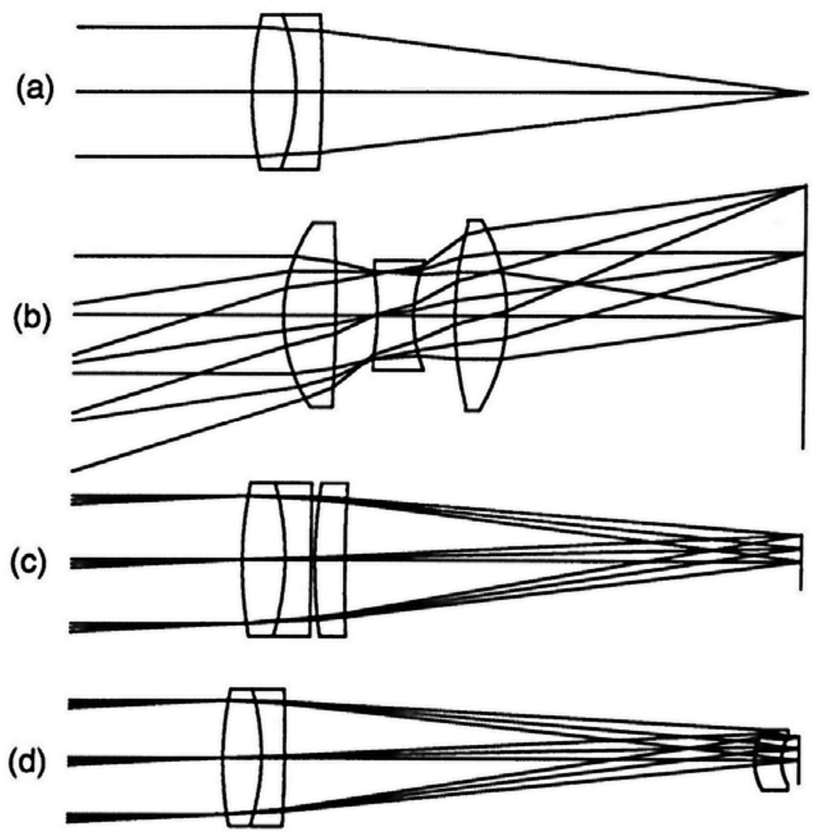
Refractive Optical Design Systems

- Many different types of lens systems used
- Want to look at each from the following

Performance Requirements

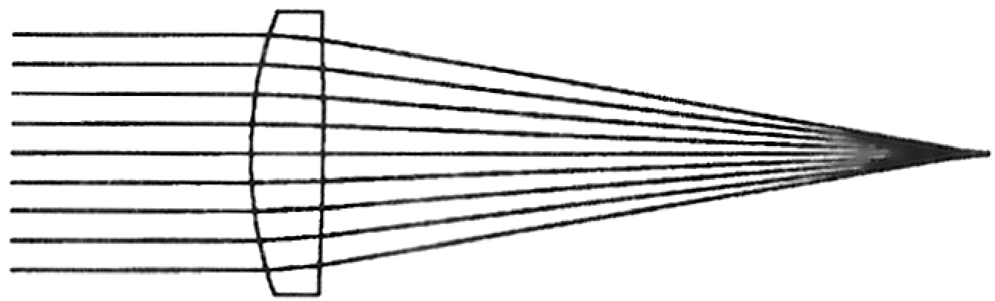
- Field of View:
  How much of a object is seen in the image from the lens system
- F#
- Packaging requirements
- Spectral Range

Figure 8.1
Doublets and Triplets



Single Element

- Poor image quality
- Very small field of view
- Chromatic Aberrations – only use a high f#
- However fine for some applications eg Laser with single line
- Where just want a spot, not a full field of view

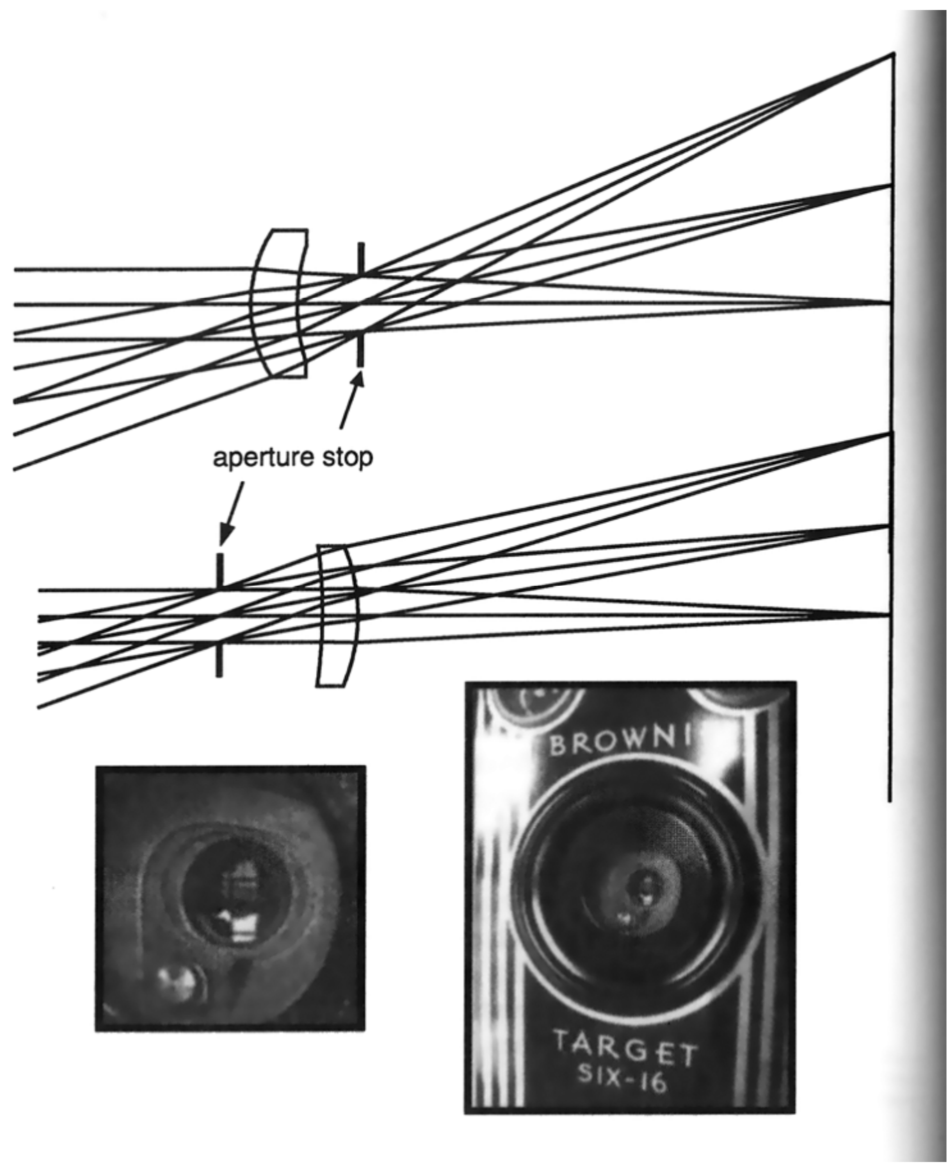


(a) Single element lens

Landscape Lens

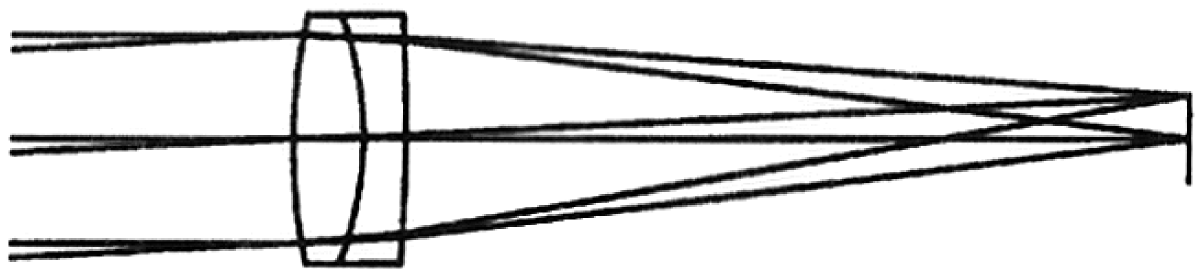
- Single lens but with aperture stop added
- i.e restriction on lens separate from the lens
- Lens is “bent” around the stop
- Reduces angle of incidence – thus off axis aberrations
- Aperture either in front or back
- Simple cameras use this

Figure 8.3
Landscape Lens with Stop Aft and Forward of Lens



Achromatic Doublet

- Brings red and blue into same focus
- Green usually slightly defocused
- Chromatic blur 25 less than singlet (for f#=5 lens)
- Cemented achromatic doublet poor at low f#
- Slight improvement if add space between lens
- Removes 5^{th} order spherical



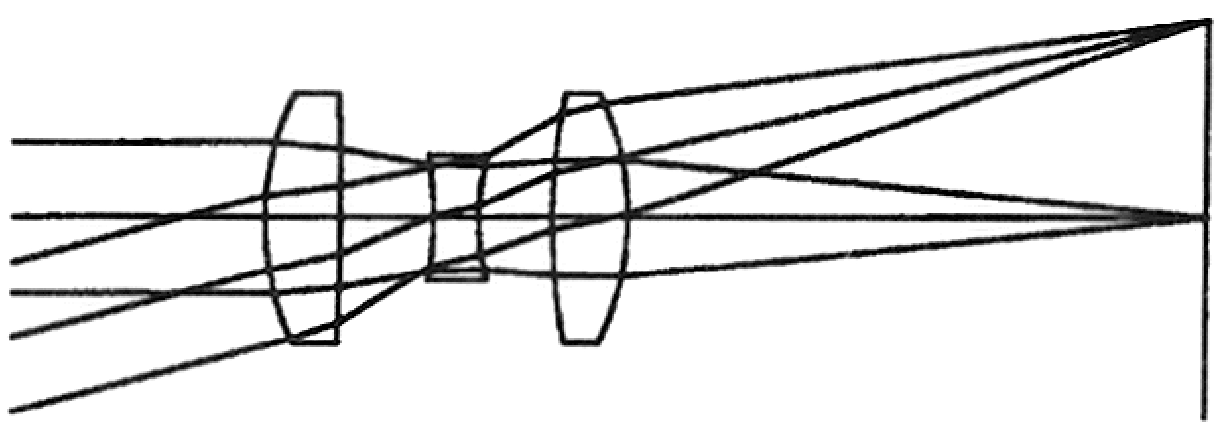
(c) Achromatic doublet

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
- 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

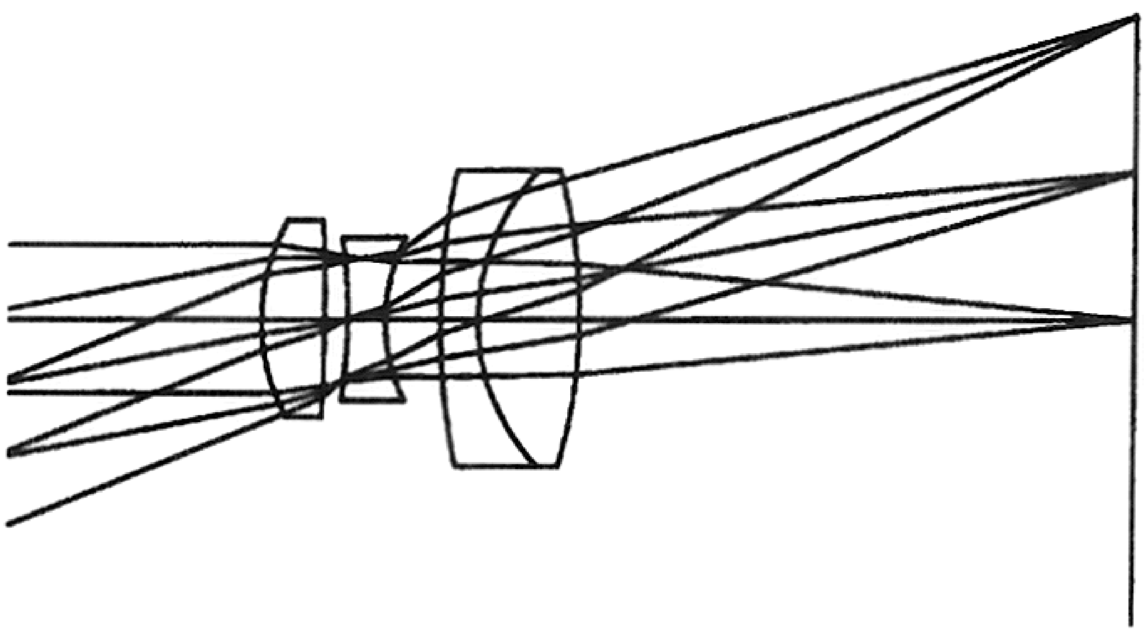
- Also control of focal length
- However tradeoffs eg f#:6 has 10^o field of view & good quality
- F#:1.4 has 30^o field of view but poor quality



(d) Cooke triplet

Zeiss Tessar

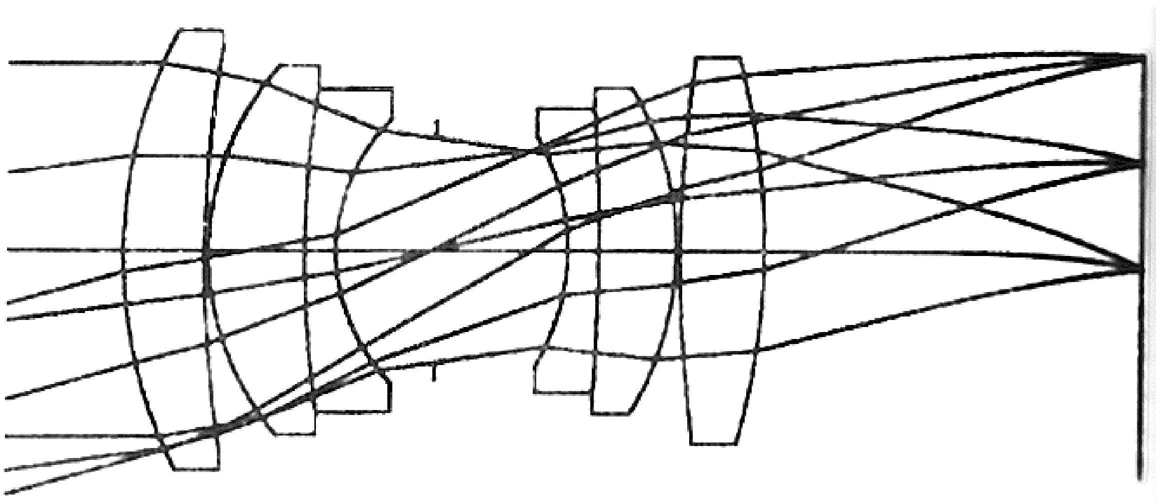
- Derived from Cooke by Paul Rudolph at Zeiss Jena in 1902
- Replaced back lens with doublet (tessares or 4 in Greek)
- Gets higher resolution, excellent contrast, very low distortion
- Want to eliminate aberrations when they occur
- “Clip at the bud”
- Lens 1 focuses light from infinity
- Lens 2 (diverging) 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 of 1920 was a Tessar



(e) Zeiss Tessar

Doublet Gauss or Biotar

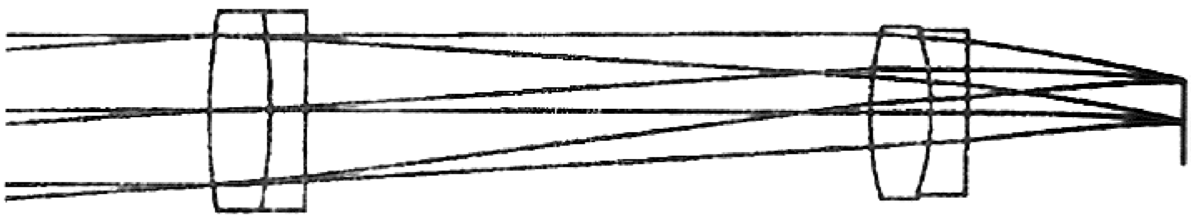
- Split optical power to minimize aberrations
- Negative element with smaller diameter for field curve correction
- For and aft spots minimize angle of incidence
- Doublet Gauss adds for & aft negative lens: more stops
- 2 positives at either end
- Symmetric pattern around stops
- Very good for high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



(f) Double Gauss

Petzval Lens

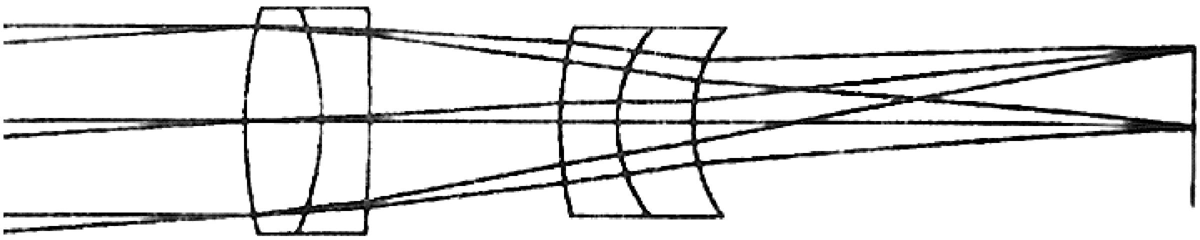
- Very old lens – designed by Joseph Petzval in 1840
- Petzval was the founder of geometric optics
- Targets smaller fields of view and moderate f# >= 3.5
- 2 separate doublets with aperture stop in between
- Lower chromatic aberrations than one doublet
- Still used in aerial cameras



(g) Petzval lens

Telephoto

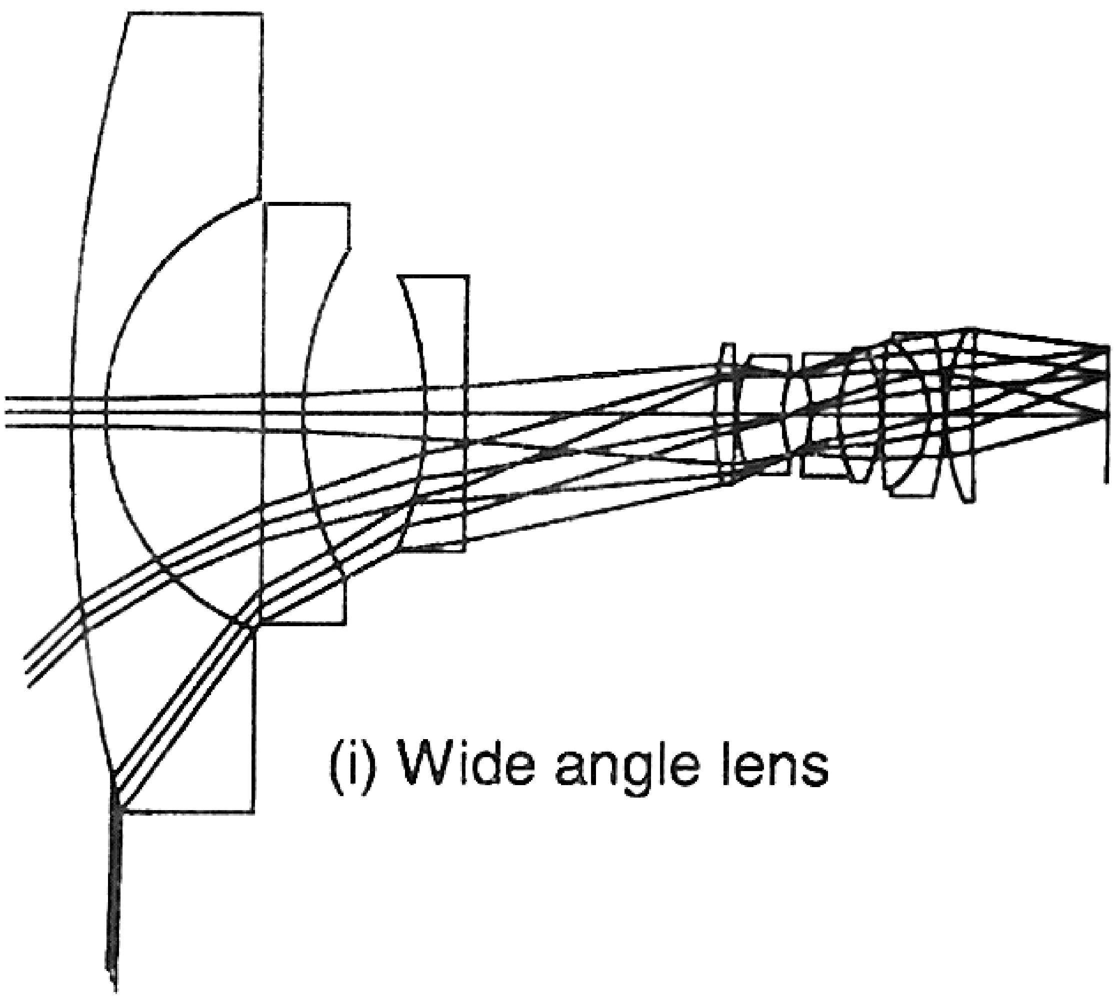
- Add negative lens to doublet
- Acts like Galilean telescope



(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

Nikor 28-200 mm zoom

200 mm 28 mm

Variable Power (Zoom) Concept

- Any single with unit power can be 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
- Need an afocal zoom

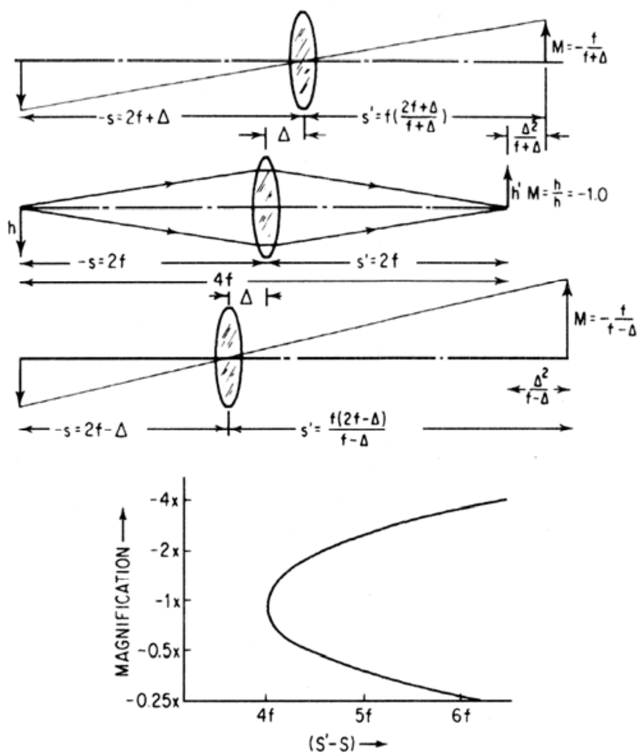
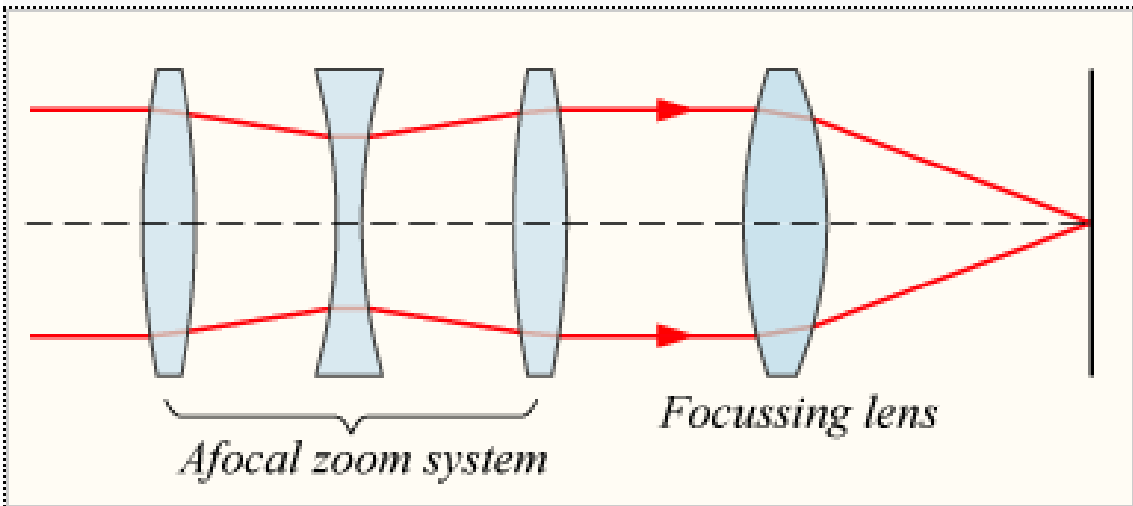


Figure 9.29 The basic unit power zoom lens. The graph indicates the shift of the image as the lens is moved to change the magnification.

Zoom Lenses Structure

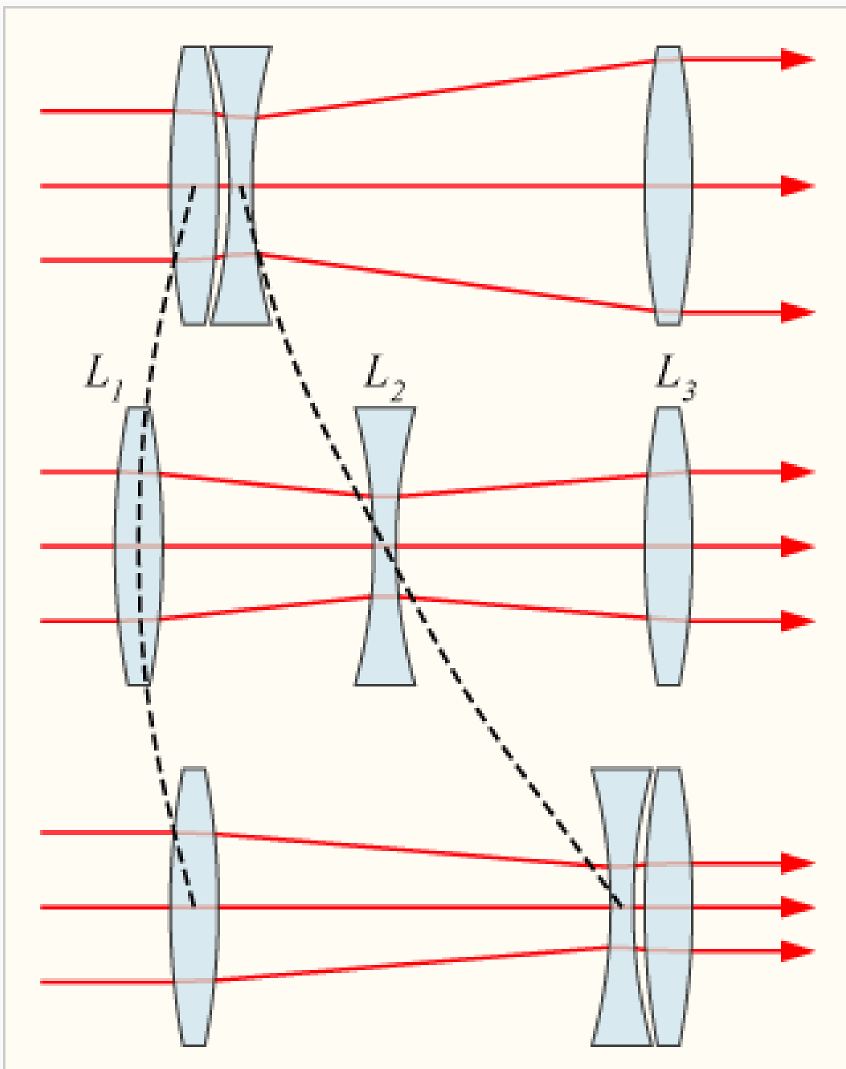
- Zoom lens consists of an afocal zoom system + focussing lens
- Afocal zoom takes in parallel light and changes diameter
- Acts as a variable beam expander
- Consists of L_1 positive, L_2 negative, L_3 positive
- Need $L_1=L_3$, $L_2<-f_1/2$
- Focusing lens creates the actual image



A simple zoom lens system

Zoom Lens Operation

- As L_1 and L_2 moves between changes amount of zoom
- L_2 close to L_1 and far from L_3, max magnification
- L_2 close to L_3 and shortest separation, min magnification
- L_1 moves forward as L_2 moves to L_3
- At the two extreme and center is afocal (parallel)
- Inbetween slight modification



Movement of lenses in an afocal zoom system

Zoom Lens Movement

- Zoom requires a complicated gear/movement system to work
- Called mechanical compensation
- In practice change two of the lens
- Create cams: L_2 moves in on path will L_1 follows the curve
- Complicated formulas to get this
- Top lenses use computer controlled servo motors now

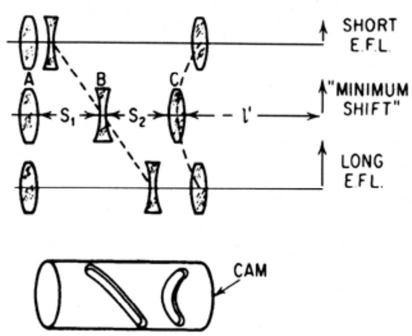


Figure 9.31 Mechanically compensated zoom system.

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 co stant value as lens B is moved.

Zoom Limitation

- Focusing lens brings the parallel light into focus
- Parfocal lens: stays in focus as zooms
- Important for video/movie cameras & still
- Varifocal allows focus to change – possible now with autofocus
- To make parfocal the fixed lens designed to focus at 3 points
- Adding additional negative makes more parfocal
- As change zoom change aberrations
- Hard to compensate for chromatic and field curvature
- Often requires additional lenses
- Min f# often decreases as zoom increases

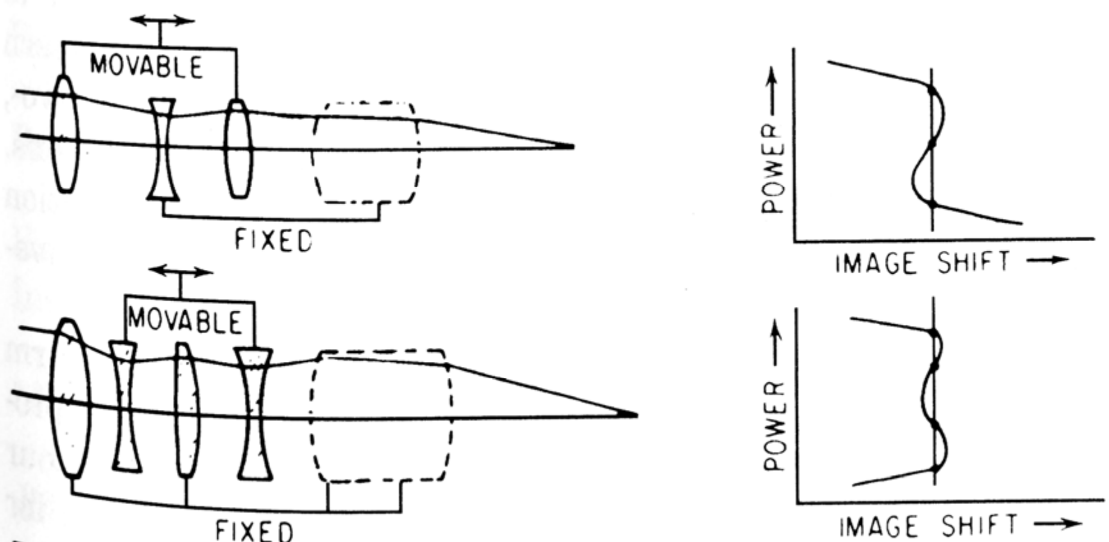
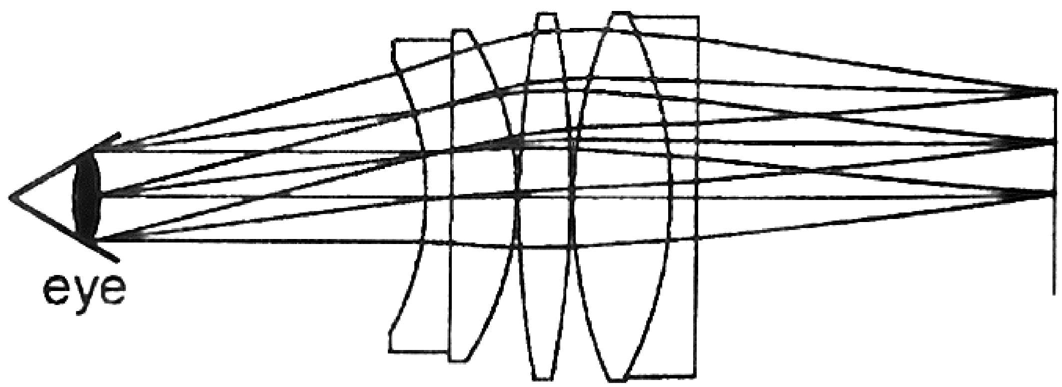


Figure 9.32 Optically compensated zoom systems. The upper system has three "active" components and three points of compensation as indicated in the upper graph. The lower system has four "active" components and four compensation points.

Eyepieces

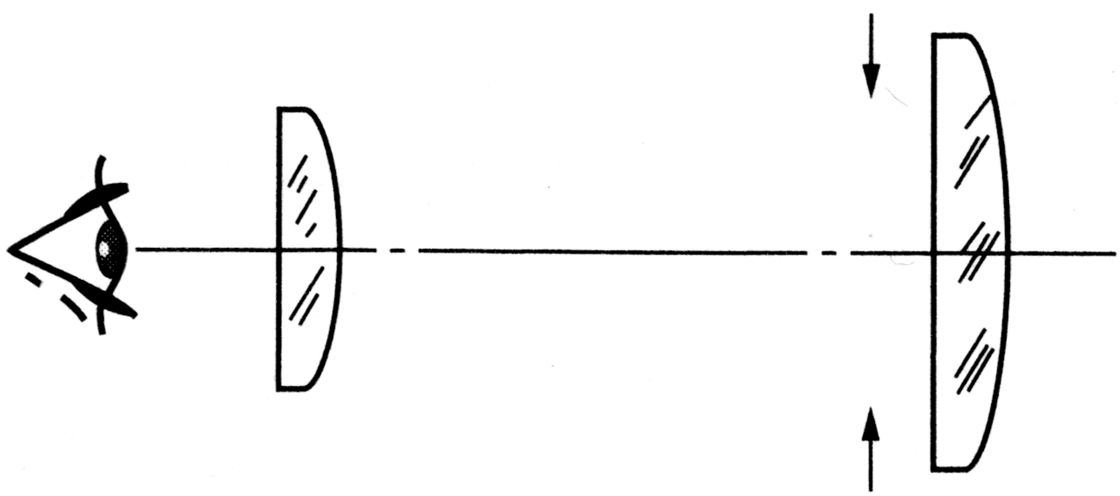
- Microscopes and telescopes use eyepieces for magnification
- Aperture stop is actually the iris of the eye for these
- Design to trace rays from the eye/iris aperture stop to image plane
- Problem is at outer edges get
  astigmatism, lateral color coma, & distortion
- Many different designs used to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



(j) eyepiece

Classic Eyepieces: Huygenian

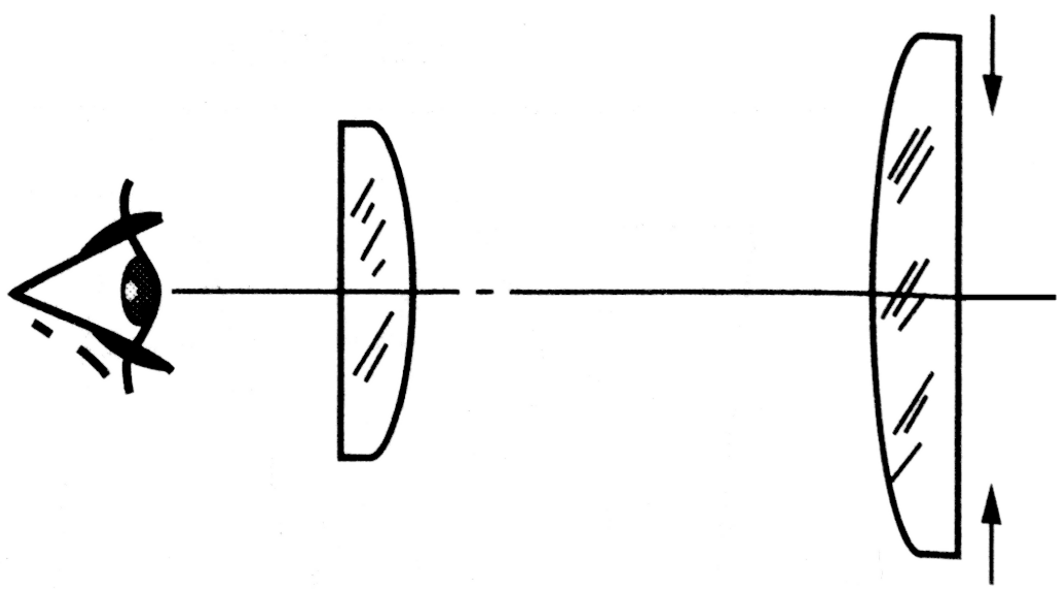
- Invented by Christiaan Huygens in the 17th century
- Huygenian: 2 plano convex with plane to the eye
- Use low index glass
- Probably the most common type used
- Correct lateral colour by spacing
- Spacing for chromatic aberration of one lens balances other
- Coma is corrected for a given objective distance
- Field stop is in “natural” position between lenses
- Image plane internal to lens – eye does most of magnification
- Field of view up to ~30-35^{o}
- 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

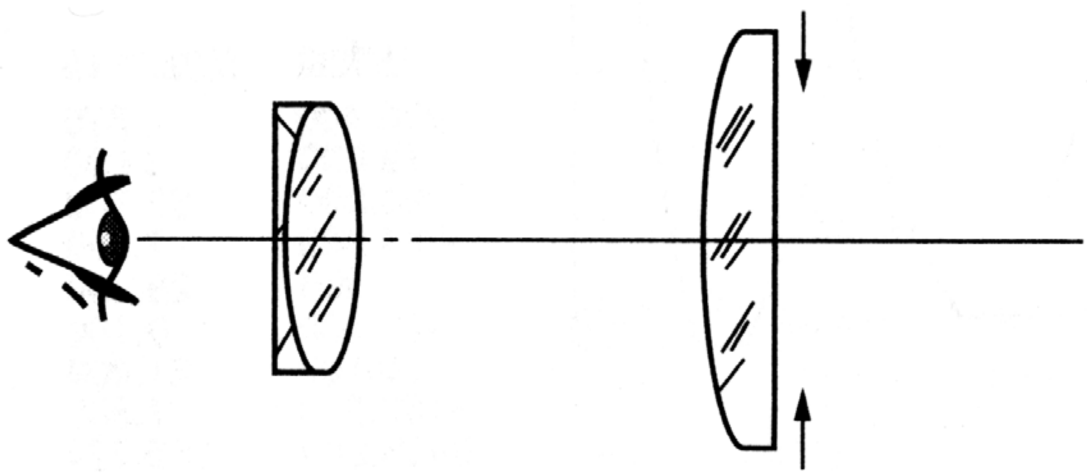
- Created by Jesse Ramsden in the 18th century
- Ramsden reduces distance between lenses
- Now planer sides on ends
- Field stop is at back of objective
- Image plane is external to lens
- Lateral colour not corrected
- but chromatic aberrations generally smaller
- Reduces spherical aberrations and distortion
- 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

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
ϕ_e/ϕ_f† (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.