Ralph E Jacobson • Sidney F Ray
Geoffrey G Attridge • Norman R Axford

THE MANUAL OF Photography

Photographic and Digital Imaging



NINTH EDITION

Focal Press

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4 The geometry of image formation

Interaction of light with matter

Imaging generally records the interaction of light or radiation with the subject, except for self-luminous or emissive subjects and uses lenses or optical systems to form an image at the photoplane of a camera. There are four principal effects of the interaction of light with an object, namely *absorption*, *reflection*, *transmission*, and *chemical change*. The first two of these always occur to some extent: transmission occurs in the case of translucent or transparent matter; and chemical change occurs under appropriate circumstances. The absorbed light energy is not destroyed, but converted to another such as heat, or sometimes electrical or chemical energy. This chapter details the behaviour of reflected or transmitted light, and the formation of an optical image.

Transmission

Some transparent and translucent materials allow light to pass completely through them apart from absorption losses. Such light is said to be *transmitted* and the *transmittance* (T) of the material is the ratio of emergent luminous flux to incident luminous flux. *Direct transmission* (sometimes miscalled 'specular transmission') refers to light transmitted without scatter, as for example by clear optical glass. If *selective absorption* takes place for particular wavelengths of incident white light, then the material is seen as coloured by transmitted light, as in the case of a camera filter. If *scattering* occurs, as in a translucent medium, the light undergoes *diffuse transmission*, which may be uniform or directional or preferential. The transmittance of such a medium may be defined as in either a general or in a specific direction.

Reflection

Depending on the nature of the surface, particularly its smoothness, the reflection of light may be *direct* or *diffuse*. *Direct* or *specular reflection* is the type of reflection given by a highly polished surface such as a mirror, and is subject to the *laws of reflection* (Figure 4.1). Light incident on the surface is reflected at an angle equal to the angle of incidence. (The angles of incidence and reflection are both measured from the *normal*, i.e. the line perpendicular to the surface at the point of incidence.) The surface brightness of a directly reflecting surface is highly dependent on viewpoint. A perfectly diffuse or *Lambertian surface*, on the other hand, reflects the incident light equally in all directions; thus its *brightness* or *luminance* is seen as constant irrespective of viewpoint. Few surfaces have such extreme properties; shiny surfaces usually produce some scattered light, and matt surfaces (Figure 4.2) may show a 'sheen'. Reflection from most surfaces combines both direct and diffuse reflection and is known as *mixed reflection*. Depending on the properties of the incident light, the nature of the material and angle of incidence, the reflected light may also be partially or completely polarized. Objects are seen mainly by diffusely reflected light which permits the perception of detail and texture, qualities not found in specular surfaces such as mirrors.

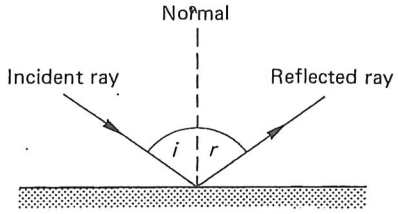


Figure 4.1 Specular reflection of an incident light ray by a plane mirror; $i = r$

Reflectance (R) is defined as the ratio of the reflected luminous flux to the incident luminous flux, and (as with transmittance) this may be defined as either general or in a specific direction. Surfaces

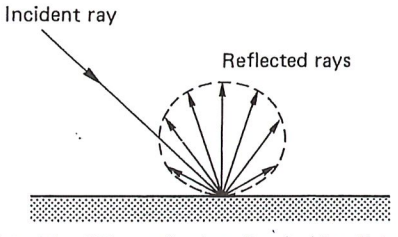


Figure 4.2 The diffuse reflection of an incident light ray by a matt surface

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Glass	*Refractive index*
Crown	1.46–1.53
Flint	1.53–1.65
Dense flint	1.65–1.92

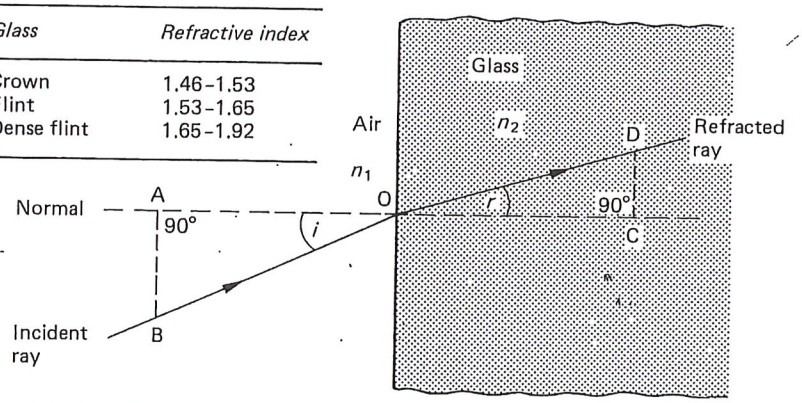


Figure 4.3 An obliquely incident light ray undergoing refraction when passing from air to glass

commonly encountered have reflectances in the range 0.02 (2 per cent) (matt black paint) to 0.9 (90 per cent).

Refraction

When a ray of light being transmitted in one medium passes into another of different optical properties its direction is changed at the interface except in the case when it enters normally, i.e. perpendicular to the interface. This *deviation*, or *refraction* of the ray results from a change in the velocity of light in passing from one medium to the next (Figure 4.3). Lenses utilize the refraction of glass to form *images*. Light travels more slowly in a denser medium, and a decrease (increase) in velocity causes the ray to be bent towards (away from) the normal. The ratio of the velocity in empty space to that within the medium is known as the *refractive index* (n) of the medium. For two media of refractive indices n_1 and n_2 where the angles of incidence and refraction are respectively i and r, then the amount of refraction is given by *Snell's Law*:

$$n_1 \sin i = n_2 \sin r \qquad (1)$$

Taking n_1 as being air of refractive index approximately equal to 1, then the refractive index of the medium n_2 is given by

$$n_2 = \frac{\sin i}{\sin r} \qquad (2)$$

The velocity of light in an optical medium depends on its wavelength, and refractive index varies in a non-linear manner with wavelength, being greater for blue light than for red light. A quoted value for refractive index (n_λ) applies only to one particular wavelength. The one usually quoted (n_d) refers to the refractive index at the wavelength of the d line in the helium spectrum (587 nm).

When light is transmitted by clear optical glass solids or prisms, refraction causes effects such as *deviation*, *dispersion* and *total internal reflection* (Figure 4.4). Deviation is the change of direction of the emergent ray with respect to the direction of the incident ray. In the case of a parallel-sided glass block, the emergent ray is not deviated with respect to the original incident ray; but it is *displaced*, the amount depending on the angle of incidence and the thickness of the block and its refractive index. A non-parallel-sided prism deviates the ray by two refractions, the deviation D depending on the refracting angle A of the prism, and on its refractive index. But when white light is deviated by a prism it is also dispersed to form a *spectrum*. The dispersive power of a prism is not directly related to its refractive index and it is possible to almost neutralize dispersion by using two different types of glass together, whilst retaining some deviation. In *achromatic lenses* this allows rays of different wavelengths to be brought to a common focus (see Chapter 6).

For a ray of light emerging from a dense medium of refractive index n_2 into a less dense medium of refractive index n_1, the angle of refraction is greater than the angle of incidence, and increases as the angle of incidence increases until a *critical value* (i_c) is reached. At this angle of incidence the ray will not emerge at all, it will undergo *total internal reflection* (TIR).

At this *critical angle* of incidence, $i_c = \sin^{-1}(n_1/n_2)$. For air ($n_1 = 1$), also for glass with $n_2 = 1.66$, i_c is 37 degrees. TIR is used in reflector prisms to give almost 100 per cent reflection as compared with 95 per cent at best for uncoated front-surface mirrors. A 45 degree prism will deviate a *collimated* (i.e. parallel) beam through 90 degrees by TIR; but for a

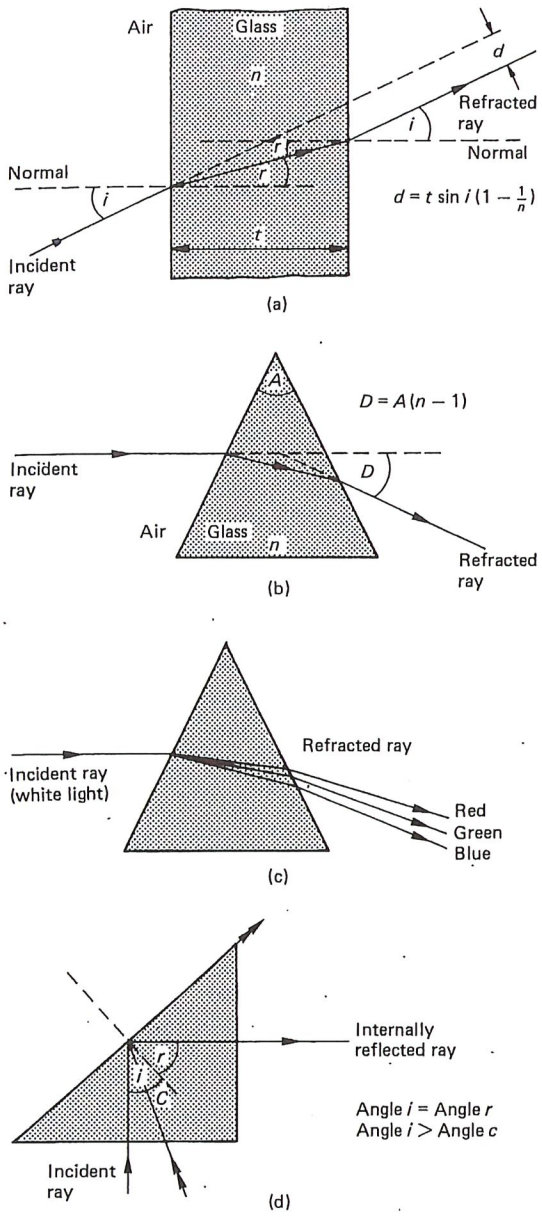


Figure 4.4 Various consequences of refraction of light by glass prisms. (a) A monochromatic light ray passing obliquely through a parallel-sided glass block, and resultant displacement *d*. (b) Refraction of monochromatic light caused by its passage through a prism, and resultant deviation *D*. (c) Dispersion of white light by a prism. (d) Total internal reflection in a right-angled prism, critical angle *C*

widely diverging beam the angle of incidence may not exceed the critical angle for the whole beam, and it may be necessary to metallize the reflecting surface.

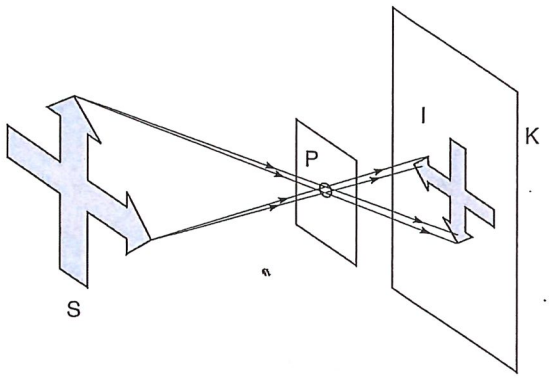


Figure 4.5 Formation of an image by a pinhole. The bundles of rays from points on the subject S pass through pinhole P and diverge to form an image I on photoplane surface K. The image is inverted, reversed, smaller and lacks sharpness

Image formation

When light from a subject passes through an optical system, the subject may appear to the viewer as being in a different place (and probably of a different size). This is due to the formation of an *optical image*. An optical system may be as simple as a plane mirror or as complex as a highly corrected camera lens. A simple method of image formation is via a *pinhole* in an opaque material (Figure 4.5). Two properties of this image are that it is *real*, i.e. it can be formed on a screen as rays from the object pass through the pinhole, and that, as light travels in straight lines, the image is *inverted*, and *laterally reversed* left to right as viewed from behind a scattering (focusing) screen. The ground-glass focusing screen of a technical camera when used with a pinhole shows such an image.

A pinhole is limited in the formation of real images, as the sharpness depends on the size of the pinhole. The optimum diameter (K) for a pinhole is given by the approximate formula:

$$K = \frac{\sqrt{v}}{25} \qquad (3)$$

where v is the distance from pinhole to screen. A larger hole gives a brighter but less sharp image. A smaller hole gives a less bright image, but this is also less sharp owing to diffraction (see Chapter 6). Although a pinhole image does not suffer from curvilinear distortion, as images produced by lenses may do, its poor transmission of light and low resolution both limit its use to a few specialized applications.

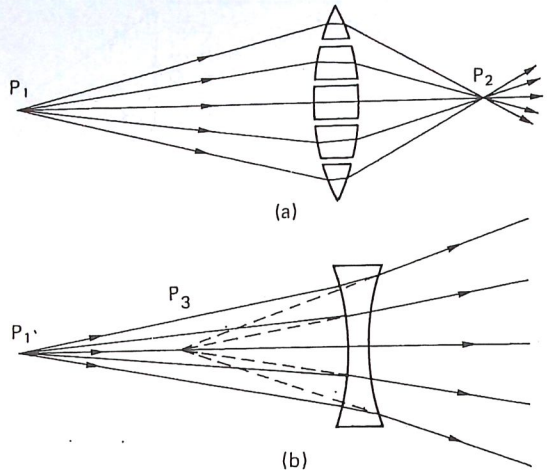


Figure 4.6 Negative and positive lenses. (a) A simple positive lens considered as a series of prisms. (b) Formation of a virtual image of a point object by a negative lens

The simple lens

A lens is a system of one or more pieces of glass or *elements* with (usually) spherical surfaces, all of whose centres are on a common axis, the *optical* (or *principal*) *axis*. A *simple* or *thin* lens is a single piece of glass or *element* whose axial thickness is small compared with its diameter, whereas a *compound* or *thick* lens consists of several air spaced *components*, some of which may comprise several elements cemented together, to correct for *aberrations*. A simple lens may be regarded as a number of prisms, as shown in Figure 4.6. Light diverging from a point source P_1 and incident on the front surface of the positive lens is redirected by refraction to form a real image at point P_2. These rays are said to come to a *focus*. Alternatively, by using a negative lens, the incident rays may be further diverged by the refraction of the lens, and so appear to have originated from a *virtual focus* at point P_3.

The front and rear surfaces of the lens may be convex, concave or plane; the six usual configurations of simple spherical lenses are shown in cross-section in Figure 4.7. A meniscus lens is one in which the *centres of curvature* of the surfaces are both on the same side of the lens. Simple positive meniscus lenses are used as *close-up lenses* for cameras. While the same refracting power in *dioptres* is possible with various pairs of curvatures, the *shape* of a close-up lens is important in determining its effect on the quality of the image given by the lens on the camera.

The relationships between the various parameters of a single-element lens of refractive index n_d, axial thickness q and radii of curvature of the surfaces R_1 and R_2 required to give a *focal length f* or *(refractive) power K* are given by the general 'lensmakers' formula':

$$K = \frac{1}{f} = (n_d - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \left(\frac{(n_d - 1)q}{n_d R_1 R_2}\right) \quad (4)$$

For f measured in millimetres, power $K = 1000/f$ in dioptres. For a thin lens, equation (4) simplifies to

$$K = \frac{1}{f} = (n_d - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \quad (5)$$

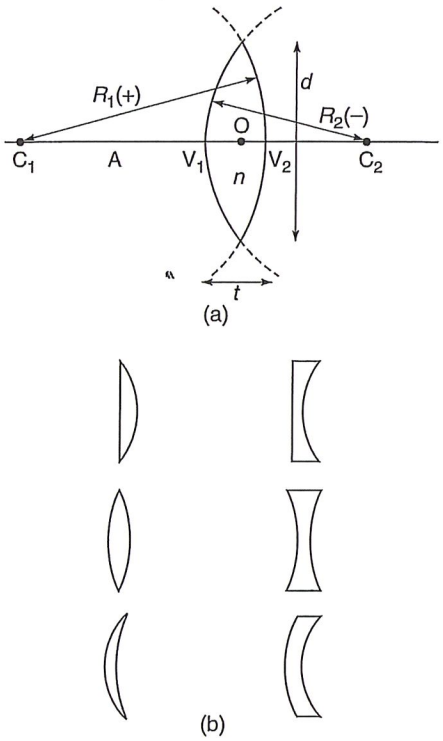


Figure 4.7 Simple lens. (a) Lens parameters; A, optical axis; C_1, C_2, centres of curvature with radii R_1 and R_2; V_1 and V_2, vertices of spherical surfaces; O, optical centre; n, refractive index; t, axial thickness; D, diameter. (b) Shape configurations: plano-convex, plano-concave, equi-biconvex, equi-biconcave, positive meniscus, negative meniscus

Image formation by a simple positive lens

Irrespective of their *configuration* of elements, camera lenses are similar to simple lenses in their image-forming properties. In particular, a camera lens always forms a real image if the object is at a distance of more than one focal length. The formation of the image of a point source has been discussed, now let

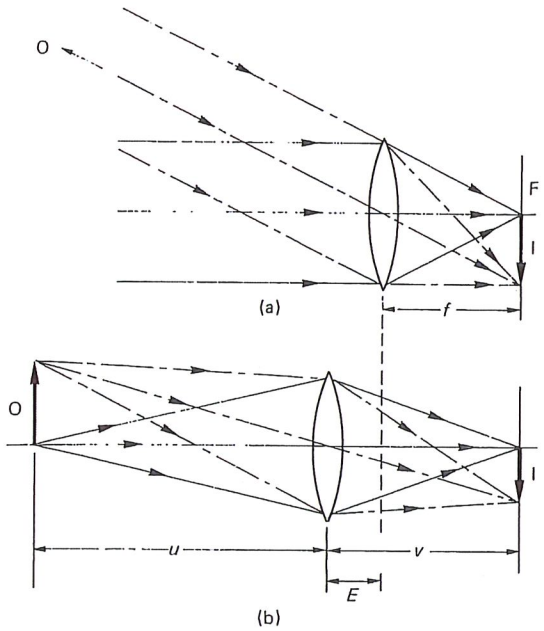


Figure 4.8 Image formation by a positive lens. (a) For a distant subject: F is the rear principal focal plane; (b) for a near subject: focusing extension $E = (v - f)$; I is an inverted real image

us consider the formation of the image of an extended object.

If the object is near the lens, the position and size of the optical image can be determined from the refraction of light diverging to the lens from two points at opposite ends of the object. Figure 4.8 shows this for a simple lens. The image is inverted, laterally reversed, minified, behind the lens and real.

To a first approximation, a distant object can be considered as being located at *infinity*. The rays that reach the lens from any point on the object are effectively parallel. As before the image is formed close to the lens, inverted, laterally reversed and real. The image plane in which this image is formed is termed the *principal focal plane* (F). For a flat distant object and an 'ideal' lens, every image point lies in this plane. The point of intersection of the focal plane and the optical axis is termed the *rear principal focus* (or simply the *focus*) of the lens, and the distance from this point to the lens is termed the *focal length* (f) of the lens. Only for an object at infinity does the *image distance* or *conjugate* (v) from the lens correspond to the focal length. As the object approaches the lens (i.e. object distance u decreases), the value of v increases (for a positive lens). If the lens is turned round, a second focal point is obtained; the focal length remains the same. The focal lengths of thick lenses are measured from different points in the lens configuration (see below). Finally, the distance of the focus from the rear surface of a lens is known as the *back focus* or *back focal distance*. This is of importance in camera design so that optical devices such as reflex mirrors or beam-splitting prisms can be located between lens and photoplane.

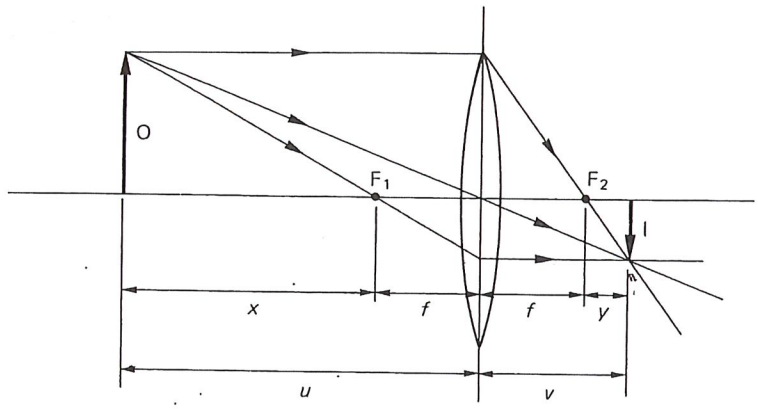
Image formation by a compound lens

A lens is considered as 'thin' if its axial thickness is small compared to its diameter and to the object and image distances and its focal length, so that measurements can be made from the plane passing through its centre without significant error (Figure 4.9a). With a compound lens of axial thickness that is a significant fraction of its focal length, these measurements plainly cannot be made simply from the front or back surface of the lens or some point in between. However, it was proved by Gauss that a thick or compound lens could be treated as an equivalent thin one, and thin-lens formulae used to compute image properties, provided that the object and image conjugate distances were measured from two theoretical planes fixed with reference to the lens. This is referred to as *Gaussian optics*, and holds for *paraxial* conditions, i.e. for rays whose angle of incidence to the optical axis is less than some 10 degrees.

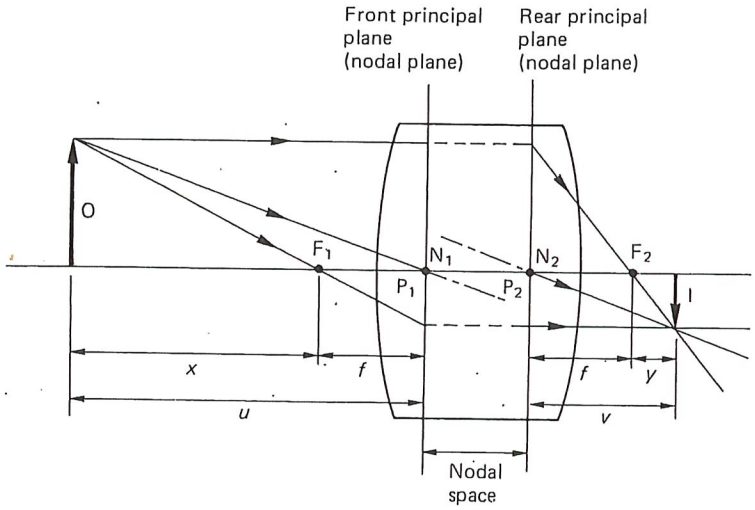
Gaussian optics uses six defined *cardinal* or *Gauss points* for any single lens or system of lenses. These are two *principal focal points*, two *principal points* and two *nodal points*. The corresponding planes through these points orthogonal to the optical axis are called the *focal planes*, *principal planes* and *nodal planes* respectively (Figure 4.9b). The focal length of a lens is then defined as the distance from a given principal point to the corresponding principal focal point. So a lens has two focal lengths, an object focal length and an image focal length; these are, however, usually equal (see below).

The definitions and properties of the cardinal points are as follows:

(1) *Object principal focal point* (F_1): The point whose image is on the axis at infinity in the image space.
(2) *Image principal focal point* (F_2): The point occupied by the image of an object on the axis at infinity in the object space.
(3) *Object principal point* (P_1): The point that is a distance from the object principal focal point equal to the object focal length F_1. All object distances are measured from this point.
(4) *Image principal point* (P_2): The point at a distance from the image principal focal point equal to the image focal length F_2. All image distances are measured from this point. The principal planes through these points are



(a) Simple lens



(b) Compound lens

Figure 4.9 Image formation by simple and compound lenses. (a) For a simple lens, distances are measured from the optical centre of the lens; distance y is the focusing extension. (b) For a compound lens, distances are measured from the principal or nodal planes (the principal planes coincide with the nodal planes when the lens is wholly in air)

important, as the thick lens system can be treated as if the refraction of the light rays by the lens takes place at these planes only. An important additional property is that they are planes of unit magnification for conjugate rays.

(5) *Object nodal point* (N_1) and

(6) *Image nodal point* (N_2) These are a pair of planes such that rays entering the lens in the direction of the object nodal point leave the lens travelling parallel to their original direction as if they came from the image nodal point. Any such ray is displaced but not deviated. If a lens is rotated a few degrees about its rear nodal point the image of a distant object will remain stationary. This property is used to locate the nodal points, and is the optical principle underlying one form of panoramic camera.

If the lens lies wholly in air, the object and image focal length of the numerous elements in the configuration (known as the *effective* or *equivalent focal length*) are equal, and the positions of the principal and nodal points coincide. This considerably simplifies imaging calculations. The value

of Gaussian optics is that if the positions of the object and cardinal points are known, the image position and magnification can be calculated with no other knowledge of the optical system. Positions of the cardinal points and planes can be used for graphical construction of image properties such as location and magnification.

Usually the nodal points lie within the lens, but in some types, either or both of the nodal points may be outside the lens, either in front of it or behind it. In a few cases the nodal points may actually be 'crossed'. The distance between the nodal points is called the *nodal space* or hiatus; in the case of crossed nodal points this value is taken as negative.

Graphical construction of images

The refraction by a lens can be determined if the paths of some of the image-forming rays are traced by simple graphical means. For a positive lens four rules are used, based on the definitions of lens properties.

(1) A ray passing through the centre of a thin lens is undeviated.
(2) A ray entering a lens parallel to the optical axis, after refraction, passes through the focal point of the lens on the opposite side.
(3) A ray passing through the focal point of a lens, after refraction, emerges from the lens parallel to the optical axis.
(4) A meridional ray (one in a plane containing the optical axis), entering the front nodal plane at a height X above the axis, emerges from the rear nodal plane at the same height X above the axis on the same side and undeviated (see Figure 4.9b).

These rules (except the last) are illustrated in Figure 4.10, together with their modification to deal with image formation by negative lenses and concave and convex spherical mirrors. Image formation is shown for a range of types of lenses and mirrors. Note that in practice other surface shapes are used such as ellipsoidal and paraboloidal as well as aspheric, principally in the optics of illumination systems for projection and enlarging. Increasingly, aspheric surfaces are used in camera lenses to reduce the number of spherical surfaces otherwise required for adequate aberration correction.

The lens conjugate equation

A relationship can be derived between the conjugate distances and the focal length of a lens. With reference to Figure 4.11, a positive lens of focal length f with an object distance u forms an image at distance v.

From similar triangles ABC and XYC,

$$\frac{AB}{XY} = \frac{BC}{YC} = \frac{u}{v} \tag{6}$$

From the figure,

$$BF_1 = u - f \tag{7}$$

Also from similar triangles ABF and QCF

$$\frac{BF_1}{CF_1} = \frac{AB}{QC} = \frac{AB}{XY} \tag{8}$$

By substituting equations (6) and (7) in (8) we obtain

$$\frac{u-f}{f} = \frac{u}{v}$$

Rearranging and dividing by uf we obtain the *lens conjugate equation*

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f} \tag{9}$$

This equation may be applied to thick lenses if u and v are measured from the appropriate cardinal points.

The equation is not very suitable for practical photographic use as it does not make use of object size AB or image size XY, one or both of which are usually known. Defining *magnification* (m) or *ratio of reproduction* or *image scale* as XY/AB = v/u, and substituting into the lens equation and solving for u and v we obtain

$$u = f\left(1 + \frac{1}{m}\right) \tag{10}$$

and

$$v = f(1 + m) \tag{11}$$

Because of the conjugate relationship between u and v as given by the lens equation above, these distances are often called the *object conjugate distance* and *image conjugate distance* respectively. These terms are usually abbreviated to 'conjugates'.

A summary of useful lens formulae is given in Figure 4.12, including formulae for calculating the combined focal length of two thin lenses in contact or separated by a small distance. A suitable sign convention must be used. For most elementary photographic purposes the 'real is positive' convention is usually adopted. By this convention, all

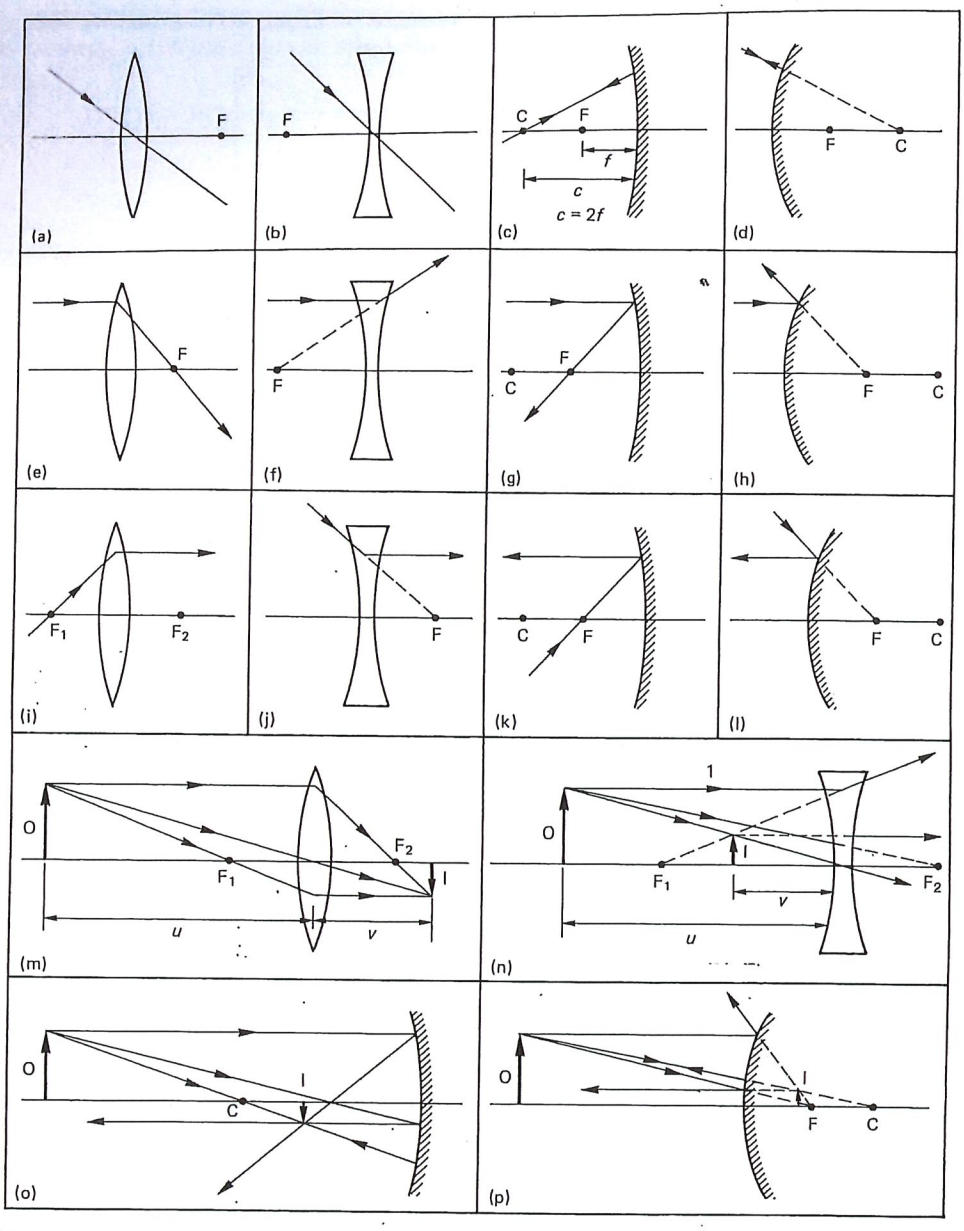


Figure 4.10 The graphical construction of images formed by simple lenses and spherical mirrors. (a) A ray passing through the centre of a positive (i.e. convex) lens is undeviated. (b) A ray passing through the centre of a negative (i.e. concave) lens is undeviated. (c) A ray passing through the centre of curvature of a concave mirror is directed back upon itself. (d) A ray directed towards the centre of curvature of a convex mirror is directed back upon itself. (e) A ray travelling parallel to the optical axis of a positive lens, after refraction passes through the far focal point of the lens. (f) A ray travelling parallel to the optical axis of a negative lens, after refraction appears as if it had originated at the near focal point of the lens. (g) A ray travelling parallel to the optical axis of a concave mirror, after reflection passes through the focus of the mirror. (h) A ray travelling parallel to the optical axis of a convex mirror, after reflection appears as if it had originated from the focus of the mirror. (i) A ray passing through the near focal point of a positive lens, after refraction emerges from the lens parallel to the optical axis. (j) A ray travelling towards the far focal point of a negative lens, after refraction emerges from the lens parallel to the optical axis. (k) A ray passing through the focus of a concave mirror, after reflection travels parallel to the optical axis. (l) A ray directed towards the focus of a convex mirror, after reflection travels parallel to the optical axis. (m) An example of image construction for a positive lens using the three rules illustrated above. (n) An example of image construction for a negative lens. (o) An example of image construction for a concave mirror. (p) An example of image construction for a convex mirror

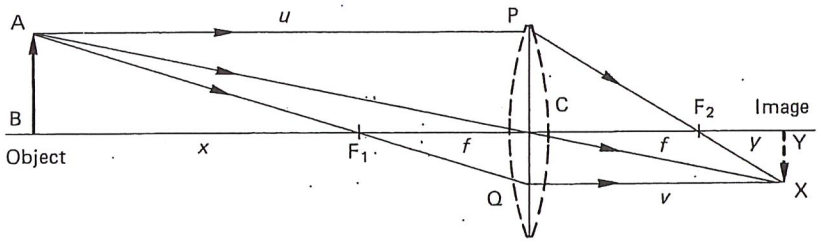
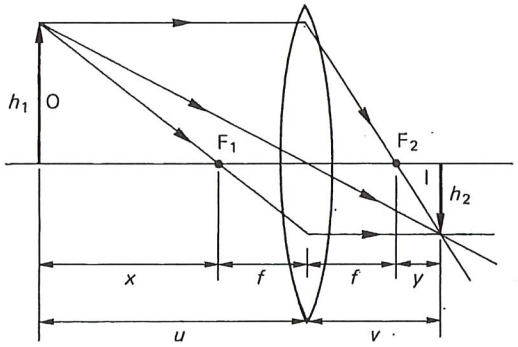
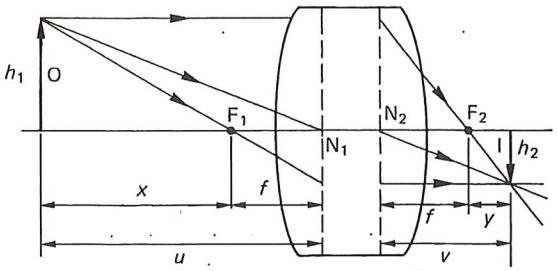


Figure 4.11 Derivation of the lens equation

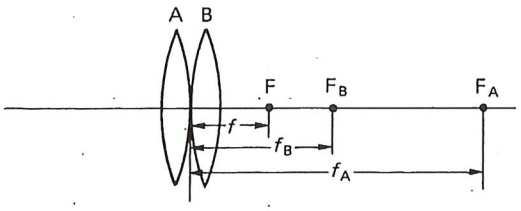


(a) Simple lens

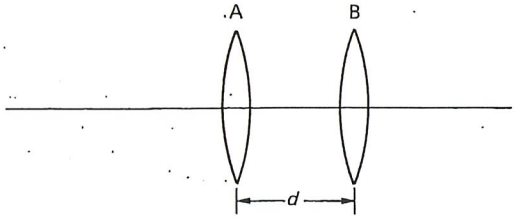


(b) Compound lens

1. $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ $\quad u = f\left(1 + \frac{1}{m}\right)$
2. $\frac{h_2}{h_1} = \frac{I}{O} = \frac{v}{u} = m$ $\quad v = f(1 + m)$
3. For $u = \infty$, or for $u >> v$, $v = f$ so that $m = \frac{f}{u}$
4. $xy = f^2$



(c) Thin lenses in contact



(d) Thin lenses separated by a small distance

$\frac{1}{f} = \frac{1}{f_A} + \frac{1}{f_B}$ or,

$\frac{1}{f} = P = P_A + P_B$

P is the 'power' (expressed in dioptres)

$\frac{1}{f} = \frac{1}{f_A} + \frac{1}{f_B} - \frac{d}{f_A f_B}$

Figure 4.12 Some useful lens formulae for lens calculations

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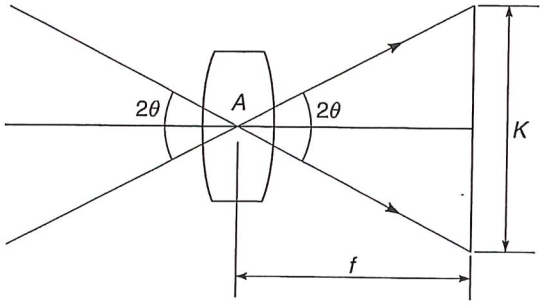


Figure 4.13 Field (angle) of view (FOV) of a lens related to format dimension

distances to real objects and real images are considered to be positive. All distances to virtual images are considered as negative. The magnification of a virtual image is also negative. An alternative Cartesian convention takes the lens or refracting surface at the origin so distances measured to the right are positive, and distances to the left are negative.

It is useful to note that when the object conjugate u is very large, as for a distant subject, the corresponding value of the image conjugate v may be taken as f, the focal length. Consequently, the magnification is given by $m = f/u$. Thus, image magnification or scale depends directly on the focal length of the camera lens for a subject at a fixed distance. From a fixed viewpoint, to maintain a constant image size as subject distance varies a lens with variable focal length is required, i.e. a zoom lens (see Chapter 7).

Field angle of view

The focal length of a lens also determines the angle of the *field of view* (FOV) relative to a given film or sensor format. The FOV is defined as the angle subtended at the (distortion-free) lens by the diagonal (K) of the format when the lens is focused on infinity (Figure 4.13).

Given that the FOV angle A is twice the semi-angle of view θ, then:

$$A = 2\theta = 2\tan^{-1}\left(\frac{K}{2f}\right) \qquad (12)$$

The field of view for a particular combination of focal length and film format may be obtained from Table 4.1. To use this table, the diagonal of the negative should be divided by the focal length of the lens; the FOV can then be read off against the quotient obtained.

Table 4.1 Table for deriving field of view of an orthoscopic lens

Diagonal/focal length (K/f)	*Field of view* (2θ) degrees*
0.35	20
0.44	25
0.54	30
0.63	35
0.73	40
0.83	45
0.93	50
1.04	55
1.15	60
1.27	65
1.40	70
1.53	75
1.68	80
1.83	85
2.00	90
2.38	100
2.86	110
3.46	120

*These values are for a lens which produces geometrically correct perspective.

As the lens to subject distance decreases, the lens to film distance increases, and the FOV decreases from its infinity-focus value. At unit magnification the FOV has approximately half its value at infinity focus.

Photographic lenses can be classified according by FOV for the particular film format for which they are designed. There are sound reasons for taking as 'standard' a lens that has a field of view approximately equal to the diagonal of the film format. For most formats this angle will be around 52 degrees. Wide-angle lenses can have FOVs up to 120 degrees or more, and long focus lenses down to 1 degree or less. Table 4.2 gives a classification of lenses for various formats based on FOV.

Occasionally confusion may arise as to the value of the FOV of a lens as quoted, because a convention exists in many textbooks on optics to quote the semi-angle θ, in which cases value given must be doubled for photographic purposes. It should also be noted that the FOV for the *sides* of a rectangular film format is always less than the value quoted for the diagonal. The horizontal FOV is perhaps the most useful value to quote.

The term 'field of view' becomes ambiguous when describing lenses that produce distortion, such as fish-eye and anamorphic objectives. In such cases it may be preferable to describe the angle subtended by the diagonal of the format at the lens as the 'angle of the field' and the corresponding angle in the object space as the 'angle of view'.

Table 4.2 Lens type related to focal length and format coverage

Focal length (mm)	*Nominal format (mm)*	*Angle of view (degrees on diagonal)*	*Lens type*
15	24 × 36	110	EWA
20	24 × 36	94	EWA
20	APS	75	WA
24	24 × 36	84	WA
24	APS	67	WA
35	24 × 36	63	SWA
35	APS	50	S
40	24 × 36	57	S
40	60 × 60	94	EWA
40	APS	47	S
50	24 × 36	47	S
50	60 × 60	81	WA
50	60 × 70	85	WA
65	24 × 36	37	MLF
65	60 × 60	66	SWA
65	4 × 5 in	103	EWA
80	60 × 60	56	S
90	24 × 36	27	MLF
90	APS	22	MLF
90	4 × 5 in	84	WA
135	24 × 36	18	LF
135	60 × 60	35	MLF
135	4 × 5 in	62	S
150	60 × 60	32	LF
150	4 × 5 in	57	S
200	24 × 36	12	LF
200	8 × 10 in	78	WA
250	60 × 60	19	LF
300	24 × 36	8	VLF
300	8 × 10 in	57	S
500	24 × 36	5	VLF
500	60 × 60	10	LF
500	4 × 5 in	19	LF
1000	24 × 36	2.5	ELF
1000	60 × 60	5	VLF
1000	4 × 5 in	9	LF
1000	8 × 10 in	19	LF

EWA extreme wide-angle; WA wide-angle; SWA semi wide-angle; S standard; MLF medium long-focus; LF long-focus; VLF very long-focus; ELF extreme long-focus.

Covering power of a lens

Every lens projects a fuzzy edged disc of light as the base of a right circular cone whose apex is at the centre of the exit pupil of the lens. The illumination of this disc falls off towards the edges, at first gradually and then very rapidly. The limit to this *circle of illumination* is due to *natural vignetting* as distinct from any concomitant mechanical vignetting. Also, owing to the presence of residual lens aberrations, the definition of the image within this disc deteriorates

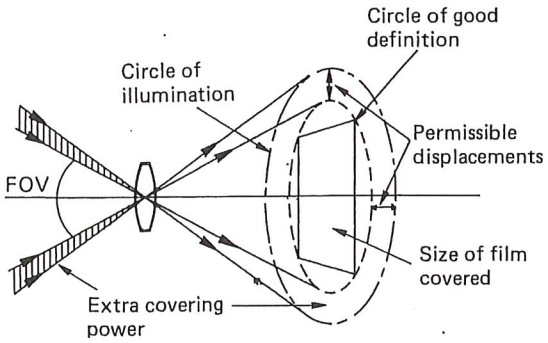


Figure 4.14 The covering power of a lens and image format

from the centre of the field outwards, at first gradually and them more rapidly. By defining an acceptable standard of image quality, it is possible to locate a boundary defining a *circle of good or acceptable definition* within this circle of illumination. The sensor format should be located within this region (Figure 4.14).

The extent of the circle of acceptable definition also determines the practical performance of the lens as regards the covering power relative to a given format. The *covering power* is usually expressed as an angle of view which may be the same as or greater than that given by the format in use. A greater FOV than set by the format is called *extra covering power* and is essential for a lens fitted to a technical camera or a *perspective-control* (PC) or 'shift' lens when lens displacement movements are to be used. The extra covering power permits displacement of the format within the large circle of good definition until vignetting occurs, indicated by a marked decrease in luminance at the periphery of the format.

Covering power is increased by closing down the iris diaphragm of a camera lens, because mechanical vignetting is reduced, and off-axis lens aberrations are decreased by this action. The covering power of lenses for technical cameras is quoted for use at *f*/22 and with the lens focused on infinity. Covering power increases as the lens is focused closer; for close-up work a lens intended for a smaller format may cover a larger format, with the advantage of a shorter bellows extension for a given magnification.

Geometric distortion

A wide-angle lens, i.e. a lens whose FOV exceeds some 75 degrees, is invaluable in many situations, such as under cramped conditions, and where use of the 'steep' perspective associated with the use of such lenses at close viewpoints is required. The large angle of view combined with a flat film plane (rather than

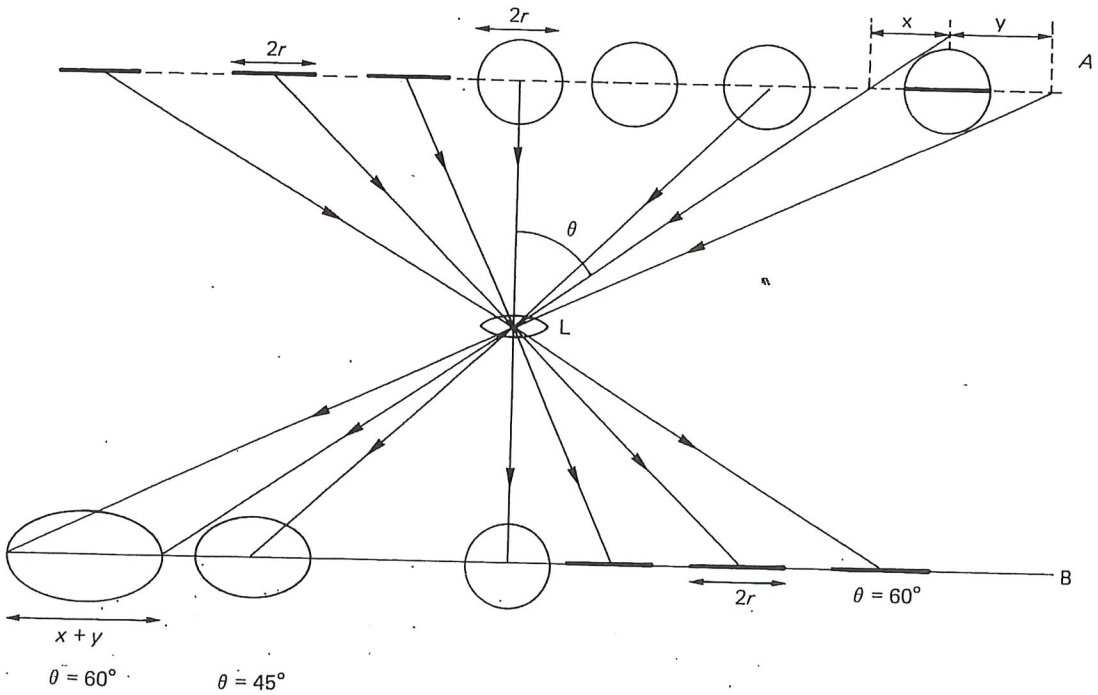


Figure 4.15 Geometric distortion by a lens. An array of spheres of radius r and lines of length $2r$ in the subject plane A are imaged by lens L in image plane B at unit magnification. The lines retain their length independent of field angle θ but the spheres are progressively distorted into ellipses with increase in θ

the saucer-shaped surface that would intuitively be thought preferable), makes shape distortion of three-dimensional objects near the edge of the field of view very noticeable. The geometry of image formation by a lens over a large field is shown in Figure 4.15, producing *geometrical distortion* which must not be confused with the *curvilinear distortion* caused by lens aberrations. Flat objects are of course not distorted in this way so a wide-angle lens can be used for the copying of flat originals. As an example of the distortion occurring with a subject such as a sphere of diameter $2r$, the image is an ellipse of minor diameter $2r$ and major diameter W, where $W = 2r \sec\theta$, given unit magnification and that r is small relative to the object distance. The term $\sec\theta$ is the *elongation factor* of the image.

Depth of field

Image sharpness

Any subject can be considered as made up of a large number of points. An ideal lens would image each of these as a point image (strictly, an Airy diffraction pattern) by refracting and converging the cone of light from the subject point to a focus. The purpose of focusing the camera is to adjust the image conjugate to satisfy the lens equation. The image plane is strictly correct for all object points in a conjugate plane, provided all points of the object *do* lie in a plane. Unfortunately, objects in practice do not usually lie in a plane, and so the image also does not lie in a single plane. Consider just two of the planes through the object (Figure 4.16). For an axial point in both planes, each point can be focused in turn but both cannot be rendered sharp simultaneously. When the image of one is in focus the other is represented by an image patch, called more formally a *blur circle*. These discs or *circles of confusion* are cross-sections of the cone of light coming to a focus behind or in front of the surface of the film.

This purely geometrical approach suggests that when photographing an object with depth, only one plane can be in sharp focus and all other planes are out of focus. Yet in practice pictures of objects are obtained with considerable depth that appear sharp all over. The reason is that the eye is satisfied with something less than pin-point sharpness. In the absence of other image-degrading factors such as lens aberrations or camera shake, a subjective measure of image quality is its perceived *sharpness*, which may be defined as the adequate provision of resolved detail in the image. Inspection of a photograph

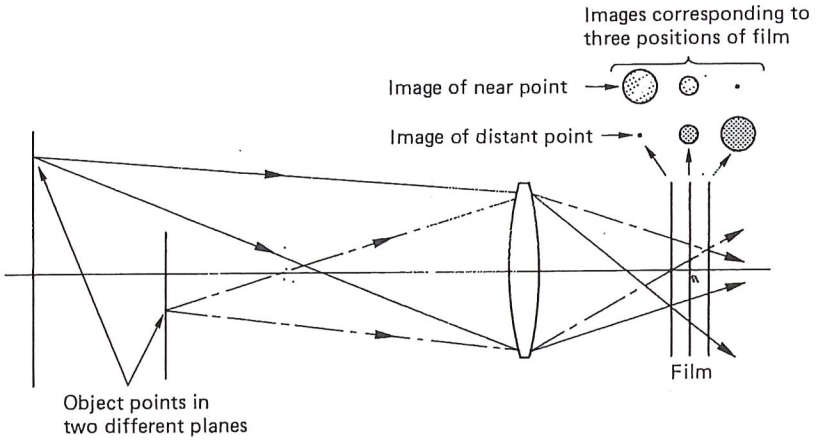


Figure 4.16 Object points at different distances and their images at different photoplanes

containing subject matter covering a considerable depth shows that the sharpness of the image does vary with depth. Detail both in front of and behind the point of optimum focus may, however, be rendered adequately sharp, giving a zone of acceptably sharp focus; this zone is termed the *depth of field*. (The term applies only to the object space and should not be confused with the related *depth of focus*, which applies to the conjugate region through the focal plane in the image space.) Depth of field is of great importance in most types of photography, the manipulation of its positioning and extent being an

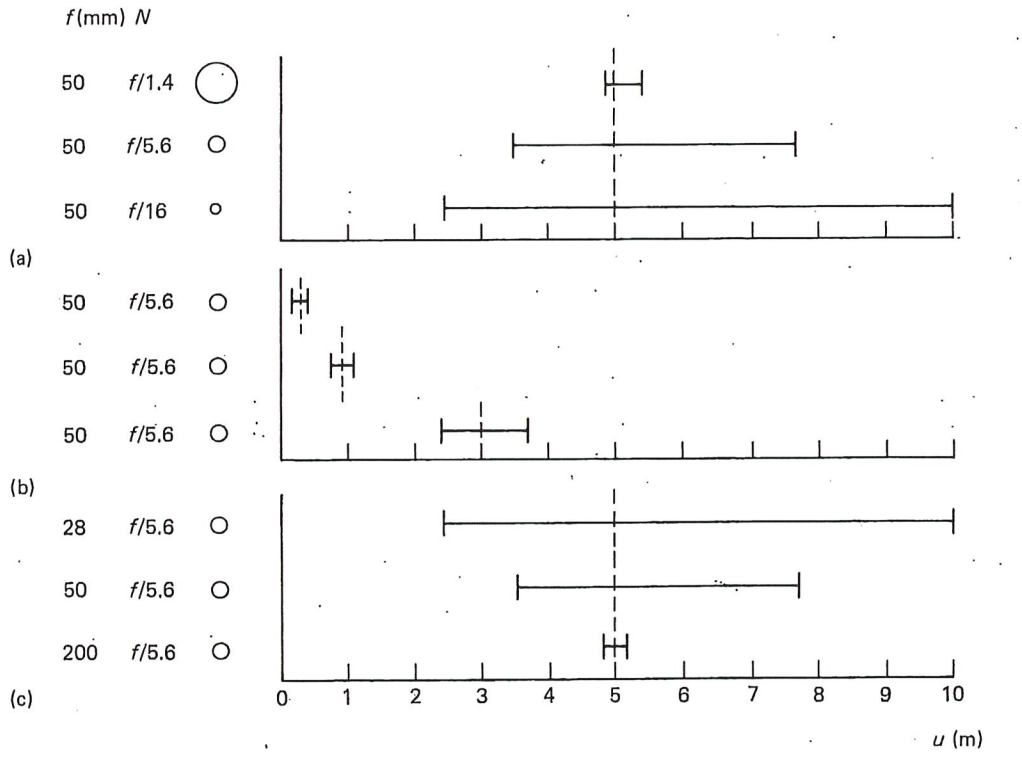


Figure 4.17 Depth of field. Three variables in general influence depth of field T at a constant value for the circle of confusion. (a) Lens aperture N, varying from *f*/1.4 to *f*/16 with a 50 mm lens focused at 5 m. (b) Focused distance u, varying from 0.5 to 3 m with a 50 mm lens at *f*/5.6 (c) Focal length f varying from 28 to 200 mm at *f*/5.6 focused on 5 m

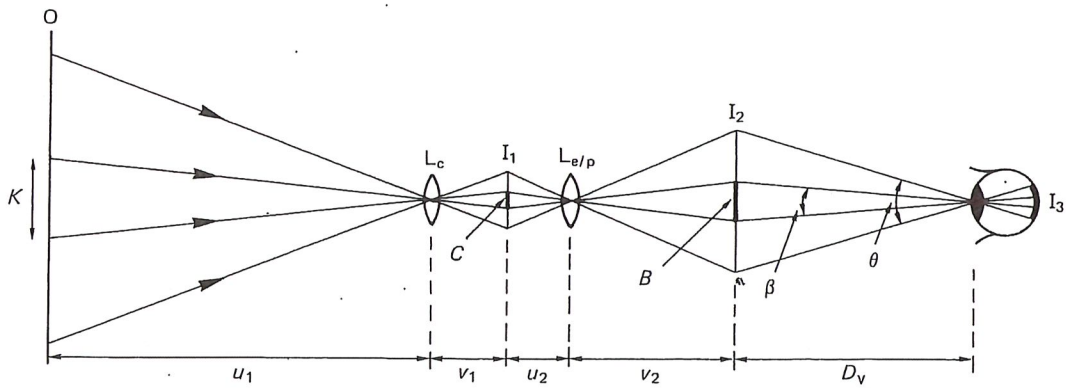


Figure 4.18 Geometry of the blur circle. Subject plane O with detail K is imaged by camera lens L_C at I_1, then re-imaged by enlarger or projector lens $L_{e/p}$ at I_2 and finally imaged on the retina at I_3. The circle of confusion C is seen as blur circle B in the cone of vision angle θ. Visual acuity is $1/\beta$. Relationships are: $m = v_1/u_1$, $M = v_2/u_2$, $K = C/m$, $B = CM$, $\beta = B/D_v$

important creative control. Knowledge of the means of extending, restricting or simply achieving depth of field is a vital skill in practical photography.

Manipulation of a camera and lens will demonstrate the control of depth of field possible by a choice of the focal length and aperture of the lens together with the focused subject distance (Figure 4.17) for a chosen circle of confusion. The various movements of a technical camera can also be used, and described in Chapter 10.

Depth of field can be quantified and calculated in terms of four variables, but first it is necessary to define 'an acceptable standard of sharpness' for a photographic record such as a print viewed in the hand. The depth of field boundaries are not as a rule sharply defined; usually there is a blending of acceptably sharp into less sharp detail. Much depends on the viewing conditions and also on aperture shape to some extent.

Visual acuity

Perception of detail, judgement of its sharpness, and depth of field in a photograph depend largely upon viewing distance and visual acuity, though other factors such as image contrast and ambient illumination are also significant. Normal vision requires muscular action to alter the refractive state of the eye in order to focus. This internal focusing is called *accommodation*, and physiological limitations set a comfortable *near distance of distinct vision* (D_v) of some 250 mm. The resolving power of the eye, or *visual acuity*, is the ability to discriminate fine details of objects in the visual field of view, and it decreases radially. It may be specified as the width of an object at a specific distance or as the angle subtended by this object or even as the width of its retinal image that is just resolved by the eye. For example, in ideal conditions a high-contrast line of width 0.075 mm can be perceived at D_v subtending an angle of approximately 1 minute of arc, and representing an image on the retina of the eye of some 5 micrometres in width. The performance is limited by the structure of the retina, which consists of light receptors of finite size. The limiting performance is seldom achieved, and a lower value of 0.1 mm line width at D_v is commonly adopted. Converted into resolving power, an acuity of 0.1 mm corresponds to a spatial cycle of 0.2 mm, being the width of the line plus an adjacent identical space such as is used on a bar-type resolution test target, giving a value of 5 cycles per mm for the average eye. The accuracy of focusing aids such as split-image rangefinders depends upon visual acuity in aligning two parts of a subject detail with a horizontal separation or 'split'.

Circle of confusion

For a photograph viewed at D_v, any subject detail resolved and recorded optically that is smaller than 0.2 mm in general dimensions may not be perceptible to the unaided eye. Thus any detail finer than this size is not required. This leads to a practical definition of resolution. A limit is set to the diameter of an image blur circle that is not distinguishable from a true point (by the unaided eye), and this is called the (minimum permissible) *circle of confusion* (C). This is arrived at by empirical means. A photograph is viewed in a *cone of vision* where acceptable visual acuity is given over a FOV of some 50 to 60 degrees. The *comfortable viewing area* has a diameter of some 290 mm at D_v. The acceptable circle of confusion is derived from what is accepted as satisfactory definition within this area.

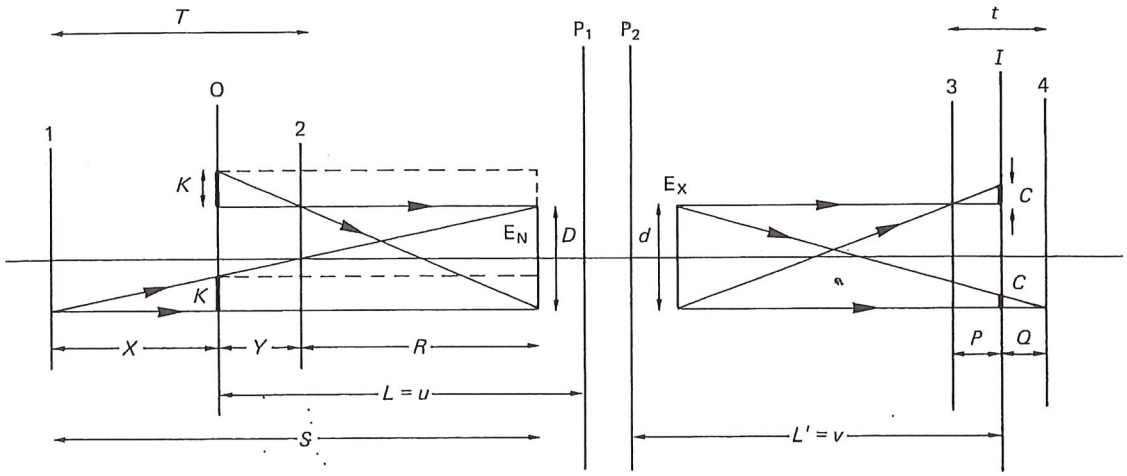


Figure 4.19 Geometry of image formation for depth of field

The obsolete 'whole-plate' size of 6.5 × 8.5 inches (165 × 216 mm, with a diagonal of some 270 mm), fitted neatly into the cone of vision at a distance of about 10 inches, and indeed for early photography was the usual size for contact prints for hand viewing. The standard lens for this format had a focal length of 10 inches (250 mm), and a contact print viewed at D_v gave correct perspective. A value of approximately 0.2 mm could be used for C to determine the required lens performance and depth of field.

Smaller formats, especially 24 × 36 mm, require enlargement to give a print for viewing at D_v with correct perspective (Figure 4.18). According to the 'rules' of perspective, a satisfactory visual rendering is given of an image corresponding spatially to the original scene when viewed at a distance equal to the focal length of the taking lens. Strictly a 24 × 36 mm image taken with a 50 mm lens should be viewed as a contact print at 50 mm, which is less than D_v. In practice an enlargement is viewed at 250 mm, but correct perspective is retained providing the proportional increase in viewing distance corresponds numerically to the degree of enlargement or print magnification M.

Obviously the value of C in the camera image must be related to subsequent enlargement and correspondingly reduced as enlargement increases. A linear enlargement of ×8 from a 24 × 36 mm negative is common practice: it gives a resultant print of 192 × 288 mm, suited to 8 × 10 inch (203 × 254 mm) print material, a size readily viewable within the cone of vision. This implies a minimum resolving power of 40 cycles/mm or lp mm^{-1} for the camera lens, the product of ×8 enlargement and visual performance of 5 lp mm^{-1}. The latter value also relates usefully to the resolving power of photographic printing paper which is approximately 6 lp mm^{-1}.

To summarize, the permissible diameter of the circle of confusion must be reduced if subsequent enlargement is to take place. In practice values of C from 0.025 to 0.033 mm are used for the 24 × 36 mm format to allow ×8 enlargement. Values of 0.06 mm and 0.1 mm are used for medium and large formats respectively.

It is worth noting that in the early days of small-format photography a criterion of 1/1000 of the focal length of the lens was used for C, giving 0.05 mm for the 50 mm lens, which was for a long time the standard lens used for the 24 × 36 mm format, and correspondingly different values for different focal lengths. This criterion was in use for many years and is still quoted by some sources. It gives values for depth of field which imply different degrees of enlargement for different focal lengths. Some confusion has arisen on depth of field matters, especially in the provision of tables and scales, as well as comparisons between equivalent lenses from different sources. The idea of $C=f/1000$ is now deprecated, and instead the value of C is taken as constant for a given format, for the whole range of lenses.

Depth of field equations

Derivations

Useful equations for the calculation of depth of field (and depth of focus) are derived from the geometry of image formation, as shown in Figure 4.19. A lens of focal length f is focused on subject plane O, distant L from the front principal plane P_1, with conjugate

image plane I distant L' from P_2. Image magnification is m. The entrance and exit pupils E_N and E_X have diameters D and d respectively. Plane O is also distant u from E_N. There are two other planes, 1 and 2, at distances R and S from E_N, rays from which to E_N intersect plane O in small circles of diameter K to be imaged in plane I as circles of confusion, diameter C, where $C = mK$.

In the object space, from similar triangles,

$$S = \frac{uD}{D - K} \tag{13}$$

$$R = \frac{uD}{D + K} \tag{14}$$

Now $m = L'/L = v/u$, and the effective aperture $N' = v/D$, so that $D = um/N'$. Taking $D = uL'/N'L$ and also $K = CL/L'$, then, substituting for D and K in equations (13) and (14),

$$S = \frac{u\left(\frac{uL'}{N'L}\right)}{\left(\frac{uL'}{N'L}\right) - \left(\frac{CL}{L'}\right)} \quad \text{and} \quad R = \frac{u\left(\frac{uL'}{N'L}\right)}{\left(\frac{uL'}{N'L}\right) + \left(\frac{CL}{L'}\right)}$$

So that

$$S = \frac{u^2(L')^2}{u(L')^2 - N'CL} \quad \text{and} \quad R = \frac{u^2(L')^2}{u(L')^2 + N'CL}$$

Considering the general photographic case, for distant subjects where m is less than unity, the object plane is near infinity, so we may put L' approximately equal to f. Likewise, N', the effective aperture, may be replaced by N, the relative aperture. For simple and symmetrical lenses, the pupils are located in the principal planes, so we may take $L = u$. Hence

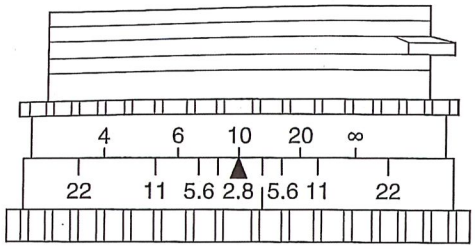
$$S = \frac{uf^2}{f^2 - NCu} \tag{15}$$

$$R = \frac{uf^2}{f^2 + NCu} \tag{16}$$

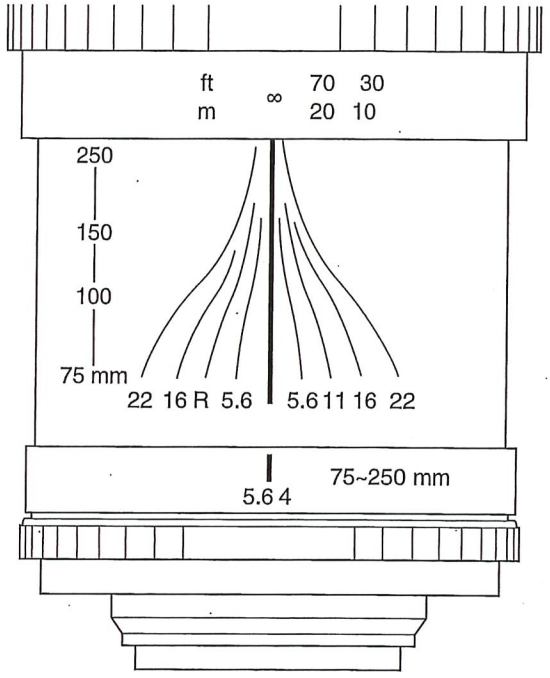
The values of S and R define the far and *near* limits respectively of the depth of field, when the lens is focused on distance u. The values may be tabulated in various ways, displayed in graphical form or provided as depth of field scales on the focusing mounts of lenses (Figure 4.20).

If depth of field (T) is defined as $T = S - R$ then

$$T = \frac{2f^2u^2NC}{f^4 - N^2C^2u^2} \tag{17}$$



(a)



(b)

Figure 4.20 Visual indication of depth of field. (a) Depth of field indicator scale. (b) Converging scales on a 75–250 mm *f*/4 zoom lens, including an infrared focus correction mark R

For practical purposes the $N^2C^2u^2$ term in the denominator may be disregarded, so to a first approximation

$$T = \frac{2u^2NC}{f^2} \tag{18}$$

This equation finds many useful applications.

Depth of field is directly proportional to the diameter of the circle of confusion, the *f*-number and the square of the focused distance, and inversely

proportional to the square of the focal length of the lens. Subject distance and focal length have the greatest influence; doubling the value of u increases T fourfold, while doubling focal length reduces T (at a fixed distance) by a factor of four.

It is of interest to note that equation (16) shows that a short-focus lens yields more depth of field than one of longer focus, provided that both are used to give the same magnification of a particular subject, in which case the two values of u differ. For example, using $C = 0.025$ mm, a lens of focal length 100 mm focused at 5 m and with an aperture of *f*/4 gives a magnification of 0.0204 and depth of field 501 mm. If a lens of focal length 25 mm is used, with u reduced to 1.25 m to give the same magnification, the depth of field at *f*/4 is now 521 mm, a little greater. However, subjective effects regarding the changed viewpoint for the subject and different performances from the two lenses can give a further subjective impression of a greater depth of field, as there is no fixed boundary that separates 'sharp' from 'unsharp'.

When the subject is closer, say 2 m for the 100 mm lens and a corresponding 0.5 m for the 25 mm lens, the depth of field at *f*/4 is 80 mm for both lenses, so that, in theory, there should be no difference.

The differences in practice are due to the approximations and assumptions made in deriving the formulae. Use of the simplified equation (17) gives identical results in both examples. In the alternative case of a fixed viewpoint and constant u, with the value of f altered by use of zoom lens (or interchangeable lens) followed by different degrees of enlargement to give the same final print magnification, then when viewed at D_v the depth of field will be seen to remain essentially constant when the actual diameter of the aperture of the lens remains unaltered. Thus combinations of 100 mm at *f*/11, 50 mm at *f*/5.6 and 25 mm at *f*/2.8, all have the same depth of field for a fixed viewpoint.

Note that the use of the criterion of $C = f/1000$ gives different values for both lenses in the example above and would indicate that depth of field is greater for the longer focal length in such circumstances, which is incorrect.

Departures from theory

The theory developed above assumes a truly circular circle of confusion; but this is not always so and marked departures from circular are found in anamorphic lenses, lenses with uncorrected aberrations and catadioptric (mirror) lenses. The 'circle of confusion' for the last of these is an annulus (caused by the central opaque disc inside the lens), and its effect can clearly be seen in out-of-focus detail. In the special case of a soft-focus lens, where undercorrected spherical aberration is used to give the desired soft effect with a core of sharpness, the diameter of the blur circle cannot be defined and calculations are meaningless. The so-called *deep-field lens* is often incorrectly taken to mean a lens possessing enhanced depth of field, but the effect is due to anti-reflection coatings which provide increased light transmittance, so that a reduced aperture may be used for a given exposure level compared with a lens of lower transmittance. It is the smaller aperture that gives the increased depth of field, not any special correction of aberrations. In practice, for an ordinary aberration-limited lens, progressive stopping down brings the depth of field closer to predicted values until diffraction effects occur.

Hyperfocal distance

Maximum depth of field in any situation is obtained by use of the hyperfocal distance. The value of S, the far limit of T, is given by equation (15). The *hyperfocal distance* (h) is defined as the value of a particular focus setting u of the lens, which makes S equal to infinity. The necessary condition is $f^2 = NCu$; then, as $u = h$,

$$h = \frac{f^2}{NC} \tag{19}$$

The concept of h allows simplification of equations (15) and (16) to

$$S = \frac{hu}{h - u} \tag{20}$$

$$R = \frac{hu}{h + u} \tag{21}$$

And likewise

$$T = \frac{2hu^2}{(h^2 - u^2)} \tag{22}$$

From equation (21), if u equals h, then R is $h/2$; when u is infinity, then R equals h. So if the lens is focused at a distance u so that u equals h, then the near limit of the depth of field is $h/2$. This gives the maximum depth of field, from infinity to $h/2$, for a given aperture N.

Cameras with fixed-focus lenses have the focus set on the hyperfocal distance (for the maximum aperture if this is variable) so as to give maximum depth of field.

Close-up depth of field

Close-up photography is defined as photography where the distance from the subject to the lens is such

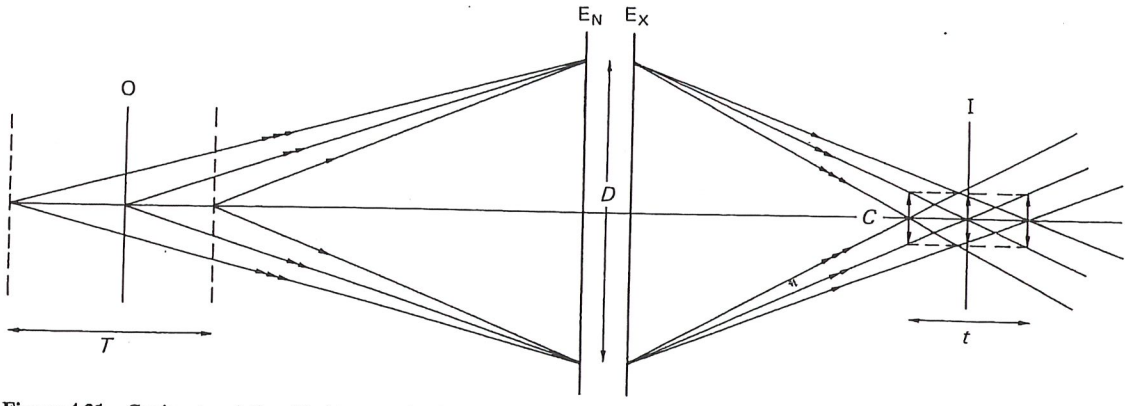


Figure 4.21 Conjugate relationship between depth of field T and depth of focus t, where $T = mt$

that magnification m is in the range 0.1 to 1.0. Referring again to Figure 4.19, the close-up depth of field T may be taken as the sum of distances X and Y, the respective distances of planes 1 and 2 from the plane of focus O, where

$$X = \frac{uK}{D - K}$$

$$Y = \frac{uK}{D + K}$$

As these planes are close to the entrance pupil, the value of K is much smaller than D and so can be neglected in the denominators, giving

$$X = Y = \frac{uK}{D}$$

Now u/D can be replaced by N'/m, and also $C = mK$, therefore

$$X = Y = \frac{CN'}{m^2}$$

The effective aperture N' may be replaced by $N(1 + m)$, where N is the marked f-number. As $T = X + Y$, we have

$$T = \frac{2CN(1 + m)}{m^2} \qquad (23)$$

Equation (23) does not involve focal length directly, so for a given magnification a long focal length is preferable to a short focal length, as it gives a longer working distance and better perspective by virtue of its more distant viewpoint, without any change in depth of field for a given f-number. Unlike general photography, the final magnification Z in the print of the subject is usually stated. So for a print enlargement of M, $Z = mM$.

Depth of focus

The term *depth of focus* applies only to the image space (Figure 4.21) and is the tolerance in the position of the film plane I, which depends on the acceptable diameter C of the circle of confusion (Figure 4.19). Alternatively, it may be regarded as the distance between the conjugate planes 3 and 4 either side of image plane I, corresponding to planes 1 and 2 respectively, which define depth of field. Planes 3 and 4 are distant P and Q respectively from plane I, and the cones of light from the exit pupil E_X of diameter d coming to focus on planes 3 and 4 form blur circles of diameter C on plane I, which is distant v from P_2, the rear principal plane. From similar triangles,

$$P = \frac{vC}{d + C}$$

$$Q = \frac{vC}{d - C}$$

But C is small compared with d and may be removed from the denominators, so

$$P = Q = \frac{vC}{d}$$

Remembering $N' = v/d$ and also $N' = N(1 + m)$, the depth of focus (t) is the sum of P and Q, so

$$t = 2CN(1 + m) \qquad (24)$$

$$t = \frac{2CNv}{f} \qquad (25)$$

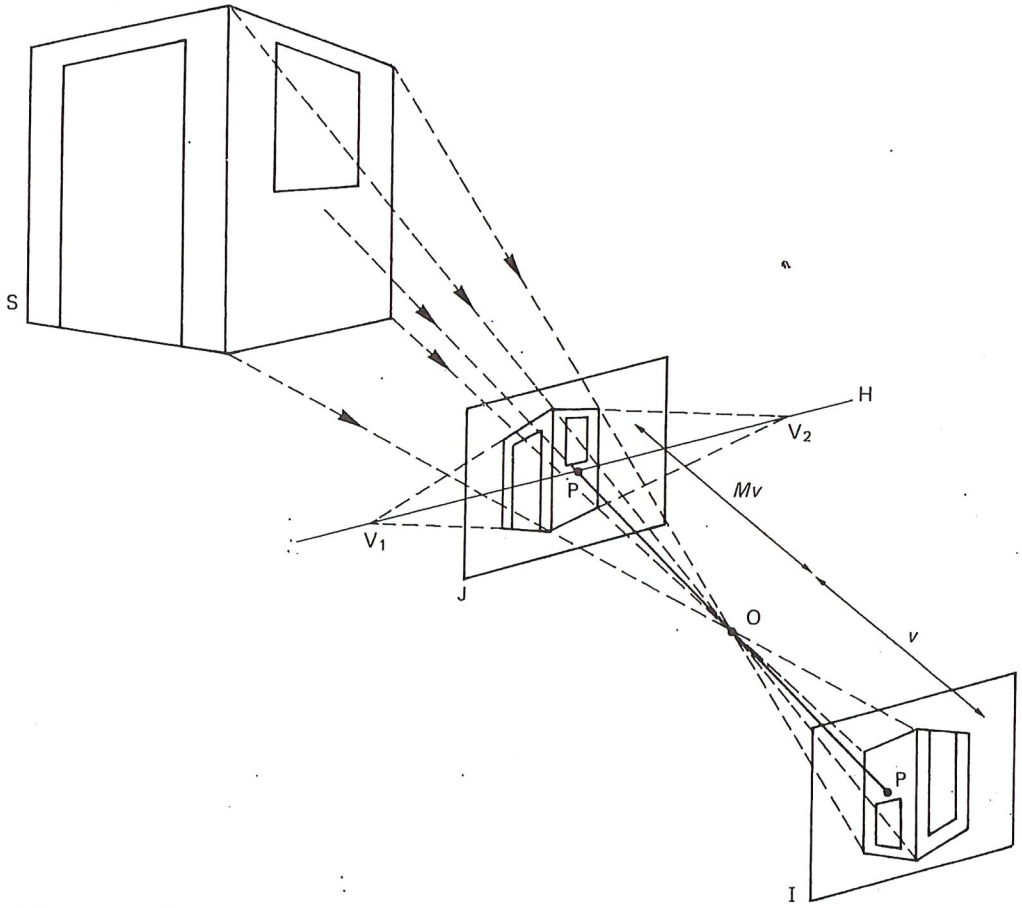


Figure 4.22 Elements of central perspective. In the diagram S represents the subject, I the optical image, O the centre of perspective, P the principal point, OP the principal distance, J the perspective of the subjected or picture plane, V_1 and V_2 the vanishing points, H the horizon line

For general photography where m is small, equations (24) and (25) reduce to

$$t = 2CN \tag{26}$$

For a large-aperture lens the depth of focus is small and the film gate or photoplane must be accurately perpendicular to the optical axis. The necessary tolerances can be relaxed for large formats where C is greater and small apertures are used; but even so, a 75 mm *f*/4.5 wide-angle lens used on a 4 × 5 inch format has only 0.9 mm depth of focus at full aperture (assuming C is 0.1 mm), so the position of the film surface in a dark-slide or roll film back must correspond very accurately to the plane of the focusing screen.

When a lens is focused close up, so that m has a significant value, the depth of focus is increased. The use of small apertures also increases depth of focus.

Perspective

Viewpoint

The term 'perspective' literally means 'to look through'; and an accurate record of the spatial relationships of objects in a scene can be obtained by placing a glass plate, 'the picture plane', in the observer's FOV, and tracing the necessary outlines on it. The reduced-size facsimile records the intersection of the projection of each subject point, converging to the *centre of perspective* or *viewpoint* (Figure 4.22), then diverging to the image plane.

The *viewpoint* is the centre of the pupil of the eye of the observer. Conventionally the picture plane is vertical, so that vertical lines in the subject remain vertical and parallel. Horizontal lines in planes parallel to the picture plane also remain horizontal and parallel, but in inclined subject planes they will

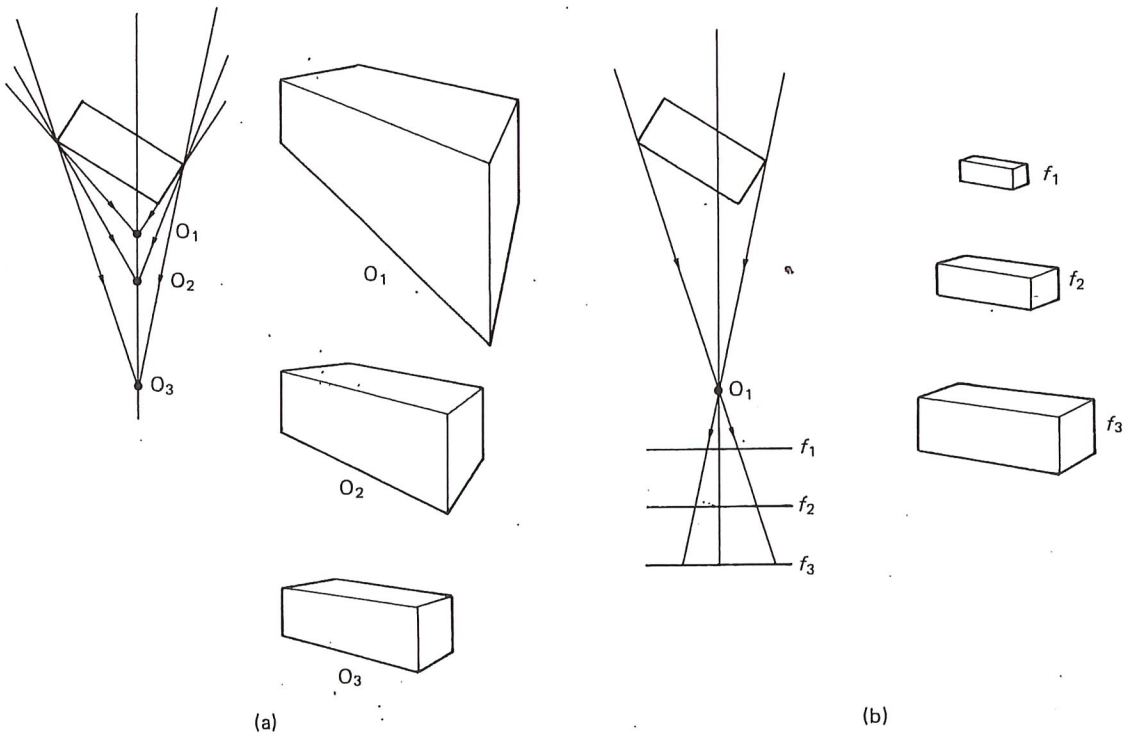


Figure 4.23 Perspective in an image related to camera viewpoint and focal length. (a) Subject appearance due to reducing the viewpoint distance and increasing the field of view of the lens. (b) From a fixed viewpoint, an increase in principal distance or focal length leaves the perspective unchanged but size altered

converge to one or more *vanishing points*, positioned on the *horizon line* of the facsimile where the visual axis intersects it at the *principal point*. The orthogonal distance between the picture plane and viewpoint is the *principal distance* of the perspective record.

By the geometry of the situation, alteration of the principal distance alters only the size of the picture and not the perspective of the spatial relationships. However, alteration of the viewpoint in terms of distance from the subject will alter the convergence and hence alter perspective.

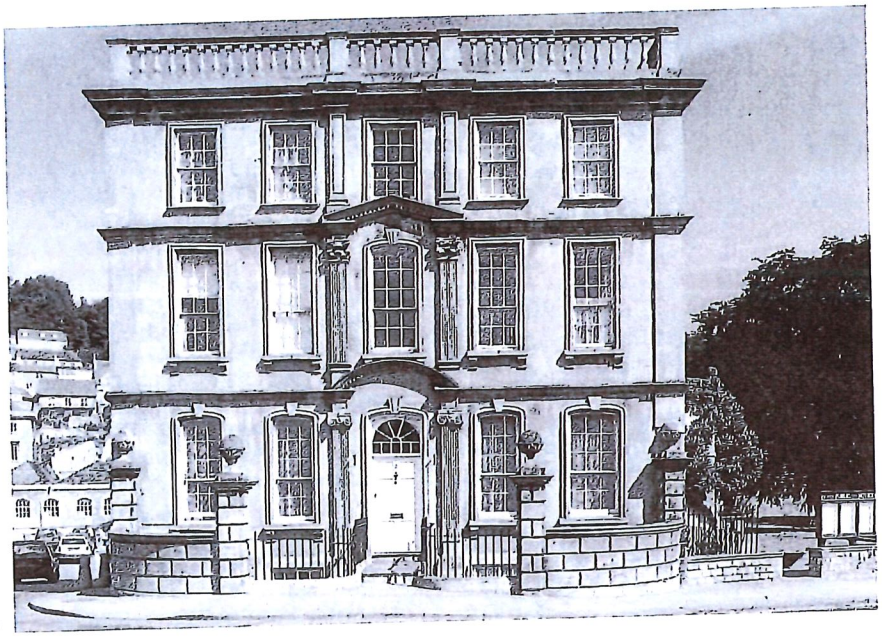
The perspective of the scene is correctly reconstructed only by viewing from the principal distance, which is then termed the *viewing distance* (D).

Camera viewpoint

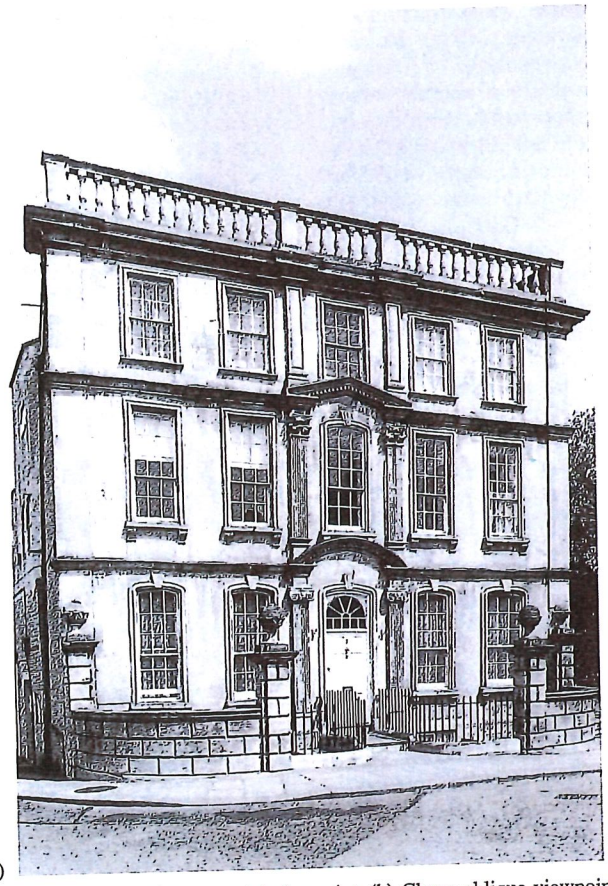
A camera records a three-dimensional scene as a two-dimensional planar image in the photoplane and in the print. By placing the camera lens at the visual viewpoint, familiar photographic parameters replace the terminology of perspective as defined above.

The convergent rays form a *central perspective* by passing through the lens, and continue diverging beyond the viewpoint to an image plane conjugate to the subject plane. The principal distance is now the image conjugate v, commonly taken as the focal length f for distant scenes. The facsimile or photographic record is now inverted and laterally reversed but can be contact printed and 'flopped' to position in the picture plane for viewing at correct distance $D = v$.

Various points need clarification. By altering the lens to one of longer focal length, v is increased and the image enlarged; but it retains identical perspective. So a charge of focal length for a given viewpoint does not alter perspective but only image size. By altering viewpoint by changing the object conjugate u, the perspective *does* change, the more obviously since a lens of large FOV may be used to include the same area of the subject from a closer viewpoint (Figure 4.23). Such 'steep' perspective can be used to dramatic effect. Figure 4.24 illustrates the alteration of perspective given by a change of viewpoint with a building chosen as the subject to show also two possible pictorial 'treatments' of the subject. A distant central viewpoint with a medium long focus lens gives an accurate view of the front elevation. A closer off-centre viewpoint with a wide-



(a)



(b)

Figure 4.24 Perspective and viewpoint. (a) Distant central viewpoint. (b) Closer oblique viewpoint

angle lens plus some rising front movement changes the shape to retain verticals, while giving more depth to the subject.

Perspective distortion

The centre of perspective or viewpoint of a camera lens is the centre of the entrance pupil for object space. The centre of the exit pupil is the centre of projection for image space. The correct viewing distance is then given by

$$D = v = f(1 + m) \quad (27)$$

This theoretical value of D cannot usually be used, especially if it is less than D_v. Small images need to be enlarged by magnification M for comfortable viewing and the viewing distance is then given by

$$D = Mv \quad (28)$$

For distant scenes, v is replaced by f as usual.

The correct-viewing-distance criterion is seldom observed for photographic images, prints being viewed at a convenient distance, irrespective of the values of f and M used (usually these are not known to the observer). Incorrect viewing gives rise to perspective distortions. In pictorial terms, a near viewpoint gives a 'steep perspective' with large changes of scale in a subject, while a distant viewpoint gives a 'flattened perspective' with only small changes of scale even in a subject of considerable depth. The perspective of a print viewed from too great a distance tends to appear steep, while that of a print viewed from too short a distance tends to appear flat. This is the reverse of the perspective effects achieved on taking the picture.

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19 Camera exposure determination

Camera exposure

Other chapters have explained image formation by a lens and the response to light of various photosensors such as film. After due consideration of subject composition, perspective and sharpness, the photographer judges the best moment to make the exposure. An optical image of appropriate intensity is transmitted by the lens and reaches the photoplane for an appropriate length of time. This *camera exposure* is controlled by the combination of lens aperture (N) and shutter speed (t). More generally, the photographic result of exposure (H) is the product of image illuminance (E) and exposure duration (t), so that

$$H = Et \qquad (1)$$

Determination of the optimum camera exposure is important for any photographic situation in terms of the resulting quality of the photographic image. Any subject contains areas of different luminances giving the overall *subject luminance ratio* (or range), so that image capture in turn gives a range of exposures at the photoplane, which on processing produces a range of monochrome or colour densities or values that form the image. With photographic materials, the range of image densities produced is predicted by the characteristic curve of the film, which depends on the type of film and the development conditions used, given the positioning of the range of log exposures on the curve, which depends on camera exposure.

Apart from exposure duration, the components of camera exposure are given by equation (13) in Chapter 5, including subject luminance, lens aperture and image magnification, with others such as lens transmittance (including the necessary exposure factor for any filter used) and vignetting, both optical and mechanical. Camera exposure may be determined by practical trial, e.g. by an estimate based on previous experience, followed by assessment of the resultant image after processing, especially if using a self-developing material. However, scene measurement using a lightmeter is preferable. Essentially this may be done by measurement of the *luminance* of selected areas (*zones*) of the subject, which is the resultant of the *illuminance* on the subject and its *reflectance*. Allowance is then made for other factors affecting camera exposure, including the *effective film speed*, which depends on film type and treatment, the chosen lens aperture or shutter speed, and any filter factor. These are all known values.

The four principal variables determining camera exposure are subject luminance, film speed, lens

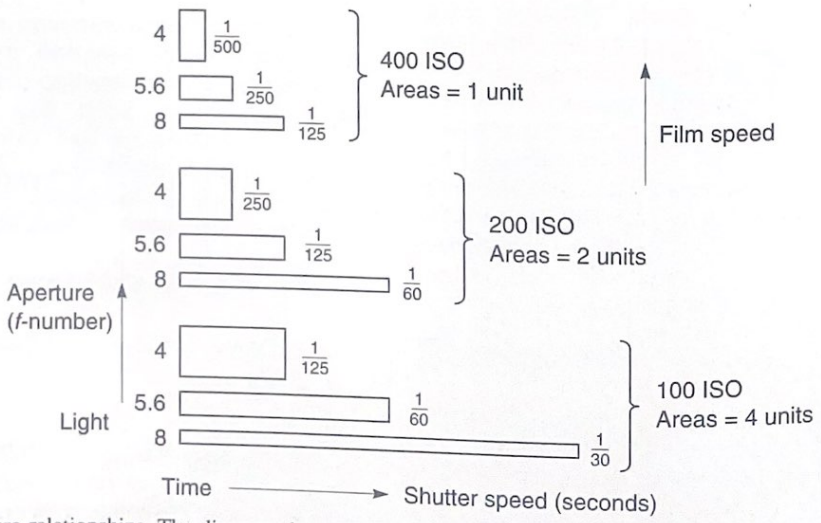


Figure 19.1 Exposure relationships. The diagram shows the relationships between film speed, exposure duration and aperture setting to give equivalent exposures (shown here as the areas of rectangles). A long exposure duration implies a reduced aperture and a slow film a larger rectangle, for a subject of given luminance

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aperture and shutter speed. As shown in Figure 19.1, for any particular camera exposure there is a range of combinations of shutter speed and lens aperture usable with a given film speed. The selection of a suitable combination is a primary creative control in photography and will be dictated by the subject itself or the treatment required. For example, a moving subject may require a certain minimum shutter speed to give a sharp image. Alternatively, the focal length of lens used or possible camera shake may also dictate shutter speed as the important factor. In such cases the aperture must be chosen to suit this exposure duration. But for subjects requiring specific depth of field or the optimum performance from a lens, the choice of aperture is important and the shutter speed is secondary. The ability to change the illumination on the subject allows more choice of both of these variables. The use of tungsten illumination or electronic flash allows such variations in practice.

Optimum exposure criteria

Before considering methods of measuring subject luminance or illumination to estimate camera exposure, it is useful to consider the criteria by which the correctness of exposure is judged. For black-and-white or colour negatives, judgement rests finally on printing quality. So a *correctly exposed negative* is defined as a negative that will give an excellent print with least difficulty. Colour reversal material will be considered later. The visual judgement of black-and-white negative quality requires considerable experience due to related printing circumstances such as the print material used and the illumination system of the enlarger, together with personal preferences for the overall density level of a negative. A long-standing empirical quality guide is that a correctly exposed and processed negative made on pictorial film will usually have some detail in the shadows (low-density regions) and the highlights (high-density regions) will just permit text to be read through them if the negative is laid on a page in good light. For images on line film the correct exposure is judged from the appearance of the low-density fine line detail, which should be completely transparent and sharp-edged, without any filling-in, and the highlights should be totally opaque.

Colour negatives are more difficult to judge visually because of the presence of coloured dye masks. Again, the presence of shadow detail is a useful clue, but these regions are heavily masked. A colour densitometer can provide a quantitative guide to optimum exposure. For example, with a red filter, readings of 0.7–0.9, 1.15–1.35 and 1.10–1.30 in regions of mid grey tone, highlight and diffuse highlight respectively can indicate correct exposure.

Other quantitative criteria for optimum exposure of negative materials relate to the systems used for determining film speed. In the case of black-and-white pictorial materials, the sensitivity may be determined from the minimum exposure necessary to give a density of 0.1 (above base + fog density), which 'pegs' this density to the image detail of lowest luminance, i.e. the deepest shadow for which detail is to be recorded. In the case of colour-negative material, this minimum density level may be 0.15 or greater. With colour transparency materials, correct exposure gives a result that retains details in the highlights (low-density regions) so that there are no totally blank ('burnt-out') areas. Note that even with subjects having white highlight areas, the minimum density above base + fog level, and the shape of the characteristic curve, are such that a minimum density value of some 0.2–0.3 is necessary to avoid the highlight appearing as a 'hole in the transparency'. Correct exposure locates the important highlights at this point on the characteristic curve (which is also used for speed determination).

Exposure latitude

From the characteristic curve of a material, the separation on the log exposure axis between the maximum and minimum useful density points is termed the *useful log exposure range*. As stated above, the subject luminance ratio to be recorded determines the *log exposure range* given to the material. This may be less than, equal to or greater than the useful log exposure range the material can accommodate, related to its intrinsic contrast properties and processing treatment. If the log exposure range is less than the useful log exposure range of the material, as may often be the case, then the *exposure latitude* of the material is the factor by which the minimum camera exposure necessary to give adequate shadow detail in the case of negatives (or highlight detail in the case of reversal materials) may be multiplied, without corresponding loss of highlight detail (or shadow detail) (see Figure 19.2). Detail may be defined as discernible density differences in adjacent tones corresponding to resolved regions of the subject.

In the case of colour-negative materials, exposure latitude also depends on use with an illuminant of suitable colour temperature. For example, an excess (or deficiency) of the blue component of the illuminant will give the blue-record layer more (or less) exposure relative to the green- and red-record layers, and place the blue exposure range on a different region of the characteristic curve relative to the other two. This reduces exposure latitude, as any exposure outside the region that is linear for all three emulsions simultaneously will result in coloured highlights or shadows.

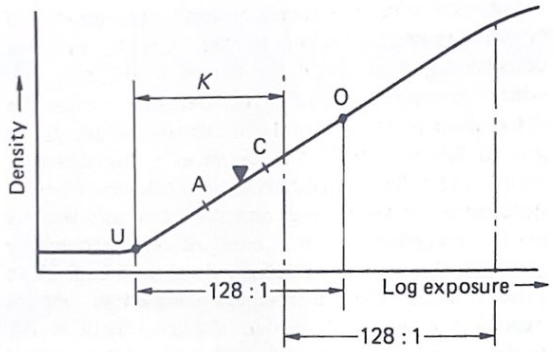


Figure 19.2 Latitude to over-exposure for negative materials. The index, U, O, A and C markings of the Weston Master exposure meter are shown relative to an average subject luminance range. The exposure latitude *K* is a multiple of the minimum useful exposure

The high contrast of colour reversal material, typically equivalent to a gamma value of some 1.4, causes a reduced exposure latitude, even with a subject whose luminance range is 30:1 or less. The lower inherent contrast of negative materials gives more exposure latitude, and the ability to record subjects of greater luminance range. Conventionally, exposure latitude is expressed as tolerance in stops or *exposure values (EV)* relative to the optimum exposure. Colour reversal materials usually have a latitude of ± 0.5 EV or less, where ± 1 EV indicates a permissible error of double or half the optimum exposure. Note that natural vignetting across an image field from a wide-angle lens may give an illumination level that varies as much as this, so a *centre spot filter* may be needed. Ideally, reversal material should be exposed to within 0.3 EV of optimum.

The DX film speed coding system used on 35 mm film cassettes can input the metering system with film exposure latitude value. Depending on film type, four alternative ranges of ± 0.5, ±1, +2, –1 and +3, or –1 EV may be used. The primary use is for automatic exposure metering; for example, if the camera is set on aperture-priority mode, and the overall subject luminance is so high that the aperture chosen requires an exposure duration shorter than that available from the shutter speed range, then if the resultant over-exposure does not exceed the latitude of the material, the shutter will be released; otherwise it could be set to lock.

Most colour-negative materials have a useful exposure latitude of up to +3 EV (factor ×8) to over-exposure, and –1 EV (factor ×0.5) to under-exposure, and give acceptable prints. Because of the fixed development conditions of colour-negative material and the non-scattering properties of the dye images (so that print contrast is unaffected by the type of illumination in the enlarger) most colour-print paper materials are available in only one or two contrast grades. Alteration of print contrast to suit particular subjects or negatives is possible by the use of contrast-altering silver masks. Black-and-white negative material has similar (or greater) exposure latitude than colour-negative material, but with the possibility of altering processing conditions to cope with extremes of subject luminance ratio, plus a range of paper grades for printing.

Subject luminance ratio

To assist exposure determination a subject can be classified by its *luminance ratio*, or (incorrectly) the 'subject luminance range'. This is numerically equal to the product of the *subject reflectance ratio* and the *lighting ratio*. For example, a subject whose lightest and darkest zones have reflectances of 0.9 and 0.09 respectively, i.e. a reflectance ratio of 10:1, when illuminated such that there is a lighting ratio of 5:1 between maximum and minimum illumination levels, has a subject luminance range of (10 × 5):1, i.e. 50:1. A high luminance ratio denotes a subject of high contrast. Luminance ratios range from as low as 2:1

Table 19.1 Subject classification by luminance range or ratio

Subject luminance ratio classification	*Luminance ratio*	*EV range*	*Average luminance as percentage of illumination*	*Weston Master series exposure meter index*	*Approximate exposure correction factor*
Very high	2048:1 (2^{11}:1)	11	11	C	+1 EV
High	512:1 (2^{9}:1)	9	14		+0.5 EV
Average	128:1 (2^{7}:1)	7	18	arrow	0
Low	32:1 (2^{5}:1)	5	25		–0.5 EV
Very low	8:1 (2:1)	3	41	A	–1 EV

to 1 000 000:1 (10^6:1). Integration of individual luminance levels gives a value for the *average reflectance* of a scene, which depends on the subject luminance ratio. Based upon appropriate scene measurements, it is usually assumed that an average outdoor subject has a luminance ratio of 128:1 or 2^7:1, corresponding to a seven-stop (or 7 EV) range.

As well as luminance ratio, the integrated luminance of all tones in a scene may be used for exposure determination purposes. The value for an 'average' outdoor scene is taken to be some 12–18 per cent and the range of colours also integrate to a mid-grey tone, usually called 'integration to grey'. Indoor studio subjects may be closer to 18 per cent reflectance. Neutral grey cards of 18 per cent reflectance are often used as substitute 'average' subjects for exposure determination using reflected light measurement. For meter calibration purposes, a subject with a reflectance ratio of 2048:1 (2^{11}:1) has a mean reflectance of some 11 per cent; with 8:1 (2^3:1) a reflectance of some 40 per cent (see Table 19.1). If the exposure meter is calibrated (as it usually is) for a mean reflectance of 18 per cent, this could result in exposure errors respectively of +80 per cent and –60 per cent. It is usually necessary with a subject matter of excessively high or low contrast to apply a *subject correction factor.*

If excessive, the subject luminance ratio may be reduced by the use of additional illumination, such as by *fill-in flash* or *synchro-sunlight* techniques. In many cameras with automatic exposure metering, a *segmented photocell* monitors the average luminance and luminance ratio of zones in the scene, such as by measuring the central area and the background separately. Supplementary fill-in light from an integral flash unit (to reduce subject contrast) may be provided automatically over a limited range of flash-to-subject distances. The required amount of flash is monitored by off-the-film measurement.

Development variations

For a given set of processing conditions, a variation in development time can be used to control the contrast of black-and-white negatives, as measured by the *negative density range* corresponding to the *log exposure range*. A change in development time alters density range (contrast) of a negative, whereas a change in camera exposure determines the position of the density range on the characteristic curve. The effects of exposure and development are summarized by the graphs in Figure 19.3. By giving normal, reduced or increased development and exposure in various combinations, some nine varieties of negative are possible. Not all of these have ideal printing characteristics, of course: some cannot adequately be matched to the available grades of printing paper, and others do not have a suitable overall density level.

For example, an under-exposed and under-developed negative is of low average density and low density range, and requires a hard grade of paper (which has a low exposure latitude and emphasizes graininess). Also, areas of low density show marks and scuffs to a greater extent than areas of higher density. On the other hand, an over-exposed, over-developed negative is grainy, and requires a long printing exposure on a soft grade of paper, which does not in general record shadows and highlights well owing to the shape of its characteristic curve. Variation in development time changes effective film speed, too; in particular, prolonged development results in a higher effective exposure index for the material, producing what amounts to an over-exposed result if the exposure was based on a normal speed rating. Reduced development, however, can match the useful log exposure range of a material to a high subject log luminance range, to yield a negative of density range printable on a normal grade of paper. A side effect of under-development is a loss of effective film speed, so the material must have its camera exposure adjusted accordingly. This technique of increased exposure (or down-rating of speed) and reduced development to deal with high-contrast scenes works best with materials of nominal speed ISO 400.

The possibilities of individual development of exposed material to suit scenes whose luminance ratios have been measured using a spot metering system, form the basis of the *Zone System* of exposure determination.

Colour-negative material cannot be treated in this way, but colour-reversal film may have its effective exposure index varied, (usually increased) by alteration of first development time, contrast is also affected, though the exact nature of the variation depends on the material.

Exposure determination

Early experience of development by inspection led to an empirical rule of exposure: 'expose for the shadows and develop for the highlights'. At a later stage, development by time-and-temperature methods, and use of printing paper with a variety of contrast grades, meant subjects could be exposed and negatives processed to a similar contrast to give acceptable prints. So the rule was modified to 'expose for the shadows and let the highlights take care of themselves', and this advice is still useful for black-and-white negatives.

Colour negatives can be exposed for shadow detail, but the minimum exposure should locate shadows on the linear portion of the characteristic curves and not on the toe regions. This gives correct reproduction of tone and colour. Provided the highlights are also on the linear portion, tone and colour reproduction are

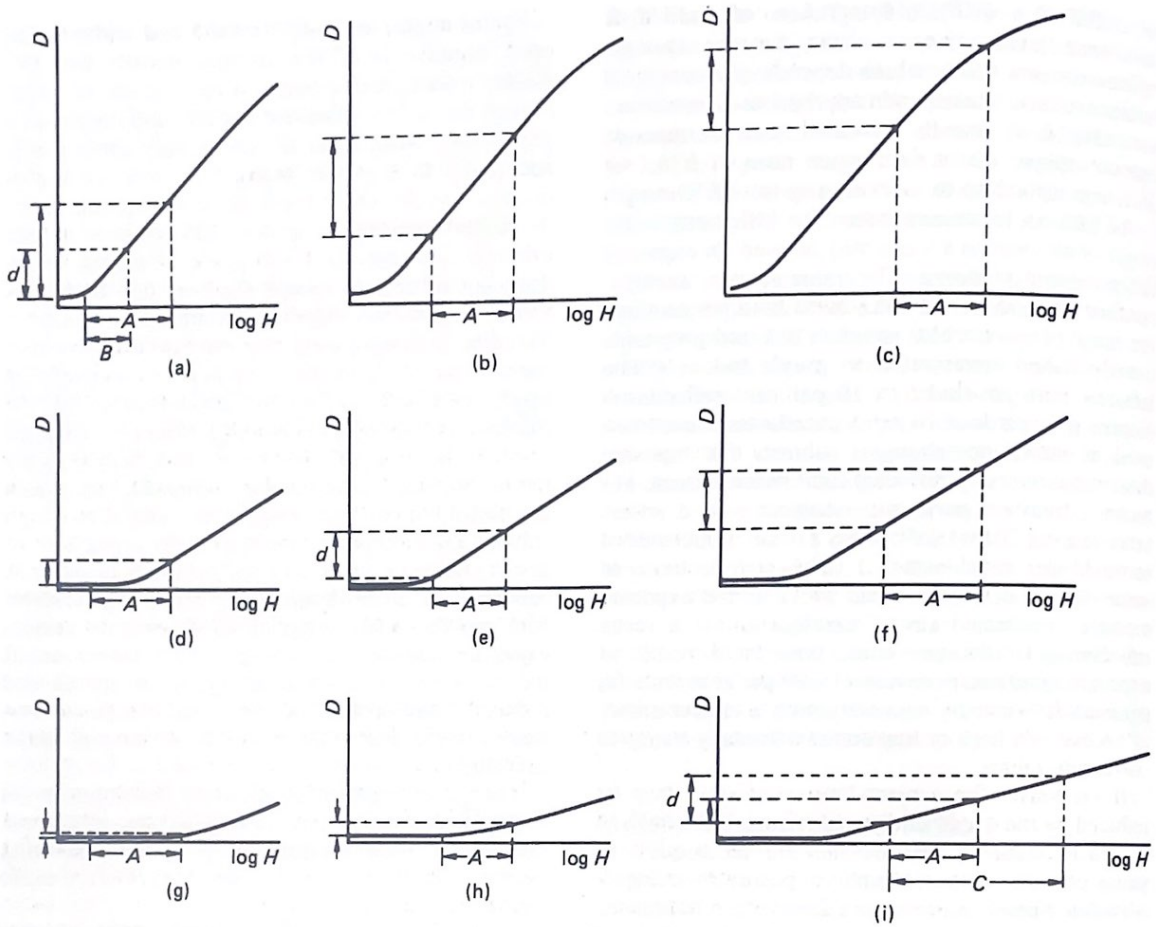


Figure 19.3 Summary of the effects of exposure and development variations on negative density range and density values. (a) Under-exposure and prolonged development. (b) Correct exposure and prolonged development. (c) Over-exposure and prolonged development. (d) Under-exposure and normal development. (e) Correct exposure and normal development. (f) Over-exposure and normal development. (g) Under-exposure and curtailed development. (h) Correct exposure and curtailed development. (i) Over-exposure and curtailed development. Key: A, normal subject log luminance range; d, negative density range, to print on normal grade paper; B, low subject log luminance range; C, high subject log luminance range

acceptable throughout the range of densities. A colour print cannot reproduce the large tone range shown in a black-and-white print, as tonal distortions acceptable in the latter are unacceptable in colour prints due to the colour-balance errors in the deepest shadows, and the low tolerance of most viewers to such 'skewed' colour balance. Such local colour imbalances are not correctable at the printing stage, as corrective filtration is only effective for *overall* colour casts.

With reversal materials, the method of camera exposure determination by measurement of both shadow and highlight luminances is equally valid, the shadows and highlights being suitably located on the characteristic curve. This time the highlights are recorded as *low* densities, as described above. So it is best to base exposure on subject *highlights*, and let the shadows 'take care of themselves'. This arrangement works for most subjects, but for high-key subjects (i.e. with no important dark areas), exposure is best increased by +½ to +1 EV to avoid a 'washed-out' appearance. Likewise, a low-key subject (i.e. with minimal highlight detail) needs a reduction in exposure of –½ to –1 EV.

It may not be convenient or easy to measure directly the highlight luminance of a subject, but an incident-light measurement gives a good approximation, since the highlights of most subjects are white or near-white, with a high reflectance, so an illumination measurement is similar to a highlight luminance measurement.

An *artificial highlight* may be provided in a scene for easy measurement of reflectance by making the exposure measurement on a matt white card. If the assumed reflectance of this is 90 per cent, i.e. 5 times more than an assumed average scene reflectance of

18 per cent, and the meter used is calibrated in the normal way, for 18 per cent reflectance, the indicated exposure should be multiplied by 5 to provide correct exposure. The artificial highlight method is useful in copying work, and is particularly worthwhile when colour slides are being exposed of subjects with unusual reflectance properties (snow scene, dark forest glades).

Practical exposure tests

If the material has no film speed rating, optimum exposure can be determined by practical tests, as for materials intended for copying, photolithography and similar tasks. The instruction sheet supplied with the material may suggest starting points for exposure level with particular illuminants, filters, development and subjects. Such techniques are suited to the studio and photographic laboratory, as processing and evaluation are carried out immediately after exposure. When using a large-format studio camera, for example, the dark-slide of the filmholder may be progressively inserted to allow a doubling sequence of timed exposures to be given. Thus a sequence of 1, 2, 4, 8 and 16 seconds exposure is given by consecutive additive exposures of 1, 1, 2, 4 and 8 seconds respectively. The camera must remain stationary during the tests, of course. For small- and medium-format cameras a similar test series is given by exposing a sequence of individual frames. Either the shutter speed can be varied while the aperture is held constant or vice versa. Of these choices, the shutter-speed variation gives a constant image luminance but may cause reciprocity-failure effects, and the depth of field is constant. If aperture variation is used, two series of exposures should be made, one with increasing and one with decreasing aperture size. This is because many iris diaphragm systems have up to a quarter of a stop backlash. Aperture variation is mandatory if flash illumination is being used.

Many cameras with integral power-wind offer an 'automatic bracketing' feature in some automatic exposure modes, so that on setting a choice of up to ±3 EV in ⅓ EV increments, a range of exposures is given with exposure variations to bracket the exposure in cases of doubt or where the necessity for a good result overrides the cost of the film. Either shutter speed or aperture may be varied in such a series.

The use of self-developing materials, usually known as a 'Polaroid test', with material of a known exposure index, gives a means of determining or verifying exposure, and may be used on location. A suitable back is used on the camera, and the results examined after exposure. Differences in exposure indexes between the self-developing film and the (colour) material can be allowed for by simple calculation or the use of a neutral density filter. Composition, positioning of subject and props, lighting balance and the presence of any undesirable reflections may also be checked.

Light measurement

Optimum exposure may be determined by measurement of the luminance of the subject (or zones of it), or, alternatively, by measuring the illumination on the subject (incident light), followed by location of the log luminance ratio in a suitable position on the characteristic curve of the material. Ideally, the luminance ratio itself should be determined; but this requires experience in locating suitable zones, and is by no means easy to measure accurately. This method is usually too complicated for everyday use. Simpler methods are preferred in practice, even though they may, in theory, be less accurate.

Measurement of luminance of darkest shadow

This method locates this tone at a fixed point on the toe of the characteristic curve, giving the correct density to the deepest shadow that is to be recorded. Practical difficulties include the necessary metering sensitivity, the effects of flare light on measurements and the effect of highlights in the field of view of the meter. Some meters have an indicator for this measurement; for example, Weston exposure meters had a 'U' mark which was set to the darkest-shadow reading.

Measurement of luminance of lightest highlight

This locates the highlight at a fixed point with the highlight detail and other tones as differing densities. Shadow detail is usually adequately recorded, but a subject of average contrast may receive more exposure than necessary. The original Weston exposure meter had an 'O' setting for this method; otherwise with other meters the indicated exposure should be divided by 5. This method is similar to the *artificial highlight* method, which works well for colour-slide material. Note that when using this method, measurements must not be made on specular highlights.

Measurement of a key tone

A subject zone of intermediate luminance, i.e. a mid-tone, is selected and located at a fixed point on the characteristic curve. Typically an exposure 10 to 16 times more than that for the shadow or speed point is given. This *key tone* may be a Caucasian flesh tone

(about 25 per cent reflectance). Control of scene illumination allows the shadows and highlights to be suitably located too. A substitution method may also be used: a medium grey card (18 per cent reflectance) is held so as to receive the same illumination as the subject it is replacing. The light meter is used close up so that the card fills the acceptance angle of the photocell. The 'arrow' setting of the original Weston meter was calibrated for such a mid-tone, as are most metering systems.

Cameras with automatic exposure control may offer an 'exposure memory lock' feature to allow the metering system to measure and set an exposure for a key or substitute tone, after which the picture is recomposed and the stored exposure given. This memory may be self-cancelling after exposure, or may require manual cancellation.

Measurement of total scene luminance

This 'integration' method accepts all the light flux from the chosen area of the subject to be photographed. Such a *reflected light measurement* is widely used, as it is simple to carry out and requires little selective judgement. It is used in hand-held meters, in flash meters and for in-camera metering systems for both ambient and flash illumination. Its high success rate is largely because the useful log exposure range of negative materials is greater than the log luminance range of the average subject.

A correction is usually necessary to the indicated values of exposure settings for subjects of very high or very low contrast, or for a subject of non-typical tone distribution, such as a high-key or low-key subject. Typical corrections necessary are a doubling of indicated exposure for high-contrast or high-key subject matter, and a halving of indicated exposure for low-contrast or low-key subject matter. The original Weston exposure meter had two exposure index marks denoted 'C' and 'A' to cope with high- and low-contrast (or high- and low-key) subjects. These settings give corrective alterations of +1 EV and −1 EV respectively.

Most cameras with an automatic-exposure mode have an associated *exposure compensation control* which offers manually-set increases or decreases of up to ±3 EV or more in increments of ½ or ⅓ EV to cope with atypical subjects or luminance distributions.

Measurement of incident light

The *incident light method* measures the light incident on the subject rather than the light reflected from it. It is an easy measurement to make with a hand-held light meter, but is not suitable for an in-camera metering system. It positions the highlights (rather than the mid-tones) on the characteristic curve, and is thus particularly suitable for use with colour-reversal materials. No information is given with regard to the shadows, and exposure corrections may have to be made if the subject is very dark or back-lit.

Exposure meter calibration

A hand-held *light meter*, commonly called an *exposure meter*, may be used to measure either subject luminance or subject illumination. It is a form of photometer not dissimilar to those used by lighting engineers, with its light value readings convertible into camera exposure settings. The usual form of meter calibration and its relationship to subject, camera and film speed parameters are shown in Figure 19.4, where a reflected light reading is being taken.

Consider a small off-axis area of the subject of luminance L that is imaged in the focal plane of the camera with image illuminance E_F. The values of L and E_F are related by equation (16) in Chapter 5, so that if the lens has a transmittance T, and f-number N, and the region is at an angle θ from the optical axis,

$$E_F = \frac{L\pi T \cos^4 \theta}{4N^2} \tag{2}$$

Equation (2) may be rewritten as

$$E_F = \frac{qL}{N^2} \tag{3}$$

where q is a constant derived from known (or assumed) values of the quantities above.

So from equation (1), the exposure H_F at the focal plane is given by

$$H_F = \frac{qLt}{N^2} \tag{4}$$

H_F can be replaced by a sensitometrically determined speed number S for the film used where

$$S = \frac{H_O}{H_m} \tag{5}$$

where H_O is a constant and H_m is the *speed point* or *minimum useful exposure*. Now,

$$H_F = kH_m \tag{6}$$

where k is constant and a multiple of H_m therefore,

$$H_F = \frac{kH_O}{S} \tag{7}$$

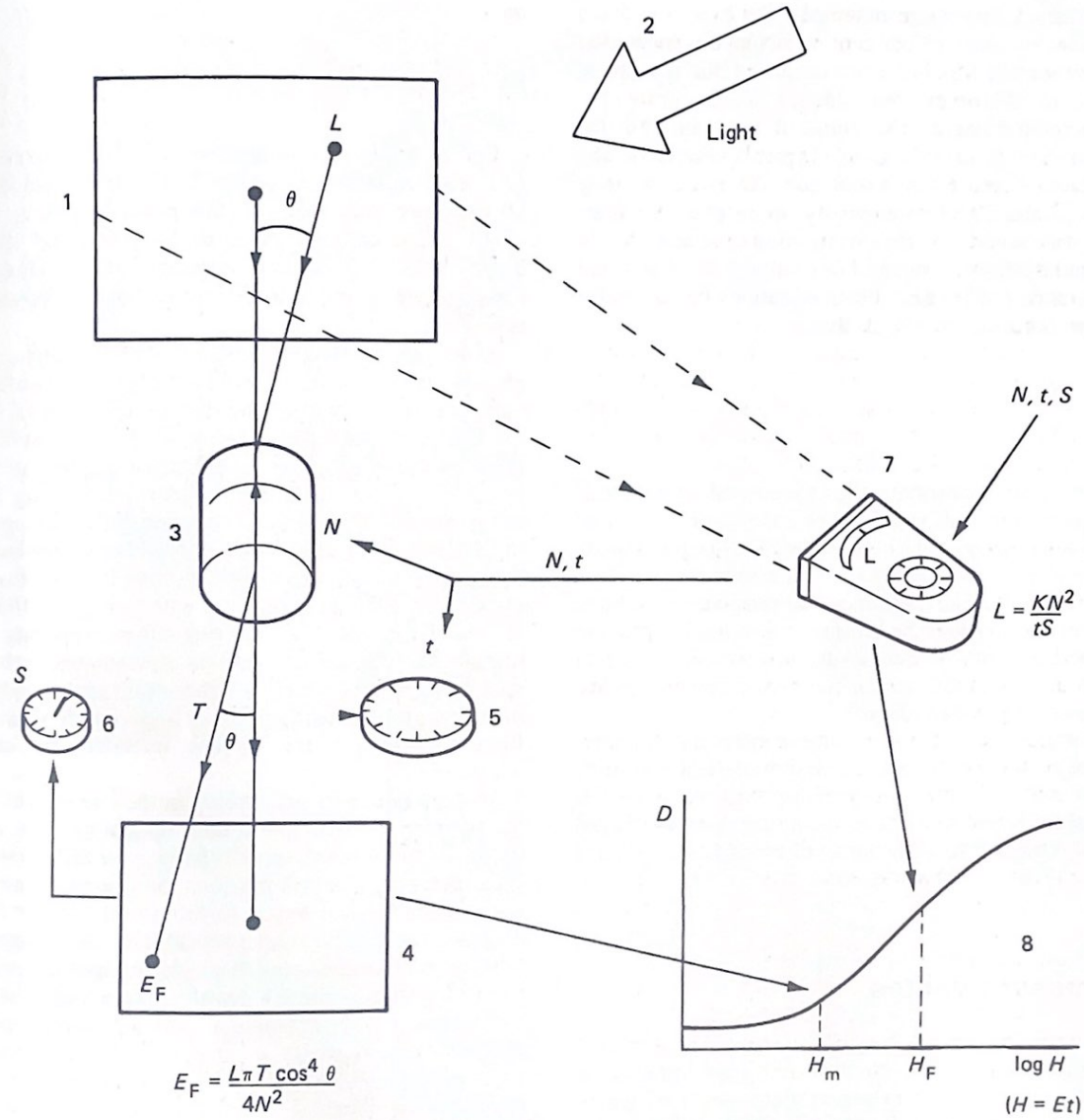


Figure 19.4 The calibration of a light meter. The subject (1) is illuminated by light (2) and imaged by the lens (3) onto the film plane (4). The camera has a shutter speed setting dial (5) and film speed setting control (6). The luminance of the scene is measured by a light meter (7). The film speed and exposure are related by the characteristic curve (8) of the film. (The other values are referred to in the text.) Film speed is determined from the value H_m and the exposure meter indicated an exposure corresponding to H_F

So, by substituting for H_F in equation (4) and rearranging, we have

$$t = \frac{kH_O N^2}{qLS} \tag{8}$$

Choosing a new constant K, usually called the *calibration constant* for luminance, gives

$$K = \frac{LtS}{N^2} \tag{9}$$

Similarly, for an incident light reading when the illuminance E_S of the subject is measured,

$$C = \frac{E_S tS}{N^2} \tag{10}$$

where C is the calibration constant for illuminance. The calibration procedures are detailed in a number of national and international standards such as those formerly published by ANSI, BS, DIN and currently by ISO.

For black-and-white materials, the exposure for a mid-tone of some 18 per cent reflectance is located at approximately 16 times that required for the speed point, to distribute the subject tones along the characteristic curve. The value of k in equation (6) would be 16 in this case. Typical values of the constants K and C for a mid-grey (18 per cent) tone are 3.33 and 20.83 respectively; more precise values may be given in the instruction manual for a particular exposure meter. For a subject of 18 per cent reflectance $L = 0.18E_S$. From equations (9) and (10), t is proportional to N^2, so that

$$\frac{t_1}{t_2} = \frac{{N_1}^2}{{N_2}^2} \tag{11}$$

Given an appropriate film speed and scene luminance or illumination value, the *calculator dials* of an exposure meter will solve equation (11) for a wide range of *equivalent pairs* of shutter speed (t) and lens aperture (N). The pair most appropriate to subject treatment may then be chosen, e.g. either to provide sufficient depth of field or to stop action. A digital readout on an LCD screen can give a comprehensive display of exposure data.

For various forms of in-camera metering, if shutter speed or aperture is pre-selected then the appropriate value of the remaining variable will be given. If *program exposure mode* is set, a combination of both t and N will be set. This mode of use is best explained in terms of *exposure values*.

Exposure values

The term *exposure value* (EV) must not be confused with *light value* (LV), which is simply a number on an arbitrary scale on an exposure meter as a measure of subject luminance or illuminance. The exposure value (EV) system originated in Germany in the 1950s and was intended as an easily mastered substitute for the shutter speed/aperture combination, giving a single small number instead of two (one of which was fractional). The EV system is based on a geometric progression of common ratio 2, and is thus related to the doubling sequence of shutter and aperture scales. The relationship used is

$$2^{EV} = \frac{N^2}{t} \tag{12}$$

Taking logarithms and rearranging

$$EV = \left(\frac{1}{\log 2}\right) \log \left(\frac{N^2}{t}\right) \tag{13}$$

or

$$EV = 3.32 \log \left(\frac{N^2}{t}\right) \tag{14}$$

For example, a combination of 1/125 second at *f*/11, from equation (14), gives an EV of 14. Similarly, all exposures equivalent to this pair will give an EV of 14. Some cameras made in the 1950s and 1960s have shutter speed and aperture setting controls linked together and to an EV scale, but this feature is now rare.

Although no longer used for such purposes, the idea of the EV scale is useful in exposure measurement practice, remembering that an increment of 1 in the EV scale indicates a factor of 2 in exposure. A primary use is to give a quantitative measure of the *sensitivity* of a metering system by quoting the minimum EV that can be measured for a film speed of ISO 100. For example, a hand-held exposure meter using a silicon cell has a typical measuring sensitivity of between EV –2 and EV –8, with a range of 16 EV. A sensitivity of EV –2 can allow metering in moonlight. The use of various attachments such as spot meter arrangements or fibre-optic probes reduce the sensitivity considerably; a high initial value is therefore needed for meters intended for such accessories.

In-camera meters are limited in their sensitivity by the light losses involved in their optical systems, and by the maximum aperture of the lens for full-aperture TTL metering. For comparisons this aperture must be quoted: for an *f*/1.4 lens a sensitivity of EV 1 at ISO 100 is typical. The operating limit of an in-camera autofocus system is quoted similarly. Another use of the EV system is the *EV graph* (Figure 19.5), where the scales on the rectangular axes are shutter speed and aperture. A series of diagonal lines connecting pairs of values of equivalent exposures represent the EV numbers. These EV loci may be extended to an adjacent graph of film speed and subject luminance. On such a graph it is possible to show the behaviour of a particular camera, for example in terms of the envelope of performance with the range of settings available. Additionally in the case of an automatic camera the different exposure modes and forms of programmed exposure can be compared.

Finally, EV 'plus' and 'minus' scales are commonly used on the exposure compensation and auto-bracketing controls of automatic cameras, and to indicate filter factors and exposure compensation for interchangeable focusing screens.

Incident light measurements

Measurements of scene reflectance or luminance are not always ideal, as some subjects have either a non-typical tone distribution, or extremes of luminance, or

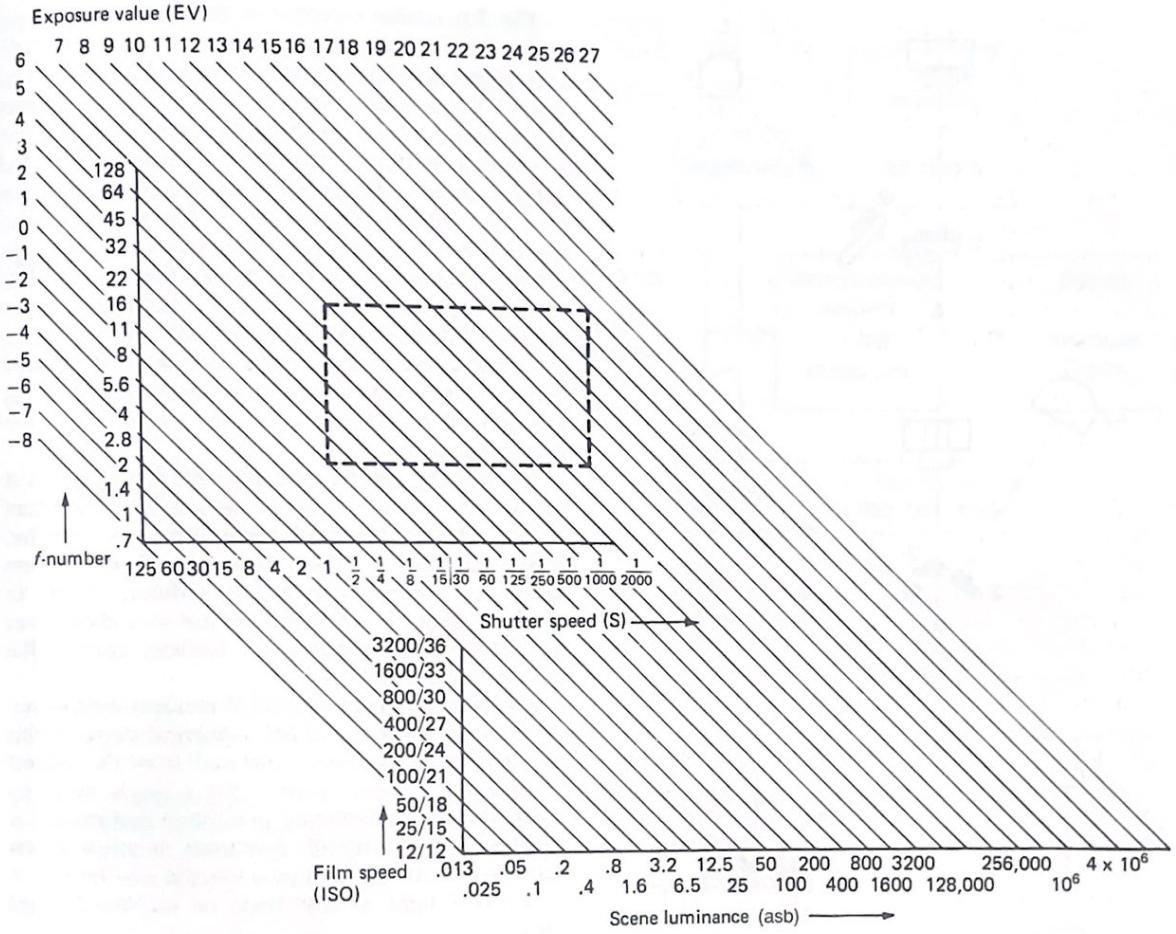


Figure 19.5 Exposure value (EV). Relationship between scene luminance and film speed can be expressed in terms of an exposure value which is a combination of aperture and shutter speed. The rectangle indicates the typical operating range of a camera fitted with an *f*/2 lens

both. Assuming that for an average scene both incident- and reflected-light measurements give the same correct camera exposure, then equations (9) and (10) are equal, so that

$$\frac{L}{E_S} = \frac{K}{C} \tag{15}$$

But as $L = RE_S$, then

$$R = \frac{K}{C} \tag{16}$$

Subject reflectance is thus assumed to be equal to the ratio of the exposure constants K and C. For example, a meter may be calibrated for a midtone so that K = 3.64 and C = 25.6, so that R is approximately 0.14 or 14 per cent. Other values such as the 18 per cent reflectance of a neutral grey test card are used as a substitute 'average subject'. The reasoning for use of an incident light reading of subject illuminance E_S is that by definition no subject can have a reflectance greater than 1.0, and exposure may be adjusted so that the brightest highlight renders an acceptable maximum or minimum density in a negative or transparency respectively. But since in equation (10) the illumination E_S is not precisely defined as to source size or direction, the light meter must integrate the incident light over a large acceptance angle to account for all contributing sources. For this purpose a translucent diffuser is placed over the photocell for incident light readings. The diffuser also reduces the response of the photocell, and different transmittance values or masks may be used to limit the reading with intense light sources such as studio flash units.

The diffuser may be flat or dome-shaped to give different forms of response. For a *flat diffuser*, if the angle between the normal to the photocell surface and

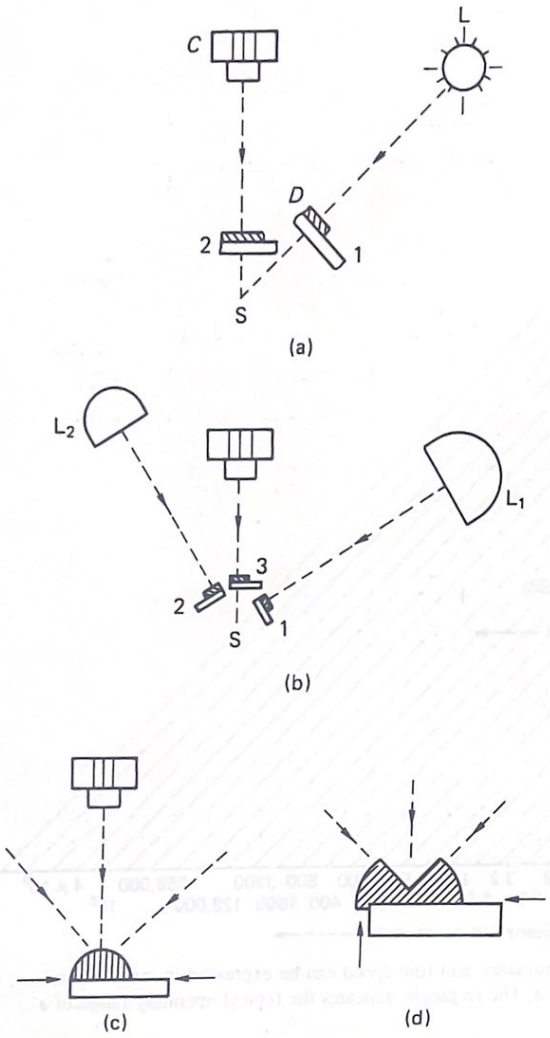


Figure 19.6 Techniques of incident light metering. (a) Flat diffuser Duplex method: C, camera; S, subject; L, brightest source; D, diffuser. (b) Flat diffuser and measurement of lighting ratio: (c) Domed diffuser taking a single reading. (d) Invercone diffuser includes backlighting

a ray of light from the primary illuminant is denoted by θ, then the response (r) is given by

$$r = k_a \cos \theta \tag{17}$$

and of a *hemispherical diffuser* by

$$r = \frac{k_b (1 + \cos \theta)}{2} \tag{18}$$

From the mathematical forms of equations (17) and (18) the flat and dome diffusers are said to have *cosine response* and *cardioid response* respectively. The constants k_a and k_b are not necessarily identical and may be the value of r when θ is zero.

The flat *cosine receptor* is directional and necessary when illuminance measurements are to be made taking into account Lambert's Cosine Law. However, when a flat diffuser is used for making measurements of illuminance for a photographic exposure, the meter is pointed in turn at the camera position from the subject, then at the brightest source of illumination from the subject (Figure 19.6). The log arithmetic mean of the two readings is then taken. This average is the mid-point of the readings on the (logarithmic) scale of the meter. This technique is called the *Duplex method*. Alternative methods include either pointing the meter towards the camera, or, pointing midway between the camera and a single illuminant, or taking averages of readings towards the camera and each illuminant in turn.

The *lighting ratio*, based upon the measurement at the subject with the meter pointed at each illuminant in turn, requires the much more directional response of a flat diffuser. For this reason many flash exposure meters are fitted with a flat diffuser. When an exposure meter is converted for use as a photometer to measure illuminance on a surface, again a flat diffuser is essential.

A more convenient method of incident-light metering is to use a diffuser of hemispherical shape; in this case the meter is simply directed from the subject towards the camera position for a single measurement. Its shape effectively presents a surface that is equally oriented in all directions relative to the subject–camera axis and its projected area relative to a beam of light at any angle of incidence is the same.

The compact *invercone* design of diffuser as used on the Weston series of exposure meters was a truncated hemisphere with an inverted cone inside it. It overhung the meter body and picked up any significant backlighting on the subject. The term 'invercone' is often generally applied to diffusers for meters.

Exposure meters in practice

The photocell

Although the majority of cameras now have some form of in-camera exposure determination system, the hand-held *light meter* or *photometer*, usually called an *exposure meter*, is still widely used. It can be used with cameras that do not have their own metering system; as a check on in-camera systems or for difficult subjects or extremely low-light conditions; for incident-light measurement; and as the basis of a system of specialized accessories for a range of light measurement tasks. It also has a role in the measurement of ambient light and electronic flash illumination.

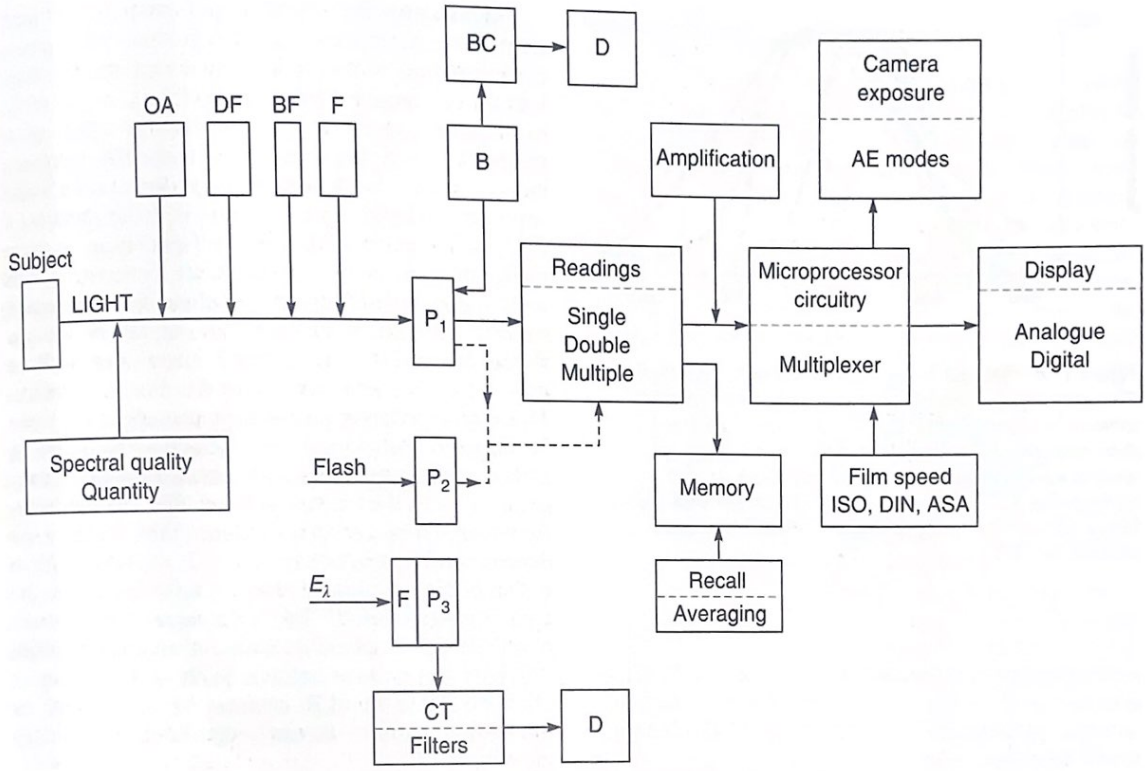


Figure 19.7 Block diagram of the principal components and features of an exposure meter. Ambient light, flash and colour temperature may all be measured. OA, optical attachments; DF, diffusers; BF, baffle; F, filter; B, battery; BC, battery check; D, display; P_1, P_2, P_3, photocells; CT, colour temperature; E_λ spectral illumination

An *exposure meter* consists basically of a light-sensitive electronic device, some means of limiting its acceptance angle, an on–off switch and a range-change switch, a power source (as necessary), a scale in light values, a set of calculator dials or readout of exposure data, and a diffuser for incident-light readings (see Figure 19.7). A variety of types of photocell are in use, including selenium 'barrier-layer' photovoltaic cells, cadmium sulphide (CdS) photoresistors, and silicon photodiodes (SPD). Their relevant properties are listed in Table 19.2; suitable circuitry is described in Chapter 9. The spectral sensitivity of the various types differs markedly (see Figure 19.8). The CdS and SPD types have high infrared sensitivity. The SPD is usually encapsulated with a blue filter to absorb IR to reduce this

Table 19.2 Properties of photocells used in exposure determination systems

Photocell type	*Se*	*CdS*	*SPD*
Battery needed	No	Yes	Yes
Amplifier needed	No	No	Yes
Speed of response	Slow	Slow	Fast
Memory effects	Eventually	Yes	No
Sensitivity	Low	Medium to high	High to very high
Linear response	Approximately	Poor	Yes
Spectral (colour) sensitivity	Matches eye	Red bias	Needs blue filter
Size	Large	Small	Small
Range change device needed	Yes	Yes	No
Electrical property	Photovoltaic	Photoconductor or photoresistor	Photovoltaic
Cost of unit	Medium	Low	High

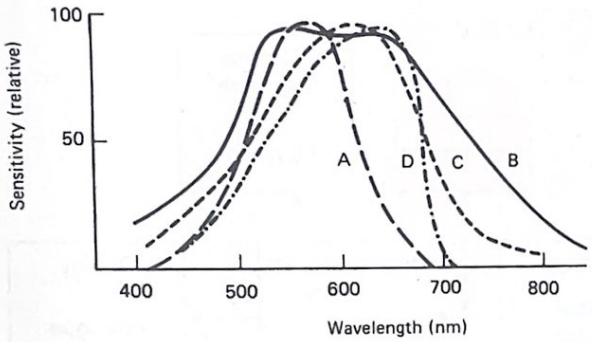


Figure 19.8 Spectral sensitivity of photocells. The graphs of relative spectral sensitivity against wavelength show the approximate spectral response or sensitivity of different photocells used in exposure metering systems. A, Visual spectral sensitivity and a filtered selenium cell. B, CdS photoresistor. C, Silicon photodiode (SPD) fitted with a blue filter ('silicon blue' cell). D, Gallium arsenide phosphide photodiode (GPD)

sensitivity and is referred to as a 'silicon blue' cell. A selenium cell is also usually filtered to match its spectral response to that of the standard CIE photopic visual response curve.

The response of the selenium cell to light is dependent upon cell area, limiting sensitivity unless the cell area is large. A plug-in booster cell can increase sensitivity by some 2 EV. The Weston series of exposure meters used a hinged perforated baffle arrangement over the large photocell to limit response at medium to high light levels. For low light levels the baffle was swung back to uncover the full cell area for greater response. This action also changed the light-value scale from high to low range.

A CdS photocell meter may have a resistor network to change its response range; alternatively it may use a neutral-density filter or a small aperture in front of the cell. The SPD gives a near-linear response over a range of some 15–20 EV and does not require a range changeover switch. Its response is unaffected by its previous exposure to light, unlike the CdS photocell.

Acceptance angle

Both the CdS and SPD photocells are small devices with a response that is independent of cell area; but require special optical arrangements when used in exposure meters. All photocells are non-imaging devices, which integrate the incident light flux. The response is restricted to the subject area covered by the camera lens, or a smaller area. Alternative techniques of integrated, small-area and spot readings are used.

Traditionally, the selenium cell meter was limited to have an acceptance angle of some 50 degrees, corresponding to the field of view of the standard lens of a camera format, but with a much more rectangular aspect ratio, to reduce the effect of a bright sky area. The removal of the baffle increases the acceptance angle to some 75 degrees, to assist sensitivity. The acceptance angle is determined by a field angle limiter of honeycomb grid type, or by a refraction type using a transparent lenticular screen with a grid in front of the selenium cell. The much smaller CdS and SPD cells may simply be located at the bottom of a cylindrical black-lined well or have a positive lens bonded to the receptor surface. These arrangements give acceptance angles of some 30 degrees, allowing more selective readings of zones of the subject area. A small viewfinder may help to aim the meter cell at the desired area. Accessory devices may reduce this angle even further to 15 degrees or even 7 degrees, with a reduction in sensitivity due to light losses in the optical system used. The *spot meter* or *exposure photometer* is a specialist meter of acceptance angle 1 degree or less (see below). Such spot metering is often available in SLR cameras as one of two or three alternative means of selective image measurement.

Optical attachments

An exposure meter is the basis of a 'system' of accessories and attachments for conversion to alternative measurements or purposes. The use of acceptance-angle reducing devices and viewfinders has been described above. Other devices may allow small-area readings of incident light to be made in the plane of the projected image on the easel of an enlarger or at the copyboard of a copying set-up. These *enlarging* and *repro attachments* may incorporate a diffuser and a plastic or fibre-optics *light guide* to enable the meter to be used flat upon the easel or copyboard. The enlarging attachment is used for techniques of printing exposure determination by comparative image photometry using a calibration obtained from an 'excellent' black-and-white print made by trial-and-error methods. Other accessories may include a small dome diffuser on a rod and flying lead to permit readings from within a table-top set-up or an *eyepiece adapter* for attachment to the viewfinder of a camera to monitor the screen image. A flexible *fibre-optics probe* attached to the photocell may act as an angle limiter or allow *ground-glass screen measurements* to be made. The meter then requires an additional calibration mark to allow for the effect of the transmission of the screen (or a comparative method may be used). A *microscope attachment* allows the meter to be fixed to the

eyepiece end of a microscope tube with the eyepiece lens removed, so as to measure the luminance of the intermediate aerial image from the objective lens and indicate exposure time by comparative image photometry from known exposure parameters. An accessory photocell probe on a flying lead can be inserted via a special dark-slide into the focal plane of a large-format camera and make small-area readings in the plane of the focused optical image. This could be considered as possibly the ideal metering arrangement. Other attachments may convert the meter into a colour-temperature meter, for measurement of electronic flash, or with a reduced acceptance angle, as a spot meter.

Most meters no longer use a moving-coil arrangement to move a pointer over a light value scale. Instead, solid-state devices give a digital read-out, and a LED or LCD panel gives the values, operational status and mode of the meter. The meter may also have a flash-metering mode, offering the same range of incident and reflected light readings and use of most of the accessories. Some exposure meters may also be used in a photometer mode where the light values are converted into luminance or illuminance readings in SI units. Alternatively, digital light meters may give a direct digital readout of the values in various chosen units.

Photometry units

The SI unit of luminance is the candela per square metre ($cd\,m^{-2}$), formerly called the *nit*. The SI unit of illuminance is the lux (lx), which represents an illuminance of 1 lumen per square metre. These units and their use in photometry are discussed in Chapters 3 and 5. Most meters that are adapted for incident-light measurements can be used for direct measurements of illuminance, using conversion tables, often supplied with the meter. Table 19.3 shows the relationships between EV numbers (for ISO 100) and illuminance values in luxes. Also shown is the relationship between EV numbers and luminance in candelas per square metre, as measured by a reflected-light meter. The relation between luminance and illuminance is that a perfectly diffuse reflector illuminated by 1 candela per square metre has an illuminance of 1 lux, so that for the same EV reading, luminance ($cd\,m^{-2}$) = $1/\pi \times$ illuminance (lx).

Unfortunately, the situation is complicated by a number of units left over from the obsolete FPS and CGS systems. These can be found in descriptions of lighting units and in the instruction booklets for older types of exposure meter. As conversion tables for these units are becoming scarce, they are included in Table 19.3. The foot-lambert (ft L) is still often

Table 19.3 Photometric units and camera exposure. Approximate corresponding values of various units of luminance and illuminance related to exposure value (EV) for camera exposure determination with a film of speed ISO 100

Subject luminance (brightness)						*Illuminance (illumination on subject)*				
EV (for 100 ISO)	*cd m^{-2} (nit)*	*stilb cd cm^{-2} (sb)*	*apostilb lm m^{-2} (asb)*	*cd ft^{-2}*	*lambert (L)*	*foot-lambert (ft L)*	*lux lm m^{-2} (lx)*	*phot lm cm^{-2}*	*lm ft^{-2}*	*EV (for 100 ISO and R = 1)*
−2	0.03		0.1			0.01	0.1		0.01	−2
−1	0.06		0.2			0.02	0.2		0.02	−1
0	0.13		0.4	0.01		0.04	0.4		0.04	0
1	0.25		0.8	0.02		0.07	0.8		0.07	1
2	0.5		1.6	0.05		0.15	1.6		0.15	2
3	1		3.14	0.09		0.29	3.1		0.29	3
4	2		6.28	0.2		0.58	6.3		0.58	4
5	4		12.57	0.4		1.17	12.6		1.2	5
6	8	0.001	25.1	0.8		2.34	25		2.3	6
7	16	0.002	50.3	1.5		4.67	50		4.7	7
8	32	0.003	100.5	3	0.01	9.34	100	0.01	9	8
9	64	0.006	201	6	0.02	18.7	201	0.02	19	9
10	128	0.01	402	12	0.04	37.5	402	0.04	37	10
11	256	0.03	804	24	0.08	75	804	0.08	75	11
12	512	0.05	1609	48	0.16	150	1609	0.16	150	12
13	1024	0.1	3217	96	0.32	299	3217	0.32	299	13
14	2048	0.21	6434	190	0.64	598	6434	0.64	598	14
15	4096	0.41	12868	381	1.29	1196	12868	1.29	1196	15
16	8192	0.82	25736	761	2.57	2392	25736	2.57	2392	16
17	1684	1.68	51472	1522	5.15	4784	51472	5.15	4784	17
18	32768	3.28	102944	3044	10.29	9568	102944	10.29	9568	18

encountered in connection with screen luminance of a projected image. The stilb (sb) was (and still is) used for the luminance of light sources and the apostilb (asb) for the luminance of non-self-luminous sources. It will be noticed from Table 19.3 that the apostilb is numerically equal to the lux; but it is a unit of luminance, not illuminance.

Spot meters

A photometer or exposure meter with an acceptance angle of 1 degree or less is usually referred to as a *spot meter*. Its applications are for precise measurement of the luminance of small areas of a large subject, for example when a long-focus lens is to be used, or if the subject matter is inaccessible or if the area of interest is itself small. A complex optical system is needed. Such a meter will typically show a field of view of some 5–20 degrees horizontally, in a viewfinder with focusing capabilities. The much smaller measuring spot area is shown in the field together with a light value scale which may be in digital form. A measuring accuracy of ± 0.1 EV is possible. The classic design of visual spot photometer used a Kepler telescope configuration and a split cube carrying a 'spot mirror' to image an internal reference light source in the measurement area. The spot was matched to the subject tone by attenuation using sliding density wedges (Figure 19.9). The principle was essentially that of the Bunsen grease-spot photometer. Two calibration indices were provided for use of either highlight or shadow readings of luminance. The image was inverted (a minor inconvenience) and could be focused for close distances.

Modern designs use an SPD, with a pentaprism to give an upright, unreversed image in the viewfinder. A flare-free arrangement uses an *aperture mirror* containing a small aperture in front of the photocell; this avoids the necessity for a beamsplitter which could otherwise affect the polarization of the emergent light. Most instruments are calibrated for a mid-grey tone, but shadow and highlight readings may also be used as well as an averaging arrangement. A digital display gives comprehensive summaries of relevant exposures for various camera modes, scene luminance range and other data. Several separate readings may be stored, displayed on recall and averaged as required. Both ambient-light and flash-metering modes are available, but incident-light readings are not possible.

SLR cameras with TTL metering systems may offer the alternative of a true *spot mode* reading. The acceptance angle of the spot field varies with the focal length of the camera lens in use, and with long-focus lenses this can be very small. A number of spot readings may be taken in the subject area, stored, averaged and the calculated exposure then given automatically by the camera in the appropriate exposure mode. This form of TTL metering should not be confused with *small-area readings*, where an acceptance angle of some 5–20 degrees is used (5–10 per cent of the viewfinder area), and calibration is for a mid-tone.

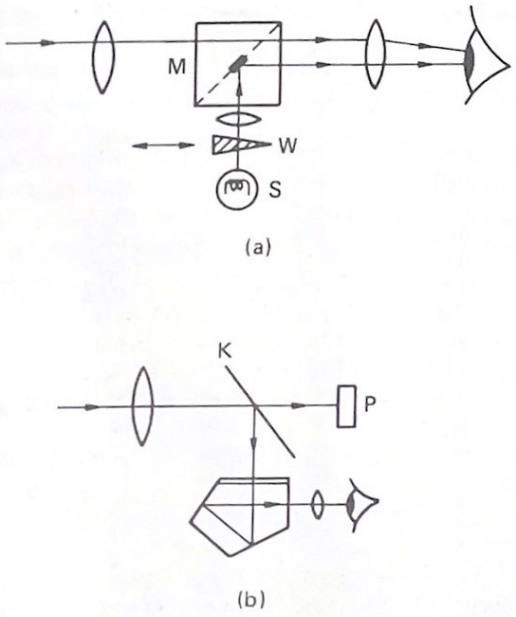


Figure 19.9 Spotmeters. (a) Visual: M, spot mirror; W, optical density wedge; S, reference source. (b) Photo electric: P, photocell; K, aperture mirror or beamsplitter

In-camera metering systems

Automatic exposure

A light metering system built into a camera body is directly coupled to the camera controls either for manual operation and setting or for use of one of several alternative *automatic exposure* (AE) modes. The necessary photocell(s) may be located in various positions, requiring different optical systems for each variant. Non-SLR cameras usually have the metering system located to read directly from the subject, possibly with a choice of reflected- or incident-light measurements. A selenium photocell may be placed as an annulus round the lens, using lenticular baffles to determine the acceptance angle.

The more compact CdS or SPD cells can be placed behind an aperture fitted with a small lens located either on the camera body or near the camera lens. The latter is preferable, as such positioning makes it possible to compensate for the effects of lens attachments such as filters. Metering sensitivity is high as light losses are low compared with TTL metering. A frame line in the viewfinder may indicate the measurement area. To provide simple allowance for film speed, a metal plate with a series of graded



Figure 19.10 A photocell on a probe inserted into a large format camera to take small area readings at the photoplane

apertures, or a tapered slit, is located in front of the photocell and is linked to the film speed setting control, using a change in the incident light, rather than electronic circuitry to provide variation of the cell output.

TTL measurements have advantages in that only the imaged area is used, regardless of the lens fitted, and compensation of exposure is usually automatic for bellows extension and optical attachments. Exceptions include infrared and linear type polarizing filters.

Such exposure compensation is particularly important when zoom lenses are being used, as the *f*-number usually changes as focal length is altered. In such cases some means of constantly monitoring image illuminance is essential.

The best location for a photocell is in the true photoplane of the camera, as realized in some insertable metering systems for large-format cameras (Figure 19.10), but an *equivalent focal plane* can be used instead. Full details of photocell locations and optics are given in Chapter 9. Such TTL systems are normally limited to simple measurements of subject luminance, and the uncertainties of exposure determination with non-average scenes using a simple integrated measurement led to the use of alternative sensitivity patterns for meters, also described in Chapter 9, to improve the proportion of acceptable exposures. The usual patterns are those of approximate full-area integration with central bias, of centre-weighted measurement (possibly with directional bias) and of small-area measurement. More

sophisticated systems may use true spot metering of very small areas, or zone measurements by multiple zone or *segmented photocells* to provide scene categorization information (matrix metering). A desired sensitivity pattern is obtained by positioning the planar photocell behind spherical or aspherical lenses, or by use of patterned Fresnel mirrors. Pairs of photocells with overlapping fields of view may also be used.

A particularly accurate form of TTL metering is that of *off-the-film* (OTF) metering, in which image luminance measurements are made using the light reflected from patterned shutter blinds or from the film surface itself during exposure; off-the-film monitoring is possible even with rapidly fluctuating light levels. For short exposure times, the patterned shutter blind simulates average image luminance over the obscured area of the film gate during travel of the slit. Flash metering uses the open gate full frame area.

In-camera metering is normally used in semi-automatic or automatic mode. In the former, either shutter speed or aperture or both together are varied manually, until a readout indicates that correct exposure has been set. The camera can be used to scan and sample the scene in chosen areas, and a modified exposure given as judged necessary. Automatic exposure offers a choice of shutter priority, aperture priority and various program modes. Additionally, *metering pattern* may be altered, an *exposure compensation control* may be used or an *exposure memory lock* employed to improve the proportion of acceptable pictures from non-average scenes.

Metering sensitivity is dependent upon the effective maximum aperture of the lens in use. Measurement may have to be carried out in a *stopped-down mode* if a lens without automatic iris diaphragm operation or maximum-aperture indexing is used. Metering is of the reflected light from a subject as the incident-light mode is not available to TTL metering systems. Metering sensitivity with an *f*/1.4 lens and ISO100 film is generally of the order of 1 EV, significantly less than that of a hand-held meter.

Programmed exposure modes

An automatic camera with choice of exposure modes includes at least one *programmed exposure mode*; this is the 'snapshot' form of setting for such a camera. This was the original form of automatic exposure as pioneered in early cameras of the point-and-shoot variety with no alternative exposure modes other than one for flash that gave a fixed shutter speed and allowed the aperture to be set manually. More recently, multi-mode cameras may offer choice of user-selectable or calculated programs as well as one set by the lens in use.

The main advantage of a programmed AE mode is that photography is speeded up when rapid response is vital to capture fugitive subject matter. Seconds can be lost in the preselection of aperture or shutter speed or the taking of a meter reading, whereas the programmed-mode camera gives a usable result almost every time on pressing the release. Even the time taken to focus can be crucial, but the combination of autofocus with programmed AE gives a swift response. Programmed exposure is also convenient at times when the user wishes to be relaxed and not to have to concentrate on decisions about exposure, as well as being a safety-net for inexperienced photographers. The principles of programmed AE, often designated on a camera as the *'P' mode*, are simple. As previously explained, the photocell output and the set film speed will determine the necessary exposure for a scene in terms of exposure value (EV), which represents a wide range of equivalent combinations of lens aperture and shutter speed. The electronic circuitry in the metering system is programmed to give one particular combination according to the EV data fed in. Examples of such programs are shown in Figure 19.11, in which a program is given as a straight line with a chosen slope and one or more changes in direction to span the EV measuring range of the camera.

A horizontal or vertical line shows that one variable is kept constant while the other changes continuously; for example, shutter speed may change continuously over the range 8 s to 1/8 s while the aperture is held constant at *f*/1.4. A sloping line shows that both variables change continuously. A steeply sloping line shows that priority is given to the maintenance of short exposure durations, to minimize the risk of camera shake or to stop subject motion, while relying upon lens performance and accurate focusing at the corresponding large aperture. A required EV of (say) 12 for correct exposure is interpreted in various ways by programmed cameras. It could mean settings of 1/30 s at *f*/11 for one camera or 1/80 s at *f*/7, 1/125 s at *f*/5.6 or even 1/500 s at *f*/2.8 for other cameras. An electronically controlled shutter and fractional control of lens aperture setting allows non-standard exposure settings. Note that a viewfinder readout of the analogue type usually indicates rounded-off values for shutter speeds and apertures; for an analogue display the values of 1/80 s at *f*/7 in the example above may be shown rounded off to the nearest conventional values of 1/60 s and *f*/8 (the actual camera exposure will be the true value). A digital display will usually show the true values.

Some decision should be left to the user as to whether shutter or aperture priority might be appropriate under different circumstances, such as moving subject matter, depth-of-field requirements, low light levels or long-focus lenses. So there is a choice of 'normal', 'action' and 'depth' AE programs. Additionally, the insertion of an alternative lens of different focal length may automatically select one of three shutter-biased program modes usually referred

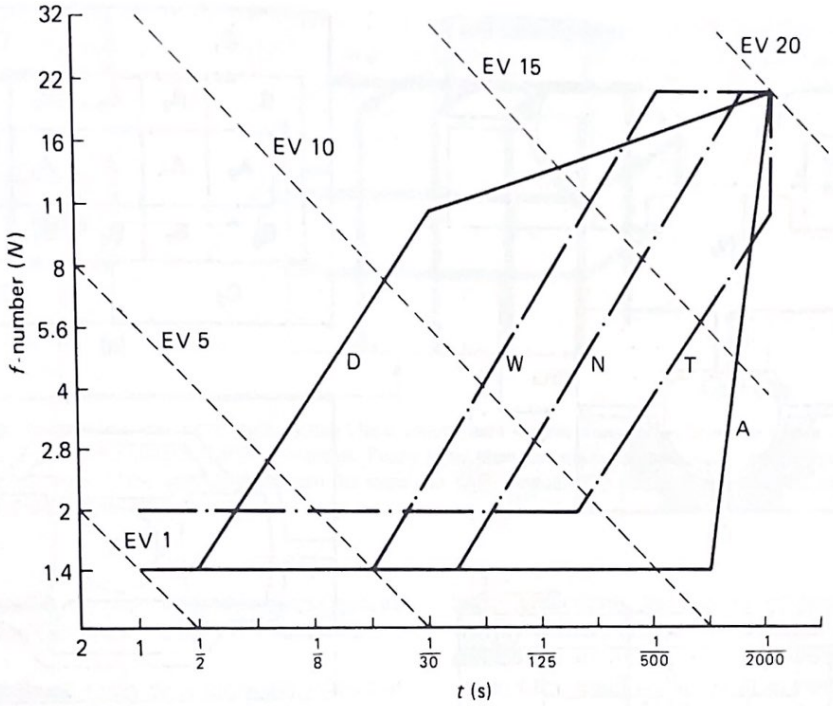


Figure 19.11 Programmed exposure modes. The EV graph shows five possible program profiles over an exposure range from EV 1 to 20. These are D (depth), W (wide), N (normal), T (telephoto) and A (action). Both D and A may be selected manually while W, N and T are usually set by the focal length of the lens in use

to as 'wide', 'standard' and 'tele', with the turning point of the program line on the EV graph at the point where the minimum hand-held shutter speed may be used. The slope of the program line may increase progressively from 'wide' to 'tele'. A zoom lens may alter the program selected continuously as focal length is altered. It may even be possible for the user to designate a non-standard program profile for the camera.

The use of any programmed AE mode requires that the lens aperture control is locked at a minimum value *AE setting* as for shutter-priority exposure mode; the aperture value is then selected by the camera in increments that may be as small as 0.1 EV. When used with a metering-pattern system capable of some analysis of tonal distribution of the subject matter, for example centre-weighted or segmented-photocell types, then programmed exposure modes are capable of producing a high proportion of acceptably exposed, sharp results. This form of 'decision-free photography' may be less acceptable in situations requiring critical creative control of focus and subject sharpness.

Segmented photocell systems

Accurate determination of camera exposure, especially by in-camera TTL AE systems, is limited by variations in subject luminance ratio and non-typical subject tone distributions, which necessitate their recognition and classification by the user. The use of spot metering, small-area and various weighted integrated readings can help, with intelligent use. An overall improvement in the percentage of successful results is possible using a *segmented photocell* or *matrix metering* arrangement for scene classification (Figure 19.12). The viewfinder image is measured,

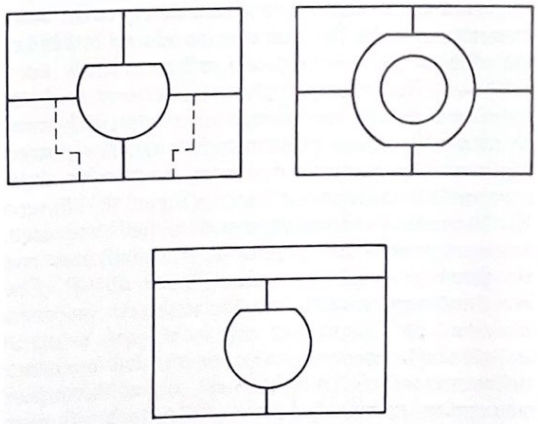


Figure 19.12 Simple arrangements of segmented photocell arrays

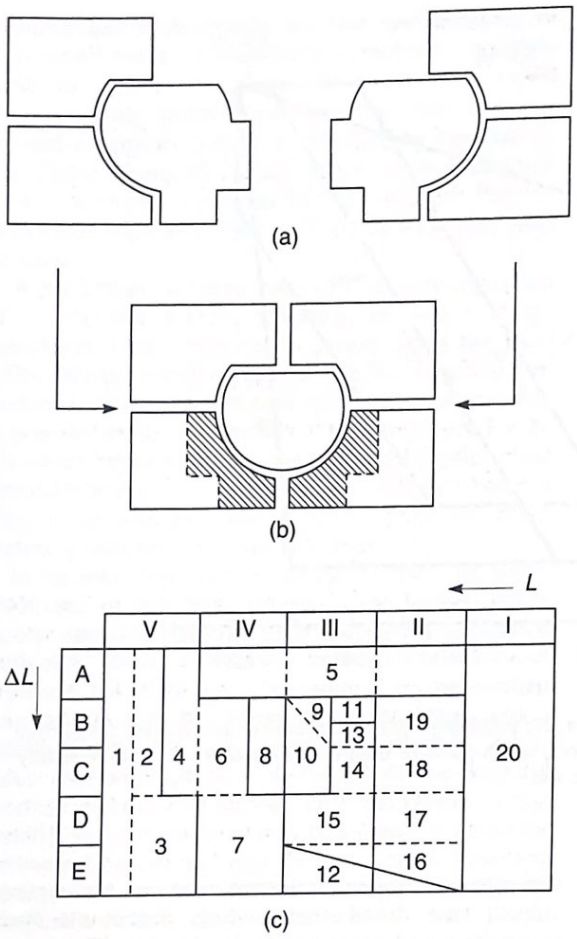


Figure 19.13 Metering with segmented photocells (Nikon AMP system). (a) Twin overlapping pairs of three segments; (b) format zones; (c) scene classification by luminance L and luminance ratio ΔL value from zones

assessed, compared to stored data on a large number of scene patterns and categorized for subject type. Adjustments are then made automatically to the basic camera exposure. The idea was introduced in 1983 in the Nikon FA camera; and other systems soon followed. For example, the screen area may be measured as five or six separate zones (with some overlap) by means of two symmetrically opposed segmented photodetector arrays, both with three independent measurement areas (Figure 19.13a and b). Numerous alternative arrays of cells are used, some of which can provide spot, small area and weighted readings as well (Figure 19.14). The weighted response data from the separate segments is classified by signal-processing techniques, using an onboard microprocessor. Analysis of zonal luminance difference values and the total subject luminance value, plus the metering pattern, allows classification into a number of computer-simulated subject types (Figure 19.13c). The basic exposure is then modified

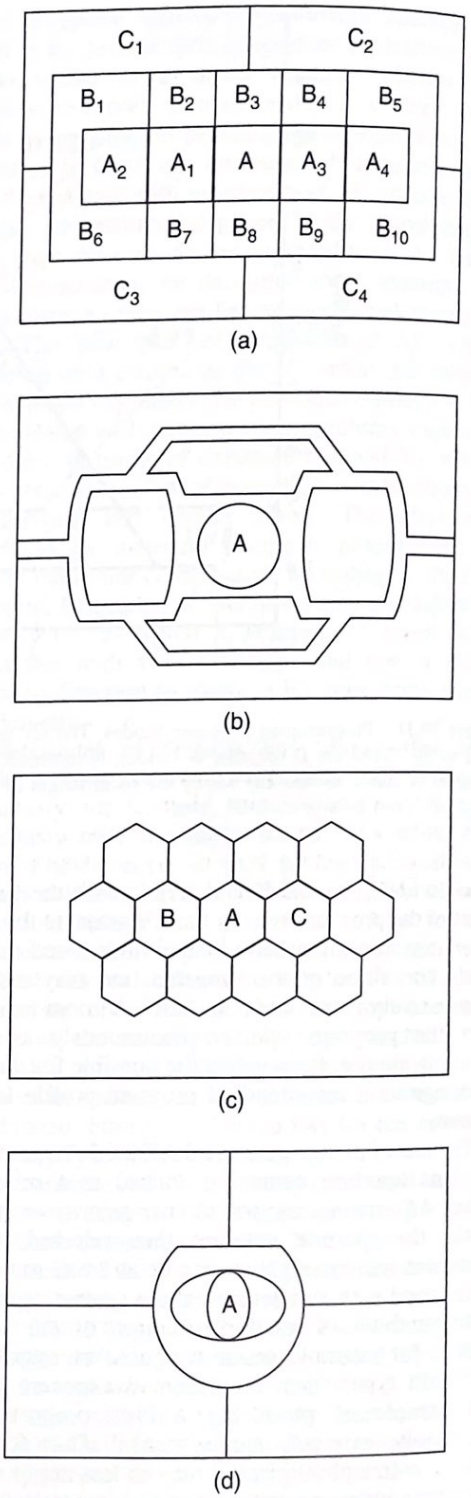


Figure 19.14 Segmented photocell arrangements. (a) Canon, 16 segments: A, spot metering. A_1 to A_4, movable spot metering and focus zones. Evaluative metering uses all segments. (b) Pentax, eight segments: A, spot metering. Other zones give centre-weighted and averaged metering. (c) Minolta, 13 segments. A simpler seven-segment inner group is also used. A, spot metering. A, B, C, centre-weighted. (d) Nikon, eight segments. A, spot metering

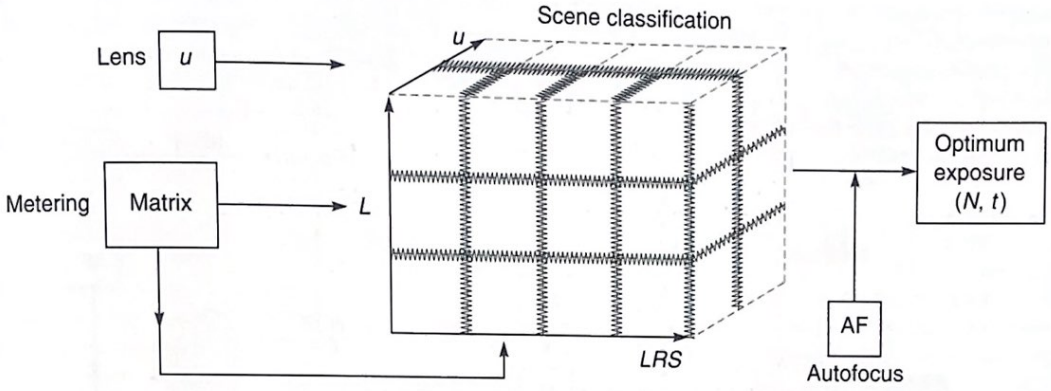


Figure 19.15 Matrix metering and fuzzy logic. Scene classification uses subject distance (u) from the lens, scene luminance (L) and luminance range of the subject (LRS) or contrast. Fuzzy logic blurs the sharp demarcation of scene types. Defocus information about the zones of the scene comes from the autofocus (AF) module. The output is the optimum exposure as an f-number (N) and shutter speed (t).

using stored data for several hundred subject types as determined from practical tests or evaluation of photographs.

The *tone distribution* may be determined, often just as a comparison of central foreground to background luminance, and if a chosen difference value in EV is exceeded, then an integral flash unit may be charged automatically and used for fill-in purposes. The lens aperture and shutter speed are optimized separately for subject distance (using autofocus data) and flash synchronization. Additionally, separate segments may be switched out or used in different configurations to provide various alternative forms of metering sensitivity patterns (spot, small-area, centre-weighted). Larger numbers of zones and segments are used in some cameras.

Scene classification

A further improvement in scene classification for automatic exposure methods is to provide subject distance (u) information from the autofocus module and focus setting on the lens. This latter requires that the focusing control has a suitable transducer and data link with the microprocessor in the camera. From the *matrix* array of photocells used to divide the scene into segments, the scene can be classified using the three pieces of data, overall scene luminance (L), luminance range of the subject (LRS) and the subject distance (u) (see Figure 19.15). The scene classification box is subdivided into a series of scenes for which optimum exposure data is stored, based on extensive practical tests, especially for non-typical scenes. The scene is matched to one of these and the optimum exposure given. The defocus data from the AF system helps determine whether the subject is central or off-centre in the frame as this can give emphasis to different segments of the matrix. By the additional use of 'fuzzy logic' procedures, the scene type boundaries are not sharply defined but overlap to some extent to avoid sudden changes in exposure, e.g. when using a motor drive, when small variations in an essentially constant scene may cause a noticeable change in exposure as the scene is inadvertently reclassified and exposure altered. The same principle can be applied in a simpler way to the use of fill-in flash to give a balanced exposure to subjects, especially of excessive contrast. A simplified flow diagram of matrix metering is given in Figure 19.16.

A matrix array of CCD photocells filtered to blue, green and red light, together with scene classification data can also be used in-camera to assess the colour temperature of a scene.

Electronic flash exposure metering

Flash properties

Electronic flash may be used as the main light source for a picture or in combination with ambient light to provide a means of reducing the subject luminance ratio. The properties of electronic flash, including production, spectral and temporal properties and the control of output, are detailed in Chapter 3; but it is useful here to emphasize its widespread use as an illuminant either in the form of a studio flash unit, or as a unit that can be attached to the camera, or as a 'dedicated' unit with secondary roles such as autofocus assistance, or as an integral unit within the camera body. The useful properties of flash are a controllable luminous output, a constant colour temperature close to that of daylight, motion-stopping abilities, low heat emission and, in some cases, strobing capability. Its only drawback is the difficulty of synchronization with a focal plane shutter at high shutter speeds. The illumination on a subject is a combination of direct and indirect light, the reflective properties of the

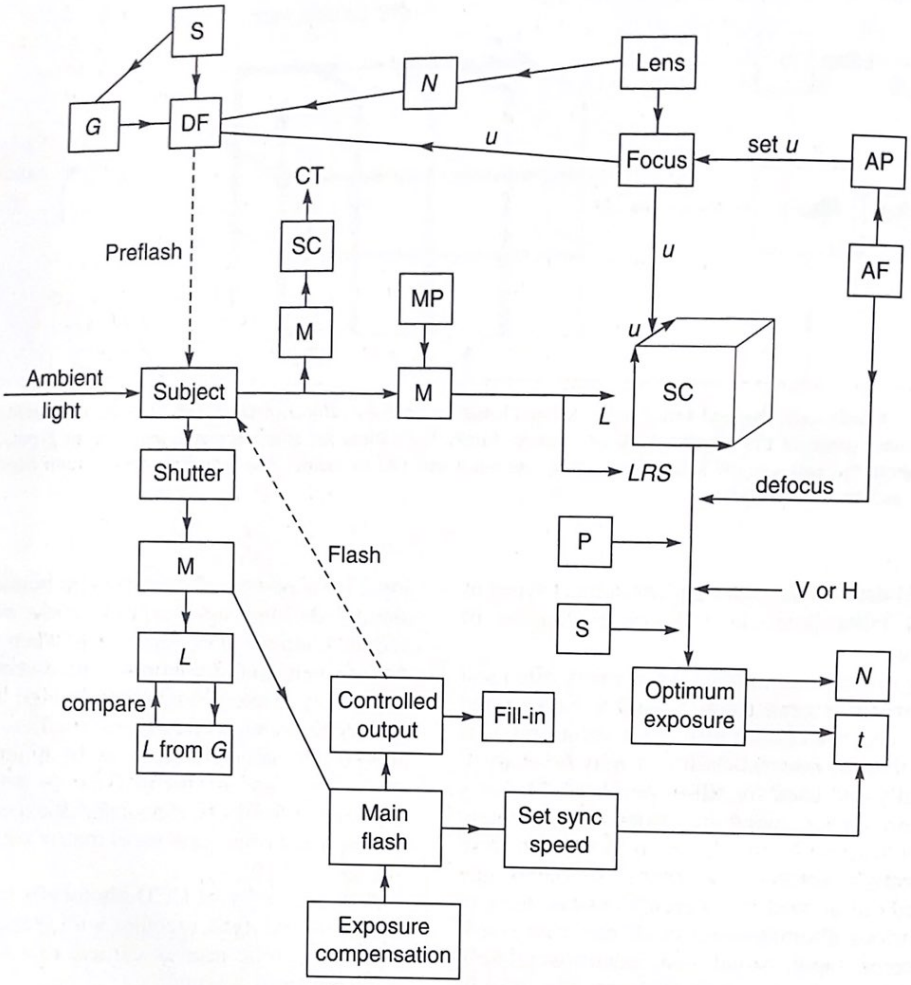


Figure 19.16 Matrix metering. A much simplified flow diagram for data and control of exposure using matrix arrays for ambient light, flash and colour temperature: S, film speed; DF, dedicated flashgun; *G*, guide number; *N*, *f*-number; *u*, subject distance; CT, colour temperature; M, matrix measurement; MP, matrix pattern; SC, scene classification; *L*, subject luminance; *LRS*, luminance range of the subject; *t*, shutter speed; P, chosen AF program; AF, autofocus module; AP, autofocus pattern; V, vertical format; H, horizontal format

surroundings of a subject often having a pronounced effect on the illumination. In the absence of any flash modelling lights, it can be difficult to allow for such effects. Also, as the flash duration is short, any visual judgement as to illumination level and the necessary exposure is not possible, so some means of flash exposure determination is desirable. Various methods are used, but in general, flash exposure control is either by use of lens aperture or alteration of flash output, due to the necessity of synchronizing the flash output with the camera shutter.

Self-developing materials

The use of these materials allows a test exposure with flash and also gives a positive confirmation of correct flash synchronization, and of ensuring, at the very least, that the 'M' setting has not been used by mistake. Flash synchronization can be checked visually by opening the camera back, placing the eye about 30 cm behind the focal plane, opening the lens aperture fully and operating the camera shutter with the camera pointed at a white wall. A bright disc indicates correct functioning. If either a star, or a segment of a disc or nothing at all, is seen, the shutter is out of synchronization.

Modelling lights

Most studio flash units have modelling (guide) lights integral with the flashtube. These lights may indicate lighting distribution and balance and can be either

turned off or left on when the flash operates. They may be tungsten or tungsten–halogen and the light output is altered in proportion to the flash output if this is variable. Studio flash units usually offer a variety of power increments, some allowing increments as small as 0.1 EV.

A conventional exposure meter may be used in conjunction with these modelling lights to provide a measure of the related flash output. The technique is simple. Using an approved lighting arrangement, a bracketed series of test exposures is made using the flash illumination and then the correct *f*-number is determined by visual inspection of the results. The subject is then metered using an incident-light technique, and from the calculator dials, a shutter speed is found that corresponds to the *f*-number determined by tests for the same film speed setting. This shutter speed marking now acts as the flash calibration index; if the lighting arrangement or subject is changed, the meter will indicate the new *f*-number required for flash exposure opposite the shutter speed marking found.

Flash exposure guide numbers

The light output and the required camera exposure for a given flash unit can conveniently be expressed by an *exposure guide number* or *flash factor* (as explained in Chapter 3). For a film of speed ISO 100 and a subject distance d (in metres), the necessary *f*-number N is given from the guide number (G) by the relationship $G = Nd$.

This guide number is often included in the alphanumeric code designation of a flash unit. For example, inclusion of the number 45 would usually indicate a basic guide number of 45 in metres for ISO 100 film material. The guide numbers *are* only guides, and practical tests are needed to establish their correctness, which depends to some extent on the effects of the surroundings, ambient light level and the shutter speed used. The guide number also changes with *fractional power output* selection as offered by many units, some of which are able to select full, half, one-quarter, one-eighth and one-sixteenth power or less, or, when a camera motor-drive setting is selected, giving reduced power and rapid recycling. Likewise an alteration in *flash covering power* to suit different lenses will also affect the guide number.

To assist the determination of the necessary *f*-number for correct exposure given the variables concerned, most flashguns incorporate some form of calculator in the form of annular dials, or as a comprehensive LED or LCD display. Additional useful data shown are the *subject distance range* covered and especially the *maximum subject distance* possible for correct exposure at the indicated *f*-number. Guide numbers are devised on the assumption of a near-point source and are based on the Inverse Square Law. A doubling of flash output or doubling of film speed used increases the guide number by a factor of 1.4. A quadrupling of output or film speed doubles the guide number. Doubling the distance between the flash source and the subject distance needs a change of +2 EV in exposure (factor ×4).

While such calculations are reasonably simple to make for one flash source, it becomes increasingly difficult to do so for two or more sources, especially if they are at different distances and of differing powers. The positioning of flash-heads without the assistance of modelling lights is a task requiring experience and skill. But as a guide to simple twin-head flash, using one flash off-camera as the main (modelling) light and the other on-camera as fill-in light, the fill-in light should provide approximately one-quarter to one-half the output of the main light.

The guide number system has been replaced in automatic flash units by the use of *variable flash output* and hence duration as a means of controlling exposure, but it is still applicable in situations such as the use of *ring flash* units or in lenses where a guide number may be set and linked to the focusing control to give a readout of the *f*-number necessary for a given subject distance. Similarly it is used in autofocus cameras where the flash output is fixed, and the appropriate *f*-number set by the distance setting from the autofocus system.

Synchro-sunlight

The use of guide numbers with fractional flash output settings of one-half, one-quarter etc. of full power is useful with *synchro-sunlight* techniques where the flash output is selected given the camera settings for the ambient-light exposure. For example, a subject at a distance of 4 metres from the camera, and in bright direct sunlight, requires 1/125 s at *f*/11 with ISO 100 film, and the fill-in flash on the camera has guide numbers of 44, 22 and 11 (in metres for ISO 100) for full, one-quarter and one-sixteenth power respectively. Using the flash at full power for a flash-only exposure would also need *f*/11. Hence at quarter power, leaving the aperture at *f*/11 provides one-quarter of the exposure; but this is suitable as the necessary fill-in for the ambient-light exposure. The use of a between-lens shutter with flash synchronization at every setting gives greater choice of *f*-number to suit the power and distance of the flash fill-in unit, although the typical shortest flash synchronization speed of a focal plane shutter at some 1/250 s is also useful.

Flash meter

The usual types of exposure meter (light meter) used for ambient light measurements cannot be used with

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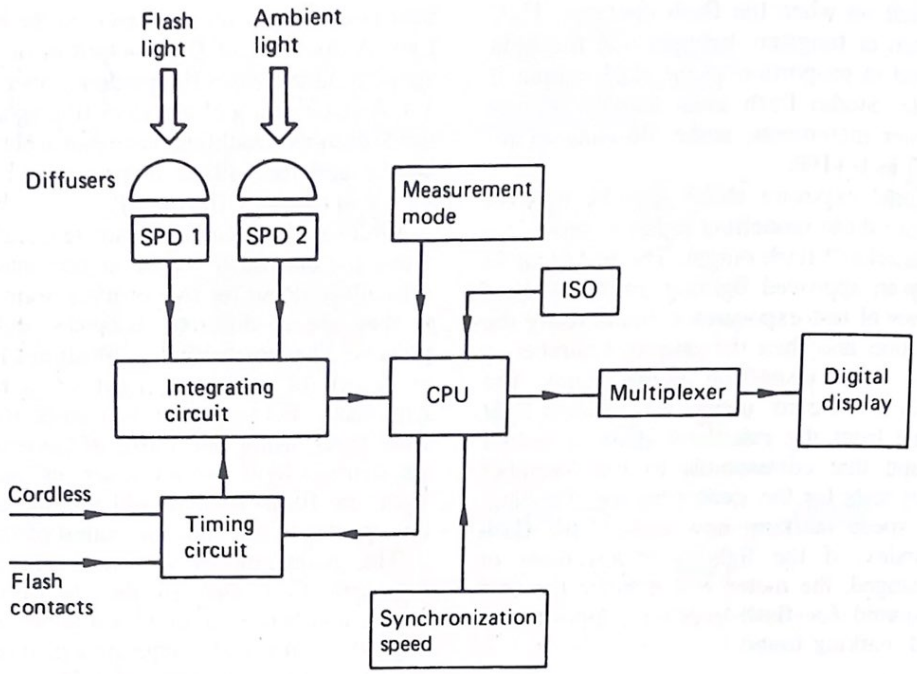


Figure 19.17 Flash meter. Schematic diagram of the usual components of a flash meter for shutter-synchronized or cordless use. Twin photocells measure both ambient light and flash light

flash owing to their slow response to changing light conditions, and their lack of synchronization with the flashgun. A *flash meter* (Figure 19.17) uses different circuitry and an SPD with a response time of 10 microseconds or less, so as to measure both the intensity and duration of the flash output from the light reflected from the subject. An integrating circuit measures the total response during a selected 'gate' time (corresponding to the shutter speed selected), and the output is usually displayed either directly as an *f*-number or as a light value for conversion into an *f*-number for use.

There are other significant differences compared with a conventional exposure meter. The meter circuitry is cleared, reset and activated on receipt of the flash output and so requires some form of synchronization with the flash unit. This may be done by a conventional flash lead from the unit and a PC socket in the flash meter. Alternatively, *cordless control* may be offered. With this system there is no electrical connection between meter and flash unit. Instead, a control switches on the meter circuitry to stand-by mode and the flash unit is operated using the 'test flash' control, or fired from the camera shutter. The photocell then responds to the momentary change in subject illumination and measures flash output. Another cordless alternative is for the flash meter to emit a pulse of infrared radiation when triggered manually; this operates suitable slave photocells on each flash unit and causes them to fire and hence be measured. A useful feature is that of 'accumulative flash' where a single flash is insufficient so the necessary illumination level is built up by multiple flashes, with a static subject of course, and the camera shutter set on 'B' for a short time exposure. In this mode the flash meter is activated, then measures and integrates several successive flashes ('pops') until the required *f*-number is indicated. No account is taken of any intermittency effects in the photographic material used.

Most flash meters take account of the ambient light as well as the flash output. This is important in the case of (for example) a slow flash synchronization speed and powerful modelling lights. The shutter speed to be used for synchronization is set into the meter, and this will determine the measurement time gate of operation, for example 1/60 s. When activated, the meter simultaneously measures both flash output and ambient light for this 1/60 s chosen and calculates the necessary aperture for the mixed lighting. Often the ambient light has little effect, especially at short exposure durations and small apertures. It may be measured by a separate photocell in the flash meter. The ratio of both sources may be indicated. Often a flash meter can also be used for ambient-light measurements alone.

Most flash meters are used principally for incident-light readings using a domed diffuser, but others use a flat diffuser particularly for balancing lighting by the ratio of outputs, and in such cases the more directional response must be taken into account. Reflected-light measurements may also be made,

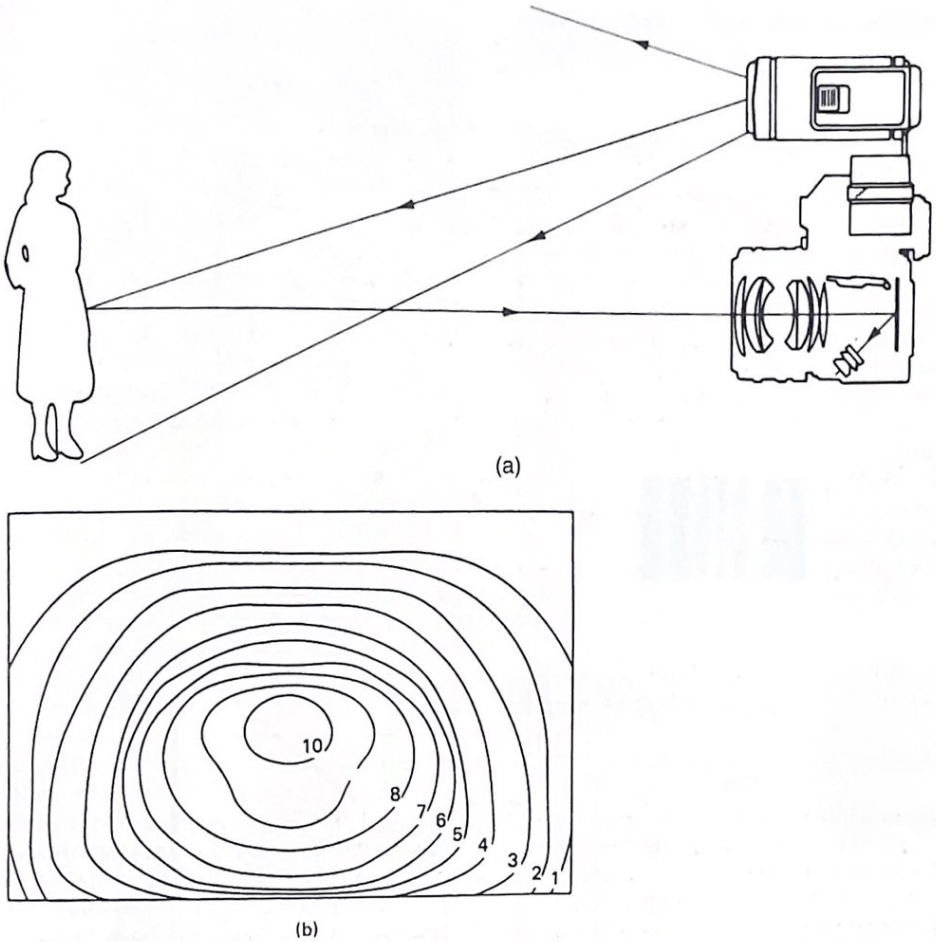


Figure 19.18 Automatic off-the-film (OTF) flash metering. (a) Principles: light emitted by the dedicated flash unit is reflected by the subject and the image luminance on the film surface is monitored by a photocell. (b) The metering sensitivity pattern may be centre-weighted and biased to the bottom of the field of view

together with the range of system accessories available, so that spot readings are also possible.

Comprehensive digital displays give a full readout of metering mode, the average of several readings and cumulative flash exposure, usually indicating *f*-number to one-tenth of a stop. Metering sensitivity is again usually assessed in terms of the minimum EV indicated for ISO 100 material. A sensitivity of 1 EV is typical.

A *chronotron* measures flash duration, the colour temperature of the flash, any colour correction filters necessary and the scene illumination in lux as well as being able to balance two sources.

Automatic electronic flash

Flash features

A great convenience is automatic exposure using an attachable electronic flash, where a fast-reacting SPD photocell operates a thyristor switch to quench the flash discharge. Full details are given in Chapter 3. The photocell monitors subject luminance (brightness during the flash emission), and calibration usually assumes a scene of average tonal distribution. Exposure errors are possible due to non-typical subject matter or measurement of luminance. For example, a small close subject with a large distant background will tend to be heavily over-exposed as the flash output endeavours to light the background to a suitable level. The photocell usually has a modest acceptance angle of some 30 degress or less, to help overcome such problems by reading from the centre of the subject area only, though some means of aiming is helpful. Since only reflected-light readings are used, the photocell must be maintained in a 'look-ahead' position, i.e. directed at the subject. *Bounce flash*, or indirect flash, requires a tilting flash reflector assembly; alternatively the photocell can be equipped with a flying lead to enable it to be used in the

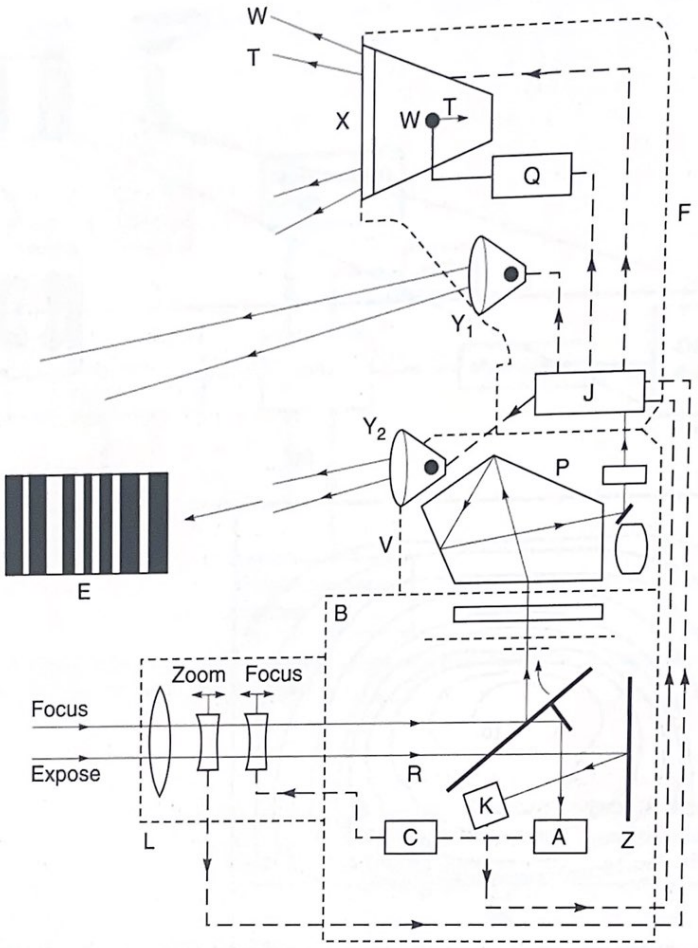


Figure 19.19 Flash metering and autofocus systems. Solid lines, light paths; dotted lines, data paths. L, lens; B, camera body; V, viewfinder; F, dedicated flashgun; P, pentaprism; A, autofocus module; K, flash metering module; C, camera CPU; J, flashgun CPU; X, flash assembly; Y_1, supplementary flash; Y_2, LED projector for focus assist; E, projected deep red pattern; R, reflex mirror assembly; Z, film surface

hotshoe of the camera. Parallax errors arise for close-up work, where the integral photocell may not be pointing directly at the subject area. In such cases a fibre-optics light guide is useful to transmit light from the subject to the photocell.

An automatic flash unit usually has an integral calculator system and display which indicates a choice of one, two or more alternative apertures or a limited continuous variation of *f*-number. At the chosen aperture, the variable flash output then gives a range of subject distances over which correct exposure is possible. The user may choose either a large aperture to extend the range of subject distance or a small aperture in order to give maximum depth of field. With nearby subjects, a large aperture also means reduced flash recycling time and more flashes per set of batteries. Manual allowance has to be made for filter factors and for image magnification in close-up work. As well as a far limit, there is a near limit to subject distance; below this over-exposure results, as the flash cannot be quenched quickly enough. Automatic flash can be used successfully for synchro-sunlight by the subterfuge of either setting a film speed some four times greater than that in use, or using an aperture two stops more than actually set on the camera. Multiple-flash set-ups, each using thyristor control, are less easy to control for correct exposure.

Off-the-film (OTF) flash measurement

Most of the limitations of attachable automatic flashguns are avoided if *in-camera flash metering* is available. This operates by means of off-the-film (OTF) measurement of image luminance. The mon-

itoring photocell operates the quench circuit of a dedicated flashgun. A special lead is required for off-camera flash. Variables such as lens aperture, filters, magnification and lens transmittance are all allowed for, and indication is given if the controlled flash duration has given over or under-exposure, to allow manual correction for a repeat photograph. A simple table or indicator on the flashgun shows the useful subject distance range with the chosen aperture and film speed. In operation, a reflected-light measurement is made of the actual image on the film surface when the film gate is fully uncovered by the shutter at a fully synchronized setting. The metering pattern is usually of weighted form and asymmetrical due to the position of the photocell optics in the base or side of the camera dark chamber (Figure 19.18).

Figure 19.19 shows the integration of photocell arrays in the camera for autofocus, autofocus assist and flash metering. The difference in reflectance of the sensitive surfaces of different emulsions does not seem to be significant, with the exception of self-developing colour-reversal material which is exposed through its base plus integral filter mosaic and so presents a dark surface to the meter.

OTF systems in general give a high proportion of correct exposures, and are especially useful for photomacrography or the use of ring flash where the subject may be close to the lens, making conventional forms of exposure measurement difficult.

Large-format cameras can use a probe-mounted photocell located in the rear of the lens panel to measure the illuminance on the film surface during the flash exposure. An alternative related system is to position a probe in the film plane, then to fire a test flash at the subject; a readout of correctness of exposure at a chosen aperture will be given.

A *programmed automatic flash mode* is available in some cameras. In this system the shutter speed is fixed at the usual synchronization setting, and the camera sets the lens aperture to an appropriate value, which is obtained from the focused distance data and the flash guide number.

Matrix flash metering

This versatile system uses a form of scene classification using a segmented photocell array or *matrix* and a series of weak preflashes emitted in the time between the reflex mirror rising and the shutter opening. Using the lens focus data and the luminance of each segment of the scene compared with the theoretical value from the guide number, the most significant segment is chosen for the automatic flash output and then this is balanced to the ambient illumination from the main meter reading and the correct amount of fill-in flash emitted. This automatic fill-in feature is invaluable using a controlled flash mixed with ambient-light exposure, if scene contrast measurements by the matrix metering system indicate that it will be necessary. No complex calculations need be done by the user.

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