Second edition

VISUAL OPTICS AND REFRACTION

A clinical approach

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Preface

The purpose of this book is to teach the principles and techniques of refraction as a clinical discipline in the context of optics, ocular physiology, and visual psychophysics. Since refractive errors also occur in diseased eyes and visual symptoms sometimes require more than spectacles, the discussions of pathophysiology may not be inappropriate.

The subject is divided into three parts: basics, technique, and management. It is a maxim of pedagogy that facts are best anchored to a rigging of theory, perhaps buoyed by a smile or a simile. Although practice transcends theory, the "art" of refraction is in cutting through irrelevancies quickly to reach a diagnosis efficiently. The section on technique emphasizes those tests most likely to give useful information in the restricted time of a busy practice. I have tried to steer a middle course between the manuals, which tell little with analysis, and the handbooks, which repeat everything without synthesis. It may be rash, even reckless, to assess how (and how not) to manage visual problems, but the reader is entitled to an evaluation even if he ultimately comes to differing conclusions. It is differences that make horse races, sometimes red faces.

An elementary treatment must necessarily be positive yet shun magisterial pronouncements. Extensive text documentation would only distract the beginner, and the advanced student will need to find his own path through the literature. The references at the end of each chapter may serve as a guide. They include papers of historic as well as current interest. Historic sidelights help enliven the subject and pay tribute to the pioneers fast fading in the flood of new research.

For this second edition almost every chapter has been completely rewritten, clinical material has been expanded, and basic science sections have been brought up to date. New chapters have been added on physiology, pharmacology, vision in children and the aged, ametropia, and strabismus. A chapter on symptoms is something of an experiment but may provide a clinically useful alternative to the more traditional regional pathologic analysis.

Written in spare moments between full-time practice, part-time teaching, and little time for anything else, this book would not have been possible without the cooperation of my patients, the indulgence of my publisher, and the forbearance of my family. My task was also made easier by help from colleagues in ophthalmology, optometry, physiology, pharmacology, and optical science. For their critical reviews of one or more chapters I should like to particularly thank Drs. L. Apt, R. E. Bannon, N. J. Bailey, M. V. W. Bergamini, J. M. Enoch, S. P. Eriksen, G. L. Feldman, J. R. Griffin, D. L. Guyton, A. E. Kreiger, A. Linksz, J. T. Pearlman, T. H. Pettit, I. S. Pilger, R. J. Schechter, D. D. Shepard, W. K. Stell, B. R. Straatsma, D. B. Whitney, R. D. Yee, and G. S. Zugsmith. Grateful appreciation is also expressed to friends in other specialties who took time to review pertinent sections, in particular, Drs. D. L. Belzer, pediatrics; N. F. Cantor, otolaryngology; B. A. Glass, neurosurgery; G. M. Putteet, psychiatry; and M. G. Wyman, internal medicine. The corrections and suggestions that emerged from these extensive reviews provided insights, integration, and perspective that could not have been achieved otherwise. I am, of course, solely responsible for any remaining errors in fact or theory.

No author could ask for more amicable cooperation than I have received from my secretarial staff, L. Alexander, K. Hargrove, D. Miller, C. Myers, and K. Rosso.

David D. Michaels

Note to the reader

A number of medications and other forms of medical treatment are reviewed in this book. While the descriptions are as accurate as possible, they should not be taken as direct instruction or recommendation for any individual patient. The contents of this book are informational only. Any specific medication should be prescribed by a physician and initiated under appropriate medical guidance.

Contents

PART ONE

BASICS

1

Light and vision

More than any other sense organ the eyes feed the brain with information by converting light into coded neural activity, although what the code is, no one is prepared to say. "Study optics," advised Voltaire, "and you will see it is impossible for objects to appear other than you see them." Nevertheless, the eyes miss a great deal because they respond to only a narrow band of radiations. The bent stick in the water, the image behind the mirror, and the mirage in the desert illustrate, sometimes painfully, that eyes can be deceived. We speak of green light and red apples, but the green turns gray in moonlight, and likely as not, the apple is a shade of yellow to the color blind. To what extent our senses can be trusted is a question of unending fascination to the epistemologist. Indeed the paradox of modern physics is that we are forever separated from a good part of the universe by a wall of indeterminacy. Truth is consistent sensation, not absolute but relative, and as Einstein proved, one cannot choose one's relatives.

THE NATURE OF LIGHT

Light travels in straight lines most of the time, like a beam of sunlight in a dusty room. If an opaque body is held in its path, a shadow is cast on a screen. In textbook diagrams, shadow edges are perfectly sharp; in reality they are diffused (Fig. 1-1). The difference illustrates the geometric and physical approaches to the subject. The mansion of geometric optics is built around a scaffold of four basic postulates: rectilinear propagation, the independence of light rays, and the laws of reflection and refraction. It serves well for most clinical purposes, but there are some vacancies. Fluorescence, lasers, and quantum thresholds cannot be explained without a brief glimpse into the basement—the domain of physical optics.

LIGHT VELOCITY

Galileo first proposed a way to measure light velocity. Two observers, each with a screened lantern, were to face each other over a considerable distance. When the first observer uncovered his lantern, the second was to immediately uncover his. The distances were too small for the experiment to work, but the principle was sound, and in 1675, Römer used the idea to measure the time for light from one of Jupiter's satellites to travel across the earth's orbit. The results came close to the actual value, now believed to be 3×10^{10} cm/sec. Astronomers measure light velocity in a vacuum; for our purposes air is similar enough to the vacuum to use as a standard reference index—the common denominator for comparing velocities. Since colored light is slowed to different degrees in denser media (dispersion), we simplify by pretending it is monochromatic. The ratio of light velocity in any medium compared to air is called refractive index (symbol n). Thus a refractive index of water = 1.33 means light travels 1.33 times faster in air than in water.

REFLECTION AND REFRACTION

Reflections in quiet pools of water have fascinated man since time began, and mirrors are by feminine acclaim the most popular optical instruments. Reflection from polished surfaces is regular, or specular. Ordinary surfaces reflect light in various directions, some reaching the eye to make them visible. Euclid named mirror optics "catoptrics" and Alhazen, about 1100 AD, stated the law of reflection: The angles of reflection and incidence are equal and lie in the same plane. One of the quirks of optical geometry is that angles are measured not with reference to the surface but relative to its perpendicular, or "normal."

When light enters a transparent medium it is slowed, that is, it is refracted. Light striking a sur-

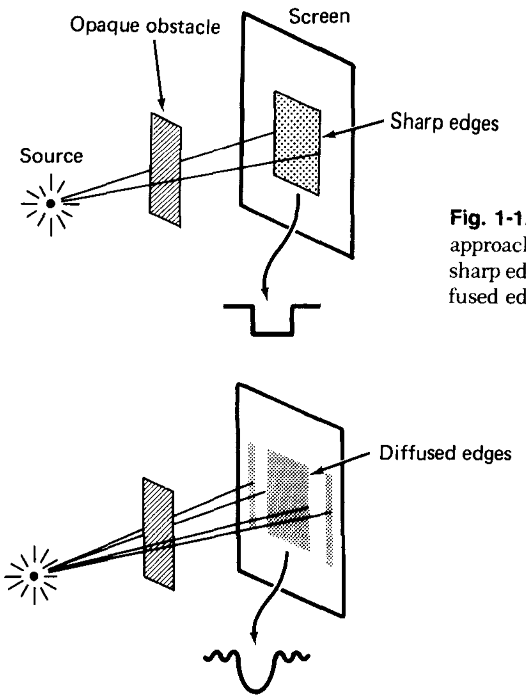

Fig. 1-1. The formation of shadows illustrates the two approaches to optics. The geometric shadow *(top)* has sharp edges; the experimental shadow *(bottom)* has diffused edges because of diffraction.

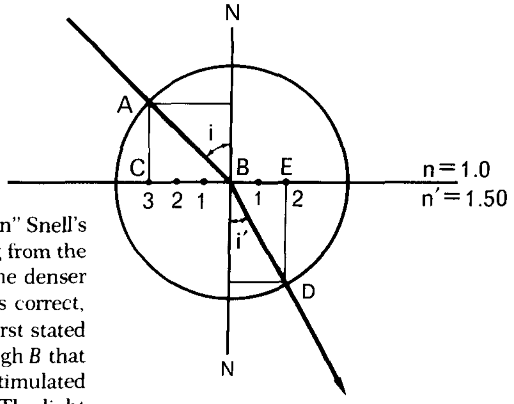

Fig. 1-2. Diagram used by Descartes to "explain" Snell's law. Descartes assumed that the ball traveling from the rarer medium *(AB)* moved half as easily in the denser medium so that $BE = \frac{2}{3} BC$. The geometry is correct, but the theory is wrong. The true principle, first stated by Fermat, is that light chooses the path through *B* that involves the least time. The same problem stimulated Bernoulli to found the calculus of variations. The light is actually slowed, not accelerated, in the denser medium.

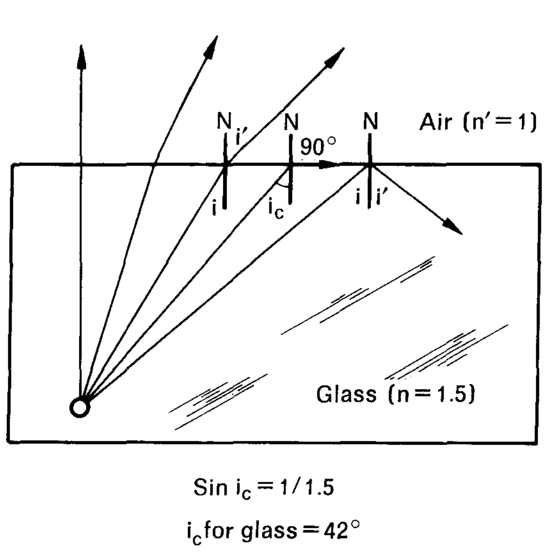

Fig. 1-3. Diagram illustrating refraction from a denser medium. According to Snell's law, the angle of refraction increases faster than the angle of incidence, and at one particular angle (i_c) the refracted ray just grazes the surface. Incident rays greater than the critical angle are reflected back into the glass.

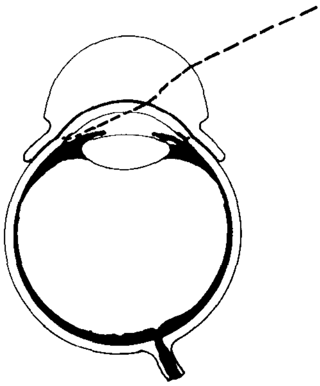

Fig. 1-4. Koeppe gonio-lens.

face obliquely continues at a new angle; if incidence is perpendicular, it is slowed but the angle is unchanged. The relation between these angles and refractive index remained a puzzle until Snell hit on the solution, but for some reason did not publish it. Instead the familiar equation was presented by Descartes (1637).

$$n \sin i = n' \sin i'$$

Snell's law states that the ratio of the sines of the angles is a constant for any two optical media (for a particular wavelength). The symbols i, i', n, and n' refer to angles of incidence and refraction in first and second medium respectively. Descartes' diagram is as useful as any to grasp the geometric essence of Snell's law (Fig. 1-2), but a more precise explanation was given by Fermat the same year Descartes gave his presentation, namely, that light chooses a path that requires the least time. Since light can retrace its path (principle of reversibility), the angles also switch; so in their computation the sequence of surfaces must be right.

An example of Snell's law is the critical angle (Fig. 1-3). A ray passing from air into a denser medium (e.g., water) is bent toward the normal; conversely a ray proceeding from water is bent away from the normal. When rays originate in denser media, there is one angle of incidence (i_c), that causes the refracted ray to just graze the surface. From Snell's law, $i_c = 1/n$, where n is the index of the denser medium, and i_c is called the critical angle. A direct goniolens alters the cornea-air interface (1.376/1.00) to a cornea-glass interface (1.376/1.52). Since the second medium is now denser than the first, there can be no critical angle, and the rays from the chamber angle previously internally reflected are allowed to escape (Fig. 1-4). Internal reflection also allows piping light down a transparent rod (fiber optics). An image can be transmitted by a series of rods if their relative orientation is maintained regardless of how the bundle as a whole is twisted.

TRANSPARENCY

The transparency of a medium is expressed as the transmission factor (T): intensity of transmitted light/intensity of incident light. The reciprocal of transparency is opacity, and $\log_{10}$ opacity is called optical density. Thus a filter having an optical density of 0.5 has a transmission of 1/3.16, or 32%. Superimposed neutral density (but not color) filters can be added algebraically by summing their optical densities. Transparent media containing suspended particles are said to be translucent. Biomicroscopy shows a transparent aqueous but translucent cornea and crystalline lens. Aqueous scatter is increased in uveitis, particularly short wavelengths, and corneal opacities also look blue. Ocular transmission is generally plotted in terms of optical density.

OPTICAL PATHS

To compare distances light travels in different media per unit time, multiply the actual distance by refractive index of the medium (optical path length). Thus light spans four units of length in air and three units of length in water ($n = 4/3$) in the same time. Paths of equal optical length are paths of equal travel time. It is more useful to establish the optical equivalence of light in different media by dividing actual distance by refractive index of that medium. This "reduced distance" expresses the equivalent effect in air. Thus light traveling four units of length in water is optically equivalent to light traveling three units of length in air. (Air is always the common denominator to which light in other media is "reduced.") To compare velocity in two media neither of which is air, divide one index by the other (relative refractive index). Problems of relative refractive index arise in computing optical power of a pseudophakos when placed in a medium of aqueous.

Waves and corpuscles

Prismatic colors were known before Newton but were believed to be a mechanical effect on light; no one wondered why another prism did not produce still more colors. In a crucial experiment, Newton showed that color lies in the light, not the prism, assuming a different corpuscle for each color. Across the English Channel, his contemporary Huygens reasoned that light, unlike sound, which cannot survive a vacuum, must be a wave traveling in an all-pervasive ether. And how, you ask, can such a wave travel over great distances, as from a star, without dissipation? "One will cease to be astonished," writes Huygens, addressing unborn generations of astonished optics students, "if one considers that an infinite number of wavelets originating at the same instant makes practically one single wave with force enough to reach our eyes." To explain why light travels in straight lines, Huygens invented a principle (named after him): Each wavelet's effect is limited to that point that touches the enveloping new wave front. By connecting equivalent points on a progressive wave, one has the direction of propagation or light "ray." But why the ray has such Euclidean wisdom Huygens did not say.

A century later, in 1807, Thomas Young repeated an experiment tried unsuccessfully by Grimaldi 150 years earlier. Grimaldi supposed that light waves interfere with each other but erred in using separate sources. Young placed two pinholes in front of the same source, thus obtaining twin waves. Catching them on a screen after each traveled a slightly different distance produced a series of dark areas on the screen. Thus interference was demonstrated as that peculiar reality in which two parts light add up to one part darkness. Diffraction is an interference effect, evident when light passes at the edge of an obstacle (interaction between unscreened wave and edge wave bending around corner). Diffraction can be demonstrated by lifting two fingers. Viewing the sky, bring fingers together and note, just before they touch, that the slit of light between them widens. Young's contemporary, Fresnel, saw in interference the solution to Huygens' puzzle. What prevented the Huygenian wavelets from traveling backward and limited their effects only to specific points was simply their mutual interference, or reinforcement. Seldom in the history of science was so much theory built on so little equipment. The wave theory was not to be challenged again until this century.

There remained the problem of Huygens' ether. "We can scarcely avoid the inference," wrote Maxwell in 1864, "that light consists of transverse waves traveling in the same medium as electric and magnetic phenomena" (Fig. 1-5). In this unifying composition light was but the visible form of a symphony of radiations, ranging from entertaining radio waves to a medley of cosmic rays. Maxwell did not live to see the vindication of his theory by Hertz who produced the first radio waves and showed they could be reflected and refracted. Still, the wave concept of light is somewhat strange—a motion in which nothing definite appears to move—and is made even more mysterious by Maxwell's equations, which expressed optical phenomena by units of electric and magnetic flux. A pebble thrown into a pool at least moves particles up and down. What particles are moved by light? And where are the eye's oscillators to receive them, like the ear drum receives sound?

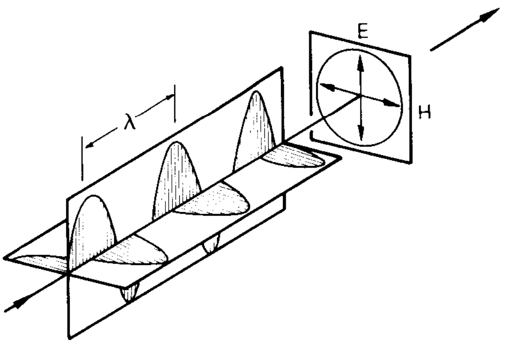

Fig. 1-5. Linearly polarized wave showing the electrical (*E*) and magnetic (*H*) vectors.

If one flips a cord tied at one end, a wave travels down the cord perpendicular to the arm movement. The energy is supplied by the arm muscles (the oscillator) and transmitted as a capacity to do work. When the walls of Jericho fell, it is rumored, at the sound of the trumpets, the concussion was transferred energy. The wave has a sine form (sinus = wave) unless the arm gets tired and the wave is dampened. As long as the arm holds out the waves repeat themselves periodically, and since the cord is fixed, their number is always a whole integer. The number of agitations per unit time (T) is the frequency (ν) and the distance the arm moves is the displacement or amplitude. Since displacement is both positive and negative, wave energy is expressed as the square of the amplitude. When the arm moves through one complete cycle, the cord produces one wavelength (λ). If T is the duration of a full vibration and ν the frequency, the wave travels a distance λ during that period; hence its velocity (c) is λ/T or $\lambda\nu$ (Fig. 1-6). When light passes into a denser medium, velocity changes but frequency remains the same; so it is wavelength that changes proportionately. Although frequency represents the reality of oscillation, wavelengths are easier to measure—thus physicists prefer rulers to stopwatches. Ordinarily, a feeble wave and one of high intensity pass through the same opening ignoring each other. It is only when they act simultaneously on a given point that action may be constructive or destructive—destructive not of energy but of distribution, as when the crest of one wave meets the trough of the other (e.g., the dark areas of Young's experiment). Since light velocity is 3×10^{10} cm/sec and a wave of visible light is about 1×10^{-5} cm long, the agitation of the arm would need be 3×10^{14} oscillations/sec. Such oscillations obviously require higher energy sources. And we also see why light waves bend around corners but are so small relative to the obstacle that the bending is seldom visible.

According to electromagnetic theory, refraction might be represented by light of certain frequency entering a medium and setting up oscillations therein

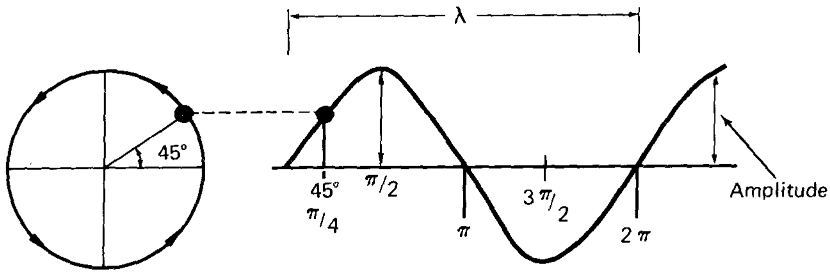

Fig. 1-6. Simple harmonic wave corresponds to a shadow cast on a moving screen by a continuously rotating ball. The angle of rotation is used to define various portions of the wave. The distance between two successive positions in the same phase is the wavelength (λ), the time for a complete wave motion to pass a given point is the frequency, and their product is the wave velocity.

whose waves combine with the light waves in constructive or destructive interference or even to block the light. But Maxwell's theory also predicted that as wavelength gets smaller, energy increases to infinity—an ultraviolet catastrophe. In fact, energy distributes itself toward the middle of the spectrum. To solve this problem Max Planck, at the turn of the century, postulated that oscillators do not give off energy continuously but in small packages or quanta. And the energy of each quantum is the product of its frequency and a constant h (now called Planck's constant): $E = h\nu$, where $h = 6.27 \times 10^{-27}$ erg-sec. The formula suggested an ultimate unit of energy, as there is an ultimate unit of matter. Five years later Einstein proposed that light also travels as quanta (or photons)—in fact as a kind of corpuscle. He showed that just as more torpedoes increase the chance of a hit but the explosion depends on the individual charge so did light displace electrons from a metal plate (photoelectric effect). Increasing light intensity increases the number of quanta, but their energy is fixed by frequency since all travel at the same velocity. Here was a theory Newton would have approved. To Pope's epitaph

> Nature and Nature's laws lay hid in night:
> God said, Let Newton be! and all was light.

A modern wit now added

> It could not last, the Devil howling "Ho!"
> "Let Einstein be," restored the status quo.

Quanta were obviously related to Planck's oscillators, and these, by tacit consent but without proof, were models of the atom. Now it was known that gaseous elements emit characteristic spectral lines. To tie these factors together Bohr, in 1913, proposed that atoms emit energy, not by continuous electron oscillations but only when an electron jumps from one stable orbit to another. His equation, based on the angular momentum of electrons, showed that the radii of electron orbits were natural integers, 1, 2, 3 . . ., to be multiplied by $h/2\pi$. Of course these jumps do not go on indefinitely for the atom requires another ticket, and the price is energy. It is thus impossible to obtain a single pure wavelength of light. Bohr's theory, confirmed by experiment, was meteoric, and it lasted all of a dozen years (to be replaced by quantum mechanics), but we find it useful to explain the operation of lasers. By 1923 Comptom demonstrated that (electromagnetic) x rays could behave like particles (Compton effect), and the modern biologist hardly thinks it remarkable that his electron microscope operates with matter, not light waves. As a simple visual concept, the quantum resembles a bullet; a wave, the parabolic path it travels. More than fattening a statistical curve by weight of numbers, light is wavelike and particle-like simultaneously.

Waves or particles? The controversy remains unsettled, and nearly any dogmatic statement one makes is likely to be proved wrong. Bohr's principle of complementarity is a modus vivendi. The principle states that an experiment that allows observation of one aspect prevents another, just as one cannot study morbid pathology and physiology in the same specimen. To observe wave properties we use our wave eye, and to study photons our corpuscular eye, but the microscope is always monocular, and we can never use binocular vision. The very act of seeing involves both aspects; waves pass through ocular media and are altered by spectacles; photons find sympathetic resonance in retinal photochemicals and are in turn transduced into nerve impulses. The wave concept works nicely in clinical optics, but if one intends to play with photochemistry, luminescence, and lasers, quanta determine the rule of the game. And the rule, called the principle of indeterminacy, says there is a statistical limit to the precision of all measurements.

RADIATION AND LIGHT

The limits of visibility are roughly between 390 and 760 nm, depending on ocular transmission and intensity. The range can be extended in the ultraviolet by removing the crystalline lens—indeed recent aphakes may complain of bluish tints (or red after images). Outside this small band of radiations the electromagnetic spectrum extends in both directions, from radio (Hertzian) waves, miles in length and longer, to cosmic rays with wavelengths 10^{-7} nm and less. Radio waves are produced by manmade oscillators and infrared by molecular oscillations. Atomic oscillations and nuclear disintegration produce waves ranging from the visible to x rays and gamma rays.

High-frequency electric oscillations (short Hertzian waves) are known clinically as diathermy. Molecular oscillations result from heating a solid to incandescence, whereupon it turns red, orange, and yellow until it is "white hot." An incandescent solid enclosed in a cavity produces a continuous spectrum, called a black body radiator, whose peak energy spectrum is shifted toward the blue end with increasing temperature (Wien's law). By a whimsy of terms, one gets white light when the black body is white hot. Color temperature provides a useful way to characterize light sources. Daylight is equivalent (not equal) to 25,000° K, an ordinary incandescent bulb to a color temperature of 2750° K, and the international candle to 2041.7° K, the temperature at which molten platinum solidifies. Gases, unlike solids, radiate characteristic wavelengths when a current is passed through them. Thus hydrogen glows a purple color (four wave bands plus others not visible), and sodium salt vaporizes with a typical yellow glow. These spectral lines identify the elements—the portraiture of spectrochemical analysis. Electrons impinging on an anticathode produce x rays. Low-voltage (grenz) or high-voltage (hard) roentgen rays are used diagnostically. Spontaneous atomic disintegration (radioactive sources) produces alpha, beta, and gamma particles; beta rays are used therapeutically.

When Newton pointed his prism at the sun, he saw consecutive colors. About 1820 Fraunhofer, aiming his spectroscope in the same direction, was startled to find several hundred dark lines. He labeled the major ones alphabetically. The lines result from absorption (scattering of certain frequencies) by atmospheric gases and provide a convenient method of identifying a particular spectral region. In evaluating the dispersion of glass, for example, one compares its effect on wave bands at the middle and two ends of the spectrum (see Chapter 3). The wavelengths are identified by their Fraunhofer letters C, D, and F.

RAYS, PENCILS, AND BEAMS

We have it on Huygens' authority that light waves are spherical surfaces concentric to their point of origin. A true representation of light would require drawing approximately 30,000 waves to the inch; the schema in Fig. 1-7 shows only a few selected wave fronts.

The curvature of a wave front in air depends on its radius; the further it travels the flatter it gets. At some point the radius is so long and the wave so flat that it is plane for all practical purposes. In visual optics this distance is taken as 6 m. In the accepted sign convention, converging waves are positive; diverging waves are negative (Fig. 1-8). A lens or mirror converging light is positive; one diverging light is negative.

The direction of wave propagation is the Euclidean ray perpendicular to its surface. If we think of the ray as a physical entity (e.g., by passing light through a small opening), we are in a mess because diffraction forever prevents isolating a single ray. Only in Euclidean geometry can matter that occupies space be represented by lines that do not. A light ray is noncommittal; it can represent equally well direction of flow of lu-

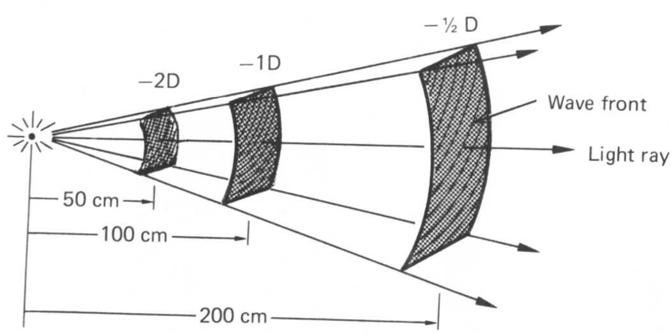

Fig. 1-7. The progressive decrease of curvature of an advancing wave front.

minous energy, wave normals, or paths of light quanta.

A group of rays passing through a limiting aperture is a "pencil." The aperture may be the pupil of the eye, the mounting of a trial lens, or the opening in a pinhole camera. The presence of an aperture is implicit in the notion of parallel rays. Since light sources always emit diverging rays, rays from a distant object only become parallel relative to some limiting aperture.

A collection of pencils is a "beam." Individual pencils making up the beam may converge or diverge, but vergence always refers to the pencils, not the beam (Fig. 1-9).

A pinhole camera illustrates rectilinear propagation and the formation of optical images (Fig. 1-10). All rays pass through the pinhole, ignoring each other, those from each object point proceeding in a straight line to an equivalent image point. The image is real; that is, it can be caught on a screen and is inverted. Its size is in the same ratio as the object and image distances. The image is made up of little patches of light that duplicate the shape of the aperture. Since the pupil is round, retinal images are made up of blur circles. Smaller apertures constrict the circles, which therefore overlap less, producing sharper images.

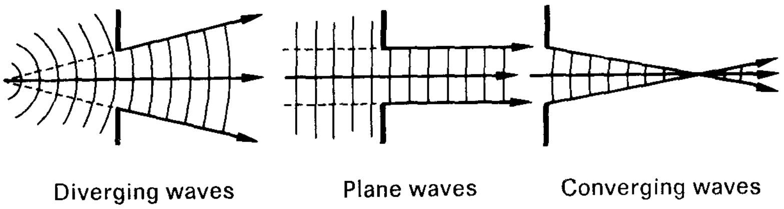

Fig. 1-8. Diverging, parallel, and converging pencils as limited by an aperture.

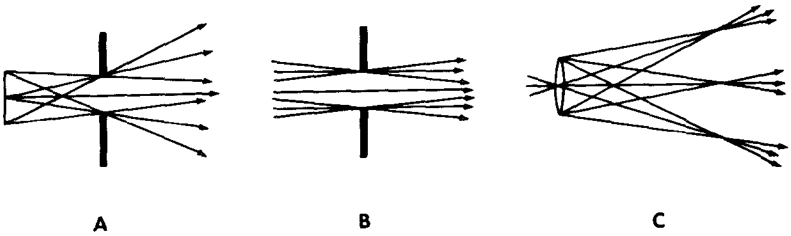

Fig. 1-9. Three light beams consisting of divergent **(A)**, parallel **(B)**, and convergent **(C)** pencils. Light "vergence" always refers to the pencils, not the beam.

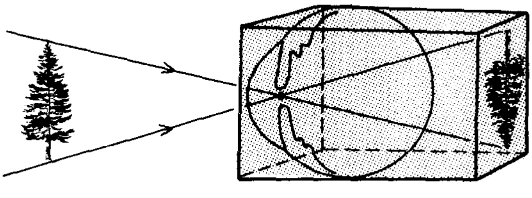

Fig. 1-10. The eye behaves in many respects like a pinhole camera. Each pencil passes through the aperture independently and forms a small patch of light on the screen (or retina) of the same shape as the opening. Since the pupil is round, retinal images are made of blue "circles."

POLARIZATION

Ordinary light consists of waves undulating at random in all directions. To prove light can be polarized, we pass it through a calcite crystal, which acts like a picket fence, isolating a single plane component. (Sound, a compression wave, cannot be polarized.) Light is an electromagnetic wave; so the crystal really behaves like an electric grid, and the direction of polarization is defined by the position of the electric (E) vector. Incident light breaks up into two rays of equal intensity called ordinary and extraordinary rays, forming double images. The crystal acts as if it had one index of refraction for one ray and another for the second. Dichroic crystals such as tourmaline pass the extraordinary rays and absorb the normal ones; two dichroic crystals may be crossed to form a variable density filter. A modified calcite crystal (Nicol prism) produces doubling in keratometry (Fig. 1-11).

Light generated by lasers is born polarized; the production method of polarization was developed by Land (1929). Crystals of quinine iodosulfate are embedded in cellulose acetate films (H sheets). The sheets are stretched and dipped into iodine solution. The iodine crystals affix themselves in the same orientation as the plastic, forming a giant grid that transmits about 50% of the vibrations perpendicular to the direction of stretch. The sheets are then cut to the desired shape and size.

Light reflected from glass surfaces at an angle of 57° is found to be polarized. This unique angle at which polarization is most complete is the polarizing angle (i_p) and its value can be derived from Snell's law: $\tan i_p = n$ where n is the index of the denser medium (Brewster's law). Certain substances such as sugar are optically active. Nitrobenzene becomes doubly refractive in an electric field, a property exploited in high-speed shutters (Kerr cells). Optical glass is isotropic but, when subject to stress, becomes birefringent (i.e., visible when placed between polarizers), a useful method of identifying heat-treated lenses or stress points from mountings. Skylight is partially polarized, evident when viewed through polarized film. The intensity of light transmitted by crossed polarizers is expressed by: $I_{max}\cos^2\theta$, where I_{max} is maximum intensity transmitted and θ the angle between polarizers (Malus' law). Polarizing sunglasses help reduce glare from sky, water, and wet roads. The reflected light is parallel to the surface; so spectacle polarizers are generally vertical. Millions of polarizers found their way into the hands of theater patrons during the brief popularity of "3-D" movies. Polarized pictures (vectographs) are used in evaluating binocular functions and in vision training. The human eye is a poor detector of polarization (even the lowly bee does better), the exception being Haidinger brushes, which provide a useful clinical test of foveal function.

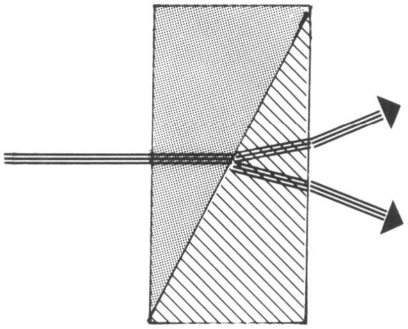

Fig. 1-11. Double image prism.

MEASURING LIGHT

Radiations are ubiquitous, serving as the ultimate source of energy. They control biologic rhythms, skin pigmentation, and vitamin D activation. On the negative side, they damage cells by inducing mutations, photosensitization, and skin cancer. Visible radiations are the adequate stimulus to the eye. Quantifying this stimulus is the business of photometry.

PHOTOMETRIC PRINCIPLES

The official definition of light by people who make their living measuring it is radiant flux evaluated with respect to its capacity to evoke visual brightness. To define a stimulus according to its sensory effects is the essence of psychophysics; hence we are told light is psychophysical. The physicist has no such problems; he measures radiations in ergs or joules per time (i.e., in watts) and cares not at all whether anyone sees them. Why must the photometrist redefine light before one can see it? Because equal amounts of radiant energy have unequal effects on the eye. Although the sun radiates approximately equal amounts of energy per unit wavelength, different colors do not appear equally bright. This inequality fluctuates when the eye is light or dark adapted, young or old, normal or color blind.

The usual psychophysical way of demonstrating the eye's unequal sensitivity is to expose different wavelengths on one side of a split field in

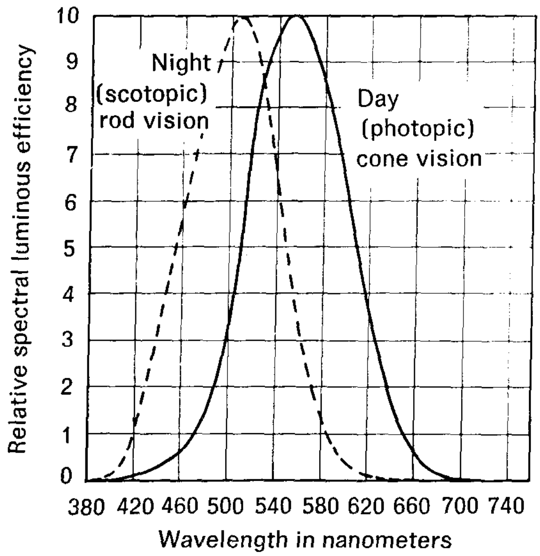

Fig. 1-12. Relative spectral sensitivity curves for photopic (cone) and scotopic (rod) vision showing the Purkinje effect on the wavelength of maximum sensitivity. (From Kaufman, J. E.: Illuminating Engineering Society lighting handbook, ed. 5, New York, 1972, Illuminating Engineering Society.)

progressive (cascading) increments while the observer adjusts a comparison field until they appear equal. The field is kept small (foveal vision), and the observer is light adapted and presumably color normal. The radiance of the adjustable field then expresses ocular sensitivity for the range of wavelengths studied and, when plotted, yields a bell-shaped curve peaking at 555 nm. Similar values can be obtained for the dark-adapted eye and parafoveal vision, but sensitivity is much greater and the peak is at 507 nm. The curves shown in Fig. 1-12 are of equal height only because results are expressed in relative units. "Spectral luminous efficiency" curves are said to express the "brightness-producing capacity" of one wavelength relative to another. In no case, of course, is brightness actually measured, only equalized by an observer acting as a null instrument. The reason photometry proceeds in this backward manner is that the eye is very poor at judging absolute brightness but quite efficient in estimating brightness differences. One must not conclude that a wavelength with relative brightness 6 is twice as bright as one with relative brightness 3; rather, the first takes half as many lumens to match the brightness of the second.

Radiometric and photometric standards were established independently of each other; hence the conversion units are arbitrary. Luminous intensity was originally defined in terms of a sperm candle, now changed to a Planckian radiator, but could just as well be qualified by a firefly if its output were reproducible. The number of lumens equivalent to 1 watt of 555 nm is currently set at 673 for photopic and 1725 for scotopic vision. Photopic and scotopic lumens are equal by definition, though their brightness and color do not look alike. In fact brightness matches for a particular state of light adaptation remain fairly constant. If one adds equal luminous energy to each side of a split field, the brightness differs, but the match remains valid (Abney's law). The matches do not hold up well in the intermediate (mesopic) range of vision.

It is conventional to express spectral luminous efficiency in relative units. They give the rate of exchange between radiometric and photometric values for similar viewing conditions, though in practice, one only cares about photopic vision. Unfortunately, even for photopic vision the conversion units vary embarrassingly from one observer to the next, especially with increasing age and at the short end of the spectrum. To liberate itself from such disconcerting individuality, photometry has officially adopted (by decree) a mixed bag of experimental values to represent an "average human observer." It is these values that are reproduced in Fig. 1-12. For every radiometric unit there is therefore an equivalent photometric unit