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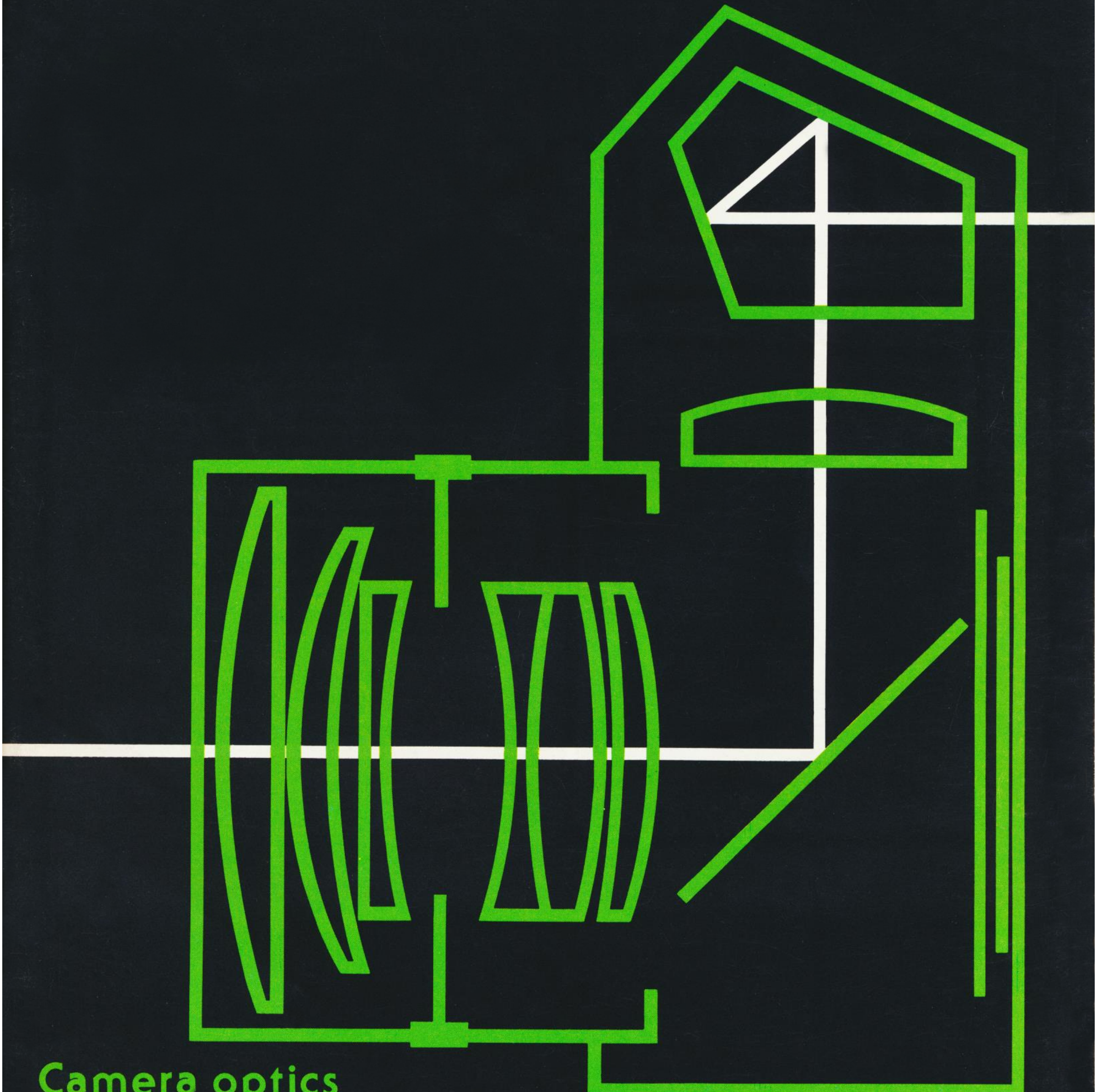

Camera optics

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ARTICLES

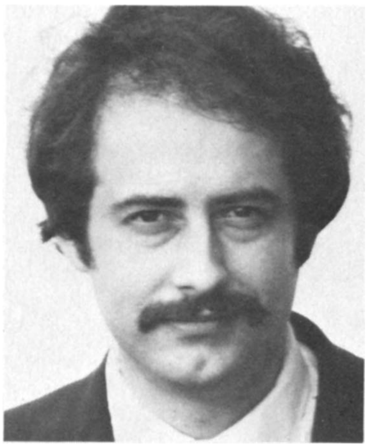
NOTES

COVER:
Adaptation of a design by Dean Hines, Director of Graphics and Publications, University of North Carolina, Asheville, North Carolina. See article on page 372.

Camera optics

MICHAEL J. RUIZ

The camera presents an excellent way to illustrate the principles of geometrical optics. This article discusses the basic camera optics of the single-lens reflex camera, the most popular camera of the professional and serious amateur photographer. The discussions below include coverage of many of the interchangeable lenses and accessories available to the owner of a modern single-lens reflex camera. Several camera experiments are described and the experimental results are compared with theoretical predictions or manufacturer specifications. Care is taken so that errors due to the thin lens approximation are eliminated in most instances. Therefore, agreement between experiment and theory is very good.



Michael J. Ruiz *(B.S. in physics from St. Joseph's College, Philadelphia, M.S. and Ph.D. in physics from the University of Maryland) is chairman of the Department of Physics at the University of North Carolina at Asheville. His doctoral thesis dealt with a relativistic quark model in theoretical elementary particle physics. Since then he has concentrated his efforts on the design of demonstrations for liberal arts courses in light and sound. His most recent work has included building and designing small electronic music synthesizers. (Department of Physics, University of North Carolina, Asheville, North Carolina 28814)*

The single-lens reflex camera

The major advantages of the single-lens reflex camera (often referred to as simply the SLR camera) are through-the-lens focusing and metering, and the capability of readily interchanging lenses. Through-the-lens focusing enables the photographer to see the scene as it will be captured on the film. There is no error due to parallax since the incoming light goes through the lens and forms an image on a ground glass plate for viewing (Fig. 1). However, the image viewed in this way may be cropped to some extent when compared to the final image captured by the film.

The lens is moved toward or away from the film in order to focus the subject. When the image is focused on the ground glass, the lens is at the proper distance from the film. A biprism or microprism in the center of the ground-glass focusing screen aids in determining when the image is sharp.[1] If the image doesn't fall on the ground-glass screen, the light rays are then refracted by the biprism or microprism, resulting in a grossly blurred image. The mirror in Fig. 1 flips up when the picture is taken and the shutter curtain moves away, exposing the film. After exposure, the mirror flips back down.

Figure 1 illustrates the major features of the SLR. Although there are about a half-dozen lens elements in the standard SLR camera lens, the group of elements acts as a *single lens*, typically with a focal length of 50 mm or 55 mm. The mirror, which reflects light to the ground-glass screen is called a *reflex* mirror (reflex is related to the word reflection). The pentaprism allows the viewer to observe images formed on the ground glass by a series of multiple reflections. These reflections are interesting since the final image viewed has the same orientation as the object to be photographed. An analysis of object and final image orientation is included in the section discussing the pentaprism.

The group of lens elements illustrated in Fig. 1 is replaced by one thin lens throughout this article. The reason for the multiple elements in camera lens design is to correct for aberrations.[2] Briefly, an aberration occurs when rays of light emanating from a point on the object do not come together in one place at the image after passing through the lens. A simple example of an aberration is chromatic aberration, where shorter wavelengths refract differently than longer wavelengths (dispersion). Chromatic aberration can be minimized by cementing a converging and diverging lens element (designed with different types of glass and outer curvatures) together. The combination is called an achromatic doublet; one can be found in Fig. 1. A six-element lens is the basic design for the modern SLR since such a design can keep aberrations to a tolerable minimum.[3]

A light-metering system (not shown in Fig. 1) measures light that travels through the lens (through-the-lens metering) giving very accurate exposure times. The exposure time varies with the aperture setting (controlled by the diaphragm). Smaller openings minimize aberrations and therefore increase the distance between the closest and farthest object that will be perceived by the eye to be in focus (the depth of field).[4] However, smaller openings require longer exposure times.

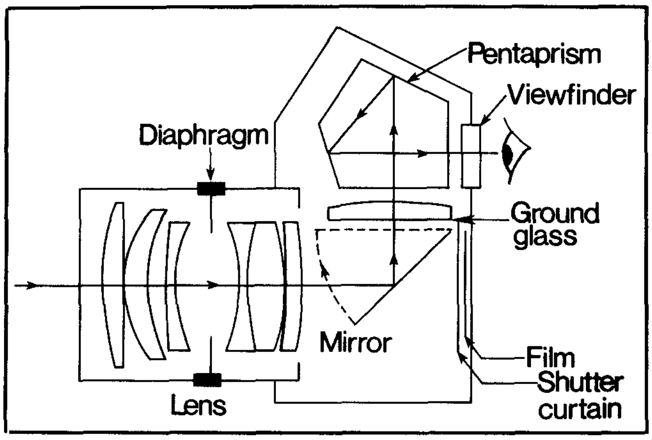


Fig. 1. Schematic diagram of the modern single-lens reflex camera.

The pentaprism

In Fig. 2 the lens elements are replaced by a single equivalent lens. Ray tracing is employed to determine the orientation of the image formed on the ground-glass focusing screen. Since the symmetry of Fig. 1 dictates that the image will be focused on the screen for the proper lens-to-film distance, only one ray is needed to locate an image point. It is simplest to consider a ray which travels through the left focal point of the lens. Such a ray refracts out parallel to the optic axis and reflects off the mirror as a vertical ray. Looking down from behind the reflex mirror in Fig. 2, the image on the screen is reversed from left to right.

The pentaprism reorients the image for viewing. A pure pentaprism (five plane surfaces along the five-sided perimeter) rotates an image[5] by 90°. Such a pentaprism does not correct the left-right reversal evident in Fig. 2. Therefore, for the camera pentaprism,[6] one of the top surfaces is replaced by a roof (two mirrors joined at 90°), giving the modified pentaprism a total of six plane surfaces along its five-sided perimeter. The roof and lower left side (Fig. 3) are mirrored. All surfaces, except the bottom

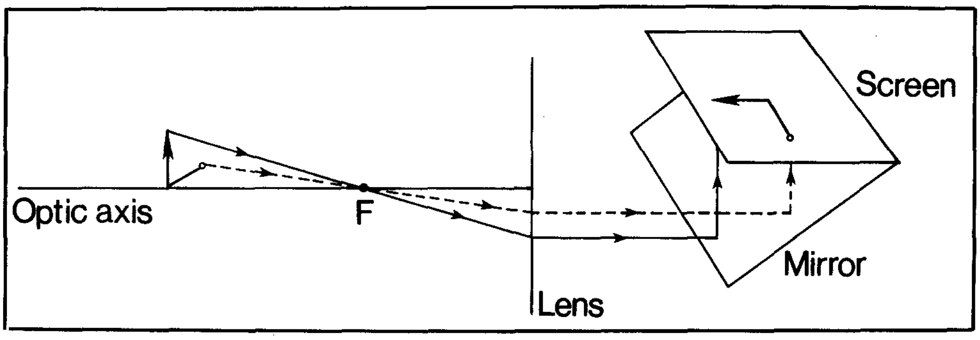


Fig. 2. Image formed on ground-glass focusing screen, after the light has passed through the lens and reflected off the reflex mirror.

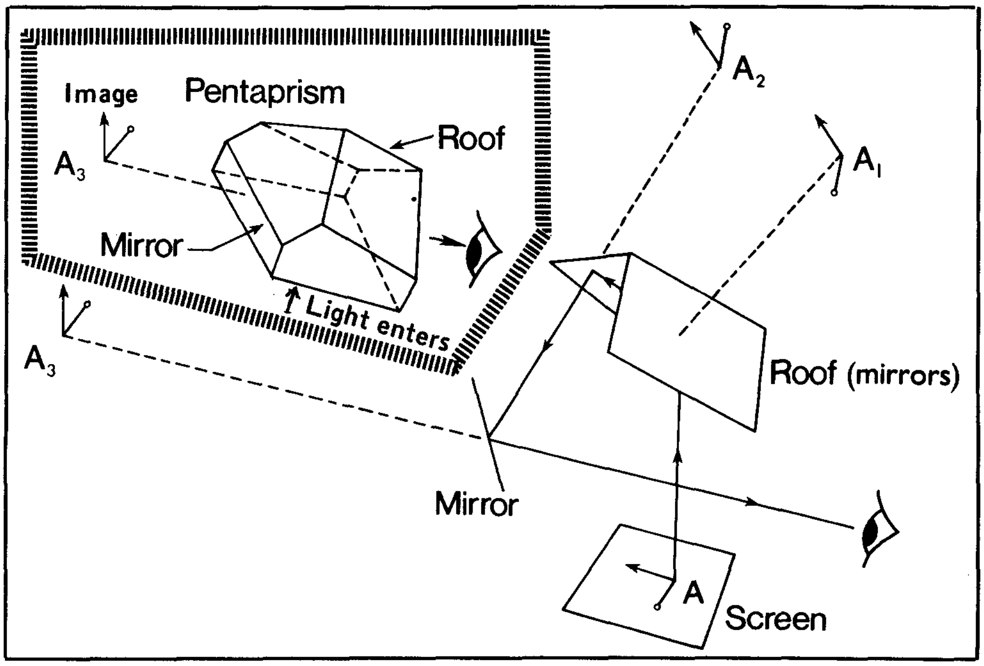


Fig. 3. Screen image A and mirrored surfaces of the pentaprism indicating three subsequent virtual images.
Inset: Pentaprism with observer viewing final virtual image.

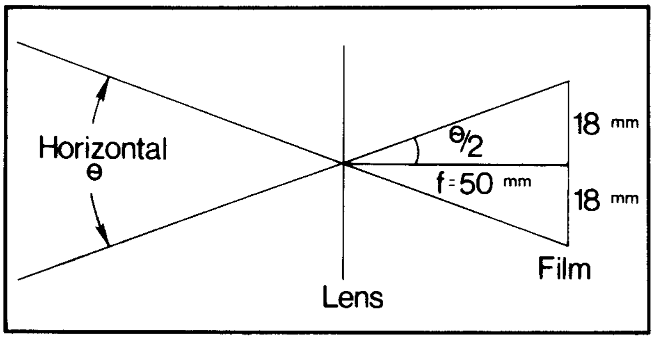


Fig. 4. Horizontal angle of view and its relationship to lens-to-film distance f (camera distance scale set at infinity) and film size.

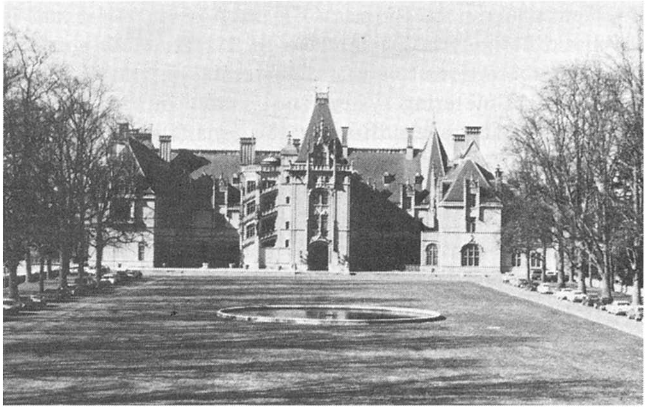


Fig. 5(a). Pentax f = 55-mm lens.

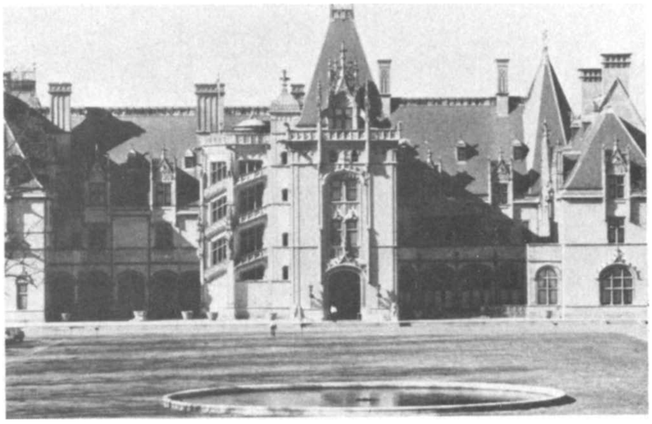


Fig. 5(b). Vivitar zoom lens set at f = 100 mm.

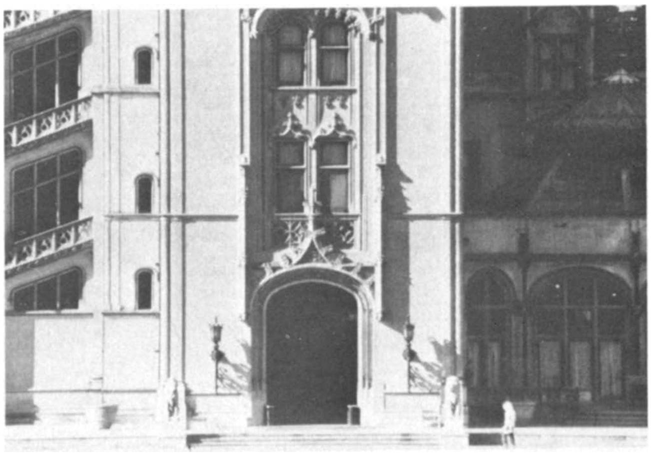


Fig. 5(c). Vivitar zoom lens set at f = 300 mm.

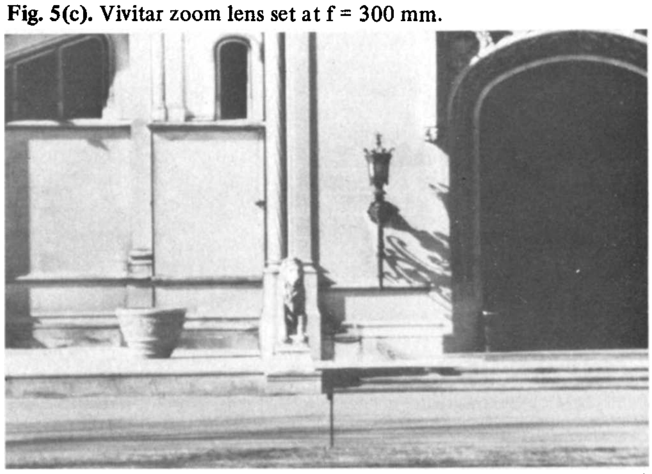


Fig. 5(d). Vivitar zoom lens set at f = 200 mm and a Soligor 3x teleconverter, resulting in a net focal length of 600 mm.

(through which light enters) and right (through which light exits), can be masked on the outside.

The roof preserves the left-to-right orientation after two reflections, i.e., image A_2, if viewed directly, has the same orientation as the screen object A (Fig. 3). This preservation of orientation can be experienced by looking into two mirrors joined by a 90° angle. When the observer blinks his right eye, the right eye of the image winks back. Students can use this method to discover how they look to others. The final reflection in the pentaprism reverses left to right in forming virtual image A_3. However, this image has the orientation of the original object in Fig. 2.

The viewfinder eyepiece is designed so that the final virtual image observed (A_3) appears life-size or nearly so. It is interesting to check this by simultaneously viewing an object directly with the left eye and through the viewfinder with the right eye. If the viewfinder image appears very close to life-size, the brain should be able to fuse the images with a little practice.

The standard camera lens

The standard lens for the SLR has a focal length of 50 mm or 55 mm. The film roll has a width of 35 mm; cameras which use 35-mm film are referred to as 35-mm cameras. However, the exposed area on the film is 36 mm by 24 mm for a single photograph. With the camera held in its usual position, a 50-mm focal length lens takes in a horizontal angle of view of about 40° for distant objects, which exposes across the 36-mm length of the film. This angle of view can be calculated from Fig. 4. Since the camera is focused on distant objects, the lens-to-film distance is virtually the focal length of the lens. The tangent of one half the angle of view is 18/50; therefore, the angle of view is $2 \tan^{-1}(18/50) = 40°$.

The angle of view listed for a lens is often given for the diagonal of the exposed area of film, i.e., 43 mm for an area of 36 mm x 24 mm. The (diagonal) angle of view for a 50-mm lens is $2 \tan^{-1}(21.5/50) = 46°$, omitting the decimal without rounding. Lenses with long focal lengths have small angles of view, e.g., a 300-mm lens has an angle of view of $2 \tan^{-1}(21.5/300) = 8°$. Such lenses are called telephoto lenses since they can focus a small portion of a distant scene (e.g., a bird in a tree) on a large portion of the 36 mm x 24 mm film area. See Fig. 5, four photographs of the Biltmore House, Asheville, North Carolina. Taking the pictures from the same position, the author used a

Pentax camera with different lenses. Note how the angle of view narrows as the focal length increases.

The distance between the lens and film (image distance s_i) is determined by the distance between the object (subject) and the lens (object distance s_o). These distances are related by the familiar formula

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} \tag{1}$$

where f is the focal length of the lens. The image is inverted and reversed left to right on the film with magnification

$$m = s_i/s_o \tag{2}$$

For a thick lens, Eqs. (1) and (2) are valid provided that s_o and s_i are measured from the first and second principal planes respectively.[7] Considering a 55-mm camera lens, the second principal plane is defined by the effective position of a 55-mm thin lens giving the equivalent refraction of parallel rays entering the front of the camera lens. The second principal plane is obviously 55 mm from the film for photographing distant objects. Since we are placing our thin lens at the second principal plane, our image distances s_i will be in accordance with thick-lens optics. Our object distances will be subject to error as our first principal plane (defined by the effective position of a 55-mm thin lens giving the equivalent refraction of parallel rays entering the rear of the camera lens) is unknown. This will induce some error in the following considerations of the focal length and near point of a camera lens. However, this presents no problem in the extension tube, close-up lens, and teleconverter experiments, where magnification factors are analyzed. The magnification factors can be calculated from s_i and f alone, using Eqs. (1) and (2). In this way the magnification factors have no error due to our thin-lens approximation.

In order to measure the focal length of a camera lens, place the camera on a tripod and open the back of the camera as if loading film. In place of the film, tape a 35-mm wide sheet of tracing paper across the film plane. Images can be viewed directly on the paper from the rear by using the shutter button lock to hold the reflex mirror up and the shutter open. It helps if bright objects are viewed and it is dim behind the camera. Focus on an object across the room and measure both the object and image sizes. From the magnification (s_i/s_o) and the subject-to-film distance ($s_o + s_i$), the focal length can be determined.

The focal length of a Pentax f = 55-mm lens was measured by the author in this way. A meter stick was placed on a windowsill 392 cm = $s_o + s_i$ from the film plane. The image size was carefully measured to be 14.5 mm, giving a magnification of 0.0145 = s_i/s_o. From this data, we have two equations with two unknowns, s_o and s_i. Solving, we find s_o = 3860 mm and s_i = 56 mm. Substituting these values into Eq. (1), we find f = 55 mm. There is no perceptible error since the object was sufficiently far from the lens so that error in taking s_o to be the distance between the object and second principal plane (thin-lens approximation) fell beyond the second significant figure.

In the preceding experiment, the image distance s_i = 56 mm corresponds to an object distance of about 4 m. By turning the lens barrel to focus on infinity the lens barrel can be observed (and measured) to move toward the film plane by 1 mm. The new image distance is the focal length (since s_o is infinity). This distance is 56 mm − 1 mm = 55 mm, in agreement with our measured value for the focal length.

By turning the lens barrel so that the lens can move away from the film plane, the camera focuses on closer objects. The closest point of focus can be determined from the maximum distance the lens can be moved from the film. Starting with the lens closest to the film and turning the lens barrel as much as possible, the lens is measured to move 9.3 mm (to an accuracy of about ± 0.2 mm) away from the film plane. With the lens farthest from the film, s_i = 55 mm + 9.3 mm = 64.3 mm. From Eq. (1) we find s_o = 380 mm, using f = 55 mm. Therefore, the film-to-subject distance is 380 mm + 64 mm = 44 cm. The manufacturer gives 45 cm as the minimum film-to-subject distance. The discrepancy is due to the thin-lens approximation. Since the object is fairly close to the lens, object distances measured from the second principal plane result in about 2% error. Direct measurement of the minimum film-to-object distance is possible by focusing on near objects through the viewfinder. However, there is an uncertainty of about 2% due to the depth of field (range of distances in tolerable focus simultaneously).

Extension tubes

Extension tubes (also called extension rings) are hollow cylindrical elements that can be placed between the lens and film, allowing the camera lens to focus on objects closer than the usual near point (45 cm in the previous example). These tubes can be used to photograph a variety of small objects such as stamps, insects, or flowers. A typical extension tube set contains three tubes. With the Pentax Extension Tube Set K, one receives three elements labeled 1, 2, and 3 with lengths 9.5 mm, 19 mm, and 28.5 mm respectively. These lengths can be checked by direct measurement.

The new near point with an extension ring in place can be calculated very easily. By way of example, consider extension ring 2. The image distance corresponding to the new near point is s_i = 64.3 mm (image distance without ring for near point of 45 cm) + 19 mm (extension) = 83.3 mm. From Eq. (1) we find the object distance to be s_o = 162 mm, corresponding to a new minimum film-to-subject distance of $s_o + s_i$ = 25 cm (thin-lens approximation).

It is more interesting to calculate magnification than film-to-subject distance since image sizes are close to object sizes with the extensions, making magnifications very meaningful. Also, the magnification calculation avoids errors due to the thin lens approximation, if we first use s_i and f to determine s_o, and then obtain the magnification from the ratio s_i/s_o. Using this procedure for ring 2, we find that the magnification m = 83.3/161.9 = 0.51.

The magnification can be measured by observing a sheet of graph paper (squares with 1-mm sides) through the viewfinder. The object (graph paper), is focused by moving the camera to or from the object since s_i (83.3 mm in the case for ring 2), must remain fixed. By counting the number of 1-mm squares visible from top to bottom, through the viewfinder, the magnification can be determined. It is best to place the graph paper on the surface of a table and use a tripod that allows close-up photographic work from above. Many tripods can be adapted to do this by inverting the central rod. For ring 2, 45 squares (a total of 45 mm) fill the vertical field of view, which corresponds to 24 mm at the film plane. Therefore, an object size of 45 mm corresponds to an image size of 24 mm, giving a magnification of 24/45 = 0.53. Unfortunately, the viewfinder usually crops some of the image, resulting in an apparent magnification which is slightly larger than the actual magnification. For the Pentax K camera, 95% of the vertical field of view is observed when looking through the viewfinder. Correcting for this, the actual magnification is (0.95)(24/45) = 0.51, in agreement with the calculated value.

In order to determine the correction factor due to viewfinder cropping, a calibration experiment must be performed. Set up the camera in the manner for determining the focal length described earlier. On a wall or flat surface (used as an object) place two pairs of points, one pair defining the extreme vertical points (top and bottom) visible through the viewfinder, the other pair defining the extreme vertical points visible on the tracing paper at the film plane. A lab partner can slowly move the tip of a pen at the wall while an observer from behind the camera calls out when the vertical limits are reached in each case. The correction factor is the ratio of the distance between the viewfinder limit points to the distance between the points marking the limits of the vertical field of view. For the Pentax K this ratio is 0.95. The value of the manufacturer for the diagonal viewfinder field of view is 93% of the film angle of view. This specification can be measured using the diagonal limits and is easily verified. The diagonal value of 0.93 is different from the vertical value of 0.95 because the cropping percentage is not the same for the vertical and horizontal fields of view.

In Table I are listed calculated and measured magnification factors along with values given by the manufacturer for the extension rings,[8] including combinations of rings connected in series. The calculated values are accurate to about 2% due to the uncertainty of ± 0.2 mm for the sliding distance 9.3 mm of the camera lens. An estimate of the experimental error for the measured values is about 1%, based on looking through the viewfinder, e.g., the 45-mm object size for ring 2 is actually 45 mm ± 0.5 mm. The overall agreement in Table I is very good.

For even greater magnifications, bellows can be used to achieve longer extensions. Also, adapters are available which allow the camera lens to be turned around, increasing lens-to-film distance to some extent. For magnifications greater than 1.0 it is advisable to reverse the lens in this way since image distances s_i begin to exceed object distances s_o. Reversing the lens insures that the longer optical path remains on the side of the lens intended by the designer (to keep aberrations at a minimum).

Table I

Magnification factors for extension rings

		Magnification Factors		
Rings	Extension (mm)	Theory	Experiment	Manufacturer[8]
None	0.0	0.17	0.17	0.17
1	9.5	0.34	0.34	0.34
2	19.0	0.51	0.51	0.51
3	28.5	0.69	0.68	0.68
1+3	38.0	0.86	0.84	0.84
2+3	47.5	1.03	1.02	1.01
1+2+3	57.0	1.21	1.20	1.18

Close-up lenses

Another way to increase the camera capabilities at close range is to attach a converging auxiliary lens to the primary camera lens. While extension tubes are satisfactory for much close-up photography, close-up lens attachments are often cheaper. However, greater magnifications can be achieved with the extension rings.

Vivitar makes a set of three converging thin lenses with diopter designations of 1, 2, and 4. The diopter value of a lens is $1/f$ where the focal length f is expressed in meters. The focal lengths of these thin lenses can be measured by the familiar burning-glass technique, i.e., focus parallel rays of light from the sun on a screen and measure the distance between the lens and the screen. If the image of the sun is too bright, distant clouds, buildings, or trees can be focused instead. The focal lengths corresponding to lenses 1, 2, and 4 (Vivitar set) are 1000 mm, 500 mm, and 250 mm respectively.

For maximum magnification, the camera lens is set at close focus so that the distance between the primary camera lens and the film is 55 mm + 9.3 mm = 64 mm. At this setting the Pentax K can focus without the close-up

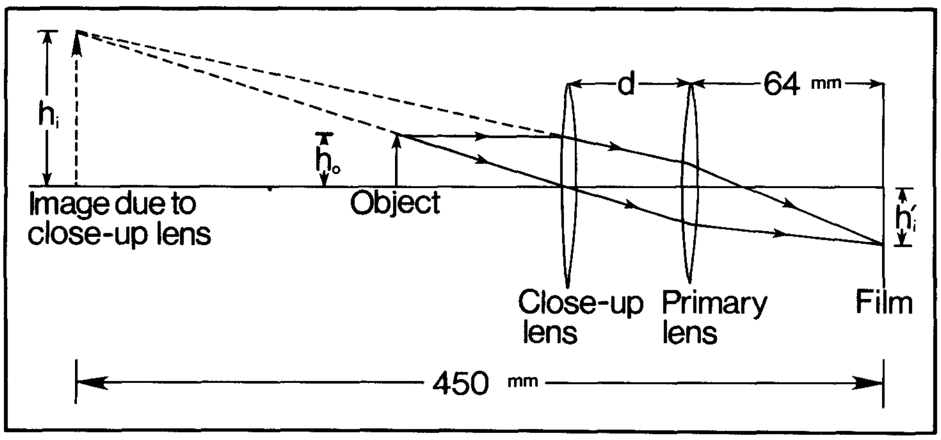


Fig. 6. Optical arrangement for close-up lens attachment to primary camera lens in order to shorten the near point of focus.

Table II

Magnification factors M for close-up lenses

Lenses	d(mm)	M_{th}	$0.95\ h_o$(mm)	M_{exp}
None	---	---	131	0.17
1	32	0.23	101	0.23
2	32	0.29	78	0.29
1+2	34	0.35	65	0.35
4	32	0.41	55	0.41
1+4	34	0.47	49	0.47
2+4	34	0.53	43	0.53
1+2+4	37	0.59	39	0.58

lenses on objects 450 mm from the film plane. The attached close-up lens allows objects to come closer as it can place an enlarged virtual image of the object at a distance of 450 mm from the film. When the auxiliary lens places a virtual image 450 mm from the film, the maximum magnification is reached (Fig. 6).

The magnification of the configuration in Fig. 6 is given by

$$M = m_1 m_2 \tag{3}$$

where m_1 and m_2 are the magnifications due to the close-up and primary lenses respectively. Since the image of the close-up lens, which acts as the object for the primary lens, is 450 mm from the film plane (the near point of the primary lens), $m_2 = 0.17$ from Table I.

The factor m_1 can be calculated from Eq. (2), where s_o and s_i are measured from the close-up lens. Since the image is 450 mm from the film, $s_i = -$ (450 mm $-$ 64 mm $-$ d), where the minus sign is inserted since the image is virtual and to the left of the close-up lens. The distance d is measured to be 32 mm when one close-up lens is attached. Therefore, for any of the close-up lenses used singly, $s_i = -354$ mm. The object distance is found readily from Eq. (1) using this image distance and the focal length of the close-up lens. For lens 2, f = 500 mm and we find s_o = 207 mm. This gives a magnification of $|s_i/s_o| = 354/207 = 1.71$ for m_1, taking the absolute value. Therefore, the total magnification $M = (1.71)(0.17) = 0.29$.

The calculated and experimental values for magnifications are reported in Table II. The experimental magnifications were measured directly by the method described in the previous section on extension tubes, i.e., by counting the number of 1-mm blocks visible through the viewfinder. Due to cropping, this value corresponds to 0.95 h_o. Since the total vertical field of view is considered, h'_i = 24 mm and the experimental magnification is h'_i/h_o. For lens 2, 0.95 h_o = 78 mm, which gives h_o = 82 mm and M_{exp} = 24/82 = 0.29.

The theoretical calculations for two or more close-up lenses used together involve approximating the combination as a thin lens with d measured from the center of the combination to the primary lens. When two thin lenses are placed together, the total diopter value is the sum of the diopter values for the individual lenses. This is a result of the familiar formula

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \tag{4}$$

which gives the total focal length for two thin lenses in contact. Therefore, for the combination 1 + 4, the total diopter value is 5, i.e., the total focal length f = 200 mm. Following the steps previously outlined for lens 2, we find s_i = $-$(450 mm $-$ 64 mm $-$ 34 mm) = -352 mm, s_o = 128 mm, and M_{th} = (352/128)(0.17) = 0.47. The error introduced by the thin lens approximation for combining two close-up lenses is less than 1%, for all three lenses, about 2%. This is estimated by comparison with the experimental results, where error is at the 1% level.

Attaching the three close-up lenses along with the three extension tubes enables the image of a penny (19-mm diam) to just fall within the horizontal field of view. The approximate magnification is s_i/s_o = 36/19 = 1.9, i.e., almost 2. Magnification is so great that the vertical field of view is not large enough to photograph the entire penny. This magnification is fully appreciated when a 36-mm x 24-mm slide of the penny is projected in a large room on a 2-m screen, giving a final magnification of about 100, i.e., 1.9 (2000/36).

Teleconverters and telephoto lenses

So far, we have considered accessories that increase the ability of the camera to magnify close objects. Now we consider a way to increase the magnification of distant objects. In order to magnify distant objects, the camera lens must have a narrow angle of view. In other words, the focal length must be long. A lens with a long focal length (greater than 100 mm) is called a telephoto lens. A relatively inexpensive way to convert a primary camera lens into a telephoto lens is to insert a teleconverter (also called a tele-extender) between the camera lens and film plane. The teleconverter is simply a cylindrical tube with a diverging lens.

Teleconverters are assigned multiplication factors, given as 2x or 3x, for example. This factor indicates what the primary lens must be multiplied by in order to obtain the new effective focal length. Using a 2x converter with a f = 55-mm camera lens results in an effective telephoto lens with a new focal length f' = 110 mm. This multiplicator factor is also the enhancement in magnification. Without the teleconverter, the magnification of distant objects is $m = f/s_o$ since s_i is essentially f. Magnification with the teleconverter is $M' = f'/s_o$. For a 2x converter $f' = 2f$ and therefore the magnification is doubled ($M' = 2m$).

The multiplication factor of a teleconverter can be measured directly by focusing on a distant object (a tree) and measuring images (on tracing paper) at the film plane, with and without the converter. The images formed with a 2x Komura and 3x Soligor teleconverter were found to be 14 mm and 21 mm respectively, while without the converter (f = 55-mm lens) the image was 7 mm. The windows of a neighbor's house (actually the distance between windows) served as a suitable distant object. Therefore, the 14-mm and 21-mm images imply that M'/m is 2 and 3 respectively, giving effective focal lengths of 110 mm and 165 mm respectively. This is in agreement with the specifications of the manufacturers.

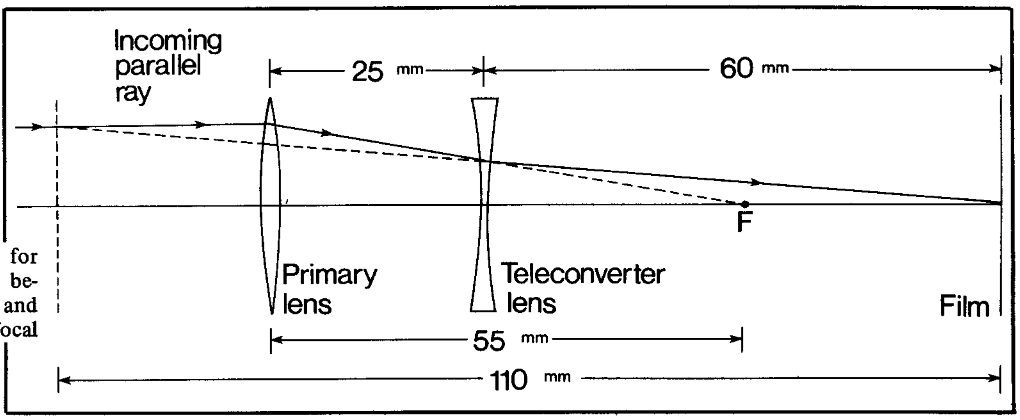


Fig. 7. Optical arrangement for insertion of teleconverter lens between the primary camera lens and film plane in order to increase focal length.

Figure 7 illustrates how the multiplication of a teleconverter can be calculated using graphical techniques. The diagram shows the parameters for the Komura 2x teleconverter. The essential feature used in determining the multiplication factor is the position of the converter along the optic axis. The Komura lens has seven elements designed closely together. Therefore, these elements can be treated together as a single thin lens. The distance between the center of the lens group (effective position of equivalent thin lens) and the primary lens is 25 mm (primary lens distance scale set at infinity). The distance between the converter lens and the film plane is 60 mm.

An incoming parallel ray of light hits the primary camera lens (f = 55 mm). The light ray refracts, heading toward the focal point of the camera lens, 55 mm away. The diverging converter lens intercepts the ray before it can reach the focal point of the primary lens. Refraction occurs at the second lens so that the final outgoing ray meets the optic axis at the film plane. The point of intersection of the incoming ray and the final ray extended backward gives the position where one lens should be located to replace the compound lens system, i.e., one refraction at this point results in the correct slope for the outgoing ray that finally hits the film in the two-lens system.[9] The equivalent focal length is the distance from the intersection to the film plane, in this case, 110 mm. Therefore, the multiplication factor for the Komura is 110/55 = 2. The factor for the Soligor can also be found in this way as long as the optical diagram is carefully drawn to scale. For the Soligor, the primary lens-to-converter distance is 32.5 mm and the converter lens-to-film distance is 67.5 mm. The equivalent focal length is found to be 165 mm, corresponding to a multiplication factor of 3.

The major disadvantage of teleconverters is the loss of light that results due to the magnification. Also, it is possible that aberrations might be noticeable with some of the very inexpensive teleconverters. However, optically matched teleconverters (also called matched multipliers) are available which are designed for specific primary lenses in order to maintain high optical quality. If one is not available for a particular camera lens, a seven-element converter lens, like the Komura, can produce fine photographic results.

A telephoto lens has basically the design illustrated in Fig. 7. However, the lens system is purchased as a unit and is attached to the camera in place of the primary camera lens. The converging-diverging system shortens the length of the telephoto lens, maintaining a long equivalent focal length at the same time. Such a lens can be designed to allow more light to enter and carefully eliminate noticeable aberrations. The telephoto lens is therefore better than a teleconverter; however, it is considerably more expensive.

Wide-angle lenses

Wide-angle lenses are lenses which have large (wide) angles of view. For example, a typical wide-angle lens with a focal length of 24 mm has an angle of view of $2\tan^{-1}(21.5/24) = 84^\circ$. These lenses are convenient when a photographer desires to capture very much of his scene. A group of people sitting in a family room might subtend a large angle, requiring a wide-angle lens to include the entire group in the photograph.

A single converging lens with a short focal length is not suitable in the design of a wide-angle lens (even without

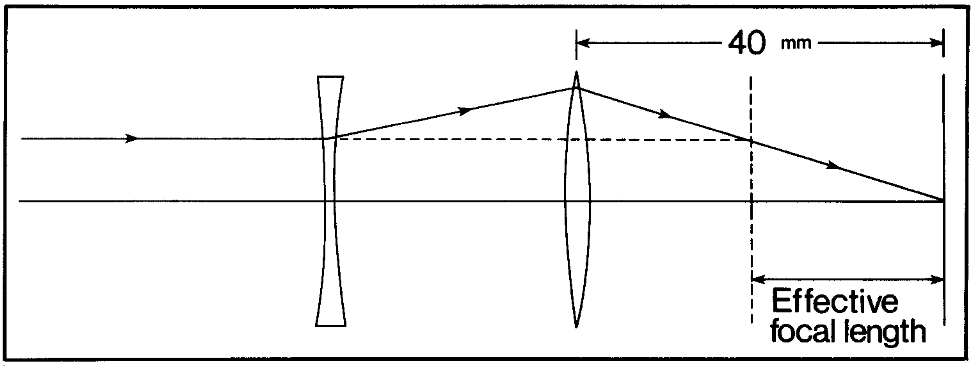


Fig. 8. Optical arrangement for diverging and converging lenses in order to achieve a short focal length and maintain enough room for the reflex mirror.

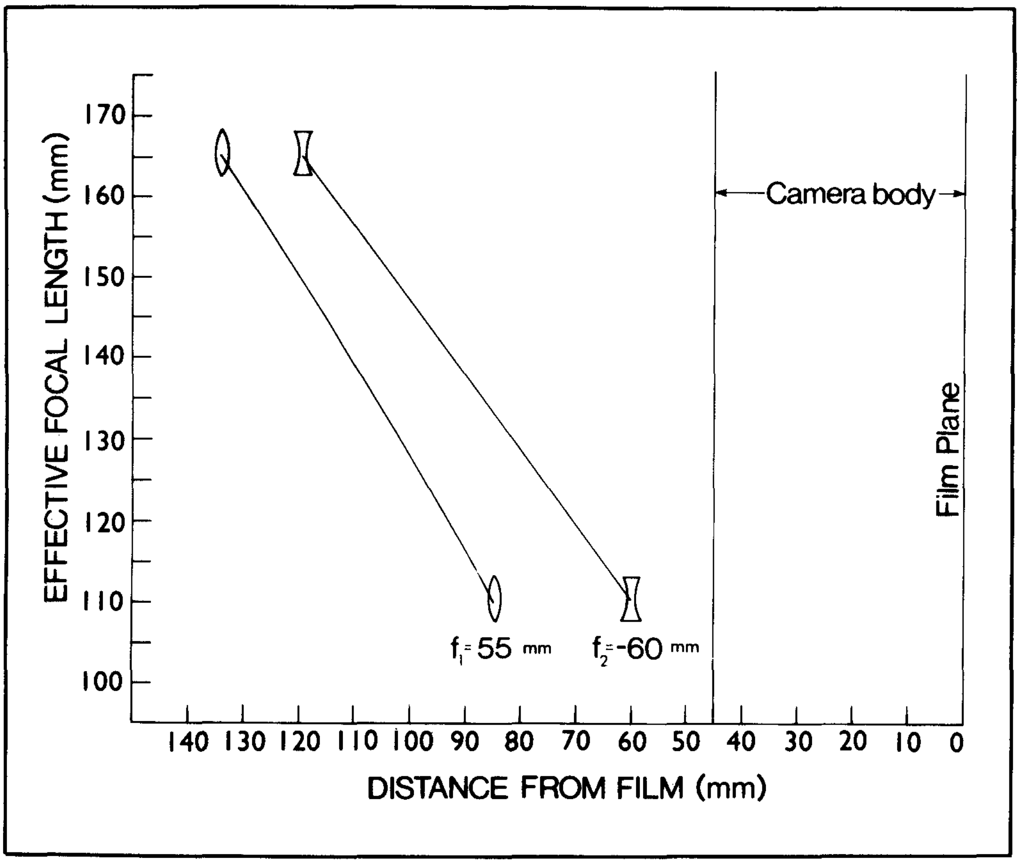


Fig. 9. A two-component zoom lens with focal length range 110-165 mm.

consideration of aberrations). The reason is simple. The reflex mirror needs about 40 mm in front of the film plane in order to swing up during exposures. The lens cannot sit as close as 24 mm from the film, which would be necessary for shooting distant subjects with a single converging lens with f = 24 mm.

A diverging-converging lens combination can be used to solve this problem. Figure 8 illustrates how such a combination acts as a wide-angle lens. The placement of the converging and diverging lens is in reverse order when compared to the telephoto configuration of Fig. 7. The arrangement in Fig. 8 is called inverted telephoto or retrofocus. The lens closer to the film is at least 40 mm away from the film plane; yet, the effective focal length is considerably shorter.

Wide-angle lenses are available with focal lengths as short as 7.5 mm (fish-eye lens). However, when the focal length is very small, e.g., 17 mm or less, there is considerable distortion. In such instances, the simple trigonometric formula using the arctangent cannot be employed to calculate the angle of view. A compressed circular image, similar to what a fish would see looking up from beneath water, with nearly 180° angle of view is possible with lenses of very short focal lengths.

Zoom lenses

Lenses are available for the SLR which have variable focal lengths. These lenses are called zoom lenses. The focal length range varies from one zoom to another. A telephoto zoom might have a range of 85-210 mm, while a wide-angle to moderate telephoto zoom might have a range of 35-100 mm. The author's Vivitar zoom has a range of 100-300 mm.

The zoom lens allows the photographer to vary the angle of view without changing lenses. A telephoto zoom is ideal at the zoo for taking pictures of distant animals. By adjusting for the desired angle of view, i.e., choosing a particular focal length within the range of the zoom, nice portraits of distant subjects are possible. The mechanics of zoom lenses is complicated. In this section, we will limit discussion to one very simple workable lens design.

A simple telephoto zoom lens is illustrated in Fig. 9. Here, we have simply used the telephoto design with a converging lens (f_1 = 55 mm) and a diverging lens (f_2 = −60 mm, focal length of the Komura 2x converter). By varying both lens positions, a range of focal lengths is possible. Note that for an effective focal length of 110 mm, the separation distance between the lenses is 25 mm and the distance between the diverging lens and the film is 60 mm (compare with Fig. 7). At the other extreme, the effective focal length is 165 mm, giving a 110-165-mm zoom.

However, the simple zoom design of Fig. 9 is not practical since aberrations cannot be corrected by multiple lens elements. The corrections achieved by introducing multiple lenses hold only over small movements of the elements. A design is needed that reduces the movement evident in Fig. 9. One such design introduces a third lens.

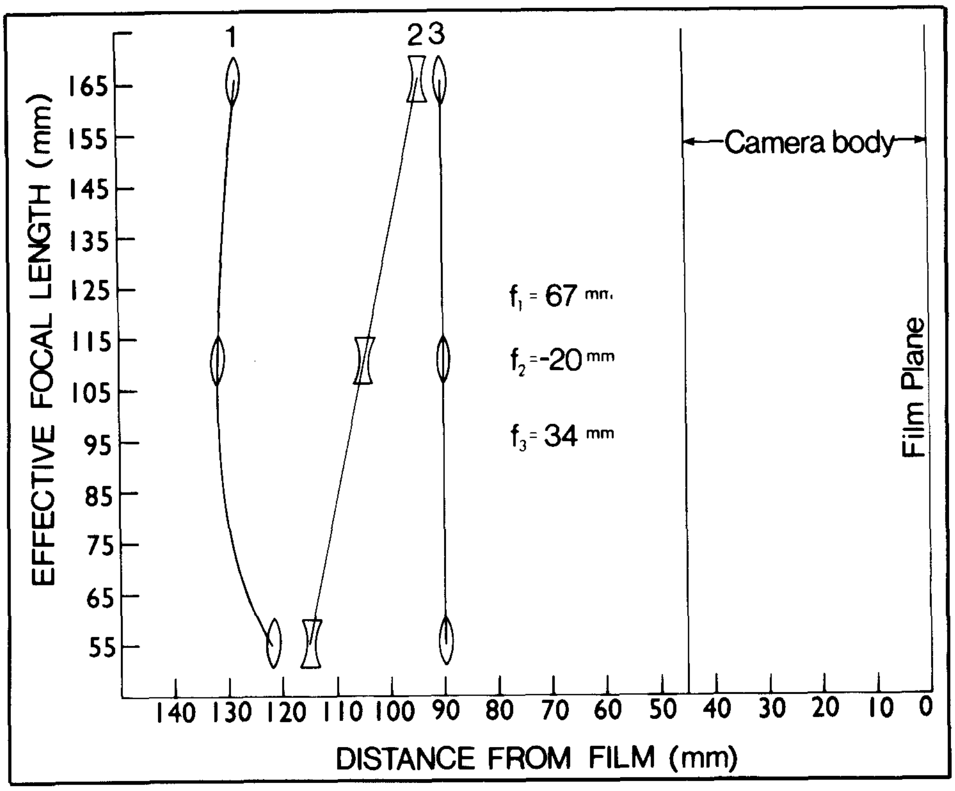


Fig. 10. A three-component zoom lens with focal length range 55-165 mm.

Figure 10 illustrates a three-component zoom, which has the advantage of much less lens movement when compared to the two-component zoom of Fig. 9.

The focal lengths of the three lenses in Fig. 10 are 67 mm, −20 mm, and 34 mm for f_1, f_2, and f_3 respectively. Lens 3 is kept fixed at 90 mm from the film and for our discussion it is assumed that distant objects are being photographed. Lens 2 slides a mere 20 mm as lens 1 moves out slightly and then back toward the film plane. This is considerably less than the 50 mm (85 mm to 135 mm) and 60 mm (60 mm to 120 mm) for lens 1 and lens 2 respectively in the two-component lens design of Fig. 9. Furthermore, the less movement in Fig. 10 achieves a much greater zoom range, 55-165 mm.

The zoom lens design described in Fig. 10 is referred to as mechanical compensation.[10] As the middle lens changes its position, the effective focal length changes with the first lens moving to compensate for an otherwise shift in the position of the final image. The diverging lens acts at unit magnification in its midposition and the focal length f_2 is related to the sliding distance d (of lens 2) and the ratio of the maximum to minimum focal lengths R realized at the end points. The formula relating these parameters is

$$f_2 = -\frac{(R+1)\,d}{(R-1)\,2} \qquad (5)$$

The sliding distance in Fig. 10 is 20 mm and $R = 165/55 = 3$. Therefore, $f_2 = -(4/2)(20\text{ mm}/2) = -20$ mm. The focal lengths f_1 and f_3 are related to the actual minimum and maximum effective focal lengths. Equation (5) appears innocent, but requires considerable amount of algebra to derive. Dozens of zoom-lens designs can be found in Ref. 11.

Since there is always additional movement in a zoom lens, the correction for aberrations cannot be minimized as well as for fixed focal length lenses. Fanatic photographers might buy three or four lenses (e.g., 100 mm, 135 mm, 200 mm, and 300 mm) rather than purchase a 100-300 mm zoom for this reason. However, unless you are interested in enlargements of slides or photographs, the modern zoom lens performs quite well and is considerably cheaper than purchasing several fixed focal length lenses.

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9. The author learned this clever trick (as a graduate teaching assistant) from Dave Falk, who assigned the problem depicted in Fig. 7 as a homework problem in "Light, Perception, Photography, and Visual Phenomena," a very popular optics course for nonscience majors developed at the University of Maryland, College Park, Maryland.
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