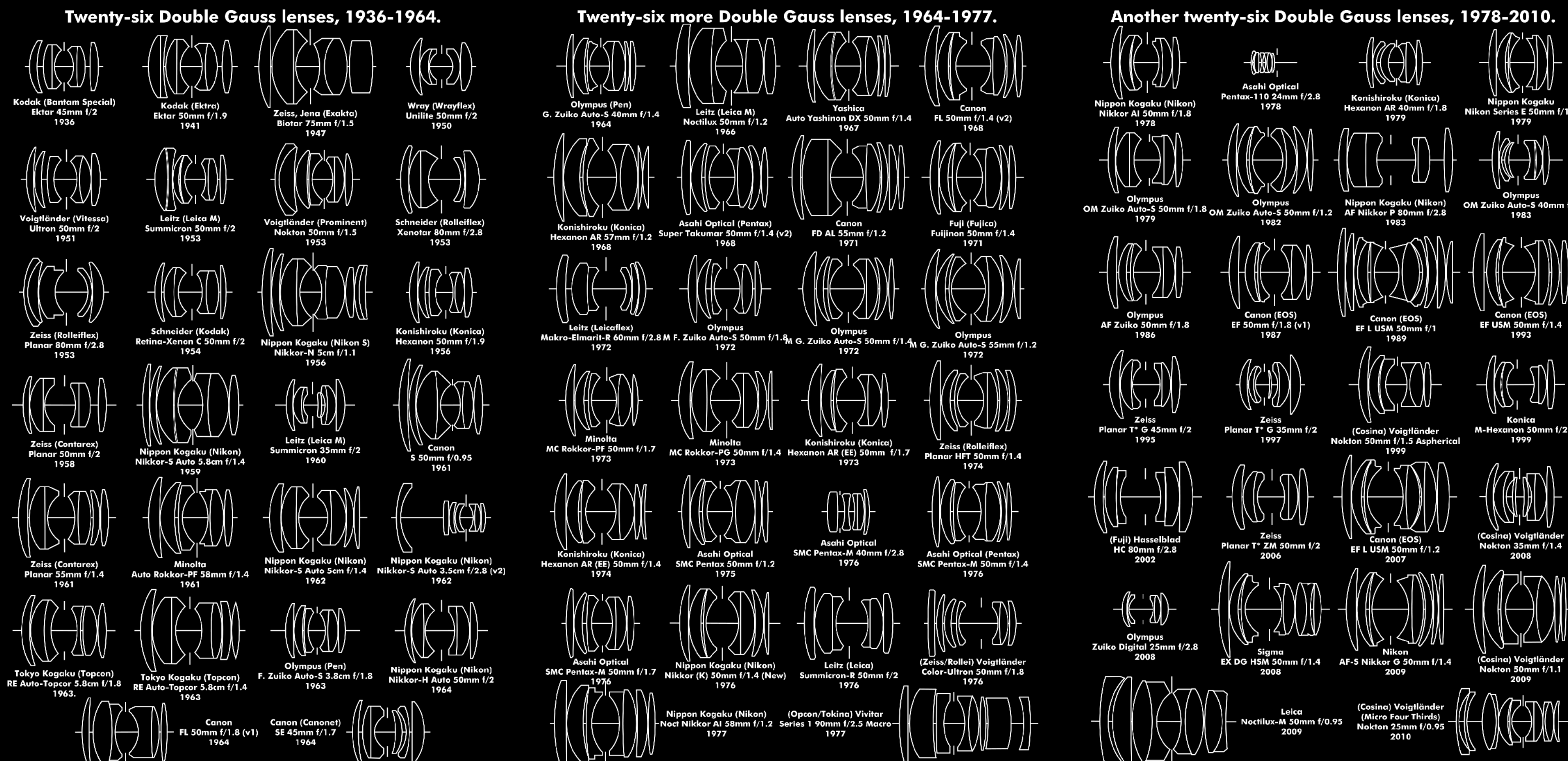
Some Double Gauss Lenses...



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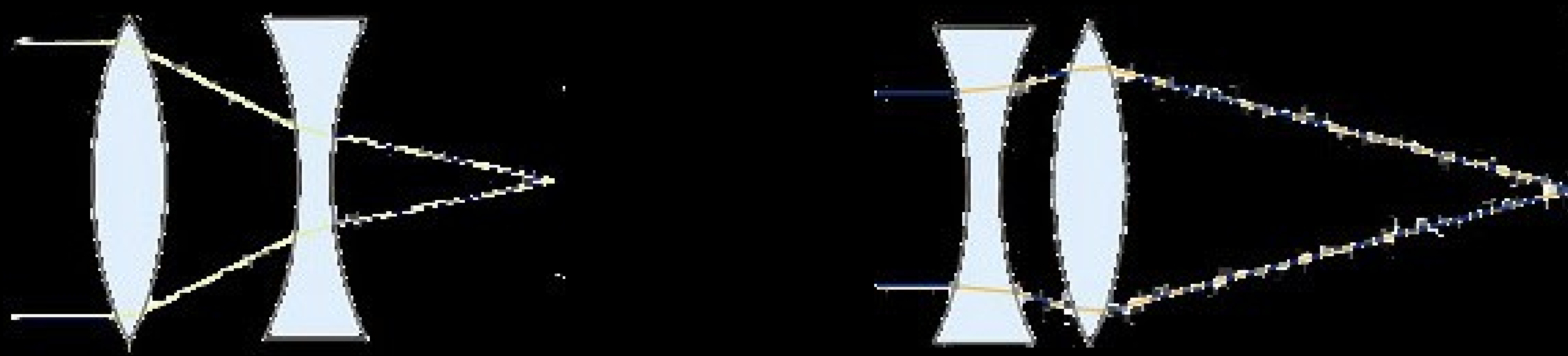
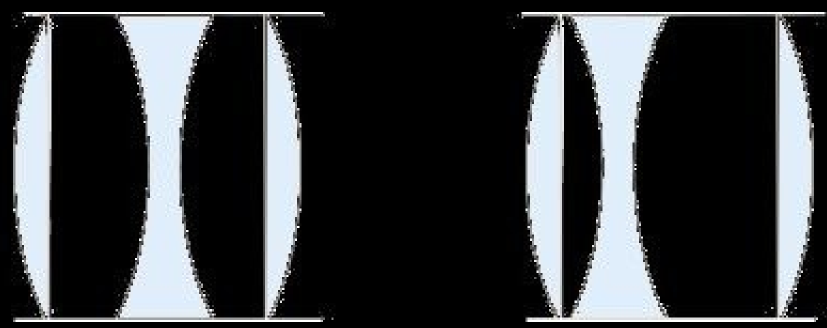
Lens Designs



- 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)