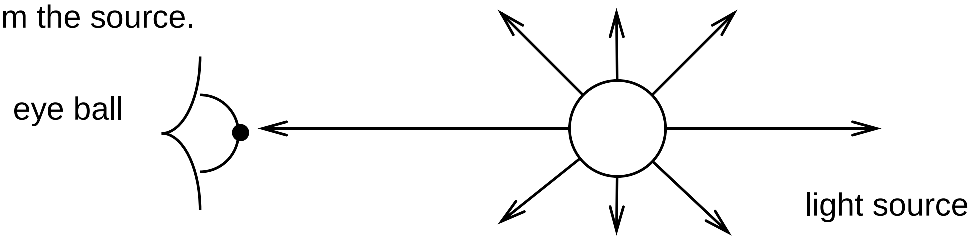
Physics 30 <u>Lesson 5</u> Introduction to Light

In the beginning of this unit on *Light*, we will not concern ourselves with what light is (particle, wave or something else), rather we will begin by working with the observable properties of light.

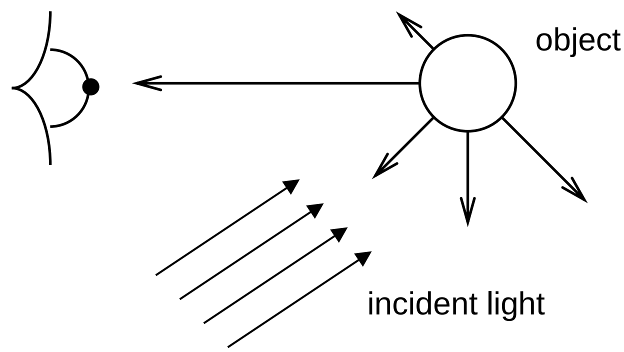
I. Sources of light

There are two basic ways that we see light:

1. We see light that is **emitted** from a source of some kind (i.e. light bulb, Sun, stars, television, etc.). Note that the eye receives only a small part of the light emitted from the source.



2. We also see light that is **reflected** from an object of some kind (i.e. pencil, paper, etc.). Note that the eye receives only a small part of the light reflected by the object.



II. Basic properties of light

The basic properties of light are:

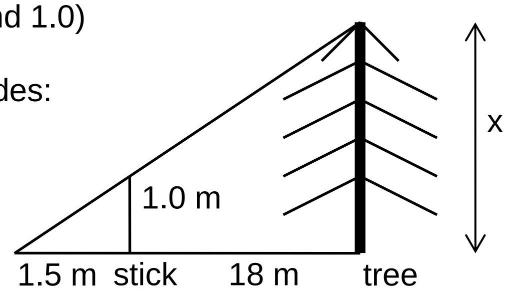
1. **Light travels in straight lines**. This is also referred to as **rectilinear propagation**. The evidence for this is that light creates shadows and it does not appear to bend around corners.
2. **Light rays obey the laws of geometry**. By using straight lines and by constructing similar triangles, we can solve many problems.
3. **Light has a constant speed in a given medium**. In vacuum or in air, light has a speed of 3.00×10^8 m/s. In water, the speed of light is 2.26×10^8 m/s.

Example 1

If a metre stick casts a shadow that is 1.5 m long and a tree's shadow at the same time is 18 m long, how tall is the tree?

We can solve this problem by noticing two similar triangles:
- the large triangle involving the tree (sides of 18 and x)
- the small triangle involving the stick (sides of 1.5 and 1.0)

Similar triangles are related by setting up a ratio of sides:



$$\frac{1.0\,\text{m}}{1.5\,\text{m}} = \frac{x}{18\,\text{m}}$$

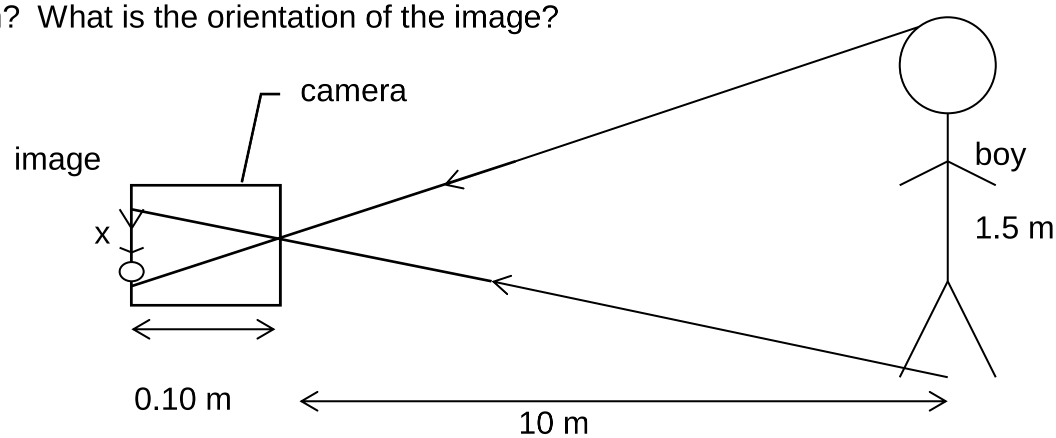
$$x = \frac{1.0\,\text{m}(18\,\text{m})}{1.5\,\text{m}}$$

$$x = \mathbf{12\,m}$$

Example 2

A pinhole camera is made from a black box where a small pin-sized hole is made at one end. Light rays from an object or light source travel through the pinhole to form an image on the other side of the box.

If a pin hole camera is used to photograph a 1.5 m tall boy located 10 m from the camera and the camera is 0.10 m long, what is the size of the image formed on the film? What is the orientation of the image?



The similar triangles involve the boy (large) and the image (small).

$$\frac{1.5\,\text{m}}{10\,\text{m}} = \frac{x}{0.10\,\text{m}}$$

$$x = \frac{1.5\,\text{m}(0.10\,\text{m})}{10\,\text{m}}$$

$x = \mathbf{0.015\,m}$ and the image is inverted (rays cross)

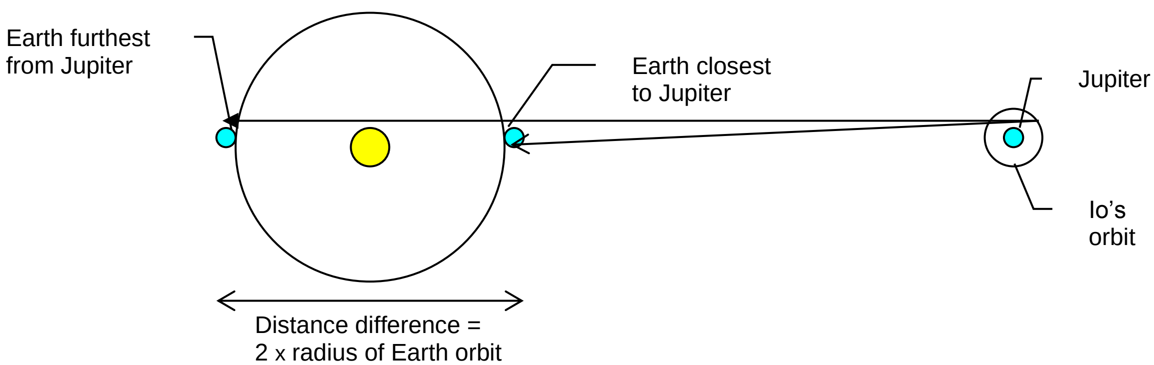
Note that of the millions of rays which pass from the boy into the camera, it is only the ones from the bottom and the top of the object *that are required* to define where and what size the image will be.

III. The speed of light

Refer to Pearson pages 648 to 652.

Galileo tried to measure the speed of light by measuring the time required for light to travel a known distance between two hilltops. He had an assistant stand on one hilltop and himself on the other and ordered the assistant to lift the shutter on his lantern when he saw a flash from Galileo's lantern. Galileo intended to measure the time between the flash and when he received the signal back from the assistant. The time was so short that Galileo realised that the reaction time was far greater than the actual time for the light to move across the distance. He concluded that the speed of light was extremely fast, if not instantaneous.

The first successful determination of the speed of light began with an observation by the Danish astronomer Ole Römer (1644–1710). Römer noted that the period of one of Jupiter's moons (Io) varied slightly depending on the relative motion of the Earth and Jupiter. When the Earth was moving away from Jupiter the period was slightly longer, and when Earth moved toward Jupiter the period was slightly shorter. The Dutch scientist Christian Huygens (1629–1695) was intrigued by Römer's result. Huygens reasoned that if they measured when Io appeared from behind Jupiter for different positions of the Earth relative to Jupiter, there should be a time difference.



When the Earth was furthest away from Jupiter Io should appear later than expected. Their measurements confirmed that this was indeed the case and the calculation

$$\text{speed of light} = \frac{\text{distance difference}}{\text{time difference}}$$

yielded the result that the speed of light was very fast.

Example 3

In an early measurement Römer measured a 1250 s time difference. If the Earth's mean radius of orbit is 1.49×10^{11} m, what is the speed of light that Römer measured?

Referring to the diagram and discussion above:

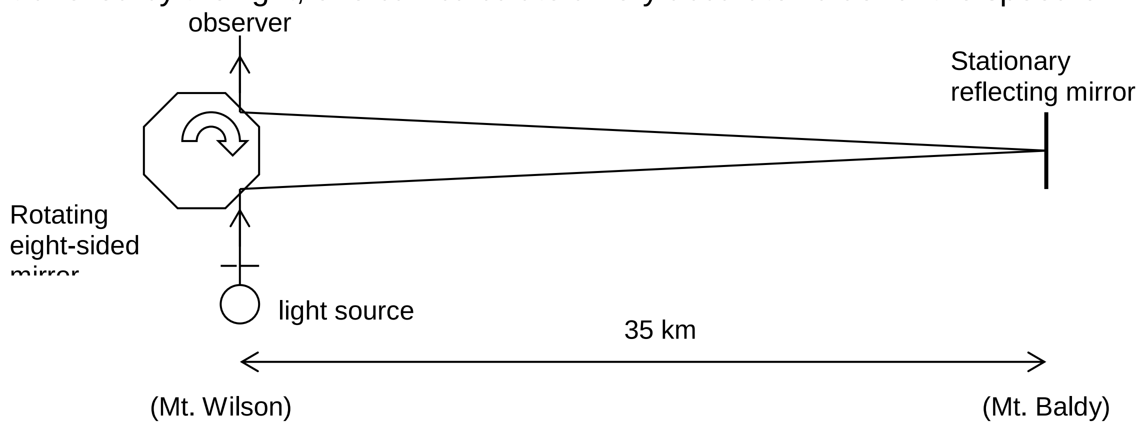
$$\text{speed of light} = \frac{\text{distance difference}}{\text{time difference}}$$

$$v = \frac{2 \times \text{radius of Earth orbit}}{\text{time difference}}$$

$$v = \frac{2 \times 1.49 \times 10^{11}\,\text{m}}{1250\,\text{s}}$$

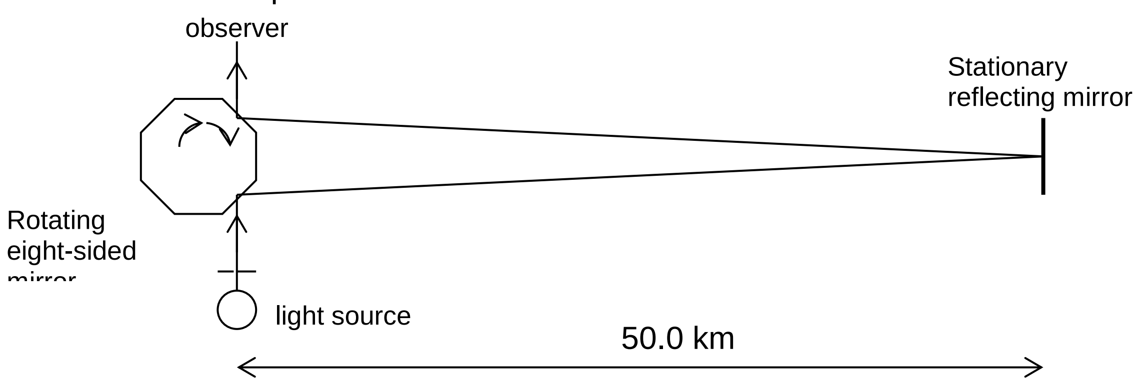
$$v = \mathbf{2.38 \times 10^{8}\ \text{m/s}}$$

Since Römer's day a number of techniques have been used to measure the speed of light. Among the most important were those carried out by Alberta A. Michelson (1852–1931). Michelson used a rotating mirror apparatus like the one diagrammed below for a series of high-precision experiments carried out from 1880 to the 1920's. Light from a source was directed at one face of a rotating eight-sided mirror. The reflected light travelled to a stationary mirror a large distance away and back again as shown. As the light travelled away and back, the eight-sided mirror rotated. If the rotating mirror was turning at just the right rate the returning beam of light would reflect from one of the mirror faces into a small telescope through which the observer looked. This only occurred if the mirror was turning at **exactly** the right rate. In this manner, the rotating mirror acted as a time piece. By knowing the frequency of rotation and the two way distance travelled by the light, one can calculate a very accurate value for the speed of light.



Example 4

In a Michelson-type experiment, a rotating eight-sided mirror was placed 50.0 km from the reflecting mirror as diagrammed below. The observer found that in order to observe the return light ray, the mirror had to rotate at 375 Hz. What is the speed of light calculated from this experiment?



a. Calculate the time for one revolution – T

$$T = \frac{1}{f}$$

$$T = \frac{1}{375\ \text{cycles}/\text{s}}$$

$$T = 2.667 \times 10^{-3}\,\text{s}$$

b. Calculate the time for the light to go to and return from the reflecting mirror – 1/8th T

$$\Delta t = \tfrac{1}{8}T = \tfrac{1}{8}(2.667 \times 10^{-3}\,\text{s})$$

$$\Delta t = 3.333 \times 10^{-4}\,\text{s}$$

c. Calculate the speed of light.

$$v = \frac{\Delta d}{\Delta t}$$

$$v = \frac{2 \times 50.0 \times 10^{3}\,\text{m}}{3.333 \times 10^{-4}\,\text{s}}$$

$$v = \mathbf{3.00 \times 10^{8}\ m/s}$$

The accepted value today for the speed of light in vacuum is

$$c = 2.99792458 \times 10^8 \text{ m/s}$$

which we usually round off to

$$c = 3.00 \times 10^8 \text{ m/s}.$$

IV. Light year – a distance

The vast majority of objects that we see in the night sky – stars, galaxies, nebulae – are very far away from us. In fact, for some objects it has taken light billions of years to reach us here on Earth. Therefore we are not seeing objects as they are, rather we are seeing them as they were many years ago when the light started toward us. These objects are so distant that it makes little sense to talk about them in terms of metres, kilometres or even billions of kilometres. A more convenient measure of distance for celestial objects is the **light year**. **A light year is the distance that light travels in one year**.

Example 5

How many metres are in a light year?

A light year is the distance that light ($v = 3.00 \times 10^8$ m/s) travels in one year (365.25 days).

$$t = \frac{365.25\ \cancel{\text{days}}}{} \times \frac{24\ \cancel{\text{h}}}{1\ \cancel{\text{day}}} \times \frac{3600\ \text{s}}{1\ \cancel{\text{h}}}$$

$$t = 3.15576 \times 10^7 \text{ s}$$

$$\Delta d = v\Delta t$$

$$\Delta d = 3.00 \times 10^8\ \tfrac{m}{s}(3.15576 \times 10^7 \text{ s})$$

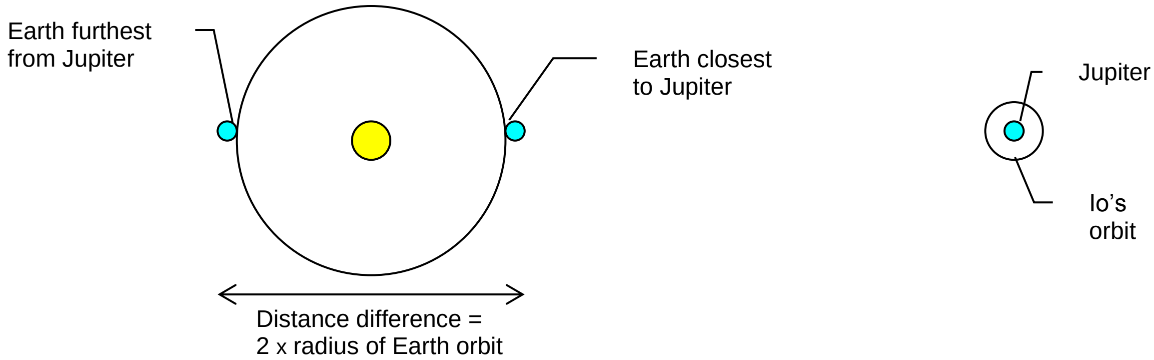
$$\Delta d = \mathbf{9.4673 \times 10^{15}\ m}$$

V. Practice problems

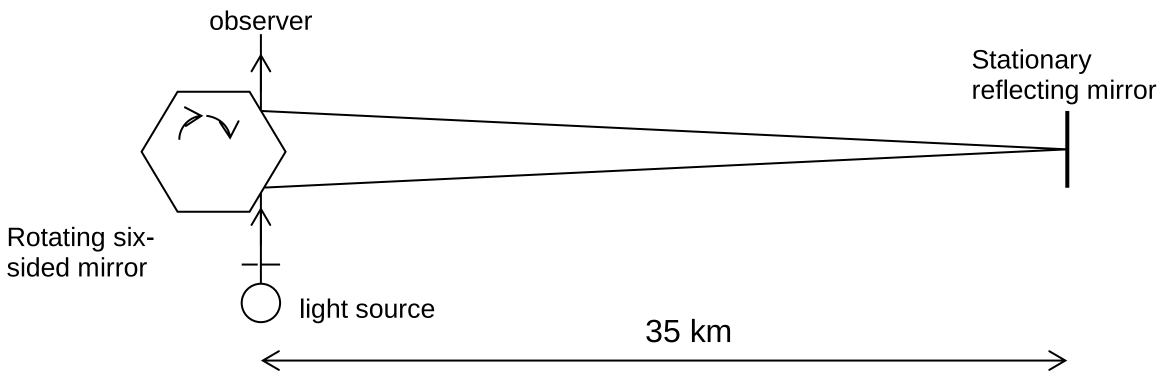
1. The flame of a candle is 30 cm above a table. A 10 cm tall glue stick container is standing 35 cm from the candle. How long is the shadow of the glue stick? (17.5 cm)

2. A pinhole camera is a device that consists of a light-proof box with a pinhole punched into one end and a screen of some kind on the other. An image is formed on the screen from light travelling in straight lines from the object through the pinhole. What is the size of the image of a person that is 1.90 m tall and is standing 7.5 m from a pinhole camera that is 25 cm long? (6.3 cm)

3. Olaf Römer noticed that the time when one of Jupiter's moons was eclipsed by the planet changed depending on the season in which the measurement was taken. When the Earth was closest to Jupiter compared to when the Earth was furthest away from Jupiter (on the other side of the Sun), there was a 1320 s difference. Römer correctly interpreted this observation to be the effect of the increased distance that light had to travel to reach the Earth. If the Earth's mean radius of orbit is 1.5×10^{11} m, what is the speed of light that Römer measured? (2.3×10^8 m/s)



4. Using the Michelson-like apparatus diagrammed below, the observer found that in order to observe the return light ray, the mirror had to rotate at 707.1 Hz. What is the speed of light calculated from this experiment? (2.97×10^8 m/s)



VI. Hand-in assignment

1. In communicating with an automatic space station, radio signals travelling at the speed of light must travel a distance of 8.7×10^9 m each way. How long does it take for a radio signal to travel to the station and back? (58 s)

2. A light-year is the distance light travels in one year. How far does light travel in three years in metres and light years? (2.84×10^{16} m, 3 ly)

3. Periodically, a star explodes. If an explosion took place on a star 10 light-years away, when would the astronomers on Earth see it?

4. Our nearest neighbour among the stars (except for our own sun) is Proxima Centauri which is 4.3 light-years away.
   A. How far is this star away in kilometres? (4.07×10^{13} km)
   B. How long does it take for light to reach us from this star? (4.3 years)
   C. Our fastest space craft at the present time could have speeds approaching 3.0×10^5 m/s. How long would it take for such a spacecraft to reach Proxima Centauri? (~4300 years)
   D. How long would it take for the spaceship that went to the moon (maximum speed 10 km/s)? ($\sim 1.3 \times 10^5$ years)

5. If the Earth's radius of orbit around the sun is 1.49×10^{11} m, how long does it take for sunlight to reach the Earth? (497 s)

6. If Galileo and his assistant were 4.7 km apart, how long would it take for light to traverse the distance? (1.57×10^{-5} s)

7. The respective radii of the Earth's and Jupiter's orbits are 1.49×10^{11} m and 7.78×10^{11} m. The difference in transit times between when the planets are closest and furthest apart is 1.00×10^3 s using modern instruments. Calculate the speed of light using these measurements. (2.98×10^8 m/s)

8. Calculate the distance from the pinhole to an object that is 3.5 m high and whose image is 10 cm high in the pinhole camera which is 20 cm long. (7.0 m)

9. Calculate the height of a building 300 m away from a pinhole camera that produces a 3.0 cm high image in a pinhole camera that is 5.0 cm long. (1.8×10^2 m)

10. A pin hole source of light shines on a card that is 5.0 cm tall located 25 cm from the light source. What is the size of shadow formed on the wall 75 cm behind the card? (20 cm)

11. A coin with a diameter of 2.0 cm is illuminated from a centred point source of light 5.0 cm away. What is the area of the shadow on a screen 20 cm from the light source? (50.2 cm^2)

12. A street lamp is 10.0 m tall and is situated 15 m from a 1.0 m high fence. How long will the fence's shadow be? (1.7 m)

13. In a Michelson method to measure the speed of light a six-sided rotating mirror assembly was used. The minimum frequency of rotation for a successful reading was 54.15 Hz. If the reflecting mirror was 450 km from the rotating mirror, calculate the speed of light. (2.92×10^8 m/s)

14. What is the approximate frequency in Hertz for an eight-sided Michelson's rotating mirror in order to produce a successful experiment when the fixed mirror is 51.52 km away? (364 Hz)

15. When verifying the speed of light, a student set up a pentagonal rotating mirror and a reflecting mirror 35 km away. At what minimum frequency must the mirror rotate so that the reflected light is seen by the observer? (857 Hz)

16. A student sets up a Michelson-type experiment for a twelve-sided rotating mirror. If the mirror spun at a rate of 125 Hz, how far was the rotating mirror from the stationary reflecting mirror? (100 km)