# TOPICS

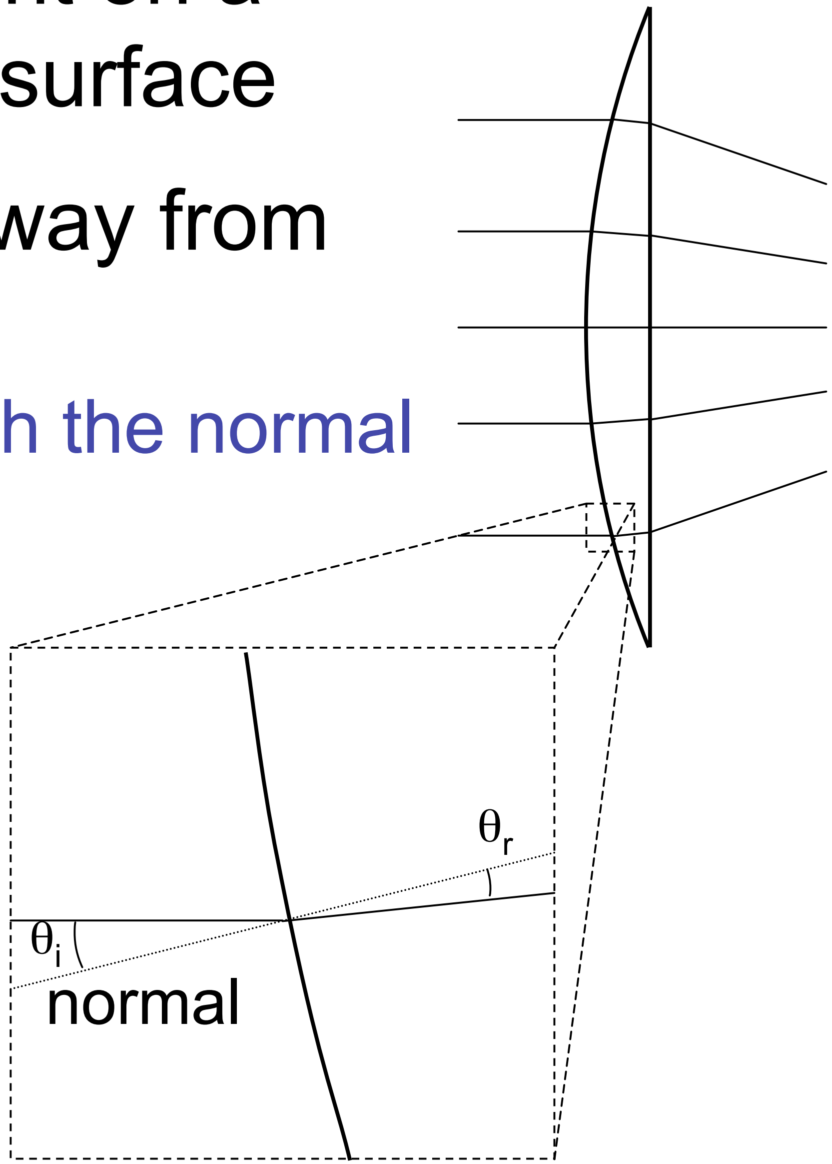
- Recap of PHYS110 *- 1 lecture*
- Physical Optics *- 4 lectures*
  - EM spectrum and colour
  - Light sources
  - Interference and diffraction
  - Polarization
- **Lens Aberrations** *- 3 lectures*
  - **Spherical aberrations**
  - Coma, astigmatism, field curvature, distortion
  - Chromatic aberrations
- Instrumental Optics *- 4 lectures*
  - Telescope, microscope
  - Stops, eyepieces
  - Instruments for the anterior eye
  - Instruments for the posterior eye

# Lecture 6: Spherical aberrations

- The paraxial approximation
- Spherical aberrations
- Reducing spherical aberrations
- Spherical aberrations in the eye

# The spherical lens

- Parallel light is incident on a lens with a spherical surface
- Light that is further away from the principle axis
  - has a larger angle with the normal
  - is bent stronger
- The light is focused

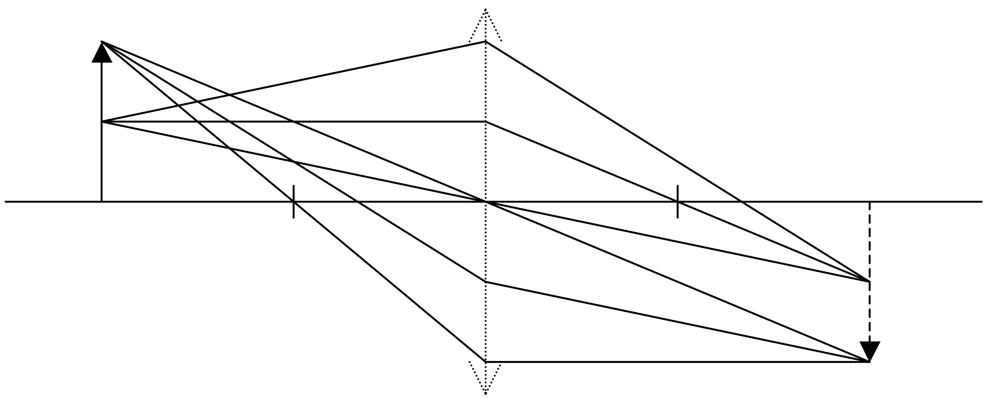


# The paraxial approximation

- Refraction at the surface of a lens is governed by Snell's law: $n_1 \sin\theta_i = n_2 \sin\theta_r$
- At small angles, $\sin\theta \approx \tan\theta \approx \theta$
  - This is called the paraxial approximation
  - Snell's law can be simplified to $n_1\theta_i = n_2\theta_r$

# The paraxial approximation

1. All the rays leaving a particular point on an object are focused on a point on the image.
2. The magnification is the same at all points on the image.
3. An object in a plane perpendicular to the principal axis is focused on a single image plane perpendicular to the principal axis.



*To produce a focused, undistorted image, all three conditions need to be satisfied!*

# Aberrations

- Aberrations arise when:
  - The paraxial approximation is no longer valid
    $\Rightarrow$***monochromatic*** aberrations
  - The refractive index of the lens varies with the light wavelength (dispersion)
    $\Rightarrow$ ***chromatic*** aberrations
- Aberrations cause blurred and distorted images

# $\sin\theta$

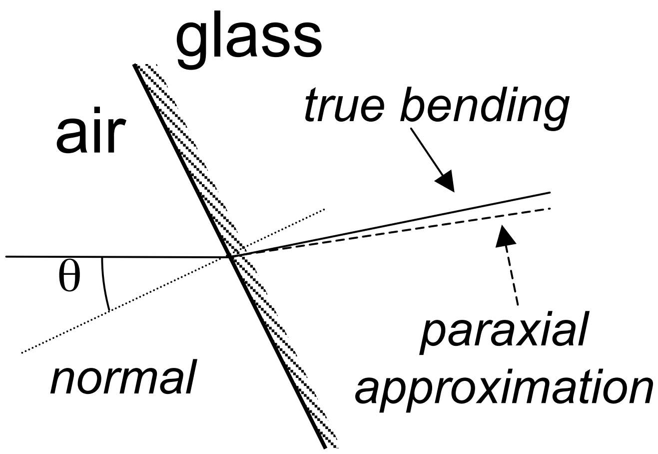
| $\theta$ (degrees) | $\theta$ (radians) | $\sin\theta$ | $(\theta - \sin\theta)/\theta$ |
|---|---|---|---|
| 10 | 0.174533 | 0.173648 | 0.0051 |
| 20 | 0.349066 | 0.342020 | 0.0202 |
| 30 | 0.523599 | 0.500000 | 0.0451 |
| 40 | 0.698132 | 0.642788 | 0.0793 |
| 50 | 0.872664 | 0.766044 | 0.1222 |

$\Rightarrow \sin\theta < \theta$

$\Rightarrow$ *Difference increases at large* $\theta$

# Bending on air-glass ($n=1.5$) interface

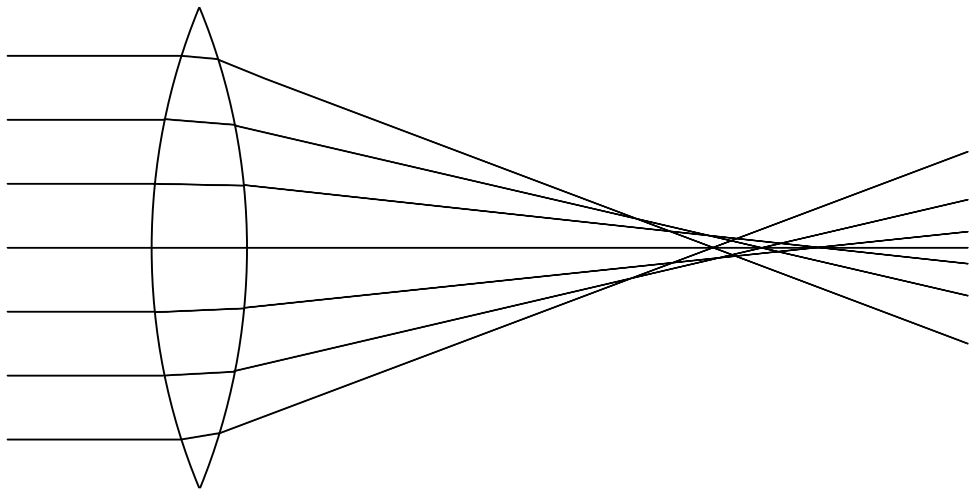
| $\theta$ | paraxial bending | Snell's bending |
|---|---|---|
| 10° | 3.33° | 3.35° |
| 20° | 6.67° | 6.82° |
| 30° | 10.00° | 10.53° |
| 40° | 13.33° | 14.62° |
| 50° | 16.67° | 19.29° |




⇒ ***True bending is stronger than the paraxial approximation,***
*in particular at large $\theta$*

# Consequences

- Parallel light far away from the principal axis focuses stronger than light close to the optical axis
- Points do not image to points
- The image is blurred



- This is called spherical aberration

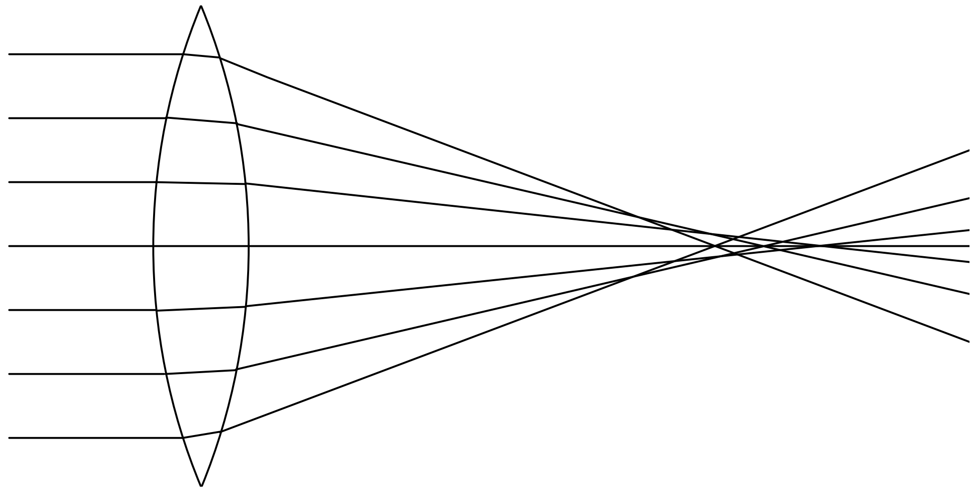
# Reducing spherical aberrations

- Aspheric lens
- Aperture stop
- Distribute bending
- High refractive index
- Doublets

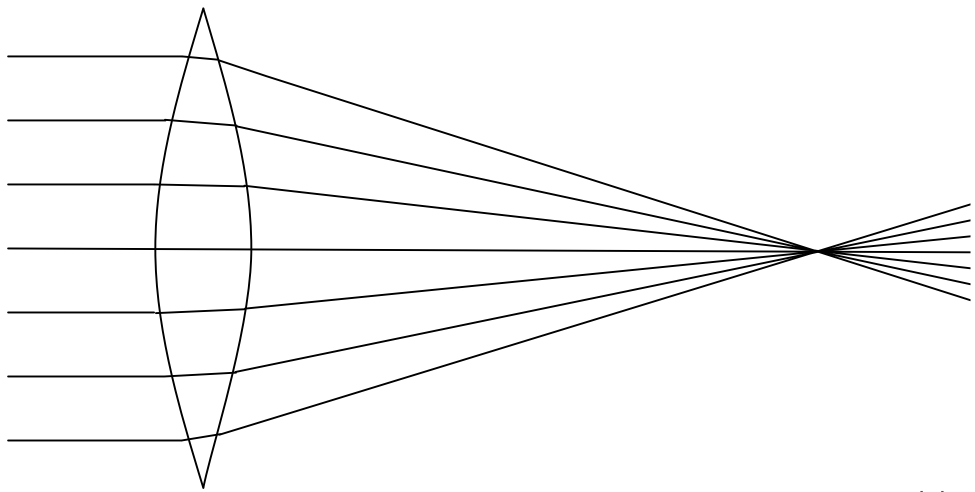
# Aspheric lenses

- A smaller curvature far from the from the principal axis reduces spherical aberrations.
- These lenses are not spherical and thus called aspheric
- They are more difficult to produce than spherical lenses

*spherical lens*



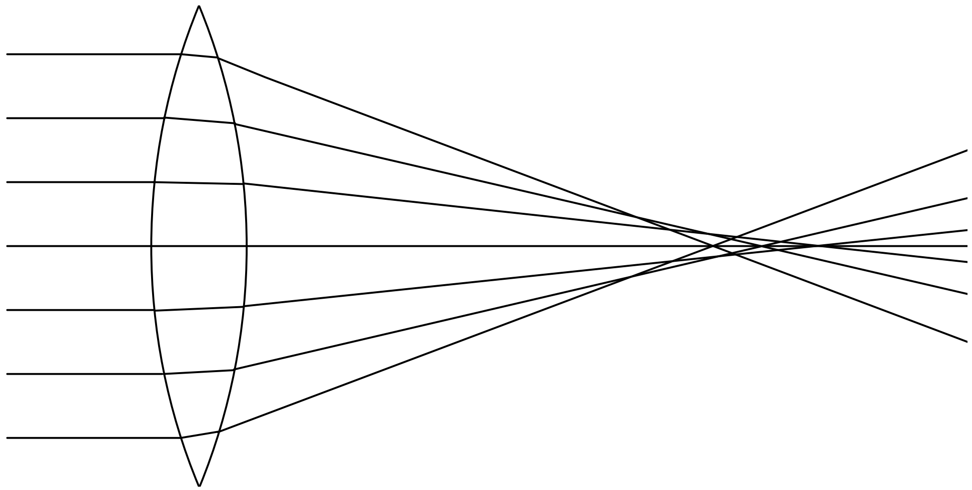
*aspheric lens*



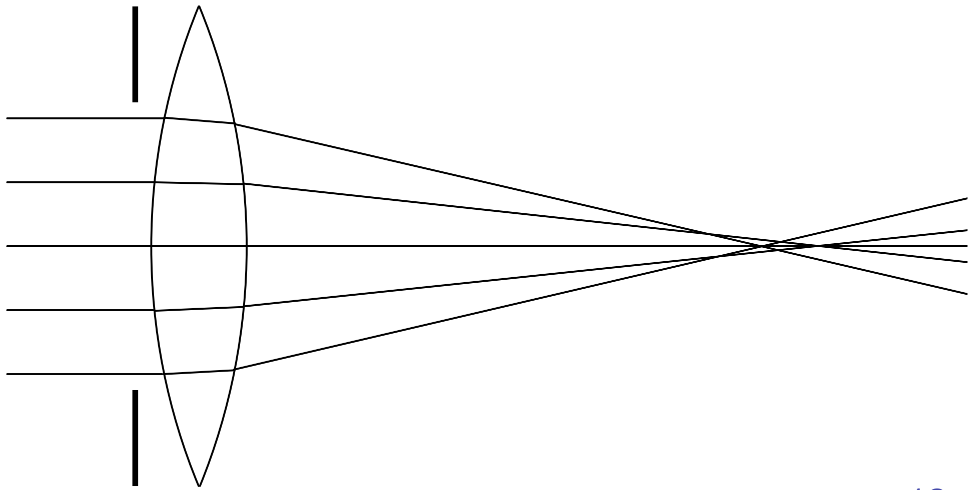
# Aperture stops

- Rays close to the principal axis have the smallest spherical aberration
- An aperture stop blocks the light far from the principal axis

*without aperture stop*



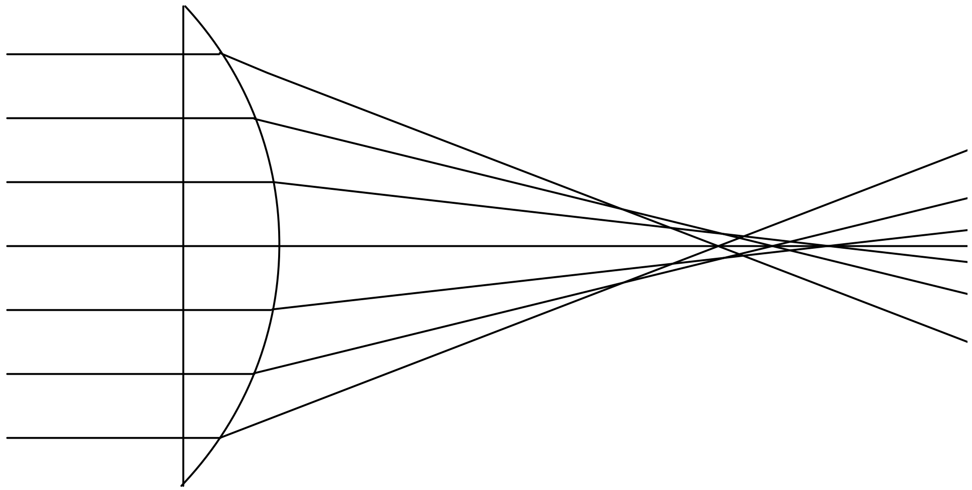
*with aperture stop*



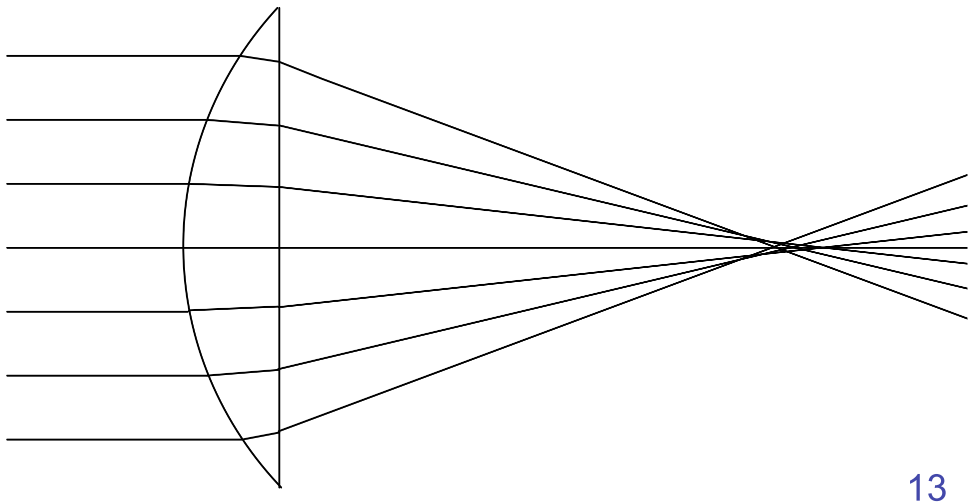
# Distribute bending

- A lens has two surfaces
- The angle of incidence of the light should be minimised
- One way to achieve that is to distribute the bending equally over the two surfaces

*poorly distributed bending*



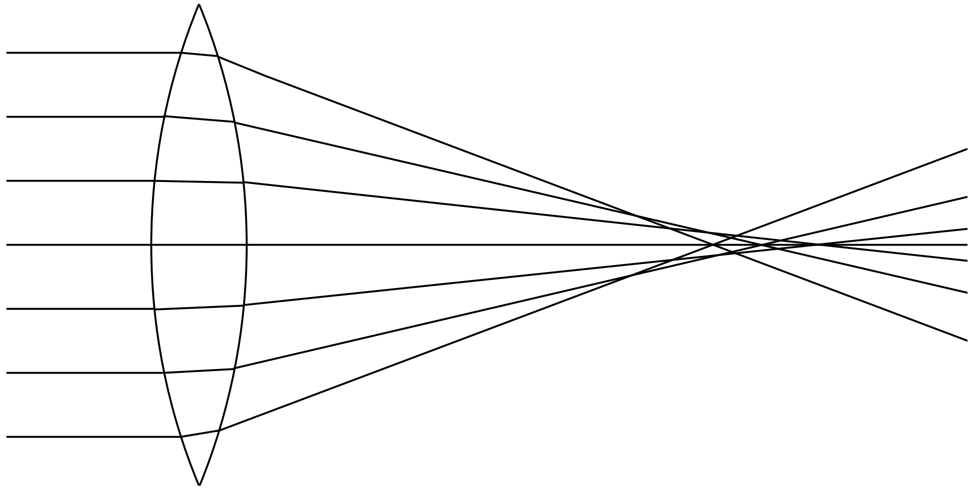
*well distributed bending*



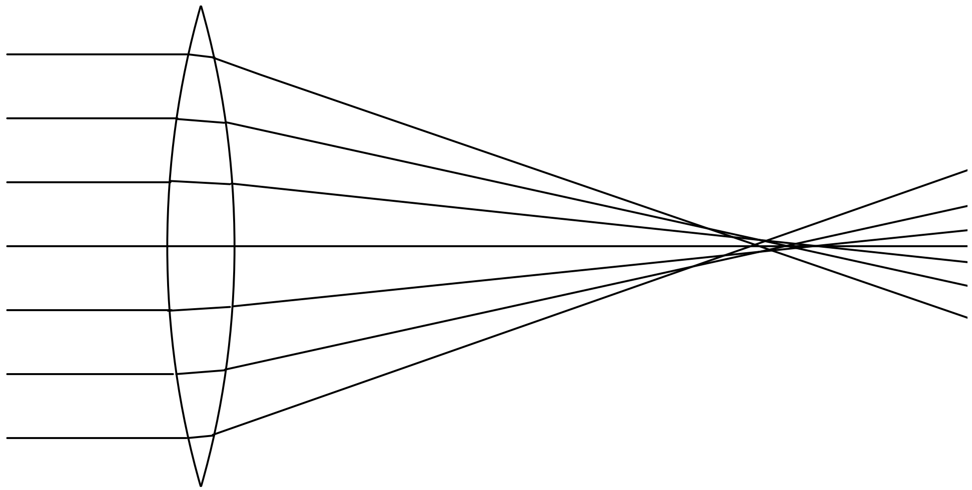
# High refractive index

- For a given focal length, lenses made from glass with a high refractive index are thinner and suffer less from spherical aberrations

*low refractive index*

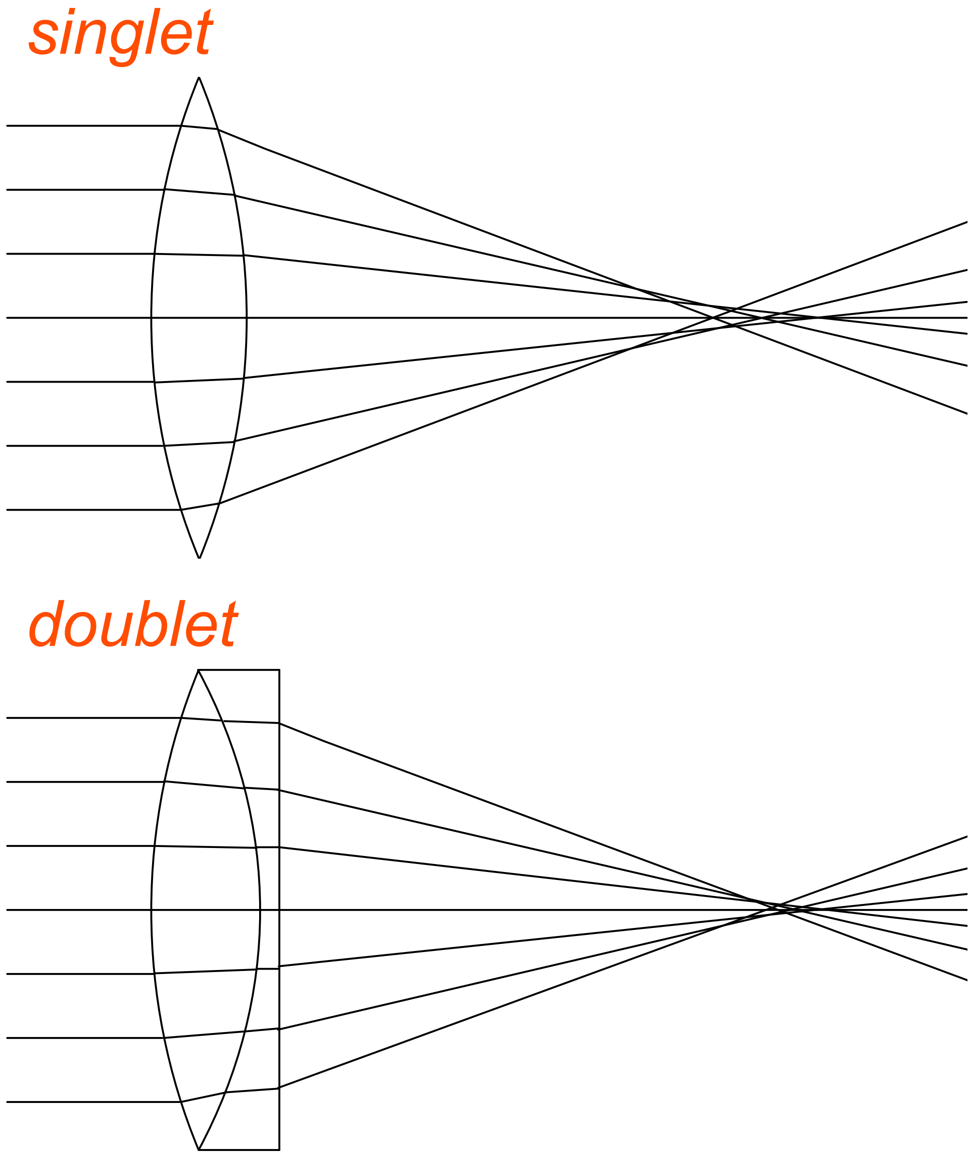


*high refractive index*



# Doublets

- Combining a convex lens with a weaker concave lens with a different refractive index can be designed to result in a converging system with reduced spherical aberrations
- The spherical aberration in the first lens is balanced by the opposite spherical aberration in the second.

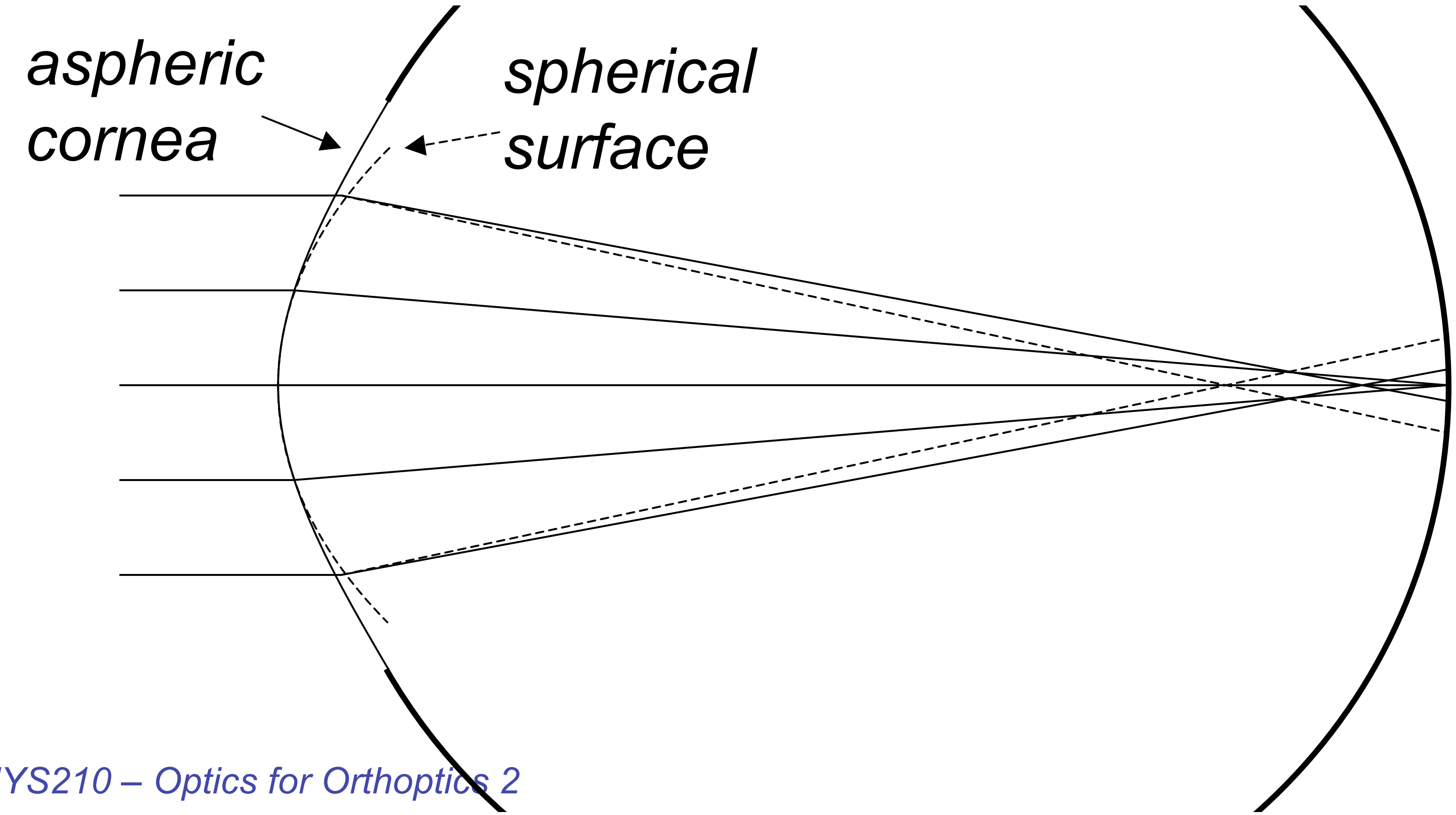


# Spherical aberrations in the eye

- Are reduced by several factors:
  - The cornea is aspheric
  - The lens has a graded index
  - The iris acts as an aperture stop
  - The retinal cones have directional sensitivity

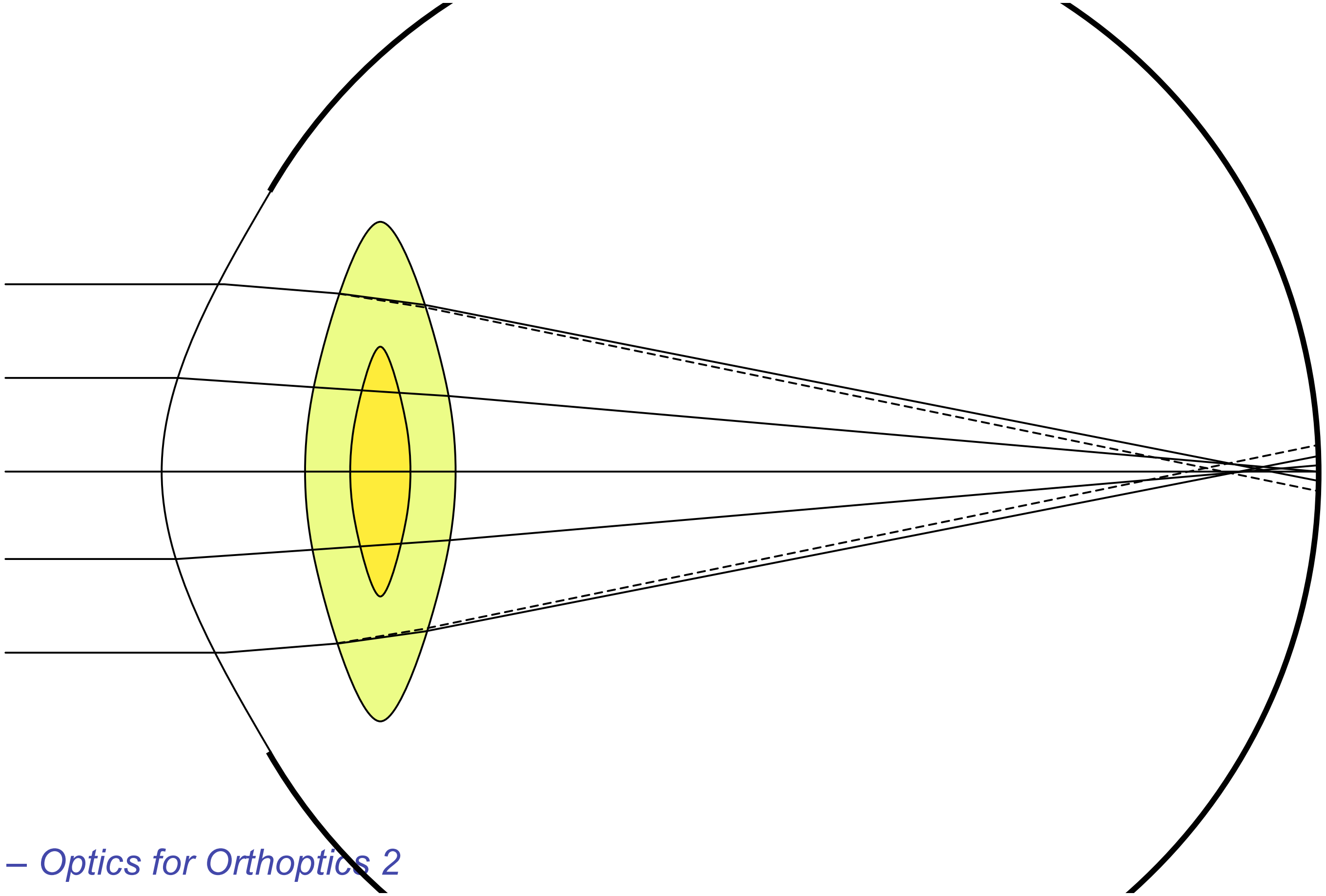
# Aspheric cornea

- Further from the optical axis, the curvature of the cornea decreases
- This reduces spherical aberrations in the same way as in aspheric lenses



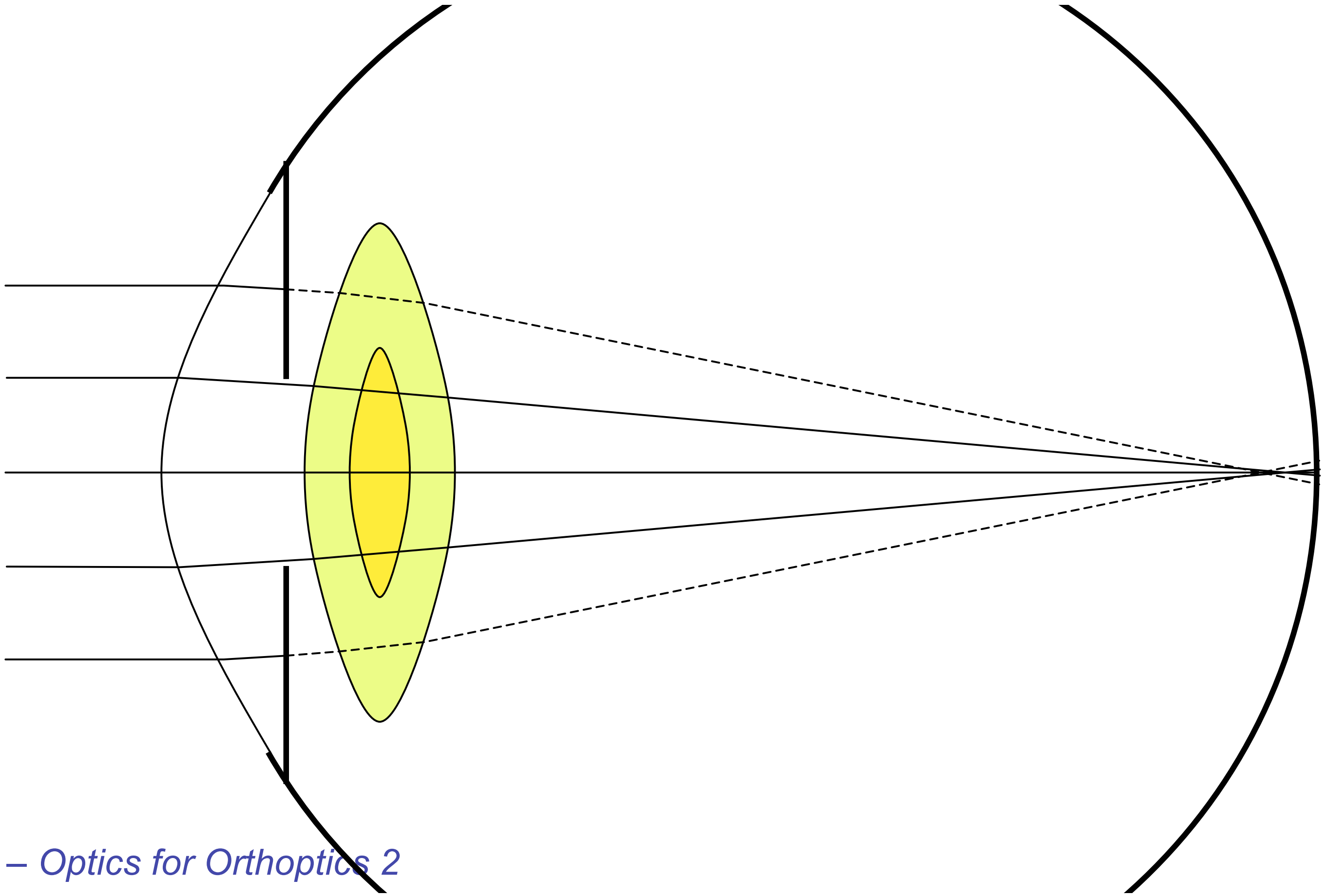
# Graded index lens

- The outer part of the lens has a lower refractive index than the centre
- This helps to reduce spherical aberrations



# The iris as an aperture stop

- The iris acts like an aperture stop
- It blocks light far from the principal axis



# Directional sensitivity of cones

- The cones are most sensitive to light that fall straight on them (paraxial rays).
- The cones are less sensitive to oblique rays that suffer more from spherical aberrations