SPECIALIZED
TELEVISION ENGINEERING

TELEVISION TECHNICAL ASSIGNMENT

PRINCIPLES OF OPTICS

712D

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FOREWORD

When one speaks of television, there immediately comes to mind a huge collection of electronic equipment, with tubes and coils and condensers liberally covering each piece of gear. Yet all of this electrical paraphenalia would be useless without the few pieces of optical equipment that are located at strategic points in the assembly.

The camera requires a lens before any image can be scanned; there must be a lens in the motion picture and in the still projector to form an optical image too; and the receiver, if it is to form a large screen picture, must have an optical system to perform this important function.

It is therefore necessary for the television engineer to have at least a practical working knowledge of optics and optical apparatus. No attempt is made in this assignment to teach lens designing, but the information to be found in it will enable the engineer not only to appreciate how remarkable an achievement the modern fast lens is, but also how to employ it successfully in the tasks demanded of it by television.

The average person knows very little concerning optical instruments; he accepts and uses spectacles, range finders, microscopes, telescopes, projectors, etc., but seldom bothers to find out the underlying principles upon which they operate. Yet these principles are by no means difficult, and in view of the importance of the instruments based on these principles, there is really no excuse for ignorance on so important a subject.

The lens in particular appears to have been known to the ancient Chaldeans 3,000 years ago, as is attested by the finding of a convex quartz lens in the ruins of Ninevah, as well as tablets with inscriptions on them too small to be read by the naked eye. The Greeks knew of the burning glass, but apparently not of the laws of refraction.

It was not until the wave theory of light became generally accepted, and the theoretical groundwork was developed, that optical instruments of great power and precision began to appear. Today's fast lens represents a triumph in many fields: in optics, where the principles are ingeniously employed in the design of the lens; in chemistry, where new types of glass were developed that permit more corrections to be applied to the earlier, cruder lenses; and even in the art of fabrication, where precision methods of production were developed whose accuracy probably exceeds that of any other process.

The information contained in this assignment will serve to give the television engineer a better knowledge how to use lenses, and will lay the groundwork for the discussion of specific optical systems to be found in subsequent assignments. This assignment is therefore an important one; study it carefully so as to be sure to master its contents.

E. H. Rietzke,
President.

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TELEVISION TECHNICAL ASSIGNMENT

PRINCIPLES OF OPTICS

GEOMETRICAL OPTICS

PROPAGATION OF LIGHT.—**Although** light is a wave motion of electromagnetic nature, the study of optics can be based upon the principles of ordinary geometry, rather than upon the advanced mathematical methods required by a wave concept. The simplified study is known as geometrical optics.

In geometrical optics light is assumed to travel in straight lines, or rays, and shadows are cast if these rays are intercepted by an obstacle. In an earlier assignment it was stated that owing to the wave nature of light, there was some spreading of the light around the obstacle, or diverging of the light passing through a fine opening, owing to a property known as diffraction. However, this is appreciable only in the case of very fine apertures or very small obstacles that are of the order of magnitude of the wavelength of the light, and for most ordinary purposes the straight-line or rectilinear propagation of light can be assumed.

VELOCITY OF PROPAGATION.—The velocity of light was first determined from astronomical observations on the heavenly bodies; later it was determined experimentally on the earth. The speed was found to be very high: 186,000 miles/sec., or 3×10^8 meters/sec. For most practical problems on the earth the light may be assumed to reach the point of pickup instantly, although in some special applications, such as the interferometer, the operation depends upon the finite velocity of the light. It is an interesting note that according to Einstein's Special Relativity theory, no body can exceed light in velocity; as the velocity of the body approaches that of light, its mass increases without limit, thereby preventing any finite force from accelerating it appreciably to a higher velocity than that of light.

Point Source.—A favorite source of light for the purpose of analysis is the point source. This is one whose emitting area is exceedingly small compared to the distances from it at which the light is utilized. Examples of point sources are concentrated beam headlight lamps, an arc light utilizing the light mainly from the incandescent electrode, a recent development by the Western Union Company in the form of a tiny arc developed in a special electron tube, and—strange as it may seem—the sun. While the latter is a huge ball of fire, at a distance of 93,000,000 miles, where the earth is located, the sun may be considered for many applications as a point source.

RAYS OF LIGHT.—Consider a point source emitting light uniformly in all directions. As shown in Fig. 1, an observer E_1 will receive energy from the source S along SE_1; another observer at E_2 will receive energy along SE_2, and so on. Actually S radiates energy in the form of waves uniformly throughout all space. As a wave expands outward, all parts of it contribute energy to all farther points such as E_1 and E_2, but the net effect is as if the energy that reaches E_1 came solely along the line SE_1, and that reaching E_2 came solely along SE_2. The reason for this is interference between the different contributions, but all that need be remembered is the net effect mentioned above.

Because of this fact, geometric optics can ignore the wave motion concept, and assume light travels along straight lines, as mentioned previously. These lines are called *rays;* two such rays in Fig. 1 are

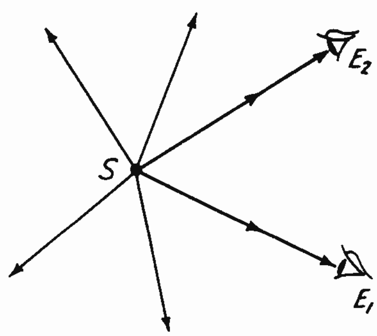


Fig. 1.--Rays of light produced by a point source S.

SE_1 and SE_2. Light optics is concerned with the modification in the intensity and direction of such rays, as produced by reflection, refraction, absorption, and transmission, and these matters will now be taken up in detail.

ABSORPTION, REFLECTION, AND TRANSMISSION OF LIGHT.—Light can travel through free space, just like radio waves (of which it is the high-frequency counterpart). In free space it travels unhampered; its energy content is not absorbed at any point and converted into another form of energy—usually heat. Light, however, can travel through many material substances, notably glass and quartz. Such substances that transmit light are said to be *transparent* or *translucent* depending upon the nature of the transmission. As another example, ordinary air transmits light very well; for ordinary distances it is practically as good as a vacuum (free space).

Clerk Maxwell, the renowned English physicist, has shown that in general electrical insulators transmit light, and electrical conductors absorb or reflect light. However, if there are conducting particles, such as carbon black, embedded in the insulator, or irregularities in its internal structure, then the transmission will be practically negligible, as in the case of a sheet of black bakelite which is a good insulator. On the other hand, if a conductor is sufficiently thin, then considerable light transmission will occur. This phenomenon is utilized in the construction of very thin and essentially transparent photoelectric surfaces composed of certain metals. Such a surface, for example, is to be found in the new image orthicon, a radically new pickup tube employed in the television camera.

The above points to the fact that light, in travelling through material substances, is not transmitted perfectly, but is absorbed to a certain extent by the material; i.e., its energy is converted into another form of energy, such as heat, and therefore lost as light energy. Absorption and transmission are on a percentage basis: if the first inch of the material absorbs 5 per cent of the light, and therefore transmits 95 per cent of the light, then the next inch will transmit 95 per cent of the energy coming through the first inch, or $.95 \times .95 = .903$ or 90.3 per cent of the initial energy, and so on.

This relationship gives rise to what is known as an exponential law of decay for the transmission, as illustrated in Fig. 2. Although

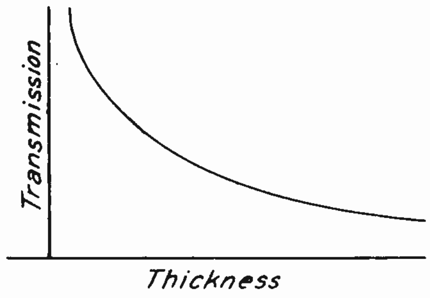


Fig. 2.--Exponential law of decay in the transmission of light in an absorbing medium.

the transmission ceases dropping rapidly after some thickness of the material has been traversed, the reduction can be so high in a specimen as to constitute negligible transmission after a small thickness. An example is the black portion of a photographic film; absorption here is due to tiny silver particles in the gelatin emulsion, and although the film is very thin, very little light may come through.

Transparent and Translucent Media.—A substance that transmits a large fraction of the light through a reasonable thickness of the material, such as glass or lucite, is said to be either transparent or translucent. The terms refer not to the degree of absorption, but rather to the method of transmission.

Suppose a point source S, Fig. 3 (A) sends rays of light through the substance, and suppose these rays come through into the air on the other side without any marked change in direction. The substance is then said to be *transparent*, even if it absorbs some of the energy and thereby cuts down somewhat the intensity of the transmitted rays. The reason is that aside from a (usually moderate) decrease in intensity, the rays coming

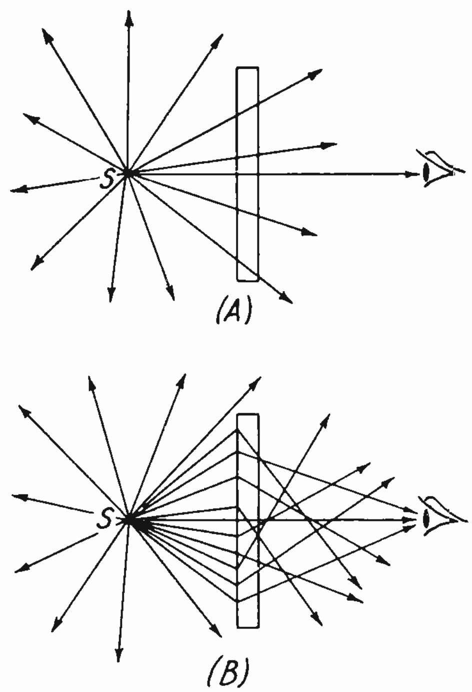


Fig. 3.--Examples of transparent and translucent substances.

through have the same direction as if the substance were not there, and an eye located at the right would see the source S and locate it properly in either case. Such transmission is sometimes referred to as *specular* transmission.

On the other hand, the substance may transmit the light, but so redirect the rays as to have them come out at all conceivable angles. This is shown in Fig. 3 (B). An eye located at the right of the substance will intercept rays from *all parts* of the substance, and as a result will not be able to locate the source. Instead, the surface of the transmitting object will be seen *as if it were the source of light;* and it is often denoted as a secondary source of light.

The material in this case is said to be *translucent* because it has broken up and redirected the ray paths. Note that the translucent substance may actually absorb less and hence transmit more light than the transparent substance; the criterion is not excellence of transmission, but *uniformity* of transmission. Translucent transmission is sometimes referred to as *diffuse* transmission.

Ordinary translucent materials are generally transparent materials whose one or both surfaces have been roughened to upset the uniformity of transmission. A good example is a ground glass sheet. The rough surface redirects or scatters the light rays by refraction, but since refraction will be discussed farther on in this assignment, no further mention will be made at this point.

Transparent substances are important for windows, etc., where the sources of light are desired to be seen, and the transparent material is present solely to afford mechanical separation between the sources and the observer. This application is too well-known to require further discussion. Translucent substances are employed as motion picture screens where rear projection is used, and in television projection receivers. The action as a screen must be deferred until the image-forming properties of lenses have been taken up.

Another application of a translucent substance is the frost glass coating of an incandescent light. The latter has a very bright filament of small area as its source of light. Such a small area source approximates a point or at least a line source of light and is very bright, thus producing glare and eye strain. By frosting the bulb, the rays coming through the bulb from the filament are so scattered as to make the bulb appear as the source of light rather than the filament, see Fig. 4. In this way a larger

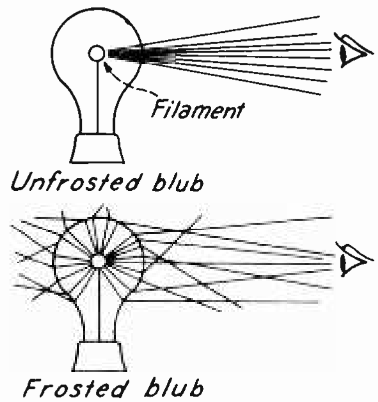


Fig. 4.--Action of an unfrosted and frosted bulb on the eye.

area seems to produce practically the same amount of total light, so that this secondary source does not appear to be as bright and glaring.

The fluorescent light is even better in this respect; the same amount of light energy is emitted by such a large cylindrical area that the brightness and glare is reduced to a very small extent. Such a source can be viewed with comparative comfort.

However, in many optical applications a point source of light is required, as in the case of a motion picture projector, search light, etc., because its rays are easier to direct or concentrate into a beam of narrow cross section. In this case a transparent rather than a translucent cover or envelope is indicated.

REFLECTION.—Reflection occurs when light energy impinging upon the surface of a material is thrown back toward the source. It thus prevents transmission through the material, but differs from absorption in that the energy remains intact in the form of light, rather than being converted to some other form of energy such as heat. Like transmission, reflection can be specular

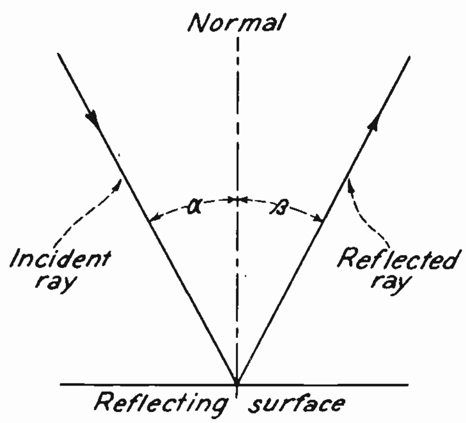


Fig. 5.--Relation between an incident and reflected ray.

or diffuse. These terms are employed more often with respect to reflection, and transparent and translucent with respect to transmission.

In order to understand either type of reflection, it is necessary to discuss the basic laws of reflection, which hold in either case. These laws are very simple. Consider a perfectly smooth plane surface, as shown in Fig. 5, that reflects light. Consider further a ray of light approaching it obliquely from the left (incident ray). Upon meeting the surface, it is reflected (reflected ray) and goes off obliquely to the right, as shown.

The basic laws have to do with the relation between the angle of approach and the angle after reflection. These angles could be measured with respect to the surface; it is more convenient to measure them with respect to the normal to the surface. This is a line perpendicular to the reflecting surface.

Suppose, as shown in Fig. 5, the reflecting surface is perpendicular to the page, so that the normal lies in the plane of the page. Suppose further that the incident ray lies also in the plane of the page. Then the first basic law is that the reflected ray *will also lie in the plane of the paper.* Stated more generally, this is: *LAW I:* The reflected ray lies in the plane determined by the incident ray and the normal to the surface at the point of contact.

The second law is equally simple. This has to do with the angle of incidence α, in Fig. 5, and the angle of reflection, β. The relation is that the two angles are equal, or stated more generally: *LAW II:* The angle of incidence equals the angle of reflection.

From these two laws all problems in reflection can be solved, although in any specific case certain short cuts may facilitate the work. It will now be of interest to see how these relations give rise to specular and diffuse reflection, depending upon the uniformity of the reflecting surface.

SPECULAR REFLECTION.—Consider once again a perfectly smooth reflecting plane surface, and a point source very far away from it.

While the waves diverge radially from the source, as has been indicated in Fig. 1, at any great distance from the source a small pencil of these rays will consist of rays that are nearly parallel. Hence the reflecting surface, if of moderate size, will intercept rays that are all practically parallel. This is illustrated in Fig. 6. The parallel incident rays

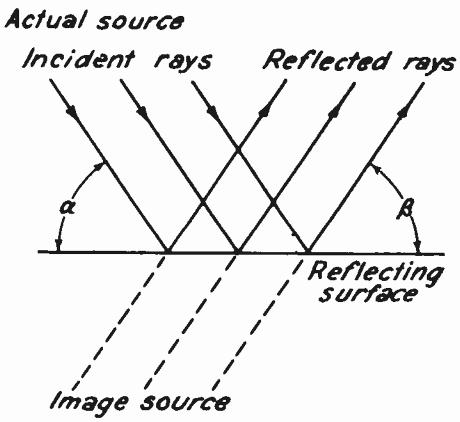


Fig. 6.--Reflection of parallel rays and resulting image source.

make a common angle α with the reflecting surface. Upon reflection *from the plane surface* they make the common angle β *which is equal* to α, hence they are parallel too. An observer intercepting these parallel reflected rays interprets them in the same way that he would interpret the incident parallel rays, i.e., as coming from a point source infinitely far away.

As indicated in Fig. 6, the apparent source of the reflected rays, or *image* source, as it is called, appears to be *below* the reflecting surface. Indeed, it is as far below the surface as the actual source is above it, and just as far to the left of the reflector; in short, the image appears to be directly below the object or actual source.

Thus, a smooth flat reflecting surface produces an image of an object placed in front of it. This is further illustrated by the arrow and its image in Fig. 7. The

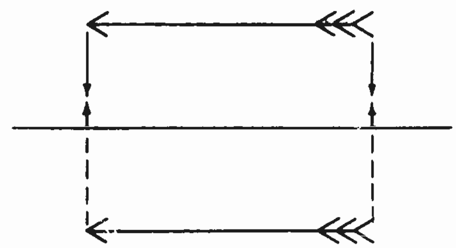


Fig. 7.--Arrow and its image formed by a plane mirror.

question of image formation of an extended object, like the arrow, will be taken up in greater detail subsequently; at this point it will be merely noted that the image appears as far behind the reflecting surface as the object is in front of it. It appears to have the same size as the object, but is reversed in the same sense as the right and left hands.

The flat smooth surface that produces these images is said to be a specular reflector, because the reflected rays have the same relationship to one another that the incident rays have; i.e., they are parallel if the incident rays are parallel. A common everyday term for a specular reflector is *mirror;* a mirror produces images of objects placed in front of it.

To illustrate further specular or mirror-like reflection, consider the smooth, concave, spherical reflecting surface shown in Fig. 8. Once again the incident rays are assumed parallel, and are presumably produced by a point source infinitely far away. Now, owing to the curvature of the reflecting surface, the reflected rays are no longer parallel to one another, but cross one another at a so-called focal point S'.

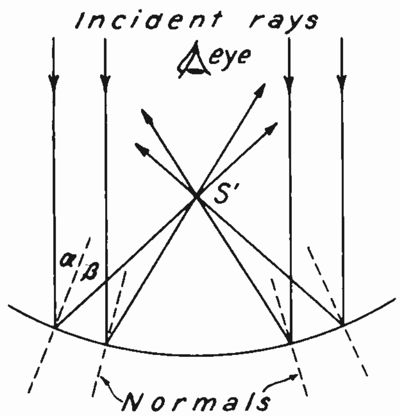


Fig. 8.—Reflection of parallel rays by a concave spherical surface.

An eye, situated as shown, would pick up these reflected rays, and interpret them as coming from point S'. Thus the eye would see a point source at S'; this would be the image of the actual point source infinitely far away. In this particular case the rays actually cross at S', hence this image is known as a *real* image, because rays actually emanate from it.

In Fig. 6, the reflected rays merely appear to emanate from a point source infinitely far away and below the mirror; such an image is known as a *virtual* image. Ordinary plane mirrors produce virtual images; the concave spherical mirror produces a real image. (More will be said about real and virtual images in the discussions of lenses).

An important point to bring out here is that even though the reflected rays in Fig. 8 are not parallel to one another, as are the incident rays, nevertheless the reflecting surface is considered to be specular. This is because the reflected rays have a definite pattern: They all cross at one point S'. Hence, as long as the reflecting surface does not break up the incident rays into a random set of reflected rays, the reflection is considered specular in nature. This will be clearer when diffuse reflection is taken up in the next section.

Diffuse Reflection.—The above specular surfaces were smooth, so that the direction of the normal from one point to the next changed slowly and uniformly, as in the case of the spherical surface, or did not change direction at all, as in the case of the plane surface. Most ordinary reflecting surfaces, however, are not so smooth and uniform, and have ridges and valleys crossing one another in all sorts of random directions. While at any point the angle of reflection equals the angle of incidence, the angles vary so abruptly from one point to the next that the reflected rays are scattered in all directions even though the incident rays may have a definite pattern.

The situation is exactly analogous to that of diffuse or translucent transmission. It is illustrated in Fig. 9. A set of parallel incident rays are assumed. Each ray meets a portion of the diffusely reflecting surface where the normal, shown in dotted lines, has a direction different from that of adjacent portions of the surface. Hence the angle of incidence differs in a random manner from one ray to the next; as a result the reflected rays are reflected in an entirely random manner. It is practically impossible to define any pattern

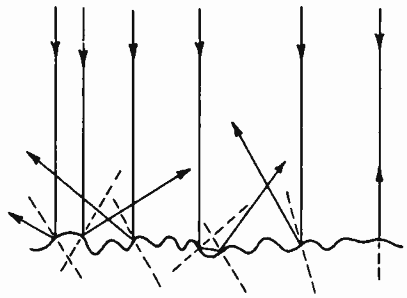


Fig. 9.—Example of diffuse reflection of a set of parallel incident rays.

for these, and so it has been found simpler to regard each small area of the survace as the source of a pencil of rays; i.e., each small area of the surface may be regarded as a secondary point source of (reflected) light.

This is indicated in Fig. 10. For clarity, only three points or small areas of the surface are shown, namely, A,B, and C. The incident rays are shown parallel; actually, it is immaterial whether they are parallel or not, so far as the reflected rays are concerned. The representation of the diffuse reflector by a collection of point sources of light is very convenient for subsequent analysis, because the action of a lens, for example, on a point source of light is relatively simple to analyze. The action of the lens on an extended surface is then simply the sum total of the effects on the individual point sources of which the surface is composed.

A question may arise in the student's mind as to how smooth a surface must be before it ceases becoming a diffuse reflector, and becomes specular instead. The answer is that the irregularities must be of dimensions less than that of the light's wavelength, which is on the order of 5×10^{-5} cm. a very small quantity indeed!

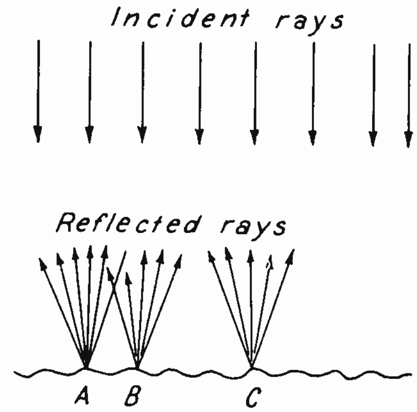


Fig. 10.—Diffuse reflector regarded as a collection of point sources of light.

When a surface is polished, all large irregularities are removed by the abrasive agent and fine scratches or irregularities are produced instead. As finer and finer abrasive agents are employed, the scratches become ultimately so fine that the above condition of smoothness is obtained, and the surface begins to exhibit a shine or specular reflection. However, large smooth irregularities, such as a waviness in a plane mirror, produce large-scale distortions between various parts of the image. In this case the reflection may still be considered as specular, but distorted.

Another point is that the *percentage* of light reflected does not directly depend upon whether the reflection is specular or diffuse. In other words, a mirror is not necessarily a better reflector than a rough surface such as magnesium carbonate. The percentage reflection depends upon the material, and upon whether it reflects all light frequencies equally well or not (as discussed in the section on color). Whether the surface reflects specularly or diffusely depends as mentioned previously, upon whether the surface is rough or smooth relative to the wavelength of light. However, if the diffuse reflector has sufficiently deep crevices in it, multiple reflections of the incident light may occur in these crevices to such an extent that very little light gets out, because at every reflection there is some absorption (since no reflector is perfect), and after many reflections most of the light may be absorbed.

Thus, as a very rough and approximate rule, diffuse reflectors do not reflect as much light as specular reflectors.

Another factor is that the latter reflectors do not scatter the light, and may even concentrate it—as in the case of a spherical mirror—so that the reflected light may be very intense at one angle to the surface, and very weak at other angles. This gives rise to a glare in the direction of maximum reflection, and may overload a television camera pickup tube, if it is located in that direction.

This is illustrated in Fig. 11, where a top view of a studio is shown. Suppose surface A in the studio set is a mirror. Then light from the spotlight S will strike camera B with concentrated affect, whereas C will receive practically no light from A. Such concentrations of light or glare produce what is known as a "hot spot" in the picture, and may overload the television system. Efforts are made to avoid such effects, although some glare is inevitable

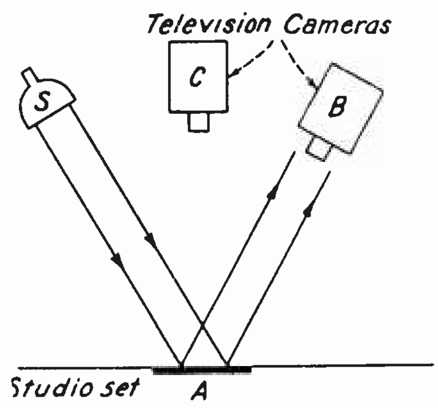


Fig. 11.—Production of "hot spot" by specular reflector in studio set.

from metallic surfaces in a scene, such as silverware, etc.

Perception of an Object.—Most objects are seen by virtue of the light reflected from their surface, although some are seen by reason of the light they transmit, such as a stained-glass window in a church. This means that most objects are not primary sources of light, but require to be illuminated by a primary source, such as an incandescent lamp, in order to be seen.

Whether that which is seen is the object illuminated, or the primary source of light itself, depends upon whether the illuminated object is a specular reflector like a mirror or whether it is a diffuse reflector, and also upon whether it is a good reflector or not. Specifically, a perfect plane mirror, which reflects 100 per cent of the incident light, would not be seen. Instead, the objects that throw light on it, whether they be primary or secondary sources of light, would be seen in virtual images behind the mirror.

This is a common, every-day occurence: chairs, tables, and other objects in a room are seen in a mirror hanging on the wall. The only way in which a perfect mirror would be perceived is that the observer would recognize the virtual images to be unreal, either because of their peculiar position, or because in attempting to reach them, he bumped into the mirror itself. Everyone is aware of the optical illusions produced by mirrors, hence the expression, "It is done by mirrors".

On the other hand, a diffuse reflecting object, such as a brick, is perceived when illuminated because it takes the incident rays and scatters them in a manner peculiar to its surface, which means variation in absorption of different areas of its surface. Since the light is scattered in so random a fashion that each small area of the brick may be considered as a secondary point source of light, each point will be focused as a corresponding image point on the retina of the eye independently of the other points.

If different areas of the brick absorb and hence reflect the light to different extents, then these areas can be distinguished from one another because of their contrast, and thus the texture of the brick perceived, as well as its position relative to other objects in the room. Seeing of most objects is therefore the perception of the variations in the light diffusely reflected from them, and the resulting contrast between areas is one of the most important requirements for clear seeing, not only by the eye, but also by the television camera.

Color.—In the case of the eye, and also of the color television camera, another effect enters of great importance. Visible light vibrations vary in frequency from about 4.3×10^{14} to 7.5×10^{14}, about a two-to-one range. Each frequency, or rather narrow group of frequencies, corresponds to a color as perceived in the brain; the lowest frequency corresponds to deep red, and the highest to violet, and in between are all the other colors of the rainbow. Below the frequency for red are the *infra-red* frequencies; these cannot be perceived by the human eye, but can be "seen" by the television pick-up tube, notably the image orthicon. Above the violet frequency are the *ultra-violet* frequencies; once again these are not visible to the eye, but can affect photo-electric cells (although the ordinary glass tube envelope is opaque to them).

White light from the sun or a high-temperature incandescent source is a certain mixture of all of the above frequencies, but artificial white lights can also be produced by the proper mixture of three frequencies, such as red, blue, and yellow, or any other trio of so-called primary colors. This will be discussed more fully in the assignment on color television.

When an ordinary source of white light shines upon an object, the various components of the light are not necessarily reflected to equal degree; i.e., some frequencies may be absorbed to a greater extent than others. Thus, a brick may absorb most of the frequencies except red, which it may reflect quite strongly. It therefore appears red in color. Another object may reflect blue most strongly; this object is blue in color.

Some objects reflect all frequencies about equally well. If so, the object appears white, grey, or dark grey, depending upon the percentage reflected, particularly relative to nearby objects. By this is meant that if two neighboring objects are non-selective in their absorptions, but one absorbs 10 per cent and hence reflects 90 per cent, while the second absorbs 40 per cent and reflects 60 per cent, then the first will appear white relative to the second, which appears grey.

It is clear that a white object is a particular kind of reflector; one that reflects all frequencies equally well. In general, objects show selective absorption and reflection; as stated previously, these objects have the color of the frequencies they reflect best. Even specular reflectors may show selective absorption. Thus, a shiny copper mirror is specular because its surface is smooth, but it may be said to absorb most of the frequencies except a band in the red, whereupon it has a shiny red appearance. Silver, on the other hand, is not only an excellent reflector, but is non-selective; it appears "whitest" and if smooth, acts as a mirror having no color.

These matters have been discussed in some detail because they are very pertinent to the behavior of a television system. More will be said concerning diffuse reflection in the assignment on studio lighting. It will be shown there that even in the case of diffuse reflection, the light may be scattered according to a certain law known as Lambert's Cosine Law, or it may be scattered through a narrow angle, and the behavior of a studio set, and also that of a receiver screen, depends very markedly on the manner of reflection or transmission of the material.

REFRACTION

It was stated previously that the velocity of light in free space is 186,000 miles/sec. or 3×10^8 meters/sec. This is its maximum velocity. In most substances that transmit light, such as glass, the velocity is considerably lower. The magnitude depends upon certain electrical qualities of the material, namely, its magnetic permeability and dielectric constant (which will be explained in later assignments). This is not surprising in view of the electro-magnetic nature of light, as first developed by Maxwell.

Owing to the reduced velocity of light in material media such as glass, water, etc., certain effects arise that are grouped under the term *refraction*. This term should not be confused with *diffraction*, explained in an earlier assignment. More particularly, oblique rays of light impinging on a material like glass, are bent out of their original path as they pass through the material, and this bending effect or refraction is the basis of operation of the prism and the lens.

WAVE-FRONT.—Before going into a detailed analysis of refraction, it will be of value to define the expression, wave-front. In Fig. 12 (A) is shown a group of parallel rays. Along each the wave motion progresses as shown with the velocity of 186,000 miles/sec. As a rough picture, one might consider each ray as a string which is oscillating sideways as shown.

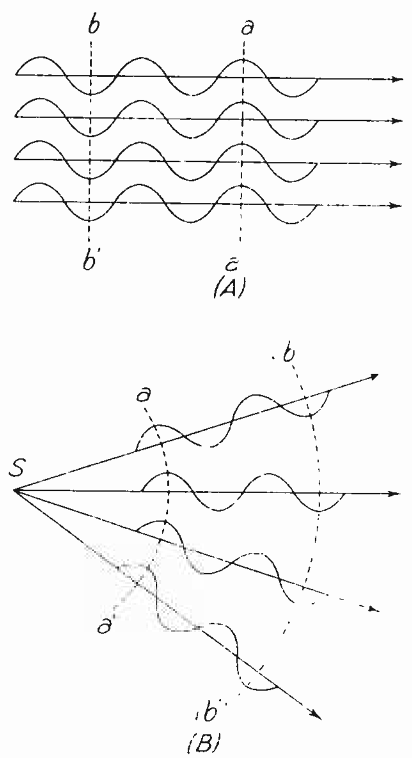


Fig. 12.--Illustration of plane and spherical wave-fronts.

Consider a cross section aa' at which each ray has a maximum upward excursion. This cross section will be a plane whose edge appears as aa' in the figure. This plane is called a *wave-front;* all points on a wave-front are undergoing exactly the same motion *in exactly the same timing.*

As a further example, consider cross section bb'. Here all rays are undergoing maximum downward excursions; the plane of which bb' is the edge of another wave-front. It is clear that in between aa' and bb' are an infinite number of wave-fronts, each differing from its immediate neighbors by virtue of the fact that the excursions on its surface are a little out of time with those of its neighbors.

For the parallel rays of Fig. 12(A), the wave-fronts are planes perpendicular to the rays. In general, the wave-front for any collection of rays (parallel or not), is perpendicular to each ray it intersects, and the ray indicates the direction of motion of that particular part of the wave-front it intersects.

As another example, in (B) is shown a series of rays diverging radially from a point source. In this case the wave-fronts, such as aa' and bb', are *spheres.* This is because from solid geometry it is known that the surface of a sphere is perpendicular to its radii, and thus the condition for perpendicularity of a wave-front to its rays is met in this case by the wave-front being a spherical surface. A spherical wave-front is in general produced by a point source.

Refraction causes a veering around of the wave-front as it enters a medium in which the velocity is different from the preceding medium. Of course, this also means that the rays are bent accordingly, but in explaining refraction, the student will be better able to visualize the veering around of the wave-front than the actual bending of its rays.

REFRACTION OF LIGHT.—Consider a plane wave that impinges obliquely upon a transparent substance in which the velocity of propagation is less than that for free space.

The arrangement is shown in Fig. 13. A plane wave-front AB

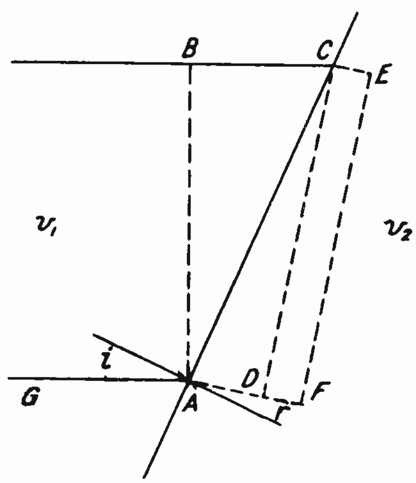


Fig. 13.--Refraction of a plane wave by an oblique surface.

impinges upon a surface CA, such that the velocity of propagation to the left of CA is v_1, and that to the right of CA is v_2. Two rays BC and GA are shown, perpendicular to the wave-front BA. Assume v_1 is greater than v_2. Since the bottom end A of the wave-front strikes the boundary surface first, it will be slowed up to a greater extent than the top end B. Indeed, in the time t that it takes B to move to C with the velocity v_1, A will have moved only as far as D with the lower velocity v_2. Thus the wave is veered around as shown, or is said to be *refracted*. The ray BC is bent around to become ray CE; ray GA is bent into ray DF. These are both perpendicular to the new wave-front CD.

The amount of bending or refraction can be calculated from a relation known as Snell's Law. This relates the indices of refraction of the two media with the angles of incidence and refraction. Accordingly these terms have to be defined. The angle of incidence is the angle that the incident ray makes with the normal to the refracting surface. This is the angle i in Fig. 13. Similarly the angle of refraction is the angle that the refracted ray makes with the normal, and is denoted by r in Fig. 13.

The index of refraction n of a medium is the ratio of the velocity of light V, in free space (vacuum), to that in the medium. Thus, for the left-hand space of Fig. 13, $n_1 = V/v_1$, and for the right-hand space it is $n_2 = V/v_2$. Snell's Law states that

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

Note that here the sines of the angles are involved, rather than the angles themselves, as in the case of reflection. The proof of Snell's Law is easily formulated from Fig. 13, and can be found in any elementary text on light. It is a very simple yet useful law, as it enables problems of ray-tracing in lens systems, etc. to be solved, and is fundamental to all problems in refraction.

Another point to note is that the law is reversible; the path of a ray from the right to the left in Fig. 13 is the same as that shown, and Eq. (1) still holds, except that angles i and r must be interchanged, as well as n_1 and n_2. Hence, we need merely say that the sines of the angles are in inverse proportion to the indices of refraction, without bothering to specify which is the angle of incidence and which is the angle of refraction.

THE PRISM.—Instead of a single oblique surface, consider two such intersecting surfaces, forming a prism. Within the prism the index

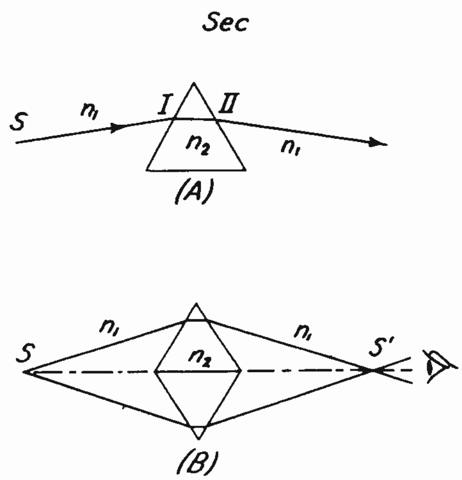


Fig. 14.--Refraction by prismatic surfaces.

of refraction is n_2, outside it is n_1. As will be observed from Fig. 14(A), a ray from the source S is bent or refracted by the front face I of the prism, and then as it emerges at face II, it is further bent towards the base of the prism. This is because the *bottom* end of the wave-front strikes face I first, and the *top* end of the wave-front leaves face II first.

Now consider two prisms arranged base-to-base, as in (B). Note the paths of the two rays shown. They intersect on the axis or base line at some point S', and then diverge from that point just as they initially diverged from S. All other rays that intercept the prism will be bent similarly to the two shown, and very approximately they will also cross at S' or in the immediate neighborhood. Hence S' is the source of a diverging pencil of rays, just as S is, and an eye, situated to the right of S', will form an image of this apparent source of diverging rays on the retina just as well as it would of the initial pencil of rays coming from S.

Thus to the eye S' will appear to be the source of light instead of S, and hence S' is regarded as an image of S. This is very similar to the image formation of the spherical mirror, only here the image is formed by a bending or refraction of the incident rays of light, whereas in the case of the mirror, the image was formed by reflection of the incident rays of light.

THE LENS.—The image-forming properties of the two prisms is rather poor in that actually the rays do not all cross at S'. In terms of wave-fronts, the incident spherical wave-front is not refracted into a truly spherical wave-front to the right of the prisms, but into a more irregular surface.

A much better result is obtained if a more gradually curved pair of surfaces is employed in place of the plane-faced prisms. In practice, spherical surfaces are employed, not because these are the true shapes for image formation, but because they are easiest to produce by machines. The result is the lens, and various types are shown in Fig. 15. Type 1 is known as a bi-convex lens; Type 2 as a plano-convex; and Type 3 as a concave-convex lens. All are characterized by the fact that they are thicker at the axis than they are at the edges, and as a result bend the rays diverging from the axis back to the axis on the other side

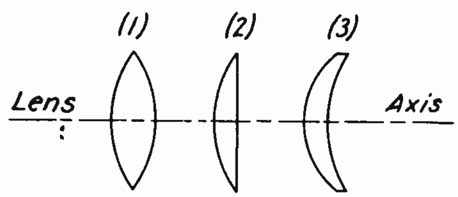


Fig. 15.--Various forms of convex lenses.

of the lens.

This is illustrated in Fig. 16, where the bending for a bi-convex lens is shown for a point source S_1 on the axis, and for a point source S_2 off the axis. The corresponding image points are S'_1 and S'_2, and S'_3 is *below* the axis. Similar

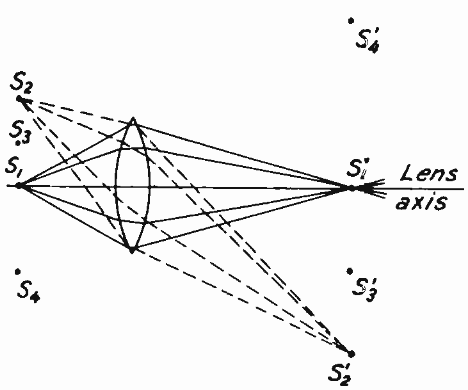


Fig. 16.--Image formation by a bi-convex lens.

effects are obtained for S_3 and S_4 and their respective images S'_3 and S'_4.

A further point to note is that if S_3 is between S_1 and S_2, then S'_3 is between S'_1 and S'_2. There is thus a one-to-one correspondence between the object and image points; if one set forms a geometrical pattern, then the other set will form a *similar* pattern. In addition, if the lens is a good one, then if S_1, S_2, S_3, and S_4, etc., are on a plane perpendicular to the lens axis, image points S'_1, S'_2, S'_3, and S'_4, etc., will also lie on a plane perpendicular to the axis, and at distances *proportional* to those of the object points. Actual lenses approximate these requirements, and the closer they do so, the better they are. The above properties indicate what is meant by the image of a continuous object, and will be discussed next.

IMAGE FORMATION.—It will be recalled that a diffusely reflecting object causes a scattering of incident light from its surface such that each elementary area or point of the surface acts as a point source of a diverging pencil of rays. Thus the diffusely reflecting object acts as a collection of an infinite number of point sources of light, one next to the other, which radiate more or less light of various colors, thus permitting the nature of the object to be divined by the observer, rather than the nature of the source illuminating the object.

Such scattering of the light from each point of the object means that less light is reflected in any one direction, but that observers in many directions can see the object rather than only those in certain favored positions. This will be made clearer by reference to Fig. 17.

Observe that any one of the eyes shown has rays of light directed toward it by points of the objects surface, such as A, B, or C.

On the other hand, if each point reflected light in a narrow pencil only, then any one of the eyes could see only a small portion of the object, namely that part whose points radiated light in the direction of the eye. Other groups of points could be seen by other eyes; no one eye could see *all* the points of the object. In general, objects, even an ordinary mirror, have at least some diffuse reflection and are seen in their entirety (as limited by the field of view of the eye) because of such diffuse reflection.

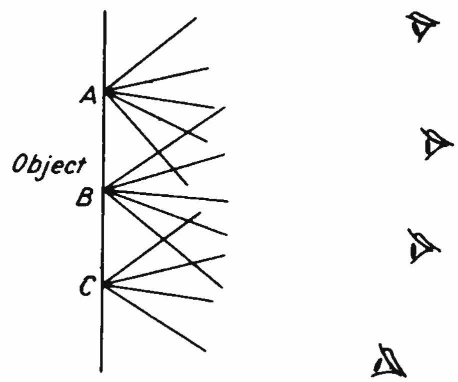


Fig. 17.—A diffusely reflecting surface can be seen by many observers.

Consider now an object that is imaged by a lens. A favorite object in optics is the arrow, because it is simple in form and has definite ends. It is shown in Fig. 18. The tip, as well as other points of the arrow, actually reflect light in all directions because the arrow is a diffuse reflector. Only a certain angle or pencil of rays of the total coming from the tip, impinge upon the lens, however. These are bent or refracted to form a similar pencil of limited angular spread at the image plane.

The same is true for the other points of the arrow. The rest of the rays from each point that does not strike the lens, proceed into space where they can be picked up and focused by another lens, if one happens to be there to intercept them. However, if the eye is located near the image tip, then it will pick up rays from this end of the image of the arrow, and not from the tail and other portions, because these do not direct rays over a wide enough angle to intercept the eye. This is clear from the figure.

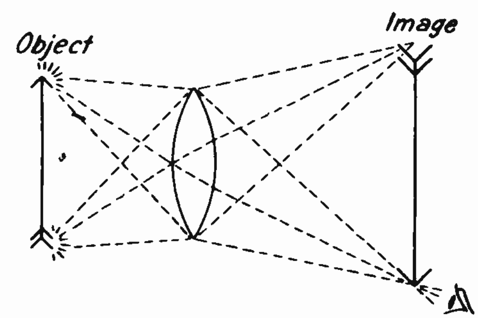


Fig. 18.—Image of an arrow formed by a lens.

Also note from the figure that the image points are reversed with respect to the object points, so that the image is *inverted*. This is a characteristic of images formed by lenses and concave spherical mirrors.

Use of a Screen.—In order that all parts of the image be seen, it is necessary that some sort of a device, called a screen, be employed *at the image plane* to scatter the light from each image point so that *all* can have rays directed toward the eye, regardless of their positions. The screen can

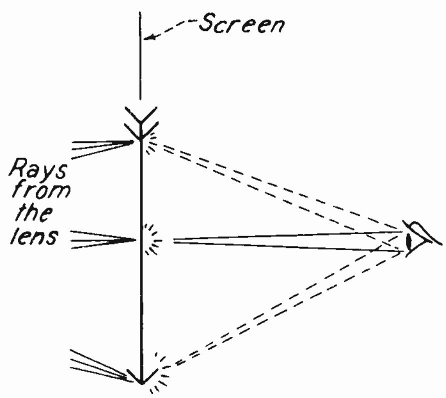


Fig. 19.—Action of a diffusely transmitting screen.

do this in one of two ways: by *diffusely reflecting*, or by *diffusely transmitting* the narrow pencils of rays diverging from the image points. This is illustrated in Fig. 19.

The solid lines represent the pencils of rays brought to a focus by the lens. They form narrow pencils of little angular spread. By interposing a screen at the image plane, of such nature that it scatters light passing through it, the narrow pencils that form the so-called *aerial image* are converted into wide-angle pencils, shown by the dotted lines. For the position of the eye shown, only a few image points representing the center of the arrow would ordinarily be seen. Through the agency of the screen, however, light from all parts of the arrow image reach the eye, as is indicated in the figure; all parts of the arrow can be seen.

The screen that accomplishes this may be simply a ground-glass sheet. The surface of the glass can be considered as consisting of thousands of little prisms, each of which bends the light passing through it in one direction or another, so that light issuing from any small area of the glass is refracted into all possible directions. The ground-glass screen has innumerable applications: we have all seen such screens used to form images in a studio camera, or in the Graflex Camera.

Television View Finder.—An application closer to television is the view finder used in a television camera. Although many cameras have picture tubes attached to them to enable the camera man to see electronically what he is "panning", nevertheless the optical type of view-finder is preferred by some because its field of view can be made larger than that scanned on the picture-tube light sensitive screen, so that the cameraman can see all that is being televised and more, and can thus tell what to avoid.

The view finder consists essentially of a lens matched to that for the pickup tube, and mechanically linked to it, and a ground glass or similar translucent screen, through which appears an image of the object scene. It is thus similar to a camera, and for that matter, to the eye itself. The ground glass should be flat and relatively smooth, yet the grinding scratches should be at least a few wavelengths of light in size, so as to scatter the light.

Reflecting Screens.—Another type of screen is one that *reflects* diffusely instead of transmitting diffusely. Such a screen throws or scatters the light back in the direction of the lens and object, hence the eye must be on that side of the screen to observe the image. This is the optical arrangement used in most motion picture theatres, although the type of theatre known as Trans-lux employs the diffusely transmitting rather than the diffusely reflecting screen.

Projection Picture Tube.— Another television application is the projection type of picture tube. Although this will be discussed in greater detail farther on, a simple diagram of the arrangement will be given here (Fig. 20). A

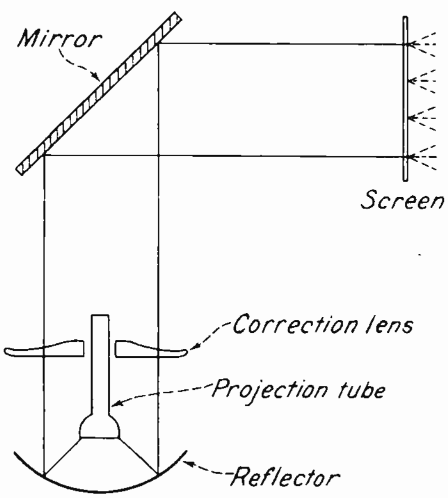


Fig. 20.— Projection picture tube system.

small but brilliantly illuminated picture tube is employed. The picture produced on its fluorescent screen faces downward. A spherical reflector below it focuses the light by reflection rather than by refraction. A plastic lens above the reflector serves mainly to correct for the spherical aberration of the reflector (to be explained later), and passes the light onto a mirror inclined at a 45° angle to the vertical, from which the light is finally focused on a diffuse transmitting screen.

Note an interesting point here; the mirror is a smooth surface and merely redirects the narrow pencils of light focused by the optical system; it does not change their angular spread. The screen, on the other hand, scatters the light passing through it, making it available to a large number of observers.

Focusing.—This also indicates that the screen must be accurately located at the plane where the individual pencils of rays converge to points, i.e., the screen must be located at the image plane. If it is located ahead or after the image plane, then it intercepts each pencil of rays where its area is larger than a point, and causes scattering from an area instead of a point. Since the areas of the various pencils overlap each other in such regions, the image formed is that of a series of overlapping areas instead of distinct, adjacent image points, and as a result the total image is a blur.

This is illustrated in Fig. 21. Note that the pencils of rays can occupy a common part of space and yet proceed independently to their respective focal points. This is a normal property of wave motion in a linear medium: independent wave motions superimpose their effects in any common portion of the medium without cross-modulating (affecting) one another. Thus, we commonly observe two beams of light crossing one another without interfering with each other's journey.

indeed, the same is true for sound waves, and other wave motions or vibrations.

In the upper diagram of Fig. 21 it scattered the light from regions where the rays had begun to diverge once again and overlap each other.

The above remarks may be

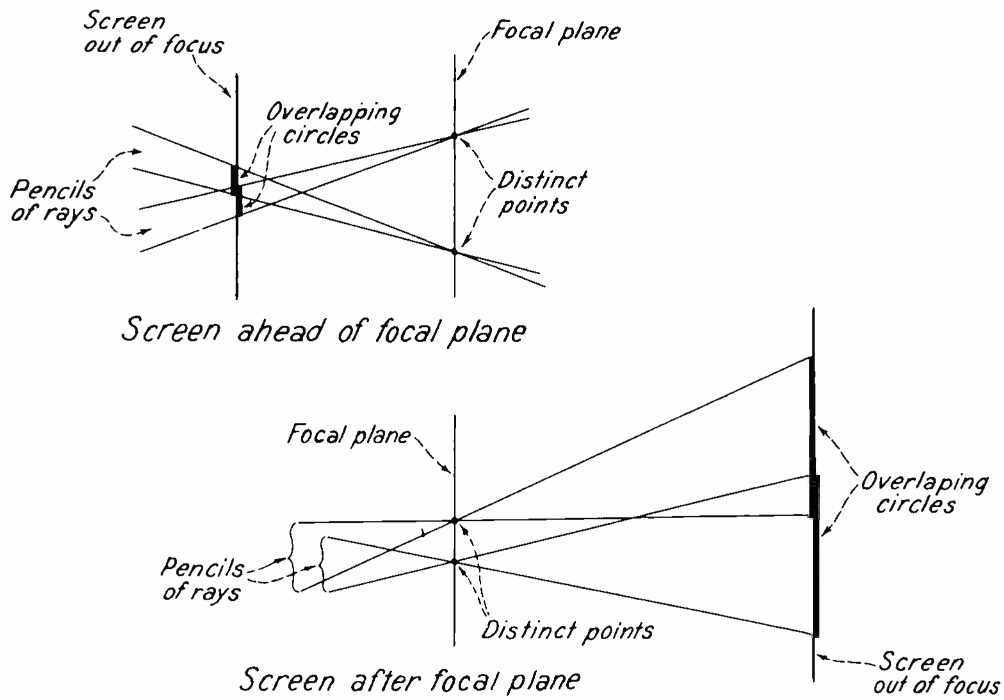


Fig. 21.--Effects of placing screen out of focus, either ahead or after the focal plane.

the screen is placed ahead of the focal plane. As shown, the pencils still have appreciable cross section, and form patches of light on the screen that overlap one another. Since the screen scatters the incident light, the patches of light cannot thereafter continue to converge to point images, but instead diverge (scatter) from the screen.

The same is true for a screen location after the focal plane, the rays diverge from the patches of light on the screen. It is true that in this case the light has already converged to points, but the screen failed to scatter the light from these distinct points; instead,

summarized as follows:

1. Diffusely reflecting objects emit pencils of rays from each point of their surface.

2. A lens is a curved transparent device in which the velocity of light is less than that in free space (or air), and which bends or refracts the above pencils of rays into converging pencils.

3. A good lens causes all pencils from one plane of the object perpendicular to its axis to converge to points once more at another (image) plane perpendicular to its axis.

4. The second set of points,

called image points, are arranged in a pattern similar to that of the object points, and distances between points in one set are proportional to the distances between corresponding points in the other set.

5. The pencils of rays diverge from the image points in the same manner as they did from the object points, but usually through a smaller angle.

6. If a diffusely reflecting or transmitting screen is interposed at the image plane, the image points are caused to diverge their rays through a greater angle of spread, so that they cover all points of space.

7. They can then be refocused by a second lens to form an image of the image, and so on. In particular, they can be focused by the lens in the eye upon the retina, thus causing a sensation similar to that produced by the original object set of points.

8. The lens forms an image inverted with respect to the object.

LENS FORMULAS

FOCUS OF A LENS.—Lenses may consist of one element or many; the element may be thick or thin. For a lens composed of one thin element, a relatively simple set of laws holds between the image and object distances, dimensions, etc.

Consider a thin lens situated between an object and its corresponding image plane, as shown in Fig. 22. For simplicity, the object will be assumed to be a point source O on the axis; the image is a corresponding point I on the other side of the axis. For every object distance o, (measured to the center of the lens), there is a corresponding image distance i.

It will be found (and can be proved) that the object and image

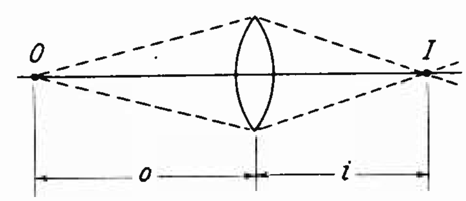


Fig. 22.--Object and image distances for a lens.

distances are related to one another by the following formula:

$$1/o + 1/i = d \qquad (2)$$

where d is a constant that depends upon the radii of curvature of the two lens surfaces, and its index of refraction. From Eq. (2), it is clear that as o is increased, $1/o$ is less, hence $1/i$ must be greater in order that the sum remains constant at the value d. This in turn means that i must decrease; hence we arrive at the rule that as o increases, i decreases.

However, as o approaches infinity, i does not approach zero, but some value greater than zero. To show this, set o equal to infinity. Then $1/o$ approaches zero, so that Eq. (2) reduces to

$$1/i = d \qquad (3)$$

or

$$i = 1/d \qquad (4)$$

Since d is a finite number, i.e., some constant, $1/d$ is a constant too,—its reciprocal.

Physically, what has happened is that the object point has receded to infinity. The lens intercepts its rays, and since these came from infinity, where they met

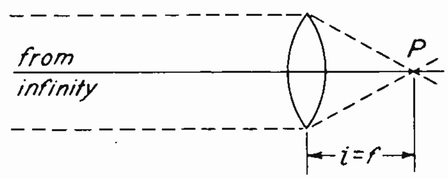


Fig. 23.--Focal point of a lens.

(at the object point) they must be parallel. This is shown in Fig. 23. The image point P where these rays meet is at a distance $1/d$ from the lens. It is the *minimum* image distance for the lens, and therefore a unique value. As such, it can be used as a measure for the lens. This is similar to a measure employed in geometry: The *shortest* distance between a line and a point off the line is the *perpendicular* to the line passing through the point. Hence, the perpendicular distance is used to measure the distance from the point to the line.

We have then that the *focal length* of a lens is the minimum image distance corresponding to an infinite object distance. Denote the focal length by f, where f is clearly equal to $1/d$. Then Eq. (2) becomes

$$1/o + 1/i = 1/f \qquad (5)$$

This is probably the most important simple formula for a lens. As an example, suppose the focal length of a lens is 5 inches, and the object distance is 20 inches. What is the image distance?

Substituting in Eq. (5), we have,

$$1/20 + 1/i = 1/5$$

Solving for i, we obtain $i = 6\,^2/_3$ inches. Similarly, if the image *distance* is 20 inches, the *object distance* will be $6\,^2/_3$ inches, i.e., the image and object distances are interchangeable. This is an important corollary of Eq. (5).

Experimentally, the focal length can be found for a *thin* lens by setting it up on a measuring stand, placing an object point source of light a suitable distance in front of it, and then placing a screen behind it—such as a sheet of white paper, and moving the screen back and forth until a sharp image point is obtained. The object and image distances from the lens are then measured, and substituted in Eq. (5), whereupon the focal length is obtained.

Specifically, suppose the object distance is found to be 8 inches, and the corresponding image distance is found to be 12 inches. Then

$$1/8 + 1/12 = 1/f$$

from which f = 4.8 inches.

Another method is to focus a distance object, such as the sun, upon the screen. The object distance is for all practical purposes infinity, so that the measured image distance is essentially the focal length, thus obtained directly without any further calculation. In passing, it is to be noted that the concentration of the sun's rays into a tiny image point concentrates so much energy in so small a screen area as to raise its temperature to possibly the ignition point. This is the principle of the burning glass.

A further precaution to be noted is that the object distance *must exceed the focal length* of the lens, or otherwise no real image will be found. If the object distance equals the focal length, then the image distance is infinite, i.e., the screen would have to be placed an infinite distance from the lens to obtain an image on it.

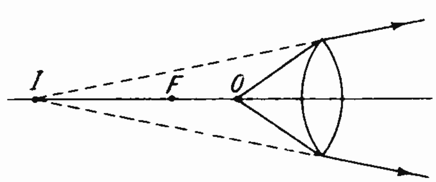


Fig. 24.--Formation of a virtual image by a convex lens when the object distance is less than the focal length.

If the object distance is less than the focal length, then a *virtual* image is obtained *on the same side of the lens as the object.* This is shown in Fig. 24. The object *O* is closer than the focal point *F*. This means that the rays from *O* diverge at such a large angle that the lens is unable to bend them sufficiently to make them converge once again on the other side. Instead, it can only make them diverge to a lesser extent, as shown.

Indeed, if the object were at F, then the rays would emerge parallel to the axis on the other side from the properties of the lens as derived previously. Hence, it is to be expected that the rays *appear* to come from a point *I*, as shown. Point *I* is known as a *virtual* image. Its distance from the lens can still be calculated by Eq. (5); that is, the mathematics still gives the right answer if properly interpreted.

For example, suppose $f = 6"$, and $o = 4"$. Then

$$1/4 + 1/i = 1/6$$

or

$$i = -12"$$

The minus sign means that *I* is on the *same side* of the lens as *O*, and 12 inches away from the lens.

A virtual image will not form an image on a screen, whether it is placed at *I*, or on the other side of the lens. It therefore does not appear to have any physical significance. This is not true, however. Suppose another lens is placed to the right of the given lens in Fig. 24, and at a distance from *I* greater than its focal length. Then, as far as the second lens is concerned, the diverging rays of light act as if they came from *I*, and will therefore be focused into a *real* image point to the right of the second lens upon a screen.

For example, suppose a second lens of 8" focal length is placed 4" to the right of the first lens. Then its distance from *I* (using the previous numerical values) will be 12" + 4" = 16" from the virtual image (now regarded as its object).

Apply Eq. (5) to this lens, and obtain

$$1/i' + 1/16 = 1/8$$

or

$$i' = 16"$$

to the right of the second lens, or 16 + 16 = 32" from *I*. This is illustrated by Fig. 25.

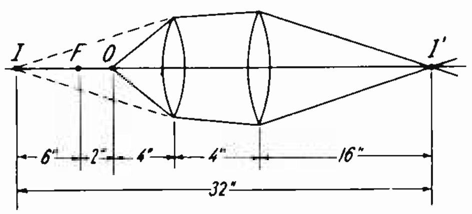


Fig. 25.--Formation of a real second image from a virtual first image.

THE CONCAVE LENS.—Another type of lens that always forms a virtual image is the concave lens, shown in Fig. 26. As is indicated in the figure, the concave lens is one that is thinner at the center than at the edges, and is similar in action to two prisms joined apex to apex.

Such a lens causes rays to diverge, so that they *appear* to come from point sources on the other side of the lens, i.e., from virtual images. In the figure the focal length is shown as *f*, and the virtual point as *F*, on the same side of the lens as the parallel incident rays. As in the preceding example, the virtual image can be focused as a real image by a second convex lens. Hence, as a general rule, the concave lens is not used by itself in an optical system, but rather in conjunction with convex lenses to produce special

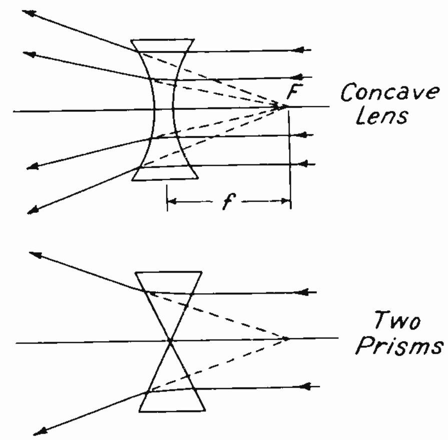


Fig. 26.--Focusing of light rays by a concave lens, showing equivalence to two prisms.

effects not readily obtainable otherwise, such as achromatism (to be explained).

MAGNIFICATION FACTOR.—The convex lens forms an image that is either an enlarged or reduced replica of the object (or as a special case, one that is of the same size). The relative size depends upon the ratio of the image to the object distance, as will be shown. Consider, as in Fig. 27, an object ABH to be focused by the lens. First, the image points corresponding to the various object points must be found.

Consider the tip of the arrow A. To locate its image, D, at least two rays from A will have to be traced through the lens in order that their intersection determine the image point. There are two, or possibly three rays that are particularly easy to trace. One such ray is AC, parallel to the lens axis. This is refracted through the focal point F, and proceeds to D as CFD.

Another ray which is readily traced is that through the center of the lens O. Such a ray AO, strikes two portions of the lens

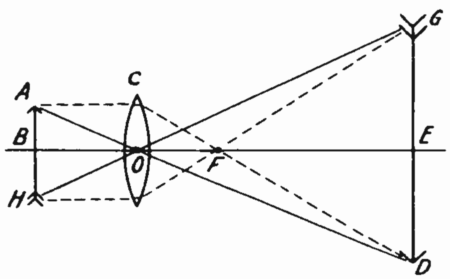


Fig. 27.--Relative size of object and image depends upon their relative distances.

surface, on opposite sides, that are parallel to one another. As a result, one unbends the ray as much as the other bends it, so that the ray comes out as OD parallel to AO. If the lens is thin, then not only is OD parallel to AO, but essentially in line with it. Thus one line AOD can be drawn, and where this intersects ACFD locates the image point D of the tip A. In a similar manner the tail H is traced to G.

Note particularly the two rays AOD and HOG that pass through the center O of the lens. These rays enable the relative size of the image and object to be determined. Thus, triangles AHO and OGD are similar (in shape), so that the following ratios are equal:

$$(GD/AH) = (OE/OB)$$

But AH is the linear dimension of the object, and GD is the *corresponding* linear dimension of the image, while BO is the object distance o, and OE is the image distance, i. The ratio GD/AH is the ratio of corresponding linear dimensions of the image and object, and is called the *magnification* factor, m. Clearly, from the geometry of Fig. 27

$$m = i/o \qquad (6)$$

It will be recalled that the image and object distances can be interchanged, although this gives the reciprocal value for m. Suppose the object is GD, and the image is therefore AH. If it were attempted to use a ray from G or D parallel to the axis, it is clear from Fig. 27 that the rays would not intersect the lens surface. The rays through O are still suitable for use in locating the image points.

Instead of parallel rays, a third type of ray can be used. This is one passing through the focal point before striking the lens, and is a useful ray if the object size is large, i.e., the particular object point is considerably off the axis. Such rays are represented by GF and DF. It will be observed that after passing through the lens, they come out *parallel* to the axis. Where these parallel emergent rays intersect, the rays through the center now locate the image points A and H.

APPLICATIONS.—Eqs. (5) and (6) serve to solve a large number of practical lens problems. As an example, suppose a motion picture film is to be projected on the light-sensitive surface or mosaic of an iconoscope (television pickup tube) for the purpose of televising motion pictures. For practical reasons it is desired to keep the distance between the lens in the motion picture projector and the mosaic in the iconoscope equal to 4 feet. The dimensions of the motion picture frame are 3/4 inch high by 1 inch wide, and the corresponding dimensions of the active part of the mosaic are 3 × 4 inches.

Television Motion Pictures.—The object (frame) and image (mosaic) dimensions furnish the magnification factor m. Thus,

$$m = 3'' \div \tfrac{3}{4}'' = 4'' \div 1'' = 4$$

Hence, from Eq. (6)

$$4 = i/o = 4'/o$$

or

$$o = 1 \text{ foot} = 12''$$

Now that o and i are known, f can be found by Eq. (5).

$$1/12 + 1/48 = 1/f$$

or

$$f = 48/5 = 9.6''$$

Thus, if a 9.6" focal length lens is employed, and the mosaic is placed 4 feet (= 48 inches) from the lens, and the latter 12 inches from the film, the frame will be magnified just enough to cover the desired area of the mosaic.

Similar problems can be solved, such as the focal length required for a motion picture lens, to give a picture on a motion picture screen of a certain size for a certain "throw" (image distance). This is exactly the same as the problem solved above.

Television Camera.—Another problem might be the following: A television camera is to employ a 6 1/2 inch focal length lens. The distance of the lens from the mosaic is 8 inches, see Fig. 28. What is the object distance? By Eq. (5) we have

$$1/8 + 1/o = 1/6.5$$

Solving for o, we obtain $o = 34.7''$ or a little less than 3 feet. The magnification factor will be, from Eq. (6)

$$m = i/o = 8/34.7 = 0.231$$

The fractional value for m indicates that the object will be

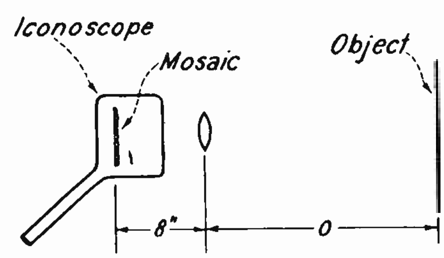


Fig. 28.--Optical system for a television camera.

reduced to slightly under one-quarter as an image on the mosaic. This is a typical example of a camera arrangement; i.e., the camera produces a reduced image of a large scene to enable it to be focused on a small film, or mosaic, etc. This is accomplished by choosing a small image distance relative to the object distance. In projection just the opposite is done in order to get an enlarged screen image of a small picture object.

Pursuing this problem still further, let us assume that the useful or scanned mosaic area is 3" × 4". What will be the object dimensions? Since m is known, these will be simply

$$\frac{3''}{0.231} \times \frac{4''}{0.231} = 13'' \times 17.3''$$

This would represent either a miniature scene or a test pattern.

On the other hand, suppose it is desired to image a scene 15' × 20' on the 3" × 4" mosaic. What will be the object distance, and incidentally the image distance? From Eq. (6),

$$m = \frac{3''}{15' \times 12} = \frac{4''}{20' \times 12} = 1/60 = i/o$$

or

$$o = 60i$$

From Eq. (5)

$$1/o + 1/i = 1/60i + 1/i = 1/6.5''$$

Solving for i, we obtain

$$i = 6.61''$$

Then $o = 60 \times 6.61'' = 396.6''$

$= 33.05'$ or 33 ft.

Wide-Angle and Closeup Cameras. Now suppose a 14-inch focal length lens is substituted for the 6.5" lens, and the same object distance of 33 feet is employed. What portion of the scene will now be focused on the 3" × 4" mosaic?

Since the object distance is given as o = 33' = 396", as well as f = 14", Eq. (5) will first be employed to determine i. Thus

$$1/i + 1/396 = 1/14$$

or

$$i = 14.51''$$

Note at this point that for the relatively large object distances employed with either lens, the image distance is very nearly equal to the focal length: 6.61" as compared to 6.5" in the first case; and 14.51" as compared to 14" in the second case. If the object distance were infinity in either case, then the reduction in image distance would only be 0.11" in the first case, and 0.51" in the second case. On the other hand, if either object or image distance is in the neighborhood of twice the focal length, the magnification factor is unity, and the lens has to shift by the greatest amount for a change in the object distance from the value $2f$.

However, to complete the problem, m must be calculated by Eq. (6). It is

$$m = i/o = 14.51/396 = 0.0366$$

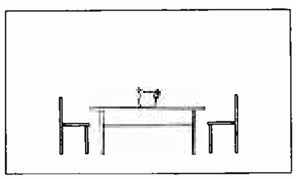
The dimensions of the part of the scene imaged on the 3" × 4" mosaic are

$$\frac{3}{.0366} \times \frac{4}{.0366} = 82'' \times 109.3''$$

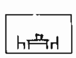
$$= 6'10'' \times 9'1.3''$$

This is less than half the scene. It means that if a longer focal length lens is employed, *then for the same object distance,* a smaller part of the scene will fill the entire mosaic area; or to put it another way, *an individual object in the scene can be made to occupy the entire area of the mosaic.* This is called a *closeup*, a single person or even a single face may thus be made to fill the entire mosaic area.

The same effect could have been obtained by moving the camera with the 6 1/2-inch focal length lens closer to the scene. However, this is not feasible in practice. Instead, by employing two cameras having lenses of different focal lengths, and situated about the same distance from the scene, the effects of *wide-angle-viewing* by the shorter focal length lens and of *closeups* by the longer focal length lens are obtained without either camera being in front of the other and thus tending to obstruct the other's view. The action is illustrated by Fig. 29.



Studio scene



View finder of short focal length wide-angle lens

View finder of long focal length closeup lens

Fig. 29.--Appearance of studio scene in the view-finders of a short focal length wide-angle lens and of a long focal length close-up lens. Both cameras are the same distance from the studio scene.

Use of Condenser Lens.—An interesting application of the lens and also of a reflector, is for the purpose of gathering light from a source to illuminate *evenly* a film or a lantern slide in a projection apparatus, such as a motion picture or "still" projector. The lens used for the purpose is called a *condenser lens*, and is shown in Fig. 30, (A) and (B).

A small source of light is assumed, such as from the positive crater of an arc lamp. Such a source, if used directly, would send oblique rays through the edges of the transparent lantern slide that would strike the projection lens at A and B, (Fig. 30A) if the projection lens were large enough. By using a condenser lens, rays even more oblique are veered around so that they pass through the slide and then through a small diameter projection lens, as shown.

Two advantages are gained thereby:

1. The field, or angular size of the object that can be imaged, is increased over that normally handled by the lens, and

2. The amount of light intercepted from the approximate point source of light by the condenser lens is even greater than that intercepted by the slide itself because of the closer proximity of the condenser lens to the source.

Of course, the diameter of the condenser lens must be larger than the diagonal of the slide, but large condenser lens are quite feasible since they normally do not have to be as perfect as the projection lens.

A point to be noted is that in (A) the source is shown imaged at the front face of the projection lens. Hence where the slide is located, the image of the source would be badly blurred. This is desirable if the source is non-uniform in brightness across its area, for the blurred image of it

The above projection system is suitable where a bright point (or small) source of light is used to illuminate an object, such as a lantern slide, that is larger than the projection lens used to focus it on the screen. In the

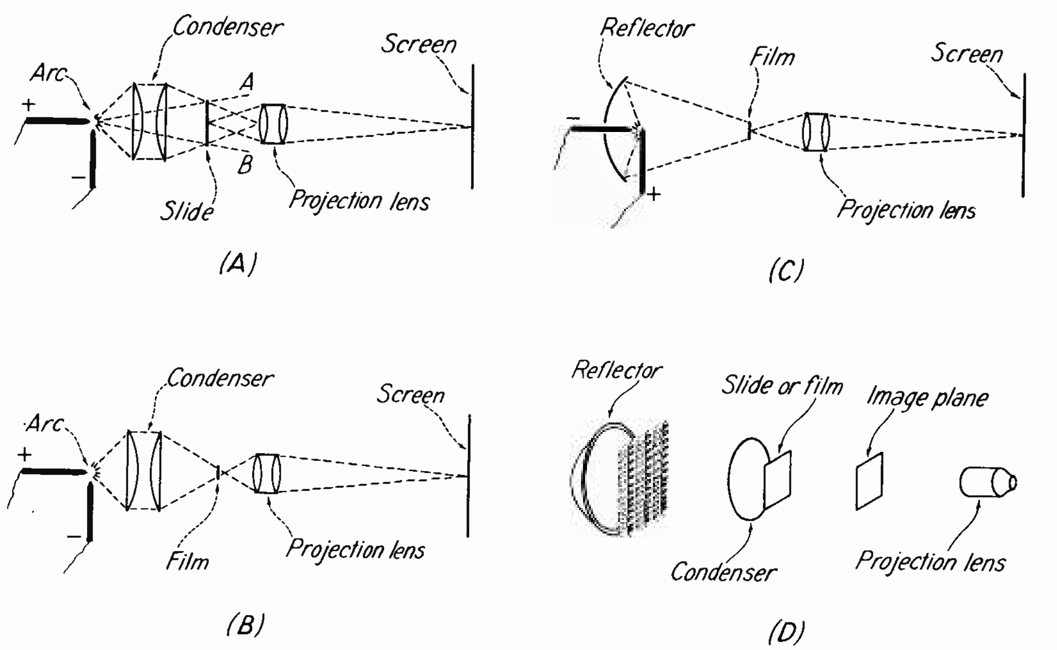


Fig. 30.— **Projecting systems, illustrating the use of condenser lenses and reflectors.**

at the object (slide) plane is therefore practically uniform in brightness, and all parts of the slide are evenly illuminated. On the other hand, the slide is located the proper distance from the projection lens so that a sharp image of it is formed on the screen. The screen, however, is clearly out of focus for any image of the image of the source to be formed by the projection lens. This is desirable, for there is no need for an image of the source to appear on the screen.

case of the projection of motion picture film, the projection lens is usually larger in diameter than the frame of film. Moreover, with high-intensity arcs, the source is fairly uniform in brightness. Hence, the projection system of Fig. 30(B) is usually employed.

Here the source of uniform brightness is actually imaged at the film, by the condenser lens. The latter is adjusted to give a magnification of about six times, so that the source image is large enough to illuminate all parts of the frame. The projection lens then forms an image of the frame as well as that of the condenser lens image of the source, on the screen. In many actual systems the film is placed somewhat to the left of the source image in order to intercept a larger cone of more uniform light. In this case it is possible to observe an image of the image of the source instead of that of the film, if the screen is moved an appreciable distance to the right. This, however, is only possible if the first image of the source is not within the focal length of the projection lens, in order that a real image be formed. (Observe that a lens can form an image of an image of the object produced by another lens.)

In (C), Fig. 30, a reflector type of light-gathering system is shown. Here a spherical or other suitably shaped mirror, usually of glass silvered on the back, is used to gather the light and compress it so that it just covers the film frame. Note that now the positive carbon of the arc is arranged to throw the light back on the reflector, rather than on the film frame. Often a condenser lens is used in conjunction with the reflector further to bend the light. The advantages of the reflector over a condenser lens are that it is lighter, and is generally of uniform thickness, and hence is not as apt to crack as the lens system when placed close to the light source to intercept a maximum amount of light from it.

Finally, in (D) is shown an incandescent source of light used in conjunction with a reflector. The lamp used operates at a considerably higher temperature than the ordinary incandescent light, and therefore furnishes much more light for the same amount of power. On the other hand, its life is only about 200 hours as compared to 1,000 hours for the ordinary incandescent light.

As shown in the figure by the solid lines, the filament consists of several parallel helical strands. The reflector is so adjusted as to form an image of these in the plane of the strands by setting the latter at the center of curvature of the reflector. However, the images of the strands are arranged to fall between the actual strands themselves, as is indicated by the dotted lines, so that a nearly uniform patch of light is obtained. This is imaged at the projection lens, so that at the object plane the illumination is practically uniform.

Incandescent sources are generally employed where the "throw" (image distance of the projection lens) is not too great. This is particularly true of "still" or lantern slide projectors used to focus test patterns on the pickup tube, and hence one will find this type of projection system used a great deal in television film studios. Motion picture film, however, is often illuminated by arc lamps even for television film cameras because of the denser (more opaque) films employed and because of the whiter light obtained.

LENS SPEED.—Although Eq. (5) concerning focal length in relation to object and image distances, and Eq. (6) concerning the magnification factor, can be used to solve a large variety of practical lens problems, there remain certain auxiliary formulas and data that are of practical importance. Among these is that concerning the speed of a lens.

This is a carry-over from photography, and refers to how fast an exposure can be made (shutter speed). This depends upon the brightness of the image, and that in turn depends upon how large the lens is in surface area to intercept the incident light, and also upon over how much area the image is spread on the image plane, i.e., the magnification.

The f-Number.—The lens area depends upon the *square* of the diameter d. Other things being equal, the greater the diameter of the lens, the brighter the image, and therefore the faster the lens is. Thus the speed may be said to be proportional to the *square* of the lens diameter.

The effect of the magnification factor m is not so readily expressed because m depends upon the ratio of image to object distance, and hence also depends indirectly upon the focal length of the lens. However, most cameras, whether television or photographic, are used to produce a reduced image of the object, i.e., m is less than unity. This also implies that the object distance o is much greater than the image distance i.

It has been shown previously that when o is much greater than i, i is very nearly equal to f, the focal length. Indeed, for $o = \infty$ $i = f$. No great error will therefore be involved in assuming i equal to f. In this case, for a given object distance o and a given focal length f for the lens, Eq. (6) becomes

$$m = f/o \qquad (7)$$

where m is clearly fractional, since o is much greater than f. Suppose next that another lens of twice the focal length or $2f$, but of the same diameter, is employed. The magnification factor is now

$$m' = 2f/o = 2m \qquad (8)$$

This means that a lens of twice the focal length produces an image of the given object twice as far away and twice as large in linear dimensions as the first image. Even so the larger image will be much smaller than the object, but relative to the first image produced by the shorter focal length lens, it is twice as high and twice as wide, etc.

It therefore has *four* times the *area* of the first image, but transmits no more light than the shorter focal length lens because the diameters have been assumed to be equal. This means that the *same* amount of transmitted light is now spread out over four times the area, so that the brightness of the larger image will be only one-quarter that of the smaller image.*

It therefore follows that the speed of a lens, other things being equal, varies *inversely as the square of the focal length,* at least for distant objects. Since it also varies *directly as the square* of the lens diameter, we can write finally, that the

$$\text{Lens speed} = K_1 \; (d/f)^2 \qquad (9)$$

*The fact that the lens of greater focal length produces a larger image has already been shown in the example illustrating the use of a long focal length lens for closeup purposes.

where k_1 is a factor of proportionality. Since d is practically always less than f, (d/f) is a fraction. To avoid fractional quantities, the reciprocal ratio (f/d) is employed.

This ratio really refers to the *lens slowness*, but common usage has made this quantity synonomous with with lens speed. Since the speed (or really slowness) is used for comparative purposes, k_1 or its reciprocal canbe taken as unity for simplicity, so that finally we have

$$\text{Lens speed} = (f/d)^2 \qquad (9a)$$

Eq. (9a) states that the ratio of f/d, or the f/-number*, as it is called, determines the speed of the lens. However, note that the *smaller* the f/-number, the *faster* is the lens; that is, the *brighter* is the image. As an example, a lens whose f/d is f/6.3 is faster than a lens whose f/d or f-number is f/8. In the first case the focal length is 6.3 times the diameter of the front lens (of a composite lens); in the second case, it is eight times the diameter. Note that the front lens is the one facing the object. Its effective diameter, however, actually depends upon the stop of the lens; the diameter referred to above is its maximum diameter.

THE DIAPHRAGM OR STOP.—There is generally interposed in the lens system a limiting aperture called the lens stop or diaphragm. It generally has the form of a set of thin steel plates or leaves, as shown in Fig. 31. When the knurled ring is rotated, a cam action causes the leaves to pivot on individual axes in such manner as to close or open the central aperture, thus varying the effective diameter of the lens. The stop may be in front of the front lens of a lens combination, but is generally located between the lens elements in the lens barrel.

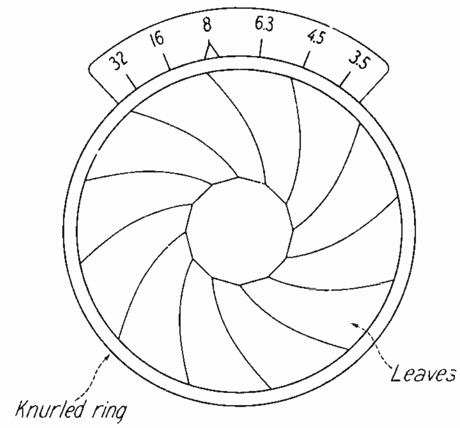


Fig. 31.—Iris diaphragm for a lens.

The designer has to calculate the effective opening; as far as the user of the lens is concerned, the markings (as indicated in Fig. 31) indicate the f-number of the lens. A slow, medium-priced lens may have an f/-number as low as f/7.7; a fast high grade and expensive lens may have an f/-number as low as f/4.5 or even an f/3.5. Exceptionally fast lenses, generally of short focal length, may have an f/-number as low as even 0.9, although such a lens is exceptionally fast.

Lenses in television cameras are generally f/3.5 for the shorter focal length lens, say 6 1/2", and f/4.5 for the longer focal length lens, say 14". The advent of the image orthicon bids fair to permit lenses of as high as f/8 or higher to employed because of the extraordinary sensitivity of the pickup tube. The advantage of a slow, high f/-number lens is that it has greater depth of field and less aberrations, which will be explained later.

*Note that this is a symbol for the f-number, and does not mean f divided by 6.3.

However, it can very well be that the view finder, if of the optical type, will use a fast, low $f/$-number lens in order to obtain an image of sufficient brightness to be viewed by the eye, since the combination not be as sensitive as the image orthicon. A further advantage will be that the view finder with the fast lens will require more precise focusing, so that when the view finder image is sharply in focus, the image on the pickup tube will surely be in focus.

As an example of how the speeds of two lenses can be compared, consider a lens whose $f/$-number is $f/8$, and one whose $f/$-number if $f/4.5$. Note that it is immaterial as to what the relative focal lengths or diameters of the two lenses are; it is only the ratio of the two quantities in either case that determines the speed. From Eq. (9a) the relative speeds are

$$\frac{\text{Speed of lens } f/4.5.}{\text{Speed of lens } f/8} = \left(\frac{8}{4.5.}\right)^2 = 3.16$$

Thus the $f/4.5$ lens is 3.16 times as fast as the $f/8$ lens.

DEPTH OF FIELD.—From the foregoing discussion it has been apparant that even an ideal lens can produce a sharp image only of an object *whose elements lie in a plane perpendicular to the lens axis.* However, most objects are three-dimensional in nature, and hence only one plane of elements in the object can be sharply focused at any one time. This would indicate a very severe limitation to the practical use of a lens.

Even in such a case, no point of the object is actually focused as an image point owing to the diffraction of light. However, this limitation is overshadowed in practice by the lens abberations (distortion) present in a camera lens, as well as the limiting resolution of the eye, of the grain in a photographic film, or the spot size in a television pickup tube. Indeed, in photographic practice, if an object point is imaged as a circular disk having a diameter no greater than possibly 1/200th of an inch, it is considered as being satisfactorily imaged. The disc is known as the "circle of confusion", a small circle of confusion can be regarded as essentially a point of light.

PRACTICAL CONSIDERATIONS.—Under such conditions, we may consider object points at various distances satisfactorily focused on the image plane. For example, in Fig. 32 are shown three object points P_1, P_2, and P_3, at corresponding distances P_1O, P_2O, and P_3O from the lens. The images are formed at P'_1, P'_2, and P'_3 on the other side of the lens.

Consider the image plane as being at P'_2. The P_1 is out of focus because its rays have not

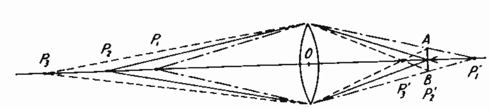


Fig. 32.—Illustration of depth of field.

quite converged at that point, and form at the image plane a circle of confusion whose diameter is AB. Similarly, P_3 is not focused because its rays have already converged to a point of P'_3, and then have diverged to a circle at the image plane. Suppose P_3 is sufficiently far back of P_2 to form a circle of confusion at the image plane of diameter AB, the same as that of P_1, and suppose further that this common diameter is the allowable size that is still considered as constituting a point focus. Thus AB might be 1/200th of an inch.

Then the distance P_3P_2 is called the *far depth of field,* and P_2P_1, is called the *near depth of field,* for the object distance P_2O. Often the entire distance P_3P_1 is called the depth of field for the object distance P_2O.* The depth of field depends upon such factors as the focal length, *f*/-number and object distance.

In general, the greater the object distance, the greater is the depth of field. Thus, distant objects are practically all in focus very close to the focal point of the lens (when *o* is large, *i* is nearly equal to *f*). In cheaper cameras of the fixed-focus type, the image distance is chosen such that all objects are approximately in focus from infinity down to a certain minimum distance of from about 6 to 8 feet.

For very small object distances, the depth of field is very small. Anyone who has observed a close-up on a motion picture screen must have noticed how badly blurred are other figures and objects behind the person focused on. However, mention was made previously that closeups can be had at greater object distances by the use of longer focal length lenses. This, then, might seem to be a way out: use a longer focal length lens, get the same size image as before, but at a greater object distance, and owing to the latter fact, obtain a greater depth of field.

Unfortunately, this will not be found to be the case. The reason is that a long focal length lens inherently has a smaller depth of field than a short focal length lens. The difference is such that this factor exactly cancels the preceding one; that is, for the same size picture of any object, the depth of field is the same whether the picture is obtained by a longer focal length lens at a greater object distance, or a shorter focal length lens at a correspondingly shorter distance.

In photographic work it is actually of advantage to use a shorter focal length lens, obtain a smaller picture *at the same object distance that would be used with a*

*The following formulas apply:

$$\text{Far depth of field} = R_1 = \frac{cq(q-1)\ (f/d)}{1-(c/d)\ (q-1)}$$

$$\text{Near depth of field} = R_2 = \frac{cq(q-1)\ (f/d)}{1+(c/d)\ (q-1)}$$

$$\textbf{Total depth of field} = R_1 + R_2$$

in which d is the diameter of the lens; (*f*/d) is its *f*/-number; *o* is the object distance; *f* is its focal length; $q = o/f$ and c is the diameter of the permissible circle of confusion.

longer focal length lens, and then enlarge the desired portion of the film. The final result is an image of the same size as that obtained directly by the longer focal length lens at the same object distance. yet the intermediate process of enlarging does not affect the circles of confusion to as great an extent, so that the depth of field is actually greater. This is one argument in favor of a short focal length lens, and explains to some extent the polularity of the miniature camera. (Of course, another and important factor is the lower cost of the film, lens and camera).

In television, this advantage does not hold because there is no similar practical method of en-

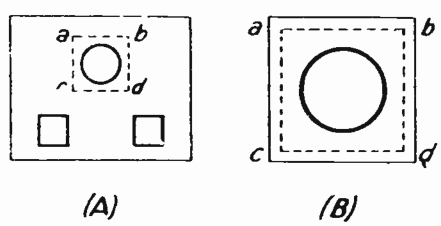


Fig. 33.--**Method of enlarging a portion abcd of the scene imaged on the camera tubes photosensitive surface by scanning only that portion of the surface, while maintaining the area of picture tube scanned unaltered.**

larging the image. It would be necessary to employ a short focal length lens, move the camera sufficiently far back to have more than the desired portion of the scene imaged on the photosensitive surface of the pickup tube, *and then scan only the portion of the scene* desired.

Thus as shown in Fig. 33(A), the scene (for simplicity) is assumed to consist of a circle and two squares. It is desired to reproduce on the picture tube screen only the area abcd containing the circle. The result is shown in (B).

To do this, it is necessary to scan only area abcd on the photosensitive surface. The resulting electrical signal contains information from area abcd, only. When impressed on the picture tube, and the latter's fluorescent screen is scanned in its entirety, area abcd will cover the entire screen, and thus give an enlarged image of a portion of the scene focused optically on the pickup tube.

However, it is impractical to reduce the scanning amplitudes (both horizontal and vertical) in the camera, particularly with one control; and what is equally important, it is particularly difficult to reduce the size of the scanning spot in the camera in the same proportion as the reduction in scanning amplitude, in order to maintain the same relative resolution. Hence, for closeups it is necessary to use either a longer focal length lens at a larger object distance, or a shorter focal length lens at a smaller object distance (with the former alternative preferred), and either arrangement results in reduced depth of field.

In Table I is given the depth of field for a 6 $^1/_2$ inch lens for various object distances and various speeds. The upper figure in each case is the far depth of field, and the lower figure is the near depth of field. Observe that the far depth of field is greater than the near depth; this is a consequence of the increase in depth of field with object distance.

The columns for $f/3.5$ and $f/4.5$

TABLE I

Object Distance	f/3.5	f/4.5	f/5.6	f/6.3	f/8
13"	.0351"	.0451	.0563"	.0623"	.0806"
	.0349"	.0449"	.0557"	.0627"	.0797"
19.5"	.1056"	.1361"	.1695"	.191"	.243"
	.0991"	.1277"	.1582"	.178"	.225"
3.25'	.532"	.687"	.860"	.968"	1.25"
	.518"	.665"	.823"	.924"	1.16"
5.96'	1.979"	2.56"	3.21"	3.64"	4.7"
	1.877"	2.39"	2.95"	3.31"	4.14"
11.38'	7.77"	10.17"	12.89"	1.237'	1.617'
	6.97"	8.85"	10.83	1.011'	1.249'
16.8'	1.44'	1.95'	3.00'	3.43'	3.8'
	1.22'	1.58'	2.43'	2.56'	2.62'
27.6'	4.3'	5.79'	7.59'	8.82'	12.31'
	3.28'	4.08'	4.91'	5.4'	6.51'
54.7'	20.2'	39.8'	41.6'	51.5'	82.9'
	11.6'	14.05'	16.4'	17.87'	21.0'

apply with fair accuracy to lenses of other focal lengths, with the provision mentioned previously that the object distance must be increased in the same proportion. For example, for the 6 1/2" focal length lens, for an object distance of 5.96' and for a speed of $f/3.5$, the far depth of field is 1.979", and the near depth of field is 1.877". For a 13" focal length lens of the same speed, the *same* far and near depths of field are obtained at twice the object distance, namely, 11.92'.

DEPTH OF FOCUS.—Just as there is a certain amount of latitude in the position of the object plane before the image becomes blurred to an intolerable degree, so too is there a corresponding amount of latitude in the position of the image plane, before the image becomes too blurred. (In short, the image and object distances do not have to be mathematically exact in practice.) The latitude in image distance is denoted by the *depth of focus*, and refers to the distance that the *image plane* can be moved from its correct position in either direction before image points grow into circles of confusion whose diameters equal the maximum permissible value, say .005". Depth of focus is of some value in indicating how much buckling of the film is permissible in a camera or projector, and also how fine a vernier must be employed in the focusing mechanism.

In Fig. 34 is illustrated this factor. For the given object distance o the correct image distance is i. If the film be moved closer to the lens by an amount r_1, i.e., $r_1 = r_2$ as is evident from the figure, then the image point grows to a circle of diameter c.

The value of r_1 or r_2 (denote it by the common value of r) is given by

$$r = (ci/d) \qquad (10)$$

However, the depth of focus is of importance only when it is small and therefore critical, and this is for minimum values of i, namely, those close to the focal length. Hence, Eq. (10) may be rewritten as

$$r \cong c(f/d) \qquad (11)$$

from which it is apparent that the depth of focus depends directly upon

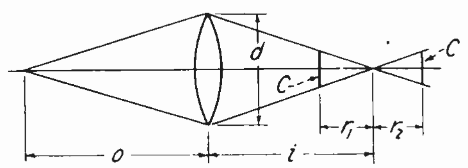


Fig. 34.—**Diagram illustrating depth of focus.**

the $f/$-number, and is independent of the focal length,—at least for fairly distant objects.

As an example, suppose an $f/3.5$ lens is to be used, and a circle of confusion of diameter equal to .005" is permissible. Then from Eq. (11),

$$r = (.005)\ (3.5) = .0175''$$

Suppose the focusing is accomplished by means of a screw and nut mechanism, and the screw has 20 threads per inch. Then one revolution of the screw advances the nut and lens by 1/20 = .05". Hence .0175/.05 = .35 or slightly over one-third revolution will bring the lens from in-focus to out-of-focus. This is an appreciable part of a revolution and thus indicates that focusing with such a screw mechansim will not be to critical.

On the other hand, for rapid changes in focusing, as may be required in practice when the camera is wheeled rapidly to or from the scene, a coarser feed may be required. This may be done by using two screw feeds in the camera, or else a geared-up mechanism, so that turning one knob or handle revolves the screw rapidly for coarse adjustment, and turning the other revolves the screw slowly for fine or vernier adjustment.

LENS ABERRATIONS.—The discussion up to this point has assumed that the lens focuses perfectly all rays from each object point into a corresponding image point. For slow-speed lenses and for objects that are not very large, so that all object points are not far from the lens axis, this is practically true. This means that all rays striking the lens are nearly parallel to the axis, and are known as *paraxial rays*.

However, as lens designers tried to cover larger objects relative to the object distance, and attempted to build faster lenses, departures from correct focusing became more apparent, and means had to be devised to correct such imperfections or aberrations, as they are called. There are five principal aberations, and while the television engineer is not particularly concerned with lens design and the elimination of such aberations, he should know their nature in order to appreciate why various types of lenses are built, and why their cost increases so rapidly with their freedom from such aberrations.

CHROMATIC ABERRATION.—The most pronounced aberration is that owing to the inability of a lens to focus all the different colors (frequencies) to the same image point. In Eq. (1) was given the fundamental law for the bending of rays of light as they pass from a medium of one refractive index to another.

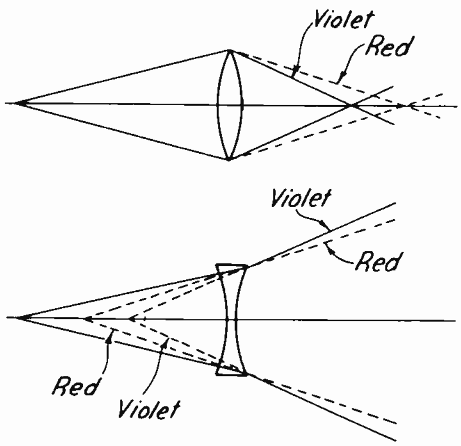


Fig. 35.—Chromatic aberration for a convex and for a concave lens.

This law forms the basis of all lens action. It happens, however, that the index of refraction of a medium in general varies with the frequency of the light, and is greatest for the highest frequency (violet); that is, the velocity of violet light is in general less than that of red light for media whose index of refraction is appreciably greater than unity.

As a result of such deviations in the index, a prism of glass can separate or *disperse* the various constituents of white light in the form of a spectrum, and this is the basis of spectroscopy. In the case of a lens, the action is as indicated in Fig. 35 for a convex and for a concave lens. It will be observed that the convergence or divergence of violet rays is greater than that for red rays.

The correction for such distortion, known as chromatic aberration, depends upon the fact that the deviation is bending and the bending of an average ray—such as green,—may vary in opposite directions for two substances. For example, for crown glass (which contains no lead oxide), the variation in refractive index, or the dispersion of the various colors, is less for a given amount of bending of the average frequency, than the dispersion of flint glass (containing lead oxide), *for the same amount of bending of the average frequency*. Or, for a given amount of dispersion, crown glass produces more bending of the average frequency than does flint glass.

Hence, if a *convex* lens of crown glass and a *concave* lens of flint glass of the proper curvature are employed, as shown in Fig. 36, it is possible for one to correct the dispersion of the other, while the *net* bending is toward the axis owing to the greater bending effect of the crown glass compared to that of the flint glass. As is shown in the figure, the flint glass tends to undo the bending effect of the crown glass, but only partially, so that a net bending is obtained, whereas the flint glass almost completely cancels the dispersion or separation of the rays of different frequencies.

A lens of this type is known as an achromatic doublet. It generally consists of two lenses whose adjacent faces have the same curvature, so that they may be

The latter effect is measured by the angle that these rays make to the lens axis, i.e., by the ratio of the distance the object point is off the axis to the object distance from the lens. This angle of view will be discussed further with reference to other aberrations, particularly curvature of the field. Coma is a kind of spherical aberration for oblique rays originating from object points off the axis.

ASTIGMATIC ABERRATION.—Another aberration closely associated with

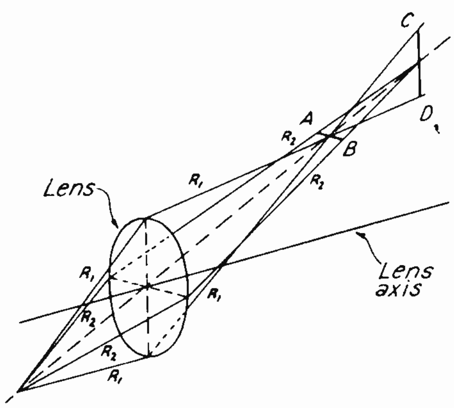


Fig. 41.--**Production of astigmatic abberration by skew rays.**

coma is astigmatic aberration, and this also refers to skew rays. This aberration indicates the failure of a converging cone of rays to converge uniformly to an image point; instead, the rays form a wedge-shaped pencil. This is shown in Fig. 41. The object point *o* is considerably off the axis. The skew rays R_1R_1 from it are directed to the top and bottom of the lens, while the skew rays R_2R_2 are directed to the sides.

After refraction it will be observed that rays R_1R_1 converge more rapidly than rays R_2R_2, so that where R_1R_1 meet, a *line focus* AB is formed instead of a point focus. Thus a screen placed at this point will have a line AB imaged on it instead of a point.

Beyond this point rays R_1R_1 begin to diverge, but rays R_2R_2 are still converging, and ultimately cross beyond AB. Where they do so, rays R_1R_1 have diverged to form another line focus CD perpendicular to AB. On the other hand, if the screen is placed between AB and CD, elliptical spots will be formed whose major axis is parallel to AB or CD, depending upon whether the screen is closer to AB or CD. About half-way between the spot will be circular and of smallest area; it is the circle of least confusion.

The effect of this aberration is best shown with respect to a wheel as an object. In three dimensions, if the point *o* is anywhere on a circle around the axis, line AB forms a corresponding image circle around the axis that is everywhere sharp. On the other hand if *o* is moved *radially* along a line passing through the axis, line CD forms a succession of overlapping lines that pass through the axis. The significance of this is that in the case of a spoked wheel, if the screen is placed at AB, the rim is sharply in focus because the successive image lines like AB overlap and do not increase the thickness of the rim image, whereas the spokes are made up of lines like AB one below the other and hence form blurred images. This is shown in

Fig. 42 (A).

On the other hand, if the screen is placed at CD, then the spokes are made up of overlapping radial lines, and are thus sharply defined, but the circumference is now blurred, as shown in Fig. 42 (B). This form of distortion is not to be confused with astigmatism of the eye, which is due to greater curvature of the cornea in one direction than the other. There the blurring is either of one set of *parallel* lines or of another parallel set perpendicular to the first.

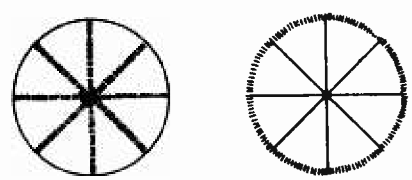


Fig. 42.--Distorted images of a spoked wheel by a lens having astigmatic aberration.

In correcting for astigmatism lines AB and CD are made to coincide; i.e., the rays are made to converge *uniformly* to a point focus. In general, spherical aberration and coma have to be minimized first before astigmatic aberration is reduced. Cheaper lenses of large *f*/number and hence slow speed, and of limited angle of view, do not require the extensive corrections that the more expensive, faster lenses need. A lens corrected for astigmatic aberration is known as an anastigmat. All lenses of speeds greater than *f*/8 are of this type, hence this type of lens is of importance to the television engineer.

Curvature of the Field.—Even if the above aberrations are eliminated, there still remains two that can be quite serious. One of these is curvature of the field. Its significance is best understood with reference to Fig. 43. Even

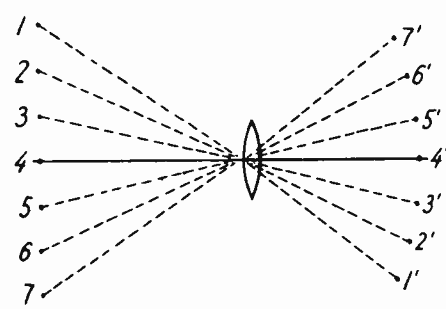


Fig. 43.--Curvature of the field.

if the two sets of focal lines can be brought together to form point foci and thus eliminate astigmatic aberration, the image points may lie on a curved surface instead of a plane, as is assumed for the object points in Fig. 43. The photographic film, or the mosaic of the iconoscope will therefore have to be similarly curved in order to have all points sharply focused on it, and the curvature may vary with the object distance. A curved screen is of course impractical, and the lens must therefore be corrected by the choice of the proper elements to obtain a flat field. Separation of the elements appears necessary to correct both for astigmatic aberration and curvature of the field.

The correction can be obtained

only over a limited range of distance off the axis. The difficulties increase as the focal length of the lens and/or its speed is increased, and also as the angle of view is increased. With respect to the latter, the ordinary photographic objective can cover a rectangle whose diagonal is at most equal to the focal length. The significance of this rule can be realized from the following:

In Fig. 44 is shown a lens that gathers rays from object points that subtend at the lens the half-angle α. Thus 2α is the angle of view of the lens. The points are spread out on the image plane so that these also subtend at the lens the angle 2α. If the object points

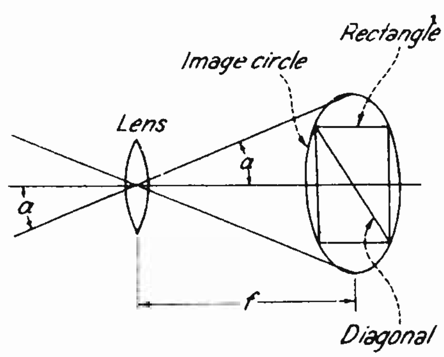


Fig. 44.—Field of view of an ordinary photographic objective.

were contained within a circle, the image points would lie within a similar circle; usually the scene viewed is of rectangular form, so that the image is of similar form as shown. The diagonal of the rectangle is clearly the diameter of the circle that has all points within the angle α indicated.

For a given size scene, the closer it is to the lens, the greater is the angle α, and hence also the larger is the image. The limit is determined by the image circle that lies in the range where the field is substantially flat. If the scene is moved too close to the lens, that is, if the lens tries to "cover" too large a field, then the image circle will invade that region where the image field is appreciably curved. In that case adjustment of the focus can bring either peripheral or axial image points into focus, *but not both*.

Hence, angle α is limited by the design of the lens, and the rule given above indicates what this angle is. Under ordinary operation the object distance is sufficiently great so that the image distance is practically equal to the focal length. Hence the geometry is such that

$$\tan \alpha = (1/2 \text{ diagonal})/f$$

and if the diagonal can at most equal f, then the maximum value of α is

$$\alpha = \tan^{-1} (f/2)/f = \tan^{-1} 0.5$$

from which $\alpha = 26.5^0$, and the field of view is $2\alpha = 53^0$.

Wide-Angle Lenses.—Often it is necessary, at least in photography, to photograph a large object, such as a building from a short distance, such as across the street. Another example is photographing a banquet scene with a camera a short distance in front of the tables. This means that the viewing angle must be large, so that the focal length relative to the diagonal of the image rectangle is comparatively short.

Such a lens is known as a wide-angle lens; it can cover an angle of about 90°, although some unusual lenses can cover an angle as great as 135° or even more.

From the foregoing it is evident that wide-angle lenses are generally relatively short focal length lenses. Ordinarily such lenses are not required in television as it is not desired to have the camera too close to the scene, and the studio is normally designed long enough to permit the cameras to be placed sufficiently far back to enable the mosaic to cover the scene. Indeed, as indicated previously, it is preferable to increase the focal length of the lens for closeup purposes rather than to use the same focal length lens and move the camera closer to the scene. Moreover, in the case of the iconoscope, physical limitations prevent lenses shorter than 6 1/2" focal length from being used.

Distortion.—The last form of aberration is known as *distortion.* It refers to the variation in magnification of object points as these are taken farther and farther from the lens axis. The magnification may decrease or increase with distance. The simplest way to illustrate this aberration is to consider a rectangle as the object. If the magnification increases with the distance from the axis, the distortion will be considered positive, and will appear as in (A), Fig. 45. This is also sometimes called *pin-cushion* distortion.

On the other hand, if the magnification decreased with distance from the axis, the distortion is considered negative, and has the appearance shown in (B), Fig. 45. This is also sometimes designated as *barrel* distortion.

Most lense, exhibit some distortion, but it is normally not objectionable. Indeed, it is at present not as noticeable as the residual distortion in the deflection waves of the pickup and picture tubes. If the lens can be

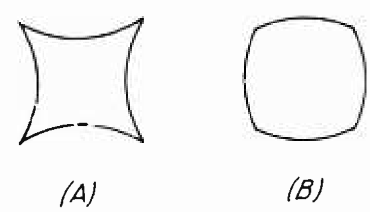


Fig. 45.--Positive and negative distortion of a rectangular object.

made up of elements that are symmetrical about a center plane in the lens, then if the stop is located there, the distortion can be reduced to a very low value. Such a lens is knows as a rectilinear lens, although if it is anastigmatic as well, it is preferably designated as an anastigmat.

TYPES OF LENSES.—From the foregoing it is clear that a lens that has a low *f*/number, a fairly wide field, and is relatively free from aberrations, is a precision device and quite expensive to construct. Many different makes have been placed on the market. and these may vary in the degree of correction of one or other of is aberrations described previously.

One of the best known is the Tessar, manufactured in Germany by Carl Zeiss and Company, and in this country by the Bausch and Lomb Company.

It is shown in cross section in Fig. 46. As will be noted, it consists of three elements, one of

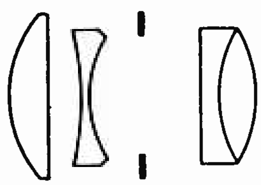


Fig. 46.—Zeiss Tessar Lens.

which is in itself a cemented doublet. It ranges in speeds down to $f/3.5$, and is noted for the excellence of its corrections.

Lenses of faster speeds are available, down to about $f/3$, but in general these are limited angle of view, i.e., of relatively large focal length compared to the size of film they are required to cover. This is possible where the film size is small, such as a motion picture frame 1" × 3/4". A lens of corresponding focal length (1.56") would require the motion-picture camera to be entirely too close to the scene, and hence a longer focal length lens is more desirable in practice. Such a lens in turn covers a much smaller angle of view relative to the 1" × 3/4" frame, and hence need be corrected over a smaller field. It can therefore be made of larger relative aperture. A similar consideration holds in the case of the projection picture tube optical system, since the picture tube screen is also relatively small compared to the focal length of the mirror.

Another well known lens is the Cooke triplet. It is shown in Fig. 47. This is an anastigmat of speeds

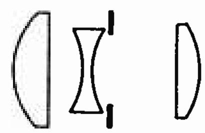


Fig. 47.—Cooke triplet lens.

as great as $f/4.5$. The final adjustment is made by adjusting the air spaces between elements, and brings out the fact that these air spaces are really lenses in effect just as much as the glass elements.

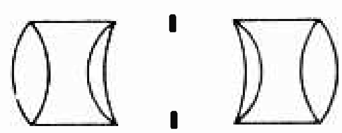


Fig. 48. —Goerz Dagor lens.

A very famous make of lens is the Goerz Dagor, made in f/numbers down to $f/6.8$. While this is rather slow for television purposes, it should be satisfactory for the more sensitive tubes, such as the image orthicon. It is illustrated in Fig. 48, from which it will be noted that it consists essentially of two symmetrical components, each of which has three cemented elements. It can be made to have a 90° angle of field, in which case it is a wide-angle lens.

REDUCTION OF REFLECTION.—It will be noted from these examples that high-grade lenses consist of many elements. There is bound to be reflection from each glass-air surface, and as a result the loss of light in such an optical system may be appreciable as compared to a single-element lens. Accordingly, the speed will be noticeably less than is indicated by the *f*/-number.

The reflections can be considerably decreased by suitably coating the lens-air surfaces. Two methods are in general available. For flint glasses having lead oxide, immersion in a one per cent solution of solium acid phosphate at 50°C results in the production of soluble lead salts, which can be washed off, thereupon leaving a surface film of silica, which can be made one-quarter wave length at any desired visible frequency by adjusting the immersion time.

In the case of the ordinary crown glasses that contain calcium fluoride, the glass can be placed over a tray containing a one per cent solution of hydrofluoric acid. The tray is cooled about 10°C below room temperature to prevent water vapor condensing on the glass; instead only the vapors of hydrofluoric acid contact its surface. About 6 hours are required to produce a quarter-wave film of what is presumed to be calcium fluoride.

The action of such films is to reduce the reflections to 25 to 30 per cent for flint glass, and as low as to 6 to 10 per cent for crown glass, of the untreated values of reflection. It appears to be based on the same principle as that of employing a quarter-wave transmission line of intermediate characteristic impedance, to match two transmission lines of different characteristic impedance (to be discussed in a subsequent assignment).

The reduction in reflection is appreciable, and the films produced are tough and can withstand considerable wear and tear. It is evident that the surfaces should not be touched by hands since the oily film left will tend to nullify the beneficient effects of the chemical treatment. The best cleansing agent is alcohol and a soft lintless rag or soft tissue. Television camera lens are generally treated to reduce reflections because the gain in transmission of light and hence lens speed is well worth while. Similar treatment is of value for kinescope screens, meter cover glasses, etc.

CONCLUSIONS

This concludes the assignment on the principles of optics, as applied to television. The general laws of reflection and refraction were given first, and then their applications to mirrors and lenses. The properties of the latter were studied with particular reference to their use in practical camera and projection systems. The most important properties studied were the relations between image and object distance and the focal length, and between image and object distance with regard to magnification factor; other practical formulas were those for the speed of a lens and for depth of field and focus.

Finally lens aberrations were taken up with a view toward fostering appreciation of the distortion difficulties surmounted by a lens of good design, and also so that the television engineer would appreciate better the limitations involved in the use of a lens. At the present time the lens is hardly the limiting factor for high resolution; rather the electrical parts of the television system set the limit to the resolving power of the system. It may in time be that the lens will be the limiting factor; if so, television will have come of age, since motion pictures attest to the excellence of images produced by modern lenses.

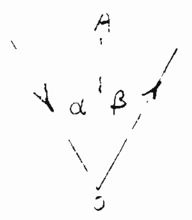
V- 9174-33

TELEVISION TECHNICAL ASSIGNMENT

PRINCIPLES OF OPTICS

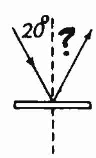
EXAMINATION

1. State in your own words the law for the reflection of light, and illustrate with a diagram.



The reflected ray makes the same angle with the normal as does the incident ray and the reflected ray is in the same plane containing the incident ray and the normal. In the diagram α is the angle of incidence and β is the angle of reflection. $\angle\alpha = \angle\beta$.

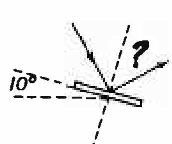
2.



(a) A ray of light is directed toward a plane mirror capable of being rotated on its axis. The ray of light makes an angle of 20° with the normal to the mirror. What is the angle that the reflected ray makes with the incident ray?

Angle between incident ray and reflected ray is Twiee the angle of incidence

$\angle = 20 \times 2 = 40°$



(b) The mirror is now turned through an angle of 10° so as to increase the angle between the normal and the incident ray. (The direction of the latter has not changed.) What is the angle now made between the incident and reflected rays?

∠ of incidence has been increased 10° for a total of 30°.

∠ between incident & reflected rays = 30 × 2 = 60°

2. (b) *(Continued)*

(c) Through what angle has the reflected ray been moved from its position in (a) by the 10° rotation of the mirror?

Move = 20°

3. In some photographic enlargers, one or more sheets of ground glass are placed between the light source and the negative to be enlarged. This produces an even illumination of all parts of the negative even though the light source may not radiate light equally in all directions. Explain.

The ground glass has a rough surface so the light is incident on minute portions of it at numerous different angles. This causes reflected and transmitted rays to be diffused so as to radiate light in all directions.

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EXAMINATION, Page 3.

4. (a) What is the action of a convex and a concave lens on a ray impinging upon it and parallel to the axis of the lens? Illustrate with two diagrams.

Parallel rays impinging on a convex lens are caused to converge forming a real image. The concave lens diverges the rays forming a virtual image on the same side of the lens as the impinging rays.

(b) Explain in your own words the action of a diffusely reflecting screen in forming an image produced by a lens.

When light strikes a reflecting surface the angle of reflection equals the angle of incidence. A diffusely reflecting surface has a rough surface so the light is incident at various angles on all the minute surface areas. This then causes the reflected rays to leave at numerous angles to the surface as a whole with the result that the image can be viewed (is visible) from various angles, rays from all points of the image being visible from all positions.

7. Given two television cameras A and B. A has a lens of 6 $^1/_2$" focal length; B has a lens of 13" focal length. The photosensitive surface in the pickup tube in either case in 3" × 4". Camera A is to cover a scene 10' wide; and camera B is to cover a scene 4' high.

(a) What is the height of the scene covered by camera A?

3 : 4 :: X : 10

4X = 30   x = 7.5'

height = 7.5' feet

(b) What is the width of the scene covered by camera B?

3 : 4 :: 4 : x

3x = 16   x = $\frac{16}{3}$ = 5.33

Width = 5.33 feet

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EXAMINATION, Page 7.

8. Referring to Question 7,

(a) How far back from the scene should each camera be located?

(A) $M = \frac{i}{o} = \frac{4}{10 \cdot 12} = \frac{4}{120} = \frac{1}{30}$ $\quad i = o/30$

$\frac{1}{i} + \frac{1}{o} = \frac{1}{f}$ $\quad \frac{1}{o/30} + \frac{1}{o} = \frac{1}{6.5}$ $\quad \frac{30+1}{o} = \frac{1}{6.5}$ $\quad o = 201.5$ inches

(B) $M = \frac{i}{o} = \frac{3}{4 \cdot 12} = \frac{1}{16}$ $\quad i = \frac{o}{16}$

$\frac{16+1}{o} = \frac{1}{13}$ $\quad o = 17 \times 13 = 221.$ inches

(b) What are the respective image distances?

(A) $i = \frac{o}{30} = \frac{201.5}{30} = 6.71$ inches

B $i = \frac{o}{16} = \frac{221}{16} = 13.81$ inches

9. (a) A television set is illuminated with lights drawing a total of 25 kw of electrical power. The television camera lens is operated at $f/3.5$. If the lens were stopped down to $f/11$, what would the electric power requirements have to be for the same output signal from the camera?

Ratio of speeds $= \frac{(11)^2}{(3.5)^2} = \frac{121}{12.25} = 9.87$

f/3.5 lens is 9.87 times as fast as f/11 lens.

Power requirements $= 25 \times 9.87 = 246.75$ KW

(b) A lens has a diameter of 2", and a focal length of 7". How does it compare in *speed* with a lens of 2 1/2" diameter and 11 1/4" focal length? (Give the numerical value.)

f/no. of 1st lens $= \frac{7}{2} = 3.5$

f/no of 2nd lens $= \frac{11.25}{2.5} = 4.5$

relative speeds:

$\frac{\text{Speed of } f/3.5}{\text{Speed of } f/4.5} = \left(\frac{4.5}{3.5}\right)^2 = 1.65$

f/3.5 is 1.65 times as fast as f/4.5

10. (a) A television camera lens of 9 3/4 inch focal length and a speed of *f*/4.5 is to be used at a distance of 8.94 feet from a studio set. What is the near and far depth of field?

Far depth of Field $= \frac{Cg(g-1)(f/d)}{1-(c/d)(g-1)}$ $f = 9.75"$ $g = o/f = \frac{8.94 \times 12}{9.75} = 11$ $d = \frac{9.75}{4.5} = 2.17$ $c = .005$

$= \frac{.005 \cdot 11(11-1)\,4.5}{1-\left(\frac{.005}{2.17}\right)(11-1)} = \frac{2.465}{.978} = 2.52$ inches

Near depth $= \frac{2.465}{1+.022} = 2.412$ inches

(b) What must the distance be for a lens of 14 inches focal length for the same depth of field?

$O_2 = \frac{f_2}{f_1} \times O_1 = \frac{14}{9.75} \times 8.94 = 12.84$ feet

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(c) The following tests are made on a lens:

A point source of light is located on the axis of the lens, and the latter stopped down until only a small central portion of its area is effective. An image of the point source is focused on a ground glass screen. The lens aperture is then opened up to maximum, and a small circular opaque disc used to cover up the central portion of the lens area. The lens now focuses by means of its peripheral area. It is found necessary to move the ground glass closer to the lens for a sharp image of the point source. What form of aberration does the lens have?

Spherical aberration