

1. FACES of OPTICS

I think, therefore I am.
Rene Descartes

1.1. GEOMETRIC OPTICS

Light brings us more than 90 % information about the world around us. Thanks to vision, we distinguish objects and orient ourselves in space. Vision helps us capture what we see and convey its images, for example, to distant descendants, as the first artists did 40 thousand years ago, by painting animals with mineral paints on the walls of caves.

Apparently, the homeland of optics should be considered Ancient Greece. The word "optics" in Greek means "perspective." Optics was a part of philosophy, its decoration, as the XIII century English philosopher Roger Bacon believed. Philosophers were engaged in mathematics, and astronomy, and physics, and logic, and ethics - all that helped to understand the world around us and ourselves. Cognition of nature through reflection was subsequently called natural philosophy.

The mechanism of vision was incomprehensible to the ancients. For several millennia, the light ray remains one of the most mysterious objects of Nature, of our Universe. The ancient Greeks believed that our vision is accomplished by eye beams emitted by the eyes. These beams originated from the fire that was lit inside the eyes by Aphrodite – the ancient Greek goddess of love and beauty.

Pythagoras and his followers (the Pythagorean school, VI–V c. BC) believed that the eyes emit a certain fluid that palpates objects (Fig. 1.1). The opposite point of view was held by Democritus and his associates (“atomists”). In their



Fig. 1.1. The ancient Greek philosopher Pythagoras on a fragment of a fresco Raphael "School in Athens" (Vatican Museum)

opinion, a mold was taken off the subject and, falling into the eye, gave the perception of the subject.

The concepts of straight line and eye beam appeared in the *Elements* and the *Optics*, the most famous treatises of Euclid, the ancient Greek philosopher and the founder of geometry who lived in the III c. BC. Later these concepts became the basis of the geometric optics – science about the trajectories of light beams in the optical elements with a different surface forms.

Euclid (Fig. 1.2) for the first time used the geometric concepts expounded by him in 13 books of the “Elements” to construct a peculiar geometry of vision in his treatises “Catoptric” and “Optics”. Euclid sets out his idea of how we see surrounding objects. A conical beam of visual rays emanates from the eye and those rays that fall on the object make it visible and determine its shape. The straightness of the distribution of visual rays Euclid puts forward as a postulate.

Because the geometry was created for various measurements on the ground, the visual rays also became sides of proportional triangles, with which it was possible to measure, for example, the height or length of distant objects. However, not everywhere in Euclidean rays emanate from the eyes. In some constructions, a Sun ray appears, reflected from the mirror, and then the rays in the constructions of Euclid acquire physical properties. A point and a straight line are the two simplest concepts of Euclidean geometry. In optics, a point and a straight line correspond to a point source of light and a light beam.

We’ll be talking about the light rays and the light beams. What is the difference between these two notions? Geometrically we can depict a ray as a straight line, as a straight trajectory, and the light beam as a lot of rays originated from the point source, the cone of rays. When we say, for example, «X-ray» we mean the beam of Roentgen radiation.

Geometric optics is based on several laws.

1. *The law of the rectilinear propagation of light* as a postulate was introduced by Euclid in the III c. BC in his work “Optics” (Fig. 1.3).



Fig. 1.2. The ancient Greek philosopher Euclid (IV c. BC)

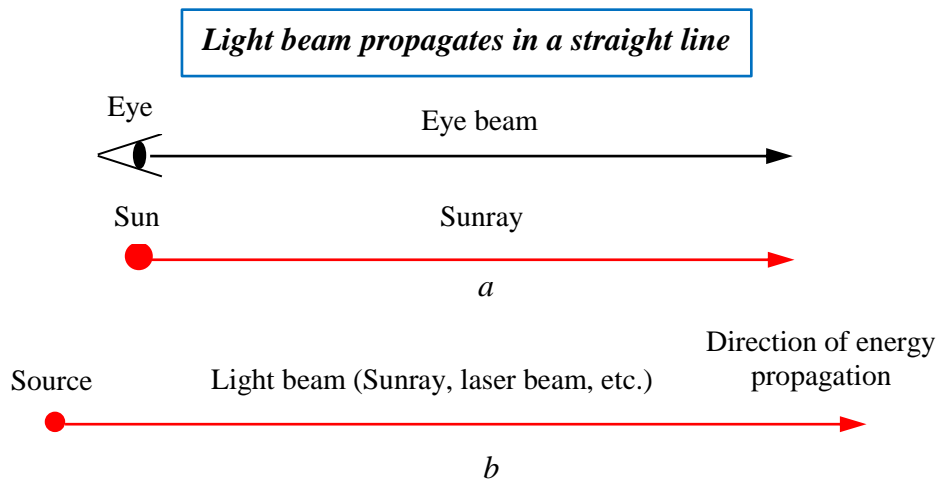


Fig. 1.3. Ancient (a) and modern (b) ideas about the light beam

This law is valid for free space and a homogeneous medium with a constant

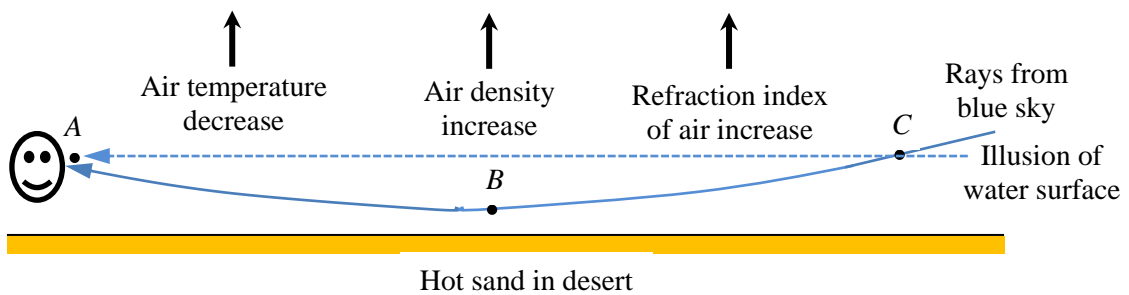


Fig. 1.4. Mirage: observer does not know about violation of the straightness of light propagation

refractive index. If we do not have information about the heterogeneity of the environment, optical illusions arise, such as, for example, a mirage (Fig. 1.4 and 1.5).

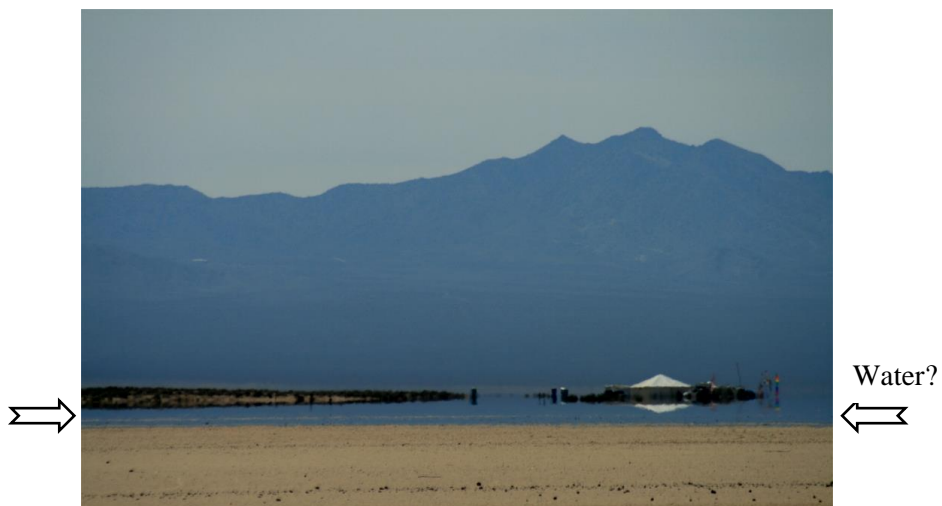


Fig. 1.5. Mirage in the Mojave Desert (California, USA). Blue stripe on the horizon seems to be water

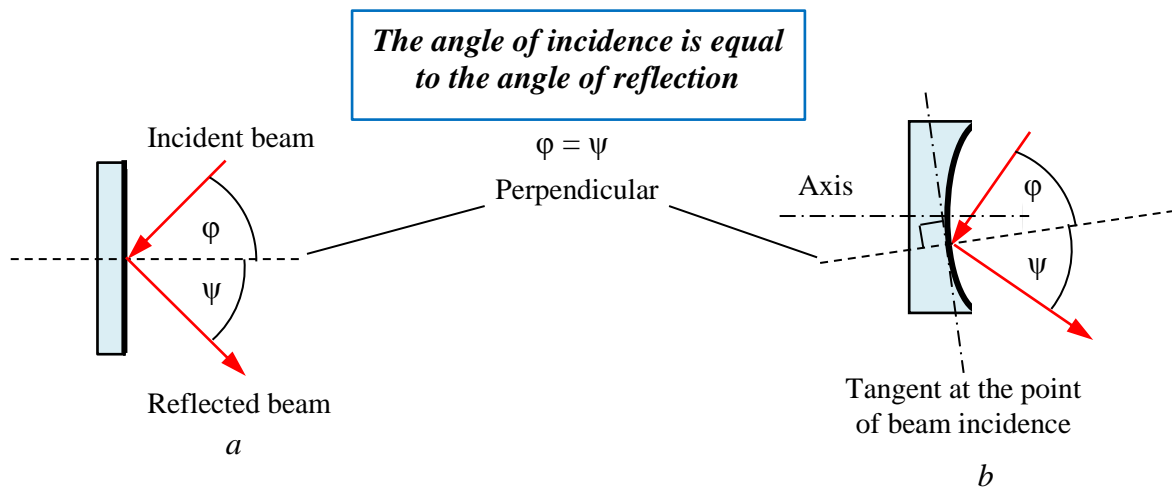


Fig. 1.6. Light reflection from flat (*a*) and spherical (*b*) mirrors

2. *The law of reflection of light* and the application of this law for mirrors with various surface shapes was considered in Euclid's work "Catoptric" (Fig. 1.6).

3. *The law of refraction of light* was described in the second century by the most outstanding astronomer of the first millennium Claudius Ptolemy and strictly deduced in 1621 by the Dutch mathematician, physicist and astronomer Willebrord Snellius or Snell (Fig. 1.7). Snell's formula is widely used in optics (Fig. 1.8).



Fig. 1.7. Scientists who discovered and investigated the law of refraction – Claudius Ptolemy (100–170) and Willebrord Snellius (1580–1660)

4. *The law of reversibility of light rays* states that a ray passing through an optical medium or an optical system from point *A* to point *B* coincides with a ray going in the opposite direction.

Rays in the forward and reverse directions are equivalent

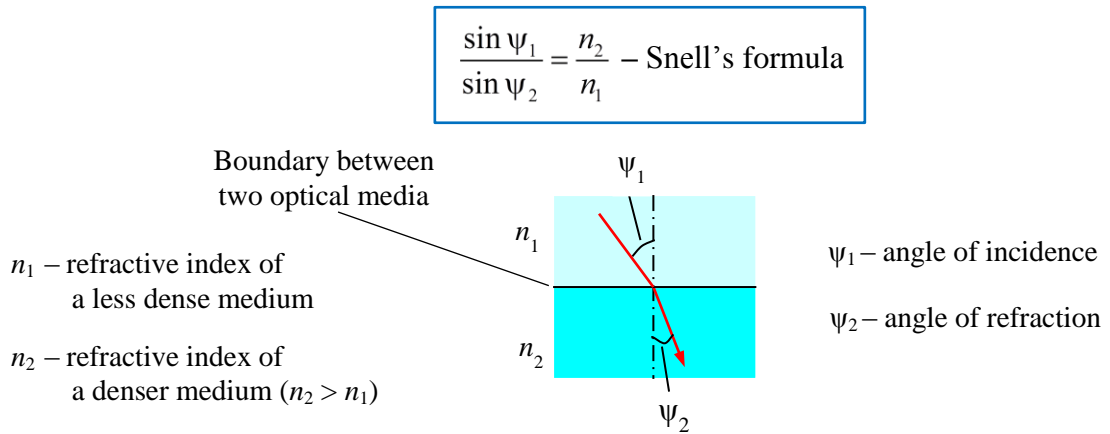


Fig. 1.8. Snell's law of refraction

5. *The law of independence of light rays* was postulated in 1021 by the Egyptian scientist Hasan Ibn al-Haytham (better known in non-Arabian world as Alhazen) in his "Book of Optics" (Fig. 1.9). Even high-power laser beams do not interact with each other.

6. *The principle of least time* (Fermat's principle) was postulated by the French mathematician Pierre de Fermat in 1662 to explain the law of reflection of light (Fig. 1.10).

This principle was rejected by contemporaries of the scientist, who considered that Fermat attributed to the light the ability to predict which path would be shortest and follow that path. In Fig. 1.4, light travels faster along the *ABC* curved path than

along the *AC* straight path. Fermat's principle was explained in the XIX century, when the wave theory of light appeared.

Intersecting rays do not affect each other



Fig. 1.9. The Arab mathematician, astronomer and physicist Hasan Ibn al-Haytham (965–1040)

Geometric optics is used to calculate optical systems, build images in them, and also to measure distances, lengths, thicknesses and other linear quantities.

Geometric optics, the foundations of which were laid in the treatises of Euclid, is one of the most important sections of modern

optics. Geometric optics solves two problems: 1) find the paths of rays in a medium with a known distribution of the refractive index and the known shape of the refractive and reflective surfaces (direct problem) and 2) find the distribution of the refractive index of the medium and the shape of these surfaces that provide the given paths of rays (inverse problem).

The path taken by a ray between two given points is the path that can be traversed in the least time



Fig. 1.10. The French mathematician Pierre de Fermat (1607–1665)

1. 2. Physical optics

An equally important part of optics is physical optics, which studies the nature of optical radiation and related phenomena. Physical optics is divided into wave optics and quantum optics. The subject of study of wave optics are such wave phenomena as diffraction, interference, dispersion and polarization of light. For quantum optics, light is a stream of particles whose energy is emitted or absorbed (by atoms or molecules) in small portions – quanta.

1. 3. Physiological optics

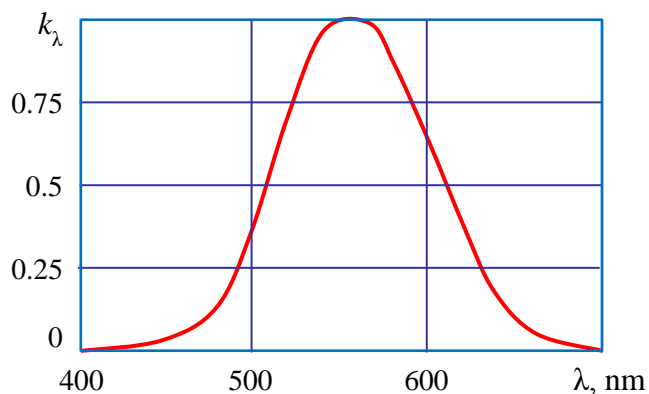


Fig. 1.11. The visibility curve – characteristic of the spectral sensitivity of the human eye

The properties of human and animal vision are studied by physiological optics. For example, it was found that the sensitivity of the human eye during the day is maximum at a wavelength of $\lambda = 550 \text{ nm}$ (yellow-green light), and in the evening – at $\lambda = 510 \text{ nm}$ (blue-green light) and at dusk we perceive red objects as black.

The visibility curve allows us to evaluate how the sensitivity of the human eye depends on the color of the radiation (Fig. 1.11). Here k_λ is the visibility factor (the efficiency of conversion by the eye of a light beam of a given color into a visual signal).

1. 4. Appendix A. An excerpt from Euclid's «Optics»

«Find the height of a given hill when the sun is shining (Fig. 1.12).

Denote the height of the hill, which we need to determine as AB . Let D be the eye, and GD be the sun's ray incident on the end of line AB and extended to the eye of D . And let BD be the shadow of AB . Draw a line EZ until it intersects with the beam at point Z and is unlit below this point. In triangle ABD , a second triangle formed, EZD . We have, DE refers to ZE as DB to BA . However, the relation of DE to EZ is known and, therefore, the relation of DB to BA is known. Since DB is known, therefore, AB is also known».

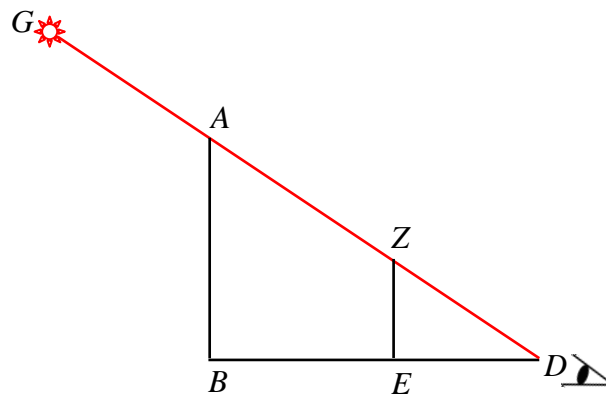


Fig.1.12. Finding the height AB
using the sunbeam GD (after Euclid)