

## Chapter 2

# A Very Brief History of Light

Invisibility is all about controlling and in some sense fooling light – it is a trick. Not a magic or mystical trick, of course, but a real, scientific slight of hand that must be carried out with great technical skill. If we are going to fool light, however, we must first understand what light is, how it moves through space, and how it interacts with matter. This chapter is all about the story of light and the incredible, many-thousand year history of how humanity has struggled to understand its diaphanous, shifting, and on occasion downright spooky nature.

The story of light builds upon the small and the large, the local and the distant. To understand what light is and how it moves we must literally look to the heavens, and we must also peer into the darkened corners of terrestrial laboratories.

### Beginning at the Beginning

“Let there be light!” So begins Genesis, the biblical account of the formation of the universe. Indeed, before there was anything, there was light. This description hardly changes in the modern day, Big-Bang theory of cosmic origins which posits that from the very earliest of moments, through to the first 380,000 years, the universe was a broiling broth of radiation. Light – electromagnetic radiation – bathed all space with one blinding, elemental glow. Indeed, a veritable pea-soup fog of lascivious light pervaded the entire juvenile universe. The cooled remnant of this natal glow is still visible to us today, nearly 13.5 billion years on from the beginning, as the cosmic microwave background radiation.

The universe was born of light, and the galaxies, the stars, the planets, and you and I are its progeny. Incredibly, nearly 10 billion years on from the first moments that signaled the beginning of the beginning, the fecund universe saw the evolution of eyes capable of, well, seeing the light. And then, about 2,500 years ago, humans (the intelligent apes) began to ask what it was that their eyes were seeing.

## The Act of Seeing

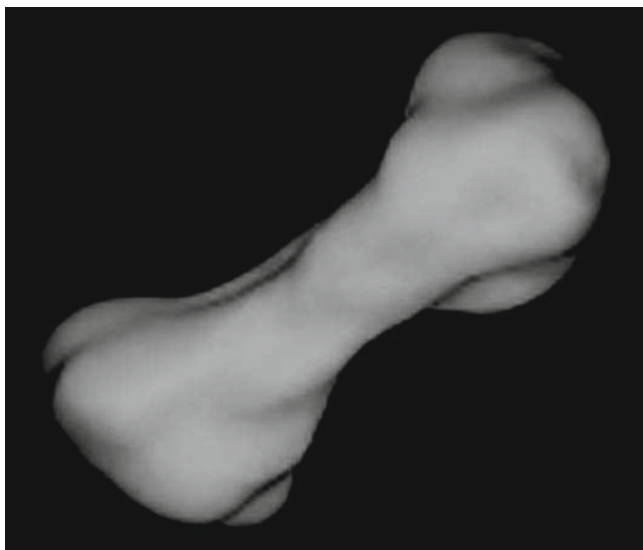
In Sir Arthur Conan Doyle's *A Study in Scarlet*, Sherlock Holmes chastises his long-suffering companion and biographer, John Watson, for observing but not seeing. Here our sympathies must lie with Dr. Watson, since in reality seeing is easy, while observing is difficult – which was perhaps Holmes's point. Indeed, we do not even need to think about seeing; our eyes and brain do it all for us without conscious effort. What we think we see, that is, observe, is something altogether different.

What is it that happens when we see? This question has a basic answer in that what we see is a representation of the physical world around us. Seeing transmits information: there is a tree over there and a sea lion balancing a ball on its nose next to it. But how has the information from the strange scene just described been obtained? Was the process of seeing, that is, the gathering of the data, a passive or an active one? The ancient Greek philosophers, as one might well expect, were the first to consider this question in detail, and in general two basic ideas prevailed.

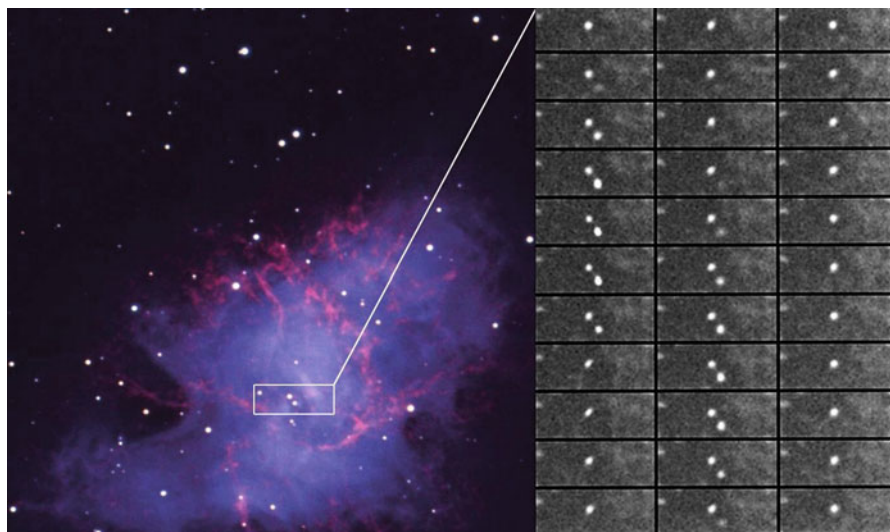
The ancient Greek were among the first to encourage active exploration. In this situation it was envisioned that a form of light (an inner fire) was generated within the eyes, and upon exiting the pupils filled the surrounding space with an active 'seeing' agent that would interact with and reflect off of solid surfaces, and then, the reflected light that returned to the eyes would reveal the vista before us – the tree, the sea lion, and the ball. A modern parallel to this idea would be that of, say, radar astronomy, where a specific signal is sent outwards by an Earth-based transmitter to be reflected from the surface of, for example, an asteroid (Fig. 2.1), with the reflected signal then being intercepted by a receiver placed next to the transmitter. In this manner, the radar transmitter is actively providing the receiver with a signal that contains information about the shape, distance and speed of the asteroid. The receiver alone will not 'see' or detect the asteroid – it needs the transmitted signal to be sent out and then reflected back in order to record the fact that the asteroid exists.

If light is not actively generated by the eye in order to illuminate the surroundings, then, so the ancient philosophers argued, perhaps all objects shed light from their surfaces. According to this idea our eyes are passive instruments. Indeed, in this case, our eyes are just receptacles in which the myriad light rays husked off the surfaces of foreground objects are brought together to create an image. We still see the tree, the sea lion, and the ball, but now the image exists independently of any observer actually viewing the scene.

To continue our astronomical observation parallel, the emission idea is similar to that of detecting pulsars. In this case a rapidly spinning, highly magnetized neutron star generates a beam of synchrotron radiation that can only be detected if it chanced to be directed towards Earth (Fig. 2.2). Casting a radio beam into space, much like a lighthouse casts a message of warning to sailors on the darkened ocean, so a pulsar's emission is modulated by the rotation of its central star. The information that a pulsar exists is thereby periodically cast off into space as a kind of flickering image. This staccato, pulsed emission process is different from that responsible for our



**Fig. 2.1** A radar image of asteroid 216 Kleopatra. The image was obtained with data collected by the Goldstone Radio Telescope. The dimensions for Kleopatra are  $217 \times 94 \times 81$  km, and the light reflected from its surface reveals that it is predominantly made of a nickel-iron alloy (Image courtesy of NASA)



**Fig. 2.2** The Crab Nebula and its central pulsar. The on–off sequence of the central pulsar is shown to the right. Whenever the pulsar beam points in the direction of Earth a flash of light is recorded. The host neutron star is spinning rapidly – indeed, it turns on its axis an incredible 30 times per second. By way of comparison, it takes our Sun over 26 days to spin just once on its axis (Image courtesy of NOAO)

image of the Sun, which advertises its optical presence by sending radiation into space equally in all directions continuously.

The philosopher Democritus of Abdera circa 400 B.C. discoursed on the emission idea of seeing, arguing that objects continually cast off images, or simulacra, of their likeness into space. The image, according to Democritus, was impressed upon the surrounding air, and it was thereby transmitted to the eye. Indeed, many of the early Greek philosophers favored the emission idea of vision, but by the turn of the fourth century B.C., the great minds of Plato and Aristotle had begun to shape the notion that a two way process was at work – one might say it was a classic compromise. There was, it was argued, an external image that was continuously husked off the surfaces of objects, but there was also an ‘inner fire’ radiating from the eye that was required to give the image husks substance. It was the observer that literally made the scene come alive. This dual – two kinds of light, internal and external – approach to seeing dominated intellectual thought for the best part of a thousand years, and it was not until the early Middle Ages that alternatives were actively pursued.

Although the classical Greek notion of what light is turned out to be quite wrong, the concept was not damaging to the search for the correct interpretation and development of ideas concerning the workings of light and its interactions with matter. Indeed, the foundations of geometric optics, still valid to this day, were first (at least in part) laid down by the great mathematician Euclid of Alexandria.

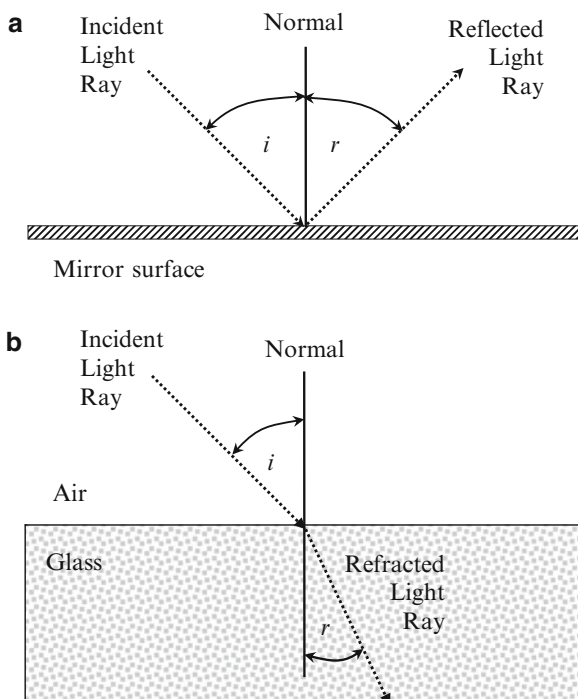
Writing circa 300 B.C. Euclid set out to explain the geometry of vision. Although much of what he wrote need not concern us here, the key, indeed, fundamental, concept that Euclid introduced was the abstract idea of a light ray. Such beams were envisioned to be thin threads of light that traveled in a specific direction (emanating from the eye as far as Euclid was concerned) in a perfectly straight line – this latter attribute being referred to as the rectilinear propagation of light. With this concept in place Euclid then argued that vision – that is, what we see – is composed of those objects situated within a vast cone of light rays, the apex of which is located at the center of the observer’s eye.

The abstract concept of a light ray, and the recognition of the rectilinear propagation of light was a brilliant first step, and although it took another 400 years to work out the details, it was eventually realized that these concepts, if combined with the idea that light rays always travel along the shortest possible path, could explain the laws of reflection and refraction. Hero of Alexandria circa A.D. 100 is often given the nod as the first philosopher to explicitly state the idea of light rays traveling along the shortest path length, and he used this property to prove mathematically the law of reflection, which we will now explain.

## **The Laws of Reflection and Refraction**

The laws of reflection and refraction are fundamental to all optical systems and calculations, and they are cast in terms of what happens to an incident light ray when it encounters a specific surface. They are expressed in terms of the angle of

**Fig. 2.3** (a) The law of reflection, with angle of reflection ( $r$ ) being equal to the angle of incidence ( $i$ ). (b) The law of refraction. When a light ray passes from a less dense to a more dense optical medium, such as from air to water, the angle of refraction ( $r$ ) is always smaller than the angle of incidence ( $i$ )



incidence, which is the angle that the initial, incoming light ray makes to the surface of reflection or refraction. These laws are:

*The law of reflection.* The angle of incidence and reflection are equal (see Fig. 2.3a).

*The law of refraction.* When a light ray passes from a less dense to a more dense optical medium (e.g., from air to water or from air to glass) the angle that the refracted light ray makes with respect to the normal is smaller than the angle of incidence (see Fig. 2.3b).

The law of refraction is clearly more complicated than that of reflection, and indeed we have not as yet explained exactly what we mean by more dense and less dense optical media (but we shall), and neither have we written the law down as a mathematical rule (but we will eventually). In fact, it took many centuries before the law of refraction could be understood and correctly written down as a useful numerical formula.

## The Writings of Alhazen

A number of medieval Islamic scholars studied and wrote on optics, but perhaps the most important work was performed by Abu Ali al-Hasan ibn al-Hasan ibn al-Haytham (965–1039), better known to European scholars through the Latinized name of

Alhazen. Alhazen studied copies of the original Greek texts and, more importantly, performed independent experiments. Indeed, Alhazen dissected and studied animal eyes in order to see how they were constructed and to learn how they might function. From such considerations he began to rework the concepts espoused by Euclid, and he specifically argued that the eye was purely a light receptor, and that there was no need for any illuminating rays to exit from within its interior. Light, according to Alhazen, was a purely external phenomenon that illuminated the objects around us, and it is the light reflected from the surfaces of these objects that interacts with the eye to produce an image of the scene.

Although Alhazen reversed the sense of direction of Euclid's light rays, he affirmed the geometric concepts developed by the Greek philosophers. Light rays still travel in straight lines, as indeed we now know they must, and they also travel along the shortest path between the object and the eye. Interestingly, while Alhazen knew that the eye contained a lens and that lenses inverted images, he argued that the lens was not actually used to shape the image in the eye. Rather, he reasoned, the image that we actually see is that produced on the outer surface of the lens. The light didn't pass through the lens to produce an image, Alhazen reasoned, because this would produce an upside down image, and clearly we see the image the right way up. Here we encounter one of the often, even to this very day, forgotten great illusions of seeing – what the eye produces is in fact an inverted image of the world around us, and it is our brain that actually inverts the perceived image. In this way, what we see with our eyes conforms to the orientation of the tactile world we experience.

## The Dreams of Dr. Mirabilis

As we move forwards into the twelfth and thirteenth centuries the main centers of learning have shifted to northern Europe, with universities being established by the Church authorities in Paris, Oxford, and Bologna. Although a scholastic approach dominated most of the thinking at this time, we do begin to see the serious consideration of new sciences and new possibilities. One of the foremost writers on optics during the thirteenth century was the Franciscan friar Roger Bacon (c.1214–1294). Given the posthumous title of Doctor Mirabilis, Bacon expounded upon the science of optics in his *Opus Maius*, printed in 1267. This remarkable text, written specifically for Pope Clement IV, covers such topics as mathematics, astronomy, astrology, dynamics, optics and alchemy. Bacon also speculates within the folds of his tome about the possibility of heavier than air flying machines, as well as the construction of new optical devices, the telescope and microscope as we would call them, to improve upon human vision. Indeed, Bacon writes that we may “shape transparent bodies, and arrange them in such a way with respect to our sight and objects of vision, that the rays will be refracted and bent in any direction we may desire, and under any angle we wish we shall see the object near or at a distance. Thus from an incredible distance we might read the smallest of letters and number grains of dust and sand.”

What incredible, imaginative and futuristic speculations these were, and they presage the very same free-thinking that drives current researchers in their quest to construct invisibility devices. Take the known and push the possibilities to the utmost limits of reasoned creativity.

Moving onwards, towards the Renaissance, the various ideas concerning the design and operation of simple optical devices (burning lenses, spectacles and mirrors) begin to converge with our modern-day understandings. What was still entirely unclear then, however, was with what speed did light move. It was known to be exceedingly fast, but how fast, and was it even possibly an instantaneous transmission?

## Too Quick, Even for Galileo

To the eagle-eyed, suspicious observer it might have at first seemed that a gang of spies or smugglers had been discovered. For indeed, in the darkness of the Florence countryside two lights were flickering on and off, caught, as it were, in the act of some strange abstract discourse. A conversation of sorts was taking place, but it was the exchange of light rays rather than sound waves that was taking place. Serious scientific investigation was at play. At stake was the determination of the speed of light, and one of the investigators was Galileo himself. The year was 1638.

Galileo turned his thoughts rather late in life to the speed with which light propagates, but he described his nocturnal investigations in his *Discourses and Mathematical Demonstrations Relating to Two New Sciences* (published in 1638). This was one of Galileo's greatest works, and it importantly laid down the foundation ideas to the modern-day theory of dynamics. Within this text, however, Galileo describes how the speed of light might be measured.

The basic idea was that two observers, each equipped with a signal lamp, should position themselves several kilometers apart. The first observer would then open the shutter to his lamp and start counting. As soon as the second observer saw the first light go on, he or she would immediately open the shutter to the lamp. If the two signalers have honed their reaction times to be as fast as humanly possible, then, if the speed of light was finite, the first observer should record a noticeable delay in the illumination of the second observer's signal lamp. Through knowing the distance between the two observers and the delay time for the light signals, the speed of light (at least in principle) could be determined.

Unfortunately, the first experiment to measure light speed was a failure. This was so not because the idea was wrong but because the time delay could not be measured with any degree of accuracy. To determine the speed of light human beings, along with their slow reaction times, would have to be removed from the experiment. It took a further two centuries before this final experimental step was completed.

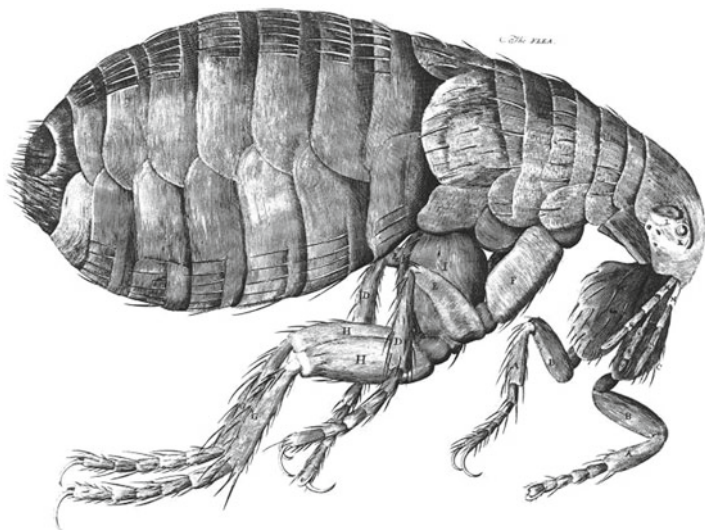


## Hooke's *Micrographia*

Robert Hooke's masterful book *Micrographia* was published by the then newly founded Royal Society of London in 1665. It was, and indeed still is, a beautifully illustrated book, and it stunned an unsuspecting public with its close-up, highly magnified, never-before-seen images of ants, flies, fleas (Fig. 2.4), wasps, gnats, and the minutia of nature. It was a marvel, making the otherwise invisible visible, causing the great diarist Samuel Pepys to eulogize about its content and Hooke to write, "By the means of the telescope, there is nothing so far distant but may be represented to our view; and by the help of microscopes, there is nothing so small as to escape our inquiry." Indeed, with the microscope, as Hooke so clearly realized, human senses could be pushed well beyond their natural limits. The world of the very small and the very distant had been opened up by applied optics. Otherwise hidden and invisible vistas were now accessible to human view.

The publication of Hooke's *Micrographia* marks a turning point in the history of science. Not only did it thrill an awestruck public audience, it also inspired many generations of natural philosophers. A young, moody, and taciturn Isaac Newton read it with enthusiasm in his Cambridge University rooms, although his enthusiasm for Hooke the man was not to last very long.

Within *Micrographia* Hooke described his ideas on light – indeed, he described his ideas on almost everything, causing some readers to complain of its excessively detailed, often obscure and labored text. To Hooke's way of thinking, however, everything in the universe was in motion – nature was never at rest. To this he added



**Fig. 2.4** The flea, as revealed by the microscope. Hooke rightly notes that, "The strength and beauty of this small creature, had it no other relation at all to man, would deserve a description." Hooke's original print is a stunning 18 in. (45.7 cm) across



the notion that all motion could be broken down into waves of one form or another; the rising and falling of tides, the phases of the Moon, ripples on a pond, even earthquakes and the repeated passage of the seasons. The world, according to Hooke, hummed like so many vibrations moving along the strings of a complex musical instrument.

Light, in Hooke's view, was an especially symmetric vibration. Unlike the modern-day picture, however, in which light of different colors is viewed as having different frequencies of vibration, Hooke thought that color was a corruption or distortion of white light. Indeed, he imagined light to spread out from an object like so many ripples on the surface of a pond. White light corresponded to those ripples that moved outward along the radii of expanding concentric circles; colors arose under refraction, however, because the path of the ripples were changed and became distorted. In modern terms it could be said that the wave front was no longer transverse to the direction of propagation. The eye, Hooke argued, could pick up on these distortions, and red light, for example, corresponded to a wave profile that had a steep rising front and a long decaying profile after the peak. Blue light, in contrast, corresponded to a wave profile that began with a shallow, slowly rising profile followed by a rapid decline after the peak. Hooke's wave and color theory was never popular, and it is indeed physically incorrect, but it set the stage for more complete wave theories to follow – especially the one outlined by Christian Huygens in his 1703 text *Dioptrica*.

## Moving Heaven and Earth

At the heart of Galileo's struggles with Church authorities was the heliocentric theory of Copernicus. The problem was not the theory itself, but the Church's insistence that Galileo should not publicly teach what he could not physically prove. Indeed, the Copernican model as originally published in 1543 had its problems – it was, in fact, fundamentally flawed with respect to its assumptions about the circular shape of planetary orbits. Using the planetary data collected by Tycho Brahe, however (who, in fact, didn't believe in the Copernican model), Johann Kepler was able to sort out the mathematical details and show that the orbits were actually elliptical, and that the speeds of the planets varied according to their position with respect to the Sun. Publishing his findings in 1609 and 1618 in two masterful works, *Astronomy Nova* and *Harmonius Mundi*, respectively, Kepler's three laws of planetary motion placed the Copernican model on a firm predictive footing.

As the seventeenth century unfolded so the acceptance of the Copernican model grew. There was no indisputable experimental evidence, however, to prove the actuality of Earth's spin and/or orbital motion about the Sun, and there was still the nagging problem that Kepler's laws had no known physical explanation. Confidence in the model was made absolute, however, with the publication of Isaac Newton's *Principia Mathematica* in 1687. This work, initially teased from a reluctant Newton by the ever diplomatic Edmund Halley, set science spinning in a new direction.

Newton's *Principia* was as revolutionary as Copernicus's *De Revolutionibus*, but rather than arriving to an unenthusiastic silence, his work was heralded with raucous acclaim. Newton had, with one text, changed the way in which science was to be done, and he established the rules and equations that described the motions of the planets. In one clean swoop, Newton explained why the Copernican model had to be right and why there should be three Keplerian laws of planetary motion – it all boiled down to gravity and the conservation of angular momentum.

Although Newton explained the theoretical side of things, the experimental verification of the Copernican model was still not established – an irritating leftover, one might say, concerning a now fully believed-in theory. Experimental evidence for Earth's motion was eventually found in 1725, however, after it had been observationally shown that the speed of light must be finite.

## Dealing with Descartes

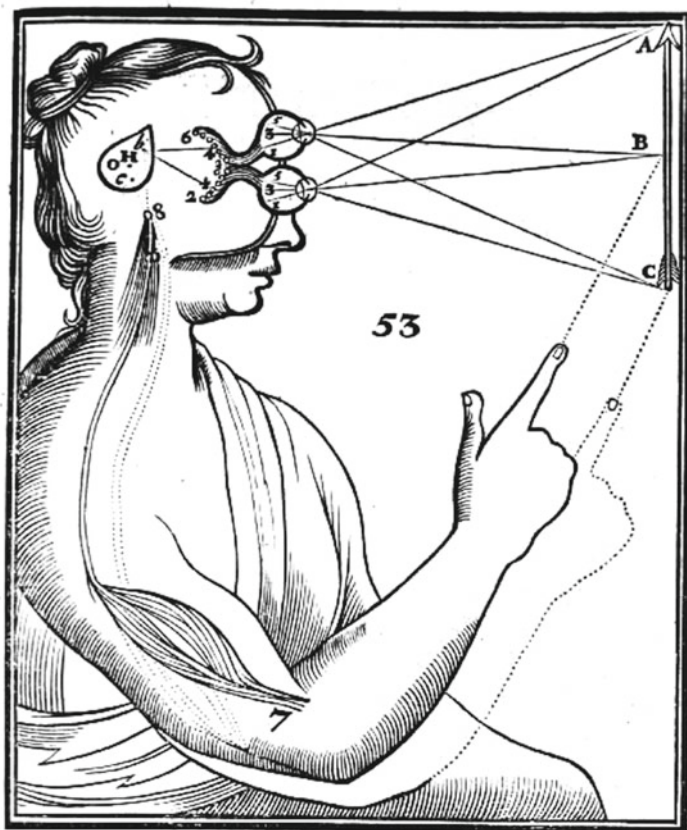
Much, if not all, of the *Principia* was written to satisfy Newton's dislike for the philosophy constructed by French savant Rene Descartes. Descartes was famous for developing a dualistic philosophy in which mind and matter were separated and distinguished according to the essence of thinking and spatial extension. All entities, and especially living ones, were thought of as machines, made up of inert and independent components, with an overarching order being imposed from within. This was the world of invisible ghosts within the machine (Fig. 2.5).

Descartes wrote about optics and light, but his reasoning is often contradictory and incoherent. Most of his ideas on light are contained within a *Treatise of Light*, which was written as part of a more extensive body of work published during the years 1629–1633. Descartes reasoned that light traveled instantaneously, as an impulse across adjacent particles, and yet allowed the speed of light to vary in different media. Indeed, Descartes never really makes it clear whether he thinks of light as being a form of motion or the movement of matter. All such philosophical wrangling aside, however, Descartes was able to reason his way to what is the correct mathematical form for the law of refraction – known today as Snell's law.

## Snell's Law

Dutch mathematician and astronomer Willebrod Snell van Roijen derived his law for the refraction of light in 1621, although he never actually published it in his lifetime. Indeed, it was to be 82 years after its discovery that the law would first see print under Snell's name.

While Rene Descartes had published his derivation of the refraction law (identical to Snell's) in 1637, it was Snell who technically made the first innovations, according, that is, to Dutch scientist Christian Huygens, who publicized Snell's



**Fig. 2.5** An illustration depicting Descartes' proposed linkage between vision, which was interpreted by the brain and mind, and the mechanisms within the body responsible for reacting to external stimuli

work in his own 1703 masterpiece *Dioptrica*. Neither Snell nor Descartes, it turns out, can really claim priority for discovering the refraction law, since in all but the detailed mathematical language, Islamic scholar Ibn al-Haytham described the relationship in his *Kitab al-Manazir* (Book of Optics) written, while under house arrest in Egypt, during the decade 1011–1021.

The modern-day version of Snell's law is expressed in terms of the refractive indices of the two media through which the light is passing. The refractive index  $n$  is a measure of the speed of light within the given medium  $V_{\text{medium}}$  compared to that in a vacuum  $c$  (its fastest possible speed): specifically,  $n = c/V_{\text{medium}}$  and this ratio is always going to be greater than or equal to one.<sup>1</sup>

<sup>1</sup>The refractive indices of various optical solids, liquids and gases are readily available in almost any compilation of physical constants.

We are now in a position to explain the term optical density introduced earlier with respect to the law of refraction (recall Fig. 2.3b). Indeed, the meaning is quite straightforward, in that the larger the optical density, the larger is the associated refractive index of the medium and the slower the light speed through it. The refractive index for air is usually taken as  $n_{\text{air}} = 1$ , although it is in fact variable according to the temperature and density of the air (as we shall see in Chap. 3). The refractive index of ice is 1.31; that of Perspex 1.495, while that of diamond is 2.417. The later result indicating, for example, that light travels nearly 2.5 times more rapidly through air than it does through a diamond.

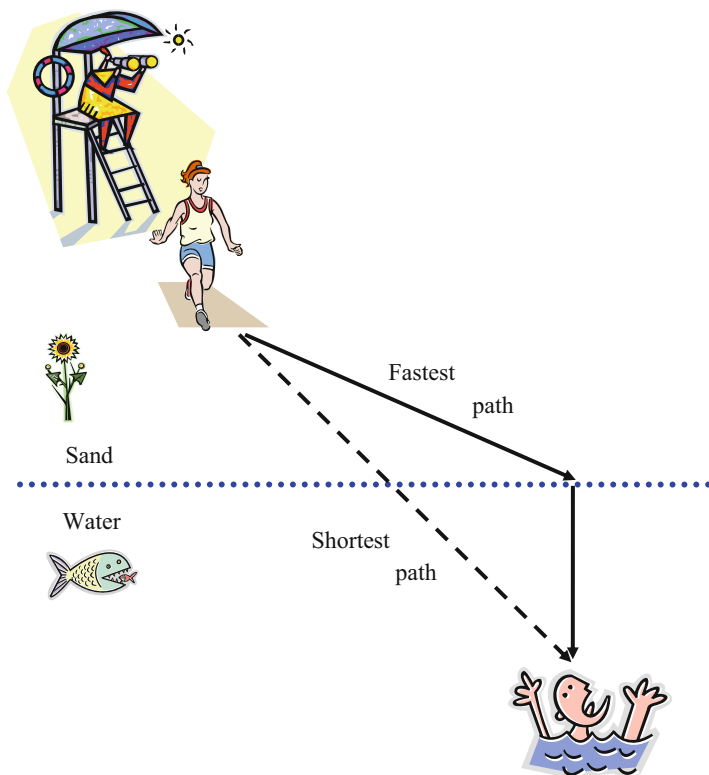
With the definition of refractive index in place we can proceed to a statement of Snell's law. If the first medium has refractive index  $n_1$ , and the second  $n_2$ , then the relationship between the incident,  $i$ , and refracted ray,  $r$ , is given by the sine of these angles such that  $n_1 \sin(i) = n_2 \sin(r)$ . Snell's law is slightly more complicated than the law of reflection (recall Fig. 2.3a), but it is nonetheless a straightforward mathematical expression and simple enough to evaluate with an electronic calculator.

## Fermat Finds the Quickest Way

Like Newton, French mathematician Pierre de Fermat was entirely unimpressed with Descartes theory of light, and he publicly said so. For Fermat this was a bad move. Descartes was incensed that his ideas should be so criticized, and he deliberately set out to destroy Fermat's reputation. Fermat, however, at least posthumously, receives the last hurrah since Fermat's principle is still taught in optics classes to this very day, whereas Descartes is rarely, if at all, mentioned.

Personal problems with Descartes aside, Fermat established the basis for what is now recognized as his principle in the mid-1650s. He built upon a classical foundation. Indeed, in the first century A.D. Hero of Alexander had noted that the law of reflection (that the angle of incidence is equal to the angle of reflection) could be explained upon the supposition that light traveled the shortest possible distance between the source and the observer. In the eleventh century Islamic scholar Alazen, took Hero's argument further and applied it to refraction – finding in consequence the forerunner to Snell's law. Fermat took this ancient idea one step further and argued in early 1662 that light travels not along the shortest geometrical path but along the path with the shortest travel time. This is a significant change in thinking and one that inherently adopts the idea that the speed of light is both finite and variable in different optical media. For Snell's law to hold true, for example, light must travel more slowly in glass or water than in air – in contradiction, in fact, to the claims of Descartes.

If Fermat's problems with Descartes were not enough to be getting on with, he sadly found no great support for his ideas on light either. The main problem was that his arguments were seen by others to imply knowledge-a-forethought to nature. How did a light ray *know* which was the path with the shortest time, it was asked, since, of course, light doesn't know and indeed it cannot reason.



**Fig. 2.6** Analog of Fermat’s principle. The lifeguard minimizes the time to reach the swimmer by minimizing the distance that she has to swim. The rationale for taking the crooked path is based upon the fact that she can run more rapidly on sand than swim through water, and thus the direct, straight-line path is not the one that has the least travel time

Philosophically, Fermat’s principle is not a problem if one views it simply as a mathematical means of calculating where a light ray will go – it is a means of deduction rather than an explanation of original cause. Eugene Hecht (Adelphi University, New York) has eloquently written before us, when it comes to Fermat’s idea, “let us embrace it but not passionately.” Not for the first time in physics, nor indeed for the last, are the means of calculating something about nature strange, spooky, and counterintuitive – we shall pick up on the problem of how light behaves, one more time, in Chap. 4.

There is a rather nice physical analog to Fermat’s principle that relates to the actions of a lifeguard and a swimmer in distress. Figure 2.6 illustrates the problem faced by the lifeguard, who is our proxy for the light ray – light goes where the lifeguard goes. Now, between the lifeguard station and the ocean is a stretch of sand-covered beach, and the lifeguard knows that she can run faster on sand than swim through water. So, in order to minimize the time in getting to the swimmer in distress she reasons that the shortest, straight-line distance between the swimmer

and the lifeguard station is not the optimal path to take. Rather she must take the path that minimizes the distance that has to be swum (because, remember, she runs faster than she swims). In this case the path taken by the lifeguard is the one that has a ‘kink’ at the sand-sea boundary, since this path minimizes the swimming distance. Fermat’s principle says that the path taken by a light ray can be calculated in the same manner as that carried out by the lifeguard. In modern optics Fermat’s principle is cast in terms of differential calculus and the determination of what are called stationary points in the optical path with respect to variations in path length.

## Newton’s *Opticks*

Although the *Principia* came into print when Newton was a relatively young 44 years old, his equally provocative and revolutionary *Opticks* appeared in 1704, when he was a stately 61 years of age. Many decades in gestation, *Opticks* was a synthesis, and sometimes rambling account, of numerous ideas. Not least among its pages are Newton’s ideas on the properties of light and how it interacts with matter. The book also outlines his revolutionary ideas on how science itself should be conducted – building, as it were, on the twin pillars of mathematics and experimentation.

The story of Newton’s ideas on light begins in 1672, at which time he described his optical experiments to the members of the Royal Society in London. “In the beginning of the year 1666... I procured me a triangular glass prism, to try therewith the celebrated phaenomena of colour” – so wrote Newton in his preamble that led up to his *experimetum crucis*. Indeed, in this “critical experiment” he described how a glass prism could be used to show that white light must, in fact, be composed of many differently colored rays. Light, he argued, is a heterogeneous mixture of different colored components that the prism is able to separate out according to their specific ‘refrangibility’ (or, as we would now say, refractive index). To Newton the color of light was simply related to the size of its transmitting corpuscles. In 1675, in another letter to the Royal Society, Newton further explained that he supposed, “light is neither aether, nor its vibrating motion, but something of a different kind propagated from lucid bodies.” With this idea, that light can be envisioned as a stream of minuscule corpuscles, Newton was at odds with his fellow countryman Robert Hooke and Dutch scientist Christian Huygens, who advocated the more vibrant, wave theory of light. For these scientists, light was an oscillation that propagated through the “aether,” or ether, a diffuse medium that pervaded all space. While the propagation of his light corpuscles did not require an intervening aether, Newton nonetheless suggested that they did, somehow, interact with it.

Unlike Descartes and many of his contemporaries Newton advocated a finite speed for the propagation of light (indeed, Dutch astronomer Ole Romer, as we shall see momentarily, had shown it must be finite in 1676). In addition to light speed being finite, Newton conjectured that its speed would vary according to the optical properties of the medium through which it was passing. He reasoned, for example, that the speed of light would be slower in air than in glass or water since in the latter,

because of their higher densities, there was a reduced quantity of aether. This was a crucial distinction between Newton's theory and its competitors, which suggested that light should move more slowly through more dense optical media. Indeed, as we shall see shortly, the speed issue was the Achilles heel of Newton's theory.

## The Inconstant Moons of Jupiter

Galileo first noticed the four moons that orbit Jupiter on the night of January 7, 1610. It was an incredible find, and Galileo knew he could profit from it; scientific fame was assured, and with the right dedication to a rich patron a better paying job was his for the taking. Writing of his telescopic discoveries in *Siderius Nuncius* Galileo suggested that the newly discovered worlds be called the Medician stars.<sup>2</sup> The Medician family was impressed by the gesture, and Galileo began to climb the slippery and more often than not dangerous slopes of the Italian Renaissance social ladder.

Now officially named Io, Europa, Callisto, and Ganymede the Galilean moons are classed among the most incredible and fascinating objects within our Solar System. Io is a volcanic world, continually turning itself inside out; Europe has a global ocean underneath an icy crust; Callisto also supports a hidden sea. Ganymede is a behemoth of a moon, and in fact outsizes the planet Mercury by several hundred kilometers. Io, the innermost of the Galilean moons, takes some 42.456 h to complete one orbit about Jupiter. Further out and therefore moving more slowly Callisto takes 16.689 days to traverse its orbital path. The moons tap out a stately round and furnish the heavens with the hands of a pointillist clock – provided, that is, we can work out how to read the message on display.

Galileo correctly reasoned that if tables of the exact transit and eclipse times of the Medician stars could be constructed from one fixed, specific location then navigators and observers at different locations could use these tables and their local time observations of the moons to determine their longitude.

Systematic observations of the Jovian moons began soon after Galileo publicized his discovery, but it was Italian mathematician Giovanni Domenico Cassini who first noted, in 1675, something puzzling about their motion – the apparent transit and eclipse times of the moons varied according to the distance that Jupiter was away from Earth. From this observation Cassini correctly reasoned, at first, that this was a direct consequence of the finite speed of light. He later changed his mind, however, and threw in his lot with the philosophy outlined by Rene Descartes and reasoned that light must travel instantaneously.

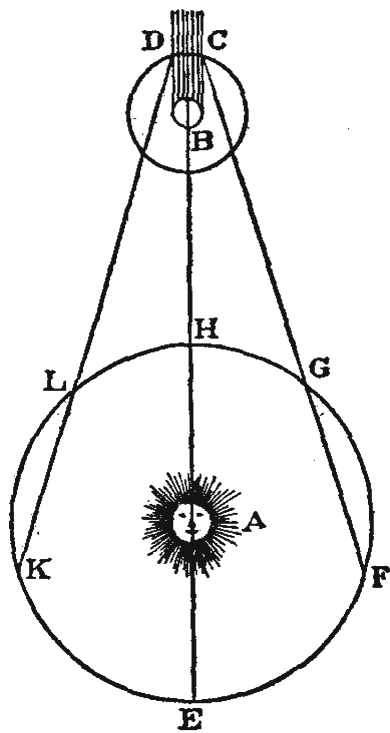
Taking a second look at the problem, however, Danish-born astronomer Ole Romer, working at the Observatory in Paris, made precise timing measurements and

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<sup>2</sup>Galileo's suggestion was never popular. The satellites (not stars) were and still are invariably known as the Galilean moons of Jupiter.



**Fig. 2.7** Romer's diagram for explaining the maximum occultation time advance and delay (compared to an imagined observer at A) for a Jovian moon. According to the location of Earth being at either E or H the eclipse times will be early and late, respectively. The speed of light can be deduced by determining how long it takes light to cross the distance HAE



concluded that the eclipse times of Jupiter's moons truly did indicate that light traveled at a fast but finite speed. Remarkably, upon announcing his results at the November 21, 1676, meeting of the *Academie des Sciences* his most vociferous opponent was Cassini.

What was it that Cassini and Romer observed? The geometry of the situation is illustrated in Fig. 2.7. The circle LHGFKEK indicates Earth's orbit around the Sun (located at A), and B indicates the position of Jupiter. The circle around Jupiter represents the orbit of one of the Galilean moons. The points C and D illustrate the locations at which the particular Jovian moon will begin and end an occultation, and these are the observable events that can be timed from Earth. What Cassini and Romer found was that compared to an imagined observer located at the Sun (A), who would see occultations and transits at equal intervals of time, the timing of the same events observed from Earth would be either early (when Earth was at position H, for example), or late (if Earth was at position K or F). The time difference, being early or late, correlates with Earth being closer or further away from Jupiter. The maximum time delay between the early and late occultation times will be that recorded between points H and E on Earth's orbit. And, this maximum time delay will correspond to the time it takes light to cross Earth's orbital diameter. In modern terms, Earth's orbital diameter is known to be about 300 million kilometers across, and it will take light some 1,000 s (or about 16.5 min) to cross this distance.

While the observational results presented by Romer proved that light traveled at a finite speed, he deferred from actually calculating its speed since at that time the physical measure of Earth's orbit was not well known. Finally, however, after more than 2,000 years of speculation, the speed of light had been brought down to size, no longer infinite, but certainly extremely fast.

## The Aberration of James Bradley

The reverend James Bradley (1693–1762) was a serious if not intimidating man. In many ways, however, he can be considered to be the founder of precision astronomy, and he certainly had a penchant for finding small angular corrections. As an astronomer he spent many nights during 1725 lying down – not sleeping, of course, but carefully peering through the lens of a long zenith telescope. The work was painstaking, exacting, and ultimately revolutionary. He was looking for a small semi-annual shift in the position of one specific star – the star gamma Draconis; also known under the Arabic name of Eltanin (meaning *Serpent*). The star had been chosen quite deliberately since it passes almost directly overhead for an observer stationed in London. By passing through the zenith the star's position could be measured with exquisite accuracy, and what Bradley was hoping to measure was a parallax effect due to Earth's motion in its orbit around the Sun over a 6-month time interval. In this manner Bradley was working at the cutting edge of eighteenth-century astronomy, and he was also hunting for one of astronomy's holiest of grails. If he could measure the parallax of Eltanin then he could calculate how far away it was, determining thereby, for the very first time, the scale of interstellar space. Bradley failed in his parallax quest, but he succeeded in finding something else that in retrospect was just as important. He proved that Earth must be in motion about the Sun.

Over the course of a year's observations Bradley tracked and accurately measured the position of Eltanin as it passed overhead. He found a 6-monthly shift of  $0.01^\circ$ . There was a problem, however, since the observed direction of the shift was not that which would be expected for parallax. It was an unexpected aberration – indeed, it was stellar aberration. What Bradley had discovered was that Earth must be in motion around the Sun (as Copernicus had said it had to be, and as everyone then firmly believed anyway), but now there was experimental proof. Galileo would have been elated – Copernicus had finally been vindicated by direct experimental measure.

The effect that Bradley had observed can be seen during any rush hour scramble on a windless, rainy day. As the pedestrians scurry to work or run for their buses, you will notice that their umbrellas are not held vertically but are distinctly angled forwards in the direction that they are moving. The umbrellas are tilted forward, not because of the wind, but so that the vertically falling rain doesn't soak their lower body and legs. People angle their umbrellas unconsciously to compensate for their motion through the rain; astronomers must do essentially the same thing and tilt

their telescopes in the direction of Earth's motion, as it moves around the Sun, in order to accurately track the position of a star.

Bradley's observations, in addition to revealing Earth's orbital motion, also allowed for a refined measure of the speed of light to be made. In a 1729 letter to the Royal Society Bradley announced his findings – the speed of light was no less than 185,000 miles per second (or about 298,000 km per second). It was an incredible result, and one that was not to be bettered by laboratory experimentation for another 120 years. Bradley's fame was in its ascendancy, and in 1742 he was awarded a plumb job, becoming Britain's third Astronomer Royal.

As we move into the early nineteenth century, it had become clear to most scientists that light must travel at an astounding speed, and that it behaved as if it were a wavelike phenomenon. But, what is a wave and how can waves be quantified? This we shall discuss next, and thereafter describe the definitive experiments that seemingly put paid to Newton's tiny corpuscular rays once and for all.

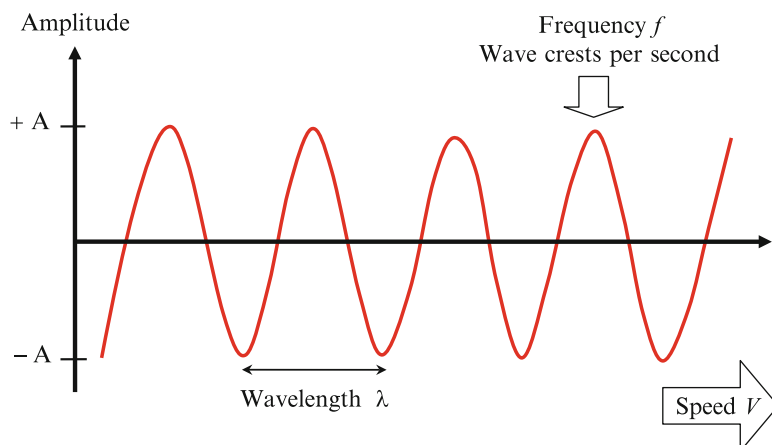
## Waves and Wave Interactions

Waves and wavelike phenomena surround us. The world literally undulates its way toward the future; the Sun rises and the Sun sets (a day-night wave), earthquakes cause the ground to tremble (surface seismic waves), and traffic on the way to work each morning stops and starts (a frustration wave?).

Waves can have many different sizes, shapes and forms, and can mix and meld. For all this variation, however, there is a remarkable theory relating to waves that was first derived by French mathematician Jean Baptiste Joseph Fourier during the second decade of the nineteenth century. Fourier showed that all periodic waves, no matter what their profile looks like, could be constructed by adding together a series of simple sine waves, each of a different amplitude and frequency (these terms are defined below). The basic unit of all waves, therefore, is the sine wave.

A sine wave is the sort of wave profile that we have all seen at one time or another. A wave rippling along a rope held between, say, two white-coat clad experimenters would be an example of a sine-like wave. With this image of a rippling rope in mind, we also learn something else about waves – a wave is a disturbance that moves through a medium (the rope in our image). That is, the wave describes the time and space deformation of the medium away from an equilibrium (or rest) position. The rope, in our specific case, periodically moves up and then down about a horizontal line (the rest position) at each and every point along its length. The wave disturbance moves along the rope, but the rope itself does not physically move between the two experimenters – all the motion in the rope is in the vertical up and down sense.

A perfect sine wave has four essential characteristics: its wavelength, its period, its amplitude and its propagation speed. The wavelength is the spatial distance,  $\lambda$ , over which the wave profile starts to repeat itself (Fig. 2.8), the period is the time taken to repeat the profile and the amplitude is a measure of the displacement of the wave away from the equilibrium (or zero) point. The time characteristic of a wave



**Fig. 2.8** Characteristics of a wave. The frequency is related to the number of wave-crests that pass a specific reference point (*vertical arrow*) per second. The speed of the wave is the product of the wavelength times its frequency

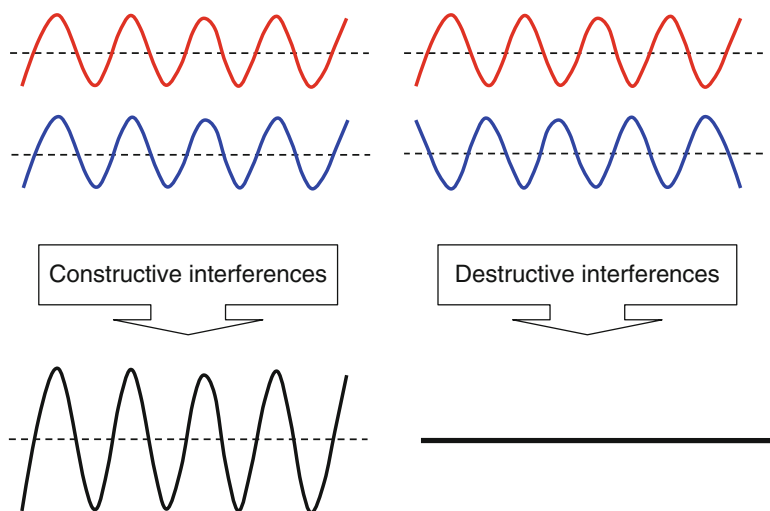
is usually expressed in terms of its frequency,  $f$ , which is just the inverse of its period. The speed  $V$  with which a wave propagates through a specific medium is related to the wavelength and frequency according to the formula:  $V = \lambda f$ .

One of the most important characteristics of waves is that they can be added together, or superimposed, to form another wave. The resultant wave, however, can look very different from the original pair, according, that is, to their so-called phase difference. If two waves are exactly in phase then the amplitudes of each will add at every instance and the resultant wave will have twice the amplitude at every point in its profile. This is called constructive interference.

If, on the other hand, the two waves are combined such that one wave is shifted one half wavelength on from the other (a phase difference of  $180^\circ$ ), then the peaks and troughs of each wave will cancel each other out, and in fact no wave will result – the summation will be a straight line. This is destructive interference. As we shall see in Chap. 5, destructive interference is one method by which aircraft can be made invisible to radar waves. The two cases of interference as just described are illustrated in Fig. 2.9. In general the phase difference can be any fraction of a wavelength – or fraction of a period – and the resultant wave summation, that is, interference, can be quite complex, as we shall see later on.

## The Triumph of Waves

With the finite speed of light established, the next problem that the natural philosophers had to sort out was the question, “What is light?” Is it a wavelike phenomenon or is it a stream of small corpuscles? Newton had made his thoughts clear in 1704: light

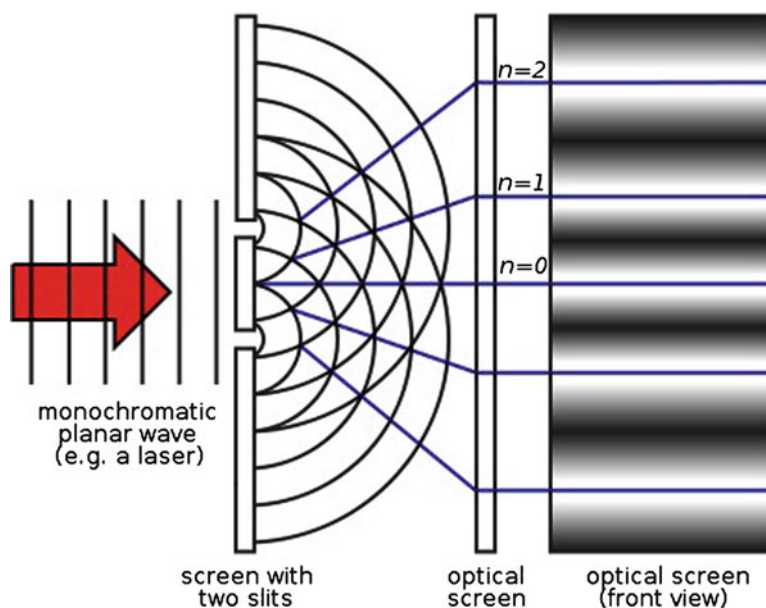


**Fig. 2.9** (a) The constructive interference of two waves. (b) The destructive interference of two waves

was composed of a stream of different-sized particles. And, while Robert Hooke had advocated an alternative wavelike theory for light, it was Christian Huygens in Holland who really established the detailed working theory.

Writing in his 1678 work *Traite de la Lumiere*, Huygens articulated his principles of wave optics. Light could be thought of as a traveling wave front that moved through space. The idea here is that we can imagine the light to stream away from an illuminated source with successive wave fronts spreading out one after the other as ever-growing spherical boundaries – just like the ripples moving over the surface of a mill pond after a stone has been dropped through its surface at some point. Importantly, Huygen’s also introduced the idea that every point on an advancing wave front could be thought of as the potential center for a new disturbance capable of generating its own specific wave front. An everyday analog of this principle is demonstrated by sound waves.

Imagine that we have two rooms that are connected by a single small doorway. In one room is an observer – or listener – and in the other room is a sound source, say a radio. Everyday experience, or if you are not convinced experimentation, now tells us that no matter where the radio is located within the one room – in a corner, in the middle, on the floor, or on the ceiling – the listener in the adjacent room will always hear the sound as if the radio is located at the door itself. (This analog, as all analogs invariably are, is limited and assumes there is no sound conduction). The same behavior as displayed by our analog sound waves should, according to the Huygens principle, also be present in light, and in 1803 the British polymath Thomas Young demonstrated that this was indeed the case. Young’s slits experiment is a classic, and it is still a standard right of passage to this very day for any student taking a college or university physics program. It is a beautifully simple experiment, and yet it delivers a result of profound importance.

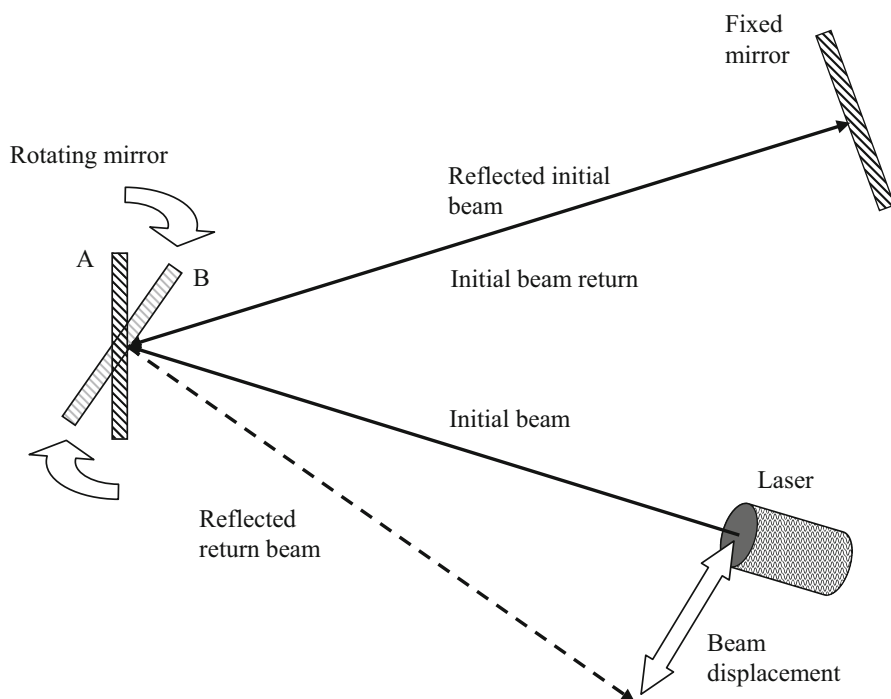


**Fig. 2.10** Young's slits experiment for the demonstration of the wavelike behavior of light (Image courtesy of [theskepticsguide.org](https://theskepticsguide.org))

The essential layout of Young's experiment is shown in Fig. 2.10. The key idea behind the experiment is to set up the conditions for constructive and destructive interference (recall earlier in this chapter). With respect to Fig. 2.10, we can imagine a parallel wave front approaching a panel in which two slits have been cut. Each of the slits in the panel will accordingly act as the source of a semi-spherical wave front, but now the expanding wave fronts will begin to cross over each other, setting up the conditions for interference. Where two wave fronts interact in a peak-to-peak manner the amplitude will be enhanced (constructive interference), and where two wave fronts interact in a peak-to-trough manner the amplitudes will cancel to zero (destructive interference). The ultimate result of the interference between the expanding wave fronts will be a series of light and dark bands being formed on a screen (to the far right in Fig. 2.10). Upon actually seeing such interference bands on his experiment's screen, light, Young concluded, must be a wavelike phenomenon.

## Faster or Slower? A Crucial Test

If, with the publication of Newton's *Principia* in 1687, French scientific pride had been deflated through the sound trouncing it gave to Descartes' plenum-packed universe of mystical whorls and eddies, so the savants of Paris were able to regain some revenge by putting Newton's optical theory to the test. The predictions between



**Fig. 2.11** Schematic outline for the rotating mirror experiment used by Leon Foucault to determine the speed of light in air and in water

the rival theories were, for once, quite clear. The wave theory required that the speed of light must decrease in a denser optical media (such as glass or water), whereas the corpuscular theory of Newton (and Descartes for that matter) required that it travel faster. It would be a case of winner takes all.

If an exact experimental measure of the speed of light through water, say, could be found, or even just a difference in its velocity recorded then the critical question could be answered. French experimental physicist Leon Foucault was the person up to the challenge, and at the heart of his experimental test was a whirling mirror (Fig. 2.11).

The beauty of Foucault's test was that it measured a relative response rather than an absolute one. The idea was not to physically measure the speed of light in water, but to see what affect a column of water had upon the position of an imaged light ray. In a modern-day version of Foucault's experiment (as in Fig. 2.11) a laser sends out a thin pencil beam of light that is directed in order to reflect off a rapidly spinning mirror. Upon being reflected from the surface of the rotating mirror the light beam is directed towards a distant stationary mirror. After reaching the fixed mirror the light beam is halfway around its path and is reflected back towards the first, still rapidly rotating mirror. When the light beam, however, encounters the rotating mirror again, it will have moved slightly around its spin axis and accordingly the light beam, after a final reflection, ends its path being directed towards a screen displaced



away from the laser. Technically, if the distances between all the mirrors and the lamp and screen are measured, and the mirror's spin rate is known, then the speed of light can be determined, but this is not the main task of this particular experiment. The point, remember, is to see if the speed of light increases or decreases during its passage through a water column.

The experiment is now half complete. The position of the returned light beam on the screen is carefully recorded – in practice this is done with a microscope and a finely divided scale. The trick now is to place a column of water (in a sealed glass tube) in the beam path somewhere between the rotating and the fixed mirror. The question then becomes, what happens to the returned beam displacement? If light travels more rapidly through water, as Newton's corpuscular theory predicted, then the returned beam will hit the screen closer to the laser than determined under the open-air configuration. This is because the light beam will hit the rotating mirror on its return path sooner than before, and the mirror will have accordingly spun through a smaller angle and the final reflection will also be at a smaller angle than in the open-air case.

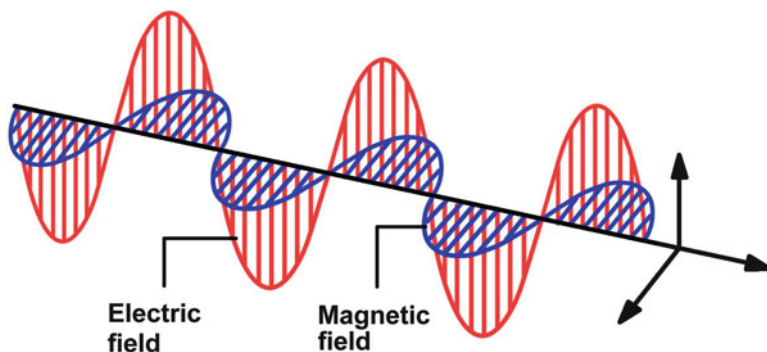
The exact opposite effect will occur if light travels more slowly through the water column. In this case, the returned light ray will take longer to reach the rotating mirror, which will have spun further around its axis, and accordingly the final reflection will intercept the screen at a larger angle of displacement than that observed in the open-air configuration. It is a brilliantly simple experiment.

Foucault fussed over the experiment but in 1850 was ready to release his findings. The water column caused the light beam to return later and the displacement was away from the laser and the in-air only reference position on the screen. Light travels more slowly through water, and Newton was wrong – the corpuscular theory had been trounced, and the wave theory advocated by Huygens and Hooke vindicated. Light must be a wave.

But with one theory eliminated another problem arose. What was it that was 'waving,' and through what kind of medium did it propagate? These were not, however, Foucault's problems to solve, although in later life he came back to refine and finesse his experiment and was able to measure ever more precise values for the speed of light.

His next experimental triumph, in 1851, was another scientific revolution. The revolution in this case was the first experimental demonstration of the spin of Earth with a giant pendulum suspended from the inside of the dome of the Parthenon in Paris. This verified experimentally the rotation theory advocated by Copernicus in 1543.

At this stage, Foucault drops from our story and the next major player we encounter is James Clerk Maxwell. As we shall see in Chap. 4, Maxwell was one of the scientific giants of nineteenth-century science – his mark is indelibly stamped on the foundations of many branches of physics, ranging from thermodynamics to optics and classical mechanics, and to the development of electromagnetic radiation theory. It was Maxwell who, in the mid-1860s, forged a link between magnetism and electricity – fields that were previously thought to be distinct. And, by forging this linkage he was able to show that light is a double wave (Fig. 2.12). The phenomenon that we call light is, in fact, a waveform with both a varying magnetic and



**Fig. 2.12** The double waveform of light. The magnetic and electric fields oscillate at right angles to each other

a varying electric component, with the two components oscillating at right angles to each other. Maxwell's analysis was new and stunning, but it took some time, nearly 30 years in fact, before it was fully realized just how stunning and useful a result it really was.

## Polarization

The polarization state of a light beam is, by convention, described according to the orientation of the plane in which the electric field vibrates (Fig. 2.12). The measurement is in the plane perpendicular to the direction of travel, and if the wave crests are all orientated in the same plane then the light is said to be linearly polarized. The plane of the electric field can also continuously rotate as it moves along, and in this case the light is circularly polarized. Not all light is polarized. Starlight, for example, is produced by a large number of randomly moving atoms, and there is no correlation between the orientations of the resultant electric field planes – the light is unpolarized.

The French mathematician Etienne Louis Malus first described the polarization of light in 1809, and it turns out that light is generally polarized in the process of reflection. The light from the Moon, for example, is polarized since the illuminated fraction that we see from Earth is, of course, reflected sunlight. Light seen in reflection from the surface of a lake or a wet road is also polarized. Indeed, by adding a polarizing component to spectacle lenses irritating glare can be reduced and image quality greatly improved. How does this work?

The way in which polarizing filters, or polarizers, work is to force the electric field orientation into one specific plane – that is, after passing through the filter the transmitted light is linearly polarized. Essentially the material out of which the polarizer is made preferentially absorbs in all but one specific direction (the polarization axis). Longer wavelength radiation, such as microwaves (to be described in

Chap. 4), can, for example, be linearly polarized by making them pass through a closely spaced grid of parallel conducting wires. Indeed, an analogy that is often used to describe polarization is that of a person trying to send a wave along a rope that at some point passes through the gap in a picket fence. The person trying to “flick” the wave along the rope must send the wave in a direction that is parallel to the boards of the fence, else the rope will physically hit one or both of the wood panels and the wave will be destroyed.

The linear polarization properties of sunglasses can be seen if a light source, say a light bulb, is viewed through two pairs of glasses. By rotating one pair of sunglasses in front of the other the brightness on the image will vary from full brightness (when the polarizers are parallel) to no image at all, that is, no transmission of light, when the polarizers are at  $90^\circ$  to each other. Indeed, the variation of brightness is described according to the angle between the two sets of polarizers. (It was, in fact, this very law that Malus described in 1809).

Polarization measurements can be used to reveal otherwise invisible characteristics of many objects. Indeed, engineers often construct plastic models of new machine parts or architectural assemblies so that they can be subject to controlled stresses and loads – the point being that the applied forces will change the polarization properties of the plastic and thereby reveal regions where failures might occur.

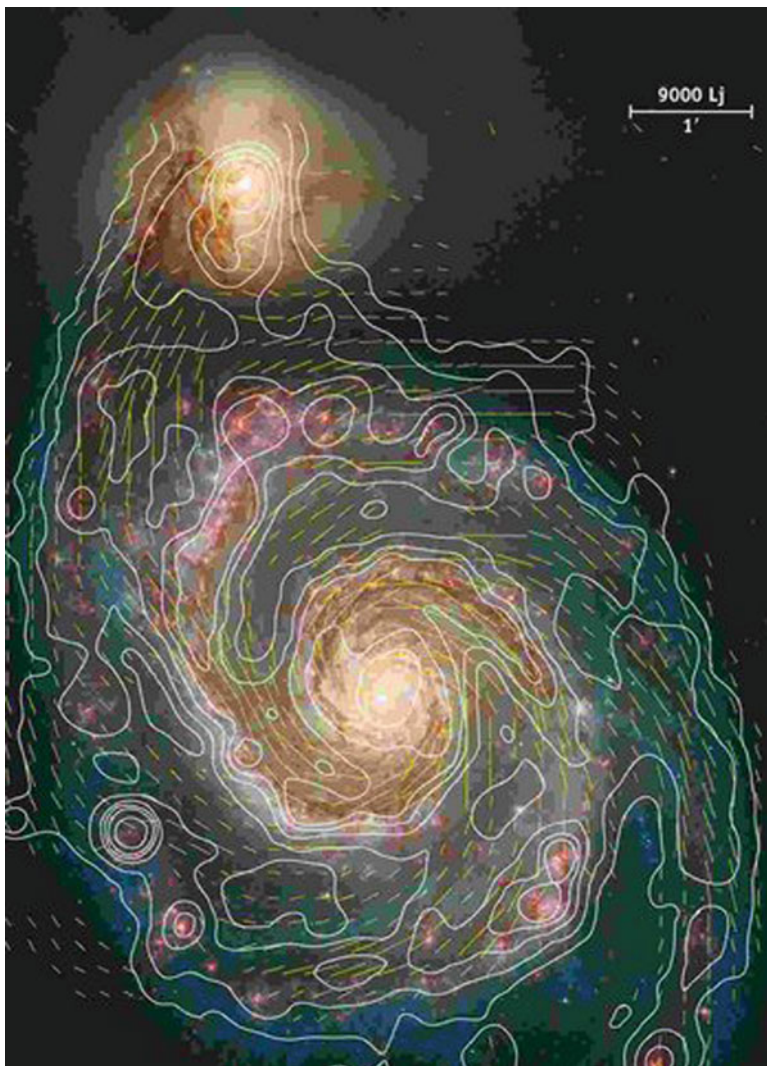
Astronomers also measure the polarization of starlight to map out the magnetic fields that wind through galaxies. This latter situation is a remarkable way of making the inherently invisible visible. Starlight itself is unpolarized, but it turns out that the interstellar medium is pervaded by miniscule but slightly elongated dust grains. These dust grains can become orientated in a direction perpendicular to galactic magnetic field lines (we shall describe the meaning of field lines in the Chap. 4). Since the grains are elongated and aligned with the magnetic field, however, they are able to scatter and partially polarize starlight. The polarization angle of the starlight can then be measured and the magnetic field line structure of the galaxy revealed (Fig. 2.13).

What a remarkable chain of circumstances this truly is – an invisible magnetic field revealed by invisible dust grains interacting with distant starlight to determine the plane of oscillation in an electric field – science fact is indeed stranger than science fiction.

## Sight and Sound

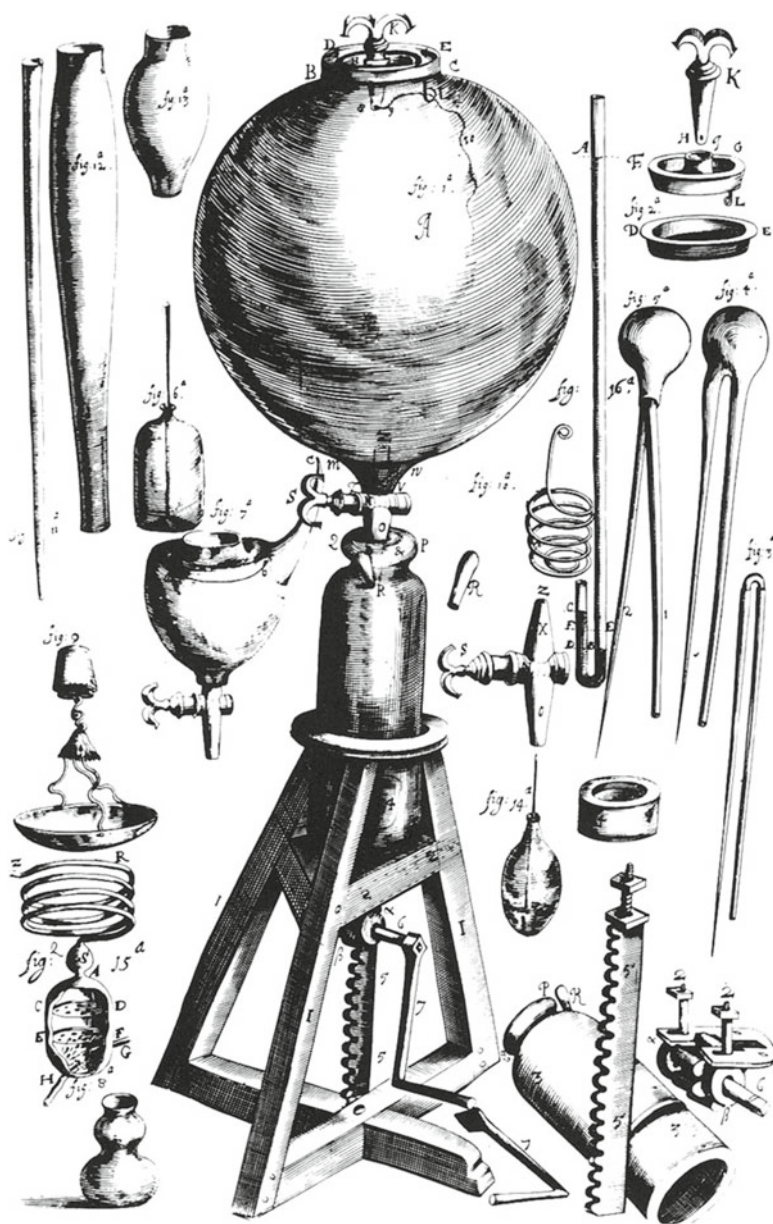
The early members of the Royal Society of London, founded in 1660, were, by modern standards, a bloodthirsty lot. They liked nothing better, for so it seems, than performing experiments involving animals – cutting them up, giving them blood transfusions, and killing them off in vacuum chambers. Well, of course, times were different then, and there was sometimes a serious point being made. The experiments with the vacuum chamber are particularly poignant to our story.

The vacuum pump was the “big science” instrument of the seventeenth century. Used by Robert Boyle, for example, to investigate air (or to be more precise regions



**Fig. 2.13** Composite image of the aptly named Whirlpool Galaxy. The optical image captured by the Hubble Space Telescope has contours of constant radio emission intensity superimposed upon it. Also shown are a series of short lines indicating the direction of linear polarization and hence, by default, the direction and shape of the galaxy's magnetic field (Image courtesy of NASA)

were air wasn't) the early vacuum pumps were the technical marvel of the age (Fig. 2.14). The investigations performed by Robert Hooke with the air pump included experiments to see what would happen to burning candles, as well as small birds and animals, when the air was removed from the glass jar in which they had been placed. Other researchers, risking life and limb, experimented upon the firing of gunpowder within vacuum jars.



**Fig. 2.14** Robert Boyle's vacuum pump, as perfected by Robert Hooke (Image courtesy of the Royal Society of London)

It was soon clear that both life and combustion needed something contained within air for their sustenance – and that something was eventually identified as oxygen. Later observations also revealed that sound waves could not propagate through a vacuum, demonstrating that it must be a pressure wave.



The propagation of sound experiment is now a classical high school science demonstration: an electric bell is placed within an inverted bell jar, and a vacuum pump is used to slowly extract the air. As the air is removed so the sound of the bell becomes weaker and weaker, eventually falling into an eerie silence.

Although this experiment tells us many things about sound waves, it is easy to miss another, perhaps more fundamental, observation. While we no longer hear the bell once the air has been removed from the vacuum jar, we can still see the bell and its parts vigorously vibrating. Light must clearly be a very different wave to sound, since light can propagate across a region in which the air has been removed. How does light achieve this remarkable trick? The answer to this question will not be revealed until Chap. 4.

In this chapter we have reviewed, albeit very briefly, the history of light. We have met some of the key players involved in explaining its properties, and we have looked at a few of the ways in which light has been experimented upon. Indeed, by learning how to weave light between lenses, mirrors and polarizers scientists have discovered two new worlds – the world of the very large, now surveyed with gigantic telescopes, and the world of the very small, scanned with ever more powerful microscopes. These optical devices extend our intellectual reach to dimensions and exotic domains otherwise invisible to the unaided eye. We are now ready, and hopefully enlivened, to take an initial look at a few of the ways in which light can be manipulated, diverted, scattered and tricked – and indeed engineered to make solid objects disappear from view.

The Physics of Invisibility

A Story of Light and Deception

Beech, M.

2012, XVII, 206 p. 135 illus., 55 illus. in color., Softcover

ISBN: 978-1-4614-0615-0