OPTICS

Optics is the part of physics which deals with the propagation and wave properties of light.

Daniel Vlk
Department of Biophysics

Geometrical optics - basic terms

Geometric optics is based on **ray model of light**

Light is defined as transverse oscillations of an electromagnetic field which propagate in discrete quanta of energy which can be considered particles. These particles have zero rest mass, they are called photons.

We can distinguish between three "types" of light. These are:

Visible light (VIS). Its wavelength l ranges from 380 to 800 nm. This light can be detected by the retinal receptors of the human eye.

Ultraviolet light (UV). Its wavelength l is shorter than 380 nm. (Oscillations with wavelength shorter than about 10 nm are called X-rays; they are beyond the scope of classical optics, and will be discussed later).

Infrared light (IR). Its wavelength l is longer than 790 nm. This radiation is also called heat radiation or thermal radiation, because it is radiated by hot bodies. Oscillations with wavelength longer than about 1 mm are called microwaves.

Optical medium (basic statements):

Any medium in which a light can propagate is called an **optical medium**. In general, we can distinguish between media which are

transparent (we can see through them)

translucent (not transparent but light can propagate through them, e.g. the so-called frosted glass)

opaque (none-transparent – light cannot propagate through them).

The media in which optical properties are identical in all the directions, are called **optically homogeneous** and **isotropic media**.

In homogeneous media, light propagates in straight lines perpendicular to its wave fronts. These lines are called **light rays**.

The contact area between the two different optical media is called the optical **boundary (interface)**.

Reflection and refraction of light: Reflection

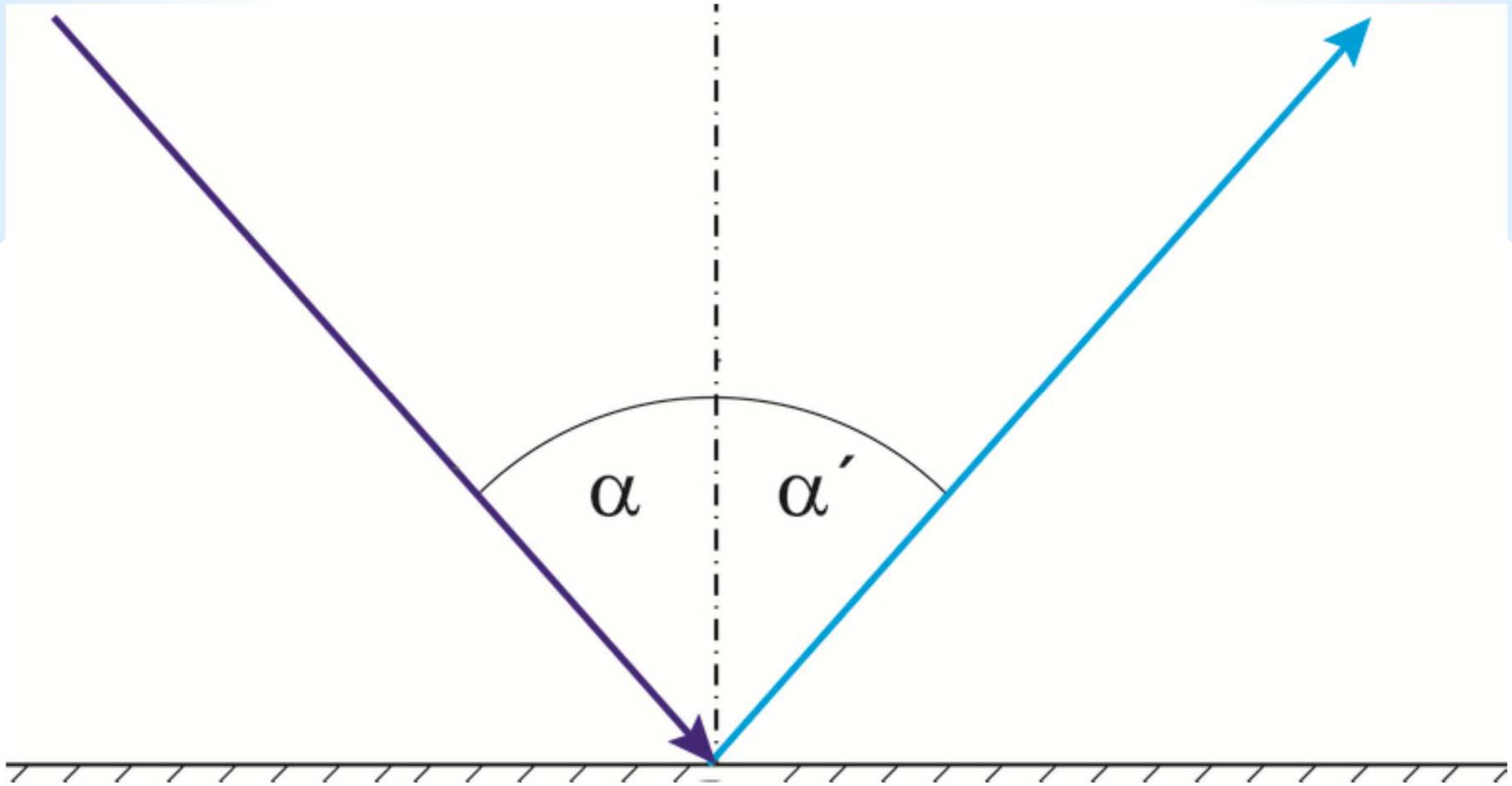
On an optical boundary, light rays aiming from medium "1" to medium "2" can be reflected or refracted. Reflected rays do not penetrate into the medium "2"; the refracted light rays do that.

Reflection:

The reflection of light is described by the **law of reflection**:

The angle of reflection α' equals the angle of incidence a. The reflected ray travels in the plane of incidence.

The plane of incidence is the plane containing the incident beam, and it is perpendicular to the optical boundary. Both angles have to be measured away from the line perpendicular to the boundary.


α
α´

Reflection and refraction of light; Refraction

The direction of a light ray changes when it passes through a boundary between two media. This property of optical media is characterised by the **index of refraction**:

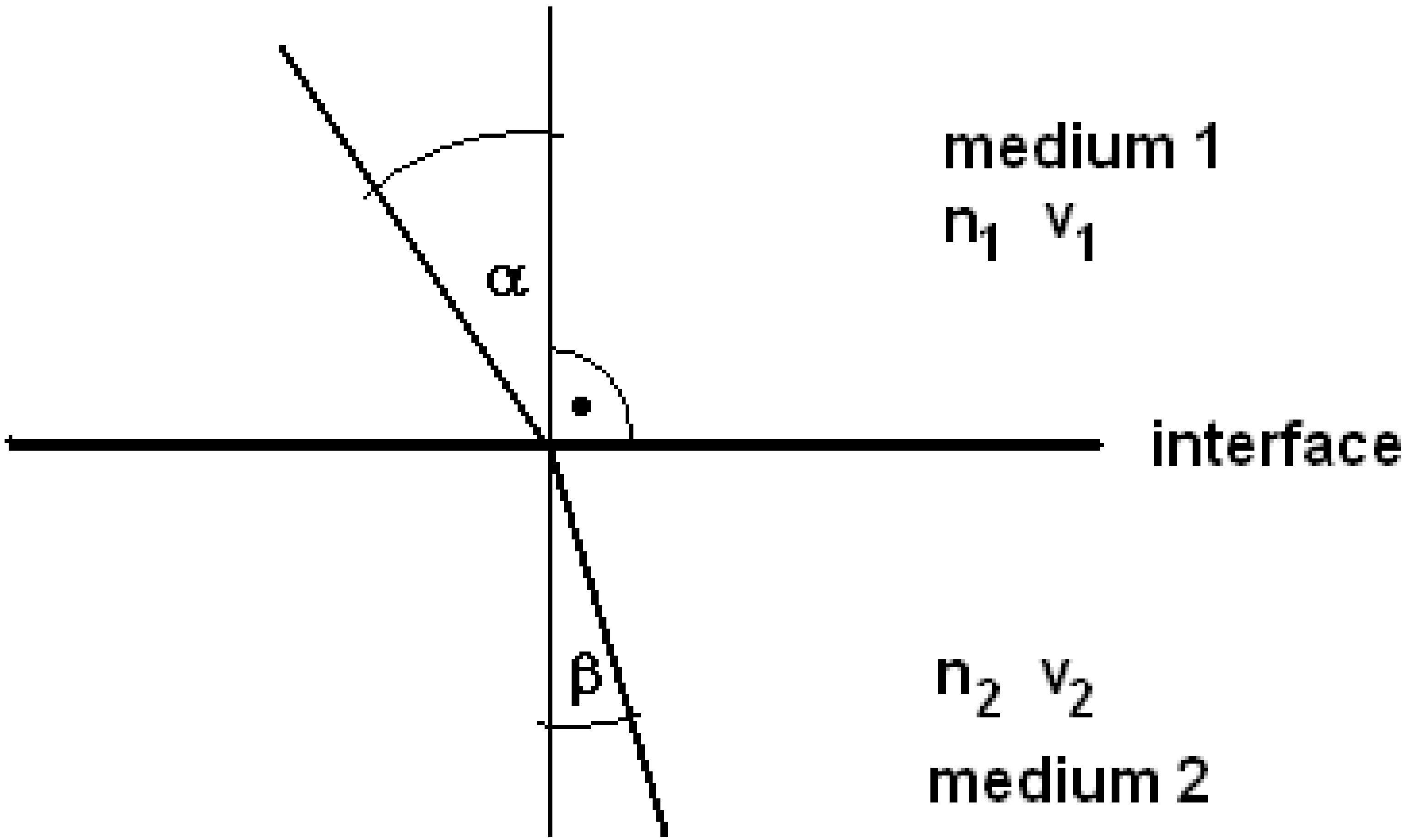
$$n = \frac{c}{v} \qquad \text{[dimensionless]}$$

where n is called the index of refraction of the respective medium, c is the speed of light in a vacuum, and v is the speed of light in respective medium. According to this formula, the index of refraction of a vacuum must be equal to 1.

If we have two optical media denoted as "1" and "2", the refraction of light is described by **Snell's law** (law of refraction)

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

where α is the angle of incidence (measured in medium "1"), β is the angle of refraction (measured in medium "2"), n_1 and n_2 are the indices of refraction, v_1 and v_2 are the speeds of light in the respective media. Both angles have to be measured away from the line perpendicular to the boundary.



For $n_1 < n_2$, the refraction is towards the line perpendicular to the boundary (a > b).
For $n_1 > n_2$, the refraction is away from the line perpendicular to the boundary (a < b).

Reflection and refraction of light; Refraction

Optical density:

We speak about a high optical density of an optical medium when its value of index of refraction is large. In the opposite case, we speak about low optical density.

Critical angle:

Consider a light beam which passes from the optical medium “1” to the medium “2”, with $n_1 > n_2$. The critical angle is the angle of incidence for which the angle of refraction is 90°.

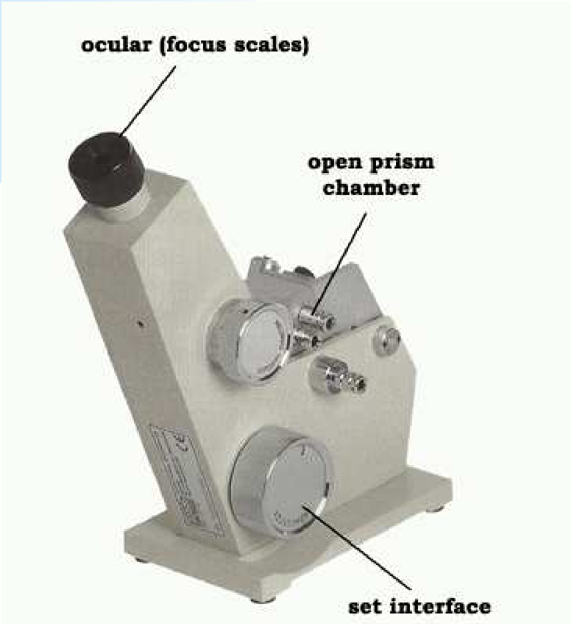
$$\frac{\sin\alpha}{\sin\beta} = \frac{\sin\alpha}{\sin 90^{\circ}} = \sin\alpha = \frac{n_2}{n_1}$$

Suppose the medium “2” is air for which $n \approx 1$.

Thus: $$\sin\alpha = \frac{1}{n_1}$$

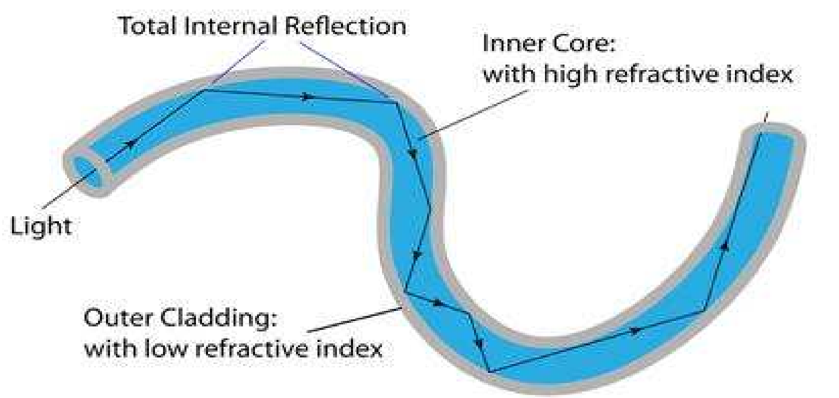
where α is the critical angle. The light travels similarly also in the opposite direction. It means that light rays coming from medium “2” to medium “1” with an angle of incidence almost equal to 90° are refracted at the critical angle.

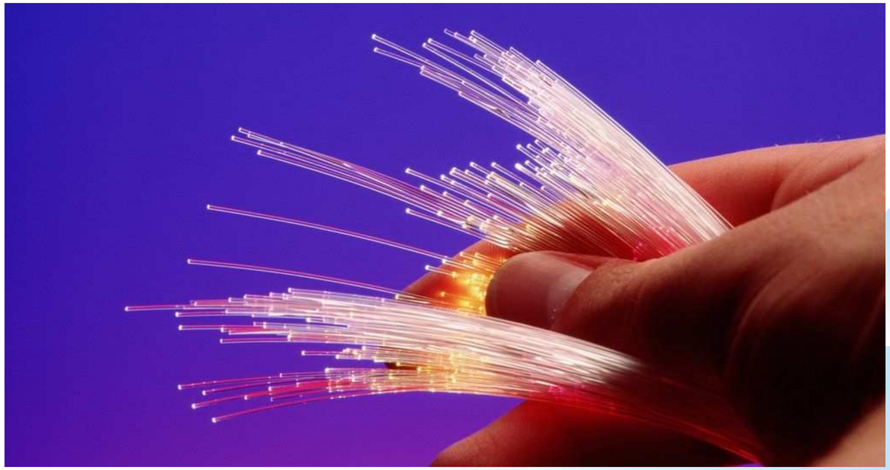
It is obvious that critical angle measurement (based on the previous sentence) can be used for the determination of the index of refraction, i.e. in **refractometry**.



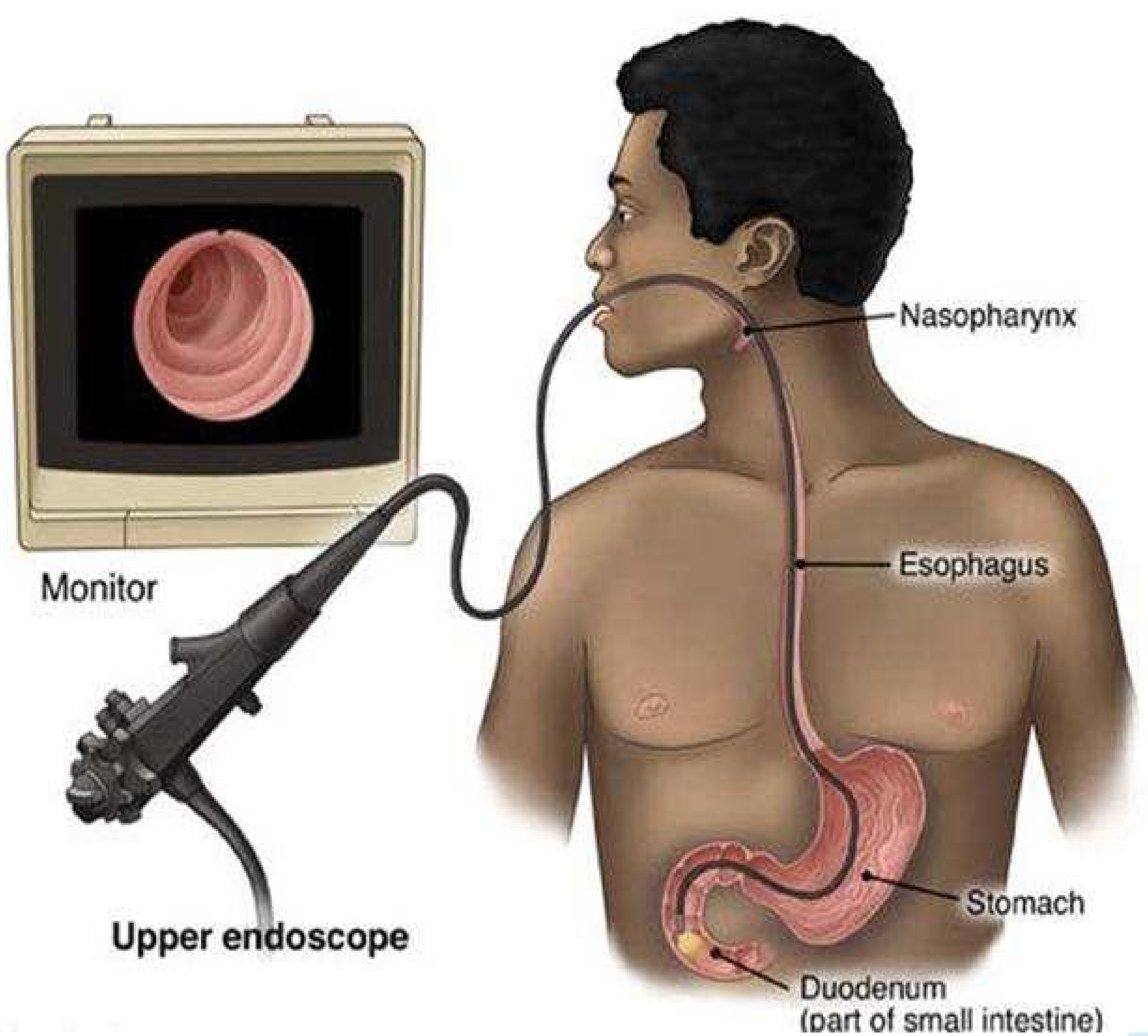
Total internal reflection:

The angle of incidence can be also greater than the critical angle. In this case, all the light rays are only reflected, and there is no refraction. This phenomenon is often used in optical instruments (totally reflecting prisms, optical fibres etc.).





Video Endoscopy



Dispersion of Light

Separation of white light into a spectrum of colors

The speed of light (index of refraction!) depends on the optical medium (see Eletromagnetic spectrum), but varies with the wavelenght of light too! (and slightly on temperature in gaseous medium). Result of this phenomenon represent dispersion through a prism, or…

Optical imaging by lenses and mirrors

Common principles of optical imaging:

Refracting optical boundaries can be used for image formation. A **real image** can be projected onto a screen; it is formed only by convergent light rays. A **virtual image** cannot be projected; it is formed by divergent rays.

Remember the following terms:

Principal axis – it is the axis of a centred system of optical boundaries (e.g. lenses, mirrors)

Principal focus – it is the point where rays parallel to the principal axis intersect (or seem to emerge from) after being refracted by a lens or reflected by the curved mirror.

The **focal distance** is the distance of the principal focus from the centre of the lens or the mirror.

The image formed by a **planar (flat) mirror** is always virtual ("can be seen only in the mirror"), erected ("standing"), of the same dimensions as the object, and symmetrical with the object (mirror is the plane of symmetry).

Optical imaging by lenses

Lenses:

In principle, lenses can be converging (with convex shape) and diverging (with concave shape). The relationship between the geometry of the lens (radii of their curvature), their index of refraction, and their focal distance is given by the **lens-maker's equation**:

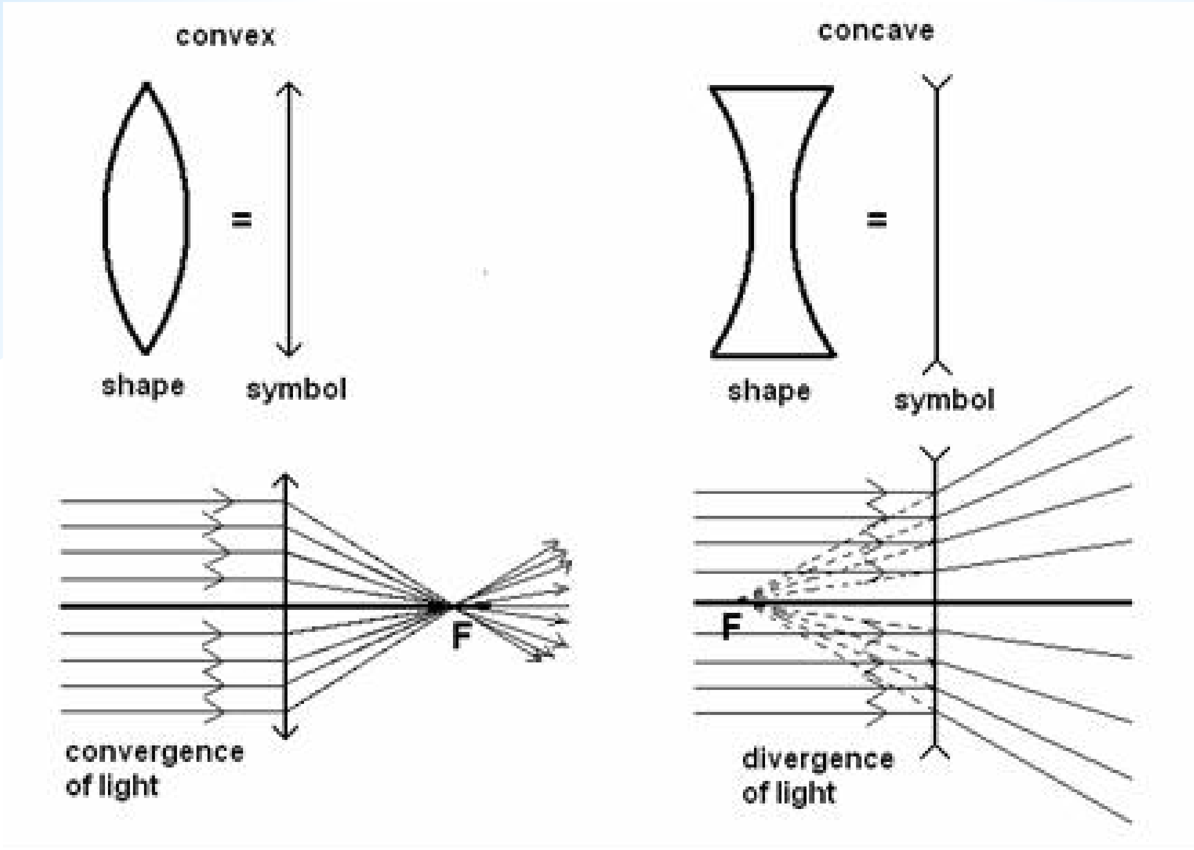
$$\frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right) \cdot \left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

where f is the focal distance [m] of the lens, n_2 is the index of refraction of the lens, n_1 is the index of refraction of the optical medium surrounding the lens, and r_1 and r_2 are the radii of curvature [m] of the lens.

The following internationally accepted **sign convention** must be used:

The radii of curvature are positive when the respective lens surfaces are convex.

The radii of curvature are negative when the respective lens surfaces are concave.



Converging and diverging lens – shapes, symbols and passage of light rays. In the converging lens, the rays coming in parallel to the principal axis are refracted *into* the focal point. In the diverging lens, such rays seem to come *from* the focal point.

Optical imaging by lenses

Dioptric power:

This quantity expresses the “strength of the lens”. It is defined as the reciprocal value of the focal distance:

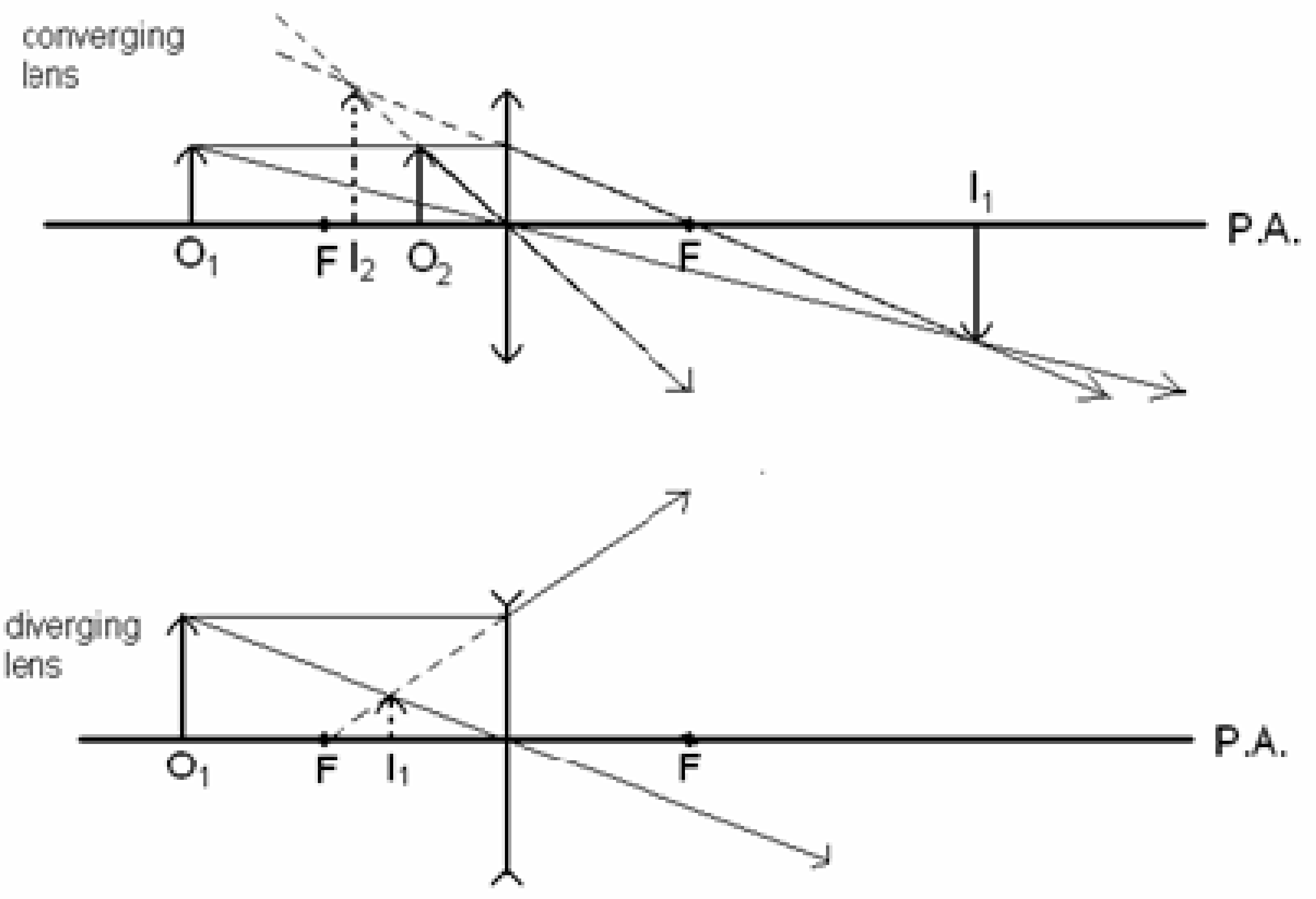
$\phi = \frac{1}{f}$ [m^{-1} = dpt = D (dioptre)]

There is also an internationally accepted **sign convention**: *The focal distance f and the dioptric power ϕ are positive in converging lenses. In diverging lenses, f and ϕ are negative*.

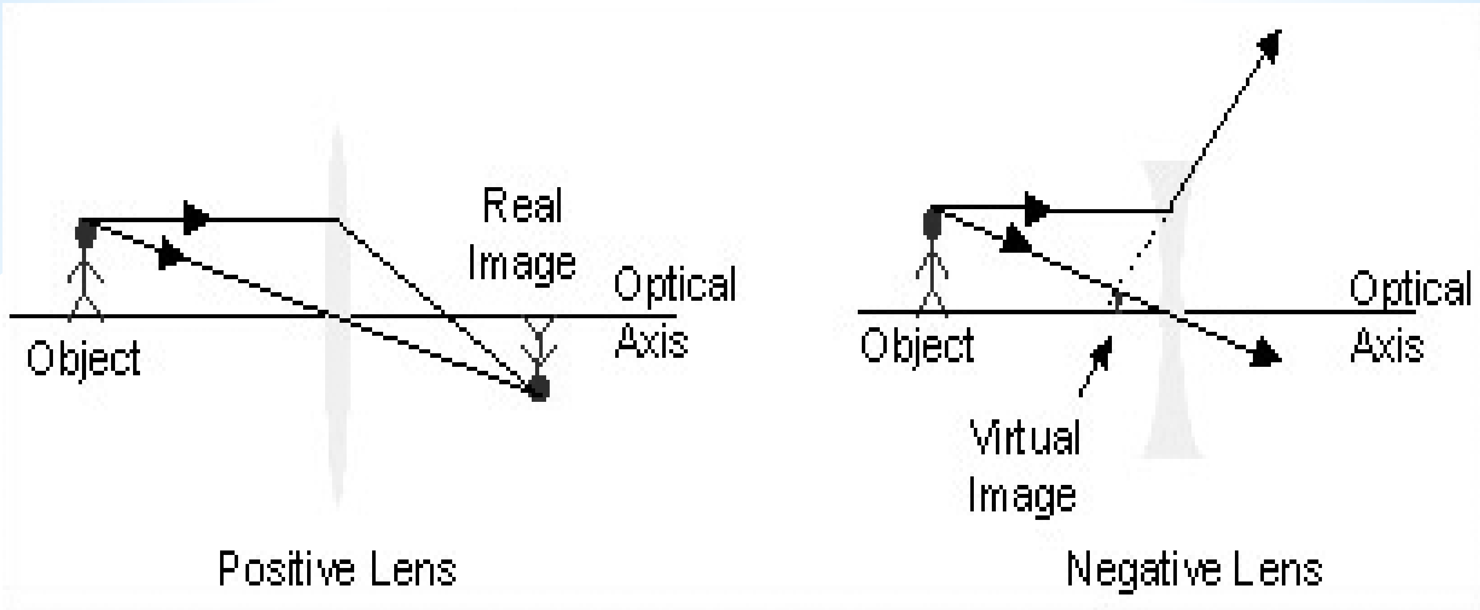
The total dioptric power of a series of lenses having the same principal axis is given by the sum of dioptric powers of individual thin and close lenses:

$$\frac{1}{f} = \phi = \frac{1}{f_1} + \frac{1}{f_2} + \ldots = \phi_1 + \phi_2 + \ldots$$

To understand the formation of an image by a spherical lens, it is necessary to know that the rays parallel to the principal axis are refracted into the back focus (in a converging lens), or that they seem to be emitted from the front focus (in a diverging lens). The direction of rays passing through the centre of the lens remains unchanged.



Schematic drawing of image formation by converging and diverging lenses. I – images, F – focal points, O – objects, P.A. – principal axis. Only the image I_1 is real.


Real
Image
Optical
Axis
Object
Positive Lens
Optical
Axis
Object
Virtual
Image
Negative Lens

Optical imaging by lenses

Some basic calculations can be done by means of the **lens equation**:

$$\frac{1}{a} + \frac{1}{a'} = \frac{1}{f}$$

where *a* is the object distance [m] from the centre of the lens, and *a'* is the image distance from the centre of the lens (object distance or image distance).

The following sign convention must be applied when using the lens equation for any calculations: *a is positive in front of the lens, negative behind the lens; a' is negative in front of the lens (the image is virtual and erected), and positive behind the lens (the image is real and inverted).*

Optical imaging by lenses

It is possible to derive some useful formulas which are often used for various calculations (see the Problems):

$$M = \frac{y'}{y} = -\frac{a'}{a} = -\frac{a' - f}{f} = -\frac{f}{a - f}$$

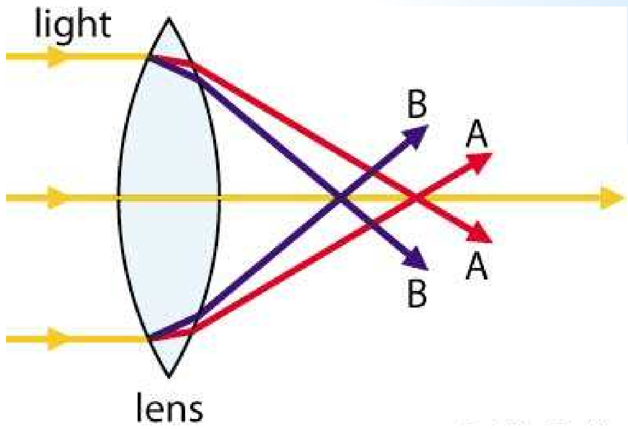
where M is the dimensionless quantity called linear (also transverse or lateral) magnification.

If $M > 0$ (a positive number) the image is erected.
If $M < 0$ (a negative number) the image is inverted.
If $M > |1|$ (M is greater than the absolute value of number 1) the image is magnified (greater).
If $M < |1|$ (M is smaller then the absolute value of number 1) the image is diminished (smaller).
y is the height of the object [m].
y' is the height of the image [m].

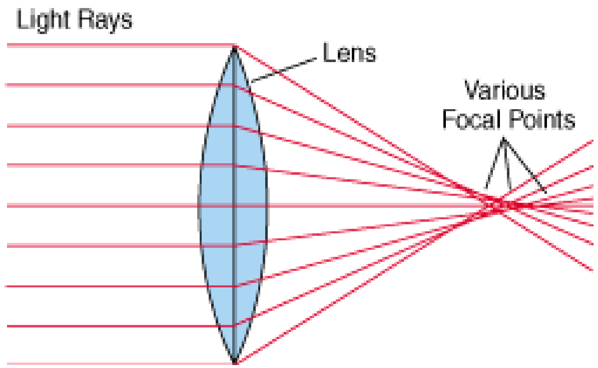
Optical imaging by lenses

Real lenses have some **aberrations**. We mention two important aberrations:

a) **Chromatic aberration** is caused by different values of refraction indices for light rays of different wavelength. i.e. different colours of light ($n_{red} < n_{yellow} < n_{violet}$). It means that the dioptric power of a lens depends on the colour of light. The rays of different colour are refracted to different foci.



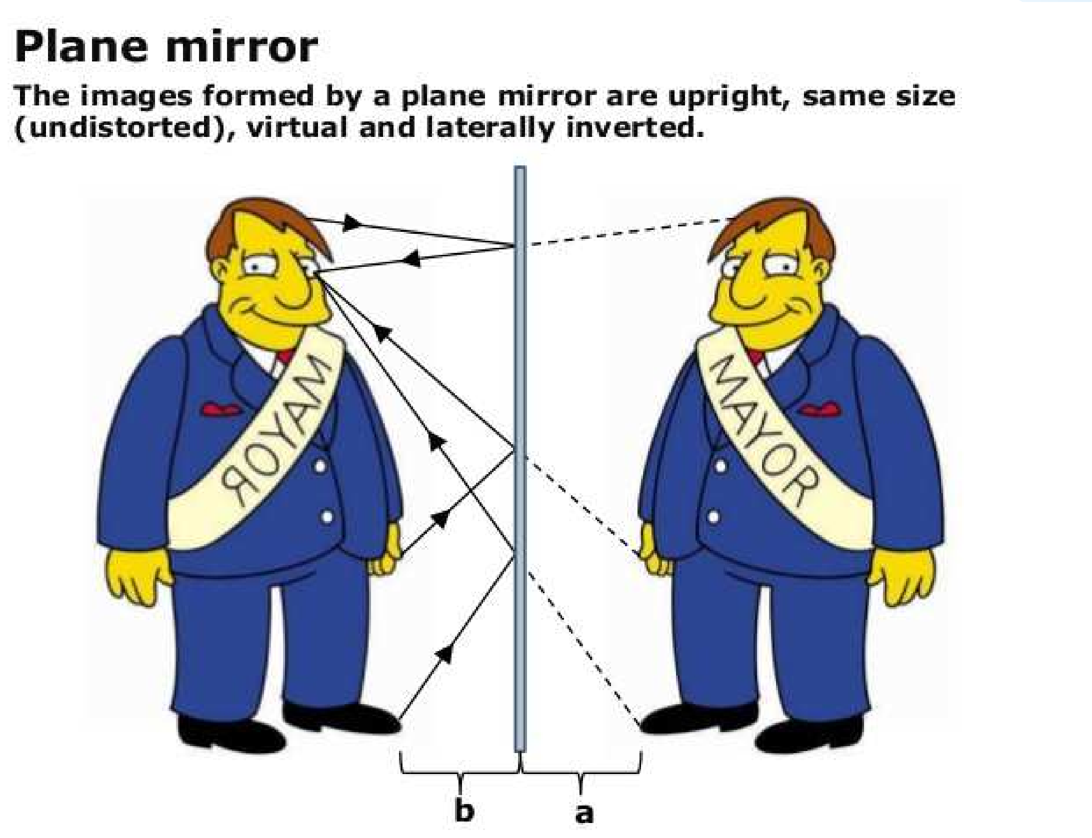
b) **Spherical aberration** is due to imperfectness of the spherical surfaces of lenses. The focus is not a single point; the rays intersect in a certain volume after being refracted. This aberration can be often observed in thick lenses.



Plane Mirrors

M = 1 no linear magnification

Front-to-back reversal image



Optical imaging by mirrors

We can distinguish between converging (i.e. concave) mirrors, and diverging (i.e. convex) mirrors.
The image equation for mirrors is very similar to that for lenses:

$$\frac{1}{a} + \frac{1}{a'} = \frac{1}{f} = \frac{2}{r}$$

where *a* is the object distance (distance of the object from the centre of the mirror, i.e. from the point at which the principal axis of the mirror intersects the mirror surface) [m], *a'* is the image distance (distance of the image from the centre of the mirror) [m], *r* is the radius of mirror curvature (note that the focus of a mirror lies in the middle between the centre of the mirror and the centre of the curvature, $r = 2f$).

The rays parallel to the principal axis are reflected into the focus (in concave mirrors), or in such a way that they seem to be emitted from the focus (in convex mirrors). The rays passing through the centre of curvature of the mirror fall perpendicularly onto the mirror surface, and they retrace their path after reflection.

Optical imaging by mirrors

Sign convention:

a, a', r, f are positive in front of the mirror, and negative behind the mirror,

$a' > 0$ – real image

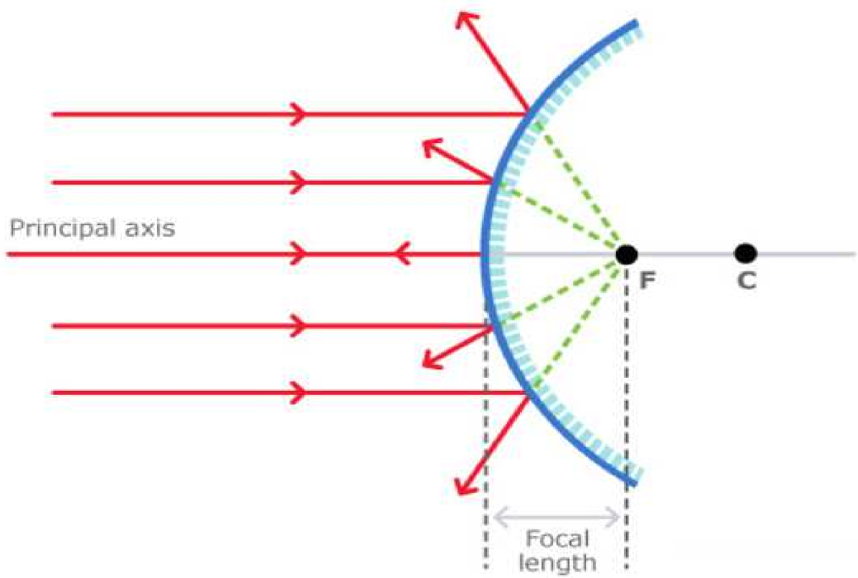
$a' < 0$ – virtual image

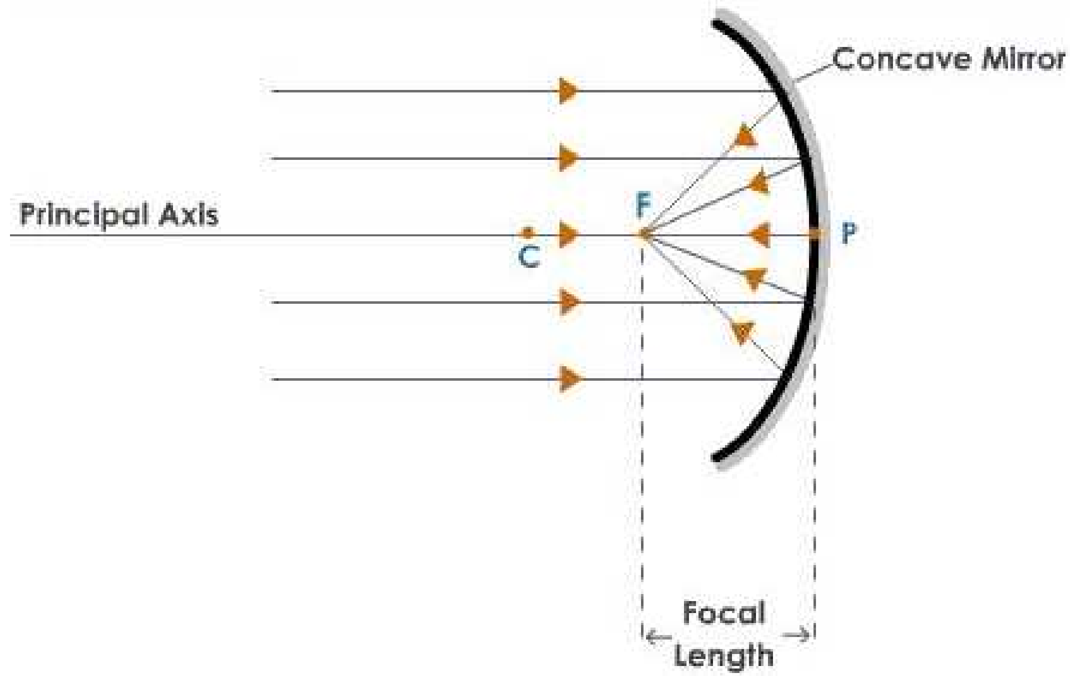
Useful formulas derived for mirrors are similar to that of lenses:

$$M = \frac{y'}{y} = -\frac{a'}{a} = -\frac{a' - f}{f} = -\frac{f}{a - f}$$

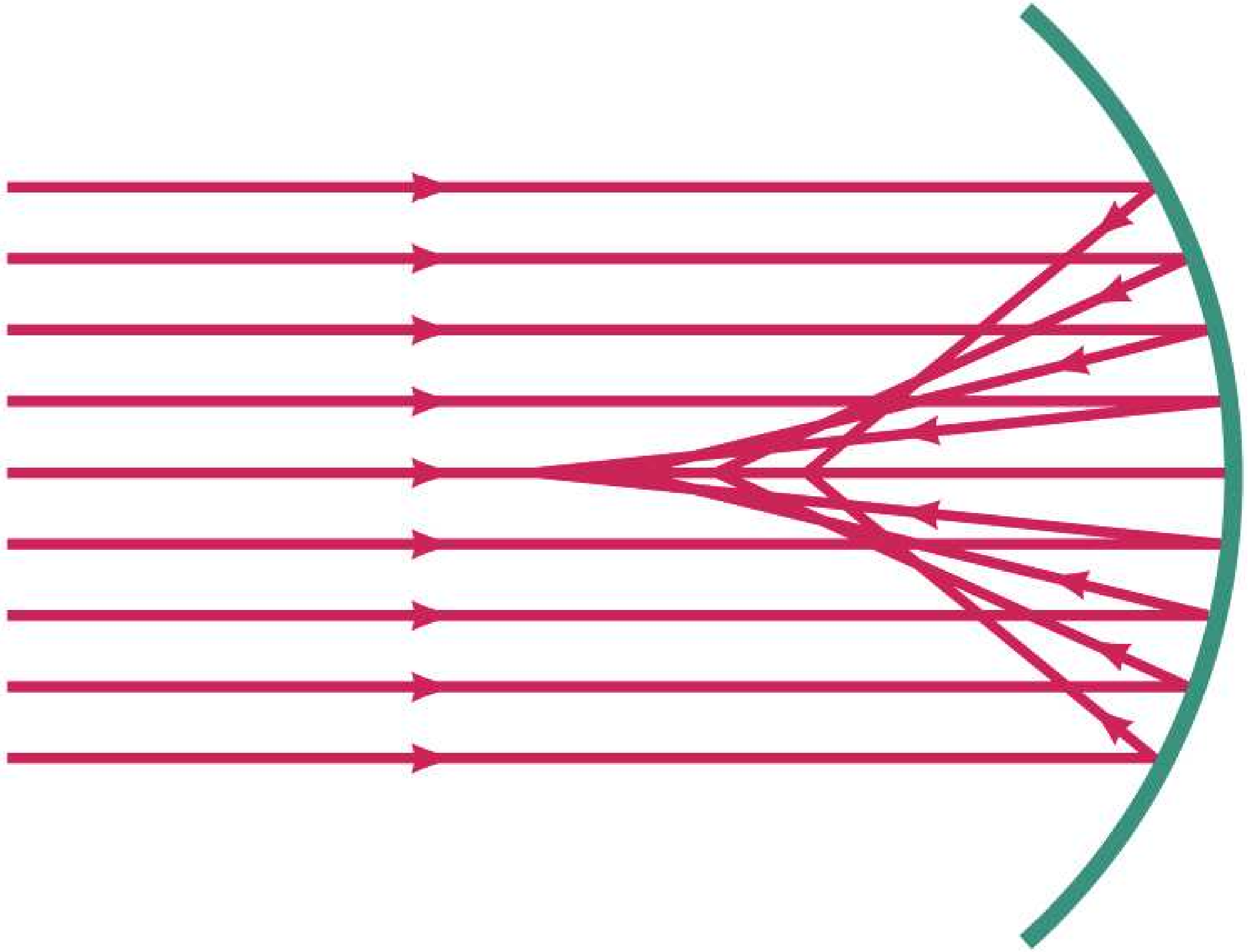
where *M* is linear (also transverse or lateral) magnification [dimensionless]. If $M > 0$ the image is erect. If $M < 0$ the image is inverted. If $M > |1|$ the image is magnified (greater), and if $M < |1|$ the image is diminished (smaller). *y* is the height of the object [m], and *y’* is the height of the image [m].

Reflection of light on convex mirror





Spherical Aberration Mirrors



Convex lens/concave mirror

$a > 2f$	$2f > a' > f$	reduced, inverted and real image
$a = 2f$	$a' = 2f$	same size, inverted, and real
$a = f$	$a' = \infty$	
$2f > a > f$	$a' > f$	enlarged, inverted, and real
$a < f$	$0 < \|a'\| < \infty$	enlarged, virtual

Concave lens/convex mirror

$\infty > a > 0$	$\|a'\| < \|f\|$	reduced, virtual