Chapter One

HISTORICAL

A STUDY of the historical development of science shows that almost every branch has passed through several well-defined phases, which in turn reflect the progress of civilisation as we know it to-day. A primitive stage, in which certain useful information was collected as a result of experience, was followed by a speculative stage associated with the Grecian philosophers. After this came a period of comparative stagnation under the sway of the schools of Alexandria and lasting until the rise of the Muslims in the seventh century A.D. Then came the experimental activity of the Arabs, lasting until the decline of their supremacy in the twelfth and thirteenth centuries; after which, for about two hundred years, there was a gradual spreading of ideas over Europe, which was emerging from the mental obscurity of the dark ages, but no marked advance in knowledge. During this time however many illustrious men were, by their writings, preparing the way for a fresh advance, notable among them being Roger Bacon the English monk. The fall of Constantinople ushered in the Revival of Learning, and in the early sixteenth century commenced that great outburst of activity which marked the beginnings of modern science. From that time until to-day worthy successors have maintained a steady advance along the lines commenced by the great pioneers.

Of all the physical sciences the study of light appears to have attracted most attention in early times. Mirrors were in use in the earliest civilisations, and the discovery of a burning-glass of rock-crystal in the ruined palace of Nimrud shows that the functions of lenses were known, at least in part. By the time of the Grecian philosophers, 500 to 50 B.C.,

men were familiar with the facts that light travels in straight lines, and that when reflected by a mirror the light coming away from the mirror makes with the surface an angle equal to that between the incident light and the surface. In addition they understood the use of lenses as burning and magnifying glasses; and a manuscript of doubtful origin, but attributed to Euclid, describes the properties of spherical mirrors.

The philosophers concerned themselves with speculations as to the nature of light. There were three principal schools of thought. Pythagoras and his disciples considered light to be due to a bombardment of the eye by minute corpuscles. Plato, with a touch of the mysticism that unfortunately is found associated with many of his ideas, imagined a stream of "divine fire" from the eye which, mingling with rays from the sun and corpuscles from the object looked at, returned to the eye and produced the sensation of sight. Aristotle's mighty intellect led him to suspect that light was a form of activity in the "diaphanes"—a kind of all-pervading transparent medium which has its counterpart in the ether of modern physics—and so made an approach to the ideas that are held to-day.

The principal contribution to knowledge made by the Alexandrines is contained in two manuscripts which are supposed to be the work of Ptolemy. In these the use of lenses is described, and experimental results concerning the bending of light on entering water are recorded, tables of angles showing this bending or refraction being given.

Of the Arabs, Alhazen (eleventh century) made the most important discoveries in optics. He described the structure of the eye, and gave an account of the magnifying power of lenses. This, possibly, was a step towards the invention of spectacles at a later date in Europe, where the works of Alhazen were widely read. During the following centuries knowledge of science was slowly spreading into Europe through Latin translations of Arabic works, but original

discoveries were few or none. Vitello in 1270 drew up improved tables of refraction and Roger Bacon in his *Opus Majus* indicated how lenses might be used in spectacles and for a telescope, as well as for projecting enlarged pictures. It is doubtful in the extreme however if he can be called the inventor of the actual instruments.

With the Renaissance came a renewal of activity, in England, France and Italy. The telescope was invented in Holland about the year 1608. Hans Lippershey, a spectacle-maker, appears to have been the first to construct a "perspective glass" using a convex and a concave lens, but Zacharius Jansen and Adrian Metius also made such instruments. In 1609 Galileo, hearing of the new invention, worked out the theory of it and independently constructed a telescope of the same kind. He made such wonderful discoveries with it that this type of glass is always known by his name.

In 1611 Kepler designed a telescope making use of two convex lenses, and had the first so-called astronomical telescope constructed, with its greater magnifying powers. Thanks to these inventions there was a great stimulation of interest in astronomy, and epoch-making discoveries resulted.

In 1621 Willebrord Snell discovered the relationship between the angles formed by light passing from air into water, a relationship that had hitherto eluded all investigators. His work was not made known, and soon after his death Descartes published the Law in its modern form, *The sine of the angle of refraction bears a constant ratio to the sine of the angle of incidence*, as his own discovery. Opinion is divided as to whether he filched this from Snell's papers: and it is best to have an open mind on the subject. At any rate Descartes put forward a theory that light is transmitted pressure, which, while comparatively unimportant in itself, may have led Huyghens to his wave-theory.

Christian Huyghens in 1690 published a remarkable paper,

in which he attributed the behaviour of light to some kind of wave-motion. He described the principle of wave-propagation known by his name, and which is developed at length in some of the earlier chapters of this book; and assuming light to consist of waves he was able to account for reflection, refraction and several other phenomena. He could not account for colour, however, and the inability to reconcile the behaviour of waves with the formation of definite shadows led Newton, after careful consideration, to reject this theory.

Newton's most famous experiment of course is the analysis of sunlight into a coloured spectrum using a prism. He formed an idea of the composition of white light which, though it has been called in question of late, was invaluable in promoting research. His principal work was concerned with the theory of the Nature of Light. Being unable to accept the wave-theory for various reasons, he developed the Emission or corpuscular theory in a masterly manner, and gave a theoretical explanation of the rectilinear propagation of light, the formation of shadows and the laws of reflection. Refraction he explained by assuming that the denser medium attracted the corpuscles in accordance with the law of gravitation, and as a result of his analysis showed that the speed of the corpuscles must be greater in the denser medium in order to fit in with the theory. Here was a point that could be tested experimentally, but the actual test was not applied until much later. A difficulty occurred when he was faced with the problem of a surface such as glass, which partially reflects and partially refracts light. He assumed that the corpuscles passed through regular alternate phases, being repelled when in the one and attracted when in the other phase.

So great was the weight of Newton's authority that for a long time the Emission theory was supreme, and the statement is often made that his masterly exposition held up the progress of the science. This is doubtful, but certainly the

wave-theory fell into obscurity. Early in the nineteenth century Thomas Young, the Foreign Secretary of the Royal Society, made some careful observations and deductions concerning the mutual action of two separate trains of waves, and discovered the principle of interference, or alternate destruction and reinforcement that occurs when two sets of waves are superimposed. He applied this to the solution of several problems such as the alternate bands of light and darkness in the fringe of the shadow of a straight edge, a fact which had been noted by Grimaldi and Newton. Young explained this and allied phenomena in terms of the inter-

Colour	Wave-length in millionths of an inch	Wave-length in millionths of a cm.
Extremest Red	32·4	81·0
Red	26·0	65·0
Orange	23·3	58·3
Yellow	22·0	55·1
Green	20·5	51·2
Peacock	19·0	47·5
Blue	18·0	44·9
Violet	16·0	40·0
Extremest Violet	14·4	36·0

ference of waves, but was ridiculed for his pains. Fresnel followed up Young's work, and in 1818 showed that all known phenomena, including the formation of shadows, could be explained assuming that light waves are transverse. He developed the complete mathematics of the subject, and designed and carried out experiments to measure the wave-lengths of light. Two striking facts were disclosed. The waves of light are exceedingly short; and difference of colour is essentially due to difference in wave-length. The table gives values of these wave-lengths for the complete range of visible light (after Silvanus Thompson).

It is their extreme shortness that causes light waves to

differ, at first sight, in their behaviour from other waves such as those on the sea. As will be seen later, Newton's objections were only apparent, and due to the fact that he did not realise how minute the waves actually are.

The final disproof of the corpuscular theory came when Foucault in 1850 showed that light travels more slowly in water than in air, a necessary requirement of the wave-theory and a flat contradiction of Newton.

In order to have waves there must be a medium to carry the waves. From their immense velocity, 186,000 miles a second, and their power of passing across interstellar space, they were supposed to be waves in a highly elastic solid; and so the elastic solid theory of ether, with its rather large demands on the imagination, came to the fore.

Subsequently Clerk Maxwell demonstrated that the waves of light were remarkably similar to electro-magnetic disturbances that would arise from rapidly oscillating charges of electricity. Maxwell's theory was published in a form difficult to understand and was neglected for a time. The brilliant experiments of Hertz, who succeeded in producing and examining the properties of electro-magnetic waves, with a length of several metres, confirmed Maxwell's ideas to the full.

Thus light has come to be regarded as a simultaneous electric and magnetic strain in the ether, which is propagated at enormous speed in the same way as is a transverse wave. The theory is very incomplete. But so satisfactory has the wave-theory proved in reconciling properties of light that at first appeared irreconcilable, and in showing the similarity that exists between such extremes as the curious penetrating X-rays and the enormously long waves used in wireless transmission, that we shall commence our study by investigating the behaviour of waves, and then apply what we can learn from them to help us to understand the fascinating behaviour of light.

Chapter Two

WAVES AND WAVE-MOTION

As our knowledge of the natural world has increased, men have come to realise more and more the prevalence of waves in all kinds of phenomena. When an explosion occurs, the light whereby we see it, the sound that reaches our ears and the earth tremor that accompanies it are all the result of waves in ether, air and earth respectively. Waves on water are the most familiar, and those properties which are common to all kinds of waves can be understood from a study of water waves.

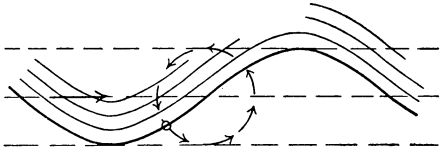

Fig. 1

Anyone who has watched the ripples that spread out on the surface of a pond into which a stone has been dropped, or who has looked over the sea from a high cliff, will have seen the apparent movement of water over the surface. But a floating object such as a cork does not move forward with the waves. At a first glance its movement appears to be merely an up and down one, although a close inspection will show that actually the object moves roughly in a circle. While passing through waves a swimmer experiences this, being carried upwards and forwards as the crest reaches him and backwards and downwards when it has passed. Now this very limited movement of the cork is similar to the movement of each of the particles of the water. The wave passes

across the water, but each of the water particles in turn makes a small to and fro movement about a fixed point. The movement of the wave is quite distinct from the movements of the particle of the medium in which the wave occurs. This is best illustrated by means of models.

A thick piece of copper wire is wound into a very loose spiral and mounted with a disk of wood at one end as shown, and a small ball of plasticine is fixed on it about half-way. The wire is placed in the beam of a lantern so that its shadow is cast on a screen. As the disk is turned a wave-motion passes along the shadow of the wire, but the shadow of the ball of plasticine moves up and down in a horizontal line.

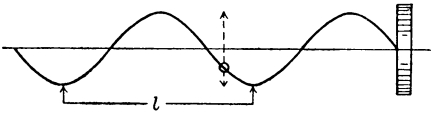

Fig. 2

When the disk is rotated at uniform speed the waves pass at a uniform rate, and the motion of the ball is seen to be similar to the movement of a pendulum. It travels backwards and forwards between two points, its speed being greatest at the middle of its path. This kind of movement, which is of universal occurrence and of the highest importance, is known as simple harmonic motion; and in general all particles of a medium through which a wave passes successively exhibit simple harmonic motion. An alternative method of showing the nature of wave-motion is described in Lewis Wright's book on Light. A grating, consisting of parallel clear spaces about $\frac{1}{16}$ of an inch apart scratched through black paint on a piece of glass, is placed in the slide carrier of a lantern. A long strip of glass is then painted black, and a wave is scratched through the paint (see Fig. 3). On passing the strip slowly through the slide carrier, while at

the same time keeping the grating fixed, a wave of bright spots of light is thrown upon the screen, and moves slowly across it.

Fig. 3

In view of its importance the following demonstration of what simple harmonic motion involves is worth noting. A weight is hung from a string in the beam of a lantern. The weight is swung in a horizontal circle, and when it is spinning steadily its shadow moves with simple harmonic

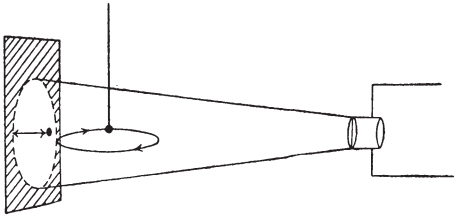

Fig. 4

motion. This helps us to understand the definition "Simple Harmonic Motion is the projection, along any diameter, of the motion of a particle moving in a circle with uniform velocity".

Returning to our shadow wave, we can now define four very important terms used in describing waves. The distance

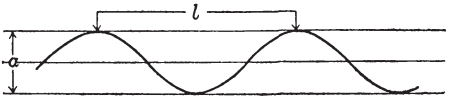

Fig. 5

between one crest and the next is known as the *wave-length*. The number of crests that pass a fixed point in a unit of time

is called the *frequency* of the waves. The distance one given crest moves in a unit of time is called the *velocity of propagation* of the wave. It will be obvious that the following relations exist between these three quantities:

$$\text{Wave-length} \times \text{frequency} = \text{Velocity}.$$

For a wave of a given intensity the oscillating particles have a fixed distance between the extremes of their vibrations. This distance from crest to trough is called the *amplitude* of the wave, and the greater the amplitude the greater is the intensity.

The shadow described illustrates wave-motion. A true wave however exhibits something further. The ripples that are caused by a disturbance such as a dropped stone, on reaching any object floating on the surface cause it to oscillate. Some of the energy of the moving stone is transferred to the floating object and manifests itself as a vibratory movement of the object. It is this transference of energy to points at a distance from its source that constitutes the most important property of a wave.

A simple machine to illustrate a true wave can be constructed as follows. Strings about 2 ft. long are hung at 3-inch intervals from a rod about 8 ft. long. Alternate strings are joined in pairs, and an elastic thread is then attached to these strings. A small weight is hung on the elastic thread between each point of attachment, the complete apparatus being indicated in Fig. 6. The end weights should be heavier than the rest.

If one end weight is drawn to one side and then released it commences to swing with simple harmonic motion. But the elastic thread drags on the second weight and imparts some of the motion of the first weight to it: and by the same mechanism the second weight passes on some of its motion to the third, and so forth. Being fairly heavy each weight