# Refractive Optical Design Systems

• Any lens system is a tradeoff of many factors
• Add optical elements (lens/mirrors) to balance these
• Many different types of lens systems used
• Want to look at each from the following

Performance Requirements

• Resolution of the lens – how good at seeing fine details
   Also compensation to reduce lens aberrations
• Field of View:
   How much of a object is seen in the image from the lens system
• F# - that is how fast is the lens
   i.e. how good is the lens at low light exposures
• Packaging requirements- can you make it rugged & portable
• Spectral Range – what wavelengths do you want to see
   Also how to prevent chromatic aberrations

Figure 8.1
Doublets and Triplets

(a)

(b)

(c)

(d)
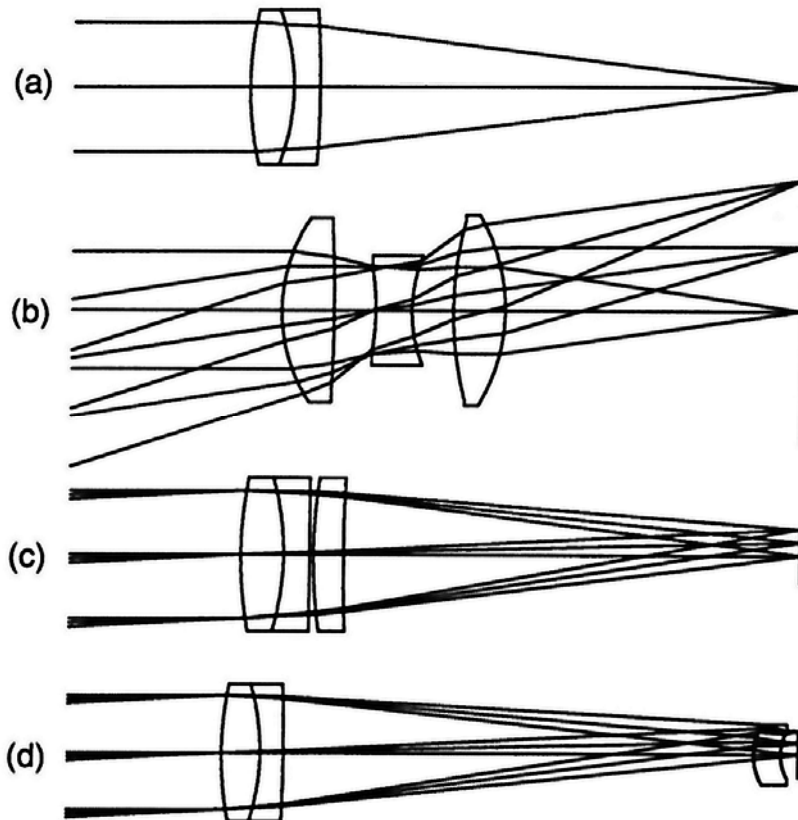
Single Element

- Poor image quality with spherical lens
- Creates significant aberrations especially for small f#
- Aspheric lens better but much more expensive (2-3x higher $)
- Very small field of view
- High Chromatic Aberrations – only use for a high f#
- Need to add additional optical element to get better images
- However fine for some applications eg Laser with single line
- Where just want a spot, not a full field of view
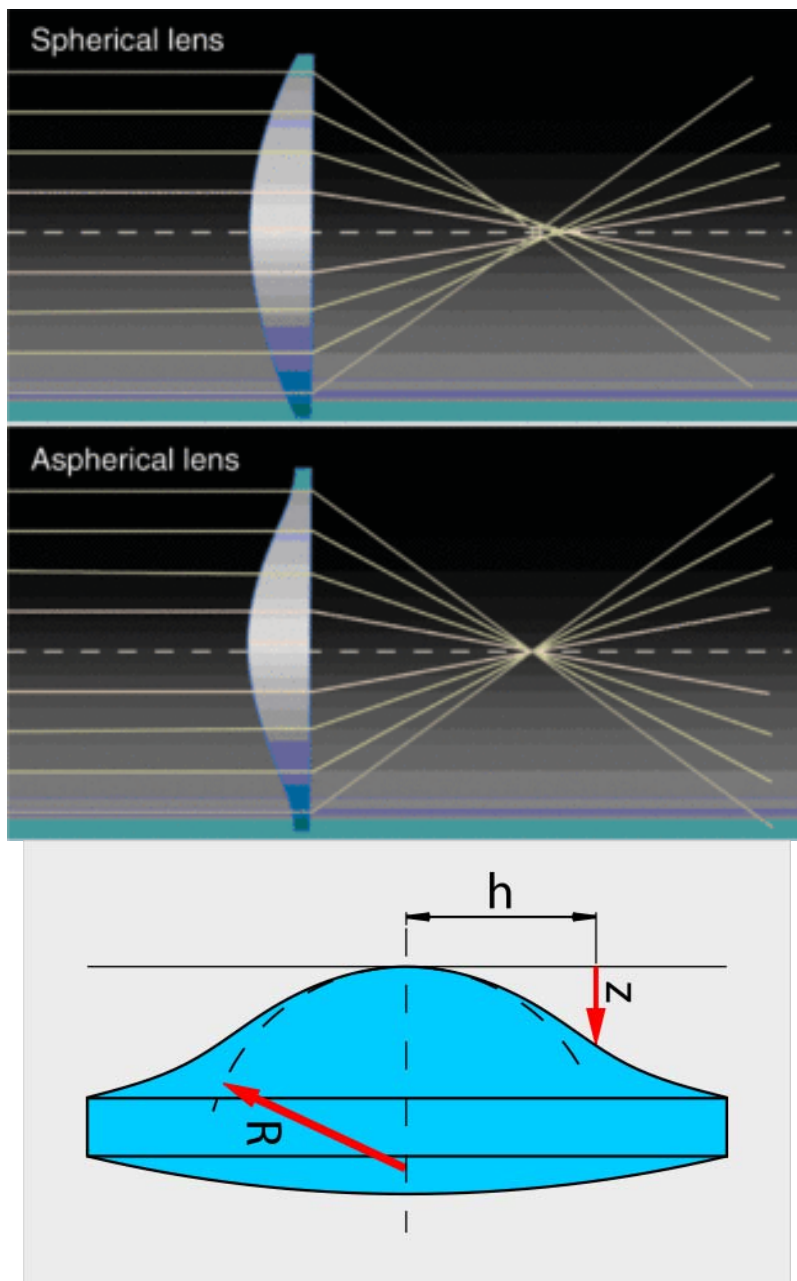
Aspheric Lens

• Aspheric corrects the higher order terms in the sin expansion

$$\sin(\theta) = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} \cdots \approx \theta$$

• To correct change the radius of curvature terms to higher orders
• Problem normal fabrication grinding easy to make spherical
• Much more complicated to grind the aspheric - higher costs
• Also difficult to combine aspherics in a system
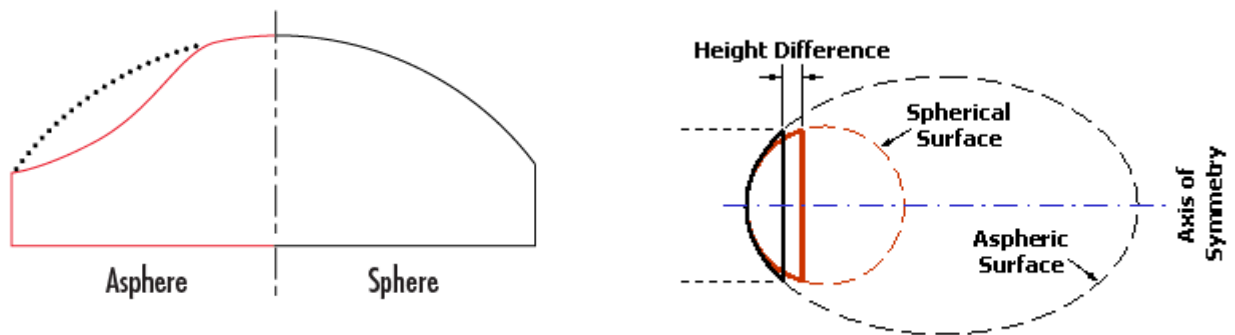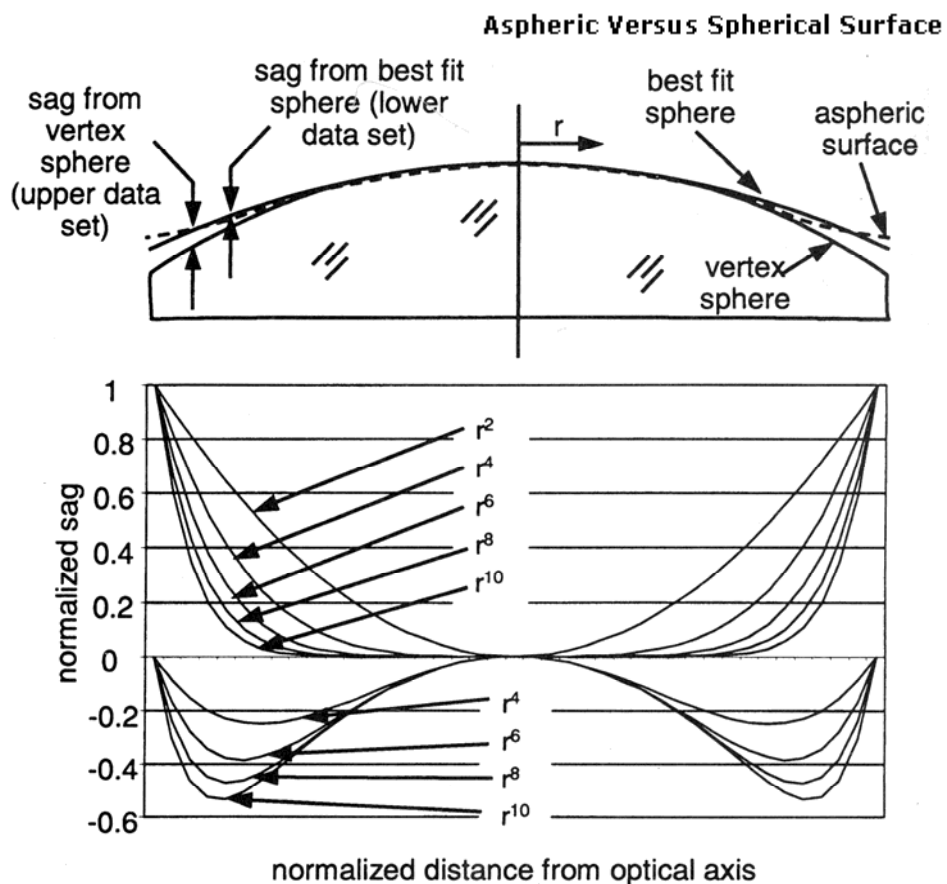• Design system with spherics then final correction with aspherics

Aspheric Versus Spherical Surface

Figure 7.8
Aspheric Sags from Vertex Sphere (Top) and Best-Fit Sphere (Bottom)

Landscape Lens

- Single lens but with aperture stop added
- i.e restriction on lens separate from the lens
- Lens is "bent" around the stop
- Reduces angle of incidence – thus off axis aberrations
- Aperture either in front or back
- Simplest cameras use this

Figure 8.3
Landscape Lens with Stop Aft and Forward of Lens

aperture stop
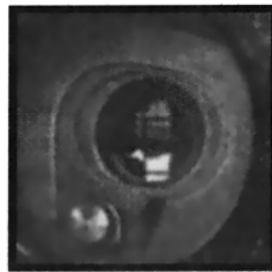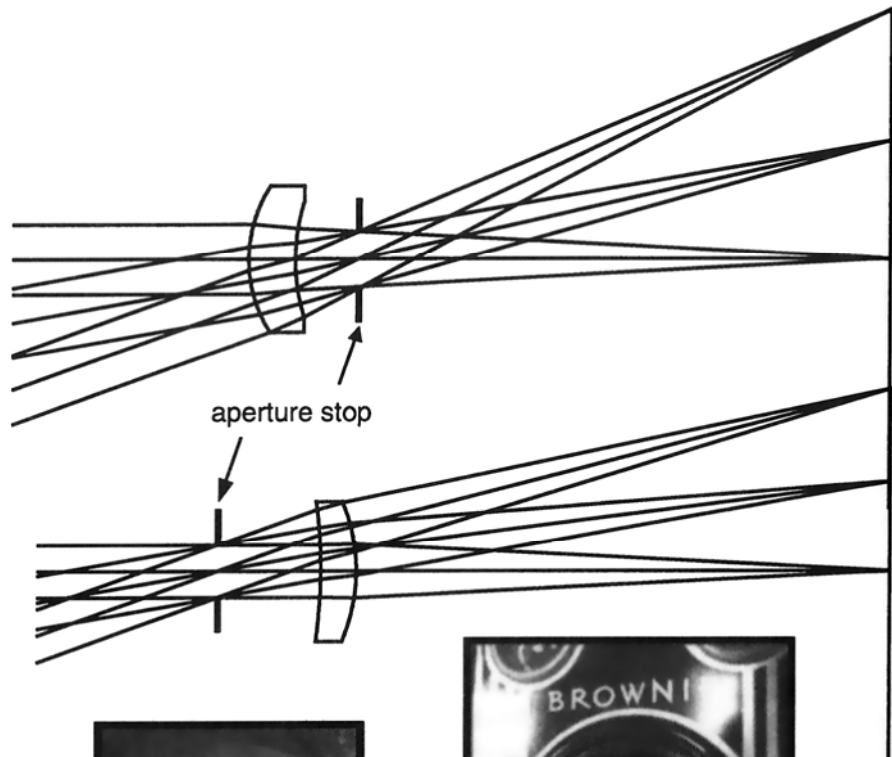
Achromatic Doublet

- Typically brings red and blue into same focus
- Green usually slightly defocused
- Chromatic blur 25x less than singlet (for f#=5 lens)
- Cemented achromatic doublet poor at low f#
- Slight improvement if add space between lens
- This adds another degree of freedom in adjustments
- Removes 5th order spherical
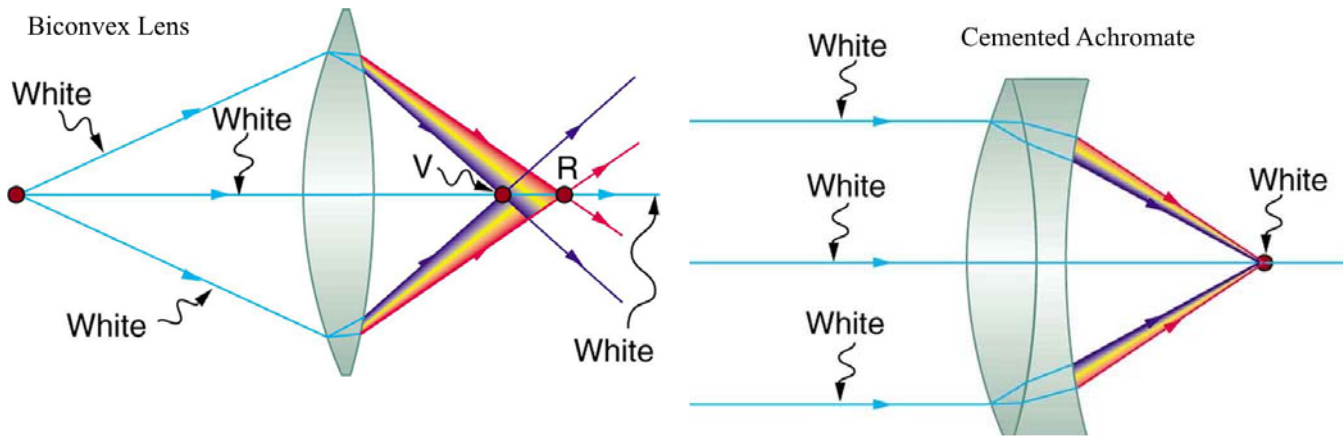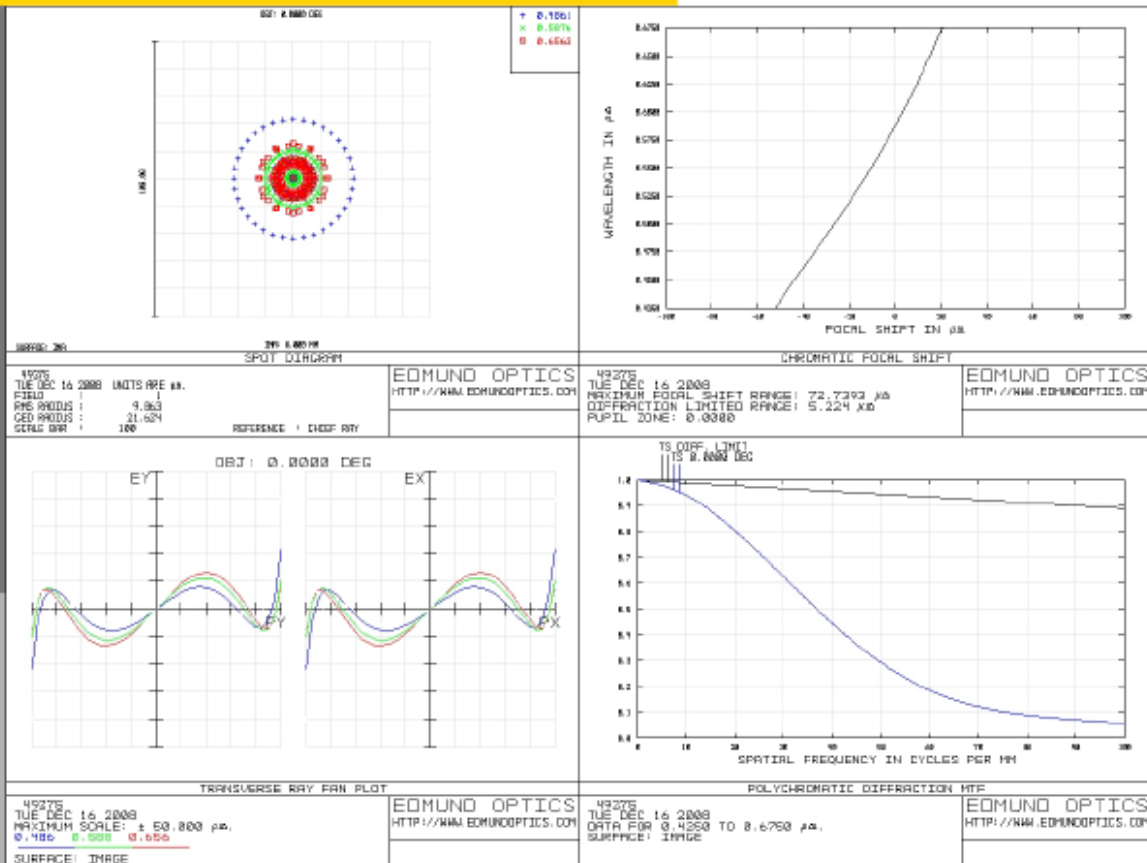
Basic Concept of Optical System Design

- Add optical elements change image size (eg telescopic lens)
- Add optical elements to correct for distortion from other elements
- Get more degrees of freedom with each element:
- Shape of front and back of lens (spherical) adds 2 freedoms
- Positive or negative lens, or aperture
- Location of the lenses (separation creates degrees of freedom)
- Different index of refraction materials adds additional freedome
- Chromatic dispersion of the glass (for chromatic aberrations)
- For chromatic corrections combine many different dispersions
- Aspheric shapes adds many degrees (many possible shapes)
- Use all these to get best tradeoff for image quality, f# etc
- Will use camera lenses design to demonstrate these

Low dispersion glass
Anomalous dispersion glass

Design without cost control   relative cost = 0.92

Design with cost control   relative cost = 0.50

LD glass   Hybrid Aspherical Lens
Glass Molded Aspherical Lens

different types of glass

single focal point

Achromatic Lens
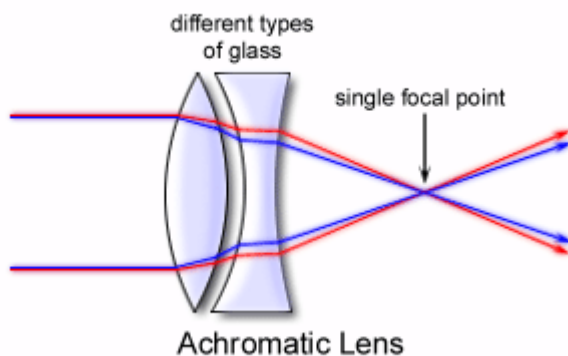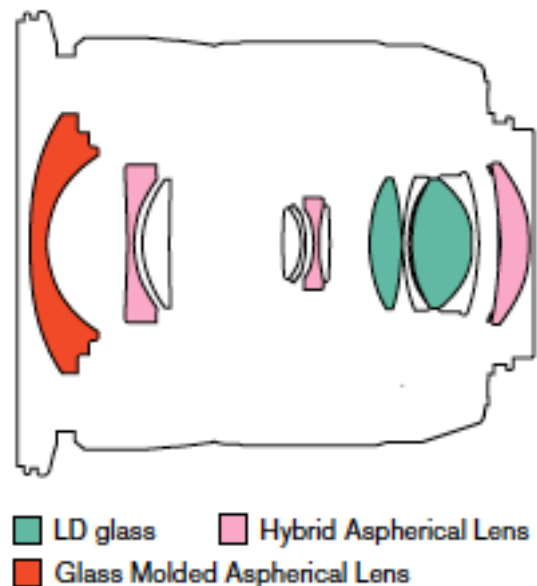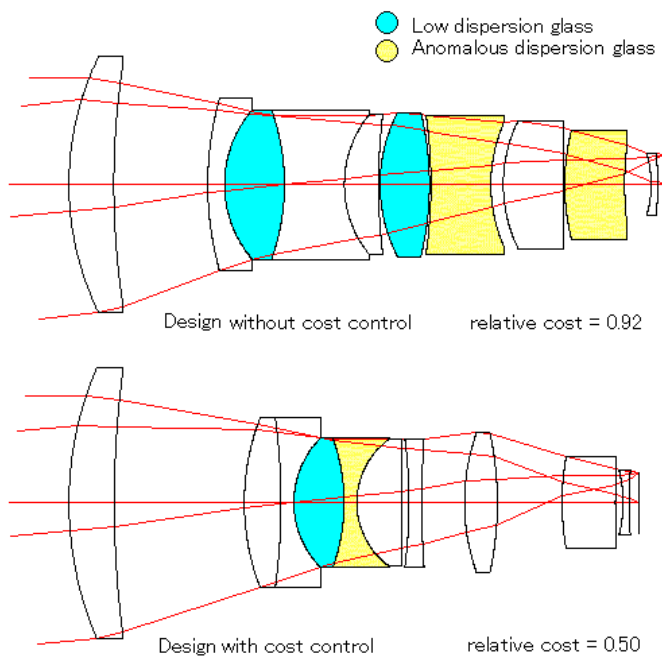
Cooke Triplet Anastigmats

- Three element lens which limits angle of incidence
- Good performance for many applications
- Designed in England by Taylor at "Cooke & Son" in 1893
- Created a photo revolution: simple elegant high quality lens
- Gave sharp margins and detail in shadows
- Key point – gain much by adding negative lens at right point
- Lens 2 is negative & smaller than lenses 1 & 3 positives
- Have control of 6 radii & 2 spaces
- Allows balancing of 7 primary aberrations
1. Spherical
2. Coma
3. Astigmatism
4. Axial colour
5. Lateral colour
6. Distortion
7. Field curvature
- Also control of focal length
- However tradeoffs f# versus field of view and quality
- eg f#:6 has 10º field of view & good quality
- F#:1.4 has 30º field of view but poor quality
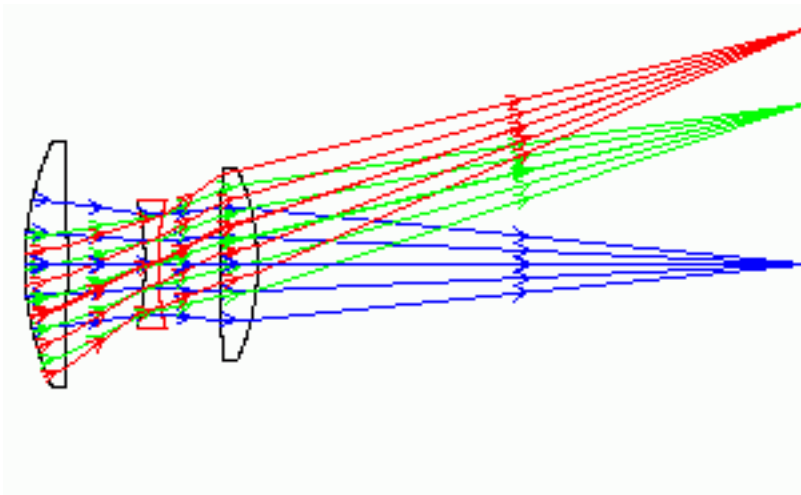
Zeiss Tessar

- Derived from Cooke by Paul Rudolph at Zeiss Jena in 1902
- Replaced back lens with achromat doublet (tessares or 4 in Greek)
- Gets higher resolution, excellent contrast, very low distortion
- Want to eliminate aberrations when they occur
- "Clip at the bud"
- Lens 1 focuses light from infinity
- Lens 2 (diverging) diverts converging light to lens 3 as diverging
- Lens 3 takes diverging rays and focuses then & sets f#
- Lens 3 makes most changes, creates most aberrations
- Thus replace with doublet
- Enhanced by special low dispersion glass developed by Zeiss
- Leica famous 50 mm f3.5 Elmar lens from 1920-60 was a Tessar
- Many fixed focal length simple camera lenses are similar to this
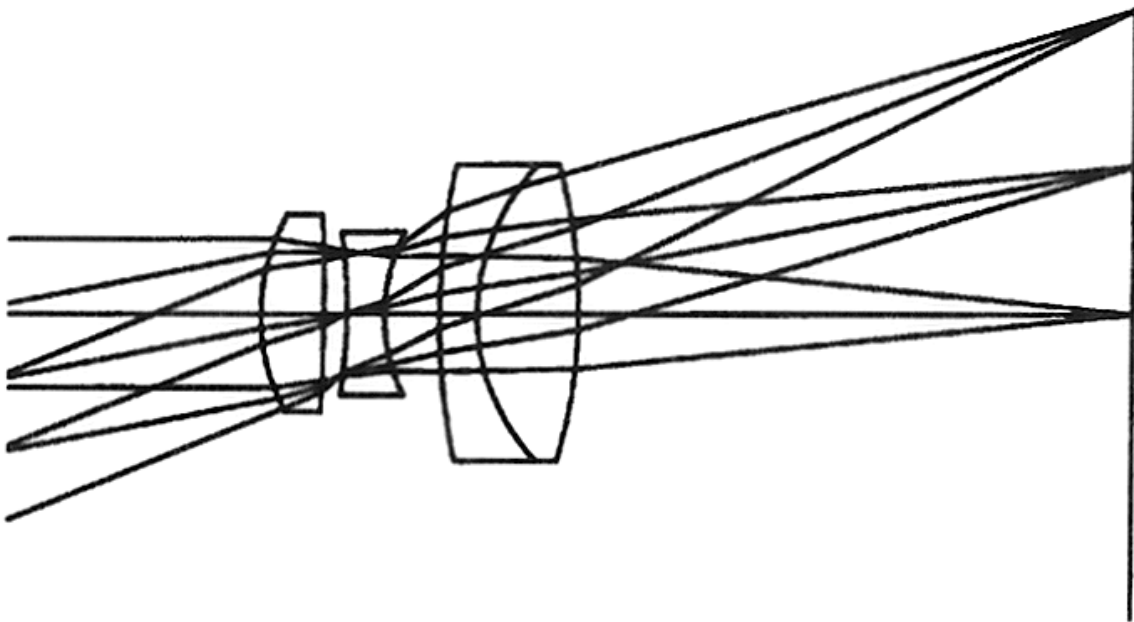
(e) Zeiss Tessar

# Doublet Gauss or Biotar

- Split optical power to minimize aberrations
- Negative element with smaller diameter for field curve correction
- For and aft spots minimize angle of incidence
- Doublet Gauss adds for & aft negative lens: more stops
- 2 positives at either end
- Symmetric pattern around stops
- Very good for high speed lenses: eg. f#:1.4
- Basis for most fix focal length high end camera lenses
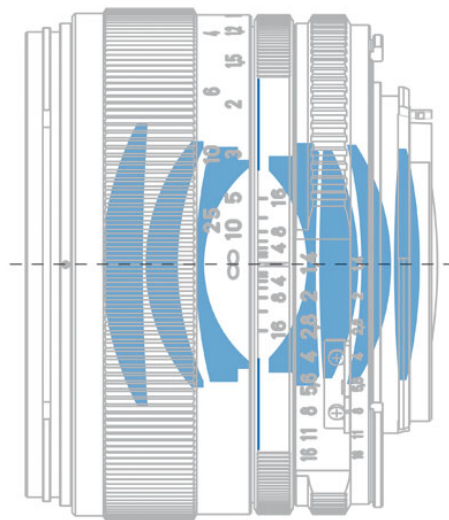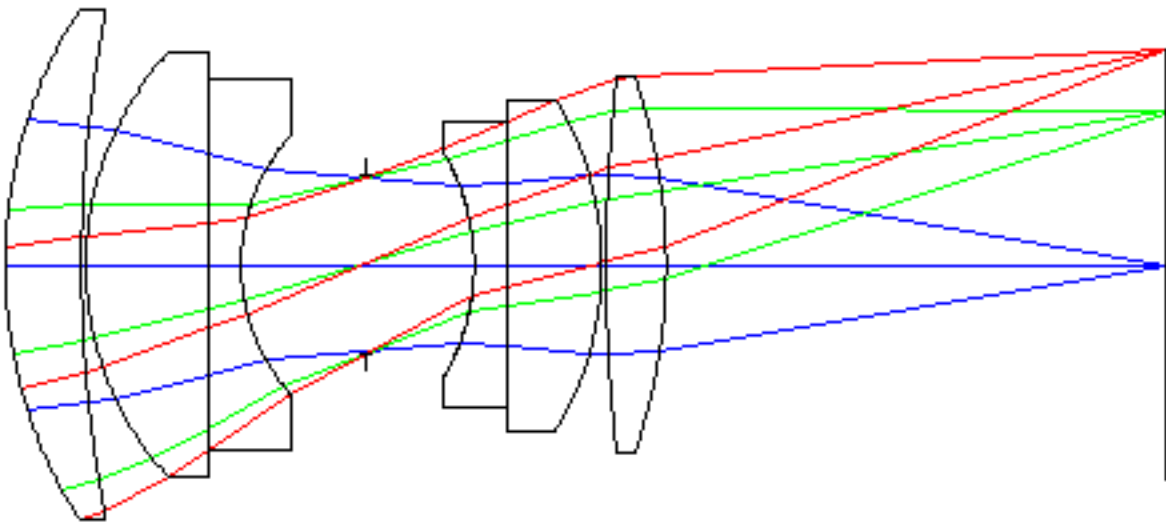
Petzval Lens

- Very old lens – designed by Joseph Petzval in 1840
- Petzval was the founder of geometric optics
- Targets smaller fields of view and moderate f# >= 3.5
- 2 separate doublets with aperture stop in between
- Lower chromatic aberrations than one doublet
- Often add space in back doublet for better images
- Still used in aerial cameras

(g) Petzval lens
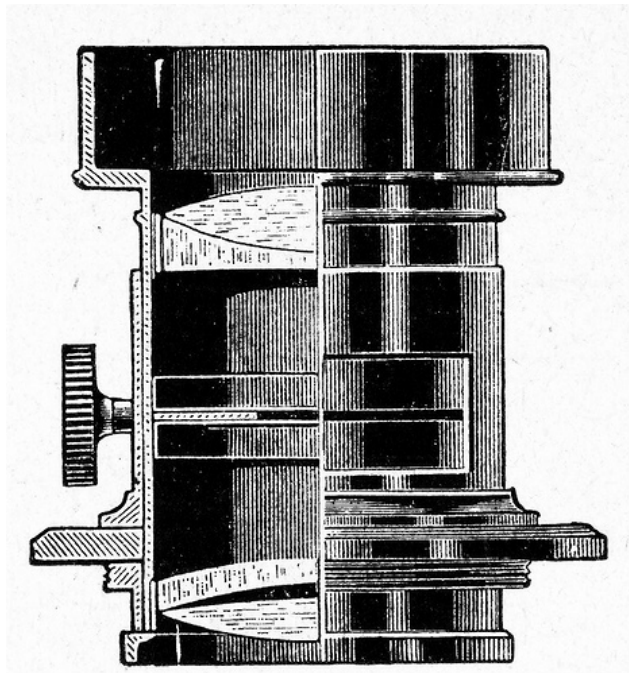
Telephoto

- Add negative lens to doublet
- Acts like Galilean telescope
- Gives non inverting image (important for photography)
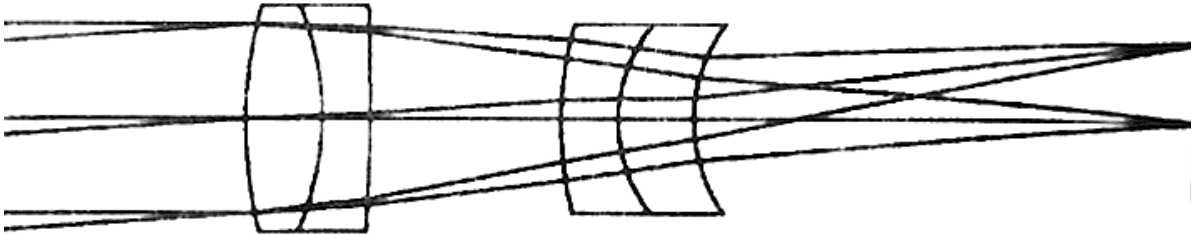
(h) Telephoto lens

Wide Angle

- Add 3 strong negative front element
- Bring light in from a wide angle – make objects seem more distant
- Then converging group with small field of view
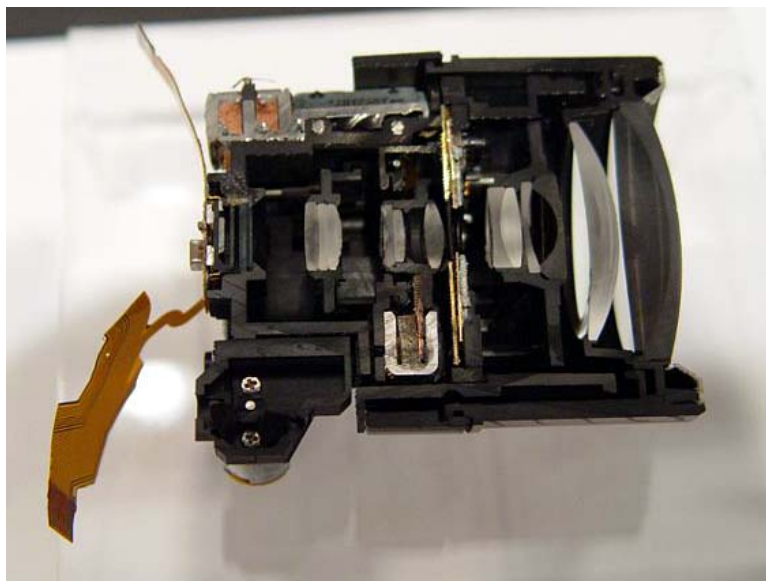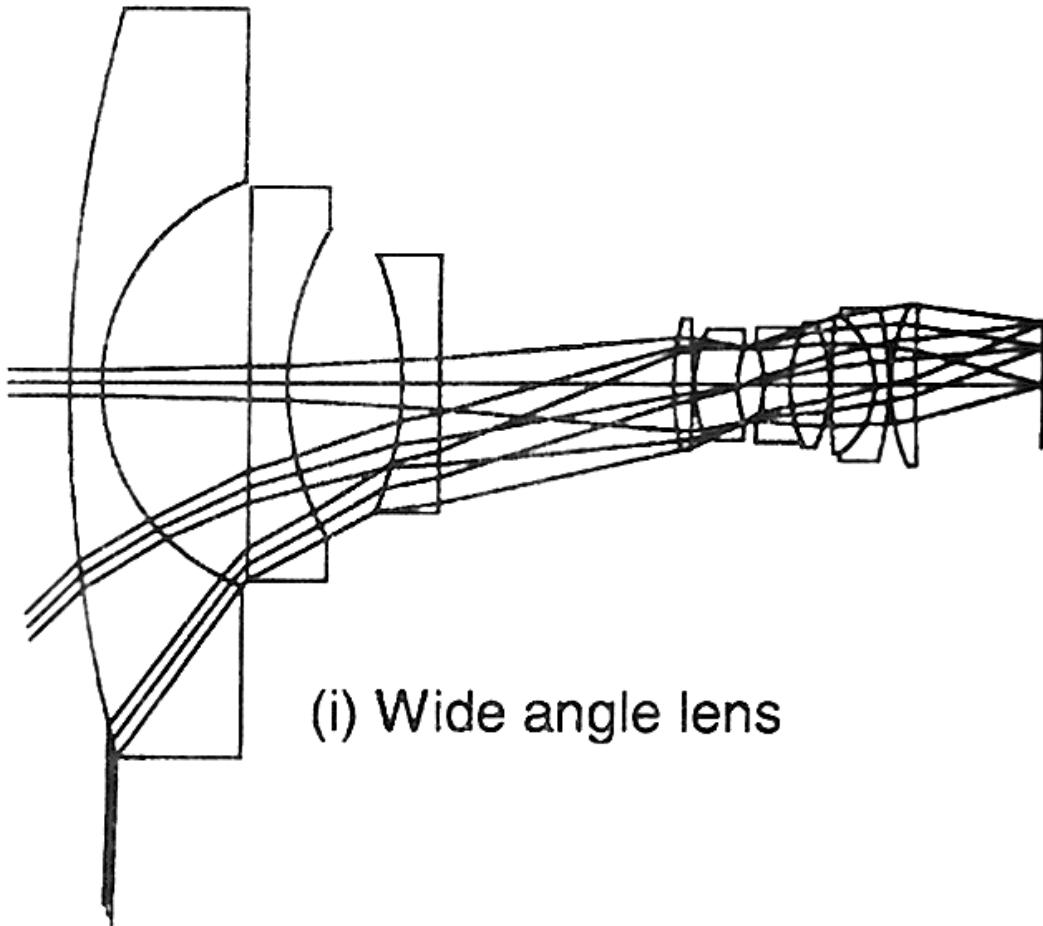
(i) Wide angle lens

Zoom Lenses

- Many camera lenses now Zoom Lenses
- Idea is to have a single lens with many focal lengths
- Eg. standard 35 mm/DSLR lens is 50 mm
- Smaller f is wide angle, larger telephoto
- Typical Zoom cover 24-70 mm,70-300mm or 28-200 mm
- Lens lengthens as zoom

Nikkor 28-200 mm zoom

200 mm   28 mm

Variable Power (Zoom) Concept

- Any single with unit power lens can act as a zoom lens
- Magnification depends on position of the lens
- If move lens towards object image larger, and s' increases
- If move lens away from object image smaller, and s' decreases
- Conjagate pairs where object to image is constant
- But magnification is reciprocal of distances
- Problem is to do this without significant changes in focus point
- Thus need an afocal zoom
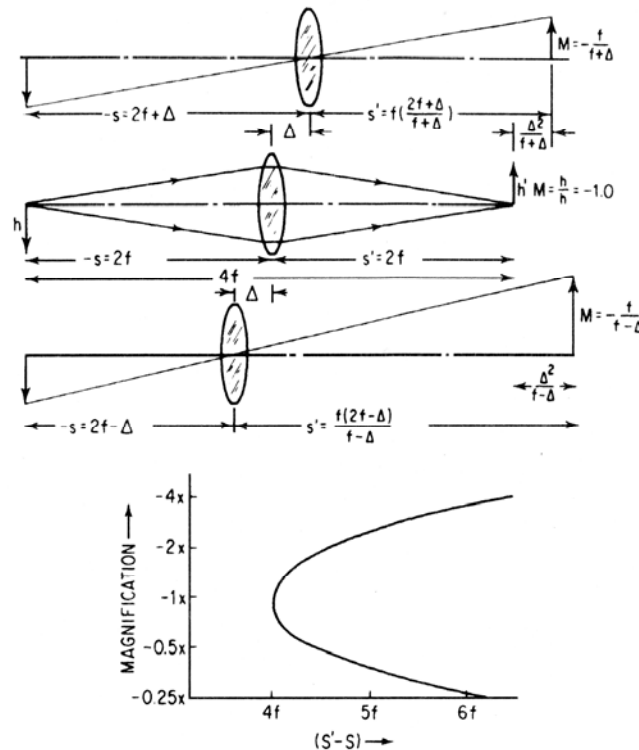
Figure 9.29 The basic unit power zoom lens. The graph indicates the shift of the image as the lens is moved to change the magnification.

Zoom Lenses Structure

- Zoom lens consists of an afocal zoom system + focussing lens
- Afocal zoom takes in parallel light and changes diameter
- Acts as a variable beam expander/beam shrinker
- Consists of lenses L_1 positive, L_2 negative, L_3 positive
- Need $L_1 = L_3$, $L_2 < -f_1/2$
- Focusing lens creates the actual image

Afocal zoom system   *Focussing lens*

A simple zoom lens system
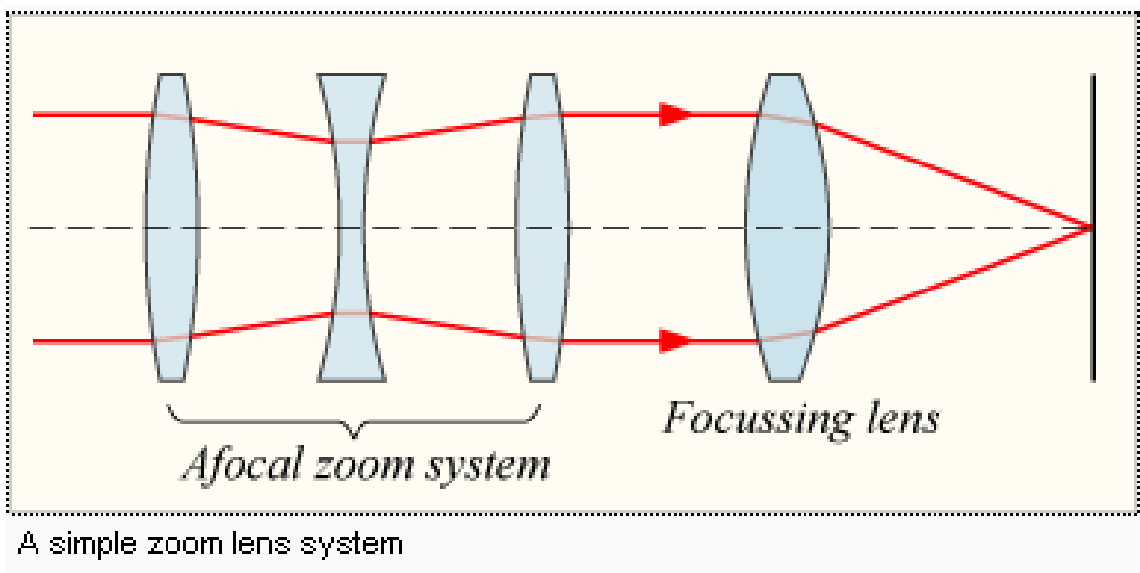
Zoom Lens Operation

- As L_1 and L_2 moves changes amount of zoom
- L_2 close to L_1 and far from L_3, max magnification (beam expander)
- L_2 close to L_3 and shortest separation, min magnification (beam shrinker)
- In practice L_1 moves forward as L_2 moved towards L_3
- At the two extreme and center is afocal (parallel)
- In between slight modification – hence lenses need to move
- Figure shows how lenses move

Movement of lenses in an afocal zoom system
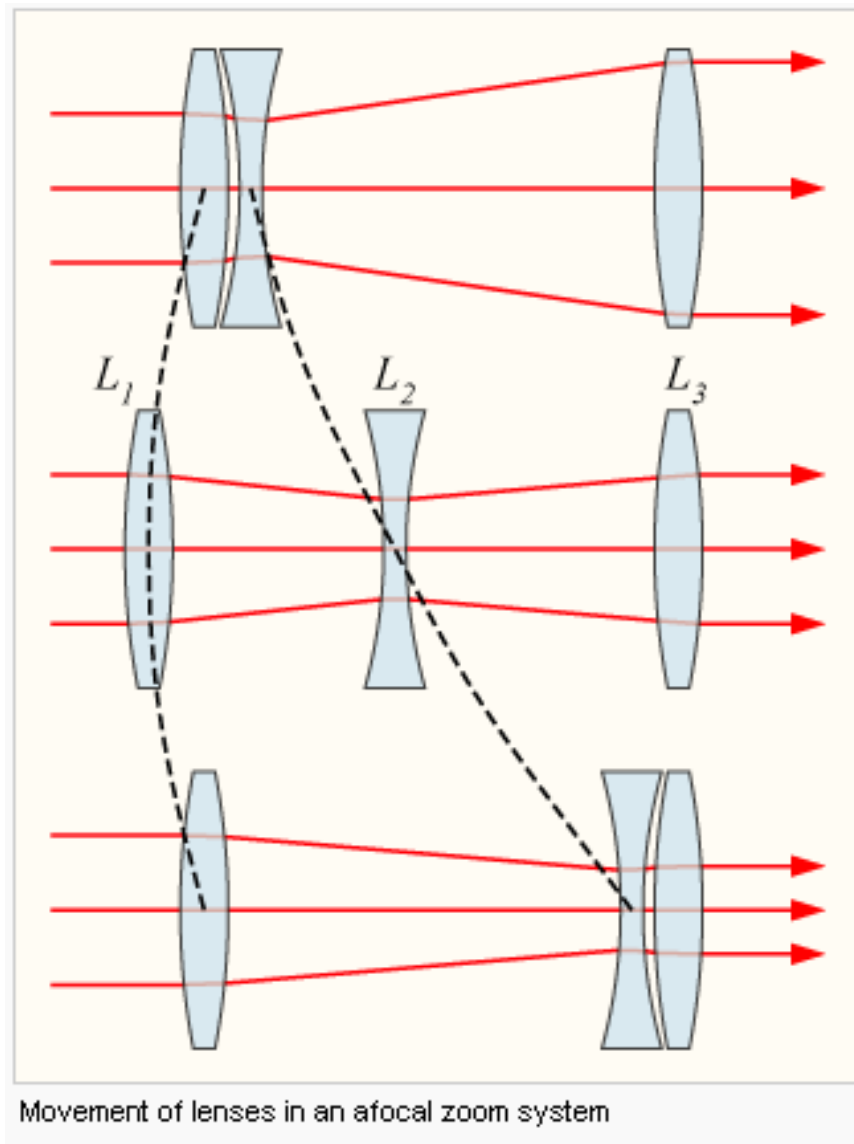
Zoom Lens Movement

- Because L_1 must move as L_2 moves system more complex
- Zoom requires a complicated gear/movement system to work
- Called mechanical compensation
- In practice change position of first two lens
- Create cams: L_2 moves in on path while L_1 follows another curve
- Complicated formulas to get this
- Newest lenses use computer controlled servo motors now
- Can create much more complex and precise movement
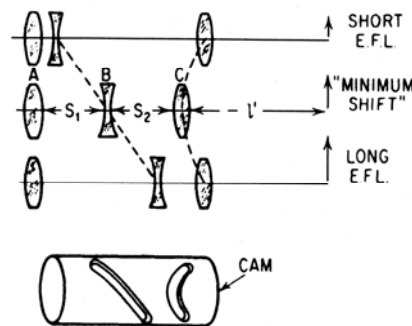
Figure 9.31 Mechanically compensated zoom system.

Given: Φ, power (1/efl) of a system at "minimum shift"

M, ratio of power at $S_1=0$ to power at $S_1=(R-1)/R\Phi_A$

$R = \sqrt{M}$

Choose: Φ_A, power of the first element. May be an arbitrary choice, or set

$\Phi_A = (R-1)/R(S_1+S_2)$ to control the length, (S_1+S_2), at "minimum shift"

Then: $\Phi_B = -\Phi_A(R+1) = (1-M)/R(S_1+S_2)$

$\Phi_C = (\Phi_A+\Phi)R(R+1)/(3R-1)$ to get Φ at the "minimum shift" position

"minimum shift" occurs at

$S_1 = (R-1)/\Phi_A(R+1) = RS_2 = R(S_1+S_2)/(1+R)$

$S_2 = (R-1)/\Phi_A R(R+1) = S_1/R = (S_1+S_2)/(1+R)$

$l' = (3R-1)/\Phi R(R+1)$

$$S_1 + S_2 + l' = \frac{(R-1)}{\Phi_A R} + \frac{(3R-1)}{\Phi R(R+1)}$$

Motion of lens C is computed to hold the distance from lens A to the focal point at a constant value as lens B is moved.

Zoom Limitation

- Focusing lens brings the parallel light into focus
- Parfocal lens: stays in focus as zooms – your ideal zoom
- Important for video/movie cameras & still
- Want image to stay in focus as you zoom in out
- Varifocal allows focus to change – possible now with autofocus
- To make parfocal the fixed lens is designed to focus at 3 points
- Adding additional negative lens makes more parfocal locations
- But adds cost to system
- As change zoom change lens aberrations (image quality)
- Hard to compensate for chromatic and field curvature aberations
- Generally only specific f# give best quality image
- Min f# often decreases as zoom increases
- To keep f# constant requires more lenses and much higher cost
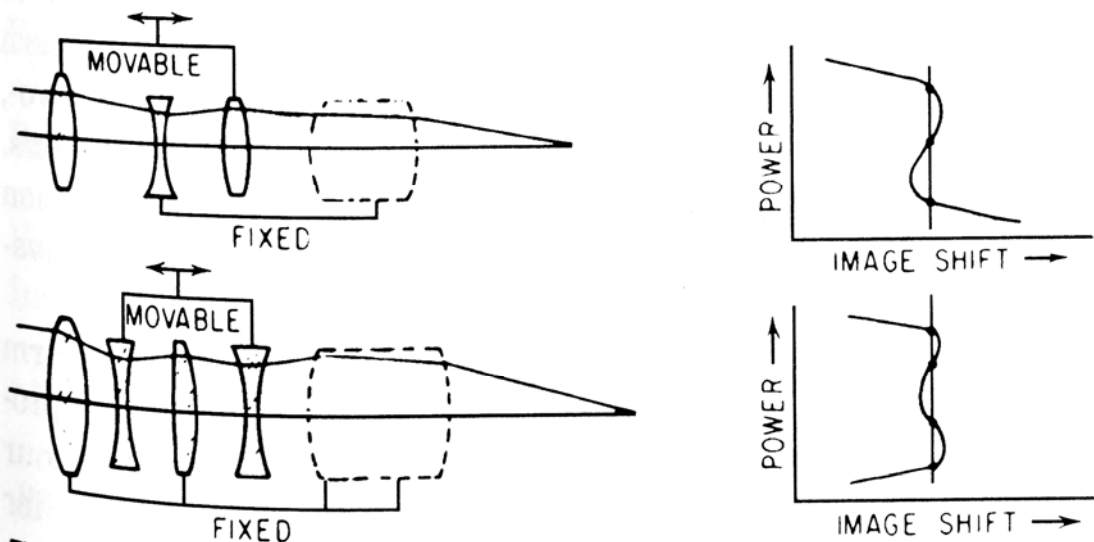
Figure 9.32 Optically compensated zoom systems. The upper system has three "active" components and three points of compensation as indicated in the upper graph. The lower system has four "active" components and four compensation points.

Eyepieces

- Microscopes and telescopes use eyepieces for magnification
- Aperture stop is actually the iris of the eye for these
- Design to trace rays from the eye/iris aperture stop to image plane
- Problem is at outer edges get
  astigmatism, lateral color coma, & distortion
- Many different designs used to compensate
- Lower magnification, less problems
- Typically 5x to 20x used
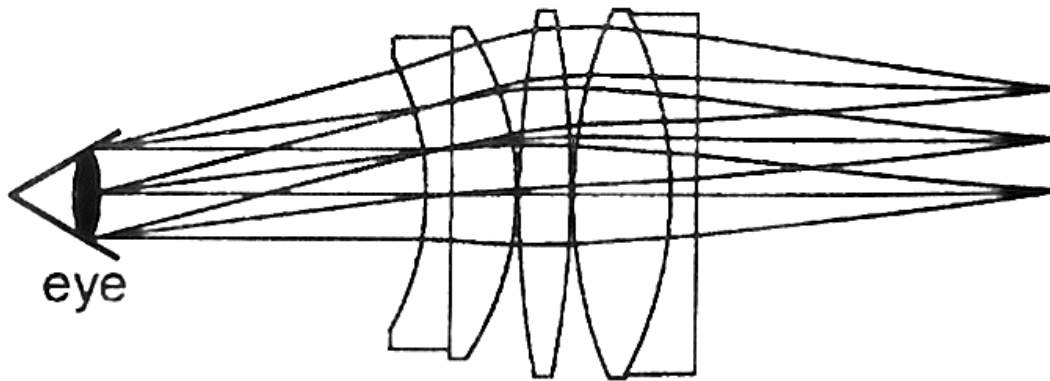
(j) eyepiece

Classic Eyepieces: Huygenian

- Invented by Christiaan Huygens in the 17th century
- Huygenian: 2 plano convex with plane to the eye
- Use low index glass
- Probably the most common type used
- Correct lateral colour by spacing
- Spacing for chromatic aberration of one lens balances other
- Coma is corrected for a given objective distance
- Field stop is in "natural" position between lenses
- Image plane internal to lens – eye does most of magnification
- Field of view up to ~30-35º
- Tends to strain eyes
- Due to **eye relief** the distance the eye must be from eyepiece
- Small distance hard to keep in focus
- Typically 2 mm – 20 mm for many eyepieces
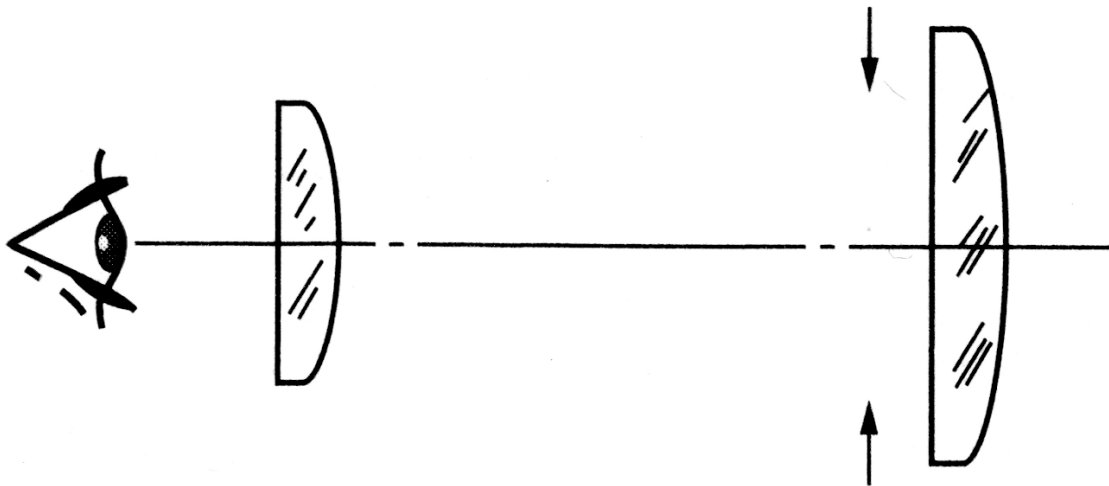
(a) Huygenian eyepiece

Ramsden Eyepiece

- Created by Jesse Ramsden in the 18th century
- Ramsden reduces distance between lenses
- Now planer sides on ends
- Field stop is at back of objective
- Image plane is external to lens
- Lateral colour not corrected
- but chromatic aberrations generally smaller
- Reduces spherical aberrations and distortion
- Coma adjusted by ratio of lens powers
- Can place a reticle (cross hair) at back flat surface
- Very good for monochromatic light
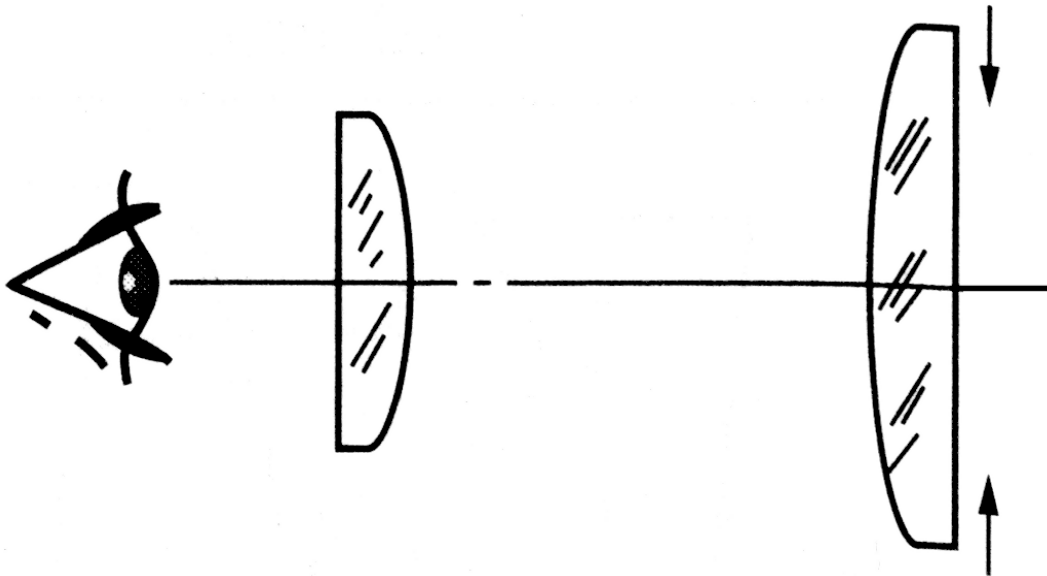
(b) Ramsden eyepiece

Kellner Eyepiece

- Carl Kellner created an achromatic eyepiece in 1850
- Ramsden with achromat added as first lens
- Often departs from plano-convex lenses
- Achromat reduces chromatic aberrations significantly
- Also space in achromat adds additional design freedom
- Field of view also larger

(c) Kellner eyepiece

KE 25mm
Wide Angle
fully coated
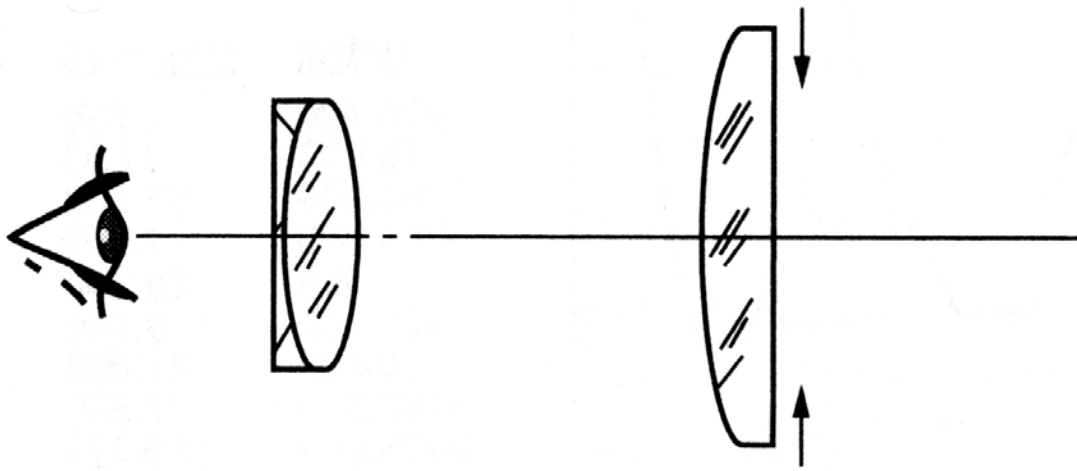
Comparing Eyepieces

- Improve as goes from Hygens to Kellner
- Kellner very good in chromatic & distortion
- Better eye relief also

TABLE 7.1 The Relative Characteristics of the Three Simple Eyepieces Shown in Fig. 7.3

	Huygens	Ramsden	Kellner
Relative			
Spherical aberration	1.0	0.2	0.2
Axial chromatic	1.0	0.5	0.2
CDM* = Lateral chromatic/h	0.00	0.01	0.003
Distortion	1.0	0.5	0.2
Coma	0.0	0.0	0.0
Field curvature (Petz)	1.0	0.7	0.7
Eye relief	1.0	1.5–3.0	1.5–3.0
ϕ_e/ϕ_f (low power)	2.3	1.4	0.8
ϕ_e/ϕ_f (high power)	1.3	1.0	0.7
Field	±15°	±15°	±18–20°
Eyepieces from MIL-141 (Ref. 7)			
Spherical aberration	1.0	0.23	0.20
Axial chromatic	1.0	0.64	0.15
CDM*	0.0	0.010	0.007
Distortion	1.0	0.5	0.4
Coma (OSC)	0.0	0.0023	0.0003
Field curvature (Petz)	1.0	0.64	0.66
Eye relief	1.0	4.1	2.5
$\phi_e/\phi_f^{\dagger}$ (10x)	1.41	1.13	1.19

*Chromatic difference of magnification.
†ϕ_e and ϕ_f are the powers of the eye lens and field lens, respectively.

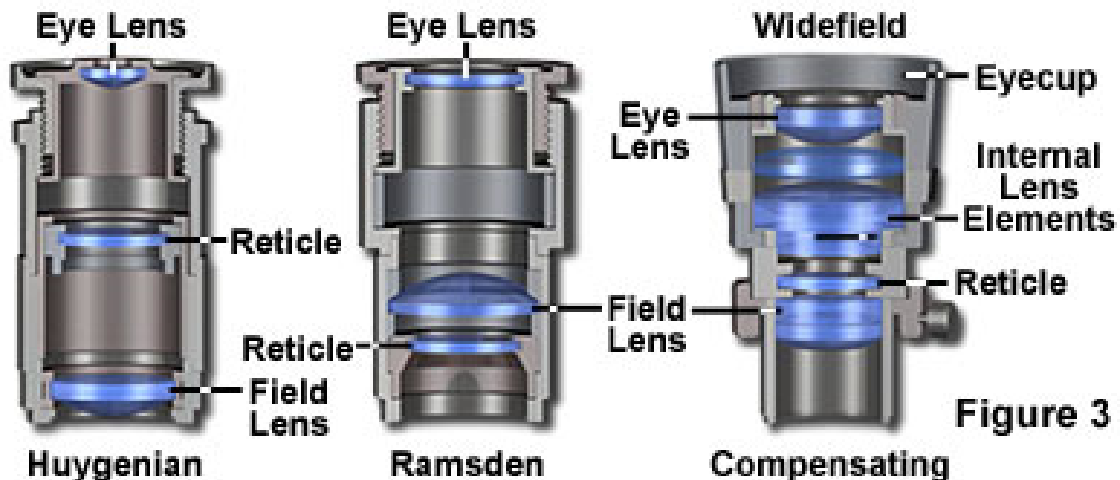## Microscope Eyepiece Anatomy and Reticle Location

Figure 3

Huygenian — Eye Lens, Reticle, Field Lens
Ramsden — Eye Lens, Reticle, Field Lens
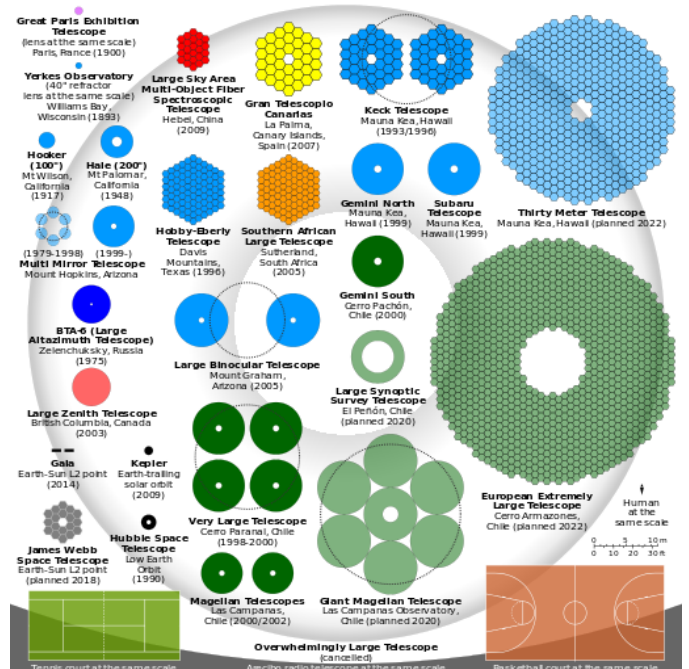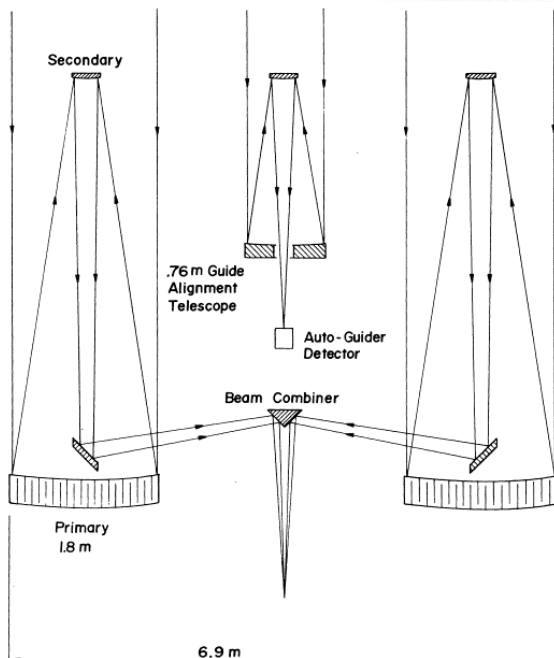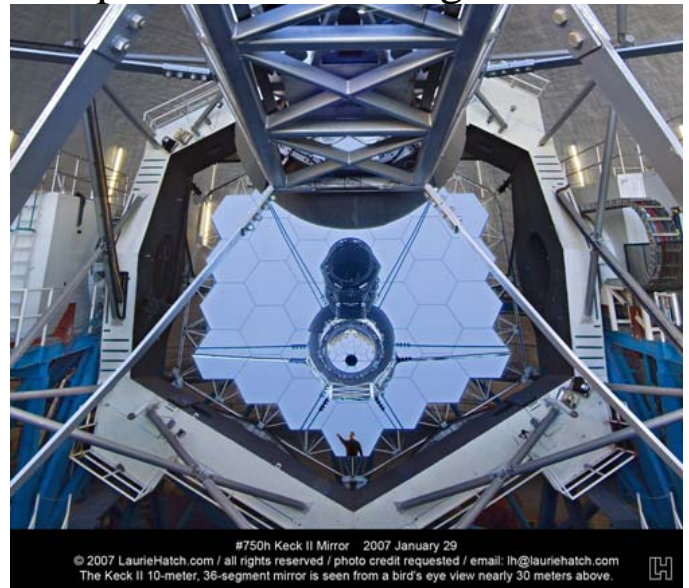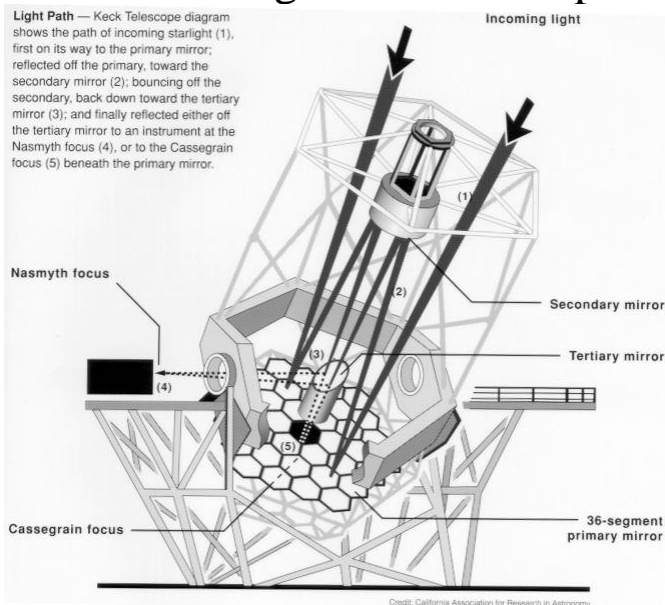Compensating (Widefield) — Eyecup, Eye Lens, Internal Lens Elements, Reticle

Big Optics Mirror Astronomical Telescopes

- Astronomy is looking at faint objects so needs big "Light buckets"
- Mirrors easier but reached a limit with 5m Hale telescope in 1948.
- Problem: collecting area is R^2 but mass is R^3
- Large systems mass caused mirror to distort surface as moved
- 2 solution: Multi Mirror 2-6 mirrors combined optically
- Segmented mirror: hexagonal sections each part of single mirror
- Segments are light, and active control mount from below
- Keck telescope in Hawaii: 36 segments: 10m mirror
- Now building 30 M Telescope & European Extreme Large 39m

Light Path — Keck Telescope diagram shows the path of incoming starlight (1), first on its way to the primary mirror; reflected off the primary, toward the secondary mirror (2); bouncing off the secondary, back down toward the tertiary mirror (3); and finally reflected either off the tertiary mirror to an instrument at the Nasmyth focus (4), or to the Cassegrain focus (5) beneath the primary mirror.

Incoming light

Nasmyth focus

Secondary mirror

Tertiary mirror

Cassegrain focus

36-segment primary mirror

Credit: California Association for Research in Astronomy

#750h Keck II Mirror   2007 January 29
© 2007 LaurieHatch.com / all rights reserved / photo credit requested / email: lh@lauriehatch.com
The Keck II 10-meter, 36-segment mirror is seen from a bird's eye view nearly 30 meters above.

Secondary

.76 m Guide Alignment Telescope

Auto - Guider Detector

Beam Combiner

Primary 1.8 m

6.9 m

Adaptive Optics in Telescopes

- Air distorts optical images- limits resolution to <0.15m mirror
- Problem for both Astronomical and orbital spy satellites
- Reason why 1.5m space telescope is better than most earth ones
- Solution: adaptive optics: deformable mirror shape to compensate
- First need a wavefront sensor to see the distortion
- Need point source ie a natural star or Laser Guide Star
- Project 589.2nm Dye laser beam
- Excites sodium atoms in air at 90 km making movable point source
- Use Micro-Electro-Mechanical-Systems Mirror
- Individual mirrors (fastest response) changes wavefront of beam
- Deformable mirror V at each segment creates nm changes in height
- Placed in focusing beam path - needs millisecond response time