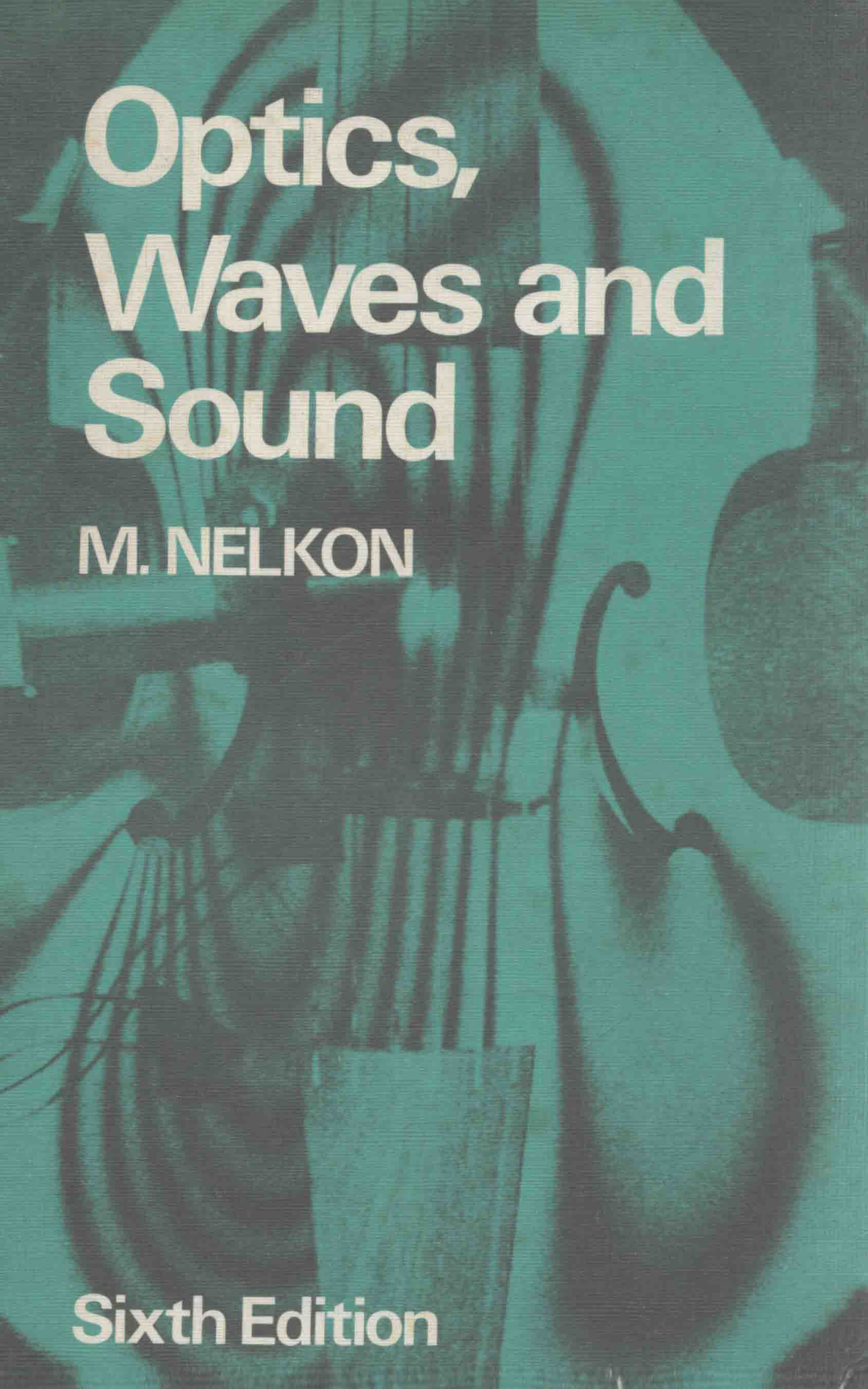

Optics, Waves and Sound

M. NELKON

Sixth Edition

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Preface to Sixth Edition

In this edition we have taken account of the revised syllabuses of the Examining Boards, including the new London Advanced level syllabus. Briefly, the main changes in the text are as follows:

Geometrical Optics

There is now a more concise account of mirrors, a more direct treatment of lenses, and early consideration of refractor and reflector telescopes. Except for basic definitions, photometry has been omitted.

Waves

This section has been expanded in accordance with the new syllabuses. It contains a general treatment of (i) mechanical and electromagnetic waves; (ii) progressive and stationary waves; (iii) reflection, refraction, interference, diffraction and polarization of waves. Sound waves, and the measurement of their velocity in air, have been fully discussed.

Wave Optics

(i) A qualitative account of the effect of lenses and mirrors on waves has been given. (ii) There are now separate chapters on interference, diffraction and polarization. The principles of holography and of the radio-telescope resolving power have been added, and the section on polarization has been expanded.

Sound

This section has been revised and now includes the case of the reflector in the Doppler effect and a brief account of high-fidelity reproduction.

Further, the Exercises at the end of chapters have been revised to include more recent questions from Examining Boards acknowledged in the Fifth Edition.

The author is very much indebted to the following for their generous assistance with the new edition: Mrs J. Pope, Middlesex Polytechnic; J. H. Avery, senior science master, Stockport Grammar School; C. F. Tolman, senior science master, Whitgift School, Croydon; M. V. Detheridge, William Ellis School, London; and D. Deutsch, Wolfson College, Oxford; S. S. Alexander, formerly Woodhouse School, London; J. Severn, William Ellis School, London; P. Betts, Woodhouse School, London. He is also grateful to R. Croft, The City University, London, and N. Phillips, Loughborough University, for providing photographs illustrating the section of holography, and to R. D. Harris, Ardingly College, Sussex. I am also indebted to Richard Gale and Trevor Hook of the Publishers for their unfailing courtesy and expert advice in the publication of this edition.

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Head of physics department, The City University, London, Figs. 26.10, 26.13, 27.2, 28.6; Dr B. H. Crawford, National Physical Laboratory, Fig. 24.19A; R. Croft, The City University, Figs. 26.6, 27.4, 27.17A; Hilger and Watts Limited, Figs. 26.11A, 26.13A, 27.8A, 27.10A, 27.16A; McDonald University, loaned Dr R. H. Garstang, University of London Observatory, Fig. 29.9C; N. Phillips, Loughborough University, Figs. 27.19A, 27.20.

Preface to Fifth Edition

This textbook deals with the principles of Optics, Sound and their associated Waves to a General Certificate of Education Advanced Level, and assumes an Ordinary level knowledge of the subject. The main part of the work comprises the Optics and Sound section of *Advanced Level Physics*, SI edition, and the chapter and page numbers have been retained. The whole work modernizes and replaces the author's textbook *Light and Sound.*

Geometrical Optics has been discussed first. Here the optical functions of mirrors, prisms and lenses have been considered and applied in optical instruments. The sign convention adopted in formulae is the *real is positive, virtual is negative* convention, and examples of its applications, including the case of the virtual object, have been given in the text. (A text using the alternative *New Cartesian* convention is given in a separate edition.)

In Sound, an account has been given of the physical principles of plane-progressive and stationary waves, and their applications to the vibrations in pipes, strings and rods. An introduction to sound recording and reproduction has also been included in the text.

Physical or Wave Optics begins with an account of the wave theory of light, followed by an introduction to interference, diffraction and polarization. It is hoped that these chapters will be particularly useful for students taking the Nuffield Advanced course.

Throughout the text numerical examples, taken from past examination papers, have been included in illustration of the subject matter and the calculus has been used only where necessary.

The author is indebted to M. V. Detheridge, William Ellis School, London, and R. P. T. Hills, St John's College, Cambridge, for reading the final section and their valuable advice. He is also indebted to L. J. Beckett, William Ellis School, London, for the opportunity to participate in teaching the new Nuffield Advanced course.

For assistance in past editions, I am particularly grateful to Professor W. C. Price, F.R.S., King's College, London University; Dr R. S. Longhurst, Chelsea College of Science and Technology; J. H. Avery, Stockport Grammar School; L. G. Mead, Wellington School, Somerset; and Professor H. T. Flint, formerly of Bedford College, London University.

I am also indebted to the following Examination Boards for their kind permission to reproduce questions set in past examinations:

University of London	(*L.*)
Joint Matriculation Board	(*N.*)
Oxford and Cambridge Joint Board	(*O. & C.*)
Cambridge Local Examinations Syndicate	(*C.*)
Oxford Local Examinations Delegacy	(*O.*)

Contents

PART THREE

Geometrical Optics

17 Introduction. Reflection at Plane Surfaces

Introduction

Light Rays and Beams

Light is a form of energy. We know this is the case because plants and vegetables grow when they absorb sunlight. Further, electrons are ejected from certain metals when light is incident on them, showing that there was some energy in the light; this phenomenon is the basis of the *photoelectric cell* (p. 921). Substances like wood or brick which allow no light to pass through them are called 'opaque' substances; unless an opaque object is perfectly black, some of the light falling on it is reflected (p. 346). A 'transparent' substance, like glass, is one which allows some of the light energy incident on it to pass through, the remainder of the energy being absorbed and (or) reflected.

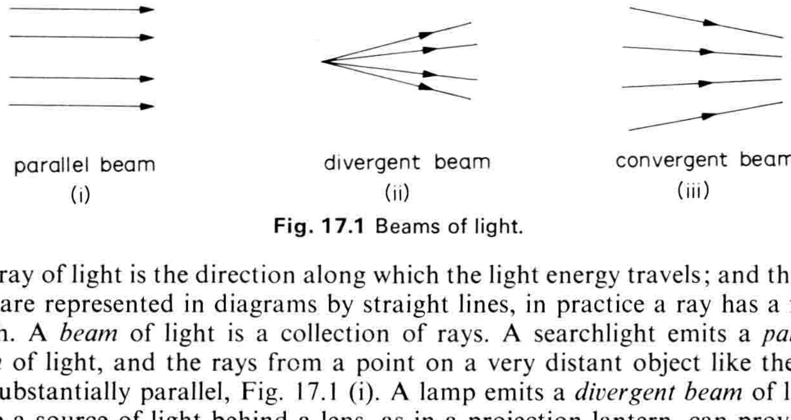

Fig. 17.1 Beams of light.

A ray of light is the direction along which the light energy travels; and though rays are represented in diagrams by straight lines, in practice a ray has a finite width. A *beam* of light is a collection of rays. A searchlight emits a *parallel beam* of light, and the rays from a point on a very distant object like the sun are substantially parallel, Fig. 17.1 (i). A lamp emits a *divergent beam* of light; while a source of light behind a lens, as in a projection lantern, can provide a *convergent beam*, Fig. 17.1 (ii), (iii).

Direction of Image seen by Eye

When a fish is observed in water, rays of light coming from a point such as O on it pass from water into air, Fig. 17.2 (i). At the boundary of the water and air, the rays OA, OC proceed along new directions AB, CD respectively and enter the eye. Similarly, a ray OC from an object O observed in a mirror is reflected along a new direction CD and enters the eye, Fig. 17.2 (ii). These phenomena are studied more fully later, but the reader should take careful note that the eye sees an object *in the direction in which the rays enter the eye*. In Fig. 17.2 (i), for example, the object O is seen in the water at I, which lies on BA and DC produced slightly to the right of O; in Fig. 17.2 (ii), O is seen behind the mirror at I, which lies on DC produced. In either case, all rays from O which enter the eye appear to come from I, which is called the image of O.

Reversibility of Light

If a ray of light is directed along DC towards a mirror, experiment shows that the ray is reflected along the path CO, Fig. 17.2 (ii). If the ray is incident along OC, it is reflected along CD, as shown. Thus if a light ray is reversed it always travels along its original path, and this is known as *the principle of the reversibility of light*. In Fig. 17.2 (i), a ray BA in air is refracted into the water along the path AO, since it follows the reverse path to OAB. We shall have occasion to use the principle of the reversibility of light later in the book.

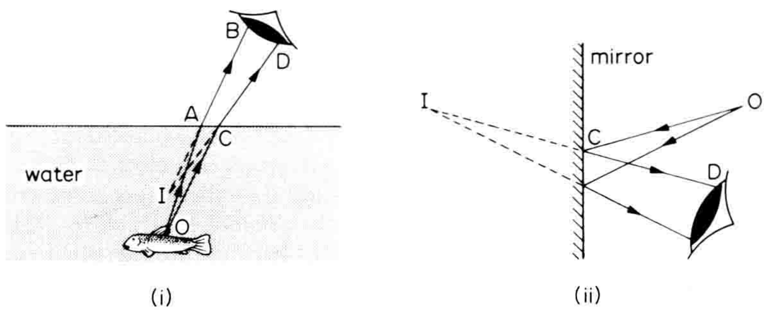

Fig. 17.2 Images observed by eye.

Luminous Flux, Lumen, Candela, Lux

We conclude this introductory section with a brief account of some of the main points in *Photometry*, the science of light measurement. Here we are concerned with the *luminous energy* emitted by a source of light, which stimulates the sensation of vision; and not with any other radiations it may emit, such as infra-red rays, for example, which are invisible.

A source of light such as a lamp emits a continuous stream of luminous energy. We give the name *luminous flux*, symbol Φ, to the 'luminous energy emitted per second'. The unit of luminous flux is the *lumen*, symbol lm. A lumen is a unit of energy per second or power, so it must be related to the watt. Experiment shows that about 621 lumens of green light of wavelength $5{\cdot}540 \times 10^{-10}$ m is equal to 1 watt.

A light source such as a lamp radiates luminous flux in all directions round it. If we consider a small lamp S and a particular direction SA, an amount of luminous flux Φ is radiated in a small cone of 'solid angle' ω drawn round SA with S at the apex. Fig. 17.3 (i). The *luminous intensity*, *I*, of the lamp is defined as the ratio Φ/ω or the 'luminous flux per unit solid angle'. Since a solid angle is measured in steradian, sr, the unit of *I* is 'lm sr^{-1}'.

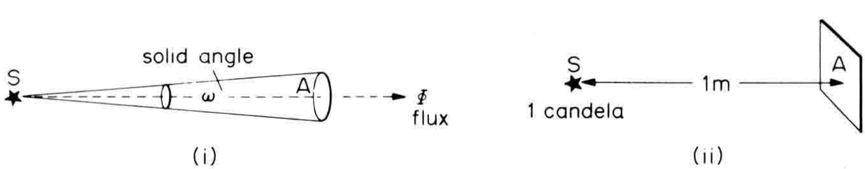

Fig. 17.3 (i) Luminous intensity, (ii) Lux.

A practical unit of luminous intensity is the *candela*, symbol cd. It is defined as the luminous intensity of 1/600 000 metre² (1/60 cm²) of the surface of a black body at the temperature of freezing platinum under 101 325 newton per metre^2 pressure. A standard is maintained at the National Physical Laboratory and here the luminous intensity of manufacturers' lamps are measured in terms of the standard. From above, $I = \Phi/\omega$, so $\Phi = I\omega$. Thus 1 lm = 1 cd sr.

We now consider the surface on which the luminous flux falls. The *illuminance* (or *illumination*), E, of a surface is defined as the 'luminous flux per unit area'. If we imagine concentric spheres of different radii r drawn round a small lamp S as centre, the total flux from S will fall on areas equal to $4\pi r^2$. So we can see that the illuminance varies *inversely as the square* of the distance from S. The unit of illuminance is the *lux*, lx. This is the illuminance of a surface A 1 m away from a lamp S of 1 cd when the light falls normally on A. Fig. 17.3 (ii).

The *luminance*, L, of a surface is the 'luminous flux per unit area' coming from that surface. The illuminance of white chalk on a blackboard is the same as the surrounding surface. The luminance of the chalk, however, is very much higher than that of the board since the reflection factor of the chalk is much greater than that of the board.

The following table summarises some of the units discussed.

	Symbol	Unit
Luminous flux	Φ	lumen (lm)
Luminous intensity	I	candela (cd)
Illuminance	E	lux (lx)
Luminance	L	cd m^{-2}

Reflection at Plane Surfaces

Highly-polished metal surfaces reflect about 80 to 90 per cent of the light incident on them; *mirrors* in everyday use are therefore usually made by depositing silver on the back of glass. In special cases the front of the glass is coated with the metal; for example, the largest reflector in the world is a curved mirror nearly 5 metres across, the front of which is coated with aluminium (p. 443). Glass by itself will also reflect light, but the percentage reflected is small compared with the case of a silvered surface; it is about 5 per cent for an air-glass surface.

Laws of Reflection

If a ray of light, AO, is incident on a plane mirror XY at O, the angle AON made with the *normal* ON to the mirror is called the 'angle of incidence', *i*,

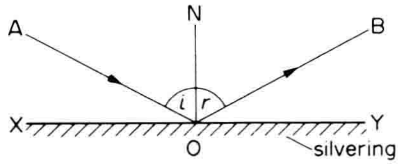

Fig. 17.4 Plane mirror.

Fig. 17.4. The angle BON made by the reflected ray OB with the normal is called the 'angle of reflection', *r*; and experiments show that:

(1) *The reflected ray, the incident ray, and the normal to the mirror at the point of incidence all lie in the same plane.*
(2) *The angle of incidence = the angle of reflection.*
These are called the two *laws of reflection.*

Regular and Diffuse Reflection

In the case of a plane mirror or glass surface, it follows from the laws of reflection that a ray incident at a given angle on the surface is reflected in a definite direction. Thus a parallel beam of light incident on a plane mirror in the direction AO is reflected as a parallel beam in the direction OB; this is known as a case of *regular reflection*, Fig. 17.5 (i). On the other hand, if a parallel beam of light is incident on a sheet of paper in a direction AO, the light is reflected in all different directions from the paper: this is an example of *diffuse reflection*, Fig. 17.5 (ii). Objects in everyday life, such as flowers, books, people, are seen by light diffusely reflected from them. The explanation of the diffusion of light

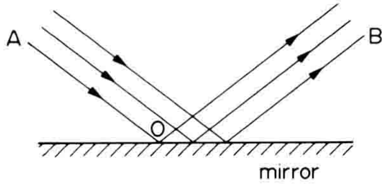

Fig. 17.5 (i) Regular reflection.

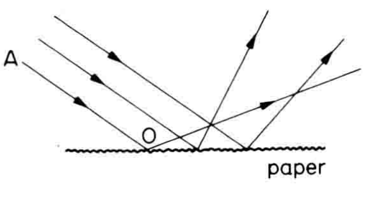

Fig. 17.5 (ii) Diffuse reflection.

is that the surface of paper, for example, is not perfectly smooth like a mirrored surface; the 'roughness' in a paper surface can be seen with a microscope. At each point on the paper the laws of reflection are obeyed, but the angle of incidence varies, unlike the case of a mirror.

Deviation of Light by Plane Mirror

Besides other purposes, plane mirrors are used in the sextant (p. 349), in simple periscopes, and in signalling at sea. These instruments use a plane mirror to change or deviate light from one direction to another.

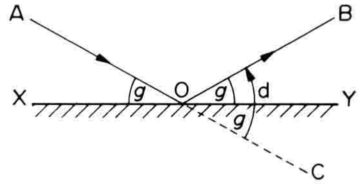

Fig. 17.6 Deviation of light by plane mirror.

Consider a ray AO incident at O on a plane mirror XY, Fig. 17.6. The angle AOX made by AO with XY is known as the *glancing angle*, g, with the mirror; and since the angle of reflection is equal to the angle of incidence, the glancing angle BOY made by the reflected ray OB with the mirror is also equal to g.

The light has been deviated from a direction AO to a direction OB. Since angle COY = angle XOA = g, it follows that

$$\text{angle of deviation, } d = 2g \quad . \quad . \quad . \quad . \quad (1)$$

so that, in general, *the angle of deviation of a ray by a plane surface is twice the glancing angle.*

Deviation of Reflected Ray by Rotated Mirror

Consider a ray AO incident at O on a plane mirror M_1, α being the glancing angle with M_1, Fig. 17.7. If OB is the reflected ray, then, as shown above, the angle of deviation COB = $2g = 2\alpha$.

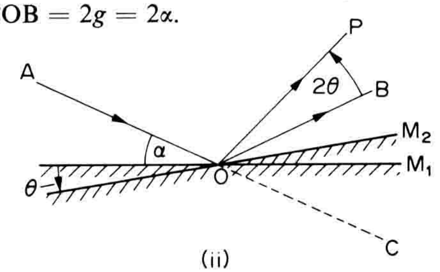

Fig. 17.7 Rotation of reflected ray.

Suppose the mirror is rotated through an angle θ to a position M_2, the direction of the incident ray AO being *constant*. The ray is now reflected from M_2, in a direction OP, and the glancing angle with M_2 is $(\alpha + \theta)$. Hence the new angle of deviation COP = $2g = 2(\alpha + \theta)$. The reflected ray has thus been rotated through an angle BOP when the mirror rotated through an angle θ; and since

$$\angle BOP = \angle COP - \angle COB,$$

then

$$\angle BOP = 2(\alpha + \theta) - 2\alpha = 2\theta.$$

Thus, *if the direction of an incident ray is constant, the angle of rotation of the reflected ray is twice the angle of rotation of the mirror.* If the mirror rotates through 4°, the direction of the incident ray being kept unaltered, the reflected ray turns through 8°.

Optical Lever in Mirror Galvanometer

In a number of instruments a beam of light is used as a 'pointer'; this has a negligible weight and so is sensitive to deflections of the moving system. In a mirror galvanometer, used for measuring very small electric currents, a small mirror M_1 is rigidly attached to a system which rotates when a current flows in it, and a beam of light from a fixed lamp L shines on the mirror, Fig. 17.8. If the light is incident normally on the mirror at A, the beam is reflected directly back, and a spot of light is obtained at O on a graduated scale S placed just above L. Suppose that the moving system, to which the mirror is attached, undergoes a rotation θ. The mirror is then rotated through this angle to a position M_2, and the spot of light is deflected through a distance x, say to a position P on the scale.

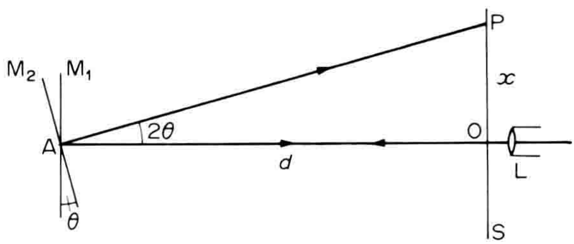

Fig. 17.8 Optical lever principle.

Since the direction OA of the incident light is constant, the rotation of the reflected ray is twice the angle of rotation of the mirror (p. 347). Thus angle OAP $= 2\theta$. Now $\tan 2\theta = x/d$, where d is the distance OA. Thus 2θ can be calculated from a knowledge of x and d, and hence θ is obtained. If 2θ is small, then $\tan 2\theta$ is approximately equal to 2θ in radians, and in this case θ is equal to $x/2d$ radians.

In conjunction with a mirror, a beam of light used as a 'pointer' is known as an 'optical lever'. Besides a negligible weight, it has the advantage of magnifying by two the rotation of the system to which the mirror is attached, as the angle of rotation of the reflected light is twice the angle of rotation of the mirror. An optical lever can be used for measuring small increases of length due to the expansion or contraction of a solid.

Deviation by Successive Reflections at Two Inclined Mirrors

Before we can deal with the principle of the sextant, the deviation of light by successive reflection at two inclined mirrors must be discussed.

Consider two mirrors, XO, XB, inclined at an angle θ, and suppose AO is a ray incident on the mirror XO at a glancing angle α, Fig. 17.9 (i). The reflected ray OB then also makes a glancing angle α with OX, and from our result on p. 347, the angle of deviation produced by XO in a clockwise direction = angle LOB $= 2\alpha$.

Suppose OB is incident at a glancing angle β on the second mirror XB. Then, if the reflected ray is BC, the angle of deviation produced by this mirror (angle

EBC) $= 2\beta$, in an anti-clockwise direction. Thus the net deviation D of the incident ray AO produced by both mirrors $= 2\beta - 2\alpha$, in an anti-clockwise direction.

Now from triangle OBX,

$$\text{angle PBO} = \text{angle BOX} + \text{angle BXO},$$

i.e.,

$$\beta = \alpha + \theta.$$

Thus $\theta = \beta - \alpha$, and hence

$$D = 2\beta - 2\alpha = 2\theta.$$

But θ is a *constant* when the two mirrors are inclined at a given angle. *Thus, no matter what angle the incident ray makes with the first mirror, the deviation D after two successive reflections is constant and equal to twice the angle between the mirrors.*

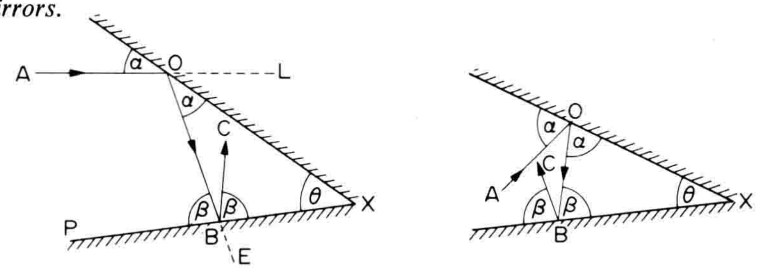

Fig. 17.9 Successive reflection at two plane mirrors.

Fig. 17.9 (ii) illustrates the case when the ray BC reflected at the second mirror travels in an opposite direction to the incident ray AO, unlike the case in Fig. 17.9 (i). In Fig. 17.9 (ii), the net deviation, D, after two successive reflections in a clockwise direction is $2\alpha + 2\beta$. But $\alpha + \beta = 180° - \theta$. Hence $D = 2\alpha + 2\beta = 360° - 2\theta$. Thus the deviation, D, in an anti-clockwise direction is 2θ, the same result as obtained above.

Principle of the Sextant

The *sextant* is an instrument used in navigation for measuring the angle of elevation of the sun or stars. It consists essentially of a fixed glass B, silvered on a vertical half X so that the other half Y is clear (see inset), and a silvered mirror O which can be rotated about a horizontal axis. A small fixed telescope T is directed towards B, Fig. 17.10.

Suppose that the angle of elevation of the sun, S, is required. Looking through T, the mirror O is turned until the view H′ of the horizon seen directly through the unsilvered half of B, and also the view of it, H, seen by successive reflection at O and the silvered half of B, are coincident. The mirror O is then parallel to B in the position M_1, and the ray HO is reflected along OB and BD to enter the telescope T. The mirror O is now rotated to a position M_2 until the image of the sun S, seen by successive reflections at O and B, is on the horizon H′ (see inset). The angle of rotation, θ, of the mirror is noted, Fig. 17.10.

The ray SO from the sun is now reflected in turn from O and B so that it travels along BD, the direction of the horizon, and the angle of deviation of the ray is thus angle SOH. But the angle between the mirrors M_2 and B is θ. Thus,

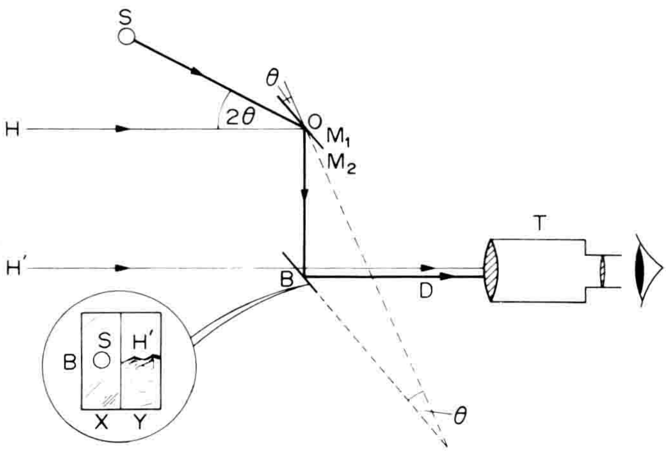

Fig. 17.10 Sextant principle.

from our result for successive reflections at two inclined mirrors, angle SOH = 2θ. Now the angle of elevation of the sun, S, is angle SOH. Hence *the angle of elevation is twice the angle of rotation of the mirror O*, and can thus be easily measured from a scale (not shown) which measures the rotation of O.

Since the angle of deviation after two successive reflections is independent of the angle of incidence on the first mirror (p. 349), the image of the sun S through T will continue to be seen on the horizon once O is adjusted, no matter how the ship pitches or rolls. This is an advantage of the sextant.

Images in Plane Mirrors

So far we have discussed the deviation of light by a plane mirror. We now consider the *images* in plane mirrors.

Suppose that a *point object* A is placed in front of a mirror M, Fig. 17.11. A ray AO from A, incident on M, is reflected along OB so that angle AON = angle BON, where ON is the normal at O to the mirror. A ray AD incident

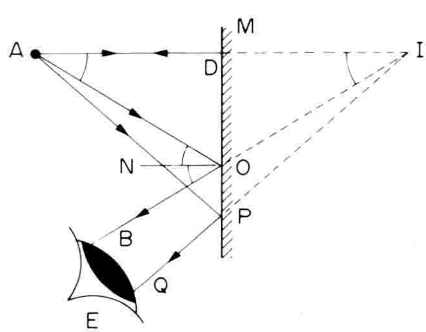

Fig. 17.11 Image in plane mirror.

normally on the mirror at D is reflected back along DA. Thus the rays reflected from M appear to come from a point I *behind* the mirror, where I is the point of intersection of BO and AD produced. As we prove shortly, any ray from A, such as AP, is also reflected as if it comes from I, and so an observer at E sees the image of A at I.

Since angle AON = alternate angle DAO, and angle BON = corresponding angle DIO, it follows that angle DAO = angle DIO. The two triangles ODA