Correcting Chromatic Aberrations

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Aberration

Definition

An abberation is the difference between a perfect image and the image formed by a real lens.

- We have used the paraxial approximation
- We have used spherical lenses
- We have used the first order series expansion of sine
- If we use the next term in the expansion, we see third-order (Seidel) aberrations:
  - Spherical
  - Coma
  - Astigmatism
  - Curvature of field
  - Distortion

Chromatic aberration

Definition

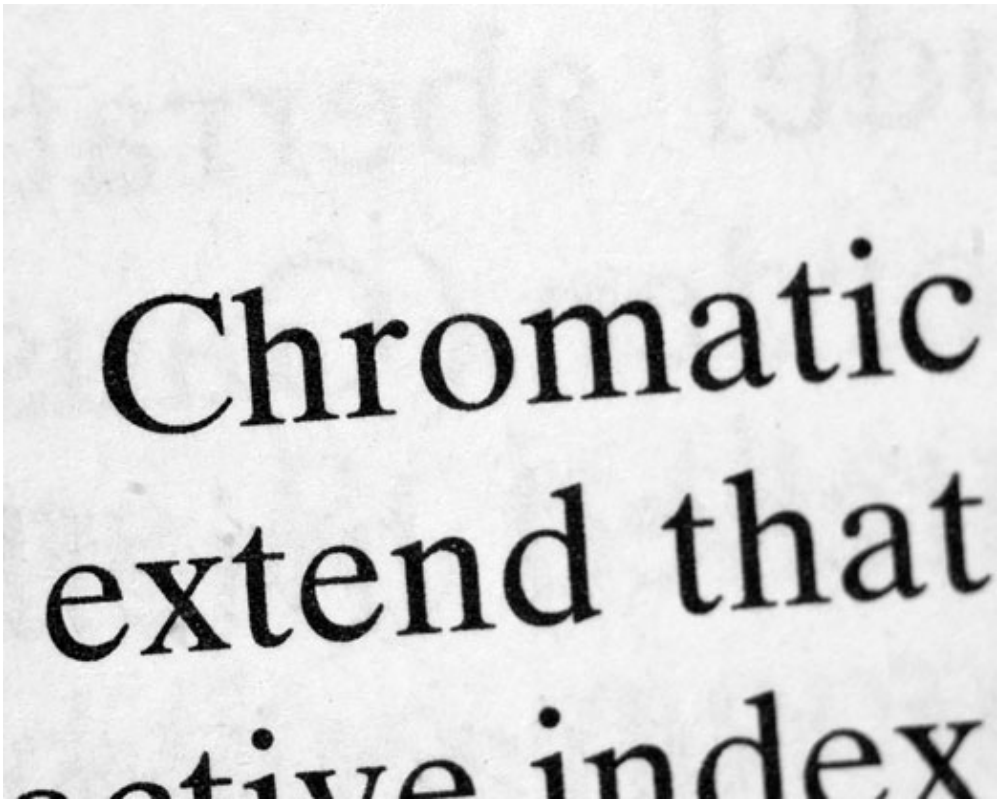
A chromatic abberation is the difference between a perfect image and the separate images formed by each color.

- Not due to departure from paraxial approximation
- Not due to the higher order terms

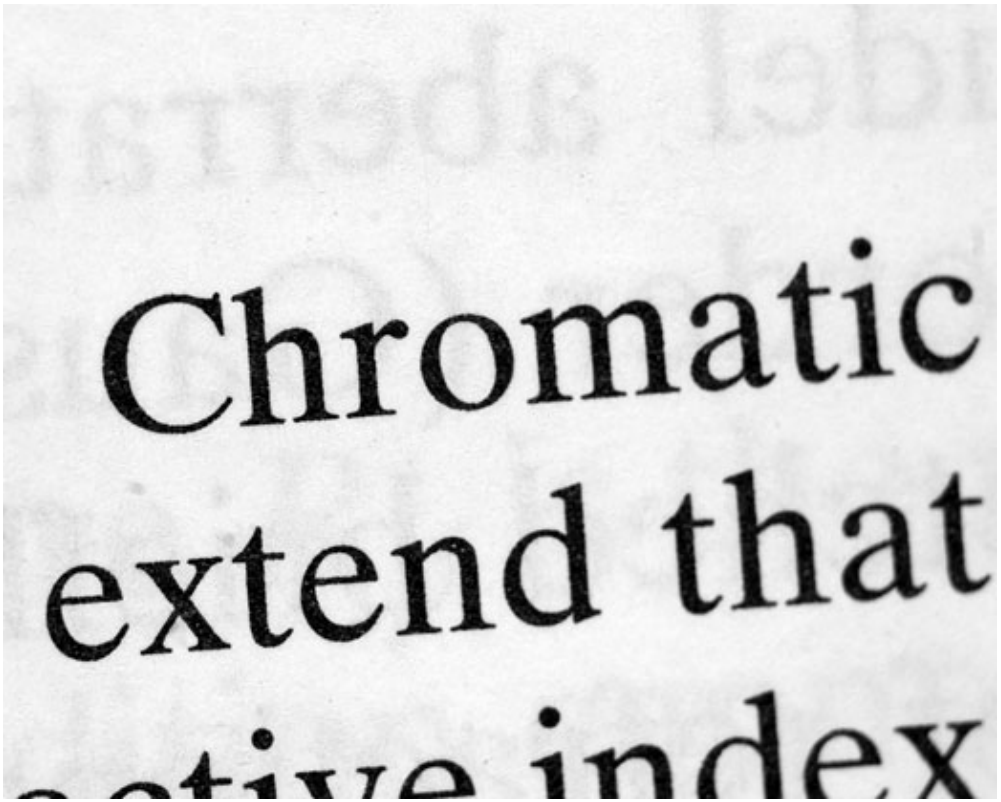
Why worry?

- In photography, you want all the colors to align.

Blue



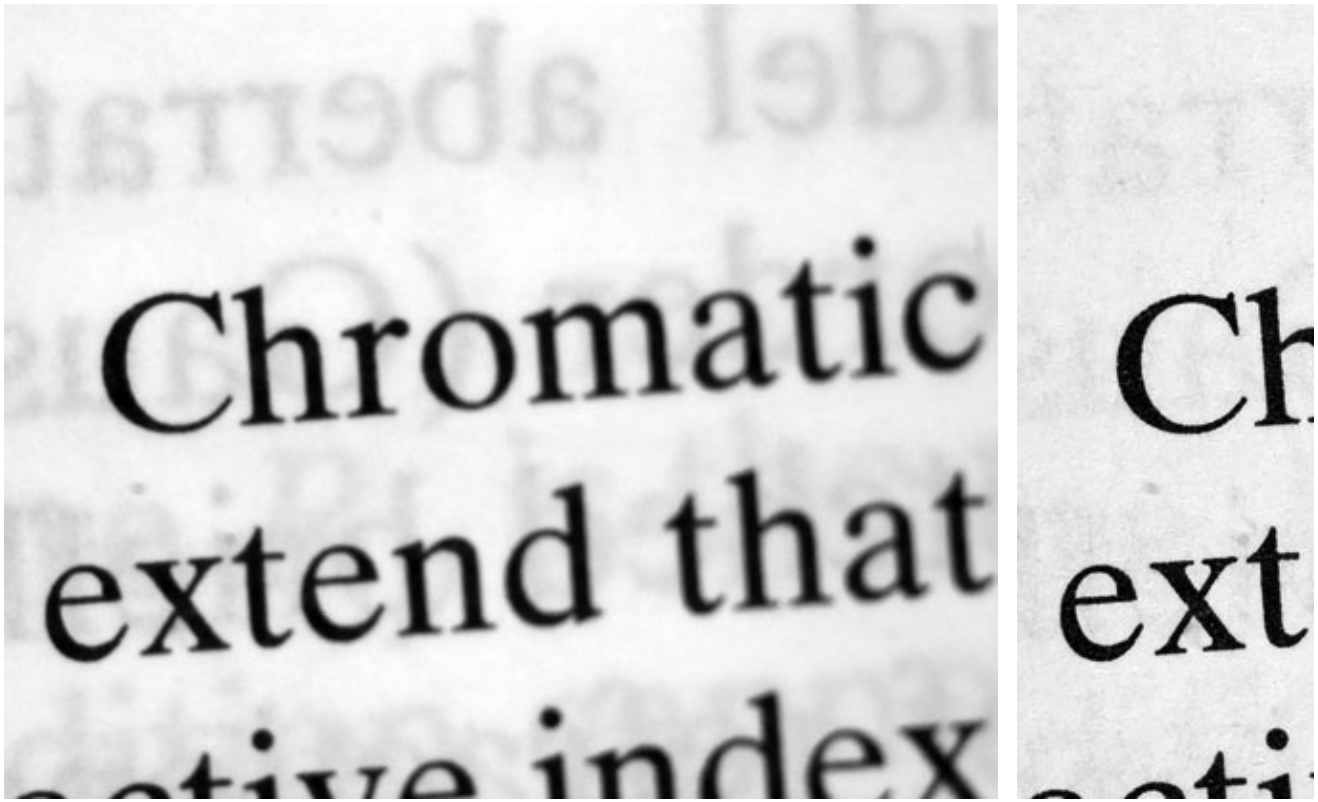
Red



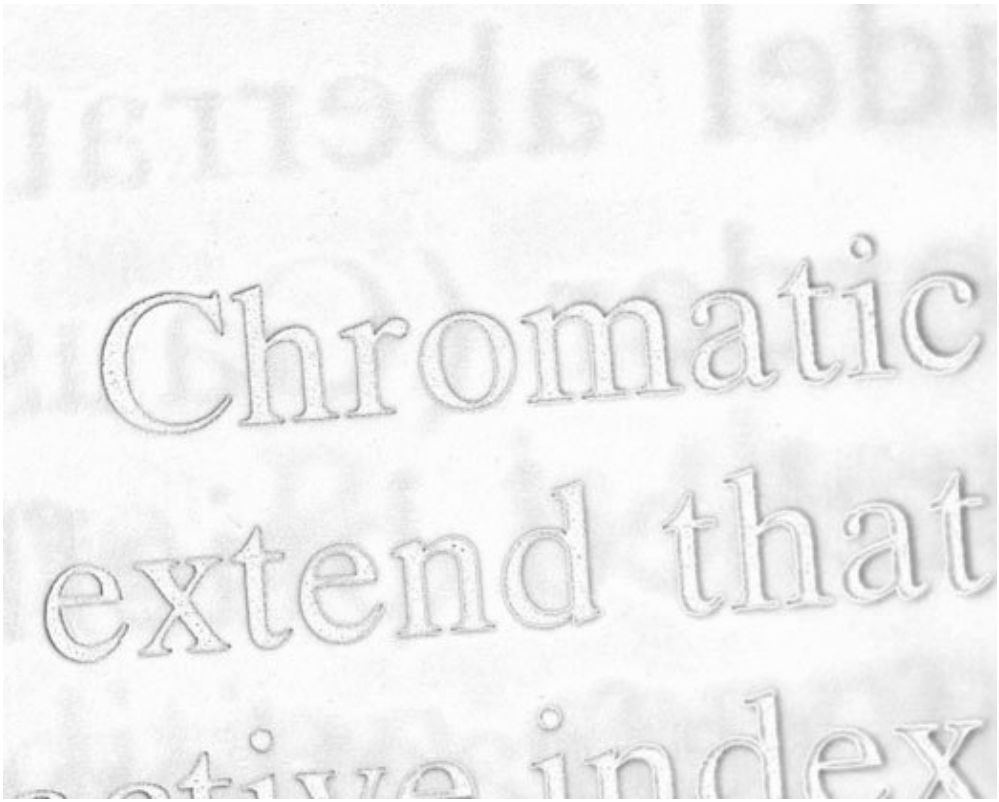
Blue-Red difference

Can you see it?

Infrared



Blue-Infrared difference



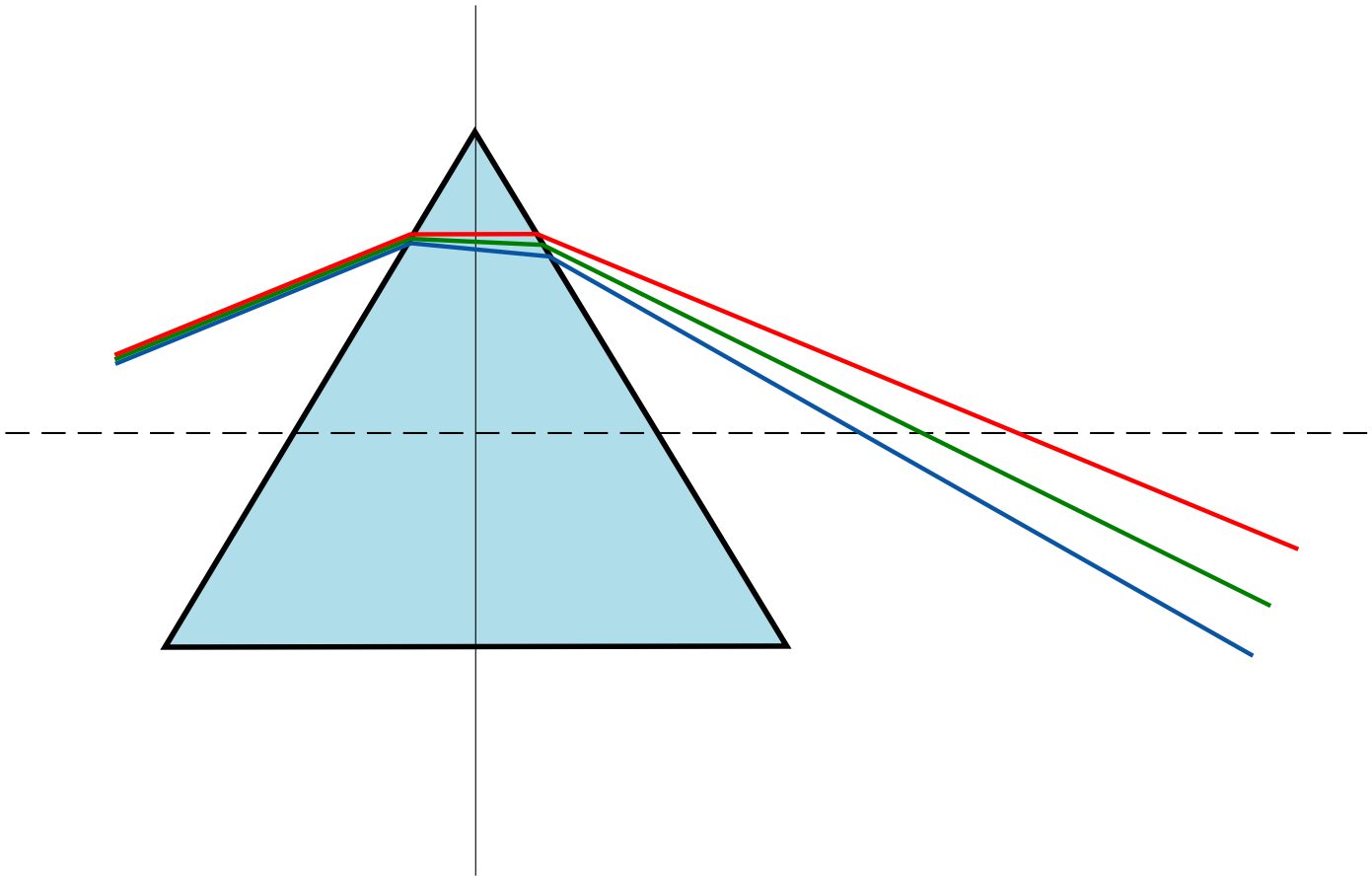
Cause of chromatic aberration

Definition

A chromatic abberation is the difference between a perfect image and the separate images formed by each color.

- Not due to departure from paraxial approximation
- Not due to the higher order terms
- Still exists when we remove these approximations

Dispersion



Dispersion

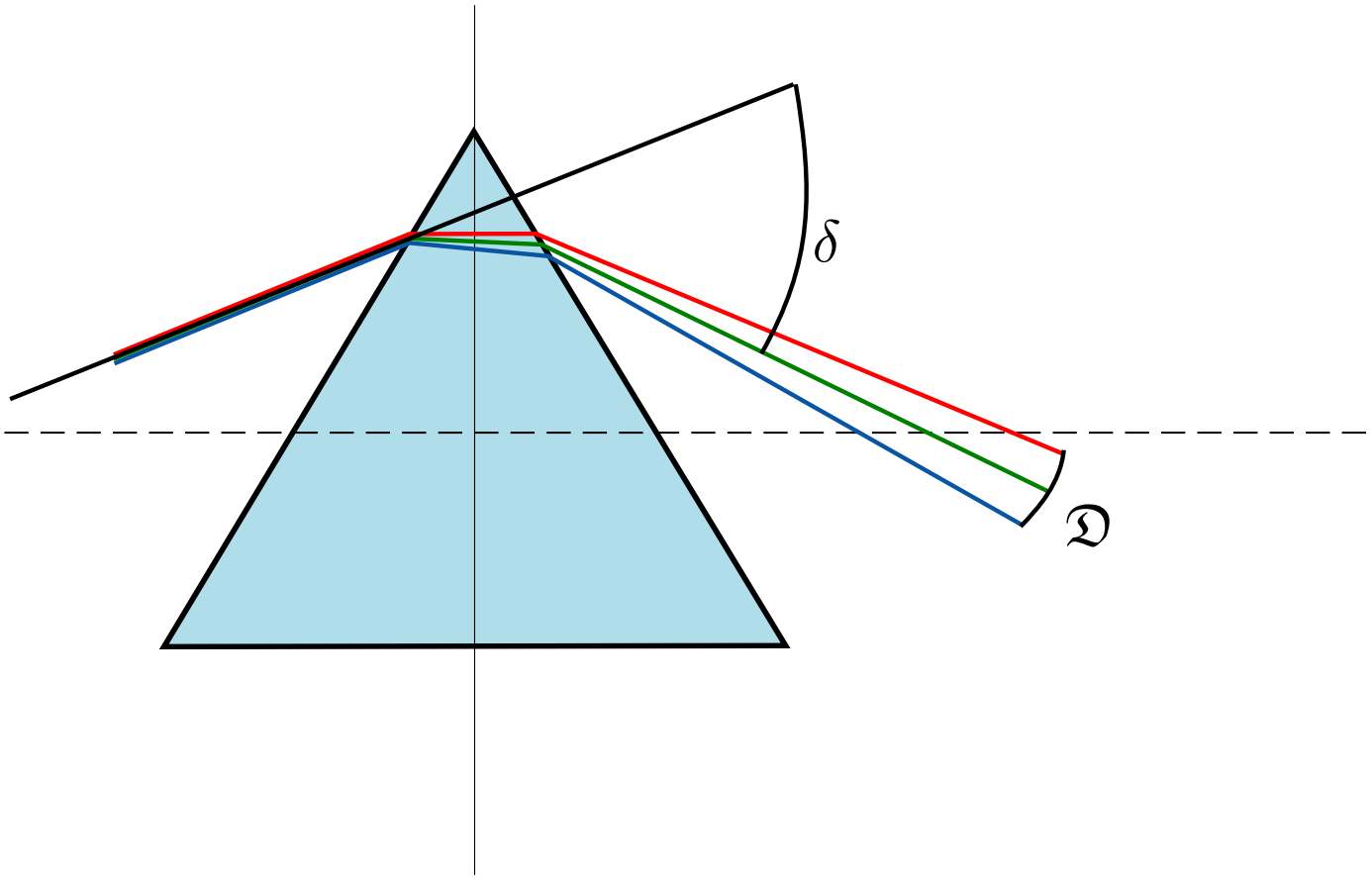
Index of refraction is function of wavelength:

$$n_\lambda = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + \cdots$$

Dispersion, given by Cauchy's formula:

$$\mathfrak{D} = \frac{\mathrm{d}n}{\mathrm{d}\lambda} = -\frac{2B}{\lambda^3}$$

Dispersion — Prism



$\delta =$ displacement, $\mathfrak{D} =$ dispersion

Fraunhofer lines

Use three representative points to describe the continuous spectrum.
For visible light, use the Fraunhofer lines:

λ/nm	label	color	n_{Crown}	n_{Flint}
486.1	F	blue	1.5286	1.7328
589.1	D	yellow	1.5230	1.7205
656.3	C	red	1.5205	1.7076

Dispersive power & Abbe number

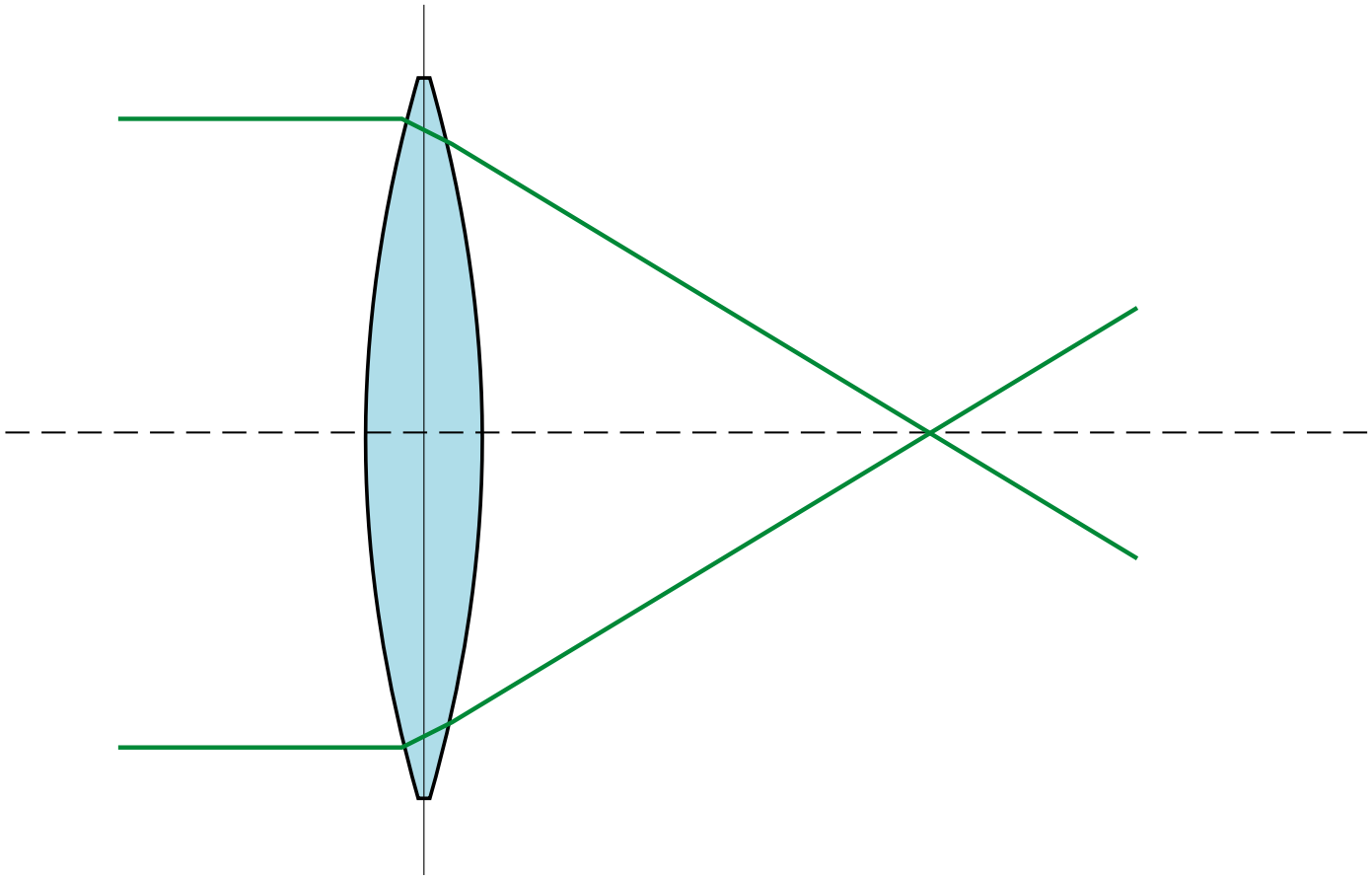
Dispersive power:

$$\Delta = \frac{\mathfrak{D}}{\delta} = \frac{n_F - n_C}{n_D - 1}$$

Abbe number:

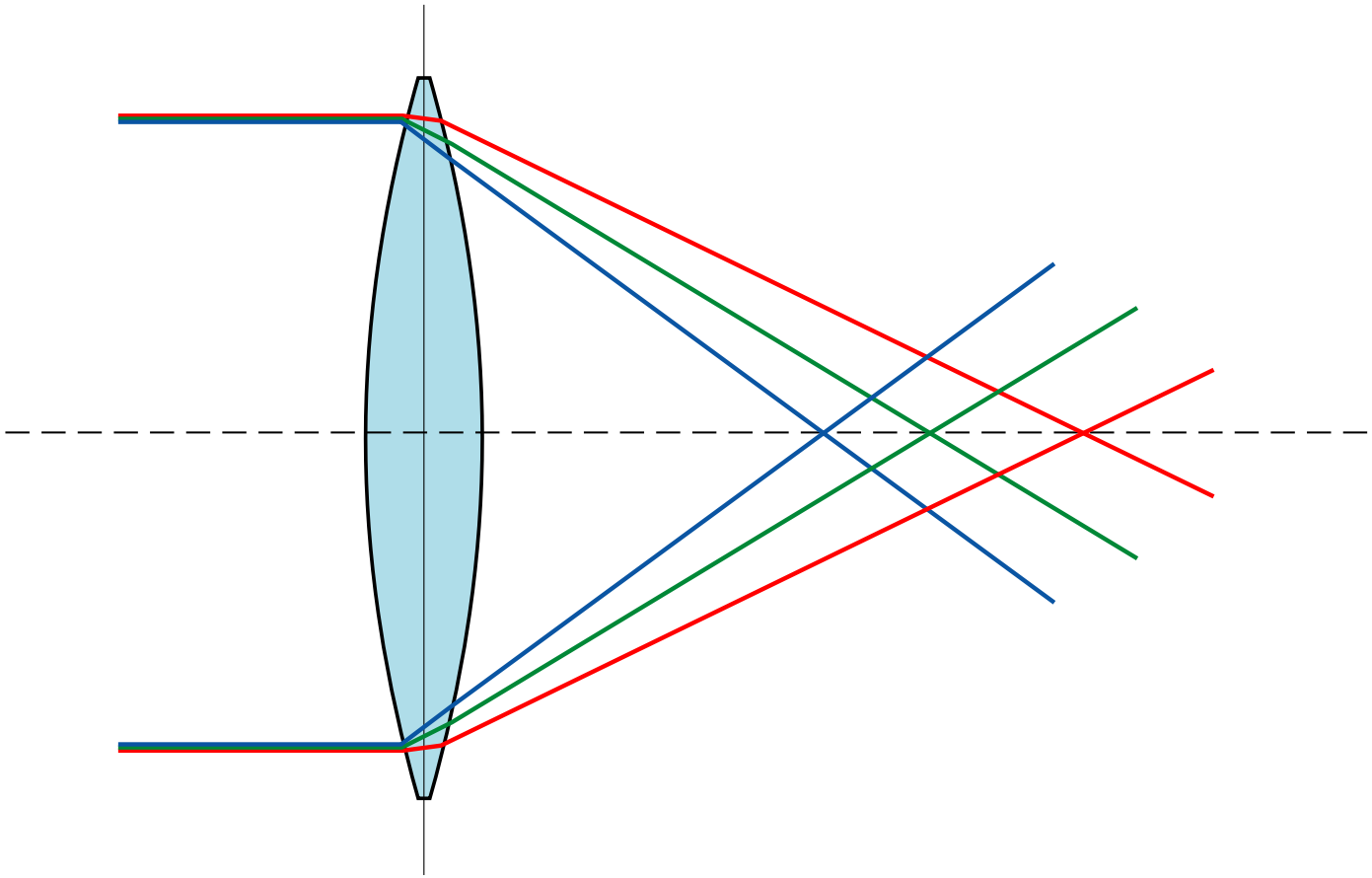
$$V = \frac{1}{\Delta} = \frac{n_D - 1}{n_F - n_C}$$

Thin Lens



First attempt: Design for center wavelength

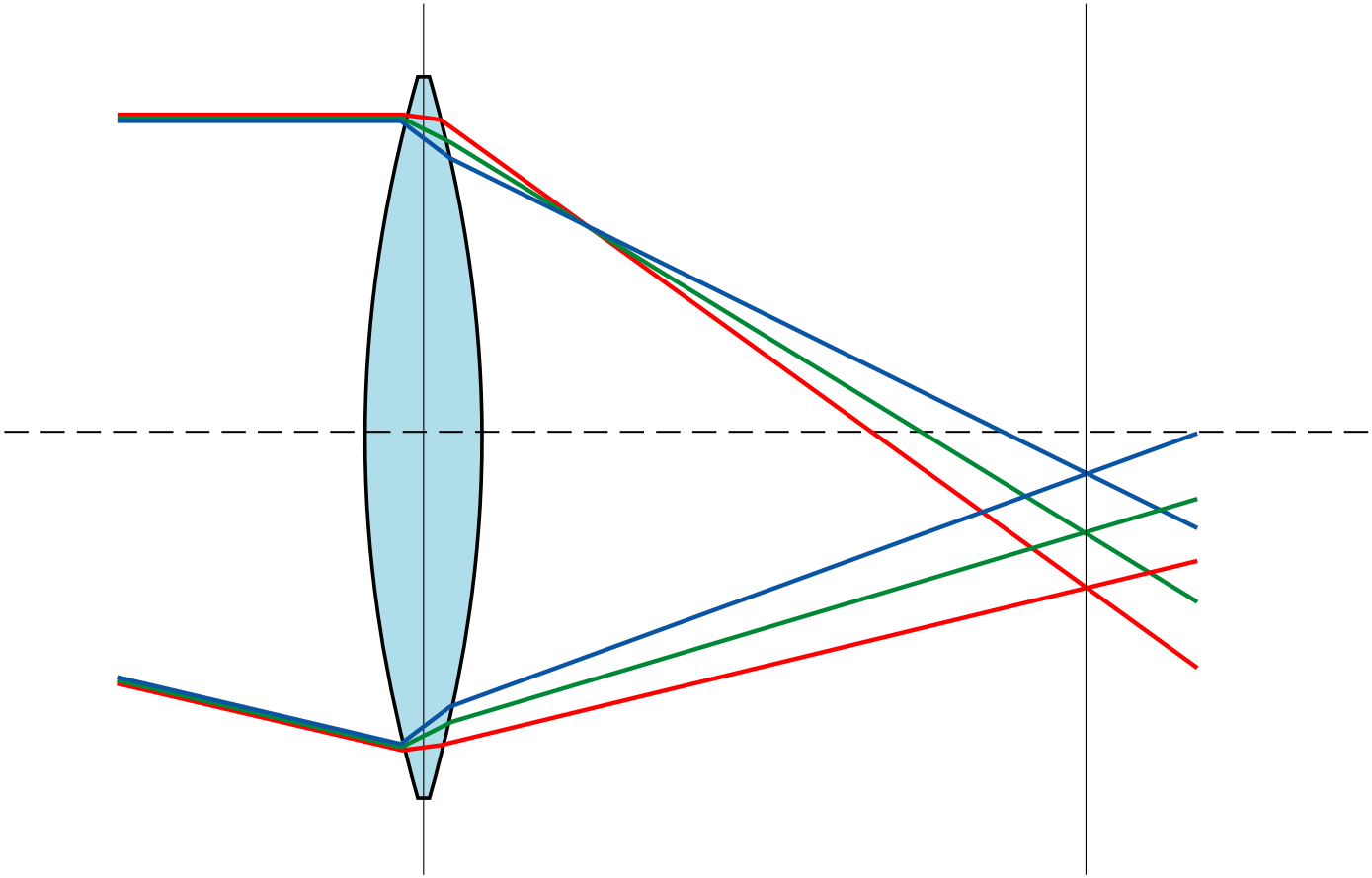
Dispersion — Thin Lens
Longitudinal chromatic aberration (LCA)



Also for paraxial ray.

Dispersion — Thin Lens

Transverse (lateral) chromatic aberration (TCA)

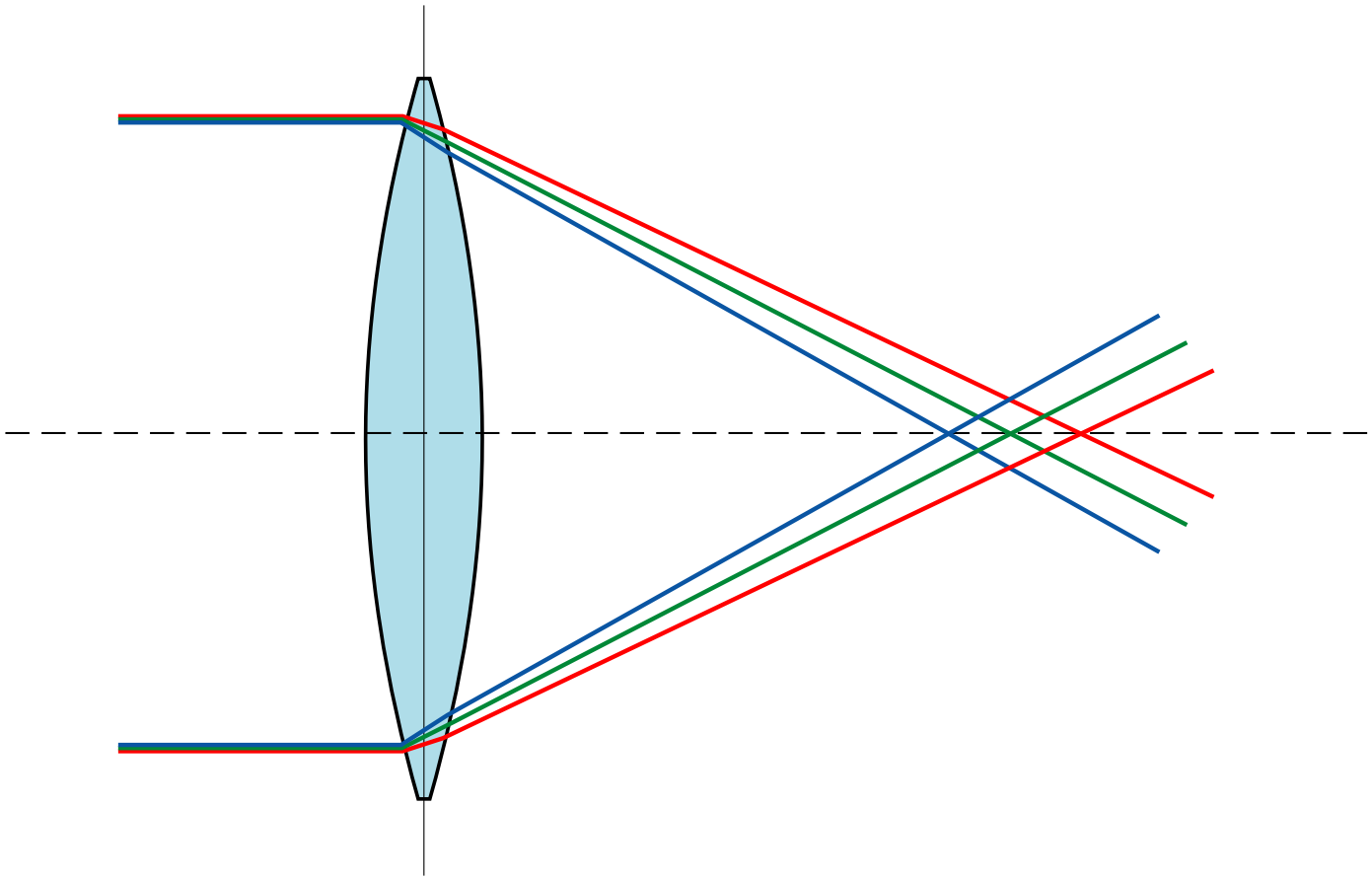


Real chromatic aberrations are a combination of longitudinal and transverse chromatic aberrations.

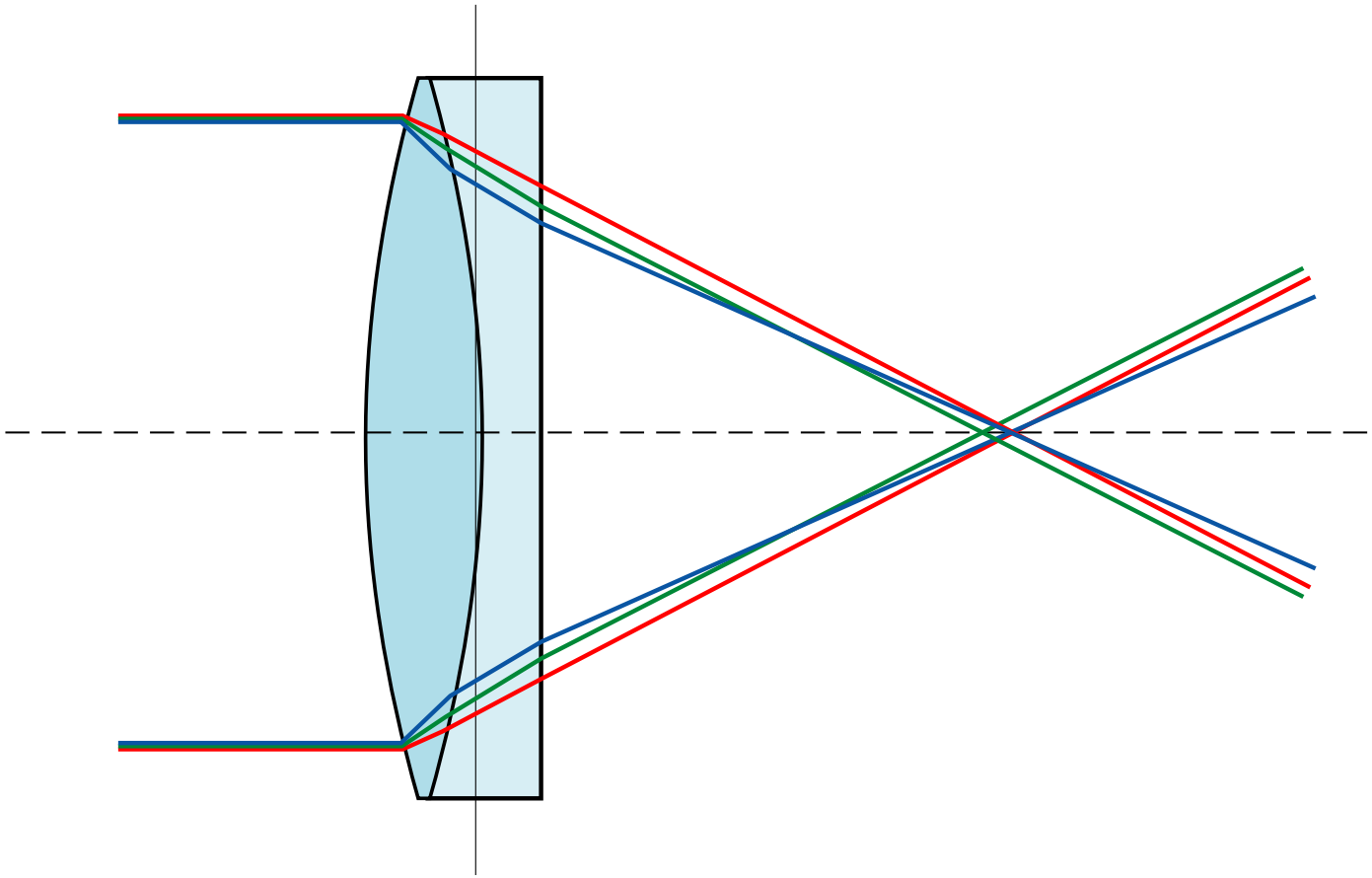
Correcting for chromatic aberrations

How do we make a lens that focuses all wavelengths of interest on the same plane?

Low dispersion glass



Achromatic doublet



Corrects for two wavelengths.

Achromatic doublet

Lens 1 crown glass, Lens 2 flint glass

λ/nm	label	color	∂n_{Crown}	∂n_{Flint}
486.1	F	blue	$+0.0056$	$+0.0123$
589.1	D	yellow	0	0
656.3	C	red	-0.0025	-0.0129

Achromatic doublet

Thin lenses separated by L:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{L}{f_1 f_2}$$

As separation goes to zero:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

Or in terms of lens power:

$$P = P_1 + P_2$$

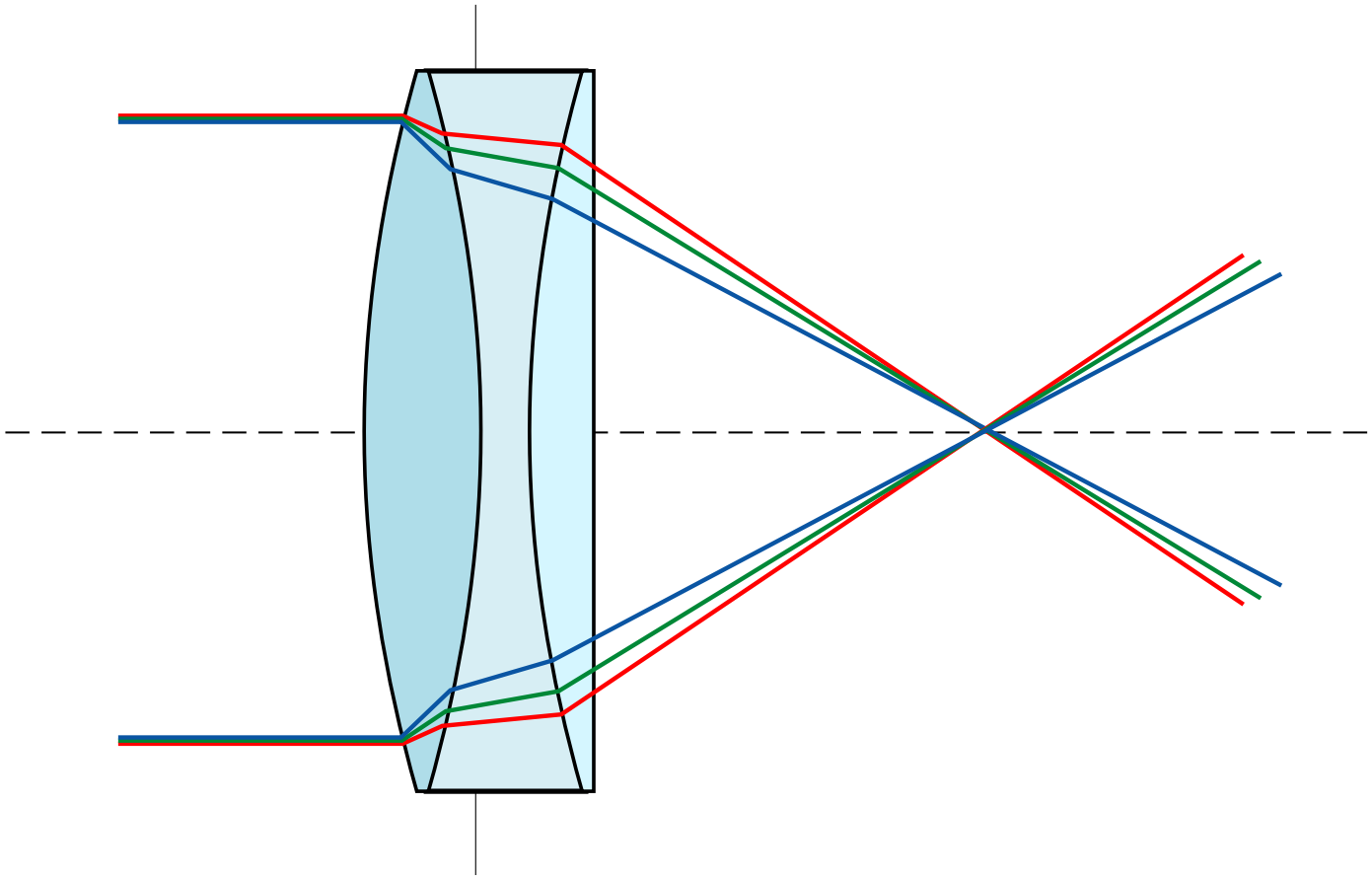
Achromatic doublet — design

For the doublet to be achromatic:

$$\frac{\partial P}{\partial \lambda} = 0$$
$$= K_1 \frac{\partial n_1}{\partial \lambda} + K_2 \frac{\partial n_2}{\partial \lambda}$$

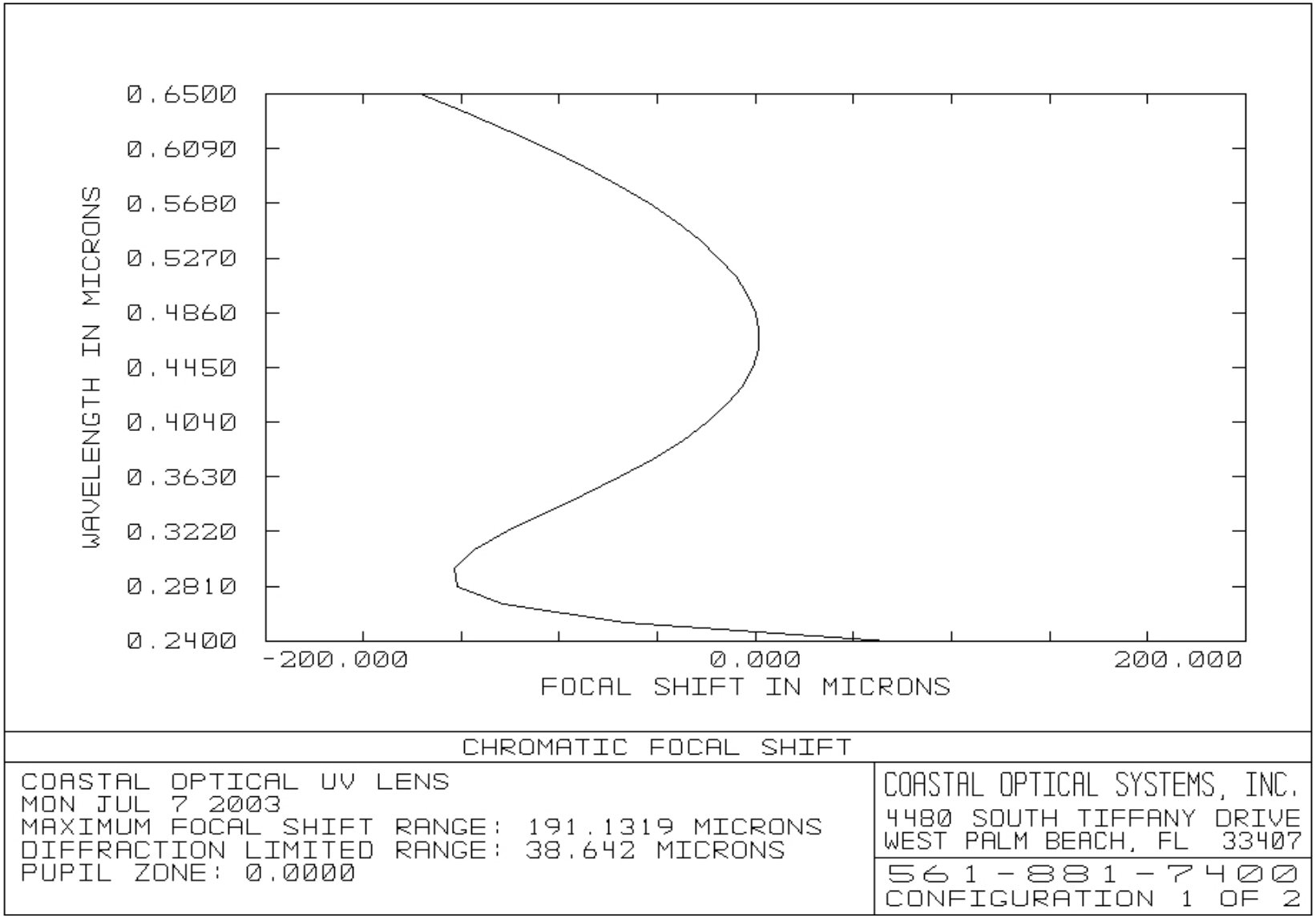
where K_x describes the curve of the lens surfaces.
We can now solve for minimum chromatic aberration at two chosen frequencies.

Apochromatic



Corrects for three wavelengths.

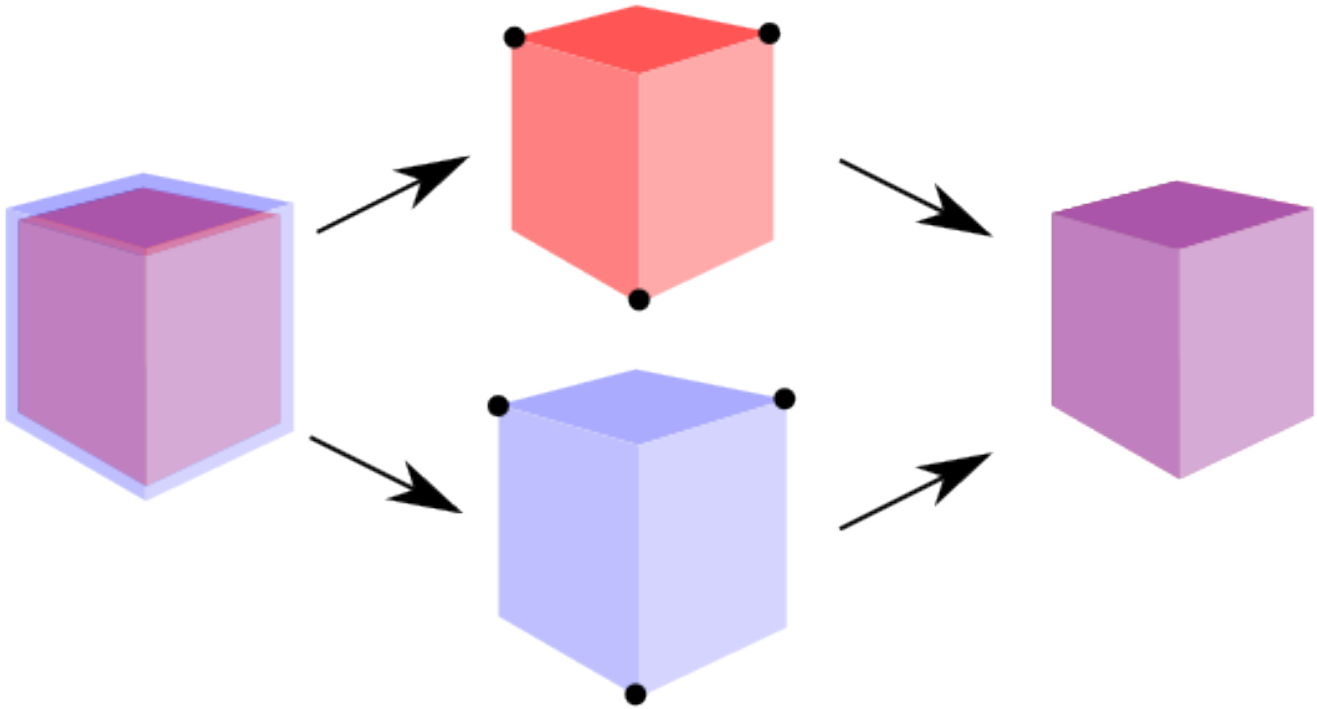
Focus shift in an apochromatic lens



post-Correcting

- Instead of correcting the problem in optics, it is possible to use post-processing in some systems.
- Digital and digitized photos allow ‘easy’ post-processing.
- Since the images are digitally processed, some correction can be done by mathematically transforming the separate color layers.

post-Correcting

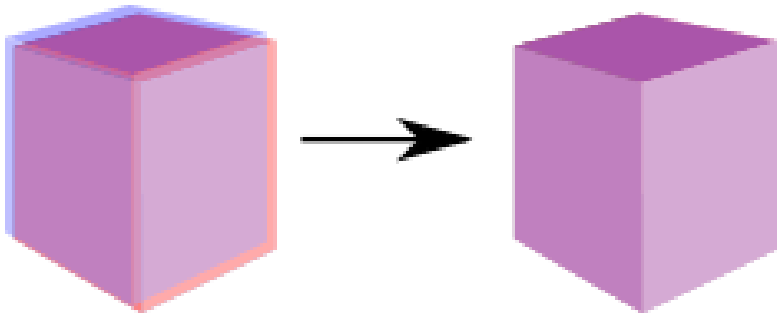


Solves lateral but not longitudinal chromatic aberrations.

post-Correcting for Bayer filter

- Digital photography creates chromatic aberrations because of the Bayer-filter.
  - A grid of colored filters to capture three colors with a wide spectrum sensor.
  - The areas sensitive to red, green, and blue are slightly shifted.
- Since the images are digitally processed, it is easy to alter the color layers to correct chromatic aberrations.
- Built into some cameras.

post-Correcting for Bayer filter



Other methods of correcting chromatic aberrations

- Use mirrors
- Use separate exposures for each color