Geometric Optics I

A ray, in physics, is the path taken by light energy, and it is usually represented by a solid line with an arrow indicating its direction of travel. A beam of light is a stream of light rays and is represented, diagrammatically, by a number of rays. The rays may be converging, diverging, or parallel.

**The currently accepted value for the speed of light in a vacuum, *c*, is**

***c* = 2.997924526 ± 0.000000011 × 108 m/s.**

The value is usually rounded off to **3.00 × 108 m/s** can be used for air or a vacuum. In other transparent media, such as water or glass, the speed is significantly smaller.

* **Index of refraction:**

The ratio of the speed of light in a vacuum to the speed light in a given material is called the index of refraction of that material. That is,



The higher the index of a given substance, the more the light is slowed down when it travels from a vacuum into the substance. For example, air, with an index of refraction of 1.0003, slows it down very title, but Zircon, with an index of 1.92, slow it down considerable more.

Sometimes the index of refraction for light going from a vacuum into a substance is referred to as **the absolute refractive index**. The value of the index for light travelling from air into the substance is so close to the value of the absolute refractive index that we only distinguish between them is rare instances.

e.g. Using the table in the margin, calculate the speed of light in Lucite. (1.99 × 108 m/s)

When light travels between two materials with different indices of refraction, the ratio of their absolute indices of refraction is referred to as **the relative index of refraction**. The relative index of refraction is:



e.g. What is the relative index of refraction for light travelling from water into glass and from glass into water. (1.13, 0.89)

# Practice

1. What is the index of refraction of a liquid in which the speed of light is 2.50 × 108 m/s? (1.20)
2. The index of refraction of diamond is 2.42. What is the speed of light in diamond? (1.24 × 108 m/s)
3. Light from the planet Uranus takes 242 min to reach the Earth. Calculate the distance from Uranus to the Earth. (4.4 × 1012 m)

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* **The Pinhole Camera:**

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The pinhole camera consists of a light-proof box with a pinhole in one end and a screen of frosted glass or tracing paper at the other end. An image is formed on the screen by light travelling in straight lines from an object to the screen. It is easier to see the image on the screen if external light is excluded by shielding the outside of the box with a dark cloth or other covering.

The rays of light from various parts of the object travel in straight lines through the pinhole and together form an inverted image on the screen. That the image is produced in the way justifies our earlier statement that light travels in straight lines. If a line is drawn through the pinhole and perpendicular to both the image and the object, it can be shown by similar triangles that



**The magnification for pinhole camera:**

The magnification, *M*, of any optical device is defined as the ratio of the height of the image to the height of the object, that is, *h*i / *h*o. The relationship



is referred to as **the magnification equation for pinhole camera**.

An image that can be formed on a screen is called a **real image**. An image that cannot be formed on a screen is called a **virtual image** (A negative sign is included in the magnification if the image is inverted.). The image formed in a pinhole camera is a real one. In physics, the characteristics of an image are stated in terms of its attitude, its size, and its type. The characteristics of the image formed in a pinhole camera are that it is inverted, smaller, and real.

e.g. Calculate the size of the image of a tree that is 8.0 m high and 80 m from a pinhole camera that is 20 cm long. (2.0 × 10-2 m)

**Practice:**

1. Calculate the distance from the pinhole to an object that is 3.5 m high, and whose image is 10 cm high in a pinhole camera 20 cm long. (7.0 m)
2. Calculate the height of a building 300 m away from the pin hole that produces an image 3.0 cm high in a pinhole camera 5.0 long. (1.8 × 102 m)
3. A 1.5 cm inverted image is produced on the screen of a camera when a picture is taken of an 80 m tall tree. What is the magnification? (-1.9 × 10-4)

* **Plane Reflectors**

When light strikes a plane (or flat) surface, angles are formed by the incident and reflected rays. The angle of incidence, , is defined as the angle between the incident ray and the normal (or perpendicular) line constructed at the point of incidence. The angle of reflection, , is the angle between the reflected ray and the normal.

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| **Laws of Reflection**   * **The angle of incidence is equal to the angle of reflection.** * **The incident ray, the reflected ray, and the normal all lie in the same plane.** | **G2** |

**Plane Mirrors:**

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| **The characteristics of an image in a plane mirror are:**   * **It is the same size as the object.** * **It is vertically erect.** * **It is virtual.** | g5 |

**Spherical Reflectors:**

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| A spherical, curved mirror may be thought of as a section of hollow sphere. If the inside of the sphere is polished to reflect light, the resulting mirror has a concave shape and makes parallel light rays converge on each other. The shiny outside of a similar section has a convex surface and makes parallel light rays diverge. Hence the terms converging mirror and diverging mirror. | G3 |

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| g4 | The centre of such a spherical reflecting surface is called the centre of curvature (*C*), and the radius of curvature (*R*) is any straight line drawn from the centre of curvature to the curved surface. The geometric centre of a curved mirror is called the vertex principal anis (P.A.). If a group of rays parallel to the principal axis strikes a converging mirror, the rays are nearly all reflected to the same point on the principal anis, called the principal focus (*F*). The distance along the principal axis between the principal focus and the vertex is called the focal length (*f* ). The Laws of Refection hold for each of these rays. Note that the principal focus is located half-way between the vertex and the centre of curvature, that is, . |

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| If a group of rays parallel to the principal axis strikes a diverging spherical mirror, the reflected rays are projected backward through the surface and they appear to have passed through a common point *F*. This point is the principal focus of the diverging mirror. It is called a virtual focus, since it is located behind the mirror where no rays can actually pass trough it. In addition, the ray directed towards *C*, the centre of curvature, is reflected back along the same path. | **g6** |

**Curved Mirrors:**

Rules for Rays in Curved Mirrors of Both Types:

1. A ray that is parallel to the principal axis is reflected through (or as if it had gone through) the principal focus – real or virtual.
2. A ray passing through (or appearing to pass through) the principal focus is reflected parallel to the principal axis.
3. A ray passing through (or appearing to pass through) the centre of curvature is reflected back along the same path.

Converging Mirrors:

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Diverging Mirror:

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**Equations for Curved Mirrors:**

Mirror Equation can be written as



where *f* is the principal focus length,  is the distance from mirror to the object, and  is the distance from mirror to the image.

The mirror equation can also be written as



where *R* is the radius of curvature and .

Sign Convention:

1. All distances are measured from the vertex of a curved mirror.
2. Distances of real objects and images are positive.
3. Distance of virtual objects and image are negative.
4. Object heights and image heights are positive when measured upward and negative when measured downward from the principal axis.

Magnification Equation of Mirrors:



where  is the height of image and  is the height of object.

The orientation of the image can be predicted, using the sign convention. The magnification is positive for an erect image and negative for an inverted image.

e.g. An object is located 30.0 cm from a converging mirror with a radius of curvature of 10.0 cm.

(a) At what distance from the mirror will the image be formed? (6.0 cm)

(b) If the object is 4.0 cm tall, how tall is its image? (0.80 cm inverted image)

e.g. A diverging mirror with a focal length of -5.0 cm produces an image of an object located 15.0 cm from the mirror.

(a) What is the distance of the image from the mirror? (3.8 cm behind the diverging mirror)

(b) What is the magnification? (0.25)

Practices:

1. Determine the image distance in each of the following:
   1. A converging mirror has a focal length of 15 cm. The object is placed at (i) 40 cm, and (ii) 10 cm from the mirror. (24 cm, -30cm)
   2. A diverging mirror has a focal length of -20 cm. An object is placed (i) 10 cm, and(ii) 30 cm from the mirror. (-6.7 cm, -12 cm)
2. A candle 3.0 cm high is placed 30 cm from a converging mirror with a focal length of 20 cm.
   1. By means of a scale diagram, locate the image and determine its height. State the characteristics of the image.
   2. Using the mirror and magnification equations, determine the image position and its height. Compare your results with those obtained in part (a). (60 cm, -6.0 cm)
3. A converging mirror has a focal length of 20 cm. Where should an object be placed so that its virtual image will be twice as tall as the object? (10 cm)

**Geometric Optics II**

* **Refraction:**

When light passes at an angle from air to glass, it immediately changes direction. Also, at the boundary between the air and the glass, most of the light passes through the glass, but some is reflected according to the Laws of Reflection. This is called partial reflection and partial refraction.

When light passes from one medium to another that is optically denser, the ray of light is bent towards the normal. The speed of light is reduced when it passes into an optically denser medium, as in the transition from air to glass. Thus, optically denser and the speed of light is reduced are synonymous when discussing the properties of a transparent medium.

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If the light travels from one medium into a less optically dense medium where its speed is greater, the ray bends away from the normal.

* **Snell’s Law:**



e.g. Light travels from crown glass into air. The angle of refraction in air is 60o. What is the angle of incidence in glass? (34.7o)

e.g. Light travels from crown glass into water. The angle of incidence in crown glass is 40o. What is the angle of refraction in water? (47.3o)

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* **Total Internal Reflection:**

The speed of the light increases, for example from glass to air, the light is reflected to a greater extent than in cases where the speed decreases. As the angle of incidence increases, the intensity of a reflected ray becomes progressively stronger and the intensity of a refracted ray progressively weaker. Also, as the angle of incidence increases, the angle of refraction increases, eventually reaching a maximum of 90o. Beyond this point, refraction ceases, and all the incident light is reflected, at the boundary, back into **the optically denser medium**. This phenomenon is called total internal reflection. **The total internal reflection** **can only occur when light rays travel into a medium where the speed of the light increases and, hence, the angle of refraction is always greater than the angle of incidence.**

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When the angle of refraction in 90o, the incident ray forms an angle of incidence that has a unique value for any two materials. This unique angle of incidence is called the “critical angle of incidence”, or simply the critical angle.



e.g. What is the critical angle for light travelling from crown glass to air? (41o)

* **Shimmering Heat and Mirages**

Warm air has a slightly different index of refraction than cold air. When light passes through a stream of warm air, as it does above a stove or barbecue, it is refracted. This refraction is not uniform because the warm air rises irregularly, in gusts. The light from objects seen through the warm air is distorted by irregular refraction, and the objects appear to **shimmer**. The same effect is observed over hot pavement in the summer. A similar phenomenon occurs when gasoline vapour rises from the car while we are filling the tank.

**Mirages** are most often associated with deserts, but they may occur over any hot, flat surface, such as a road on a summer day. What appears to be a sheet of water sometimes appears on the highway a short distance ahead of us, but we never reach it because it is an optical illusion. We are deceived because we associate reflections from ground level with pools or lakes and make the natural inference that the road is wet.

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* **Dispersion**

It has been known, at least since the days of the ancient Egyptians, that fragments of clear, colourless glass and precious stones emit the colours of the rainbow when placed in the path of a beam of white light. This phenomenon called **dispersion**. As a source of light, Newton used a small round hole in one of his window shutters at Cambridge. A prism placed in a beam of sunlight coming through the hole produced an elongated patch of multi-coloured light on the opposite wall. Newton called this a **spectrum** and noted the colours – red, orange, yellow, green, blue, indigo, and violet.

The dispersion of light is simply the result of different colours of light being refracted by different amounts. In other words, each colour has a slightly different index of refraction in the same medium.

The colours of the spectrum may be recombined by means of a lens to form white light. This process, called **recomposition**. Newton also demonstrated recomposition by painting the spectral colours on a disc and rotating the disc at a high speed. The rotating disc appeared white.

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A Single Lens

We are going to study some behaviors of a single convex or concave lens now.

**A converging lens (positive lens, convex lens):**

**Parallel rays striking a converging lens are refracted inward.**

**A diverging lens (negative lens, concave lens):**

**A diverging lens spreads parallel rays outward uniformly.**

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In lenses, the geometric cnetre is called the optical centre (O). A linge drawn through the optical centre perpendicular to the surfaces of the lens is the principal axis. If a lens is thin, a group of rays parallel to the principal axis refracted through a point on the principal axis called the principal focus (F). The focal length (f) is the distance between the principal focus and the optical centre, measured along the principal axis. A lens amy be tured around so that the light can pass through it from the opposite side. It is found that the focal length is the same on both sides, even if the curvature is different. To distinguish between them, the secondary principal focus is usually expressed as F´.

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* **Rules for Rays in Thin Curved Lenses of Both Types:**

**Ray-1:** A ray that is parallel to the principal axis is refracted so that it passes through (or appears to pass through) the principal focus (F).

**Ray-2:** A ray that passes through (or appears to pass through) the secondary principal focus (F´) is refracted parallel to the principal axis.

**Ray-3:** A ray that passes through the optical centre goes straight through, without bending.

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A real image is one formed by converging rays; it can be cast on a screen. A virtual image is one formed by diverging rays or converging rays; it cannot be cast on a screen, but it certainly can be viewed directly.

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* The Thin Lens Equation:



**A diverging lens has negative focal length. For converging lens, if it formed a virtual image on the same side of the lens as the object, the image distance is negative.**

e.g. We wish to place an object 45 cm in front of a lens and have its image appear on a screen 90 cm behind the lens. What must be the focal length of the appropriate positive lens? (+0.30 m)

Magnification:

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The magnification is negative whenever the image is inverted and positive when the image is right-side-up.

e.g. Where must a postage stamp be placed in front of a magnifying glass (converging lens; f = 10 cm), if a virtual image is to be formed 25 cm in front of the lens? What is its magnification? (7.1 cm, 3.5)

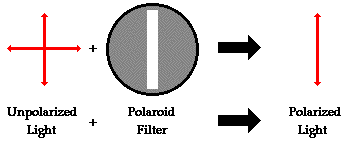
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**Polarization:**

If the displacement of the particles of a medium by a transverse wave is all in the same plane, we say that the wave is plane-polarized. A transverse wave vibrating in a variety of planes can be generated in a rope by moving it up and down and then side ways in raped succession. If the rope passes through a vertical slit, the waves will be confined to vibrating up and down in the vertical plane. If these vertically polarized waves encounter a second slit that is horizontal, the energy will be absorbed and the wave stopped completely. Only transverse waves can be polarized. Longitudinal waves cannot.

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A light wave is an [**electromagnetic wave**](http://www.physicsclassroom.com/class/waves/u10l1c.cfm#emmech) that travels through the vacuum of outer space. it is sufficient to merely say that an electromagnetic wave is a [**transverse wave**](http://www.physicsclassroom.com/class/waves/u10l1c.cfm#transverse) that has both an electric and a magnetic component. The most common method of polarization involves the use of a **Polaroid filter**. Polaroid filters are made of a special material that is capable of blocking one of the two planes of vibration of an electromagnetic wave. (Remember, the notion of two planes or directions of vibration is merely a simplification that helps us to visualize the wavelike nature of the electromagnetic wave.) In this sense, a Polaroid serves as a device that filters out one-half of the vibrations upon transmission of the light through the filter. When unpolarized light is transmitted through a Polaroid filter, it emerges with one-half the intensity and with vibrations in a single plane; it emerges as polarized light.



Two Polaroid filters oriented with their polarization axes perpendicular to each other will block all the light. Now that's a pretty cool observation that could never be explained by a particle view of light.