Lens Aberrations Fundamentals

Optical Engineering

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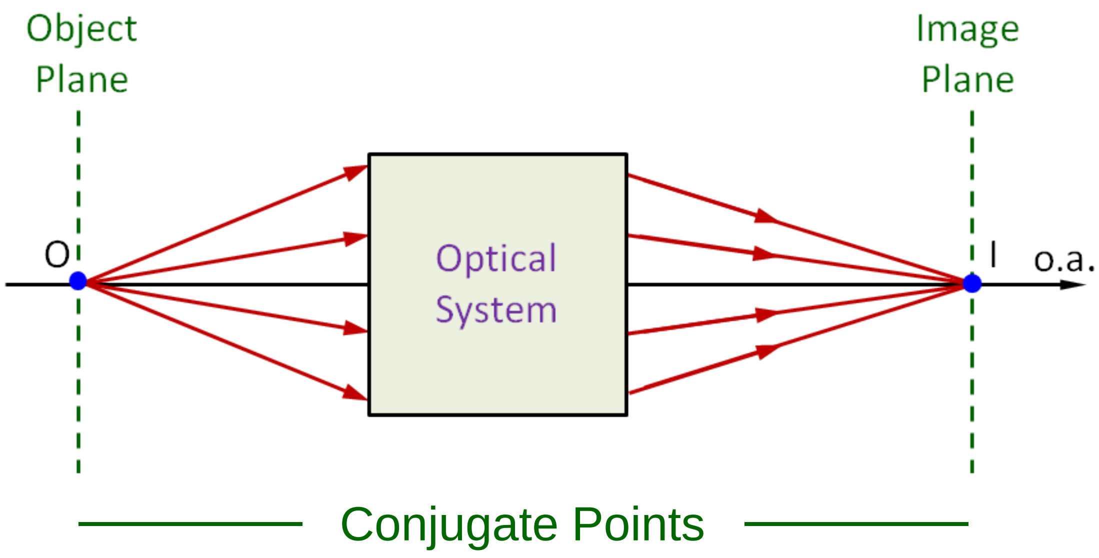
Imaging



Imaging Limitations

- Scattering
- Aberrations
- Diffraction

F. L. Pedrotti and L. S. Pedrotti, Introduction to Optics, 2nd Ed., Prentice Hall, 1993.

Aberrations
(3rd order – Seidel)

Chromatic

$$\sin x = \underbrace{x - \frac{x^3}{3!} + \frac{x^5}{5!}}_{\text{3rd order}} + O(x^7)$$

$$\cos x = \underbrace{1 - \frac{x^2}{2!} + \frac{x^4}{4!}}_{\text{3rd order}} + O(x^6)$$

optics.hanyang.ac.kr/~shsong/20-Aberration%20theory.pdf

Monochromatic

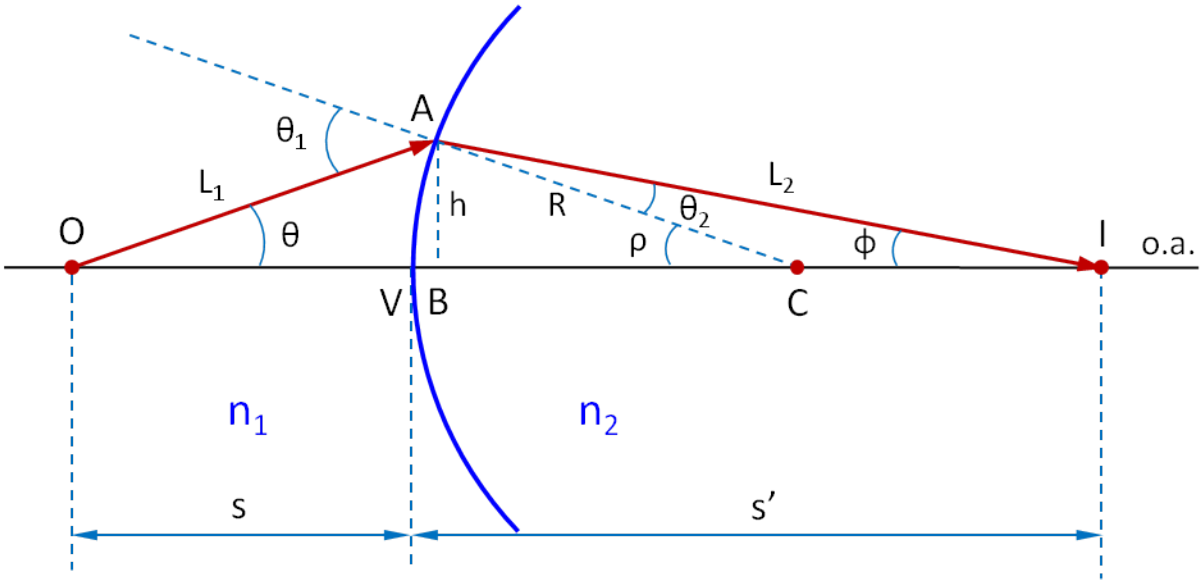
Unclear Image

- Spherical
- Coma
- Astigmatism

Deformation of Image

- Field Curvature
- Distortion

Spherical Aberration



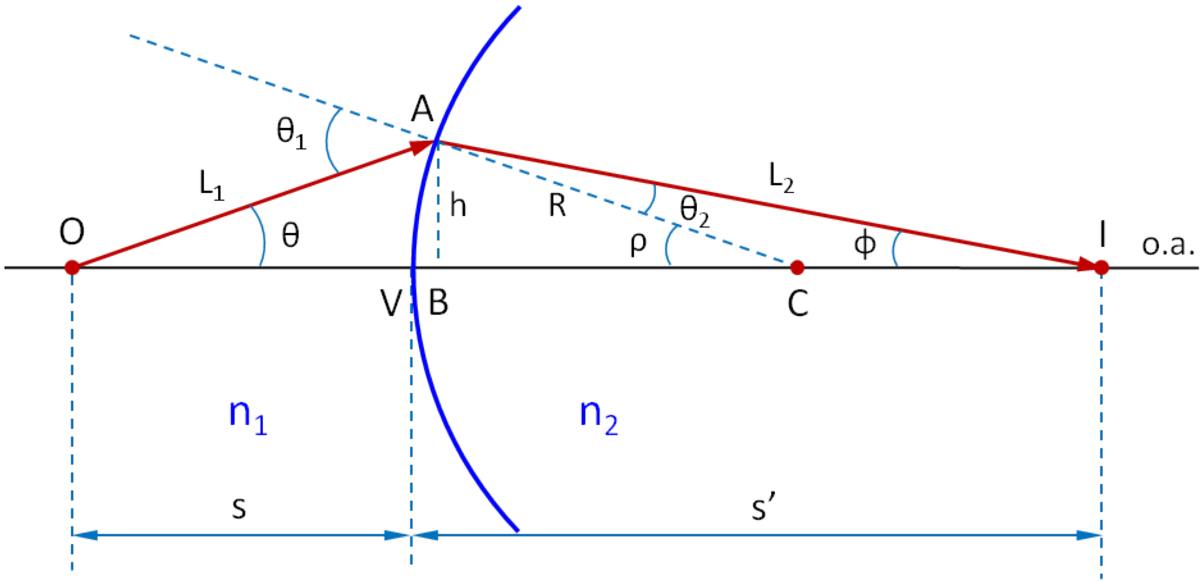
Paraxial Approximation: $$\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}$$

Fermat's Principle:

$$\begin{aligned}
OPL &= n_1(OA) + n_2(AI) = n_1 L_1 + n_2 L_2, \qquad \text{where} \\
L_1 &= \left[R^2 + (R+s)^2 - 2R(R+s)\cos\rho\right]^{1/2}, \qquad \text{from OAC} \\
L_2 &= \left[R^2 + (s'-R)^2 + 2R(s'-R)\cos\rho\right]^{1/2}, \qquad \text{from IAC} \\
\frac{d(OPL)}{dh} &= 0 \Longrightarrow n_1\frac{dL_1}{dh} + n_2\frac{dL_2}{dh} = 0 \Longrightarrow \left[n_1\frac{dL_1}{d\rho} + n_2\frac{dL_2}{d\rho}\right]\frac{d\rho}{dh} = 0 \Longrightarrow
\end{aligned}$$

$$n_1\frac{R(R+s)\sin\rho}{L_1} = n_2\frac{R(s'-R)\sin\rho}{L_2},$$

Spherical Aberration (continue)



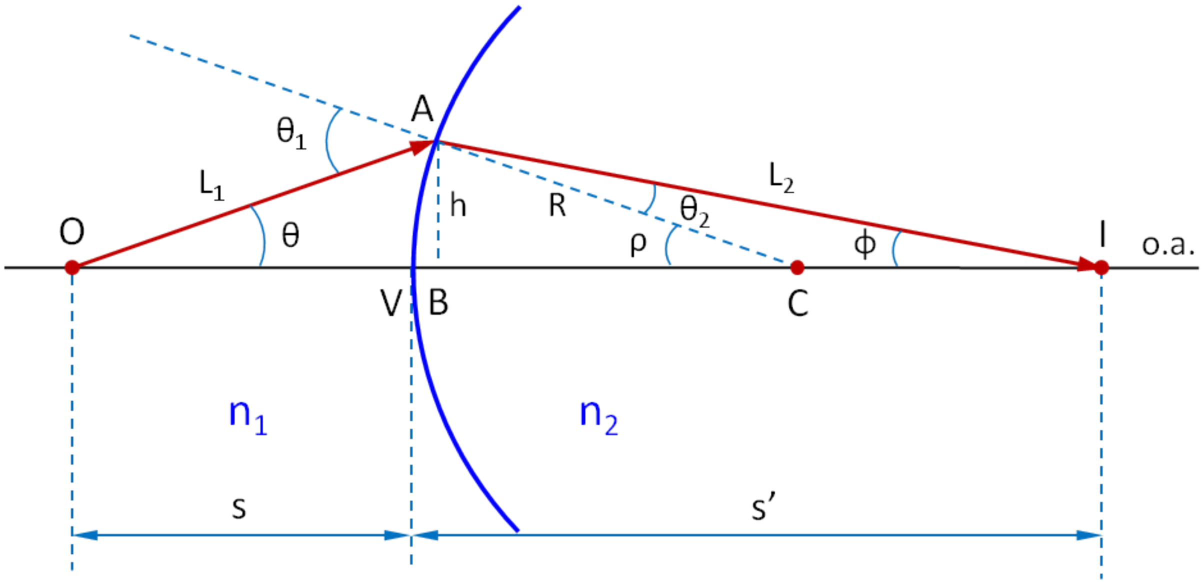
Fermat's Principle:

$$\frac{R^2}{\sin^2\rho}\frac{1}{(s'-R)^2}+2R\frac{\cos\rho}{\sin^2\rho}\frac{1}{(s'-R)}+\frac{1}{\sin^2\rho} = \frac{n_2^2}{n_1^2}\frac{L_1^2}{(R+s)^2\sin^2\rho}.$$

$$\begin{aligned}
x^2+\beta x+\gamma &= 0, \qquad \text{where} \\
\beta &= 2\frac{\sqrt{R^2-h^2}}{R^2}, \\
\gamma &= \frac{1}{R^2}\left[1-\frac{n_2^2}{n_1^2}\frac{L_1^2}{(R+s)^2}\right], \\
\Delta &= \beta^2-4\gamma=\frac{4}{R^2}\left[-\frac{h^2}{R^2}+\frac{n_2^2}{n_1^2}\frac{L_1^2}{(R+s)^2}\right], \\
x_{1,2} &= \left.\frac{1}{s'-R}\right|_{1,2}=\frac{-\beta\pm\sqrt{\Delta}}{2},
\end{aligned}$$

$$\boxed{x_1=(1/2)(-\beta+\sqrt{\Delta})\rightarrow s'=(1/x_1)+R}$$

Spherical Aberration (continue)



Using Trigonometry and Snell's Law:

$$\frac{\sin\theta}{R = AC} = \frac{\sin(\pi-\theta_1)}{R+s = OC} = \frac{\sin\rho}{OA} \implies \sin\theta_1 = \frac{R+s}{R}\sin\theta,$$

$$n_1\sin\theta_1 = n_2\sin\theta_2 \implies \sin\theta_2 = \frac{n_1\sin\theta_1}{n_2} = \frac{n_1}{n_2}\frac{R+s}{R}\sin\theta,$$

$$OAC \implies \rho = \pi-\theta-(\pi-\theta_1) = \theta_1-\theta,$$

$$ACI \implies \phi = \rho-\theta_2 = \theta_1-\theta_2-\theta.$$

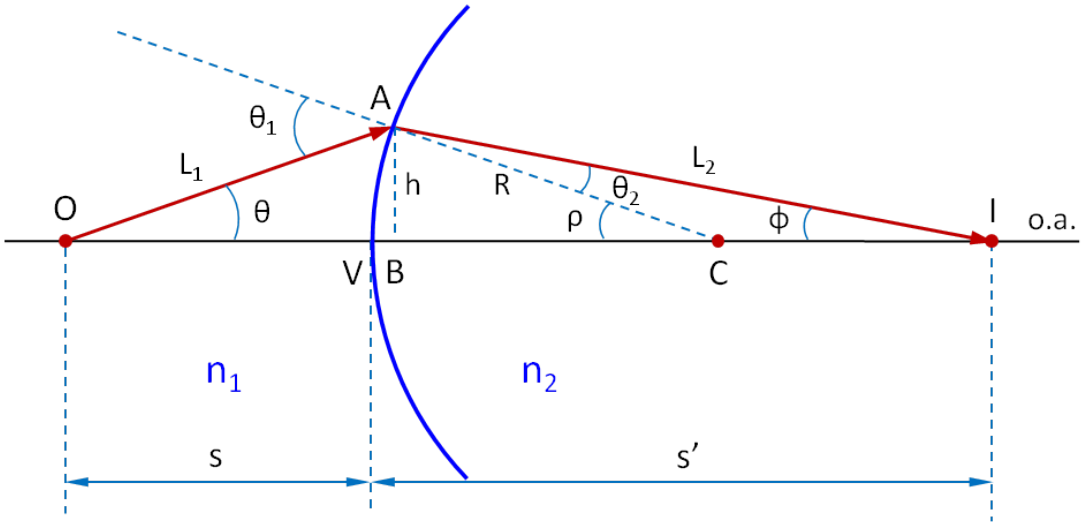
Triangle OAI:

$$\frac{\sin(\pi-\theta_1+\theta_2)}{OI = s+s'} = \frac{\sin\phi}{OA} = \frac{\sin\theta}{AI},$$

$$OA = R\frac{\sin\rho}{\sin\theta} = R\frac{\sin(\theta_1-\theta)}{\sin\theta}.$$

$$s' = R\,\frac{\sin(\theta_1-\theta)}{\sin\theta}\,\frac{\sin(\theta_1-\theta_2)}{\sin\phi} - s$$

Spherical Aberration (3rd order – Seidel)



3rd order – Seidel

$$\sin x \simeq x - \frac{x^3}{3!} + \frac{x^5}{5!}$$

$$\cos x \simeq 1 - \frac{x^2}{2!} + \frac{x^4}{4!}$$

$$(1+x)^{1/2} \simeq 1 + \frac{x}{2} - \frac{x^2}{8}$$

$$\alpha(A) = (n_1 L_1 + n_2 L_2) - (n_1 s + n_2 s') \quad \text{where}$$

$$L_1 = \left[R^2 + (R+s)^2 - 2R(R+s)\cos\rho\right]^{1/2}, \quad \text{from OAC}$$

$$L_2 = \left[R^2 + (s'-R)^2 + 2R(s'-R)\cos\rho\right]^{1/2}, \quad \text{from IAC}$$

$$\cos\rho = (1-\sin^2\rho)^{1/2} = \left(1 - \frac{h^2}{R^2}\right)^{1/2} \Longrightarrow$$

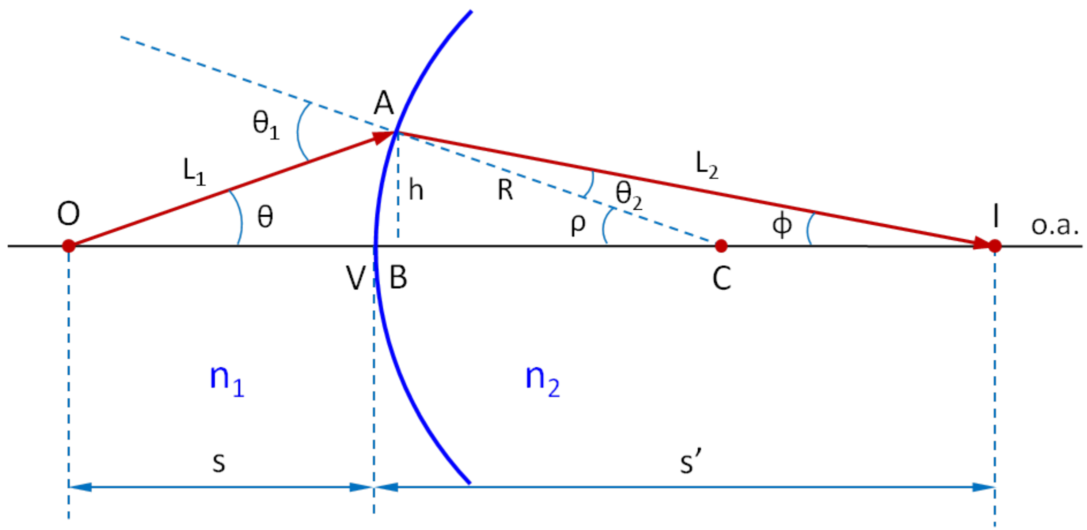
$$\cos\rho \simeq 1 - \frac{h^2}{2R^2} - \frac{h^4}{8R^4} \quad \text{resulting in}$$

$$L_1 \simeq s\left[1 + \frac{h^2(R+s)}{Rs^2} + \frac{h^4(R+s)}{4R^3s^2}\right]^{1/2}$$

$$L_2 \simeq s'\left[1 + \frac{h^2(R-s')}{Rs'^2} + \frac{h^4(R-s')}{4R^3s'^2}\right]^{1/2}.$$

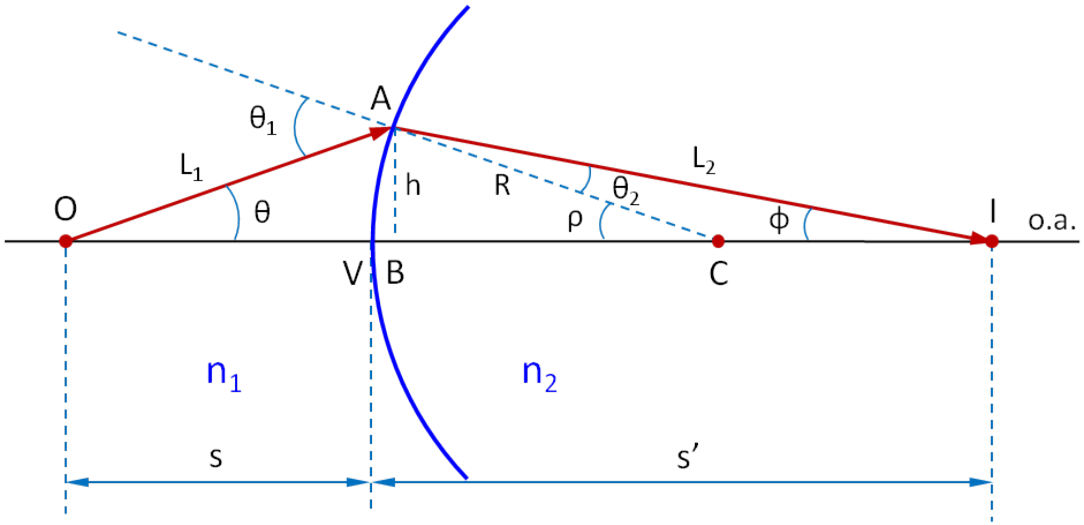
$$(1+x)^{1/2} \simeq 1 + (x/2) - (x^2/8)$$

Spherical Aberration (3rd order – Seidel)



$$
\begin{aligned}
L_1 &\simeq s\left[1+\frac{h^2(R+s)}{2Rs^2}+\frac{h^4(R+s)}{8R^3s^2}-\frac{h^4(R+s)^2}{8R^2s^4}\right],\\
L_2 &\simeq s'\left[1+\frac{h^2(R-s')}{2Rs'^2}+\frac{h^4(R-s')}{8R^3s'^2}-\frac{h^4(R-s')^2}{8R^2s'^4}\right], \qquad \text{resulting in}\\
\alpha(A) &\simeq \frac{h^2}{2}\left[\frac{n_1}{s}+\frac{n_2}{s'}-\frac{n_2-n_1}{R}\right]\\
&\quad -\frac{h^4}{8}\left[\frac{n_1}{s}\left(\frac{1}{s}+\frac{1}{R}\right)^2+\frac{n_2}{s'}\left(\frac{1}{s'}-\frac{1}{R}\right)^2-\frac{1}{R^2}\left(\frac{n_1}{s}+\frac{n_2}{s'}-\frac{n_2-n_1}{R}\right)\right].
\end{aligned}
$$

Spherical Aberration (3rd order – Seidel)



$$OPL = n_1 L_1 + n_2 L_2 \quad \text{with}$$

$$L_1 \simeq s\left[1 + \frac{h^2(R+s)}{2Rs^2} + \frac{h^4(R+s)}{8R^3s^2} - \frac{h^4(R+s)^2}{8R^2s^4}\right],$$

$$L_2 \simeq s'\left[1 + \frac{h^2(R-s')}{2Rs'^2} + \frac{h^4(R-s')}{8R^3s'^2} - \frac{h^4(R-s')^2}{8R^2s'^4}\right],$$

$$\frac{d(OPL)}{dh} = 0 \Longrightarrow$$

$$n_1\frac{R+s}{Rs} + n_1\frac{h^2}{2}\frac{R+s}{R^3s} - n_1\frac{h^2}{2}\frac{(R+s)^2}{R^2s^3}$$

$$+n_2\frac{R-s'}{Rs'} + n_2\frac{h^2}{2}\frac{R-s'}{R^3s'} - n_2\frac{h^2}{2}\frac{(R-s')^2}{R^2s'^3} = 0 \Longrightarrow$$

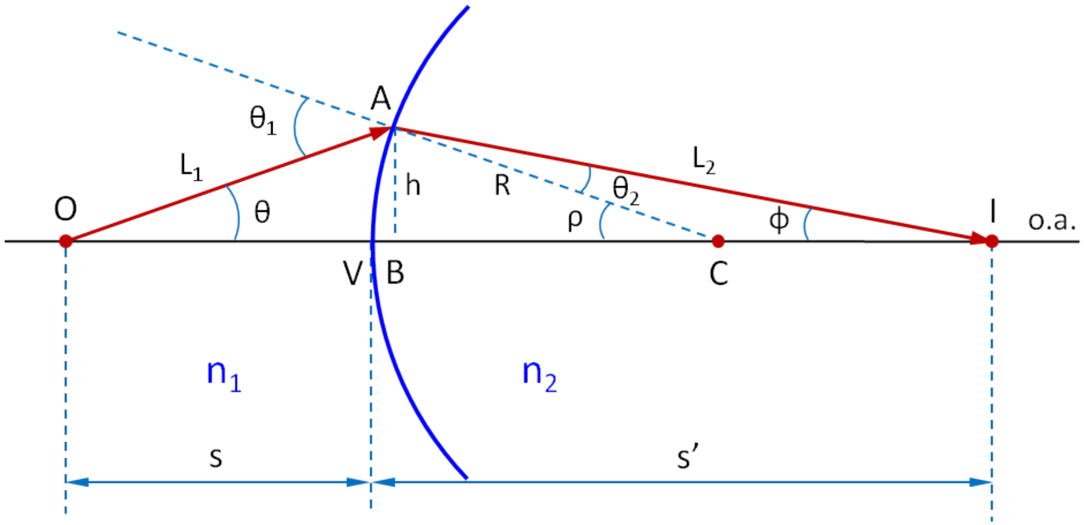
$$X\left(1 + \frac{h^2}{2R^2}\right) = \frac{h^2}{2}\left[\frac{n_1}{s}\left(\frac{1}{s} + \frac{1}{R}\right)^2 + \frac{n_2}{s'}\left(\frac{1}{s'} - \frac{1}{R}\right)^2\right] \quad \text{where}$$

$$X = \frac{n_1}{s} + \frac{n_2}{s'} - \frac{(n_2 - n_1)}{R}.$$

$$X = \frac{h^2}{2}\left[\frac{n_1}{s}\left(\frac{1}{s} + \frac{1}{R}\right)^2 + \frac{n_2}{s'}\left(\frac{1}{s'} - \frac{1}{R}\right)^2\right],$$

$$\frac{n_2}{f_p} = \frac{n_2 - n_1}{R},$$

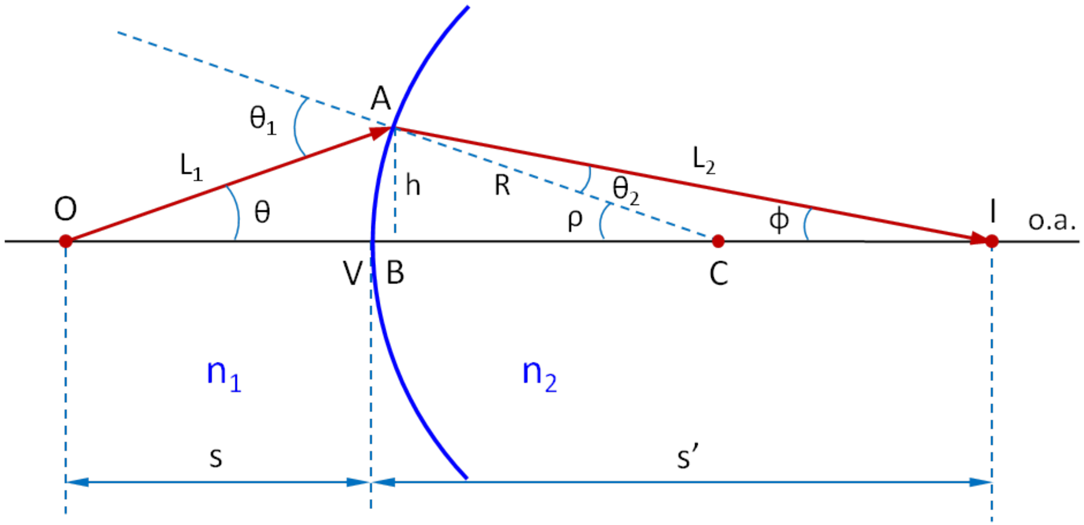
Spherical Aberration (3rd order – Seidel)



3-order Approximation:

$$\frac{n_1}{s}+\frac{n_2}{s'}=\frac{n_2-n_1}{R}+\frac{h^2}{2}\left[\frac{R}{f_p}\frac{n_1^2}{n_2}\left(\frac{1}{R}+\frac{1}{s}\right)^2\left(\frac{1}{R}+\frac{n_1+n_2}{n_1}\frac{1}{s}\right)\right]$$

Spherical Aberration (3rd order – Seidel)

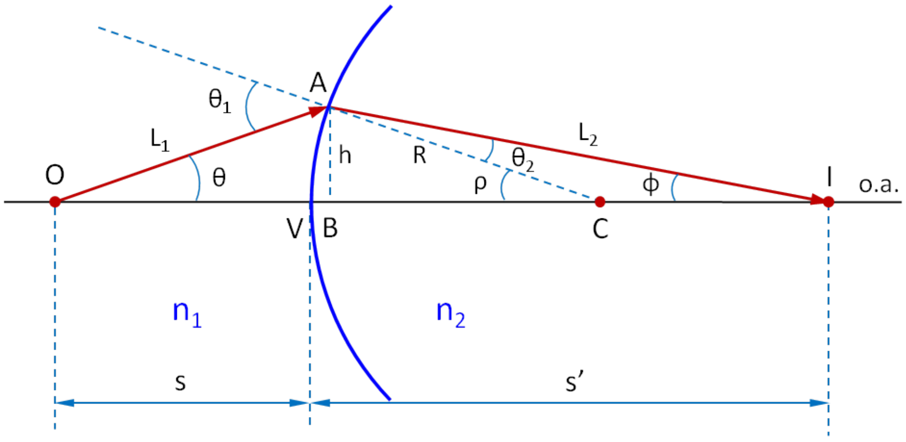


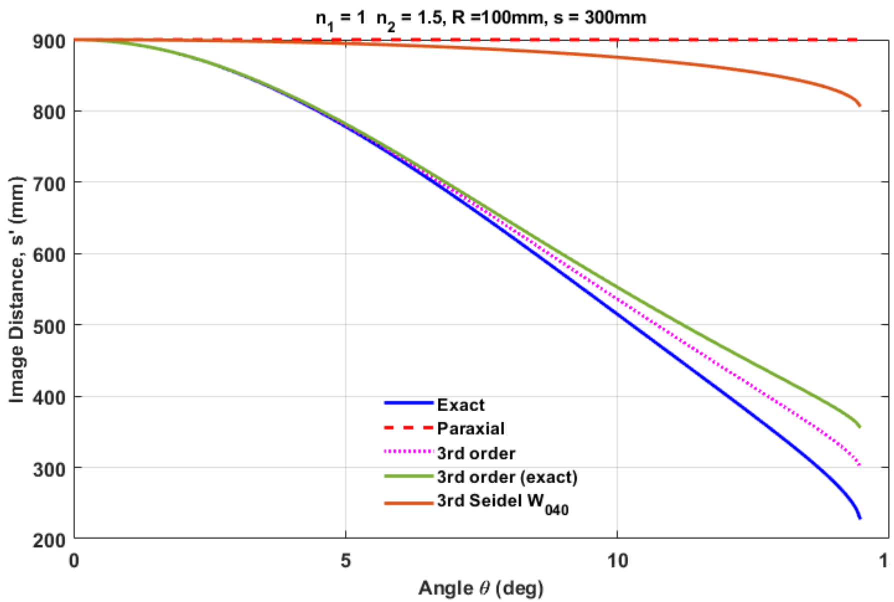
3-order Approximation (without any more approximations-exact):

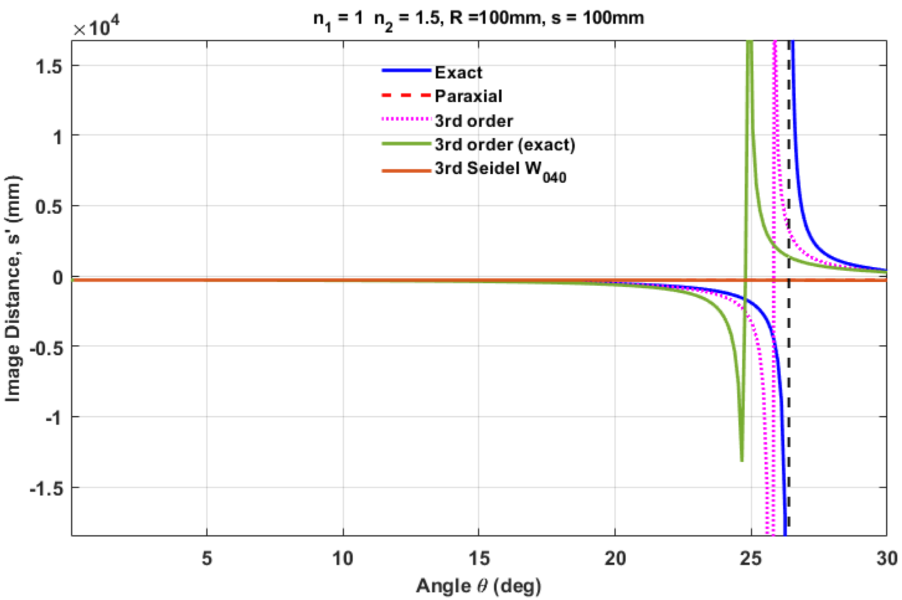
$$\left(\frac{n_1}{s}+\frac{n_2}{s'}-\frac{n_2-n_1}{R}\right)\left(1+\frac{h^2}{2R^2}\right) = \frac{h^2}{2}\left[\frac{n_1}{s}\left(\frac{1}{s}+\frac{1}{R}\right)^2+\frac{n_2}{s'}\left(\frac{1}{s'}-\frac{1}{R}\right)^2\right]$$

$$\begin{aligned} a_0\psi^3+a_1\psi^2+a_2\psi+a_3 &= 0, \qquad \text{where} \\ \psi &= \frac{1}{s'}, \\ a_0 &= \frac{h^2}{2}n_2, \\ a_1 &= -\frac{h^2 n_2}{R}, \\ a_2 &= \frac{h^2 n_2}{2R^2}-\left(1+\frac{h^2}{2R^2}\right)n_2, \\ a_3 &= \frac{h^2}{2}\frac{n_1}{s}\left(\frac{1}{s}+\frac{1}{R}\right)^2-\left(1+\frac{h^2}{2R^2}\right)\left(\frac{n_1}{s}-\frac{n_2-n_1}{R}\right). \end{aligned}$$

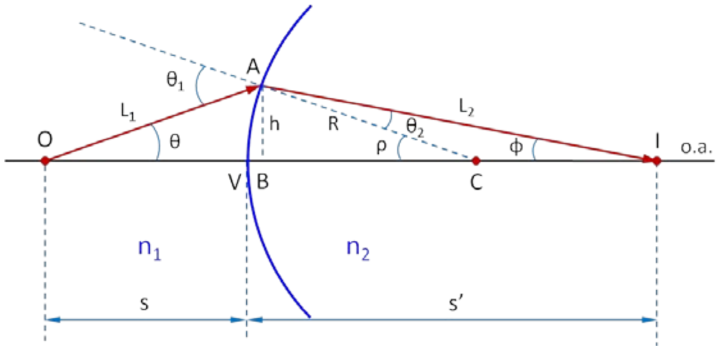
Spherical Aberration - Example

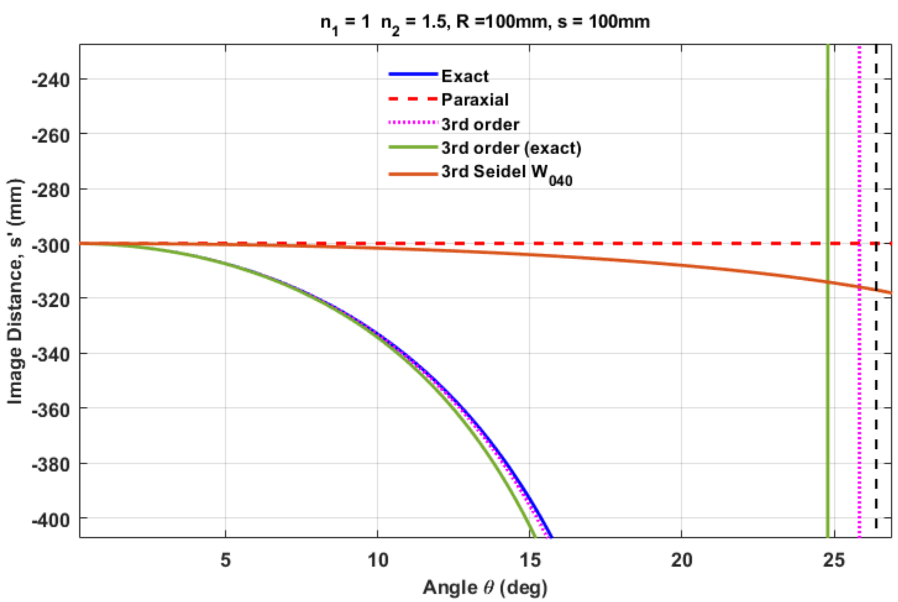


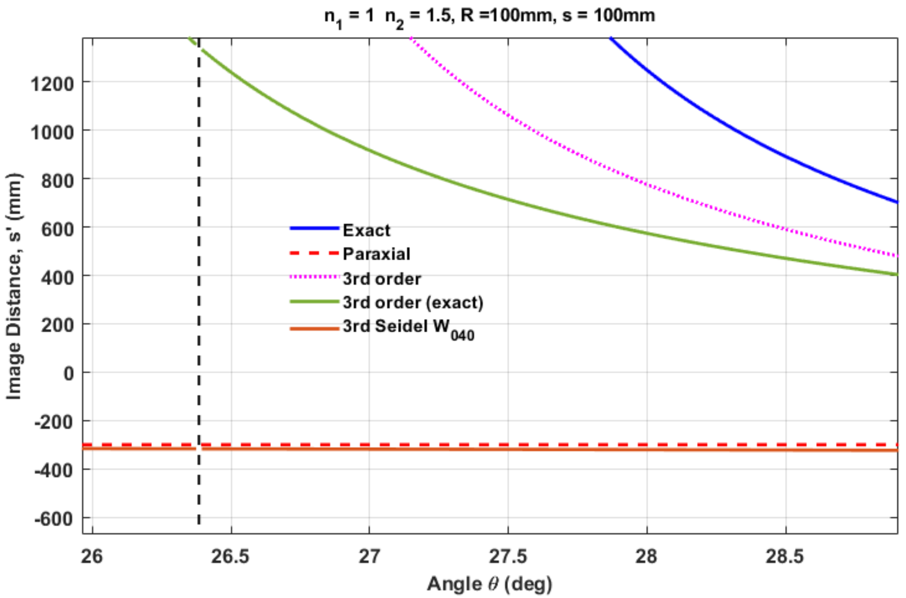




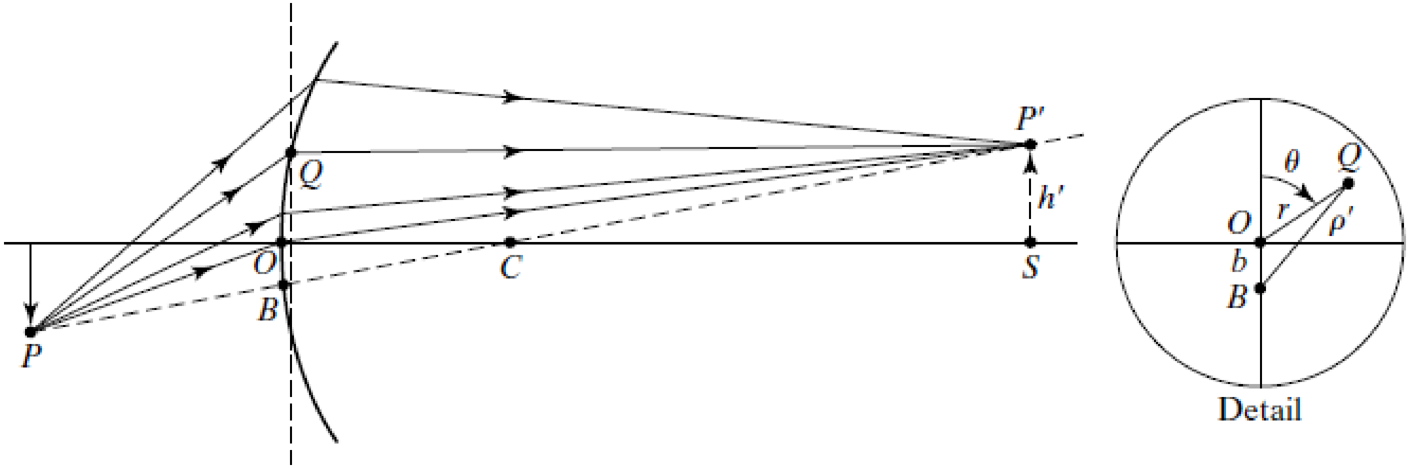
Spherical Aberration - Example







Aberrations (3rd order – Seidel)



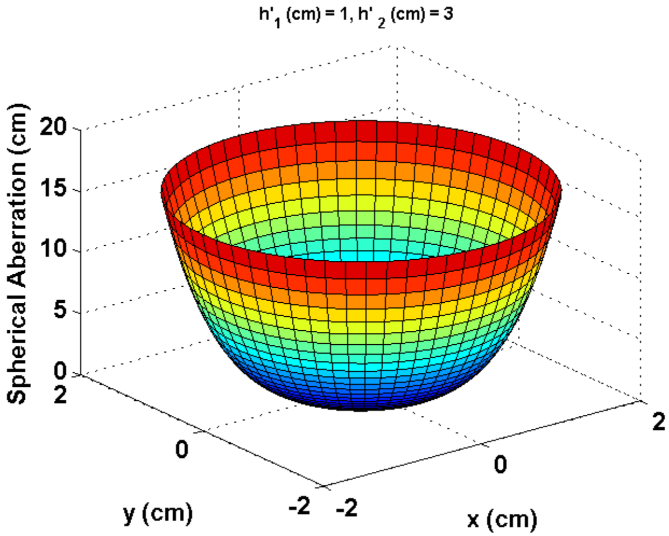
$$a(Q) = \ {}_0C_{40}r^4 + {}_1C_{31}h'r^3\cos\theta + {}_2C_{22}h'^2r^2\cos^2\theta + {}_2C_{20}h'^2r^2 + {}_3C_{11}h'^3r\cos\theta$$

r^4	:	Spherical Aberration
$h'r^3\cos\theta$	:	Coma
$h'^2r^2\cos^2\theta$	:	Astigmatism
h'^2r^2	:	Field Curvature
$h'^3r\cos\theta$	:	Distortion

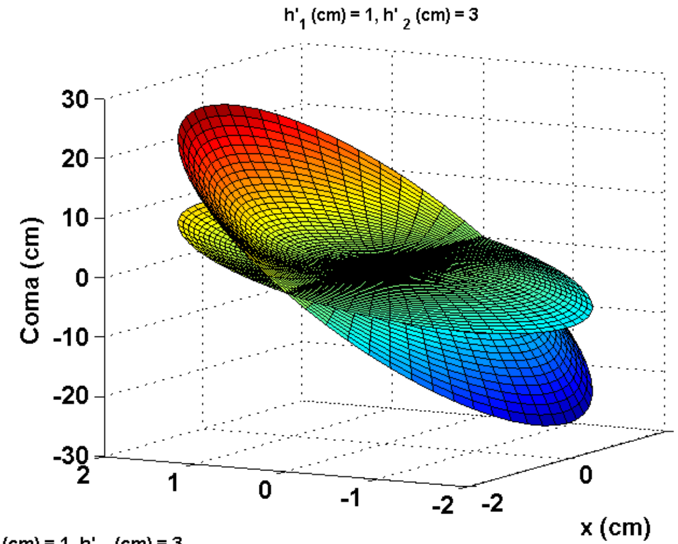
F. L. Pedrotti et al., "Introduction to Optics", 3rd Ed., Prentice Hall, New Jersey,2006

Aberrations (3rd order – Seidel)

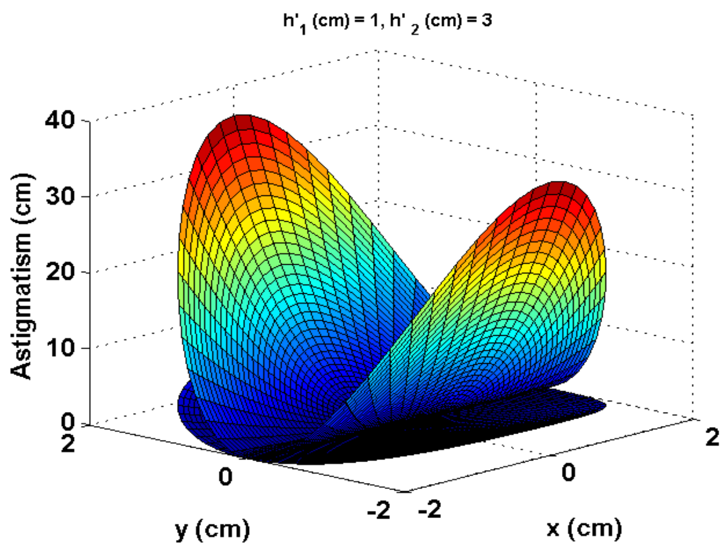
r^4 : Spherical Aberration



$h' r^3 \cos\theta$: Coma

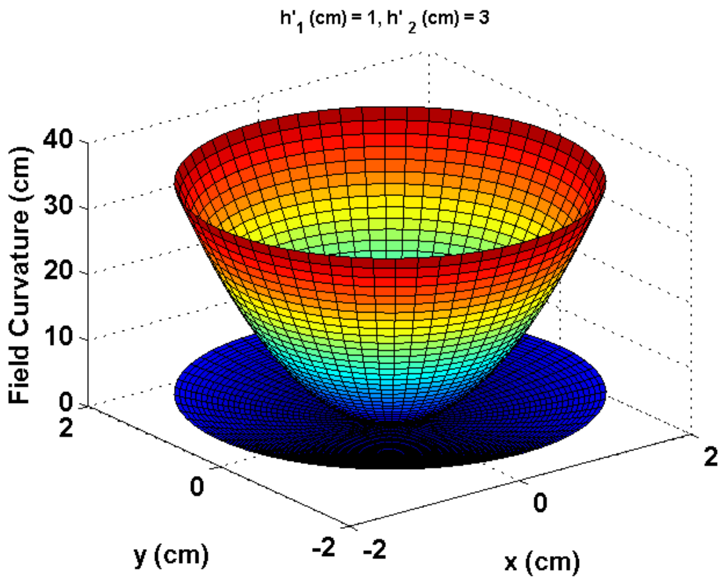


$h'^2 r^2 \cos^2\theta$: Astigmatism

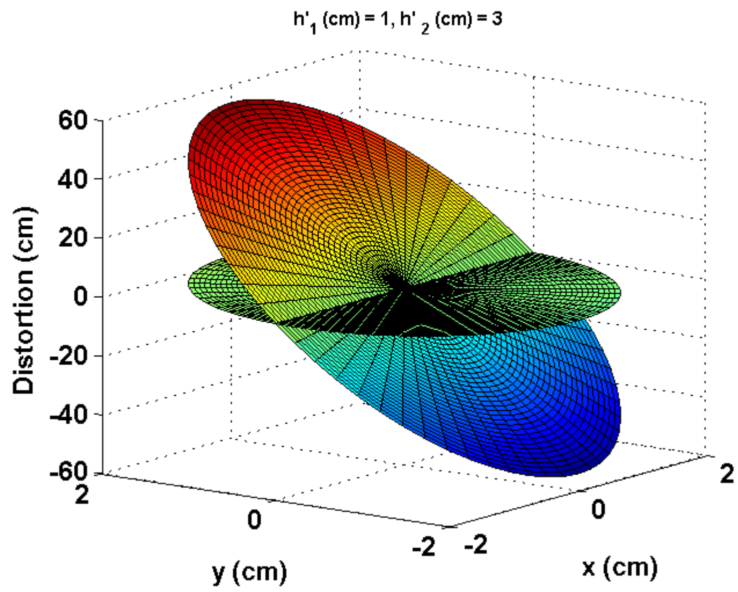


Aberrations (3rd order – Seidel)

$h'^2 r^2 \quad : \quad \text{Field Curvature}$



$h'^3 r \cos\theta \quad : \quad \text{Distortion}$



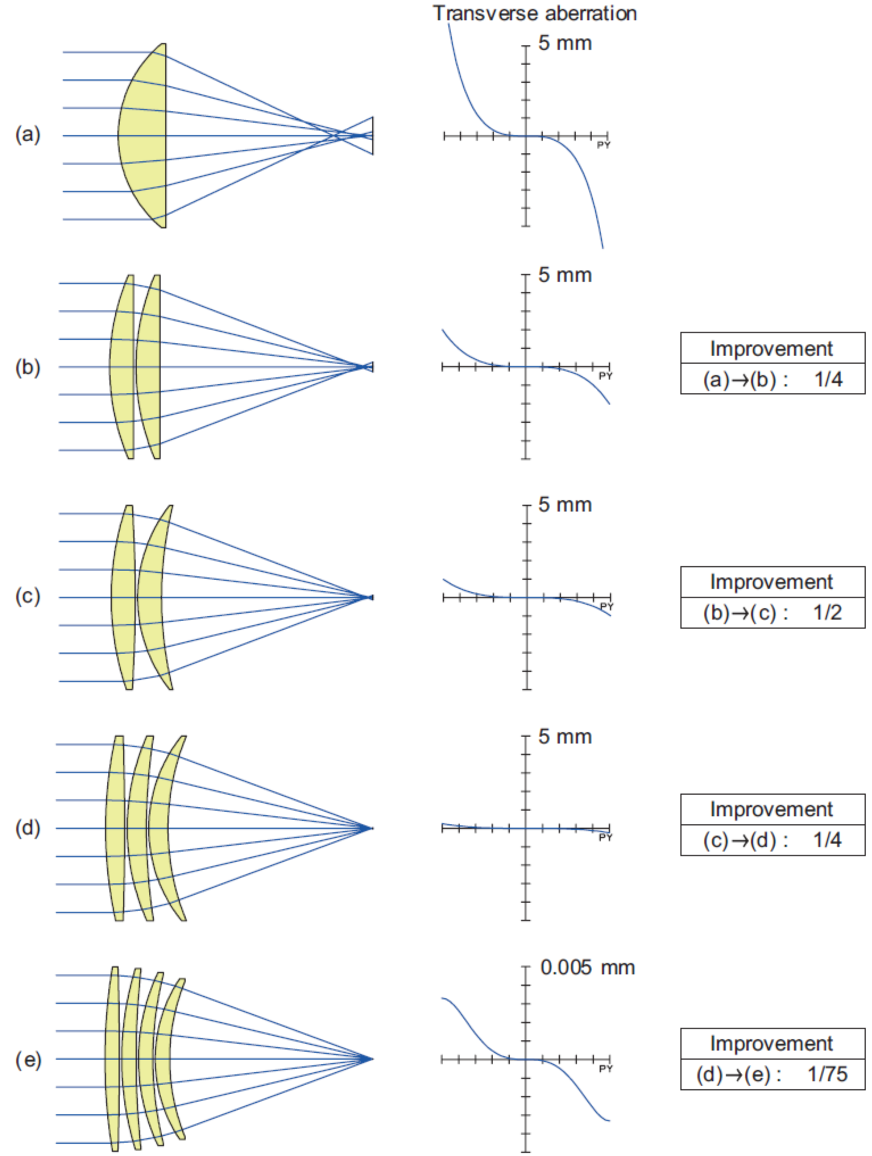
Lens Aberrations and Common Corrections

Aberration	Character	Correction
1. Spherical aberration	Monochromatic, on- and off-axis, image blur	Bending, high index, aspherics, gradient index, doublet
2. Coma	Monochromatic, off-axis only, blur	Bending, spaced doublet with central stop
3. Oblique astigmatism	Monochromatic, off-axis blur	Spaced doublet with stop
4. Curvature of field	Monochromatic, off-axis	Spaced doublet
5. Distortion	Monochromatic, off-axis	Spaced doublet with stop
6. Chromatic aberration	Heterochromatic, on- and off-axis, blur	Contact doublet, spaced doublet

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

Lens Aberrations and Corrections Approaches

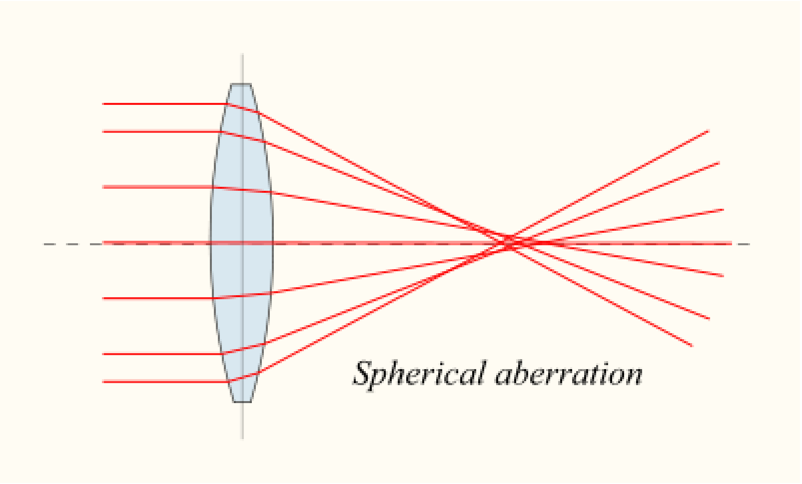
- Lens Bending
- Power Splitting
- Power Combination
- Distances
- Refractive Index
- Dispersion
- Gradient Index Materials
- Cemented Surfaces
- Aspherical Surfaces
- Diffractive Surfaces



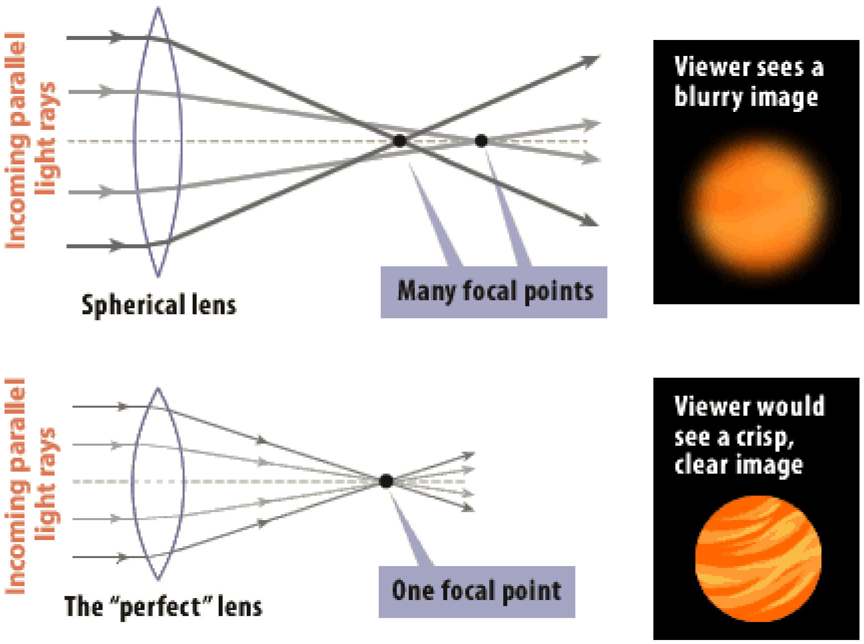
Example: Splitting and bending. In the examples shown *f ′ = 100 mm, the aperture is f/1.4, the refractive index n = 1.5.* Note the change in the scale for the transverse aberration diagram in case (e) with four elements. The transverse aberration is shown with respect to the Gaussian image plane.

Handbook of Optical Systems, Ed. H. Gross, vol. 3, 2007

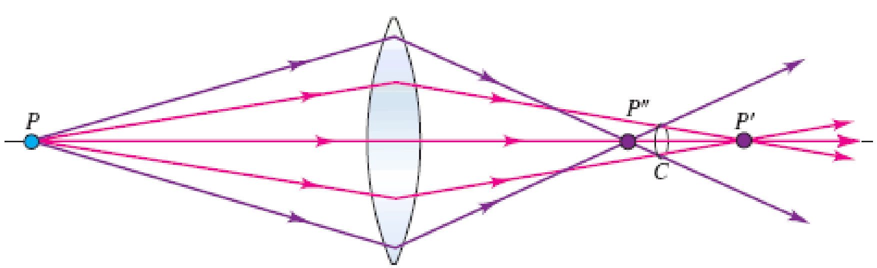
Spherical Aberration

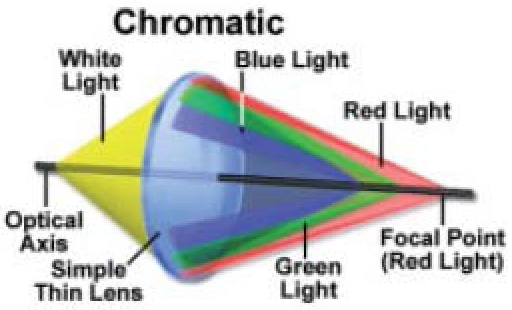


http://en.wikipedia.org/wiki/Lens_(optics)



http://amazing-space.stsci.edu/resources/explorations/groundup/lesson/basics/g11/





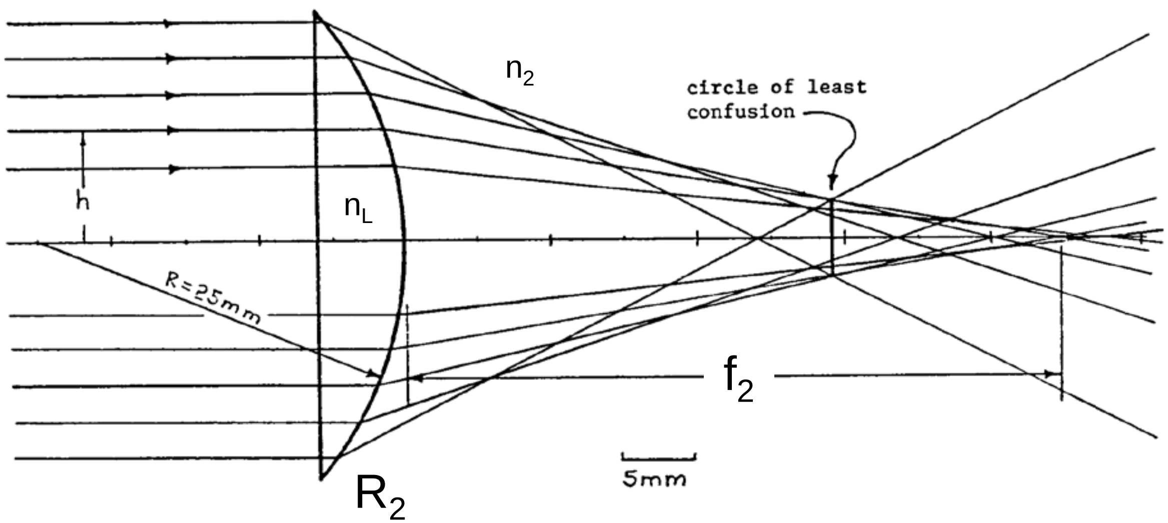
Spherical Aberration Example

https://www.wehelpchicagosee.com/blog/2015/01/28/high-definition-hd-vision-154460

Plano-Convex Lens

A plano-convex lens has a radius of curvature of R and an index of refraction, n. A collimated beam of light is incident upon the plano side of this lens in air as shown in the figure. Accounting for the plano-convex shape of the lens, the focal distance as defined in the figure, for an axial ray of displacement h from the principal axis is

$$f_2 = \frac{h}{\tan\left[\sin^{-1}\left(\frac{n_L}{n_2}\frac{h}{R_2}\right) - \sin^{-1}\left(\frac{h}{R_2}\right)\right]} - R_2 + \sqrt{R_2^2 - h^2}.$$

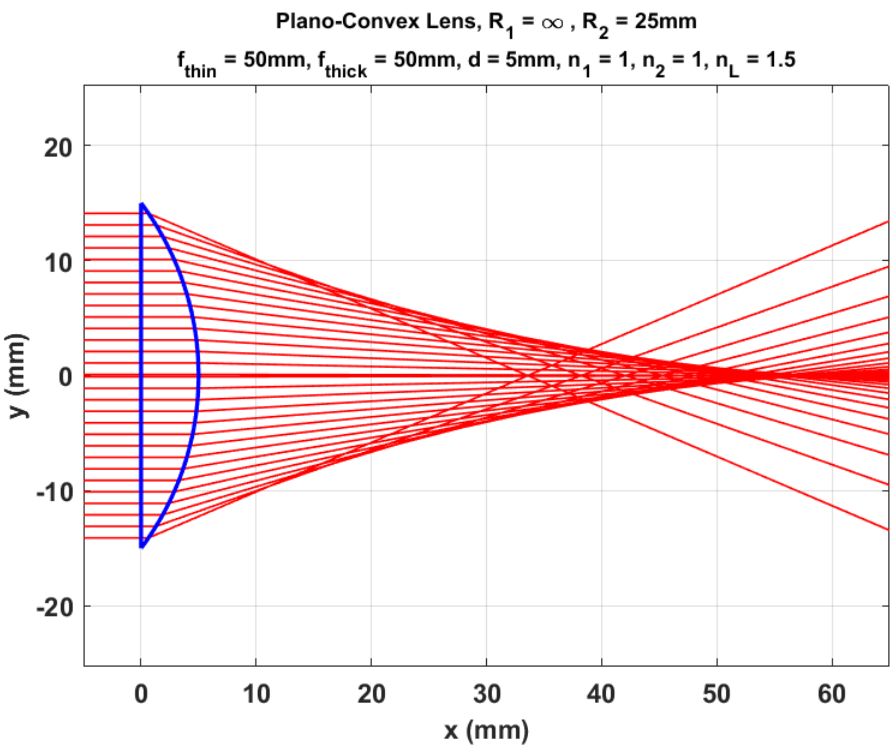


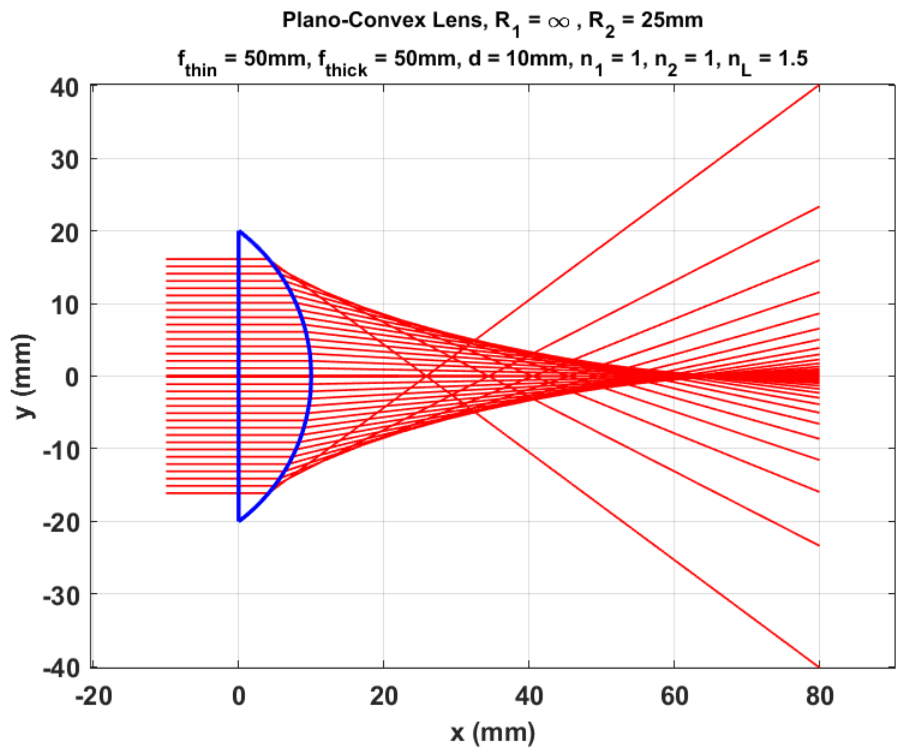
$h(mm)$	$f(mm)$
5.0	47.7
7.5	44.7
10.0	40.2
12.5	33.8
15.0	24.1

Fig. 1. Focusing of rays by plano-convex lens showing significant spherical aberration.

Notes from Prof. T. K. Gaylord in "Optical Engineering" Class (Georgia Tech)

Plano-Convex Lens

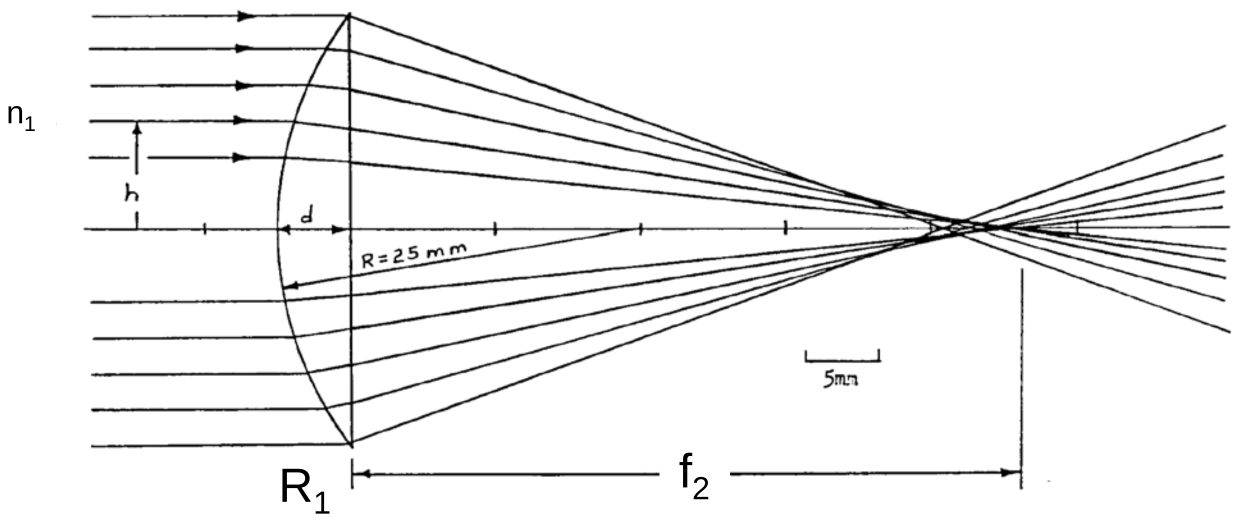




Convex-Plano Lens

A convex-plano lens has a radius of curvature of R, a thickness d, and an index of refraction, n. A collimated beam of light is incident upon the convex side of this lens in air as shown in the figure. Accounting for the convex-plano shape of the lens, the focal distance as defined in the figure, for an axial ray of displacement h from the principal axis is

$$f_2 = \frac{h - \left(d - R_1 + \sqrt{R_1^2 - h^2}\right) \tan\left[\sin^{-1}\left(\frac{h}{R_1}\right) - \sin^{-1}\left(\frac{n_1 h}{n_L R_1}\right)\right]}{\tan\left\{\sin^{-1}\left[\frac{n_L}{n_2} \sin\left[\sin^{-1}\left(\frac{h}{R_1}\right) - \sin^{-1}\left(\frac{n_1 h}{n_L R_1}\right)\right]\right]\right\}}$$

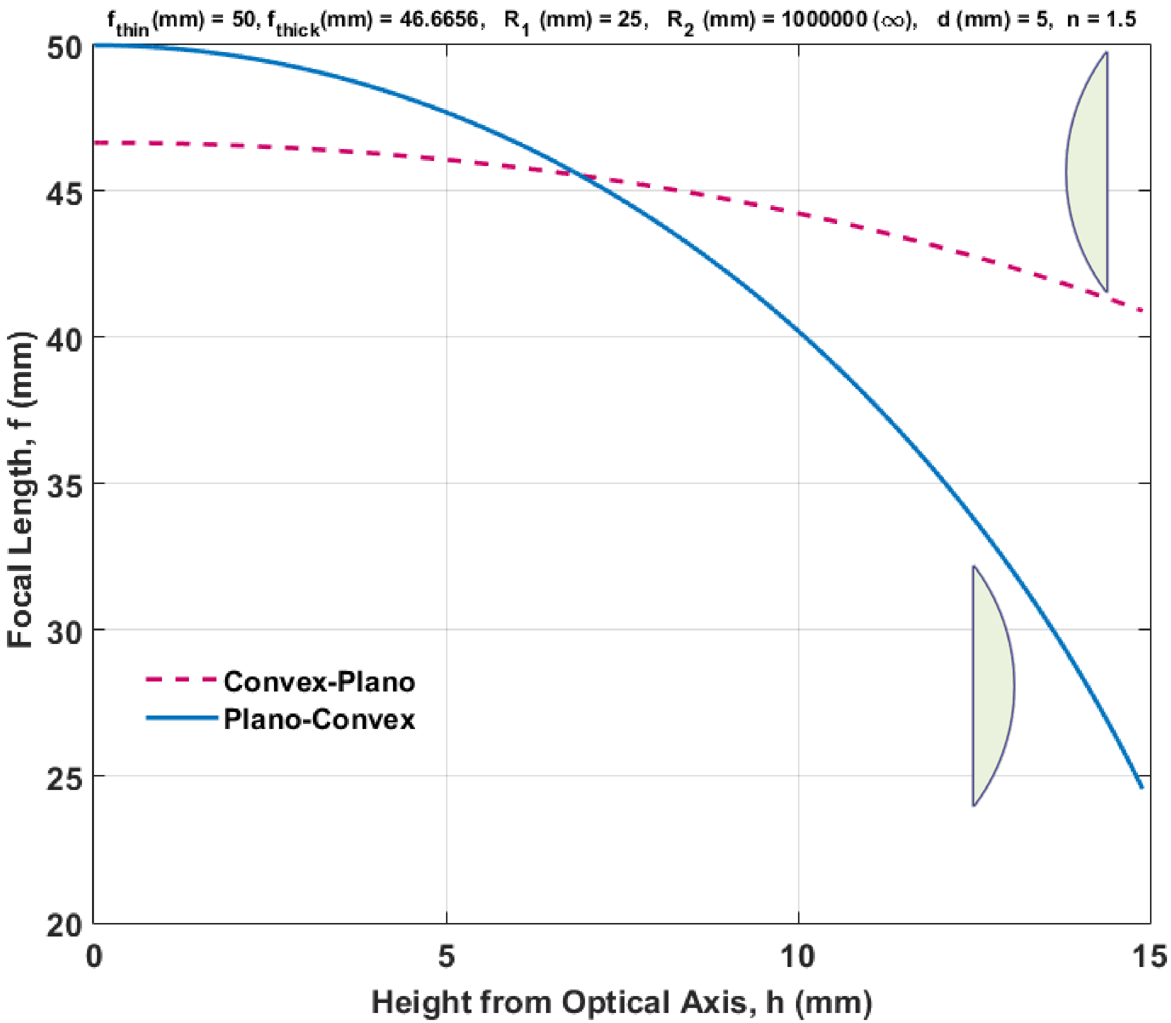


$h(mm)$	$f(mm)$
5.0	46.1
7.5	45.3
10.0	44.3
12.5	42.8
15.0	40.8

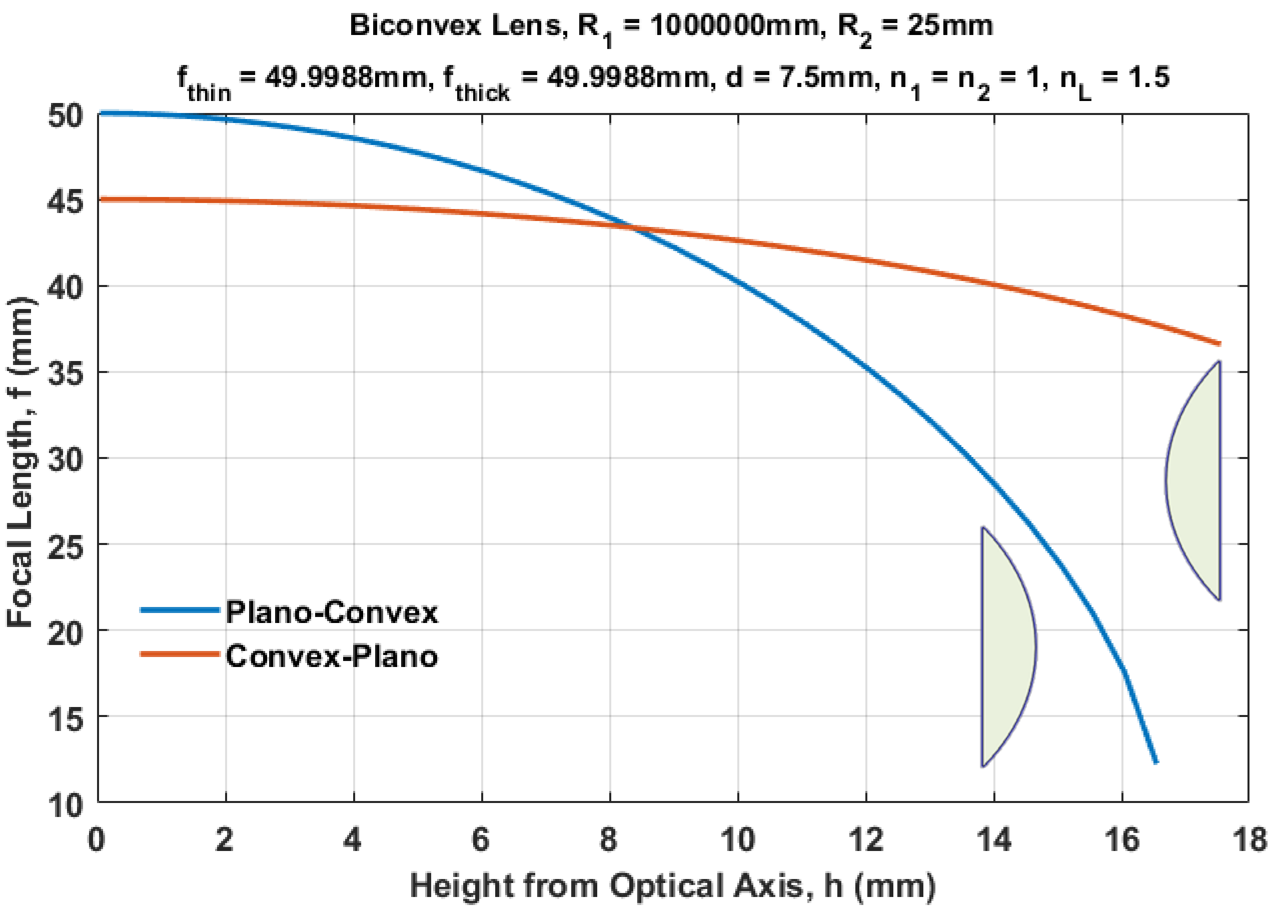
Fig. 1. Focusing of rays by convex-plano lens showing relatively small spherical aberration.

Notes from Prof. T. K. Gaylord in "Optical Engineering" Class (Georgia Tech)

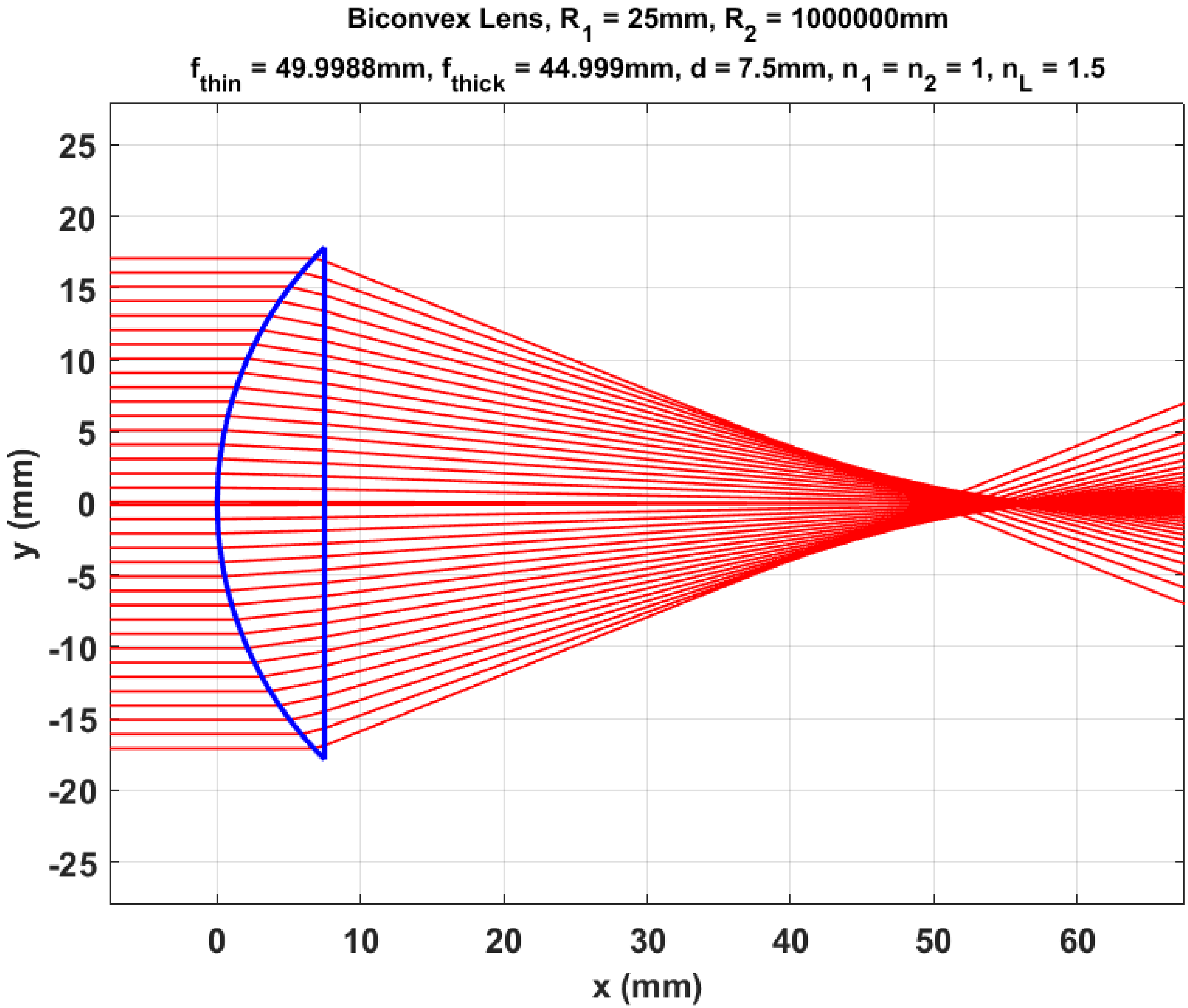
Comparison of the Spherical Aberration of a Plano-Convex Lens and a Convex-Plano Lens



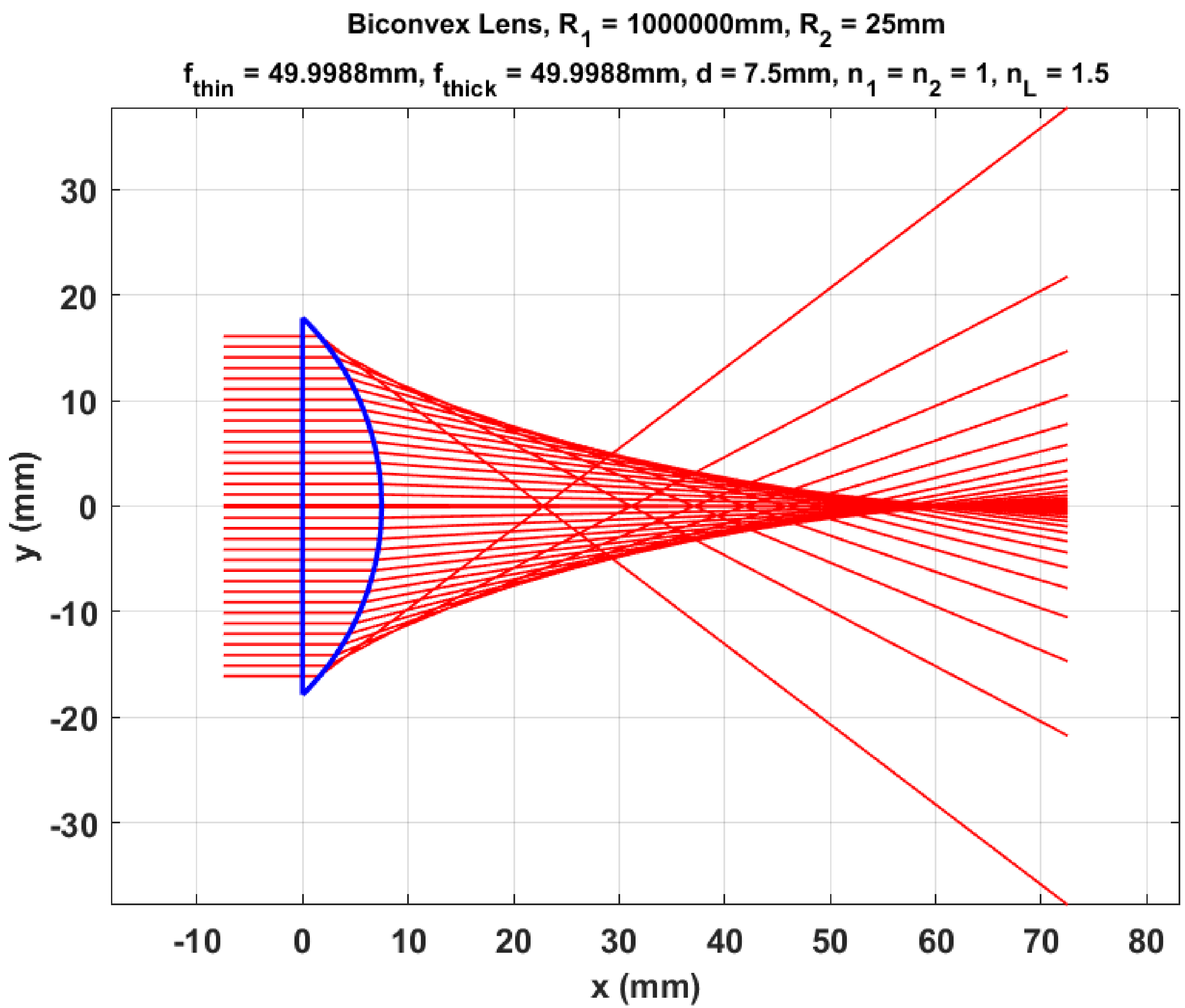
Convex-Plano Lens



Convex-Plano Lens



Convex-Plano Lens



Biconvex Lens

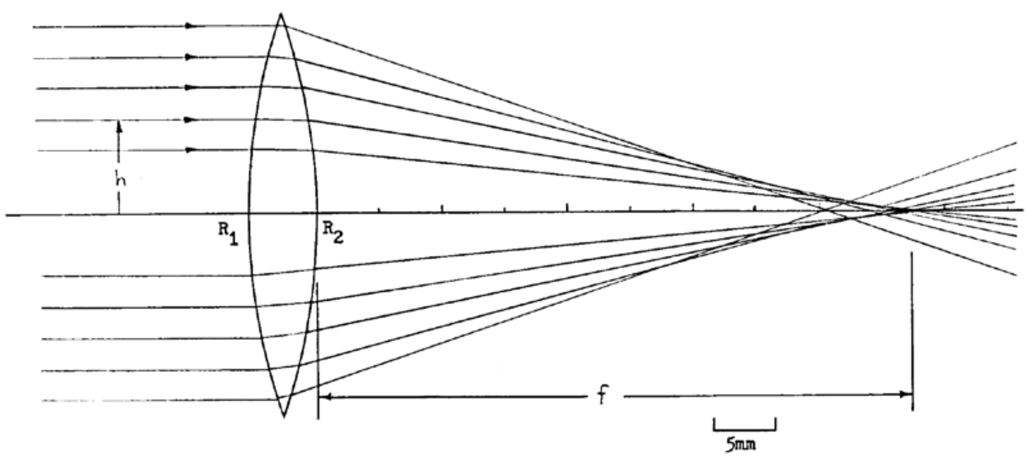
A biconvex lens has radii of curvature of R_1 and R_2, a center thickness of d, and an index of refraction n. If R_1 and R_2 are taken to be magnitudes, the focal distance of this biconvex lens in air for an axial ray of distance h from the principal axis is

$$f = \left\{ n\left\{ (R_1 + R_2 - d)\ sin\left[sin^{-1}\left(\frac{h}{R_1}\right) - sin^{-1}\left(\frac{h}{nR_1}\right)\right] + \frac{h}{n} \right\} \right/$$

$$sin\left[\left(sin^{-1}\left\{\left(\frac{n}{R_2}\right)(R_1 + R_2 - d)\ sin\left[sin^{-1}\left(\frac{h}{R_1}\right) - sin^{-1}\left(\frac{h}{nR_1}\right)\right] + \frac{h}{R_2}\right\}\right)\right.$$

$$-\left(sin^{-1}\left\{\left(\frac{1}{R_2}\right)(R_1 + R_2 - d)\ sin\left[sin^{-1}\left(\frac{h}{R_1}\right) - sin^{-1}\left(\frac{h}{nR_1}\right)\right] + \frac{h}{n\,R_2}\right\}\right)$$

$$\left. + \left[sin^{-1}\left(\frac{h}{R_1}\right) - sin^{-1}\left(\frac{h}{nR_1}\right)\right]\right]\Bigg\} - R_2$$

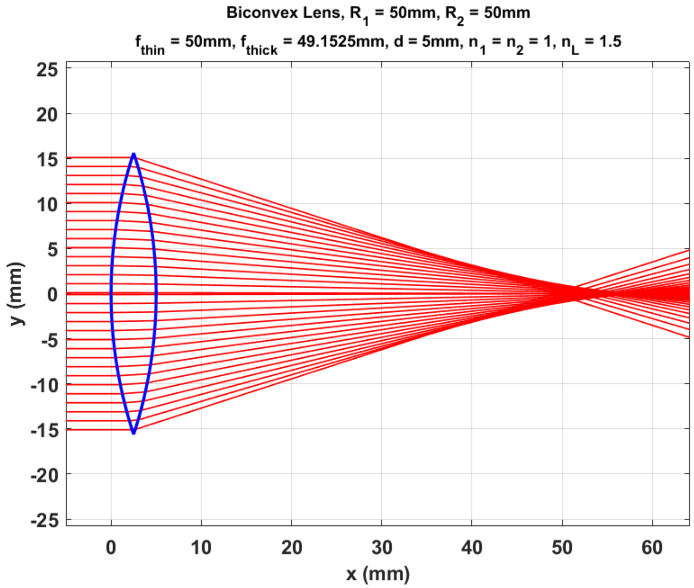


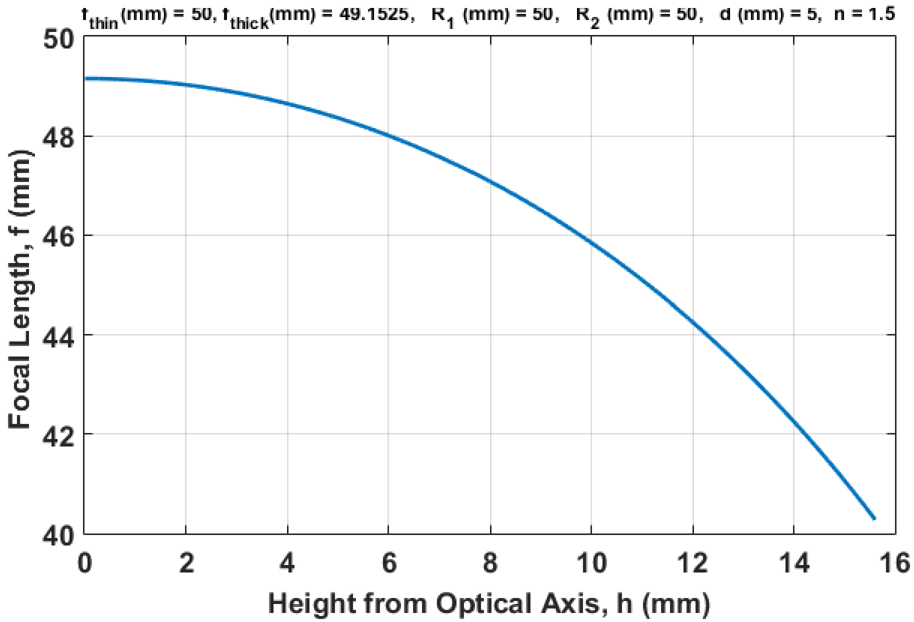
$h(mm)$	$f(mm)$
5.0	48.3
7.5	47.3
10.0	45.8
12.5	43.8
15.0	41.1

Fig. 1. Focusing of rays by biconvex lens showing spherical aberration.

Notes from Prof. T. K. Gaylord in "Optical Engineering" Class (Georgia Tech)

Spherical Aberration of a Biconvex Lens

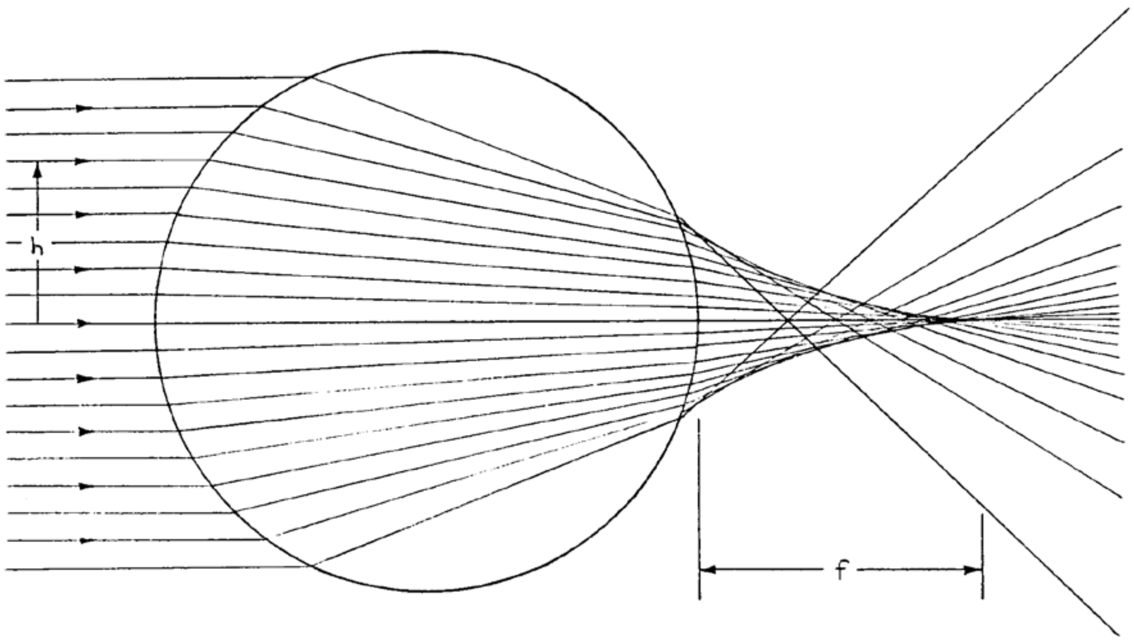




Sphere Lens

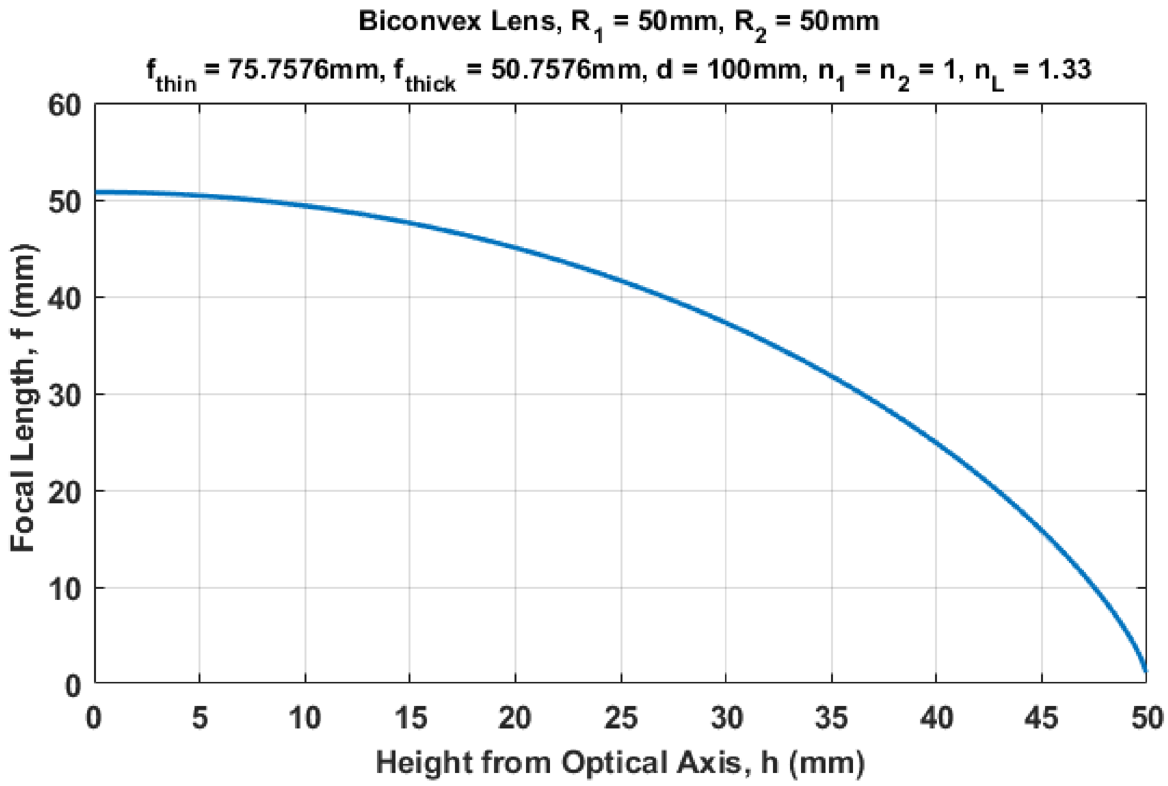
A sphere of radius R and an index of refraction n may be used as a lens. The focal distance of this lens in air for an axial ray of distance h from the principal axis is

$$f = R\left\{\left[\left(\frac{h}{r}\right) \Big/ \sin\left\{2\left[\sin^{-1}\left(\frac{h}{R}\right) - \sin^{-1}\left(\frac{h}{nR}\right)\right]\right\}\right] - 1\right\}$$



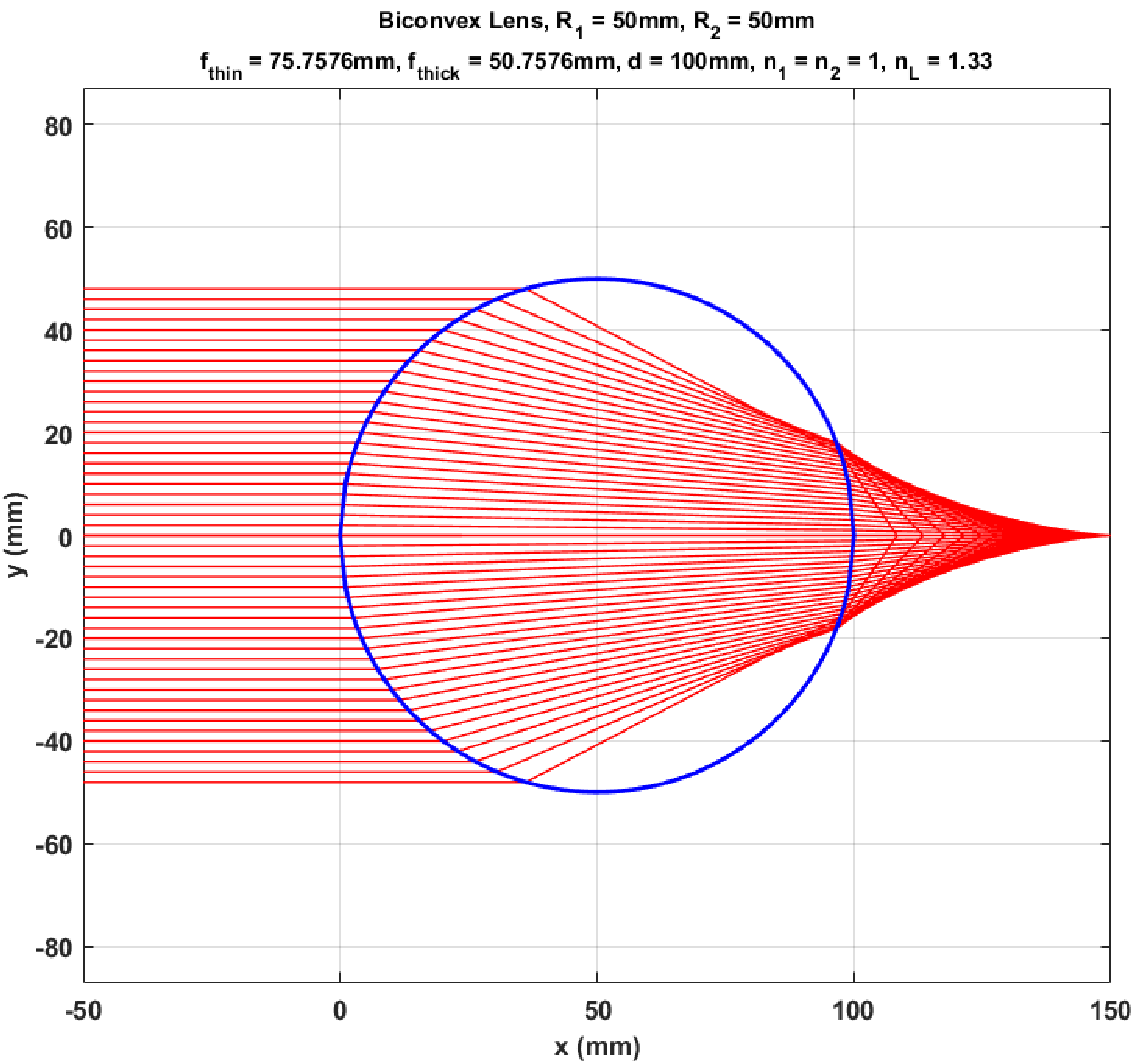
Notes from Prof. T. K. Gaylord in “Optical Engineering” Class (Georgia Tech)

Spherical Aberration of a Dielectric Sphere

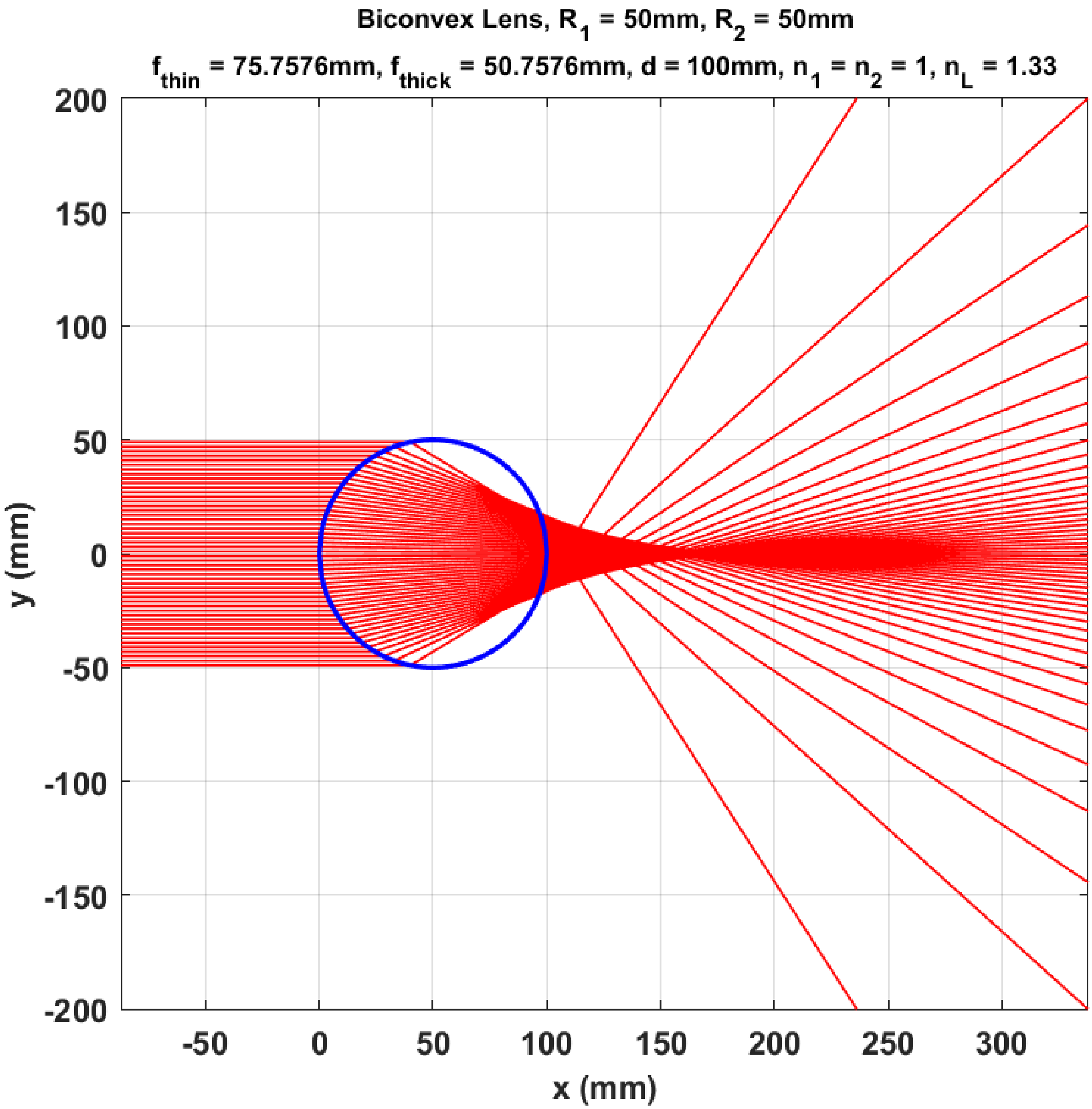


h (mm)	f (mm)
5	50.4
10	49.4
15	47.6
20	45.0
25	41.6
30	37.3
35	31.8
40	24.8
45	15.8

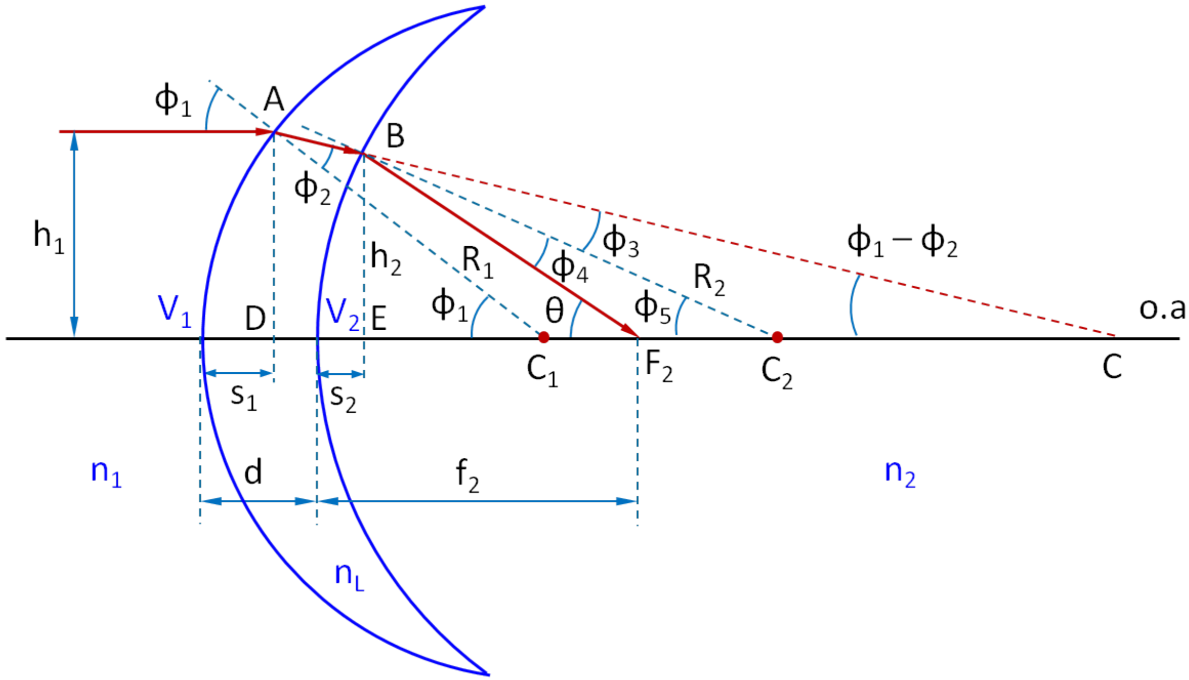
Spherical Aberration of a Dielectric Sphere



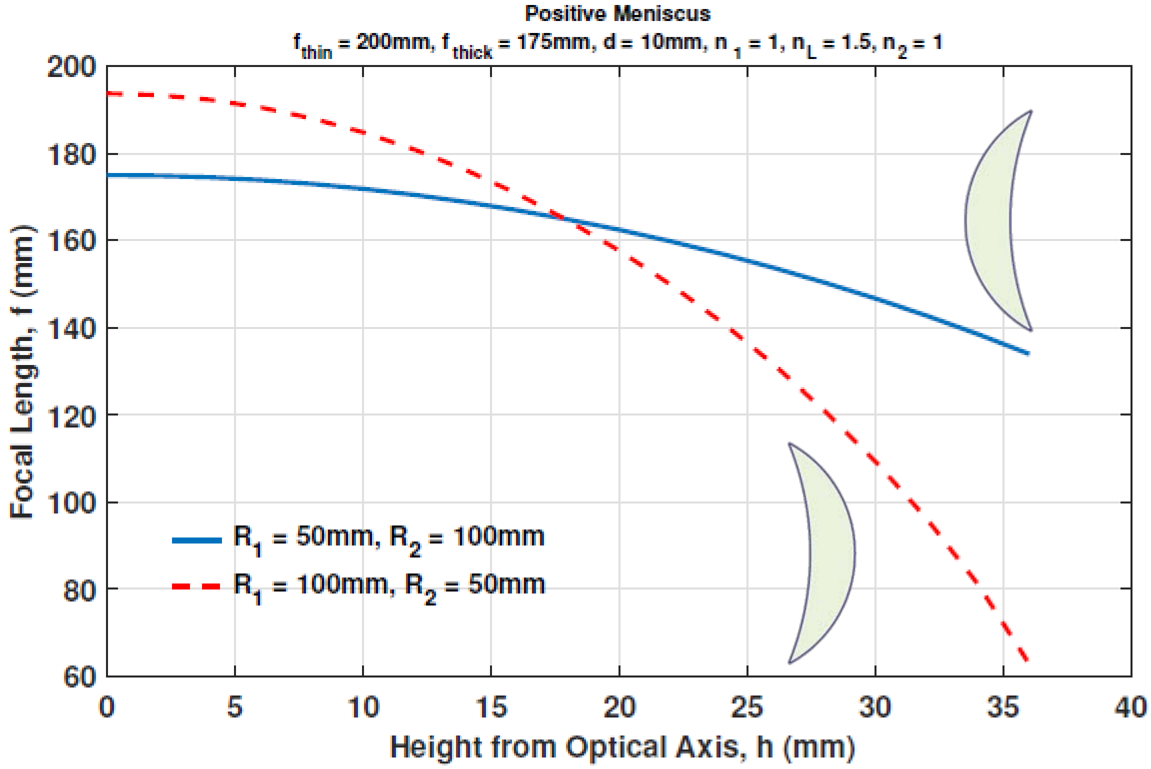
Spherical Aberration of a Dielectric Sphere



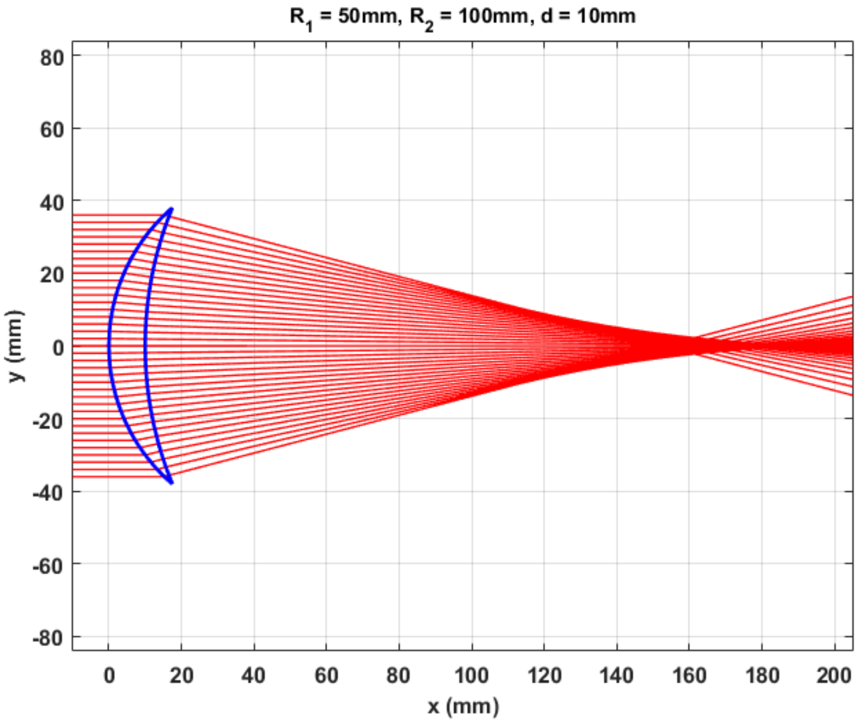
Spherical Aberration of a Positive Meniscus

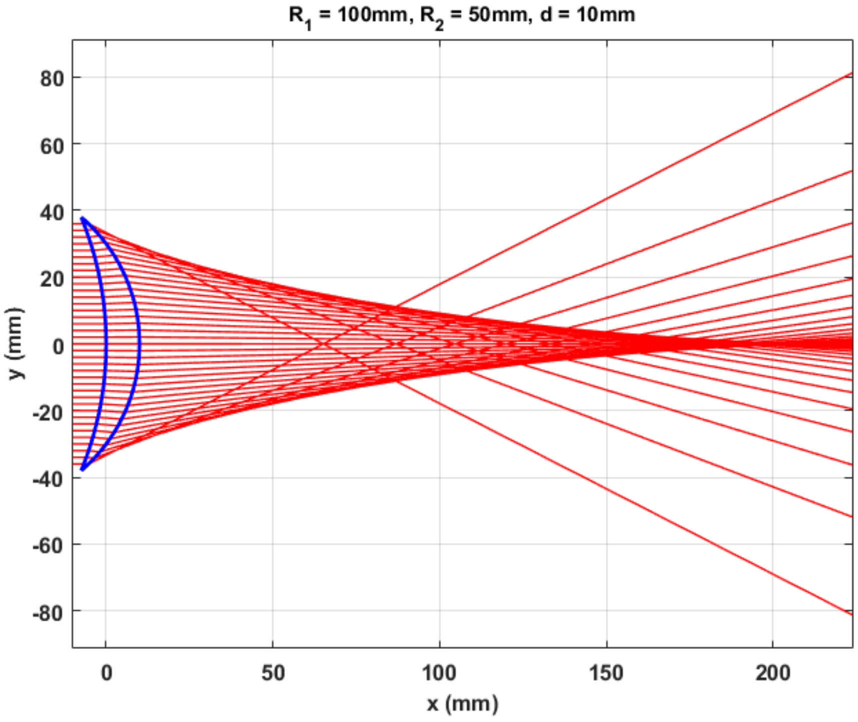


Spherical Aberration of a Positive Meniscus

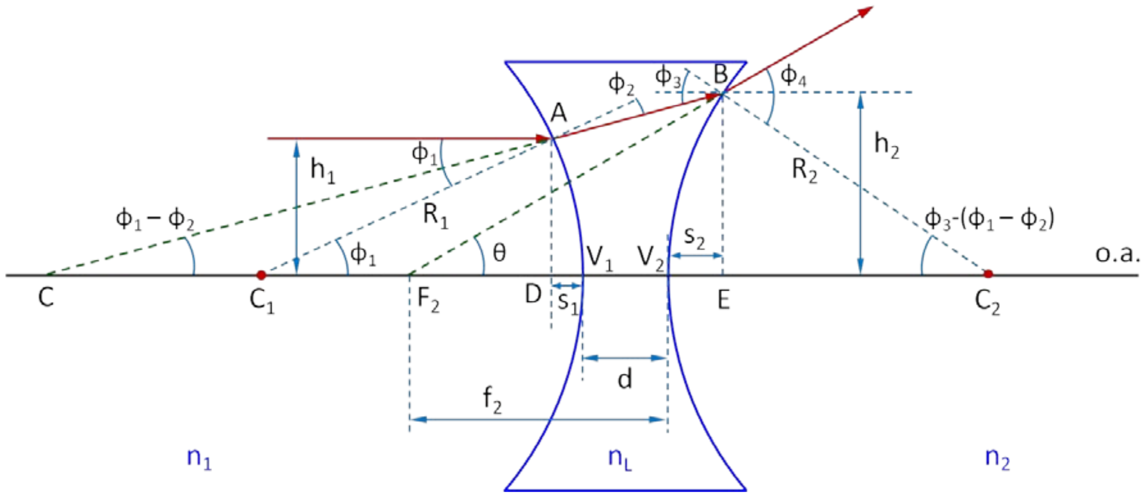


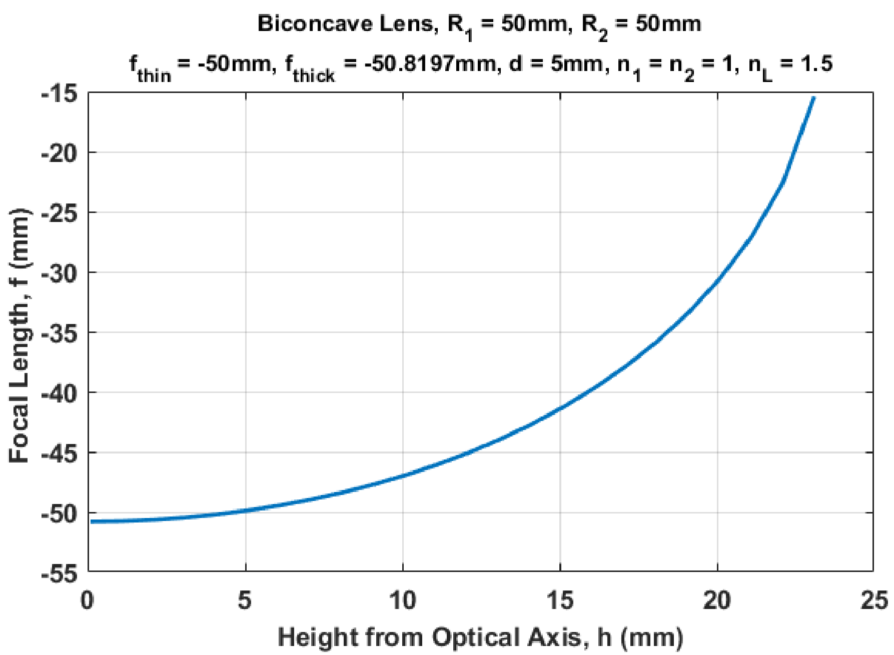
Spherical Aberration of a Positive Meniscus

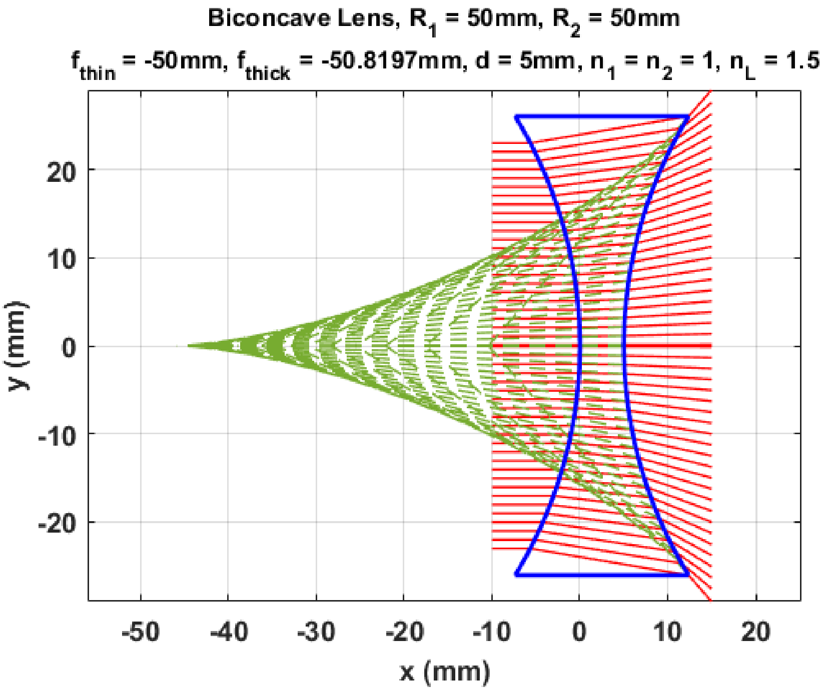




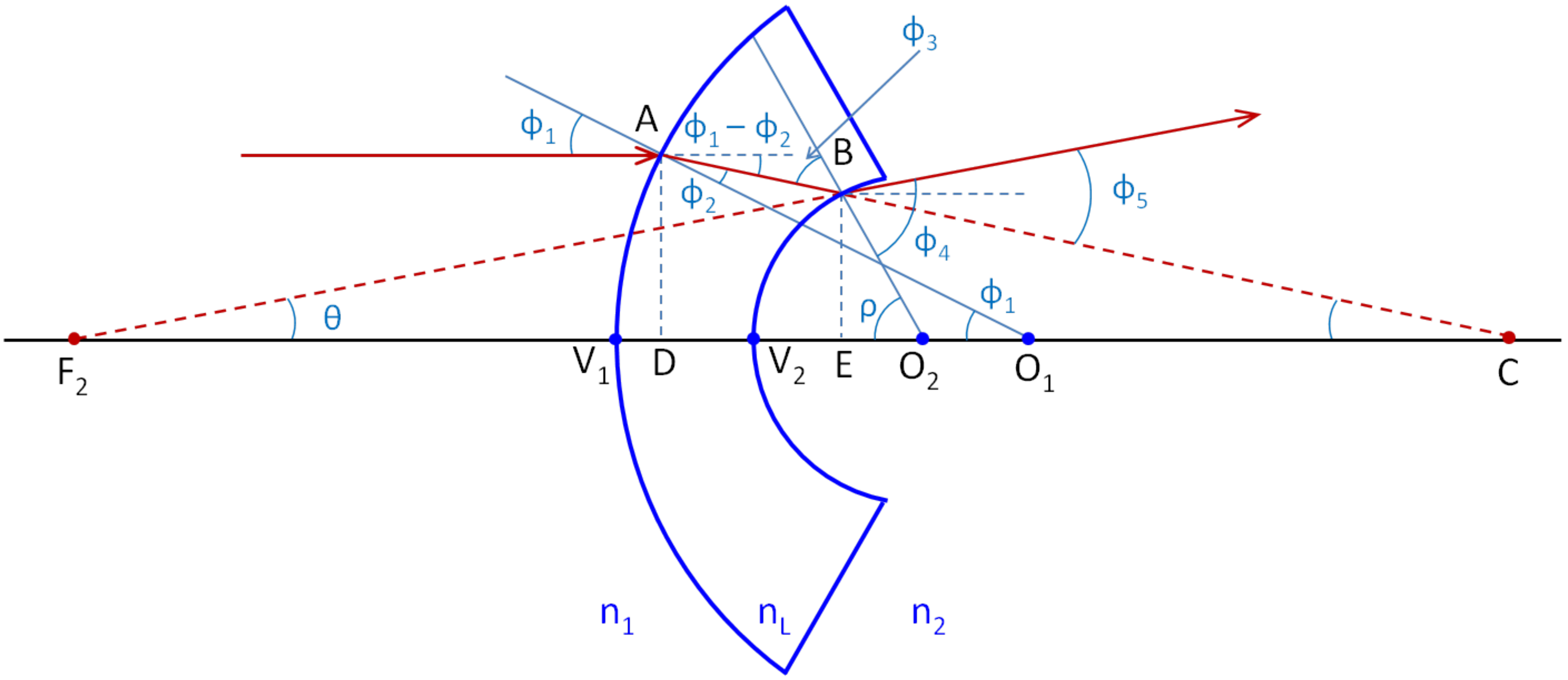
Spherical Aberration of a Biconcave Lens



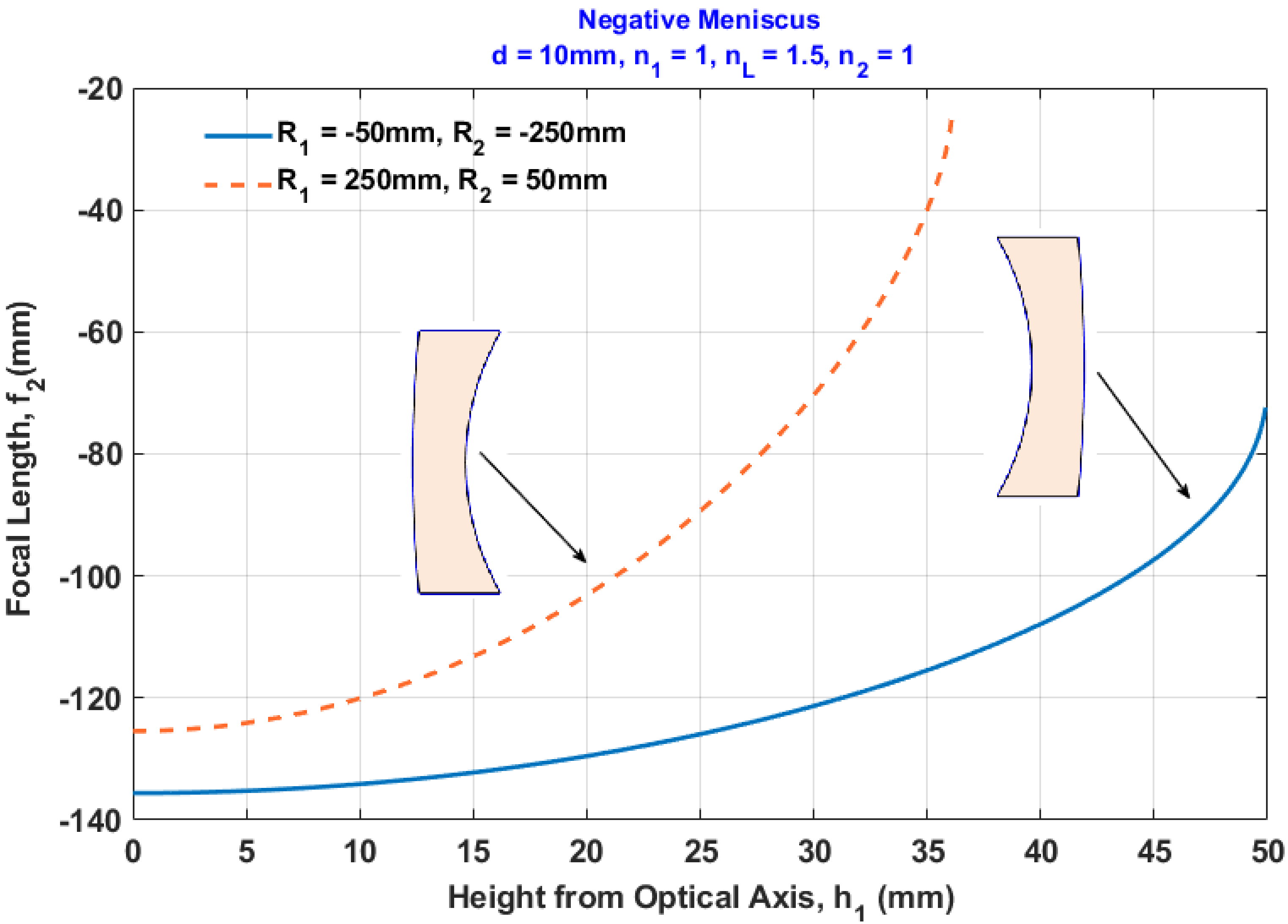




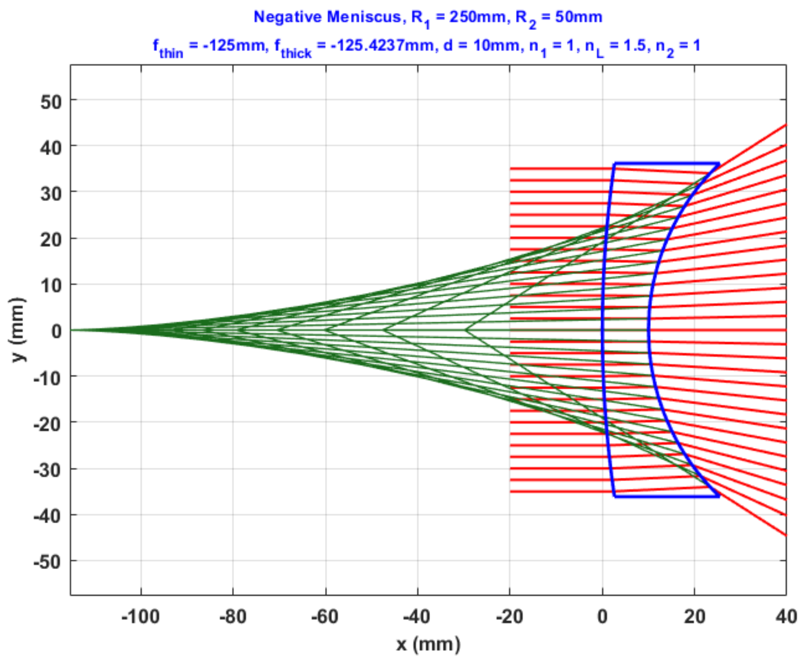
Spherical Aberration of a Negative Meniscus

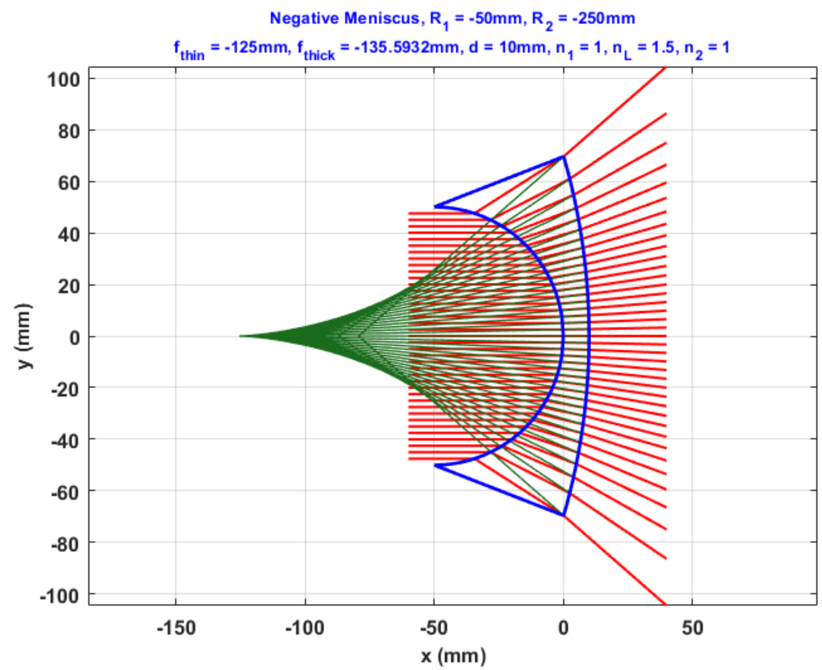


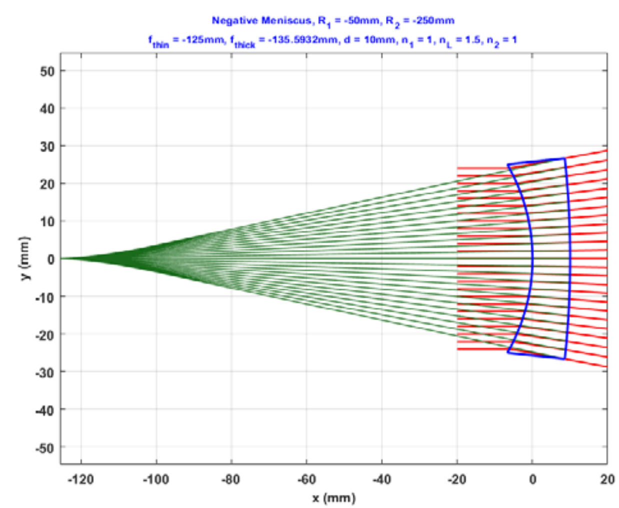
Spherical Aberration of a Negative Meniscus



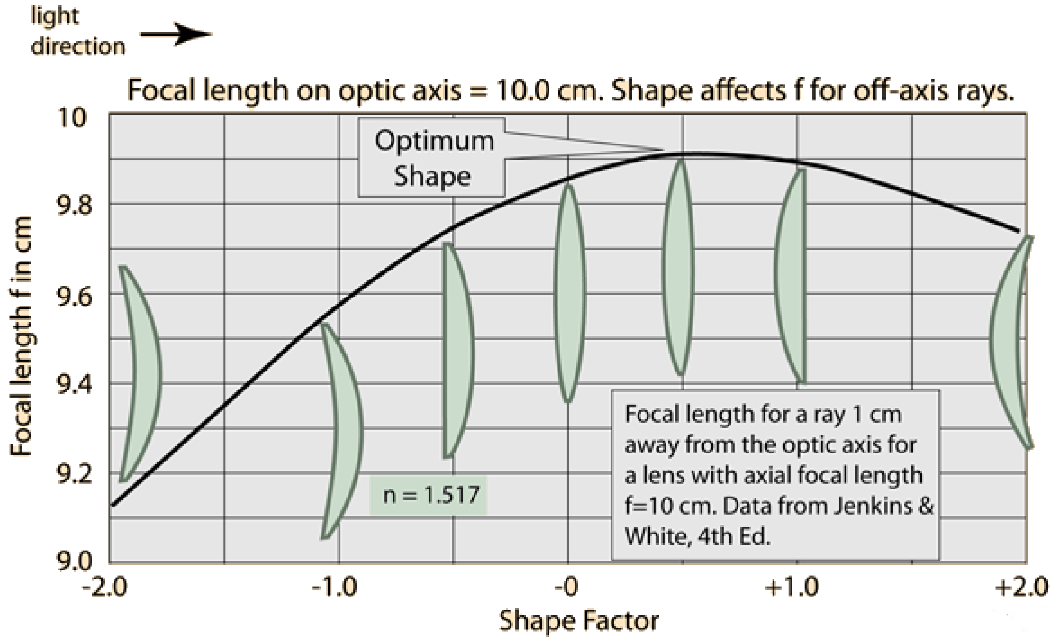
Spherical Aberration of a Negative Meniscus







Spherical Aberration



http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/imggo/meniscus.gif

Shape Factor

$$\sigma = \frac{R_2 + R_1}{R_2 - R_1}$$

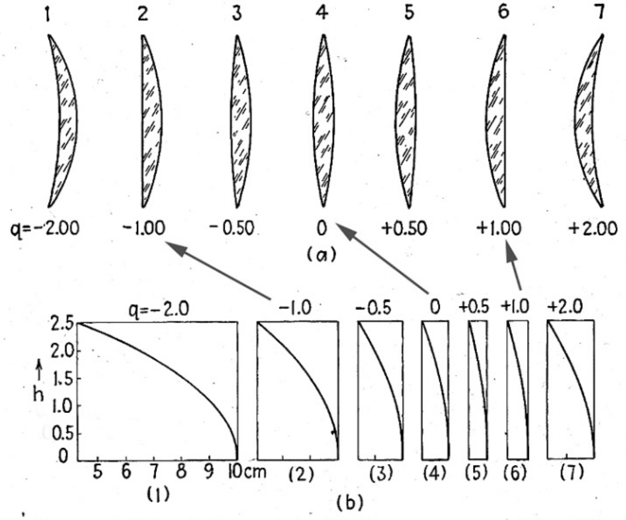
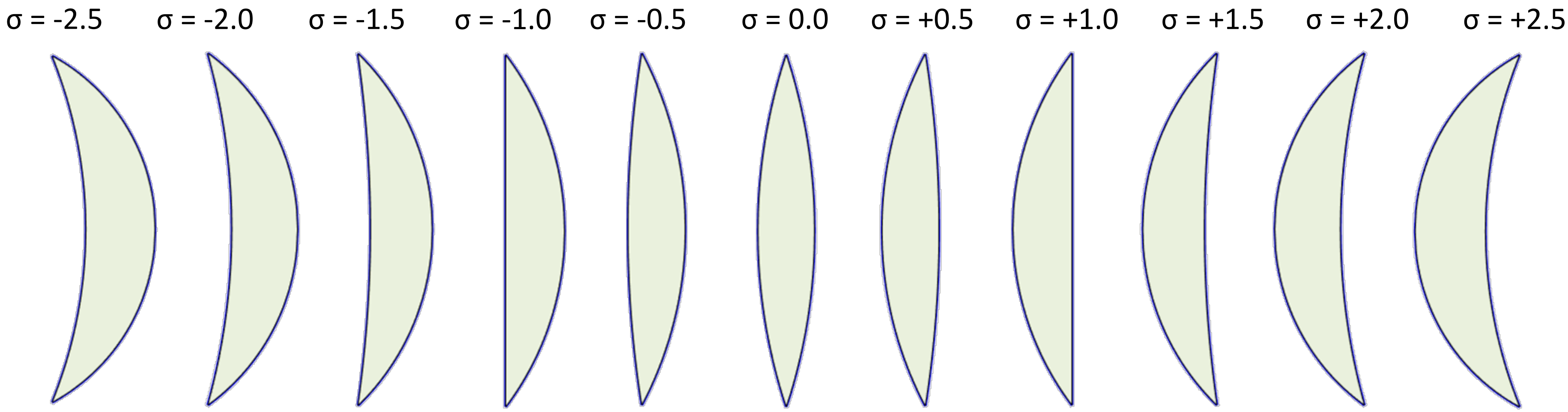


FIG. 9C (a) Lenses of different shapes but with the same power. The difference is one of "bending." (b) Focal length vs. radius for these lenses.

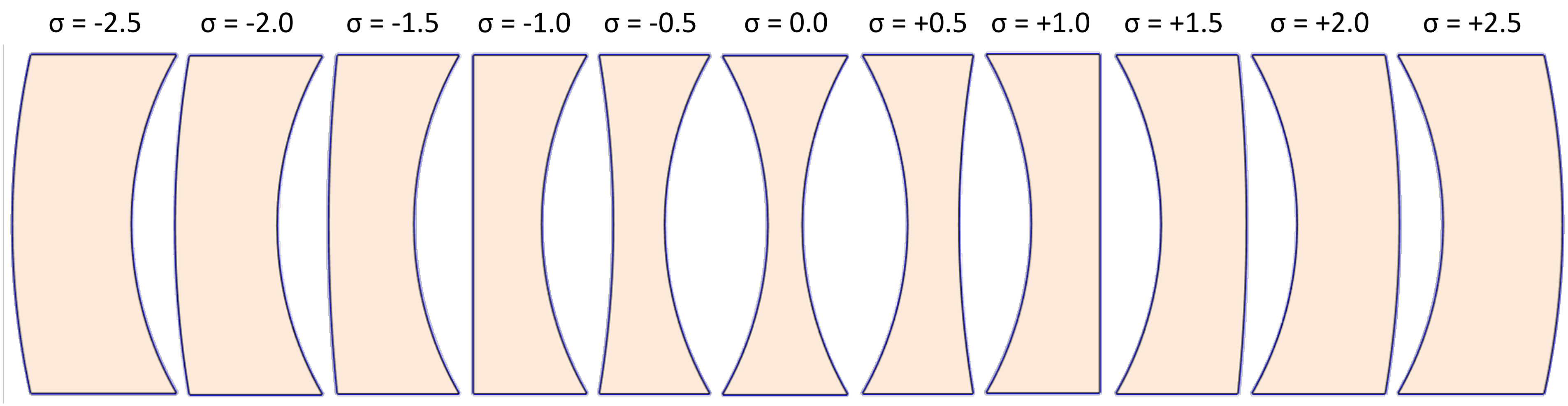
Jenkins and White, "Fundamentals of Optics", 4th Ed., McGraw-Hill, 2001

Spherical Aberration – Shape Factor

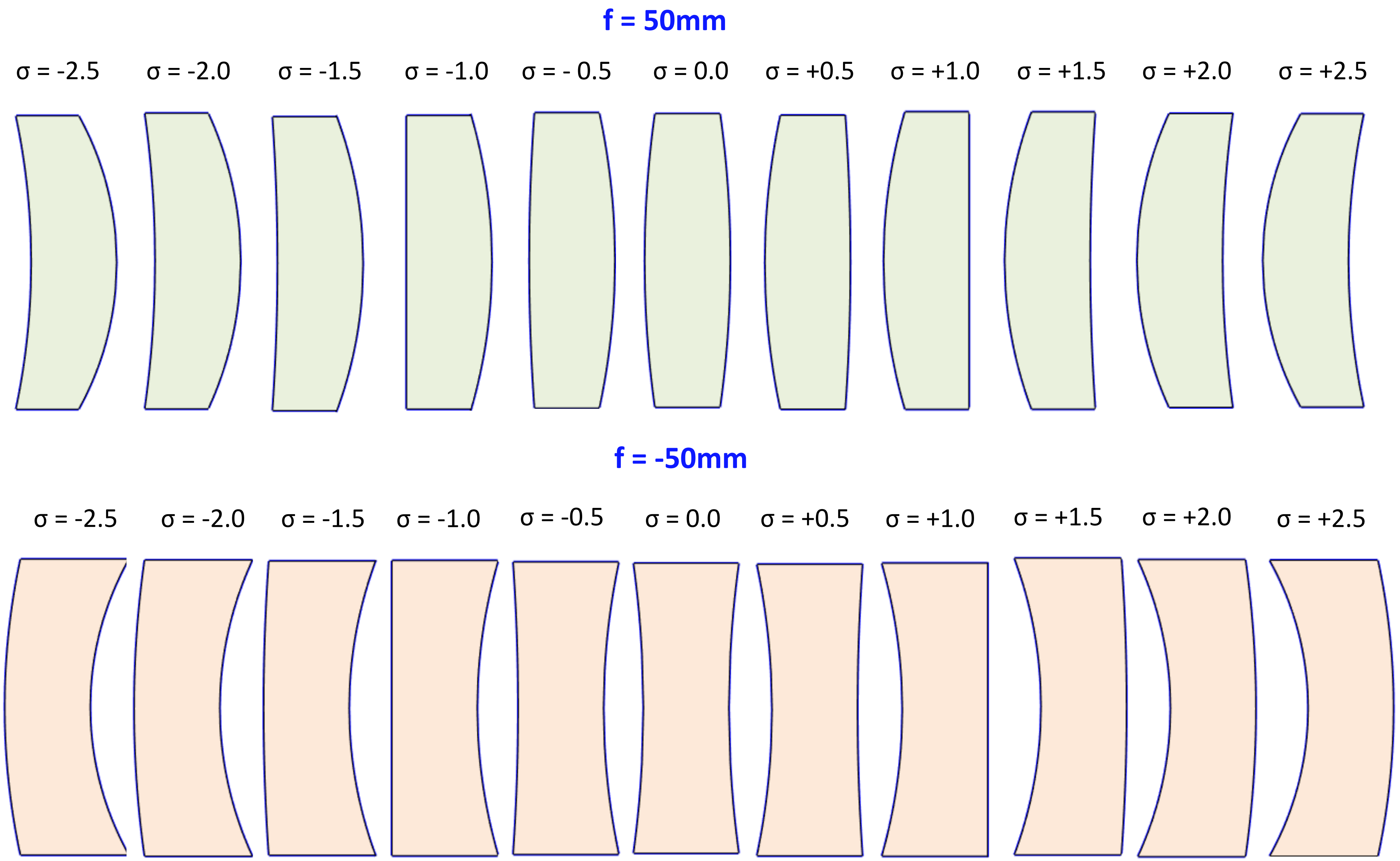
f = 50mm



f = -50mm



Spherical Aberration – Shape Factor

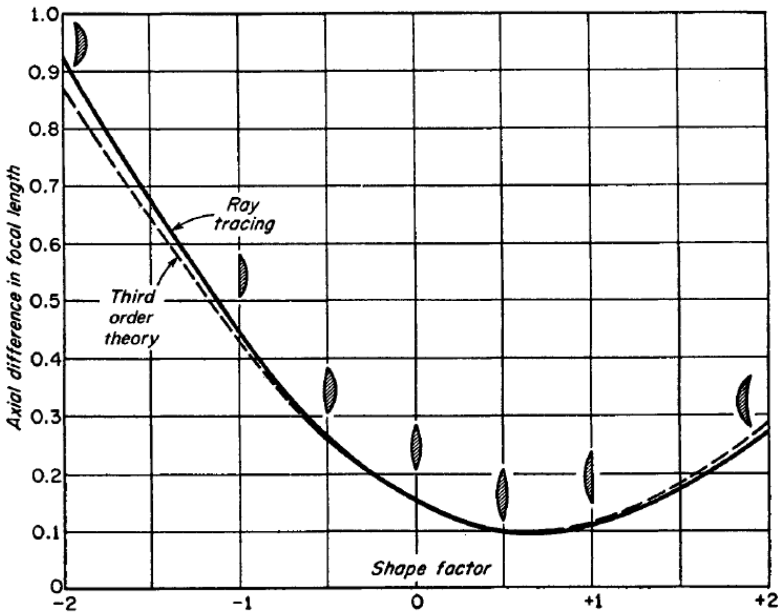


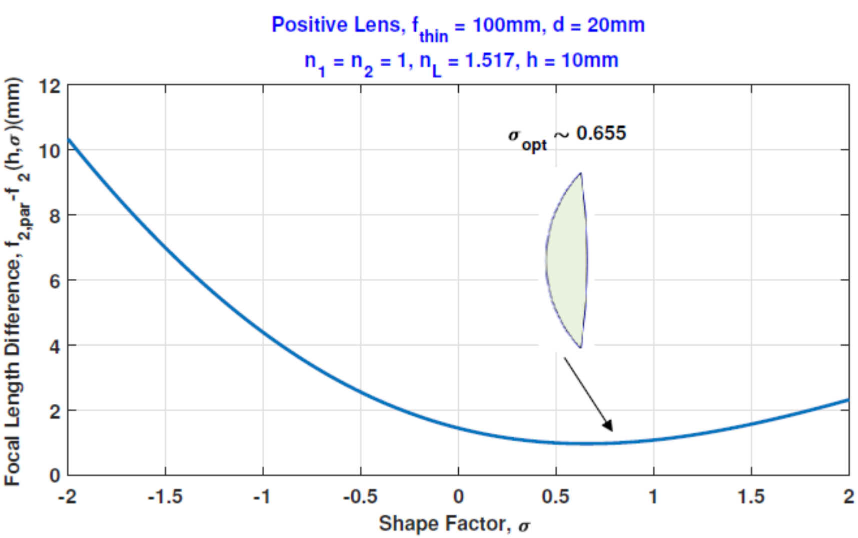
Spherical Aberration (3rd order)

$$\frac{1}{s'(h)} - \frac{1}{s'(0)} = \frac{h^2}{8f^3}\frac{1}{n(n-1)}\left[\frac{n+2}{n-1}\sigma^2 + 4(n+1)p\sigma + (3n+2)(n-1)p^2 + \frac{n^3}{n-1}\right]$$

$$p = \frac{s'-s}{s'+s}, \quad \sigma = \frac{R_2+R_1}{R_2-R_1}$$

$$\sigma_{opt} = -\frac{2(n^2-1)}{n+2}\frac{s'+s}{s'-s}$$

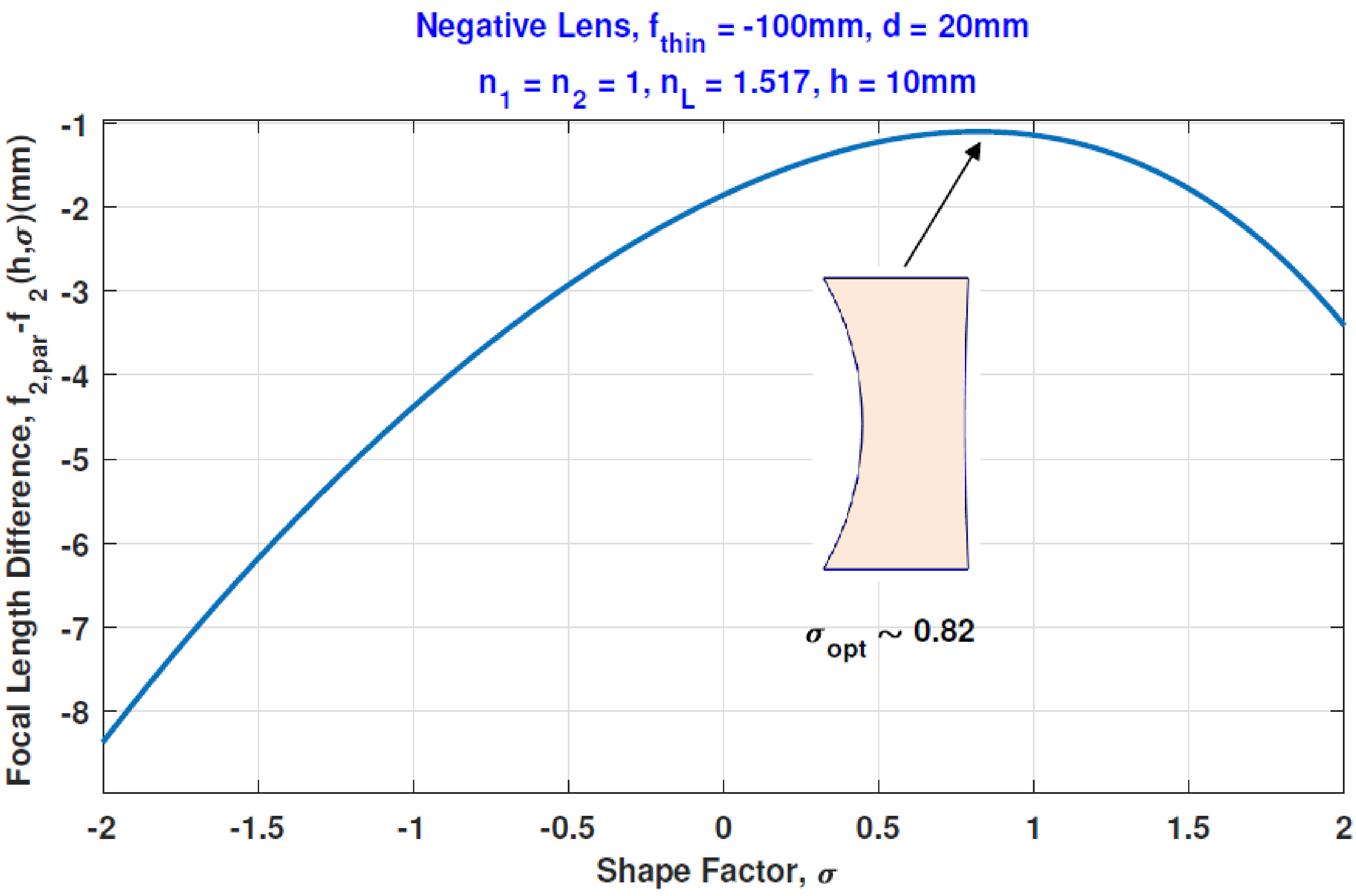




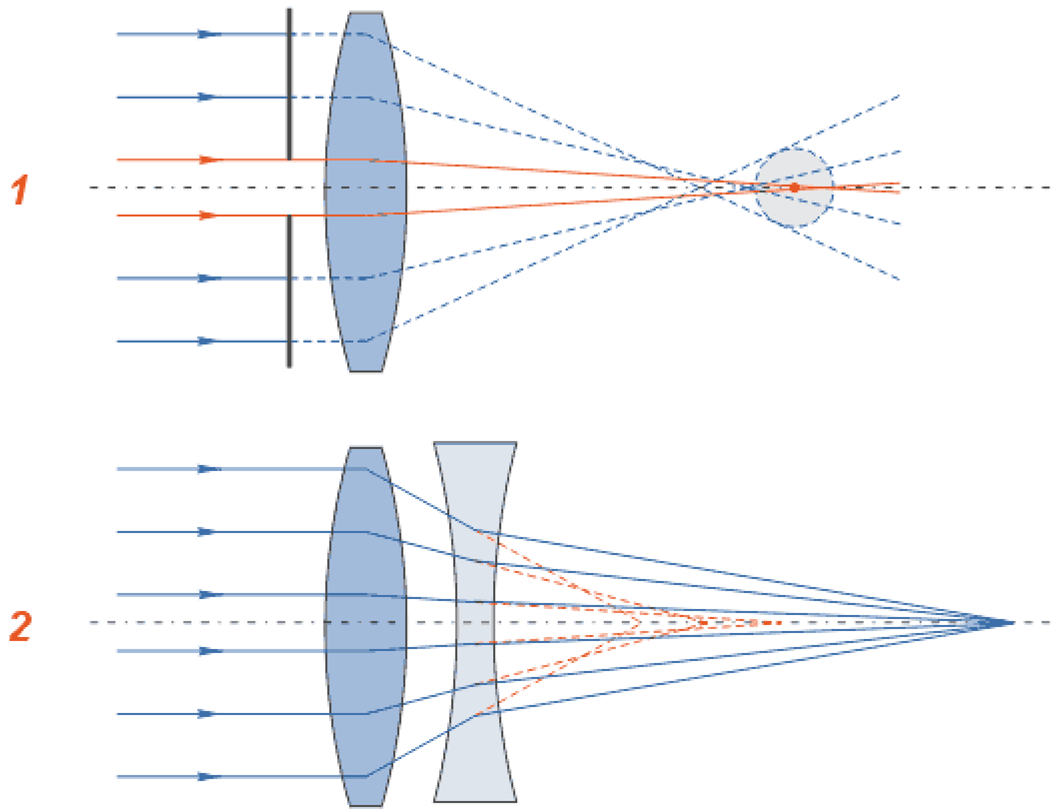
$$\sigma_{opt,3rd} = 0.74 \qquad \sigma_{opt} = 0.655$$

Jenkins and White, "Fundamentals of Optics", 4th Ed., McGraw-Hill, 2001

Spherical Aberration for Negative Lenses



Spherical Aberration Correction



Astigmatism

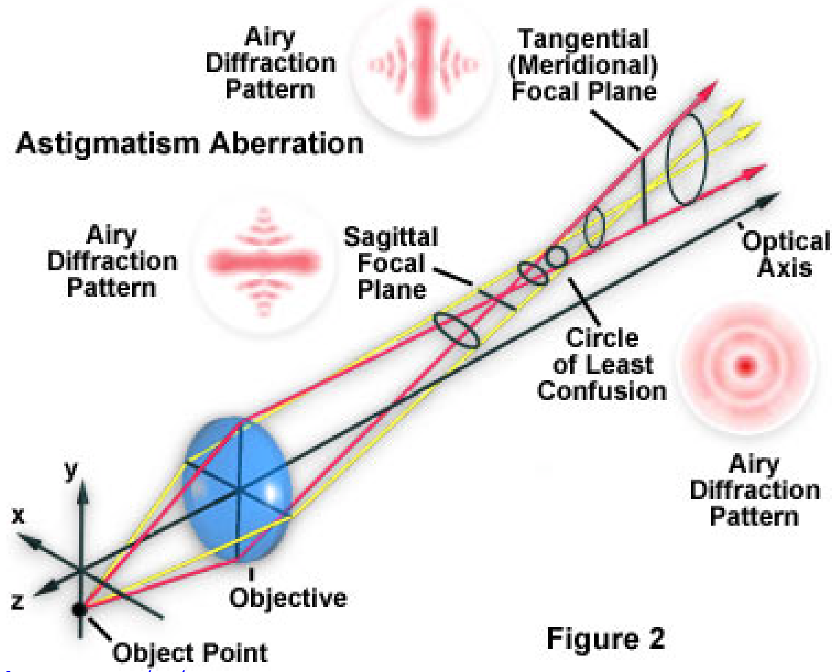
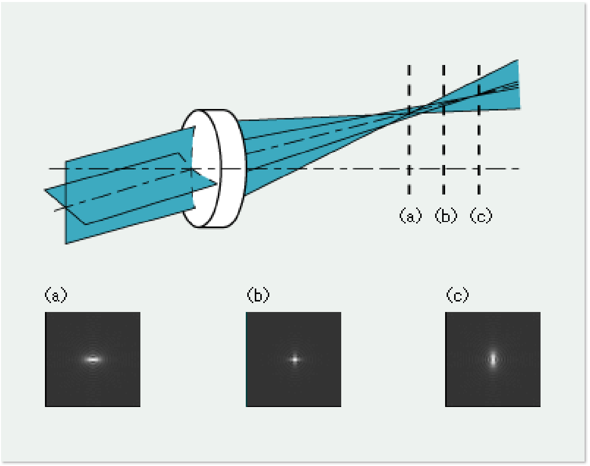
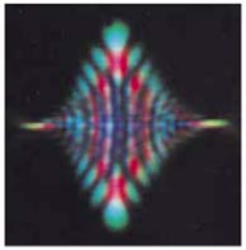
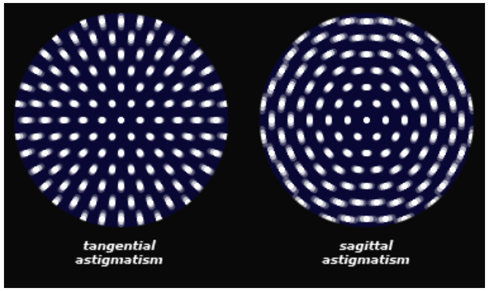


Figure 2

https://www.olympus-lifescience.com/en/microscope-resource/primer/java/aberrations/astigmatism/#:~:text=Astigmatism%20aberrations%20are%20found%20at,location%20of%20the%20focal%20plane.







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

Astigmatism

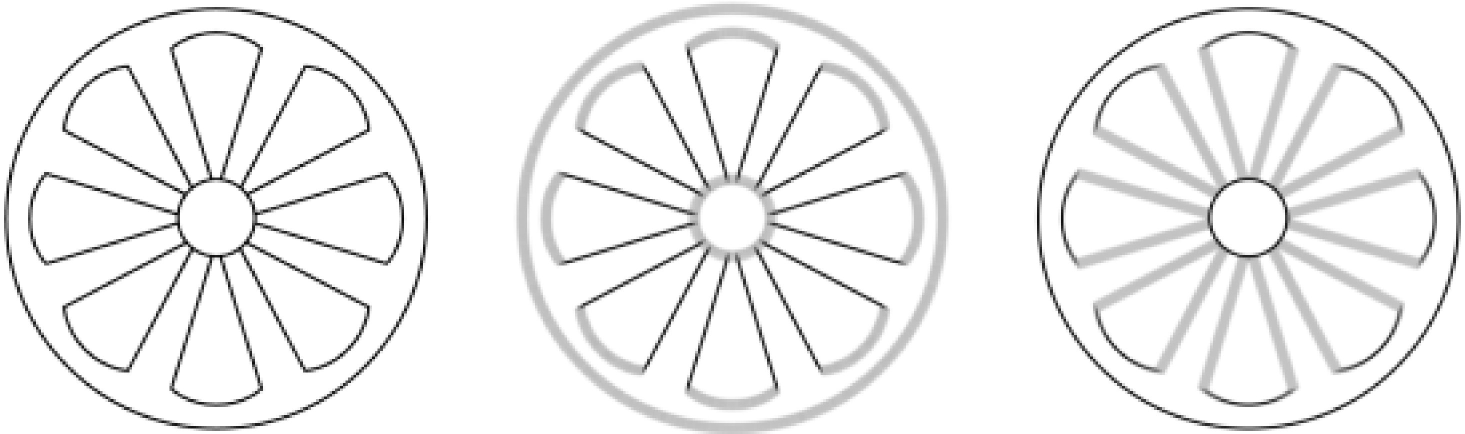
no astigmatism

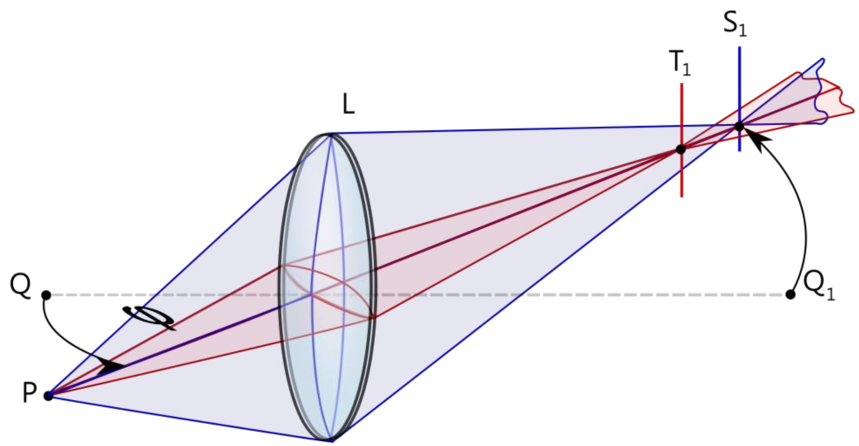
Horizontal Focus

Tangential Focus

Vertical Focus

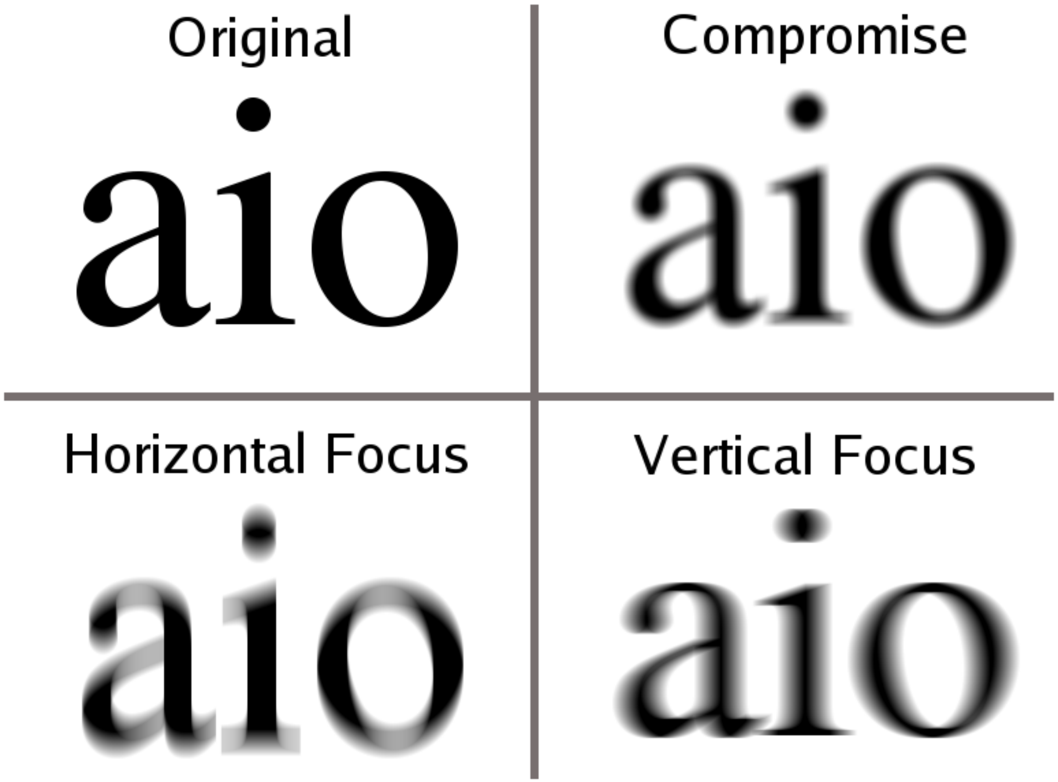
Sagittal Focus

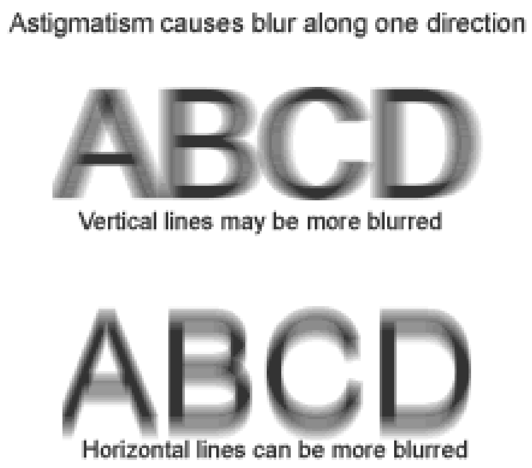




https://en.wikipedia.org/wiki/Astigmatism_(optical_systems)

Astigmatism (Examples)

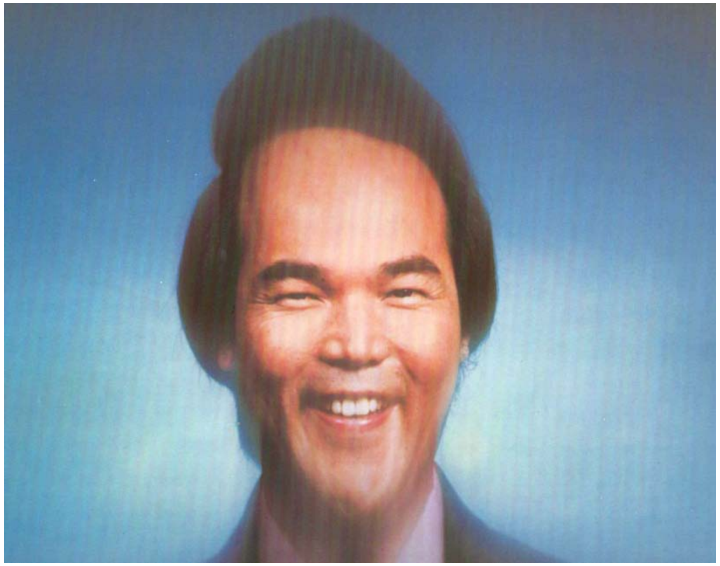


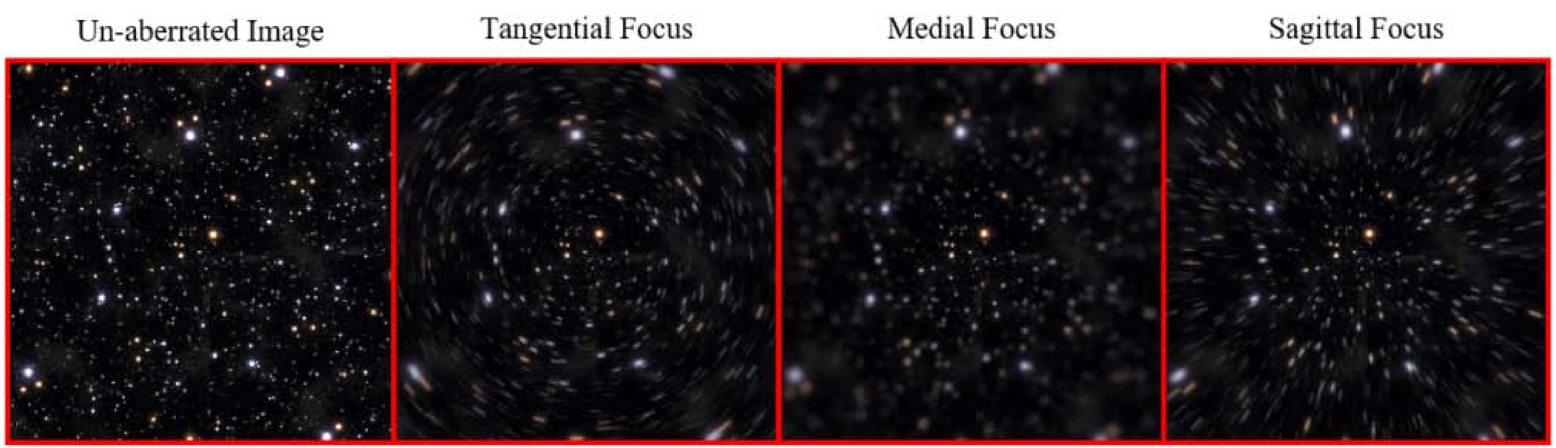


http://acuitylaservision.com/category/all-about-eyes/medical-blog-acuity/page/3/

https://en.wikipedia.org/wiki/Astigmatism_(optical_systems)

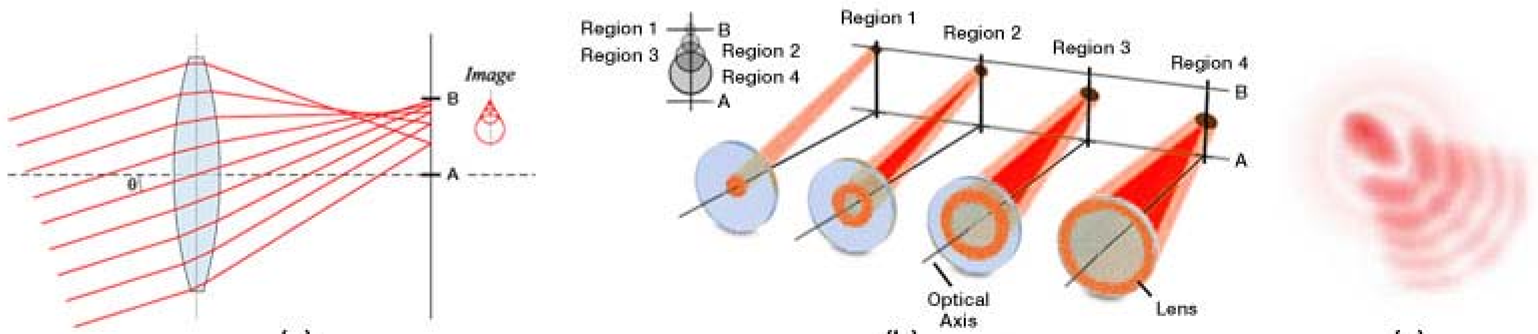
Astigmatism Causes Blurring of the Image





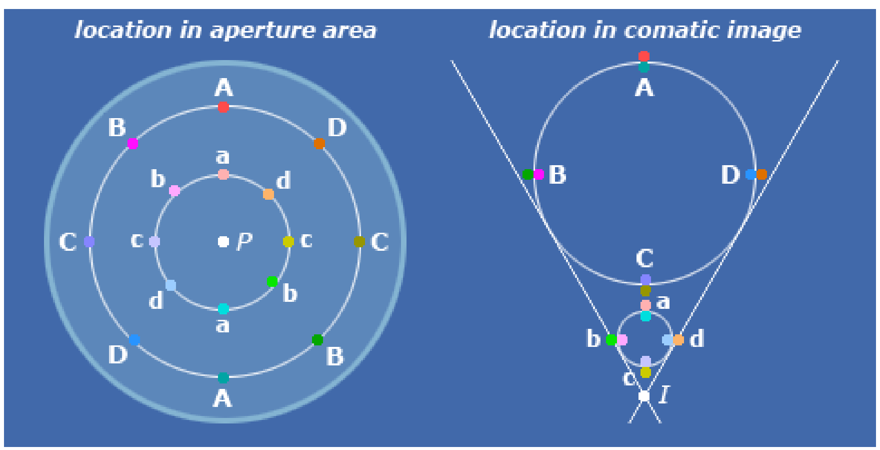
http://eckop.com/wp-content/uploads/2017/05/Fig-1.14-Tangential-and-Sagittal-Foci.png

Coma

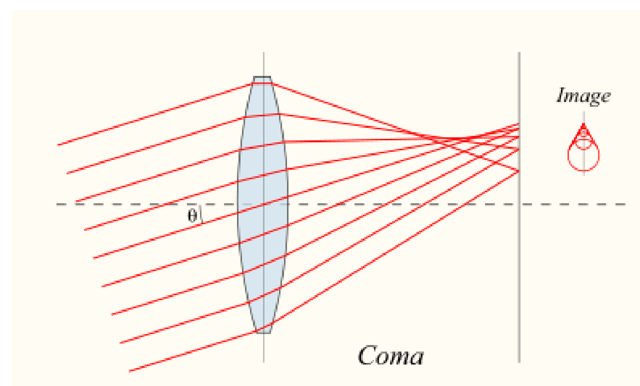


(a) (b) (c)

http://www.cheyennezjphotographer.com/photography/lenses-2/

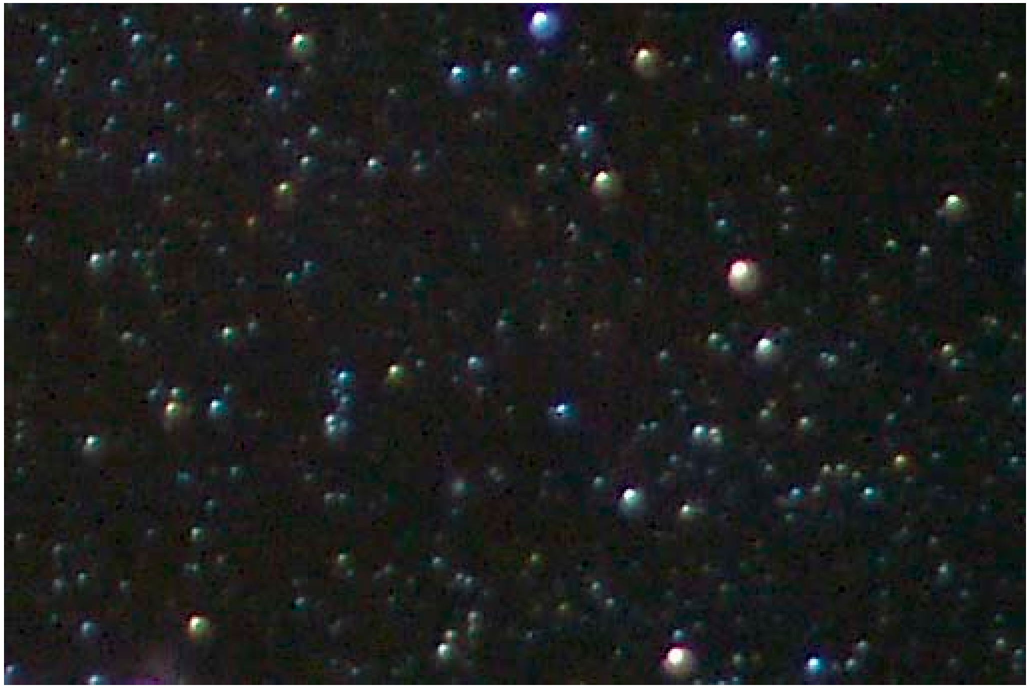


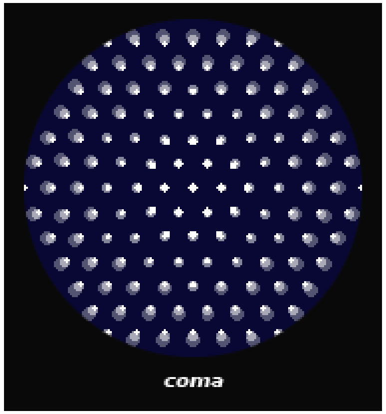
https://www.handprint.com/ASTRO/ae4.html

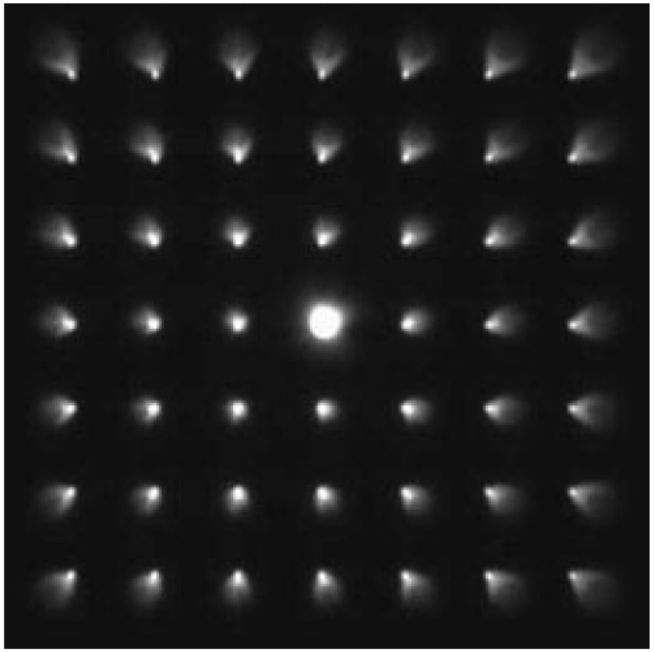


http://en.wikipedia.org/wiki/Lens_(optics)

Coma (Examples)



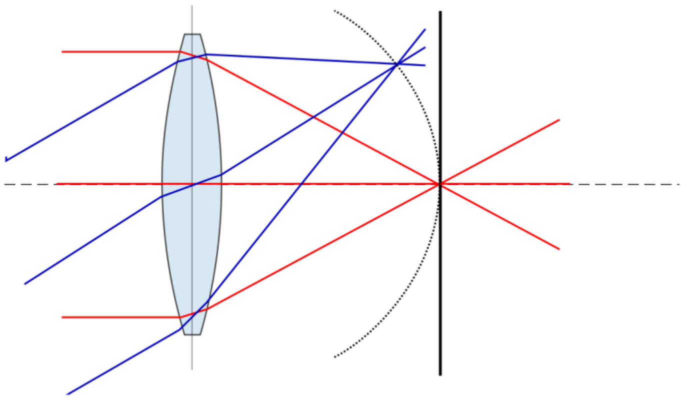




http://www.handprint.com/ASTRO/ae4.html

Field Curvature

Field curvature: the image "plane" (the arc) deviates from a flat surface (the vertical line).



https://en.wikipedia.org/wiki/Petzval_field_curvature

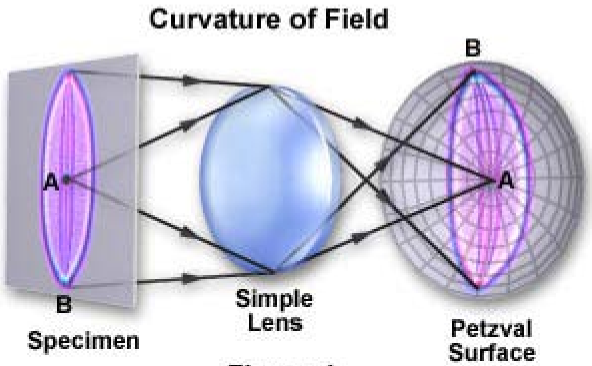
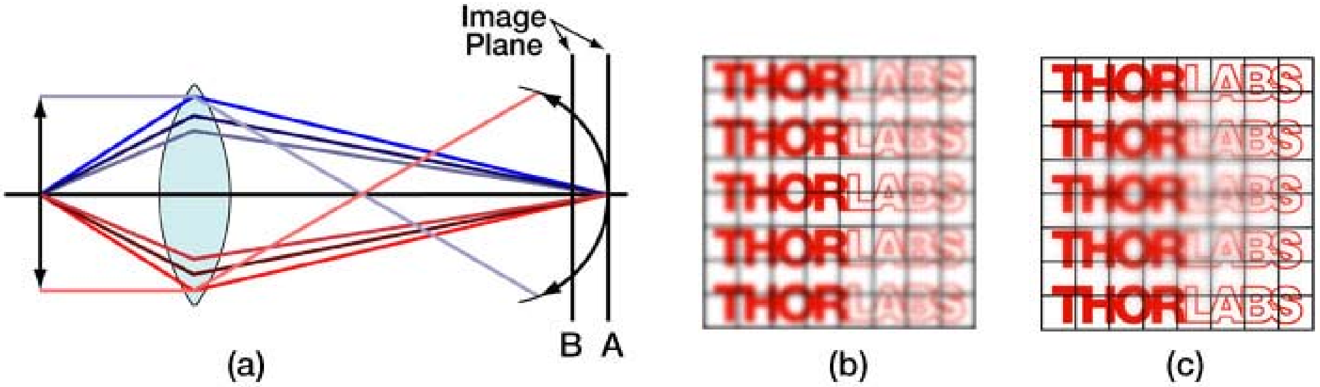


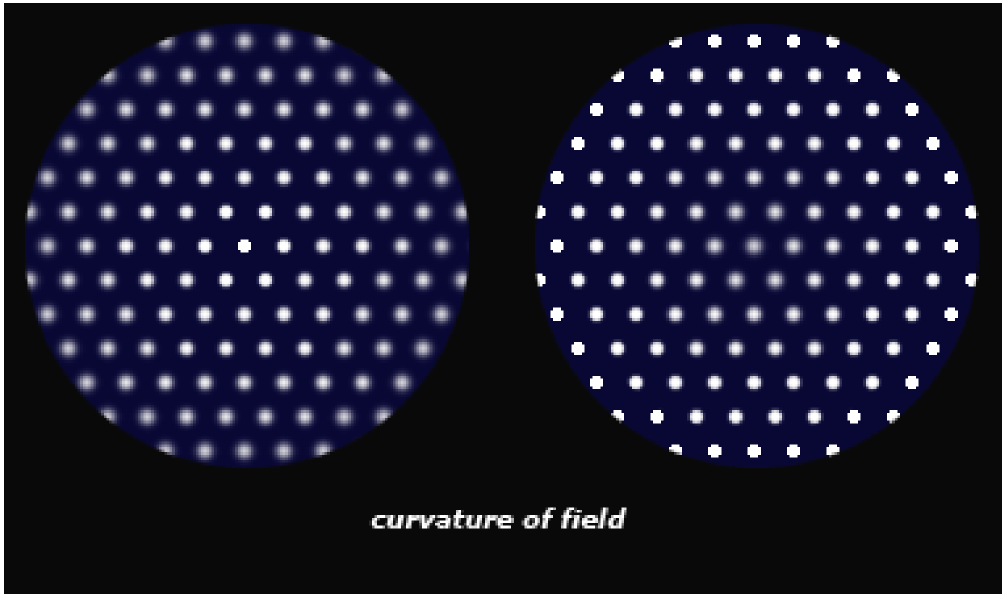
Figure 1

http://www.microscopyu.com/tutorials/java/aberrations/curvatureoffield/



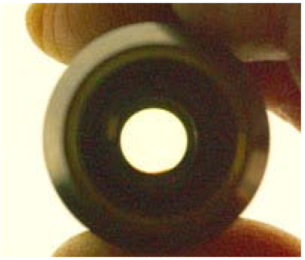
https://sites.astro.caltech.edu/~dmawet/teaching/2018-2019/ay105-lab-experiment_7-1.pdf

Field Curvature

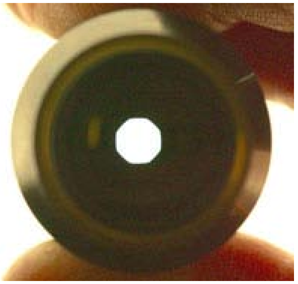


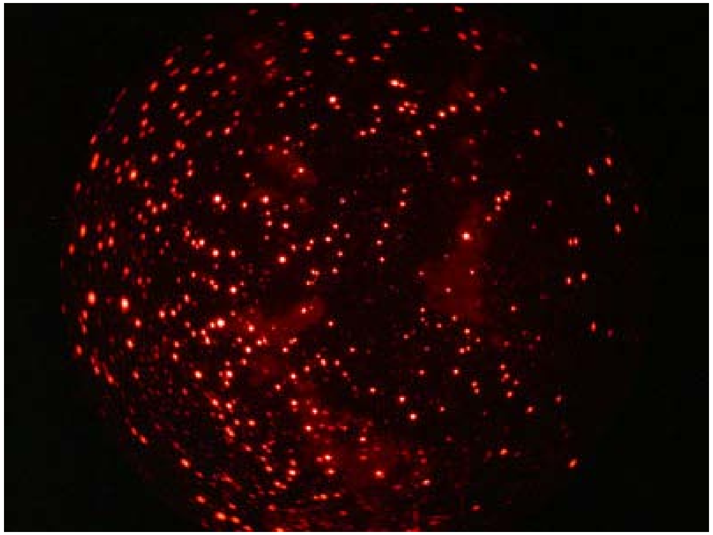
http://www.handprint.com/ASTRO/ae4.html

Field Curvature



Notice that with a closed iris the distortion is greatly reduced, however the light gathering power of the lens is also reduced. Under dim fluorescence conditions the decrease in pixel intensity may be unacceptable.

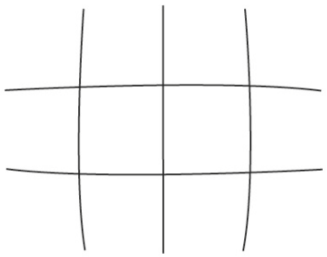




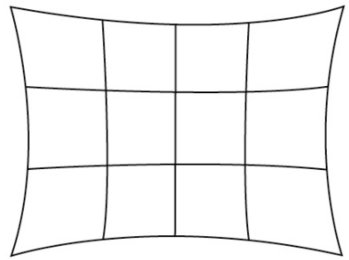
https://microscopy.berkeley.edu/Resources/aberrations/curvature.html

Distortion

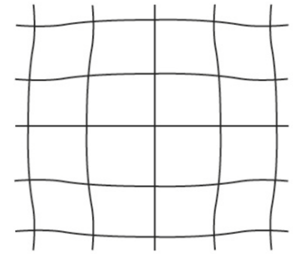
Barrel Distortion



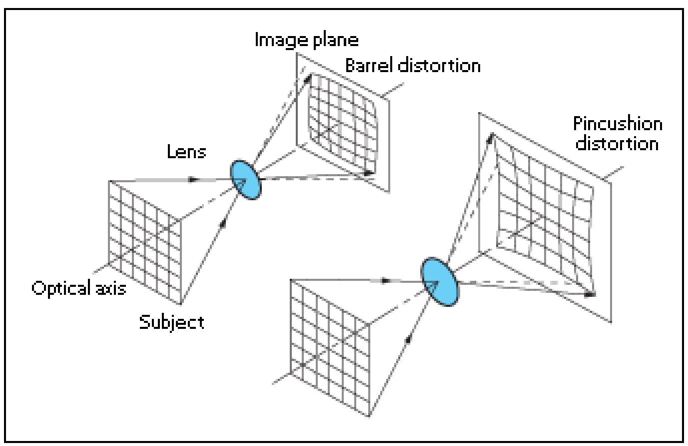
Pincushion Distortion

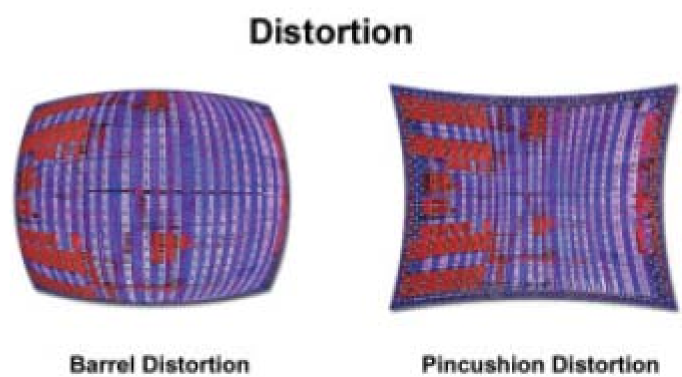


Moustache Distortion

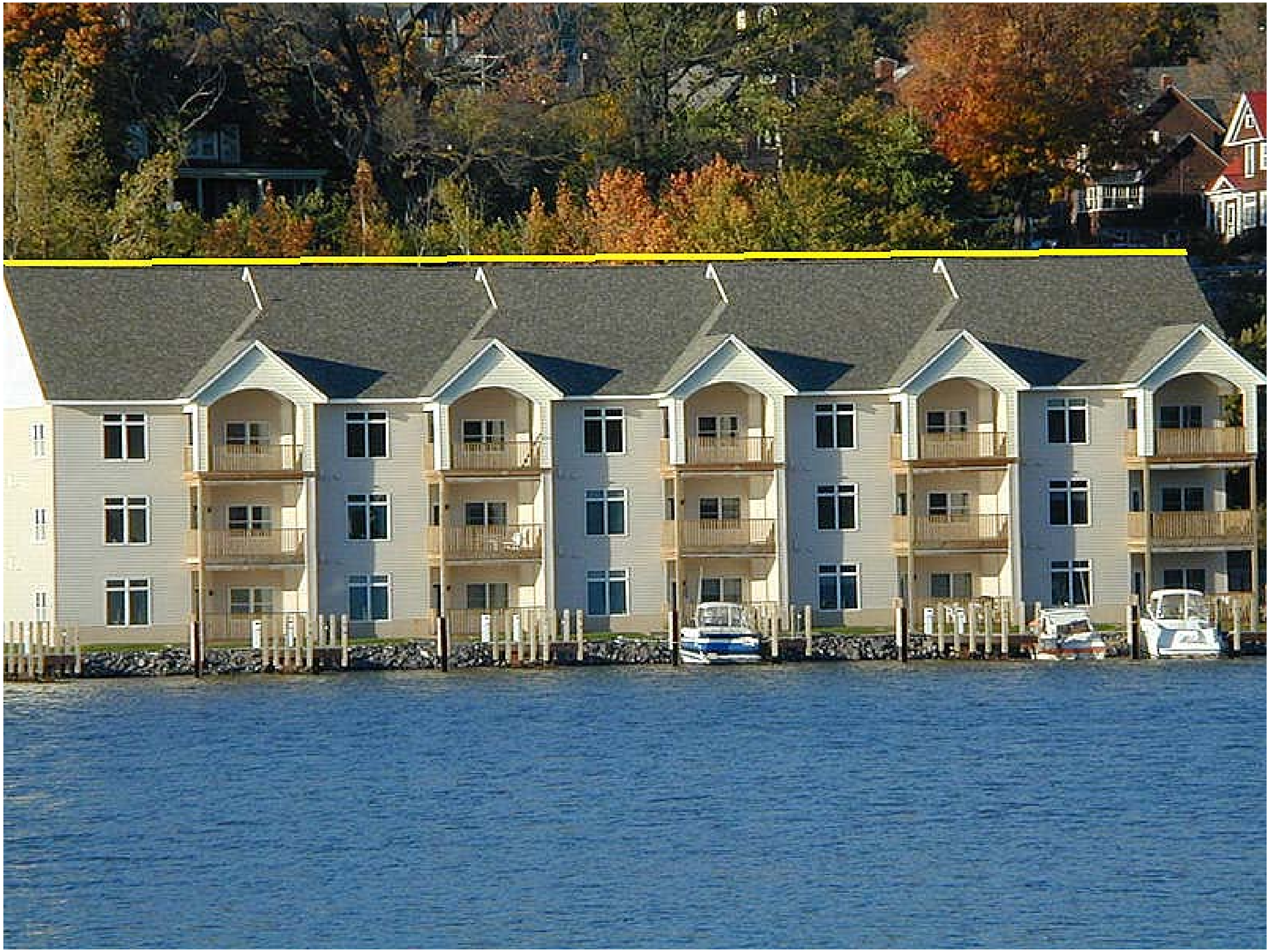


https://www.bhphotovideo.com/explora/photography/tips-and-solutions/optical-anomalies-and-lens-corrections-explained





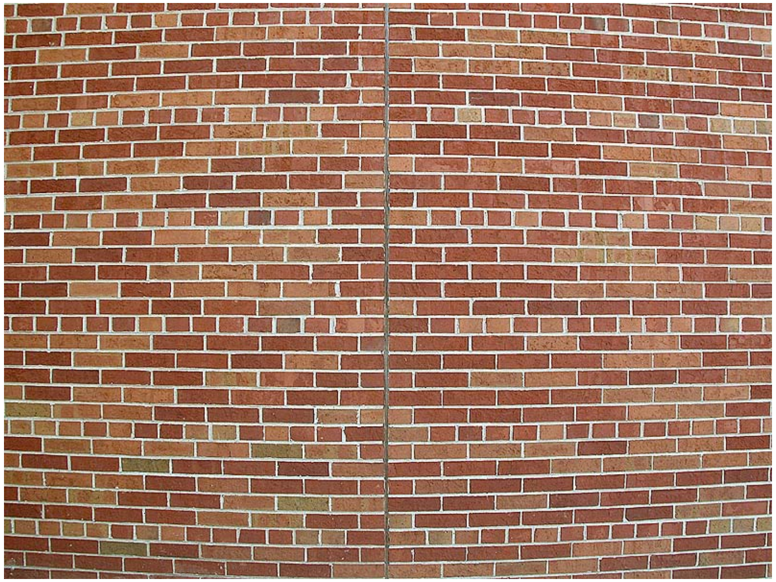
Pincushion Distortion Aberration



Barrel and Pincushion Distortion Aberrations

https://www.bhphotovideo.com/explora/photography/tips-and-solutions/optical-anomalies-and-lens-corrections-explained

Barrel Distortion Aberration



Distortion

Pincushion distortion aberration

Barrel distortion aberration

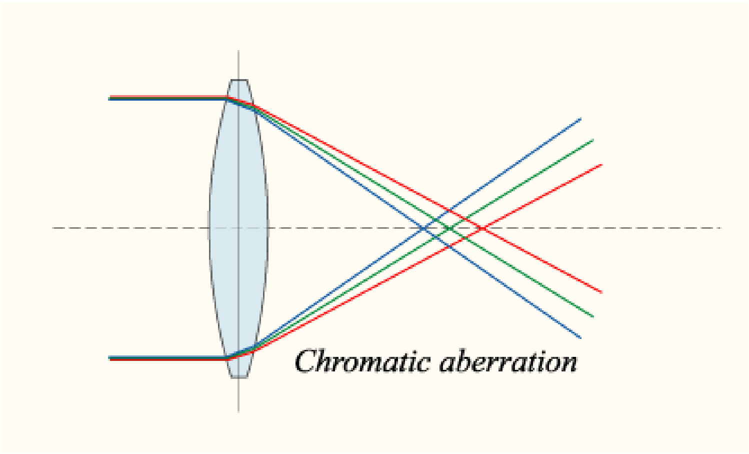
http://www.azurephotonics.com/22.files/image010.jpg

Distortion Aberrations

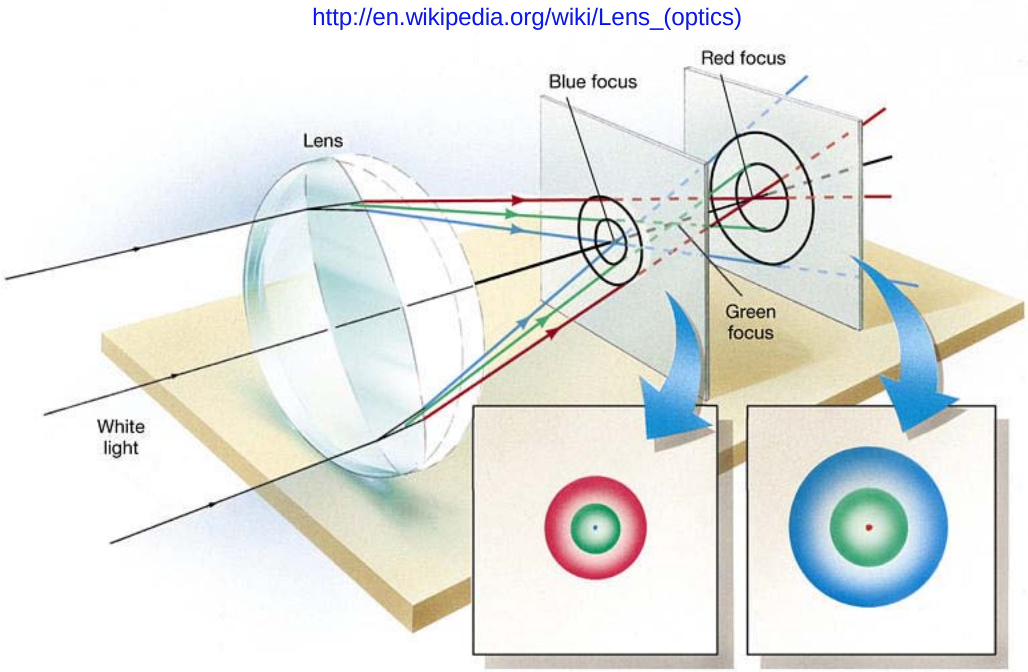
Barrel distortion aberration

Pincushion distortion aberration

Chromatic Aberration

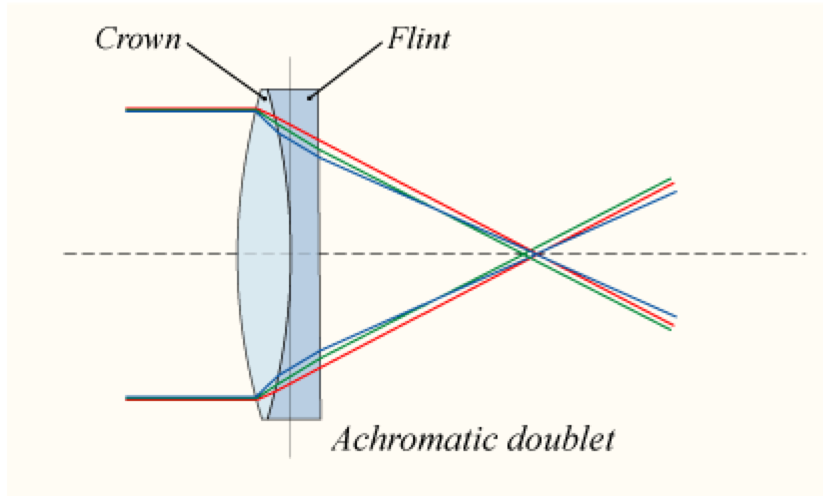


http://en.wikipedia.org/wiki/Lens_(optics)

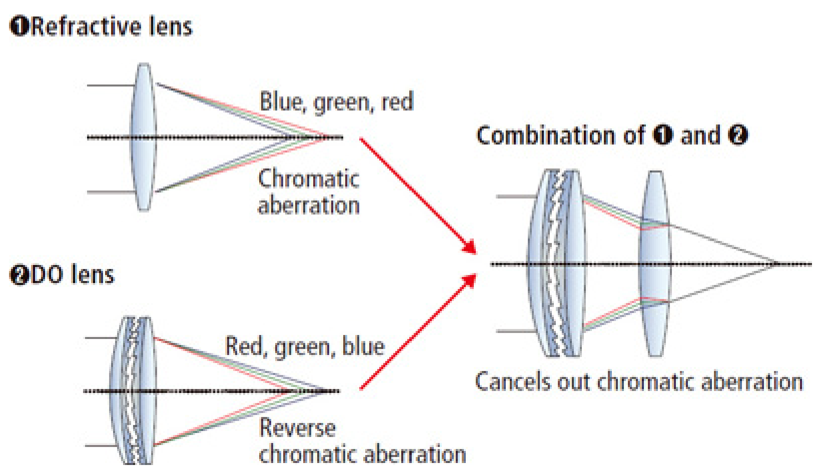


http://pages.uoregon.edu/jimbrau/BraulmNew/Chap05/FG05_05.jpg

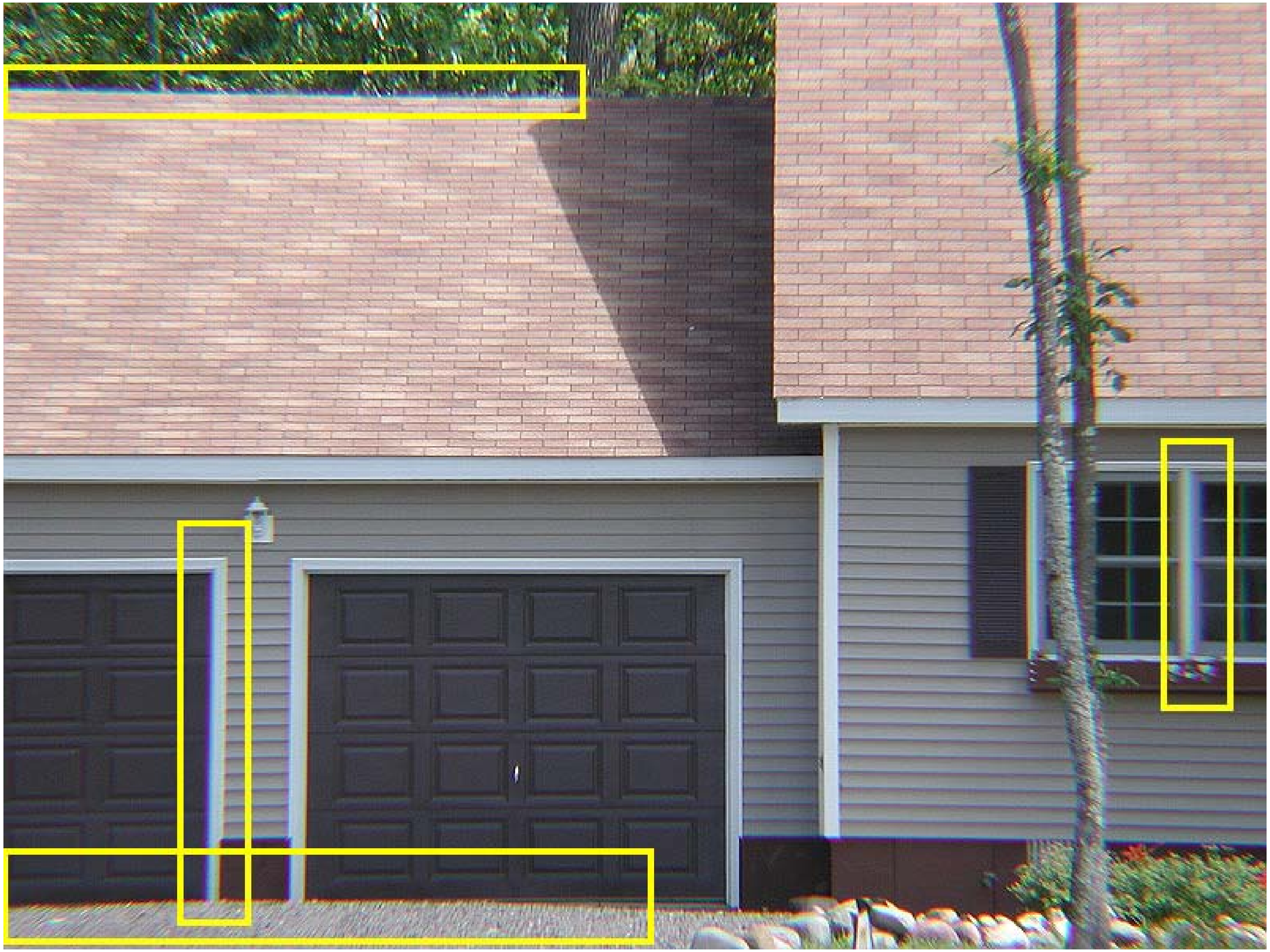
Chromatic Aberration Correction



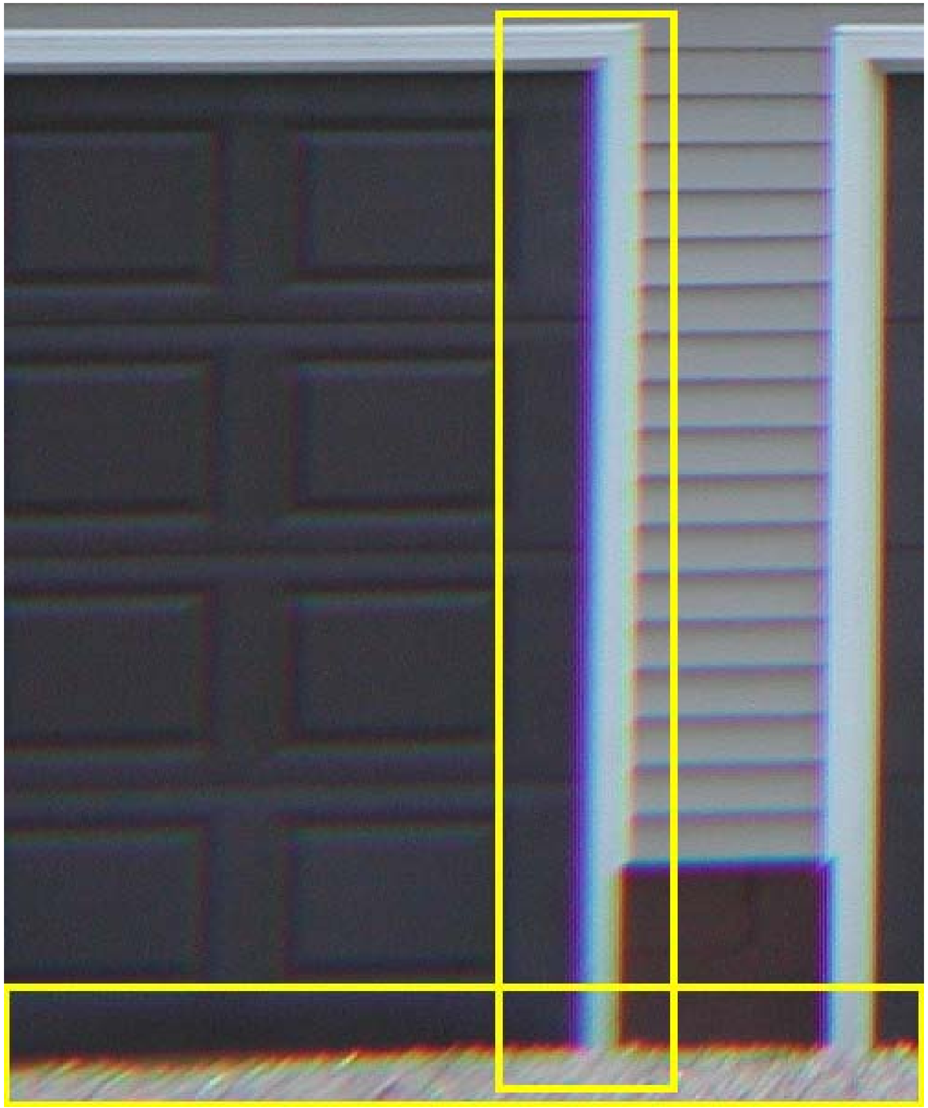
http://en.wikipedia.org/wiki/Lens_(optics)



Chromatic Aberration



Chromatic Aberration



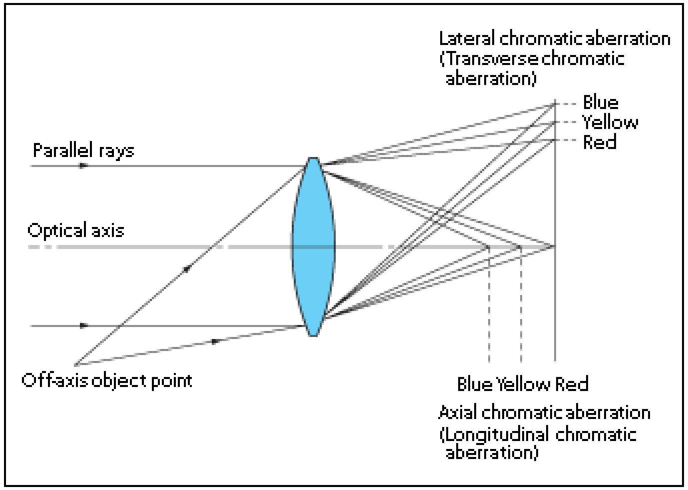
Chromatic Aberration

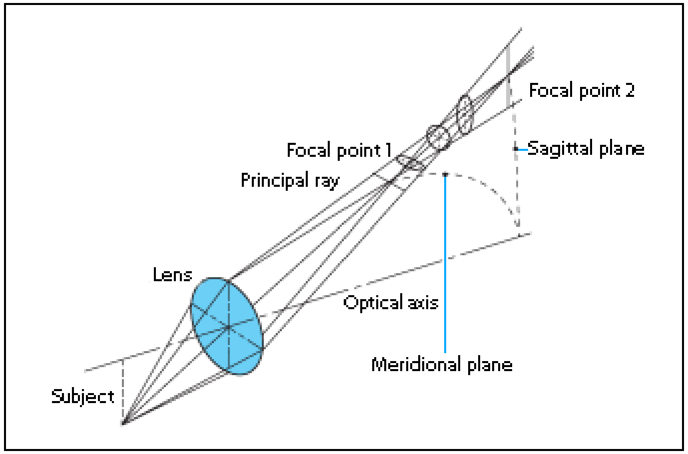
https://en.wikipedia.org/wiki/Chromatic_aberration

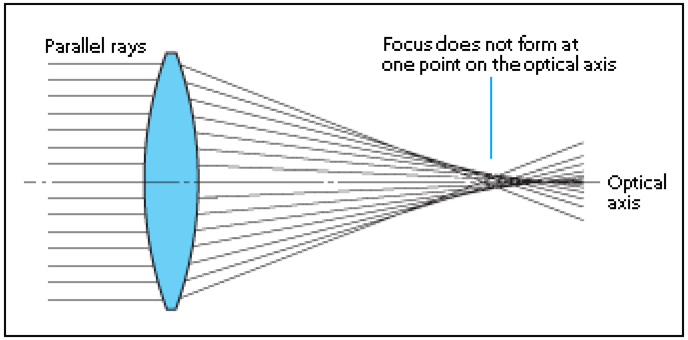
https://photographylife.com/what-is-chromatic-aberration

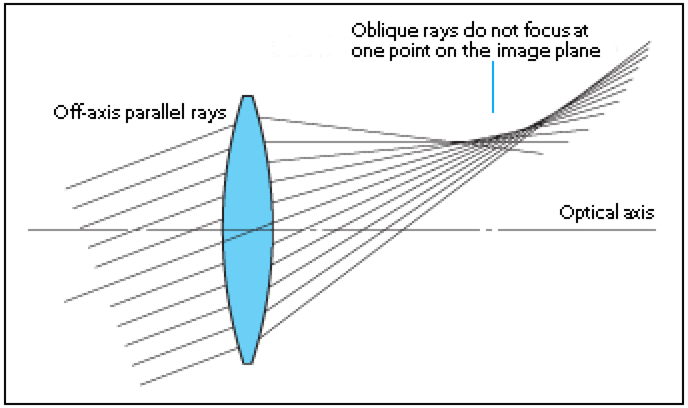
Chromatic Aberration

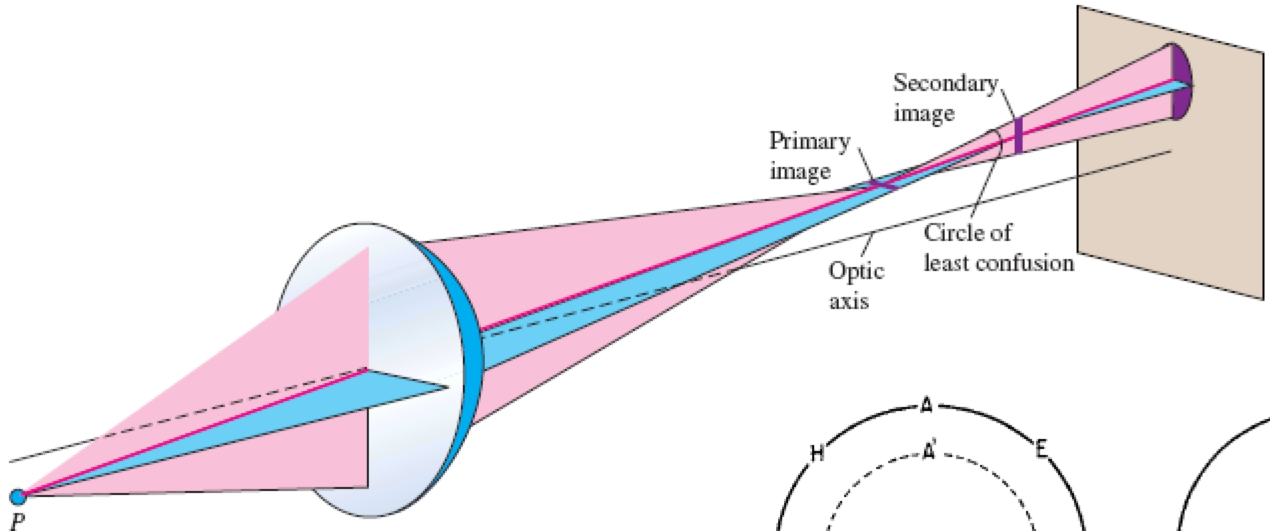
https://digital-photography-school.com/chromatic-aberration-what-is-it-and-how-to-avoid-it/

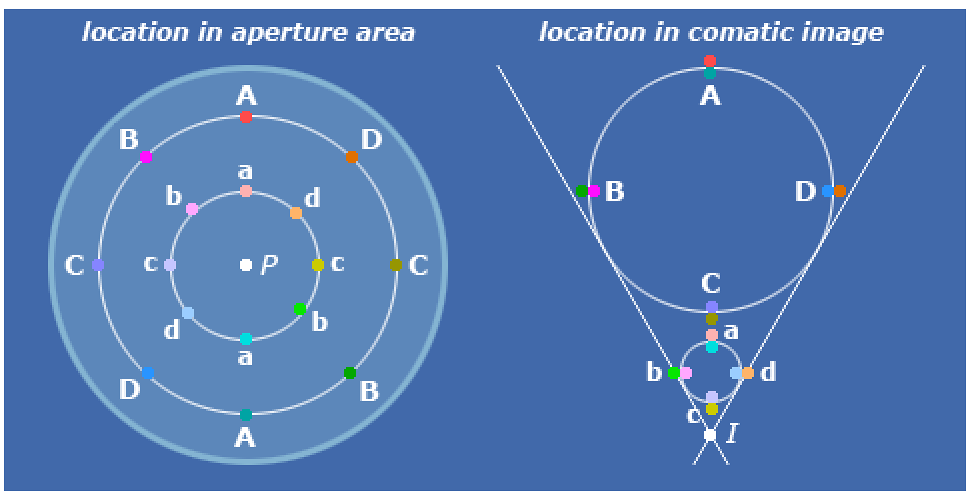

Lateral chromatic aberration
(Transverse chromatic
aberration)
Blue
Yellow
Red
Parallel rays
Optical axis
Off-axis object point
Blue Yellow Red
Axial chromatic aberration
(Longitudinal chromatic
aberration)


Focal point 2
Sagittal plane
Focal point 1
Principal ray
Lens
Optical axis
Meridional plane
Subject


Parallel rays
Focus does not form at
one point on the optical axis
Optical
axis


Oblique rays do not focus at
one point on the image plane
Off-axis parallel rays
Optical axis





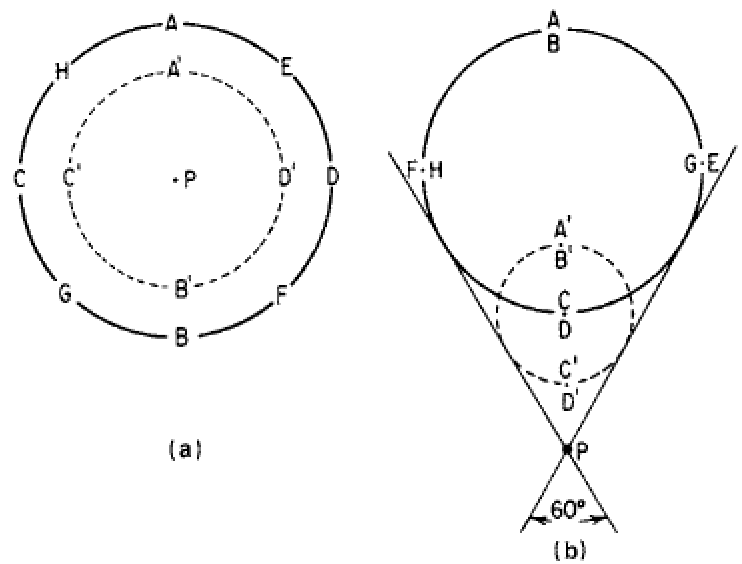


Figure 5.6 The relationship between the position of a ray in the lens aperture and its position in the coma patch. (a) View of the lens aperture with rays indicated by letters. (b) The letters indicate the positions of the corresponding rays in the image figure. Note that the diameters of the circles in the image are proportional to the *square* of the diameters in the aperture.

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