Lecture 7b: optics

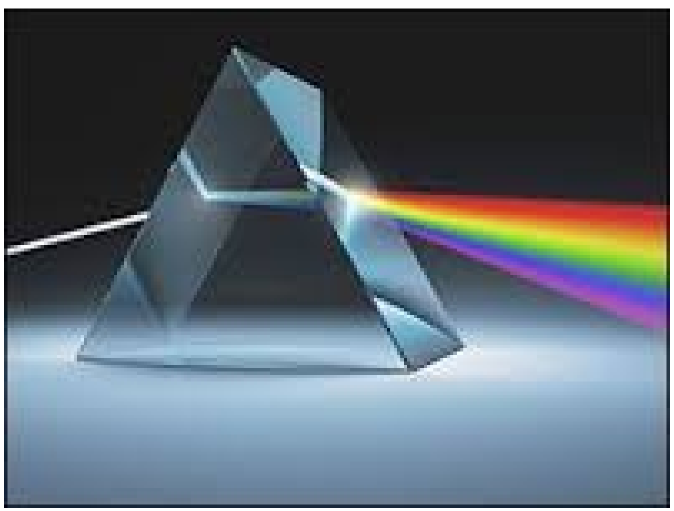
Content:

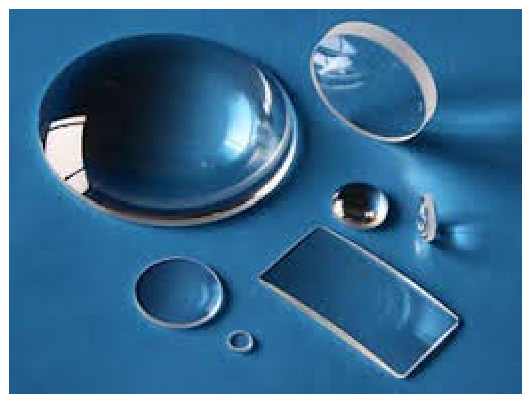
- introduction to optics
- geometrical optics, lenses, mirrors
- electron microscop, laser
- black body radiation

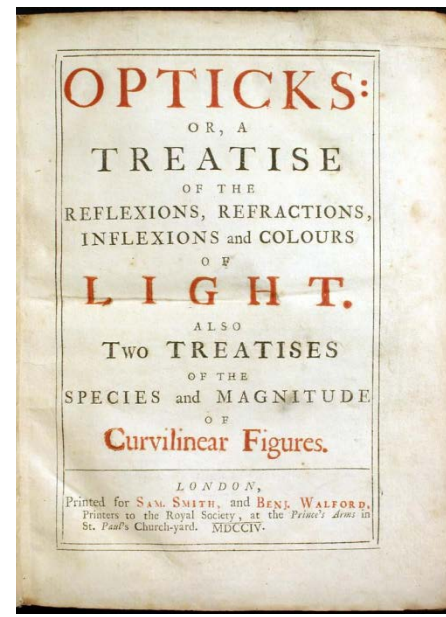
Optics

Optics is the branch of physics which involves the behaviour and properties of light, including its interactions with matter and the construction of instruments that use or detect it.

Optics usually describes the behaviour of visible, ultraviolet, and infrared light. Because light is an electromagnetic wave, other forms of electromagnetic radiation such as X-rays, microwaves, and radio waves exhibit similar properties.





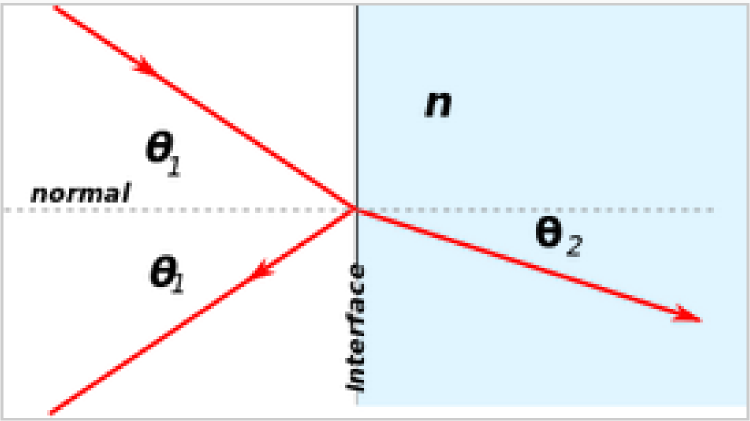


Cover of the first edition of Newton's Opticks.

Optics

Different directions in optics:
- geometrical optics,
- wave optics,
- electromagnetic optics,
- quantum optics.

Geometrical optics (ray optics) describes the propagation of light in terms of "rays" which travel in straight lines, and whose paths are governed by the laws of reflection and refraction at interfaces between different media.

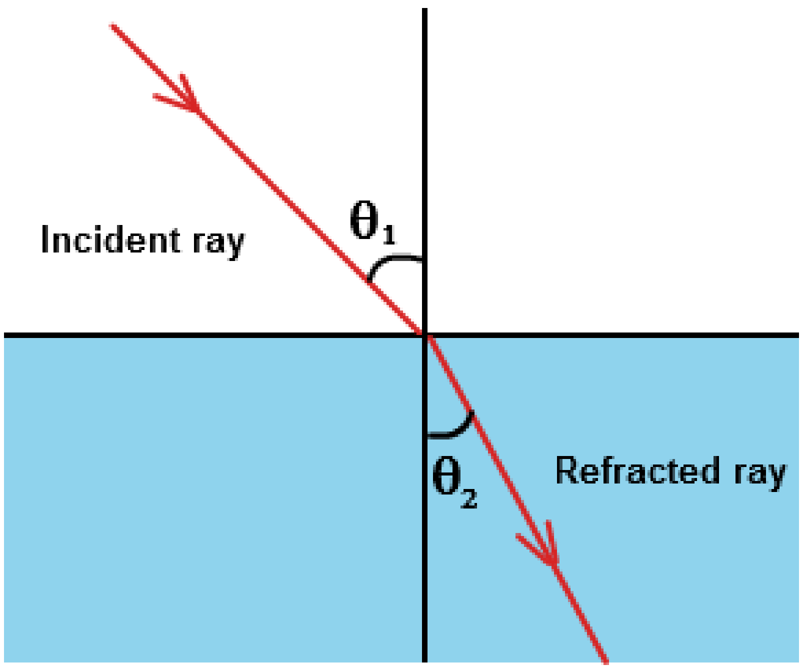


Geometry of reflection and refraction of light rays

Snell's law of refraction - repetition

Snell's law states that the ratio of the sines of the angle of incidence θ_1 and angle of refraction θ_2 is equivalent to the ratio of phase velocities (v_1/v_2) in the two media, or equivalently, to the opposite ratio of the indices of refraction (n_2/n_1):

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$



Index of refraction n of a material is a dimensionless number that describes how light propagates through that medium.
It is defined as:

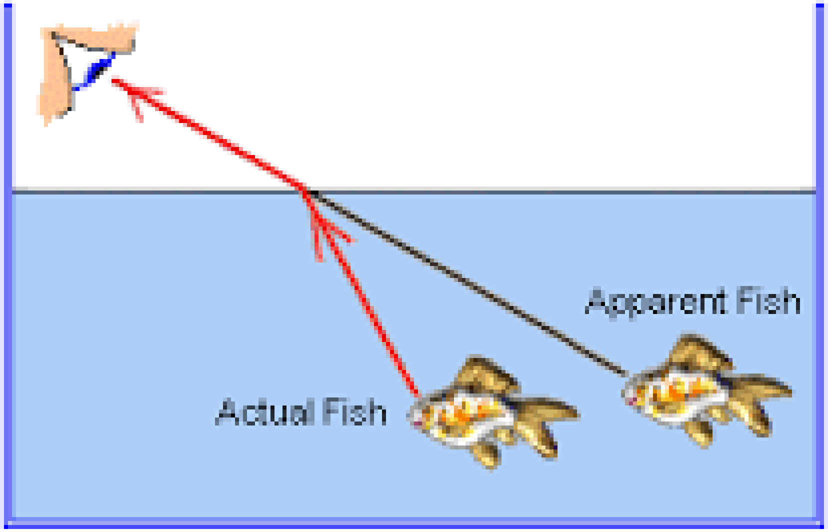
$$n = \frac{c}{v}$$

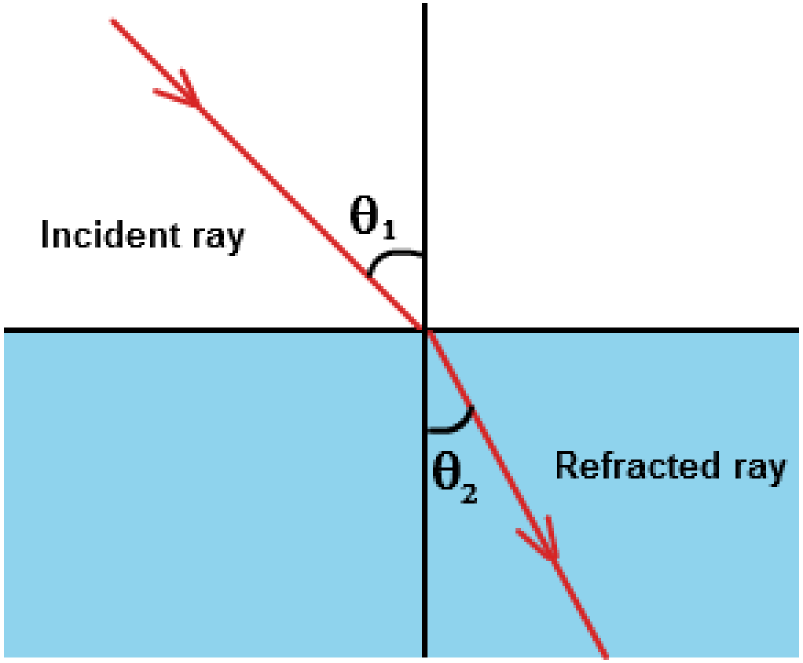
where c is the speed of light in vacuum and v is the phase velocity of light in the medium.

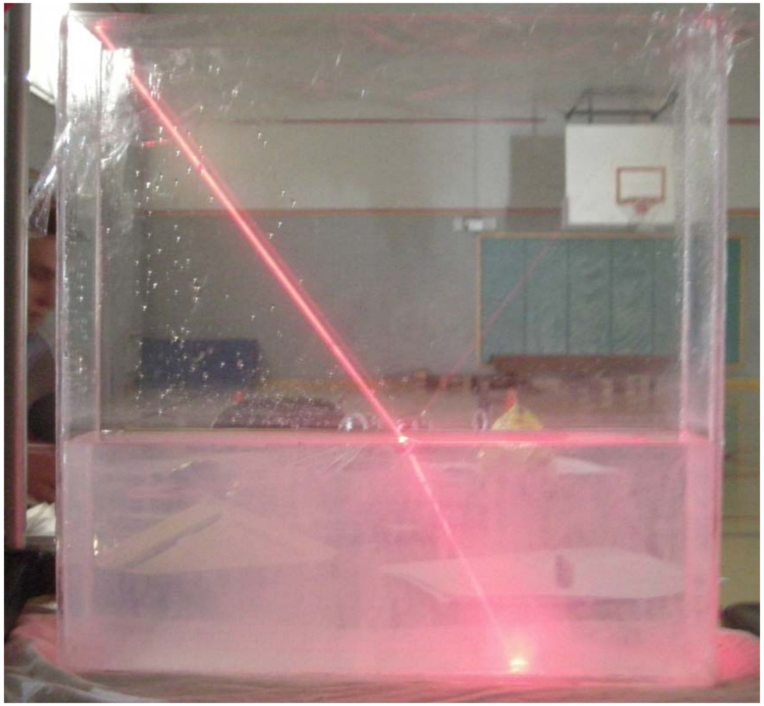
Repetition from lecture Nr. 7, slide Nr.25

Snell's law of refraction

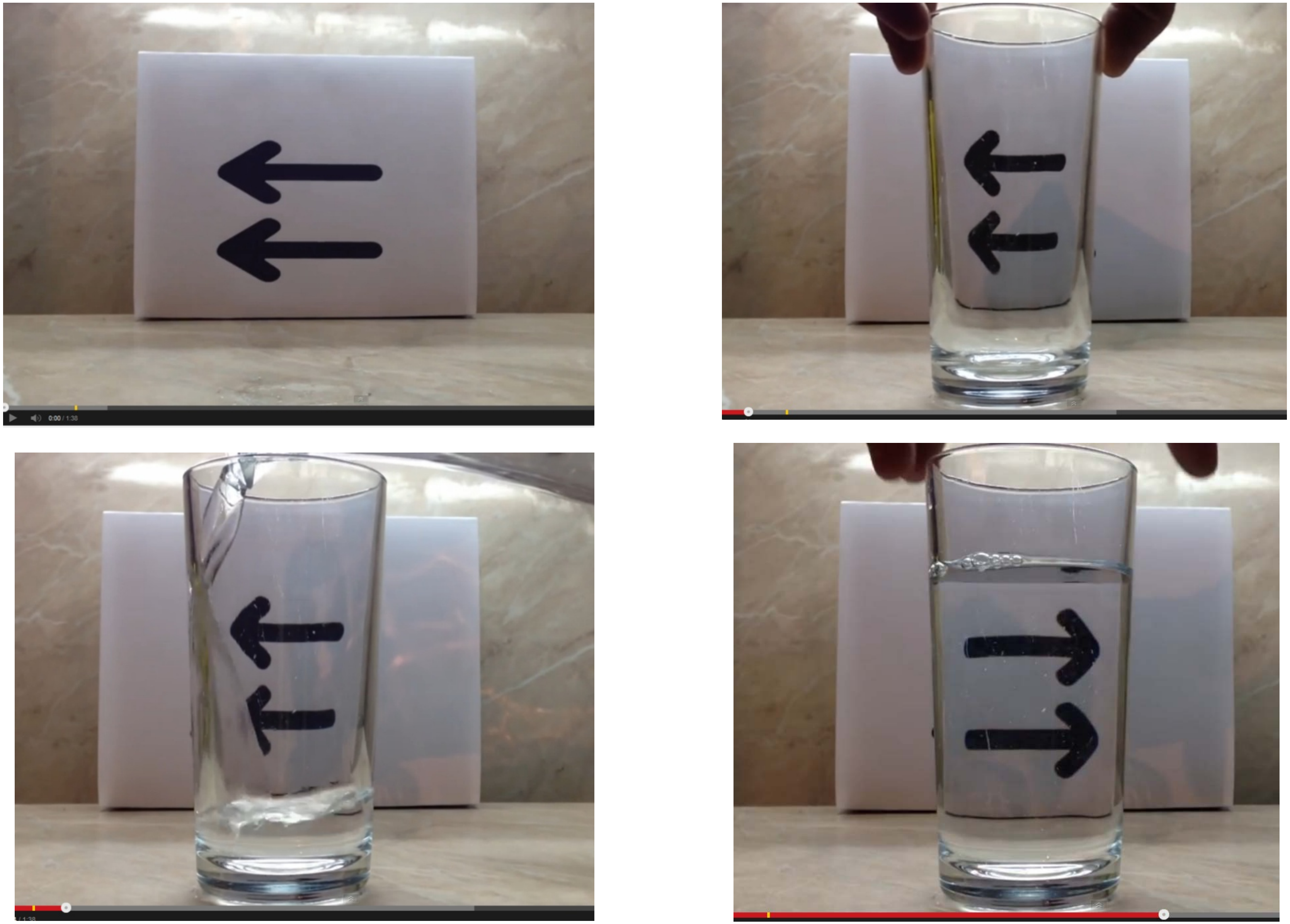
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$







Experiment with a glass of water: http://www.youtube.com/watch?v=G303o8pJzls



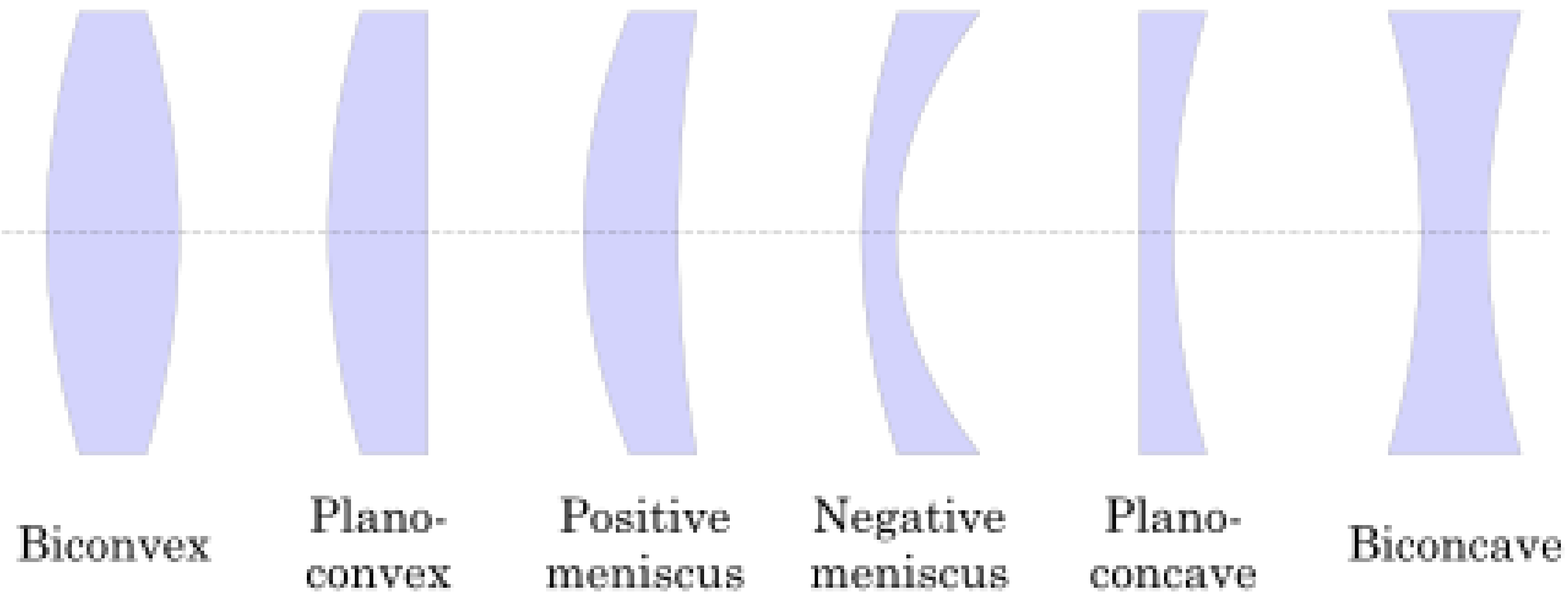
foundations of geometrical optics - lenses

A lens is a transmissive optical device that affects the focus of a light beam through refraction.

A lens can focus light to form an image, unlike a prism, which refracts light without focusing.

Devices that similarly refract radiation other than visible light are also called lenses, such as microwave lenses or acoustic lenses.

Lenses are classified by the curvature of the two optical surfaces:

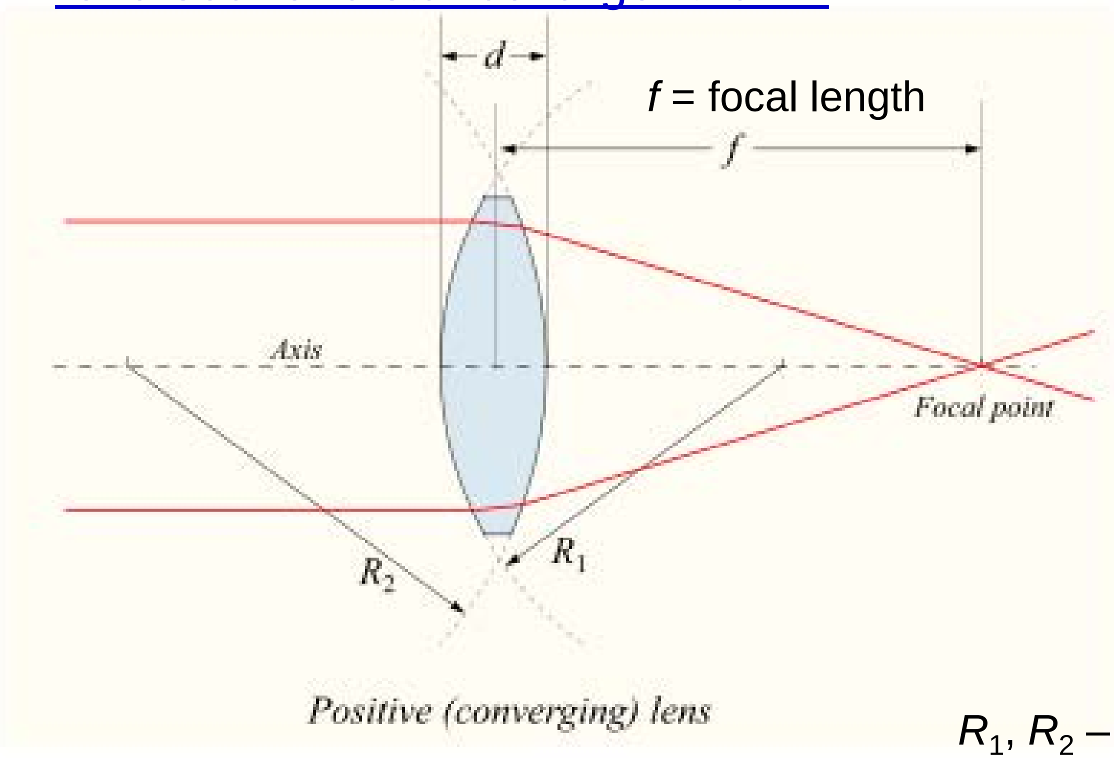


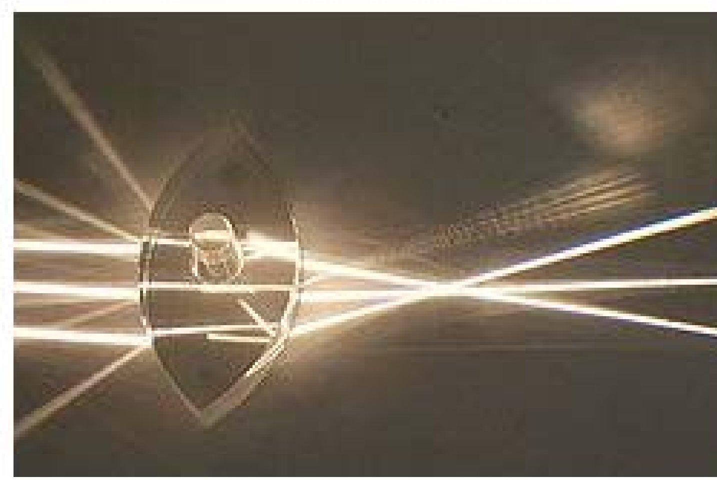
foundations of geometrical optics - lenses

Most important are biconvex (positive, converging) and biconcave (negative, diverging) lenses.

If the lens is biconvex or plano-convex, a collimated beam of light converges to a spot (a focus or focal point) behind the lens. The distance from the lens to the spot is the focal length of the lens (commonly abbreviated *f* in diagrams and equations).

Displayed image is reduced for distance smaller than f and reversed for distance larger than *f.*



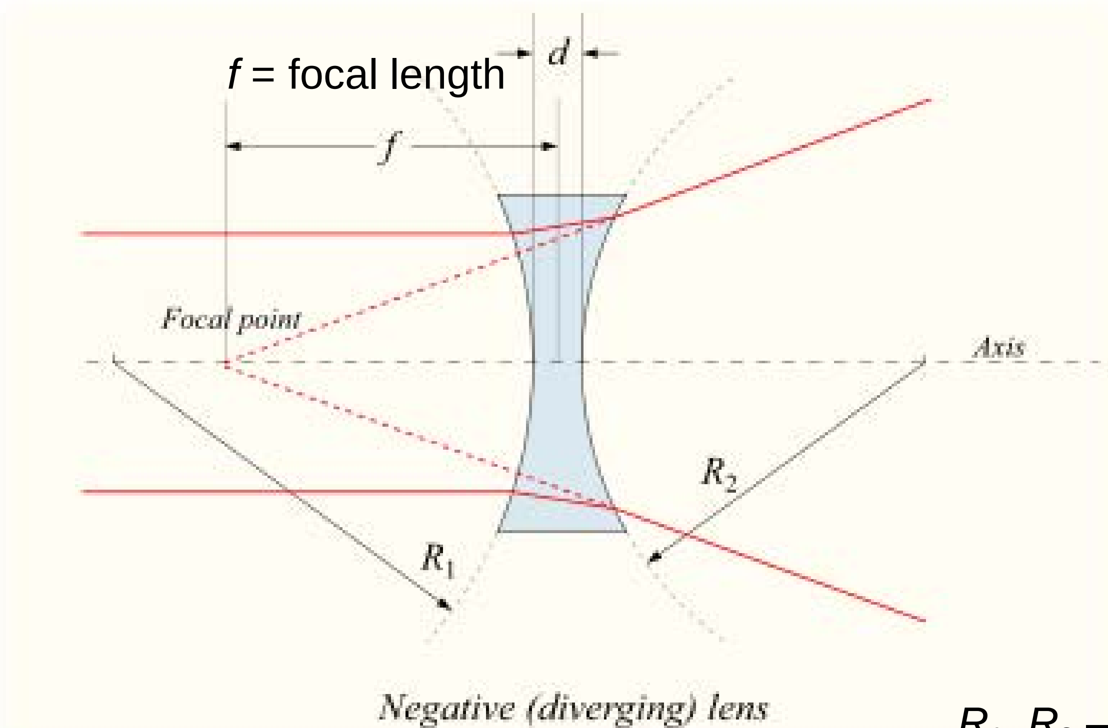


R_1, R_2 – curvature radii, *d* – thickness of the lens

foundations of geometrical optics - lenses

Most important are biconvex (positive, converging) and biconcave (negative, diverging) lenses.

If the lens is biconcave or plano-concave, a collimated beam of light passing through the lens is diverged (spread). The beam, after passing through the lens, appears to emanate from a particular point on the axis in front of the lens. The distance from this point to the lens is also known as the focal length, though it is negative with respect to the focal length of a converging lens.



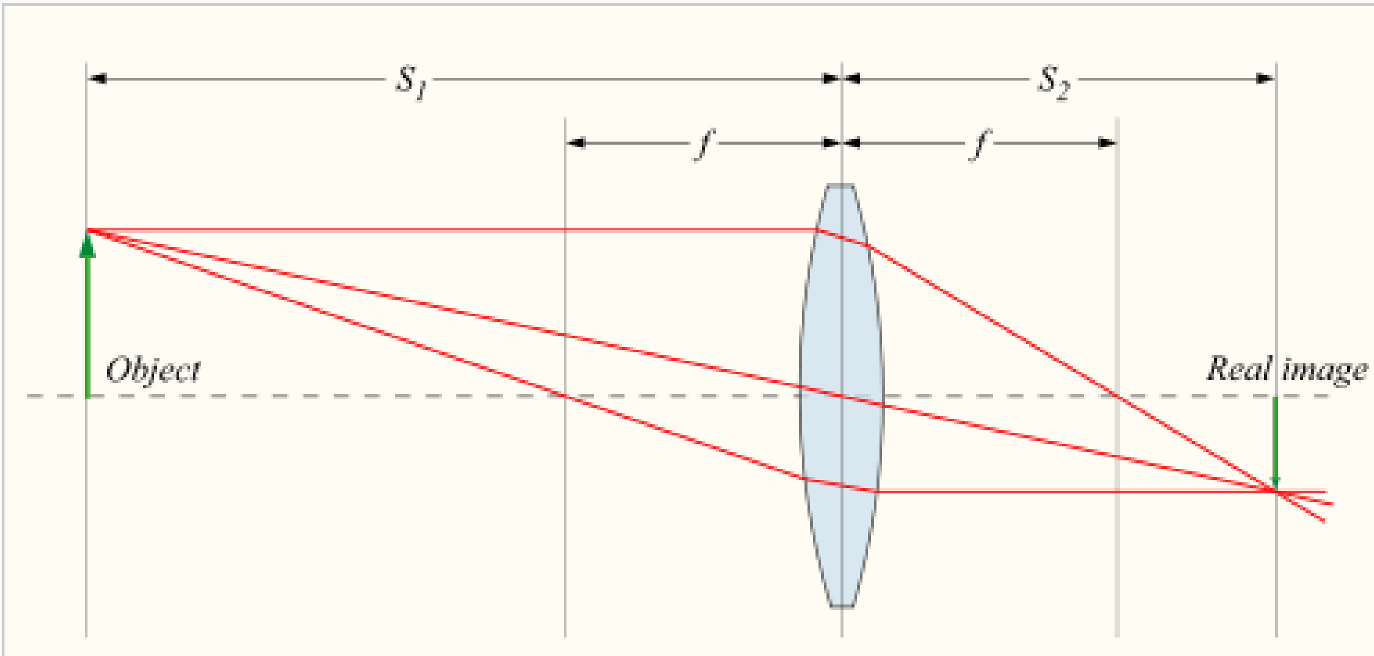
R_1, R_2 – curvature radii, d – thickness of the lens

foundations of geometrical optics - lenses

Thin lens formula: (d is small compared to R_1 and R_2)

If the distances from the object to the lens and from the lens to the image are S_1 and S_2 respectively, for a lens of negligible thickness, in air, the distances are related by the thin lens formula (f – focal length):

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}.$$



A camera lens forms a *real image* of a distant object.

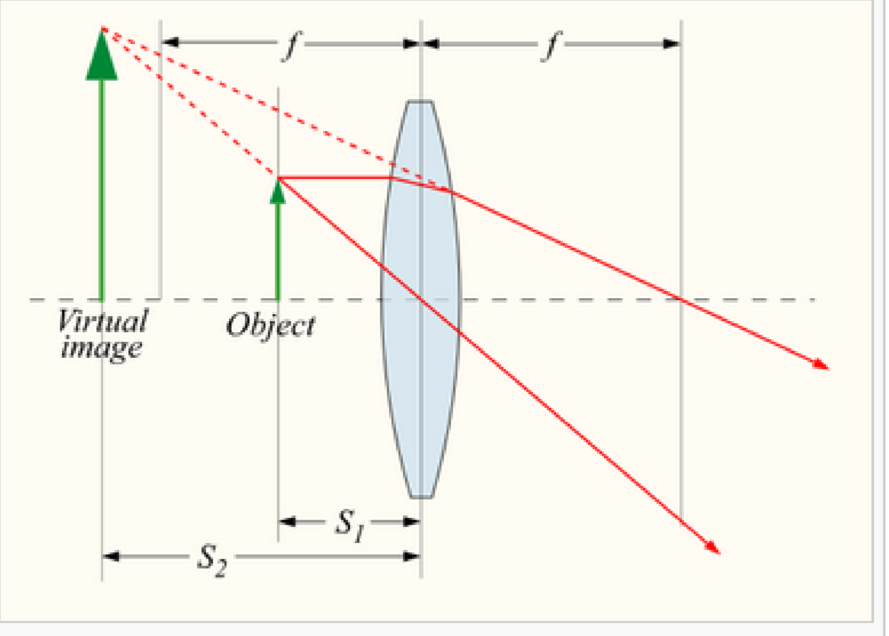
Therefore, if an object is placed at a distance $S_1 > f$ from a positive lens of focal length f, we will find an image distance S_2 according to this formula. Such image is called **real image**.

This is the principle of the camera, and of the human eye.

foundations of geometrical optics - lenses

Thin lens formula: (d is small compared to R_1 and R_2)

In some cases (distance $S_1 < f$) resulting S_2 is negative, indicating that the image is formed on the opposite side of the lens from where those rays are being considered. Since the diverging light rays emanating from the lens never come into focus, and those rays are not physically present at the point where they appear to form an image, this is called a virtual image.



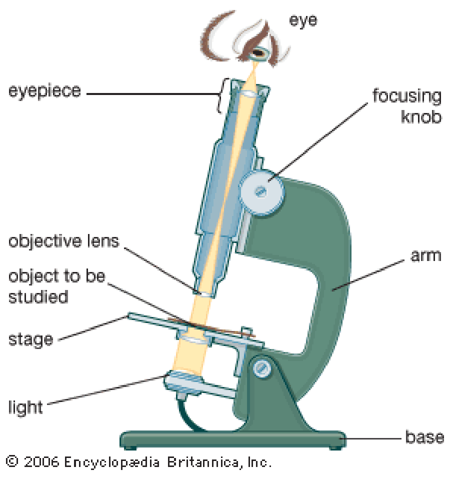
Virtual image formation using a positive lens as a magnifying glass.

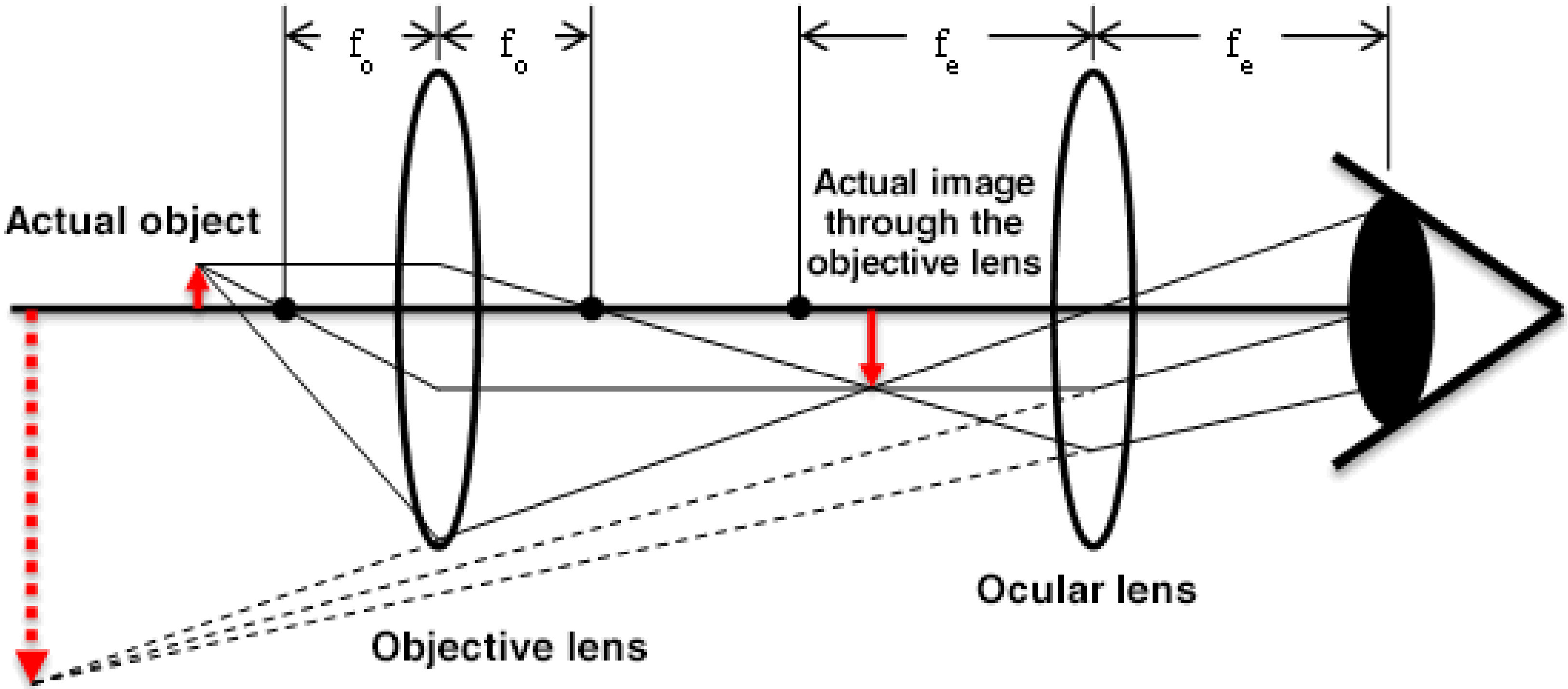
This is exactly what we can see when looking through a magnifying glass (and finaly – this effect is used in an optical microscope).

foundations of geometrical optics - lenses

Optical (light) microscope:

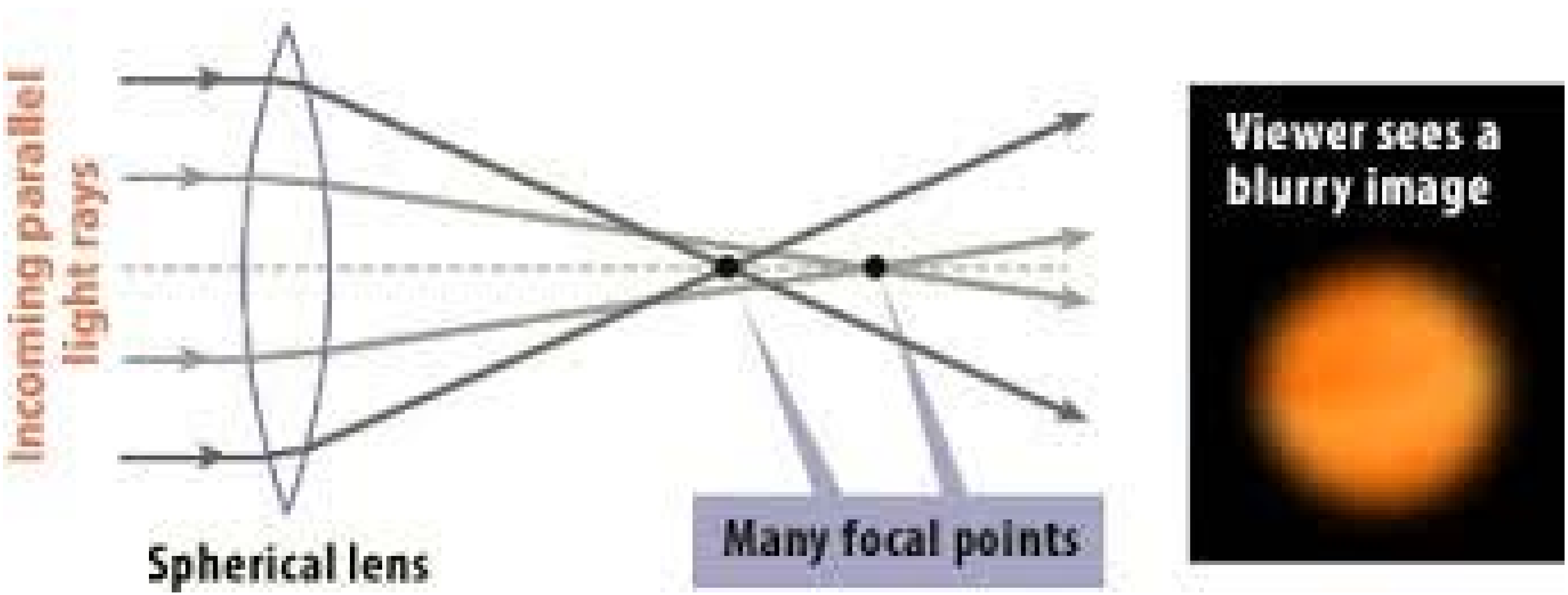
Uses visible light and a system of lenses to magnify images of small samples.



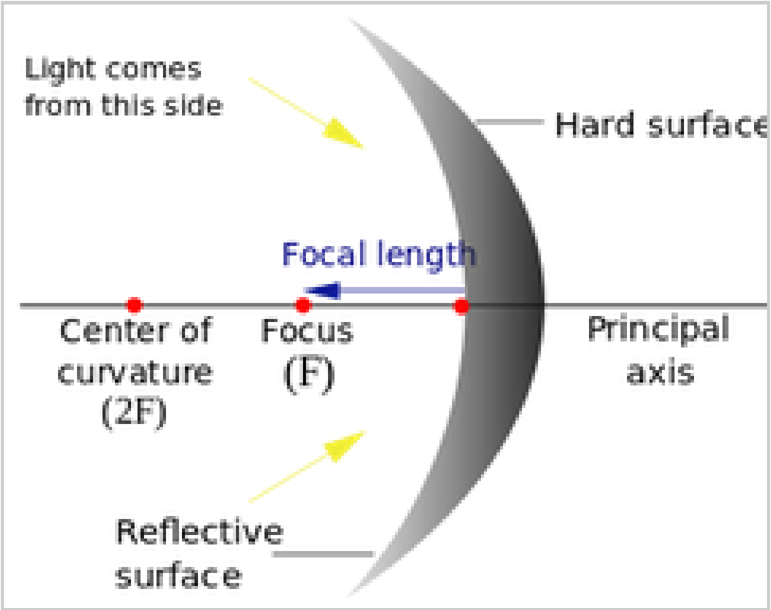


foundations of geometrical optics - lenses

Spherical aberration occurs because spherical surfaces are not the ideal shape for a lens.
Spherical aberration causes beams parallel to, but distant from, the lens axis to be focused in a slightly different place than beams close to the axis (like there would exist several focal points).
This manifests itself as a blurring of the image.

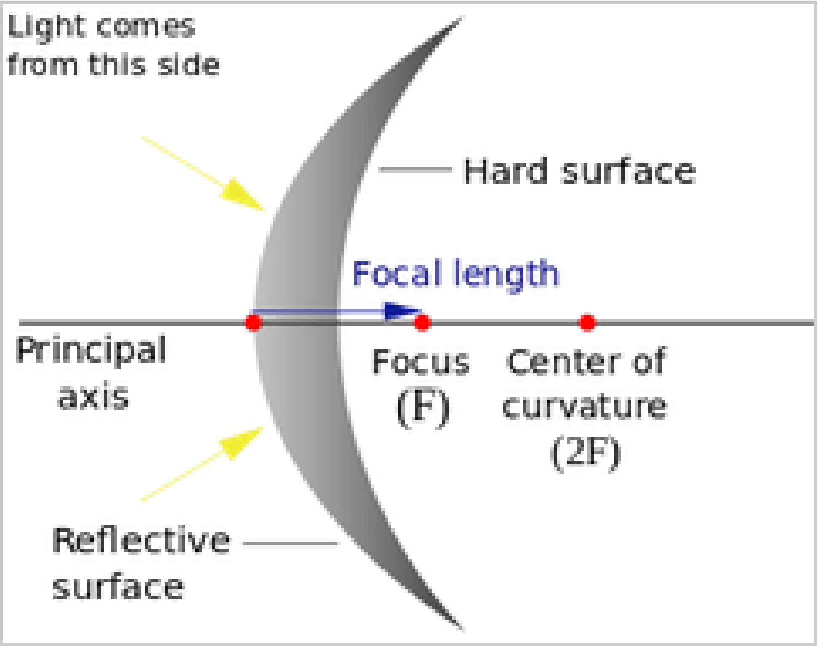


foundations of geometrical optics – mirrors (concave and convex)



A concave mirror diagram showing the focus, focal length, centre of curvature, principal axis, etc.

converging light



A convex mirror diagram showing the focus, focal length, centre of curvature, principal axis, etc.

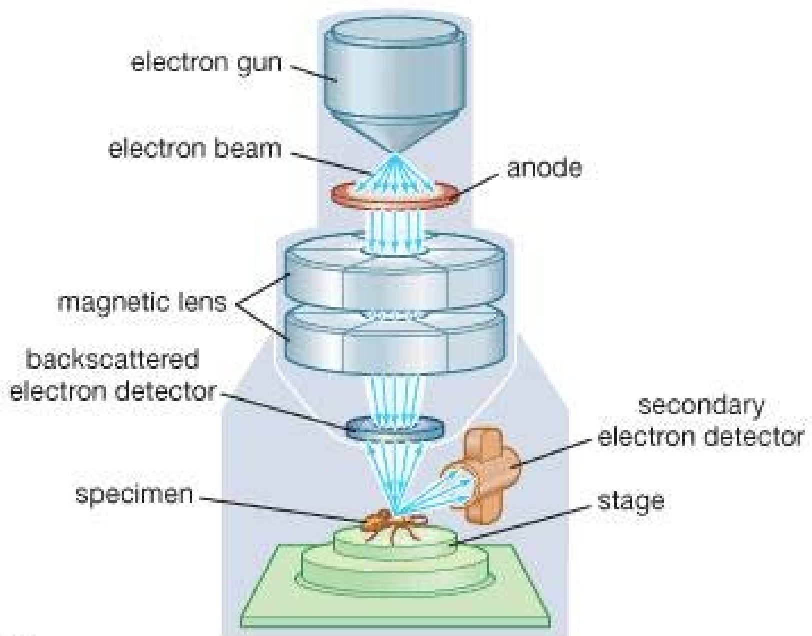
diverging light

Electron microscope:

An electron microscope is a microscope that uses a beam of accelerated electrons as a source of illumination. Because the wavelength of an electron can be up to 100,000 times shorter than that of visible light photons, the electron microscope has a higher resolving power than a light microscope and can reveal the structure of smaller objects.

A transmission electron microscope (TEM) can achieve better than 50 pm resolution and magnifications of up to about 10,000,000x

whereas most optical microscopes are limited by diffraction to about 200 nm resolution and useful magnifications below 2000x.



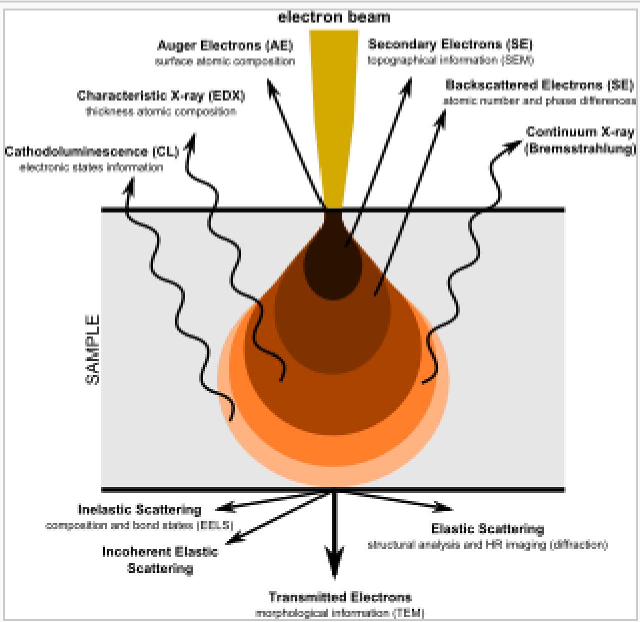
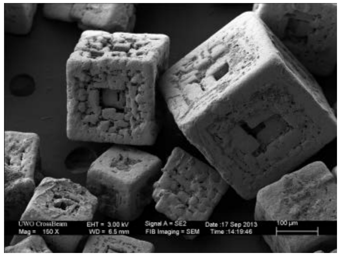
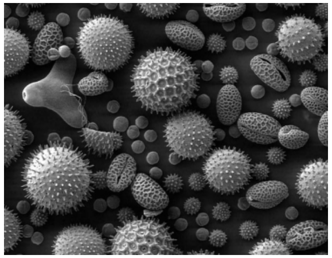


Diagram illustrating the phenomena resulting of the interaction of highly energetic electrons with matter.





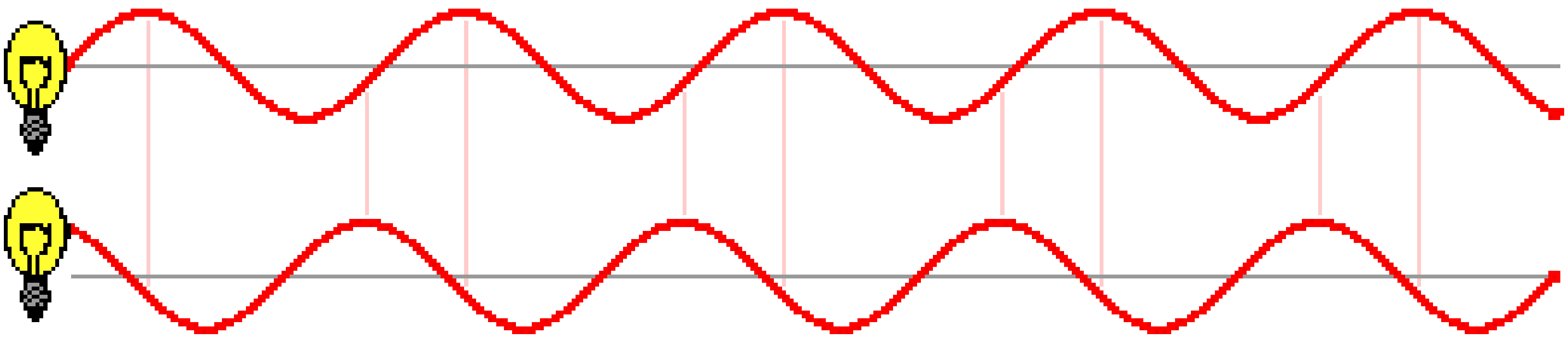
Laser

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.

The term "laser" originated as an acronym for "Light Amplification by Stimulated Emission of Radiation".

The first laser was built in 1960 by T.H. Maiman at Hughes Research Laboratories, based on theoretical work by C.H. Townes and A.L. Schawlow.

A laser differs from other sources of light in that it emits light coherently (coherent wave sources have a constant phase difference).

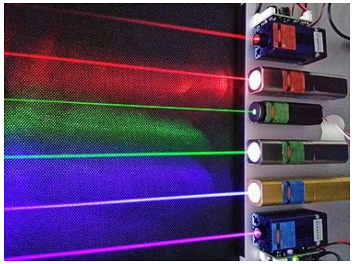


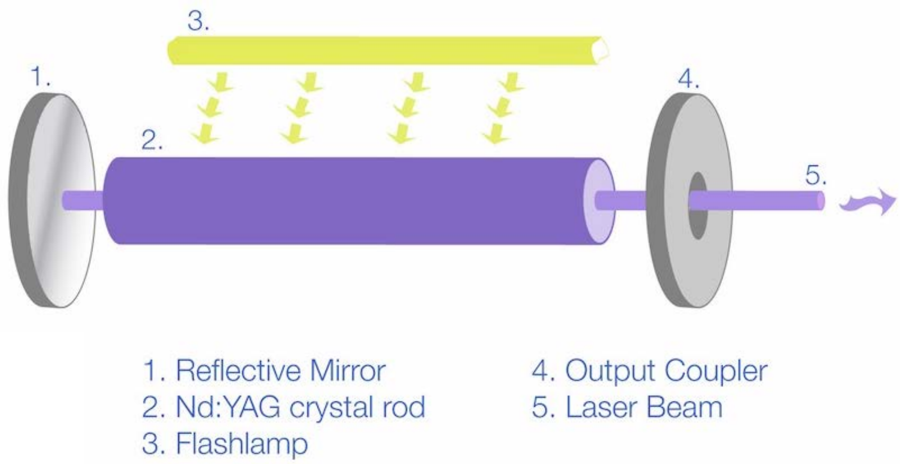
These two waves are coherent - they have a phase difference which is constant over time.

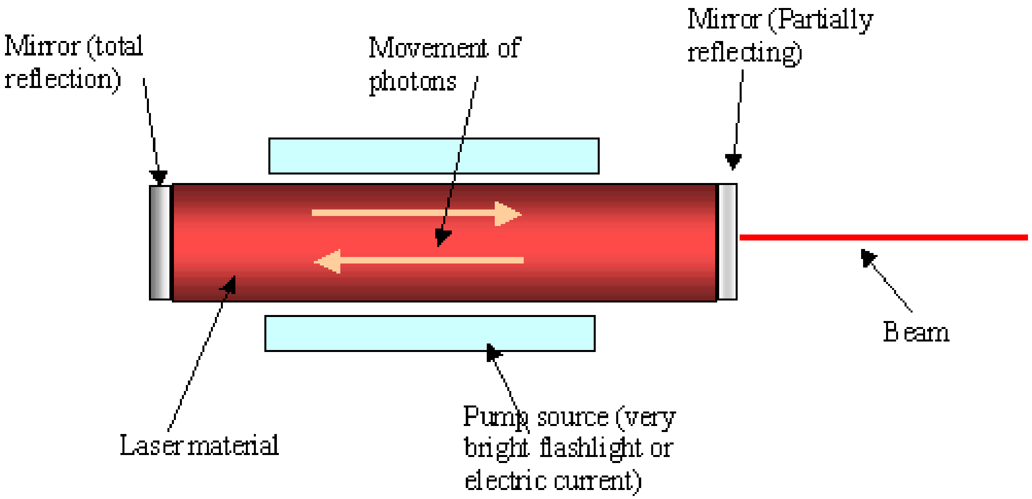
Laser

Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography.

Spatial coherence also allows a laser beam to stay narrow over great distances (collimation), enabling applications such as laser pointers. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can emit a single color of light.





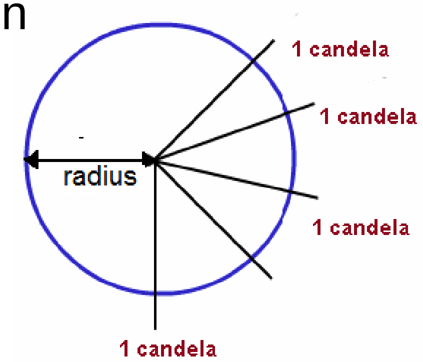


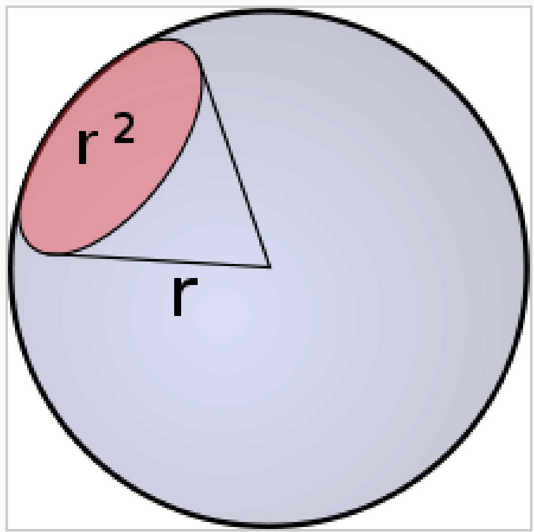
Unit of luminous intensity – candela

The candela (symbol: cd) is the SI base unit of luminous intensity (*J*); that is, luminous power per unit solid angle emitted by a point light source in a particular direction.

Comments: Luminous intensity is a measure of the wavelength-weighted power emitted by a light source in a particular direction per unit solid angle.

Solid angle (symbol: Ω) is the two-dimensional angle in three-dimensional space (unit: a steradian, symbol: sr). A full sphere has a solid angle of 4π sr.





Any area on a sphere which is equal in area to the square of its radius, when observed from its center, subtends precisely one steradian.

Official SI definition:

candela	cd	luminous intensity	• **Current** (1979): The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^{12} hertz and that has a radiant intensity in that direction of $\frac{1}{683}$ watt per steradian.

Unit of luminous intensity – candela

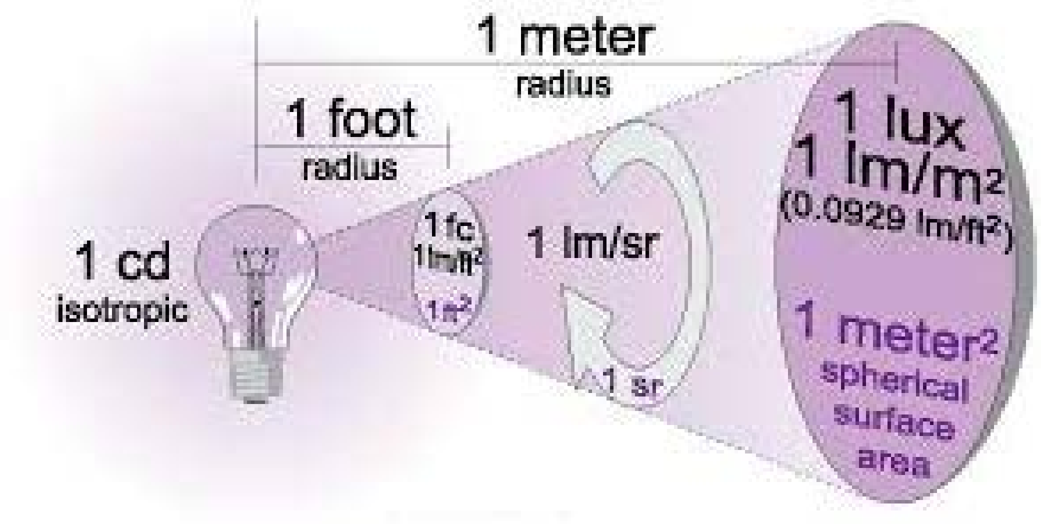
Connection to lumen.

The lumen (symbol: lm) is the SI derived unit of luminous flux, a measure of the total quantity of visible light emitted by a source.

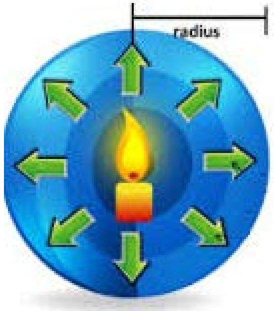
Lumens are related to lux in that 1 lux is 1 lumen per square meter (lux, symbol: lx is the SI derived unit for illuminance).

The lumen is defined in relation to the candela as

1 lm = 1 cd·sr.



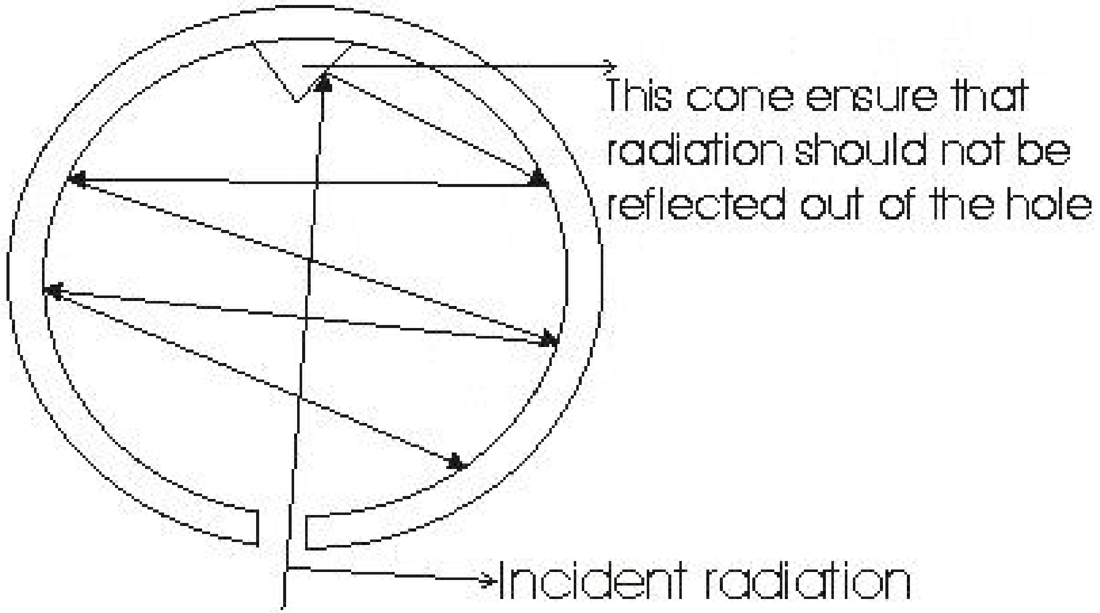
A full sphere has a solid angle of 4π steradians, so a light source that uniformly radiates one candela in all directions has a total luminous flux of 1 cd · 4π sr = 4π cd·sr ≈ 12.57 lumens.



black body radiation – important part of EM physics

A black body is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence.
An opposite case - a white body (with a "rough surface) reflects all incident rays completely and uniformly in all directions.

scheme (approximation)



A black body absorbs all radiation incident upon it, but due to the energy conservation law it re-radiates the energy. This radiation has its typical character and it is not dependent upon the type of radiation which is incident upon it.

<u>Comment:</u> Black-body radiation is the type of electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment (so not only the radiation of a black body system).

black body radiation – important part of EM physics

Based on the classical physics EM theory (so called Rayleigh-Jeans law), the energy of blackbody radiation should be shared by all wavelengths of light (emitting more energy as the frequency increases). This yield a total sum of emitted energy, which was too high – so called „the ultraviolet catastrophe“. Experiments have shown different character of the spectrum of emitted radiation – some wavelengths get more energy than others.
This behaviour was then later explained by Plank’s law of energy quantization.