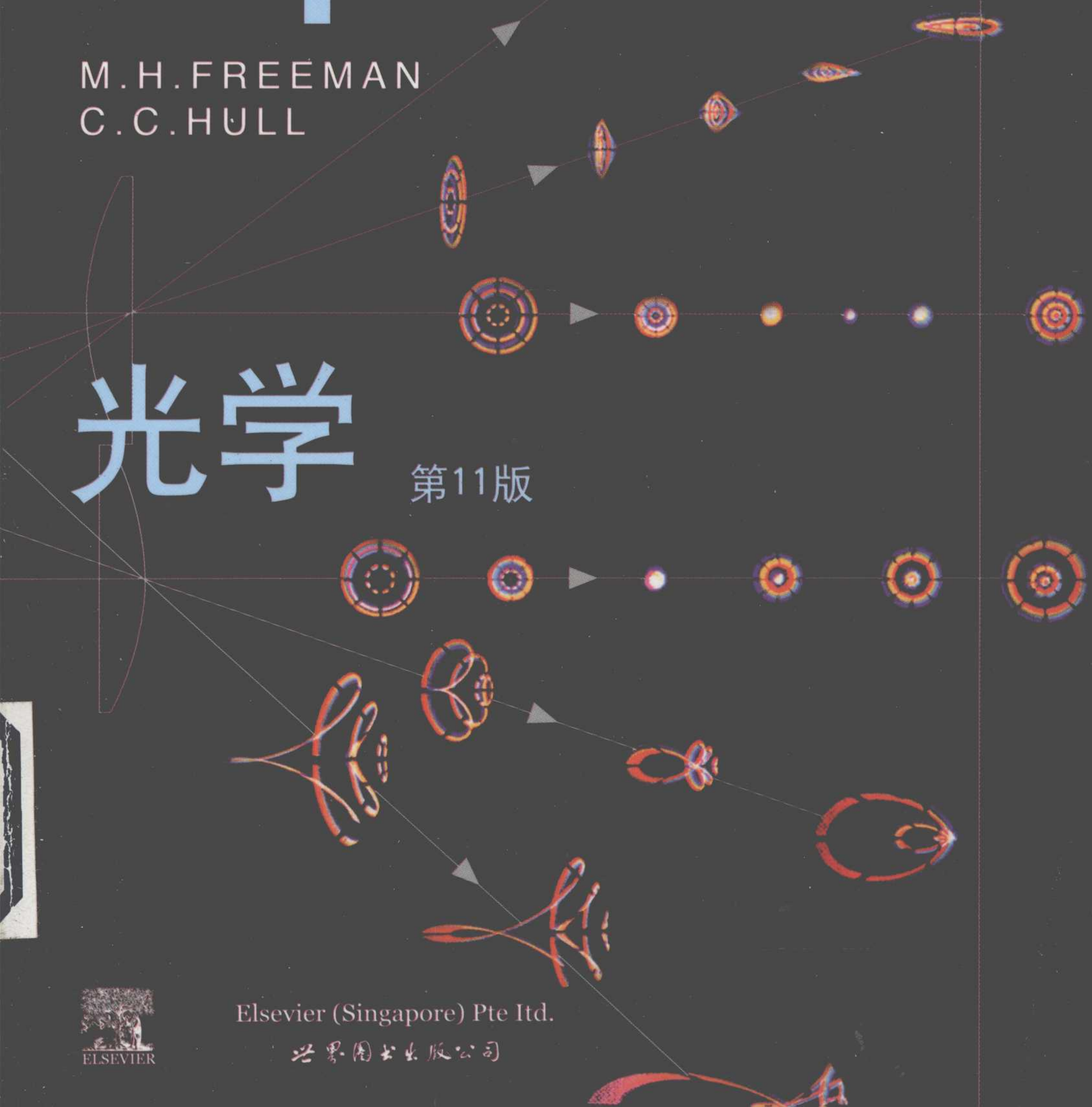
ELEVENTH EDITION

Optics

M.H.FREEMAN
C.C.HULL

光学

第11版



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M. H. Freeman PhD, MPhil, BSc, MInstP
Optics and Vision Limited, Denbigh, Clwyd; Visiting Professor, Department of Optometry and Neuroscience, UMIST, Manchester

C. C. Hull PhD, DIC, MInstp, CPhys
Senior Lecturer in Clinical & Visual Optics, Department of Optometry and Visual Science, City University, London

Chapter 15:
W. N. Charman DSc, PhD
Professor of Visual Optics, Department of Optometry and Neuroscience, UMIST, Manchester

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Optics 11th ed.
By M. H. Freeman, C. C. Hull
ISBN:0-7506-4248-3

Authorized English language reprint edition published by the Proprietor.
Reprint ISBN: 981-2592-64-4

Elsevier (Singapore) Pte Ltd.
3 Killiney Road
#08-01 Winsland Hose I
Sinagpore 239519
Tel: (65) 6349-0200
Fax: (65) 6733-1817

First Published 2005
2005 年初版

Printed in China by Beijing World Publishing Corporation under special arrangement with Elsevier (Singapore) Pte Ltd. This edition is authorized for sale in China only, excluding Hong Kong SAR and Taiwan.

书　　名：Optics 11th ed.
作　　者：M. H. Freeman
中 译 名：光学 第 11 版
出 版 者：世界图书出版公司北京公司
印 刷 者：北京世图印刷厂
发　　行：世界图书出版公司北京公司（北京朝内大街 137 号　100010）
联系电话：010-64015659, 64038347
电子信箱：kjsk@vip.sina.com
开　　本：24 开　　　印　张：24
出版年代：2005 年 4　月
书　　号：7-5062-6600-8/ O・453
版权登记：图字:01-2005-1282
定　　价：86.00 元

Preface to the eleventh edition

The study of optics goes back thousands of years. Early reports can be traced to the Ancient Greeks, notably Aristotle and Democritus speculating about vision and Archimedes' famous "burning glass." The fact that the subject is alive and kicking after so long is evidenced by the explosion in the latter half of the twentieth century of communications, entertainment, manufacturing, and medical applications all based on optics. However, the basic principles of classical optics have not changed in recent years and we have to go back to 1953 to find a Nobel Prize winner in the field (Frits Zernike for the phase contrast microscope). With optics underpinning so much modern technology, the authors believe that there is still a significant need for a basic teaching text in optics. In fact, if anything the need is increasing in many scientific fields and there is no sign that this will change in the coming years.

It is almost seventy years since this book was first published under the authorship of W.H.A. Fincham. The second author, M.H.F., has been involved since the eighth edition and now welcomes a third author, C.C.H., to ensure continuity. Reading Walter Fincham's first preface again, we are struck by how the basic tenets underpinning the first edition of *Optics* still apply today. The eleventh edition is likewise aimed at students who require a knowledge of basic optics, particularly as applied to the visual system and visual optical instruments, but do not necessarily have a strong mathematical background. Emphasis has been placed on a sound qualitative understanding of optical principles backed up with mathematics to allow us to quantify that understanding. The mathematics is therefore subservient to the optics rather than intrinsically bound up with it as in many other texts aimed at training physicists. There is value in both approaches and the authors have experience of both. However, the target audience is assumed to only have a basic competency in mathematics and areas such as calculus and complex notation are avoided.

The changes for the present edition include a complete rewrite of Chapter 15 "The eye as an optical instrument" by W.N. Charman, a leading expert in this field. The authors are gratefully indebted to Professor Charman for his contribution. Chapter 10 and large sections of Chapter 9 have also been rewritten to include discussion of optical sources and detectors, and to significantly update the approach to radiometry, photometry, and an introduction to colorimetry. Corrections and amendments have also been made to Chapters 7 and 8, and the problem sets have been revised and expanded. With all this change it is inevitable that some errors will remain. We hope that students and teachers using this text will keep us informed of any mistakes so that future editions may continue to be improved.

M.H.F. and C.C.H.
Wales and London, 2003

Preface to the first edition

During recent years considerable progress has been made in bringing the teaching of optics in line with practical requirements, and a number of text books dealing with Applied Optics have been published. None of these, however, caters for the elementary student who has no previous knowledge of the subject and who, moreover, is frequently at the same time studying the mathematics required.

This book, which is based on lectures given in the Applied Optics Department of the Northampton Polytechnic Institute, London, is intended to cover the work required by a student up to the stage at which he commences to specialize in such subjects as ophthalmic optics, optical instruments and lens design. It includes also the work required by students of Light for the Intermediate examinations of the Universities.

The first eleven chapters deal with elementary geometrical optics, Chapters XII to XVI with physical optics, and the last three with geometrical optics of a rather more advanced character.

The system of nomenclature and sign convention adopted is that in use at the Imperial College of Science and the Northampton Polytechnic Institute, London. The sign convention is founded on the requirement that a converging lens shall have a positive focal length measured from the lens to the second principal focus. This is easily understood by the elementary student and is the convention commonly used throughout the optical industry. In ophthalmic optics – the most extensive branch of optical work at the present time – lenses are always expressed in terms of focal power; this idea has been introduced quite early and used throughout the work.

The solution of exercises plays an important part in the study of a subject such as Optics, and it is hoped that the extensive set of exercises with answers will be found useful. Typical examples from the examination papers of the London University, the Worshipful Company of Spectacle Makers and the British Optical Association are included by permission of these bodies.

My best thanks are due to my colleagues Messrs H. T. Davey and E. F. Fincham for their valuable assistance in the preparation of the diagrams, which, together with the photographs, have been specially made for the book. I wish particularly to express my indebtedness to Mr H. H. Emsley, Head of the Applied Optics Department, Northampton Polytechnic Institute, for reading the manuscript and for his very valuable help and suggestions given during the whole of the work.

January, 1934

W.H.A.F.
London

List of Symbols

a	Angle of normal, apical angle of prism
d	Axial distance between lenses
D	Diopters, reciprocal of length in meters
$e(e')$	Axial distance from first (second) principal plane
$f(f')$	First (second) focal length
$f_v(f'_v)$	First (second) vertex focal length
f_E	Equivalent focal length
$F(F')$	First (second) focal power
$F_v(F'_v)$	First (second) vertex focal power
F_E	Equivalent focal power
g	Axial distance between foci of lenses (Section 5.6)
$h(h')$	Height of object (image) from axis
H	Lagrange invariant
$i(i')$	Angle to the normal of incident (reflected/refracted) ray
K	Oblique power
$l(l')$	Axial distance of object (image)
$L(L')$	Vergence of object (image)
m	Magnification
$n(n')$	Refractive index in object (image) space
$P(P')$	First (second) principal plane
r	Radius of curvature
R	Curvature
s	Sag (sagittal) distance
$u(u')$	Axial angle/slope of incident (reflected/refracted) ray
V	V-value (Abbe Number) dispersive power
v	Deviation of ray
$w(w')$	Angle subtended by distant object (image)
W	Wavefront aberration
$x(x')$	Axial distance from first (second) focus, Newton's Law
x	Lateral distance from axis - out of diagram
y	Lateral distance from axis - in plane of diagram
z	Axial distances (along optical axis)
Δ	Prism diopters
λ	Wavelength
ρ	Lateral distance from axis (general $= \sqrt{(x^2 + y^2)}$
ν	Frequency
ω	Angular frequency

Sign convention See section 3.4

Contents

Chapter 1

The basics of light and optical surfaces

1.1 Light and optics

The branch of science known as Optics is mainly about light and vision. It also includes the study of other radiations very similar to light but not seen by the human eye.

Light is a form of radiant energy. Radiant heat, radio waves, and X-rays are other forms of radiant energy. Light is sent out through space by **luminous sources**. Most of these are able to emit light because they are very hot. The high temperature of these sources means that their constituent atoms are in a state of considerable agitation, the effects of which are transmitted outwards from the source in all directions.

A piece of dark metal, when cold, emits no radiation that we can see. When gradually heated, it sets up a disturbance in the form of vibrations or **waves** in the surrounding medium, which radiate outwards at very high speed. At some distance away we can feel the effect as heat; we detect this form of radiation by our sense of touch. As the temperature rises and the vibrations become faster, the metal is seen to glow red; the radiation is such that we can see its effects; it is in the form of light. We detect this form of radiation by our sense of sight, the eye acting as a detector. With a further rise in temperature the metal passes to a yellow and then to a white heat.

The exact nature of light is not completely known, but a working idea of these "wave motions" can be found in the ripples that occur when the calm surface of water is disturbed by dropping a stone into it. The important characteristics of the disturbance are: the speed or **velocity** at which it travels outwards; the distance

Table 1.1

Radiation	*Velocity* (ms^{-1})	*Frequency* (Hz)	*Wavelength* (nm)
Radio	3×10^8	1×10^6	3×10^{11}
Heat			
Thermal infrared	3×10^8	30×10^{12}	10 000
Near infrared	3×10^8	300×10^{12}	1000
Light			
Red	3×10^8	395×10^{12}	759
Yellow	3×10^8	509×10^{12}	589
Violet	3×10^8	764×10^{12}	393
Ultraviolet	3×10^8	1000×10^{12}	300
X-rays	3×10^8	3×10^{18}	0.1

between the wave crests, called the **wavelength**; and the **frequency** or rate of the rise and fall of the water surface. These will be studied in more detail in Chapter 9 where it will be shown that the velocity is equal to the frequency multiplied by the wavelength.

In the case of light, heat, and radio waves, the velocity has been found by experiment to be 186 000 miles per second or 300 million meters per second. We find that the frequency of the vibration is greater for light than for heat and, as the increasing temperature of metal showed, the vibrations are faster for yellow light than for red light (which appeared first). As the velocity (in vacuum) is the same for all colours, it follows that the wavelength is longer for red light and shorter for yellow light and blue light. Table 1.1 gives typical wavelengths and frequency values from each type of radiation. A more complete description is given in Section 9.4.

When the metal is white hot it is emitting all colors equally. The nature of white light was investigated by Sir Isaac Newton (1642–1727) when he passed a narrow beam of white light through a glass prism and found that a white patch on a screen was now broadened out into a spectrum with the colors the same as those seen in the rainbow. The white light is said to be *dispersed* into its constituent colors and the effects of these on the eye and with different optical materials are studied in Chapter 13.

1.2 Rectilinear propagation of light (or: Light travels in straight lines)

Any space through which light travels is an optical medium. Most optical media have the same properties in all directions and are said to be isotropic. Some exceptions are described in Chapter 11. Also, most optical media have these same properties throughout their mass and are said to be homogeneous. Again, there are some exceptions and these are described in Chapter 11.

When light starts out from a point source B (Figure 1.1) in an isotropic homogeneous medium, it spreads out uniformly at the same speed in all directions; the position it is in at any given moment will be a sphere (such as C) having the source at its center. Such imaginary spherical surfaces will be called light fronts or **wavefronts.** In the case of the water ripples the disturbance is propagated in one plane only and the wavefronts are circular.

Huygens (1629–1695), usually considered to be the founder of the wave theory of light, assumed that any point on a wave surface acted as a new source from which spherical "secondary waves" or "wavelets" spread out in a forward direction.

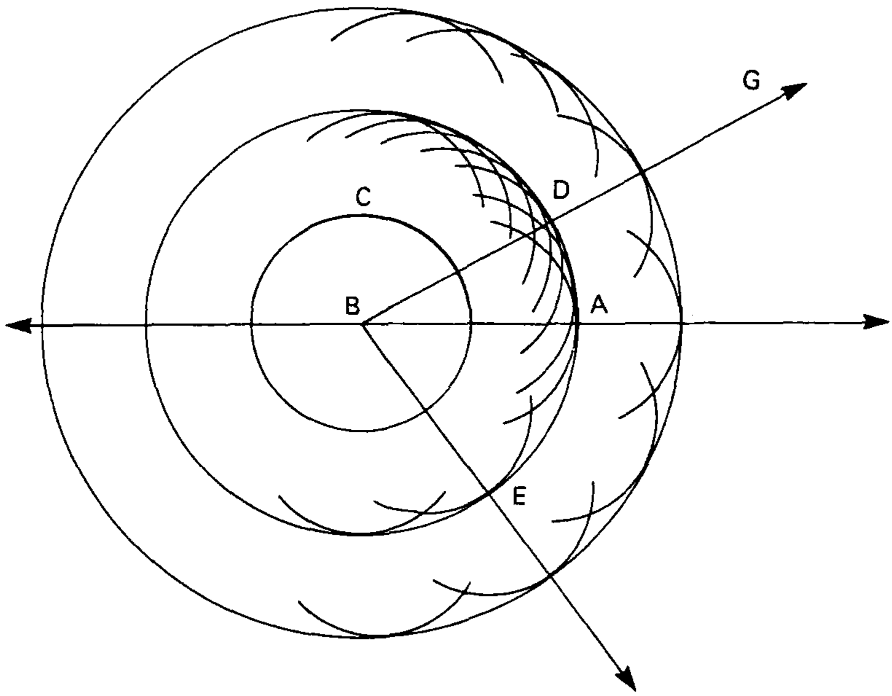

Figure 1.1 Huygens' construction for the propagation of light using wavefronts and wavelets

The surface DAE, which touches or envelops all these wavelets, forms a new wavefront which is again a sphere with its center at B. This action can be repeated as long as the medium remains isotropic and homogeneous. Huygens refined this idea by assuming that the wavelets travel out in a forward direction only and that their effect is limited to that part which touches the enveloping new wavefront. This concept is known as **Huygens' principle** and, with developments by Fresnel (1788–1827) and Kirchhoff (1824–1887) is used to explain the effects of interference and diffraction in Chapters 12 and 13. The basic construction of wavelets defining the new wavefront enables us to find the change in the form or the direction of the wavefront on passing to a new medium or on reflection at a surface.

From Figure 1.1 it is clear that the path, such as BDG, traveled by any part of the disturbance, is a straight line perpendicular to the wavefront. For a large number of optical effects it is enough to assume that this is how light travels. We speak of such a line along which light travels as a **ray**. Neither wavelets nor rays actually exist but both provide a useful way of dealing with the actions of light.

A luminous source, such as B in Figure 1.2, will be seen only if the light from it enters the eye. Thus, an eye in the region between C and K, or between D and L, of the two screens CD and KL will see B because the light from B reaches these regions without interruption. An eye located between c and d will not see the object B because the opaque screen EF shields the region cEFd which is said to be in shadow. B will be visible to an eye at e just beyond the limits of the shadow region.

If we have two opaque screens KL and MN, with circular holes at kl and pq, the screen MN will be illuminated over a circular patch mn but will be dark everywhere else, and an eye placed at the aperture pq will not see the source B.

The fact that B is invisible to any eye placed in the region cEFd and visible to one placed in the region kmnl shows, as was seen from Huygens' principle, that the light

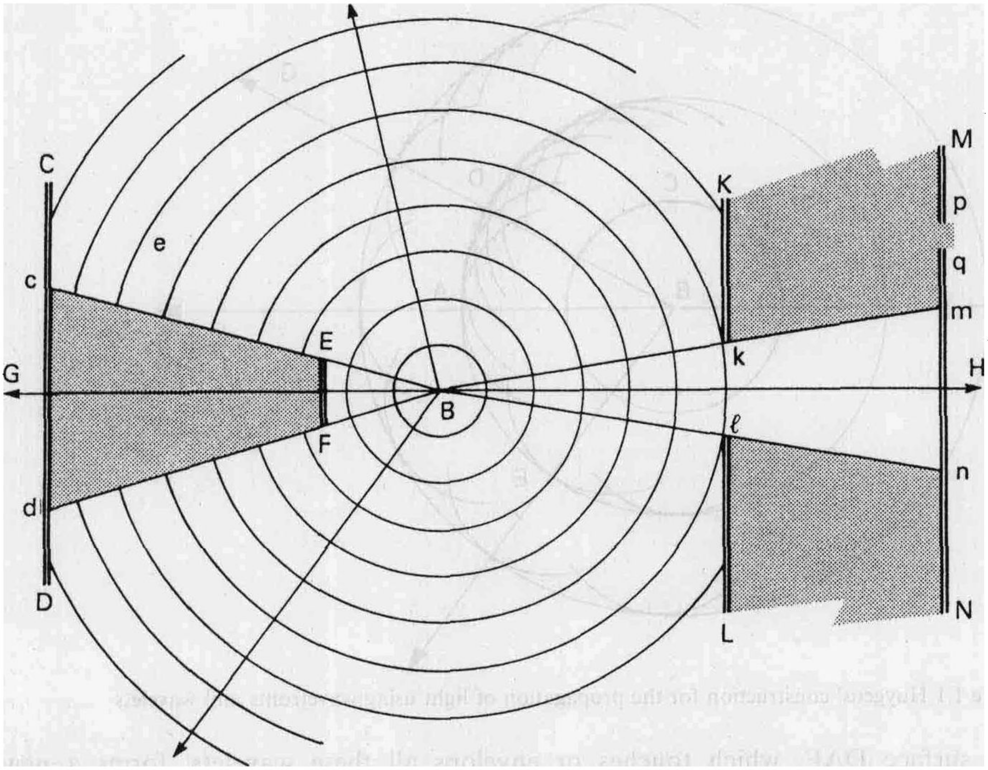

Figure 1.2 Rectilinear propagation of light shown using four opaque screens, a point source of light at B and apertures at *kl* and pq

effect at any point is due to that part of the light which has traveled along the straight line joining the point to the source.

If the shadow cd and the bright patch mn were studied more closely it would be found that they did not have sharp edges even when the source B was a very small point. The light waves, in passing the edges of these apertures, bend round into the space behind them in the same way as water waves may be seen curving round the end of a jetty or breakwater. Light waves are so very small that this bending or **diffraction** is a very small effect and special methods have to be used to see it at all (Chapter 13).

1.3 Pencils and beams

The light from a point source which passes through a limiting aperture, such as kl of Figure 1.2, forms a small group of rays which is called a **pencil** of light. Sometimes the word **bundle** of rays is used to mean the same thing. The term ray bundles is most often used in optical design work with computers and in the calculation of aberrations (Chapters 17 and 14). We will use the word pencil for most of this book. Pencils of rays can also be thought of as coming from any point on a large extended source or illuminated object. The aperture that defines the pencil may be an actual hole in an opaque screen or the edges of a lens, mirror or window.

In Figure 1.2, the pencil formed by kl becomes larger as it gets further away from B and the limiting aperture. We say that the light in this pencil is **divergent**. Sometimes the pencil is **convergent**, getting smaller along the direction of the light. This is the case with a convex lens when the light pencil converges to a point or **focus**. This focus is the **image** of the object point from which the light started. Beyond the focus the pencil diverges. When the object point or the focus is a very large distance away, the rays in the pencil will be almost parallel. The pencil will be parallel when the object or the image is at infinity. Divergent, parallel and convergent pencils, with their corresponding wavefronts, are shown in Figure 1.3. The ray passing through the center of the limiting aperture is called the **principal ray** or **chief ray** of the pencil.

The pencils of light described above start out at a point source of light. If the source of light or the illuminated object is larger than a point, we imagine that such extended sources or extended objects comprise a large number of point sources. When an aperture is restricting the light from the extended source, each point on the source has a pencil of rays going through the aperture (Figure 1.4(a)). This collection of pencils is called a **beam** of light. The edges of the beam may be diverging or converging independently of the pencils of light that form it. Thus, if light from the sun passes through an aperture (Figure 1.4(b)), the individual pencils from each point on the sun will be parallel but the pencils are not parallel to each other and the edges of the beam are divergent. The beam from a lens (Figure 1.4(c)) may be divergent while the pencils of light in it are convergent. In this book the terms divergent, convergent, and parallel light refer to *the form of the pencils* and *not to that of the beam.* We will study beams more in Chapter 7.

In Figure 1.5, BC′D′ is the section of a pencil diverging from a luminous point B, and limited by an aperture CD at position A. The width of the rectangular aperture is GE and FH and a rectangular patch of light is formed on a screen at position A′. The patch has the height C′D′ and the corners E′, F′, G′, and H′. In the similar triangles ABC and A′BC′,

$$\frac{C'A'}{CA} = \frac{BA'}{BA} \tag{1.1}$$

Because the light spreads out uniformly in all directions, all the other dimensions on the light patch are in the same proportion to their corresponding dimensions of the aperture.

Thus,

$$\frac{E'F'}{EF} = \frac{BA'}{BA}$$

$$\frac{E'G'}{EG} = \frac{BA'}{BA} \text{ etc.}$$

and

$$\frac{\text{Area } E'F'H'G'}{\text{Area EFHG}} = \frac{E'F' \times E'G'}{EF \times EG} = \frac{(BA')^2}{(BA)^2} \tag{1.2}$$

This means that the area of the cross-section of a pencil varies as the square of its distance from the source, since the amount of light in a pencil depends only on the amount given out by the source. This effect is very important in the science of photometry and will be studied in Chapter 10. If the source is large compared with the aperture a different effect is found.

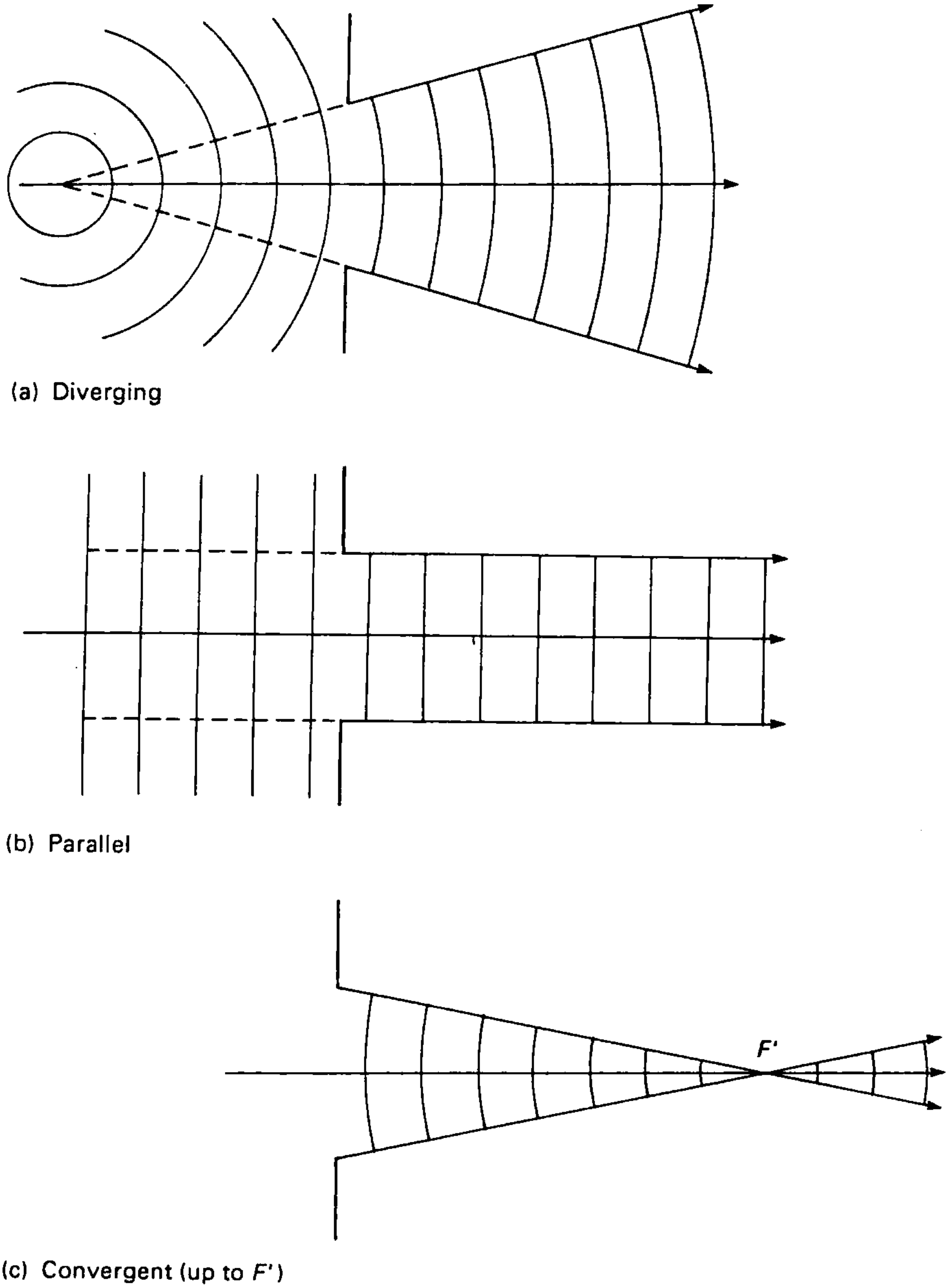

Figure 1.3 Light pencils and wavefronts

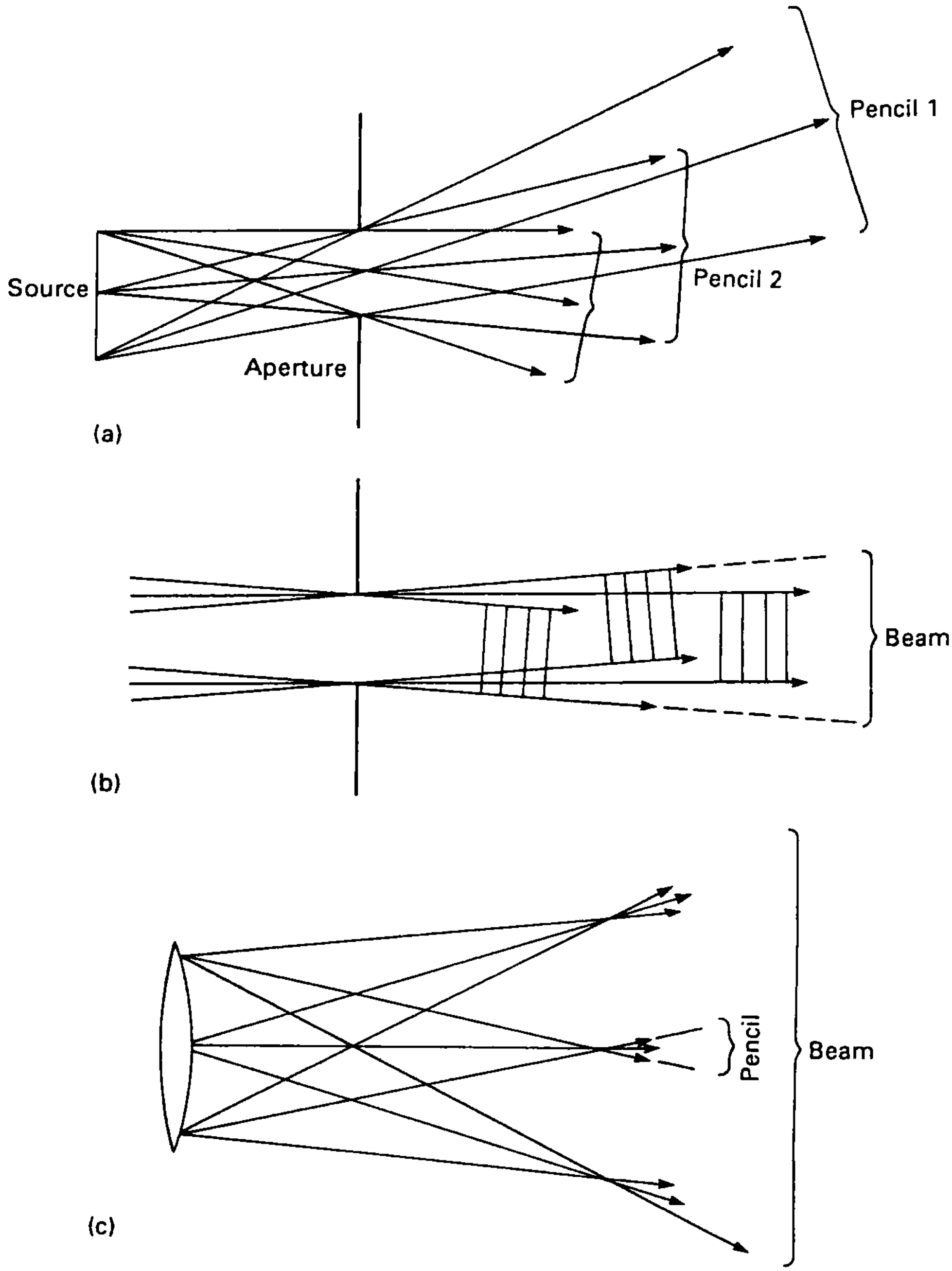

Figure 1.4 Pencils and beams

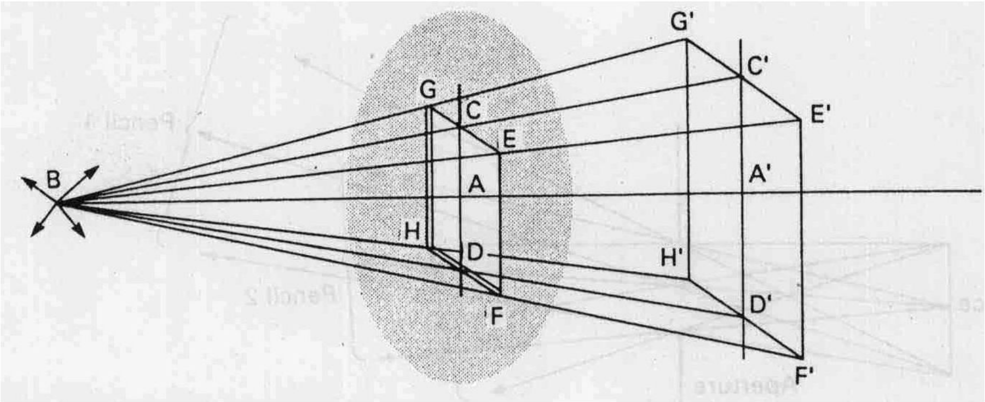

Figure 1.5 Width of a bundle or pencil

In this chapter and most chapters of this book we are more concerned with the actual size of images and shadows rather than their area. This means that Equation 1.1 forms the main basis for our calculations.

1.4 The pinhole camera

The action of a pinhole camera shows that light travels in straight lines and therefore this device provides a verification of the law of rectilinear propagation of light. As its name suggests, the pinhole camera uses a small hole to form images. The light from each point on an illuminated object, on passing through a small aperture in an opaque screen, forms a narrow pencil and, if the light is received on a second screen at some distance from and parallel to the first screen containing the aperture, each pencil produces a patch of light of the same shape as the aperture. Because the light travels in straight lines, the patches of light on the screen are in similar relative positions to those of the corresponding points on the object. The illuminated area of the screen is similar in shape to that of the original object but is turned upside down or **inverted** (Figure 1.6(a)).

If the aperture is made small (a pinhole), the individual patches of light will overlap only to a small extent and a fairly well defined picture or image of the object is formed. As can be seen in Figure 1.6(b), the size of the inverted image of any object will depend on the distances of object and image from the aperture. By using the mathematics of similar triangles again, we find that

$$\frac{h'}{h}=\frac{l'}{l} \tag{1.3}$$

The degree of sharpness of the image formed by a pinhole can never by very good because if the diameter of the hole is made very small the effects of diffraction (Chapter 13) begin to blur the image. Also, the illumination of the image is very low compared with that of a camera having a lens, which will have a larger aperture allowing more light to pass through. The pinhole camera image is free from distortion (Chapter 7) and has large depth of focus; that is, the images of objects at greatly varying distance are all reasonably sharp at any screen position.