PART V

LIGHT

LIGHT SOURCES

L-1. Projection Lanterns. Projection lanterns are of two types, tungsten filament and carbon arc. For ease in operation, the filament lamp is best, but for many experiments the intensely bright carbon arc gives superior results. Each type has its advantages, and both should be available if possible.

For some demonstrations in Light and for many others where a small piece of apparatus if projected may be seen by the entire class, it should be possible to remove independently the projection
lens, the slide holder, and the lens tube or bellows. Then next to the condensing lenses may be placed a shelf or bench on which the apparatus is supported for projection. The projection lens can be mounted on a separate stand. One way of accomplishing this is shown in Fig. 284, where the projection lens \( P \) is supported by an adjustable clamp and pieces of apparatus may be placed on the shelf \( S \), whose height is likewise adjustable.

The lantern should be equipped with a vertical projection attachment, so that objects (such as a dish of water) that must be kept in a horizontal plane may be projected (Fig. 285).

The lantern is also very convenient for illuminating circular openings, slits, and thin films in experiments on diffraction and interference, the objects being placed where the condensing lenses form the brightest image of the source.

**L-2. Incandescent Lamps.** Lamps with straight filaments such as are used in show-window lighting are available in several sizes and power ratings. They are especially useful for diffraction and interference experiments (L-73, etc.).

Miniature lamps (flashlight) are made for operation from batteries or small transformers for various voltages up to 6 or 8 v. Colored Christmas-tree lights operating at 14 v are convenient for some experiments.

Automobile lamps are made in many styles, from the very bright double-filament headlight type (21, 32, and 50 cp) to single-filament lamps having a very short straight length of finely coiled wire. Sockets for these lamps may be obtained from automobile supply houses, or the lamps may be used without sockets by soldering a short length of lamp cord directly to the terminals. A 6-v lamp is a very useful source; it can be run from a storage battery or a transformer, and when operated at 10 v it furnishes an intense light, though its life is shortened.

A “point” source, sold under various trade names, is made by a tungsten arc in vacuum. It consists of a small tungsten bead

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1 For example, General Electric T-6½, T-8; Westinghouse T-14.
that is raised to incandescence by ion bombardment, giving a very intense and steady source of small area.

Photoflood lamps are available that are much more brilliant and much richer in violet light than ordinary lamps, because they are purposely overloaded at 110 v. They are excellent for producing intense illumination as well as for showing by comparison with ordinary lamps the increased whiteness produced by a hotter source. Any standard lamp may be similarly overloaded, e.g., by an autotransformer (E-238).

A convenient holder for standard lamps can be made from a piece of 7/8-in. brass tubing, 10 to 18 in. long, threaded at one end to fit the base of the ordinary keyed or keyless lamp socket. The connecting cord enters through the brass tube. This holder can be clamped in any position on an ordinary stand.

**L-3. Neon and Argon Glow Lamps.** Inexpensive glow lamps equipped with the standard medium base for operation on 110-v direct or alternating current are available. On direct current, they amount to polarity indicators. On alternating current, they give flashes of double the a.c. frequency. They can be used for stroboscopic illumination and as spectroscopic sources in the laboratory but are not bright enough for projection in the lecture room. The argon lamp has enough ultraviolet radiation for some experiments on fluorescence (L-114).

**L-4. Sodium and Mercury Vapor Lamps.** The recently developed sodium vapor lamp makes possible an intense source of monochromatic radiation. It is valuable in demonstrations of color perception, interference, diffraction, and spectroscopy. Quartz mercury vapor lamps are excellent for showing effects of ultraviolet radiation; they are, however, expensive. Less expensive glass lamps are obtainable for lecture and laboratory use, or they may be constructed according to directions given elsewhere.¹

**LIGHT PATHS MADE VISIBLE**

**L-5. Invisibility of Light.** A wooden box, 6 by 6 by 18 in., is constructed with a hinged top and glass front. A hole about 2 in. in diameter is cut in each end and a piece of mailing tube inserted in each hole to reduce stray light. The inside of the box is painted a dead black. A lens of focal length 6 to 8 in. is mounted in one of the end apertures and masked down to about 1-in.

aperture with a black diaphragm. The inside of the box is coated with oil or glycerin to render the interior dust free. A carbon or tungsten arc is placed at the outside focus of the lens and adjusted so that a parallel beam passes through the center of the opposite aperture. No evidence of light can be seen in the interior of the box. This condition will be altered if a white card is introduced into the box so as to interrupt the path of the beam.

**L-6. Optical Disk.** A disk of metal a foot or more in diameter whose surface is painted white and whose rim is graduated in degrees is mounted on an axis about which it can rotate. The disk is supported vertically by a stand that also carries a shield in the form of a short cylinder at right angles to the disk (Fig. 286). An opening is cut in the shield at the height of the center of the disk, over which may be slipped shutters containing one or more horizontal slits. When a parallel beam of light is directed at these slits, the paths of the separate beams passed by the slits are made visible on the surface of the disk. Sections of mirrors, prisms, lenses, etc., may be clamped to the face of the disk and the result of reflection or of refraction made visible. Numerous
experiments in geometrical optics are possible with this apparatus.

A substitute for the optical disk is the following. An open arc (Fig. 287) is mounted on the floor close to the wall and turned so as to send a beam of light upward. A plano-cylindrical lens $L$ is mounted below a slotted cover. The slots are closed with sliding covers so that as each cover is slowly withdrawn a ray is "drawn" up the wall. Cylindrical lenses and mirrors can be introduced above the cover and the paths of the rays traced after reflection and refraction.

**L-7. Optical Tank.** A long trough with glass sides and ends is useful for many experiments. It is filled with water to which a small amount of fluorescein or other fluorescent material has been added, by means of which the paths of the rays of light are made visible to the class. The size of the tank depends in part upon the lenses and other accessories that are to be used with it. A suggested size is 3 by 3 by 36 in. A convenient addition is a mirror running the length of the tank just above it and tipped at 45° so that the class can look down into the tank from above as well as into it from the side. Such a tank is useful for showing reflection and refraction phenomena; it can also be used for showing scattering and polarization (L-127).

The frame supporting the glass sides must be of rigid construction so as to carry the weight of the glass and water without appreciable distortion. Otherwise the stresses are apt to crack the joints. The joints should be made watertight with some form of aquarium cement or glue that will not grow hard and crack during the long intervals when the tank is idle and dry, or peel off and cause leaks when the tank is filled with water.

For reflection, refraction, and total internal reflection, a large flat-sided battery jar filled with water containing a small amount of fluorescein will serve nicely to show the light paths to a whole class. A sheet of flashed opal glass (milk glass) set vertically at a small angle with the beam will make it visible both below and above the surface of the water.
L-8. Gauze Screen. A rectangular wooden frame 2 ft wide and 3 or 4 ft long is held in a vertical plane by a clamp. Across the frame are stretched white threads or fine cotton strings 2 or 3 mm apart. When a lens is placed near one end of the frame and a beam of light directed upon it, the beam after passing the lens will be caught and scattered by the threads so that a large class can see the light paths. By using a small section of a similar screen before the lens, the incident as well as the refracted rays are made visible. A simplification of this plan is to use cheesecloth in place of the threads. It can be stretched tight by fastening it to rectangular metal rods at top and bottom, leaving the sides unobstructed, or it may be held taut in an iron hoop by light helical springs. If two rectangular rods are screwed or clamped together with the cloth between them, at both top and bottom, the upper rods may be held in a clamp, and the weight of the lower ones will keep the cheesecloth stretched. A screen of this type is especially useful for showing lens action, chromatic aberration, spherical aberration, and distortion. The optic axis of the lens should be in the plane of the gauze.

L-9. Smoke Box. A large wooden box, say 15 by 15 by 60 in., is equipped with a glass front and hinged top. Windows are cut in the ends, and the box is painted black inside. When it is filled with smoke or ammonium chloride fumes, the light scattered by the particles will make the light paths visible. (For the method of making ammonium chloride smoke, see A-5.) Lenses, mirrors, prisms, etc., may be set inside the box, so that light paths may be seen before and after reflection or refraction. The box is useful for showing lens combinations, as in telescopes and microscopes (L-54, 55).

L-10. Chalk Dust. A very simple expedient for making light paths visible is to clap two dusty blackboard erasers together above the light beam. The chalk dust will make the beam visible; but the region filled with the dust is limited and variable, and the dust soon settles.

PHOTOMETRY

L-11. Inverse Square Law of Intensity of Illumination. Connect the output of a photocell (A-91) to the lecture-room galvanometer. Remove the condensing lenses from a projection lan-
tern, preferably of the arc type, and place the cell in a position to give maximum galvanometer deflection when illuminated by the lantern. Double and then triple the distance of the cell from the source, and note the inverse square relation.

The way in which area increases as the square of the distance from a point can be illustrated with a wire frame in the form of a pyramid of square section (Fig. 288). If the edge at the base is three units, for example, then a square of edge two units can be placed in the frame at one-third the distance to the vertex and a square of one unit at two-thirds the distance.

**L-12. Joly Diffusion Photometer.**

Two blocks of paraffin (sold in grocery stores) about 2.5 by 5 by 0.5 in. with a sheet of tin foil or cardboard between them are clamped between two strips of thin wood and set vertically between the two sources of light that are to be compared, so as to be seen edge on. The sources are moved until the blocks match in appearance.

The arrangement can be improved and made less perishable by placing the paraffin blocks at the middle of a box open at both ends and painted black inside. The edges of the blocks are observed through a glass window set in one side of the box. The blocks are held between two glass plates, which prevent the paraffin from flowing in warm weather. This arrangement eliminates stray light and makes photometric comparisons possible without darkening the room. The apparatus can be seen by a large class, and quantitative measurements are easily made.

**L-13. Rumford Shadow Photometer.** A laboratory support rod is set vertically 1 ft in front of a screen. The two sources of light to be compared are placed so as to cast separate shadows of the rod on the screen and are moved until the shadows appear to have the same intensity. Electric light bulbs are satisfactory sources; they should be mounted on stands (L-2) so that they can be moved about. The edges of the shadows may be hazy, and there may be marked color differences in the shadows, so that this method of comparison is not particularly accurate. The dis-
Light

L-14. Modified Bunsen Grease-spot Photometer. A triangular box (Fig. 289a) is made of light wood, the long side 26 in., the short side 5 in., and the depth 5 or 6 in. Across the hypotenuse of the triangle is stretched a piece of white paper PP on which is a row of 10 or 12 grease spots made with hot paraffin. A 40-w bulb is placed at S near the side BC to illuminate the spots from inside the box. The inside should be painted white or covered with white paper or Bristol board to help diffuse the light from S to all the grease spots. A light outside the box placed so as to illuminate the paper is moved until its distance is such as to make one of the grease spots nearly disappear. Spots on one side of this then look brighter and on the other side darker than the surrounding area. This apparatus, which illustrates the principle of grease-spot photometers, can be made quantitative in principle, though not, perhaps, very precise, by calibrating it with the aid of an illuminometer (foot-candle meter).

A Bunsen grease-spot photometer and a Lummer-Brodhun photometer may be shown if desired, but they are suitable for observation by only one student at a time. Modern photoelectric illuminometers and photographic exposure meters may be exhibited.

L-15. Rectilinear Propagation of Light. An incandescent lamp is surrounded by a housing, the front of which is closed with a sheet of heavy paper or cardboard. A projection lantern without lenses may be used. By means of a steel wire 1 or 2 mm in diameter, a hole is pricked in the paper, and the light passing through it to a screen will produce thereon an inverted image of the lamp filament. The best size for the hole must be found by trial; too small a hole will not allow enough light to pass through, while too large a hole will not produce a sharp image. As more
and more holes are pierced in the paper, each forms its own image of the filament, and these images may overlap. The illumination of the screen is the result of the superposition of all the different images of the source.

The same effect may be shown by using a 6-v, 32-cp lamp in a small box with a hole in one side. Pinholes of different sizes are made in a disk arranged to turn so that any hole can be brought in front of the opening in the box. The light from each pinhole in turn falls on the screen to produce an image large enough for the class to see. An empty chalk box is satisfactory. The cracks can be closed with black gummed tape. Any of the methods described in L-6 to L-10 may be used for showing rectilinear propagation.

**L-16. Pinhole Camera.** Two boxes are made, one to slide snugly within the other (Fig. 289b). One end of the inner box is closed with a piece of opal glass G. The end of the outer box is closed with a brass plate through which is bored a 1-mm hole H. The observer looks through the end of the inner box at E to see an inverted image of external objects on the glass plate G. The size of image may be varied by sliding the inner box in and out. The camera can be used in a fully lighted room provided that the end E is arranged to fit over the forehead and the bridge of the nose so as to exclude extraneous light.

On a bright sunny day, the pinhole camera effect may be shown on a large scale. The room is darkened, and light is admitted only through a hole 1 or 2 in. in diameter in a curtain or shutter. Inverted images of outside objects or passers-by may be seen on the opposite wall. If the background is dark (e.g., grass, shrubbery, or a brick building), an assistant dressed in white, walking back and forth within the proper area, perhaps waving his arms, makes a good object. With snow on the ground, he should of course wear dark clothes. The size of the image depends upon the distance of the screen from the hole.

A photograph of a local building made with a camera in which the lens has been replaced by a pinhole may be exhibited either as a lantern slide or by opaque projection. To make the pinhole, a thin brass plate is marked with a punch by a sharp hammer blow, and the resulting bulge is filed until the first trace of an aperture appears. With such a pinhole, an exposure of about half an hour in full sunlight is required to produce a photograph of good
quality. Pinholes of reproducible size may be made by puncturing aluminum foil with a sewing needle, noting the depth to which the needle penetrates the foil.

L-17. Speed of Light. It is scarcely practicable to measure the speed of light as a demonstration experiment. However, by using a small mirror mounted on a high-speed top, 1 an appreciable effect over moderate distances may be shown by Foucault’s method. The principle of Fizeau’s toothed-wheel method may be demonstrated by use of sound instead of light (see S-S1). It may be sufficient simply to set up mirrors and light source on the lecture table so that the student may visualize the arrangement of optical parts used in one or more of the standard methods employed for determining the speed of light.

REFLECTION

L-18. Plane Mirror. The virtual image formed by a plane mirror may be demonstrated by superposing it on a real object. A light is placed in front of a sheet of glass, behind which, at an equal distance, is placed a glass of water. The image of the light appears to be in the water. To make the experiment visible to a large class, the apparatus should be mounted on a rotating table so that it can be turned. This also enables the class to see by the parallax effect that the image is located behind the mirror but is fixed with respect to it. If the lecture room is banked so that the seats in the rear are high, it is important to locate the light low enough and to have the sheet of glass tall enough so that the image may be seen from the uppermost seats. A convenient source of light is a candle or a small electric light run from a transformer or storage battery.

A large letter F is cut from cardboard and mounted in front of a plane mirror on a rotating table. The interchange of right and left is evident. With two mirrors set at an angle of 90°, the image can be brought back to proper orientation.

L-19. Reflection at Normal and at Grazing Incidence. The difference in the amount of light reflected from glass near normal incidence and near grazing incidence can be readily shown by holding a large sheet of clear glass in the beam of light from a

lantern. The glass is held near the lantern, set midway between two walls, and the light is reflected first to a spot on one wall nearly in line with the original beam (grazing incidence) and then to another spot on the opposite wall almost behind the source (normal incidence). The intensity of the reflected light at grazing incidence is many times that at normal incidence.

If it is desired to keep the position of the illuminated spot unchanged, the lantern may be turned around through 180° while the mirror is turned through 90°. One may compare the intensity of beams reflected by plane glass and by a well-silvered mirror. At normal incidence, there is great contrast; at grazing incidence, almost none. A single sheet of glass, half clear and half silvered, is convenient for rapid comparison.

L-20. Multiple Reflections in Plane Mirrors. Two plane mirrors, which may be hinged together, are placed on a rotating table so that they stand vertically. Between them is placed a small source of light such as a flashlight or automobile taillight. The multiple images can be seen by a large class if the source is placed close to the vertex of the dihedral angle formed by the mirrors. When a sheet of clear glass held in a slotted block is set vertically between the two mirrors, so as to form approximately an isosceles triangle with them, the number of images visible is greatly increased. By raising the front edges of the two mirrors and slightly tilting the sheet of glass backward, the images can be made visible to those in the raised seats of the lecture room. If the single light source is now replaced or supplemented by several differently colored Christmas-tree lights, some very beautiful effects can be produced, and the principle of the kaleidoscope can be shown to the entire class at once.

By placing two mirrors exactly at right angles to one another, it is possible "to see yourself as others see you." Right and left are interchanged without distortion so that the student has the illusion of looking at himself in a plane mirror, but he may be surprised at the behavior of his image if he winks his right eye!

The number of reflections increases as the angle between the two mirrors is reduced. If two mirrors are placed nearly parallel, the number of reflections is very large ("barbershop effect"). Place a bright headlight bulb midway between two parallel mirrors, and observe the multiple reflections through a peep-hole made by removing the silver from a small area of one mirror.
L-21. Plane Mirrors—Special Combinations. If two plane mirrors make an angle of 90° with one another, then a ray of light incident upon one of them is turned through 180° and reflected back parallel to itself regardless of the direction of incidence, so long as the incident ray is in a plane normal to both mirrors. If three mirrors are mutually perpendicular (like the three faces forming one corner of a cube), then a ray of light incident on the system will be reflected parallel to itself regardless of the direction of incidence. This principle is used in many road signs where the letters or other characters are made of many mirrors of this type. Such reflectors are available at automobile supply stores.

L-22. Laws of Reflection. The fact that when light is reflected from a plane mirror the angle of reflection is equal to the angle of incidence may be shown with any mirror and source of light. However, it is more convenient to use an optical disk (L-6). A beam of light falls upon a mirror whose plane is perpendicular to the disk. By turning the disk and with it the mirror, it is shown that the reflected beam turns through twice the angle through which the mirror is turned.

L-23. Concave Mirror—Phantom Bouquet. This experiment has many forms. The method in all is to superpose part or all of the real image of an object \( O \) (called the "bouquet"), formed by a concave spherical mirror, on some other object \( C \) (called the "vase") so that a person viewing the combination will have the illusion that it is all real (Fig. 290). For satisfactory results, the image \( I \) of the bouquet produced by the mirror must actually fall in the proper position with respect to the vase \( C \) so that parallax will not destroy the illusion. The observer must be able to see only \( C \) and the image of \( O \) and not \( O \) itself, which is the reason for the shield. The illumination of the bouquet \( O \) and of the vase \( C \) must be such as to preserve the illusion. Both should be illuminated in corresponding manners by the same type and intensity of light. Thus \( O \) will be lighted from the side next to the mirror by \( L_1 \), while \( C \) will be lighted from the side next the observer by the light \( L_2 \), all lights to be hidden if possible. The mirror should be as large as possible, but it is equally important to use a mirror
with a large ratio of diameter to focal length. Thus the brilliance is increased and the angular field covered by the image is enlarged. Generally the object is put just below the center of curvature of the mirror, and the part seen is just above it. The class is asked first to see the illusion and then to locate the bouquet.

L-24. A blackened porcelain receptacle is mounted on the under side of the top of a wooden box, and just above it, in full view on top of the box, is mounted a second (white) receptacle. The interior of the box is painted dead black. The black receptacle contains a 40-w tungsten lamp; the white one is empty. A concave mirror is set behind the box so as to form a real image of the lamp above the empty socket. When properly adjusted, the arrangement gives the illusion that the lamp is situated in the upper socket; but when the lamp is turned off by an external switch, the image disappears.

L-25. Concave Mirrors—Caustics. Large cylindrical mirrors that are excellent for showing caustics and other phenomena to a large class can be cheaply and easily made from thin strip metal fastened to a wooden form. Cut out of plywood the shape of the mirror desired—spherical, parabolic, etc. To the curved edge of this form screw or nail a strip of thin nickel or tinned iron sheet about 2.5 in. wide. If now the inside surface of the board is painted white or covered with a white paper or Bristol board, the caustic formed by the mirror is easily seen. A semicircular mirror of 6- to 7-in., radius and a parabolic mirror of corresponding size are convenient. When illuminated by a bright source, they can be seen by a large class.

L-26. Ellipsoidal Mirror. The parallel beam formed by a converging lens using incident light previously reflected from the distant focus of an ellipsoidal mirror is more intense than if the same source is at the nearer focus of the ellipsoid (which is also the focus of the lens) because reflection, in the first case, concentrates the radiation from 180° into a much smaller cone.

Cut out of plywood an ellipse 50 cm long by 30 cm wide, which has a focal length of about 5 cm (Fig. 291). Mount an electric-light socket accurately at each focus. Fasten a strip of monel metal or other highly reflecting material 17 cm wide around the
edge of the board, leaving an opening about 3 cm wide at one end. Place a condensing lens opposite the open end, with one focus at the adjacent focus of the ellipse. Screw into each socket a single-filament lamp (e.g., Westinghouse T-14, 6 v), and cover with black paint that side of the most distant lamp that faces the lens, to insure that the only light that reaches the lens from the distant lamp arrives by reflection from the ellipsoid. By operating the two lamps alternately with the aid of a two-way switch, it will be found that the more intense beam originates at the distant lamp. For a parabolic mirror formed by rotating mercury, see M-143.

**L-27. Convex Mirror.** The reduced, virtual image seen in convex mirrors is doubtless familiar to most students. Distortion of image is frequently observed when parts of an object are at different distances from such a mirror. An amusing example of this distortion is seen when reflection takes place from a convex surface of high curvature, such as a small steel ball (Fig. 292). The ball, $\frac{1}{2}$ in. to 1 in. in diameter, is held 3 or 4 in. away from the observer's eye. The image is viewed with a strong lens. The observer's nose takes on ludicrous proportions. For convenience, lens and ball may be held in a wire frame; if a 4-in. lens and $\frac{1}{2}$-in. ball are used, they may be separated 3 in. The shorter the focal length of the lens, the more exaggerated the effect.

**REFRACTION**

**L-28. Refraction.** The image of a straight wire is projected on a screen. Near the wire on the side next to the projection lens is held a thick rectangular block of glass making a considerable angle with the normal to the light beam. A part of the image of the wire on the screen will be displaced. If thick glass is lacking, a parallel-sided glass vessel of water (projection cell) may be used. Refraction of light by water may be shown with the optical tank (L-7). The ripple-tank method (S-49) of showing refraction
of surface waves is useful for emphasizing the relation of refraction to wave velocity.

L-29. Refraction by Shadow with Cube of Glass. A cube or large rectangular block of glass is placed on a sheet of white paper (Fig. 293). A strip of cardboard or metal of the same height as the block of glass and twice as long is set vertically against it as shown. A straight-filament lamp is placed horizontally with its filament parallel to the edge of the metal strip and in such a position as to throw a shadow of the projecting edge of the strip at the lower corner of the block. The light refracted by the block will fall much nearer the obstacle, and the edge of the shadow within the cube will be easily seen. The index of refraction of the glass can be calculated from the dimensions. The filament and refracting edges may be set vertically and the whole apparatus mounted on a rotating table so as to be more easily visible to the class.

L-30. Refraction Model. An axle 3 or 4 in. long rolls on two independent wheels 1 in. in diameter. It will roll with little friction down a slightly inclined board. If it is rolled at an angle across the line of separation between a plain board and a cloth-covered one, it will change its direction, as a ray of light is refracted. "Total internal reflection" can also be shown.

L-31. Refraction by Gases. The change of index of refraction of air with temperature may be shown by allowing the light from a strongly illuminated pinhole to cast the shadow of a Bunsen burner on the screen (H-137). When the gas is lighted, the rising, turbulent air will be made clearly evident on the screen far above the flame. Any hot object will show the same shadow effect by the convection currents rising from it.

A related experiment may be performed by holding a warm object in the optical path of one arm of a Michelson interferometer. The interference fringes are displaced in the neighborhood of the object (L-72).

L-32. Mirage. A piece of sheet metal several feet long and 3 to 6 in. wide is supported on stands horizontally above the lecture table. It is heated by a row of gas burners placed beneath
it, spaced closely enough so that the heating is fairly uniform. A pipe closed at one end and drilled with a row of closely spaced small holes (M-58) may be used in place of the separate burners. The pipe must be at least an inch in diameter, and the holes must be small; otherwise most of the gas will escape before reaching the far end of the pipe. At one end at about the height of the metal plate is placed a 40-w lamp (Fig. 294). Close to the end of the plate is held a piece of fine ground glass or light paper $B$ on which small figures of trees, houses, etc., have been drawn with India ink. The figures should be about an inch high, and the bottom of the figures or the foreground should be in line with the metal plate. Between the light and the plate may be set a second ground-glass screen $A$ to diffuse the light. If now the eye is placed about on a level with the plate, a "mirage" will be seen. By careful adjustment, the small figures will be seen inverted in the "lake" above the metal plate.

The gas-heated plate of the preceding paragraph may be replaced by an electrically heated unit (Fig. 295). The unit consists of a wooden frame $FF$ about 3 in. square and 9 ft long, to the top of which are fastened five or more bridges $B,B$ of the cross section shown in Fig. 296a. The bridge proper is cut from heavy brass and carries on its top two strips of asbestos tape each 1 in. wide. Beneath the bridge is a block of asbestos or other insulating material that supports four nichrome heater strips of such width and thickness that their resistance will allow them to be connected directly to the 110-v power line and still give a good deal of heat. The top of the wooden frame is covered with asbestos to keep it from scorching or catching fire. To prevent
sagging, both the heater and the asbestos strips are kept under tension by the spring and lever mechanism shown in Fig. 296b. A rectangular frame $LL$ is fastened to the main frame $FF$ by an axle rod at $D$. The asbestos strips are attached to the upper rod of this frame, and the heater strips are attached to an insulating block $N$ that is connected to the lower rod of the frame by springs. It is evident that the springs will keep both sets of strips taut. To prevent the heater strips from touching each other and causing a short circuit, asbestos string is woven between them at appropriate intervals. To confine the heated air and to overcome the disturbance of cross drafts and convection currents, boards some 8 or 10 in. wide and 8 or 9 ft long are placed at either side of the unit. This makes a trough of quiet heated air 3 or 4 in. deep.

![Diagram](image)

**Fig. 296.**—Details of heater shown in Fig. 294: (a) bridge supporting heater elements; (b) spring and lever arrangement for keeping strips taut.

**L-33. Refractive Index—Christiansen Filters.** If a liquid mixture is adjusted to have the same index of refraction as that of a piece of glass immersed in it, light will not be reflected at the interface between the two, and the glass will not be visible. Thus a block of glass lowered into such a liquid by a black thread seems to disappear, leaving only the thread visible. A rod of glass dipped into the liquid and withdrawn seems to drip liquid glass. A parallel-sided glass vessel containing a quantity of finely powdered glass is opaque but becomes transparent when the liquid is added. However, since the two indices of refraction can be the same for only one wavelength, the powder-liquid mixture can be made into an excellent Christiansen color filter. Soft glass should be used, and the composition of the liquid adjusted by trial. The glass is boiled in aqua regia to free it of grease and dirt and thoroughly washed with water. It is then dried and placed in a glass vessel. Enough carbon disulfide is

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added to wet the glass, and then benzene is poured in, a little at a time. As the mixture begins to become transparent, it transmits first red, then yellow, and so on. A permanent setup may be made by drawing down the neck of a flask after the powdered glass has been put into it. The liquid mixture, adjusted to the proper proportions by previous trial, is then added. The flask is packed in a freezing mixture to reduce the vapor pressure of the inflammable liquid and wrapped in a towel to guard against injury in the event of an explosion. The neck of the flask is then sealed off. The cold flask is opaque but as it is warmed up, either with a small flame or with the hands, it exhibits colors.

The following liquids are suitable: cedar oil; glycerin; carbon disulfide with benzene, amyl acetate, or phenyl phthalate. The proportions will depend on the index of refraction of the glass as well as on that of the liquids themselves. Pyrex glass is not suitable on account of its high index; soft glass should be used. Clear fused quartz is very satisfactory.

L-34. Total Internal Reflection. Light incident on the end of a curved rod of glass or fused quartz will, by total internal reflection, be carried to the other end without loss through the sides. The ends of the rod should be square and preferably polished. The light source should be small and bright and placed as close to the end of the rod as possible. By using flashlight or small 6-v bulbs, the filament may be put near the end of the rod. Another way to illuminate the rod is to focus the light from an intense source upon its end. The rod should be passed through tight-fitting holes in two or three screens so that no light can reach the far end of the rod except through it. A white surface, such as a sheet of heavy paper, is held near the exit end of the rod, tilted so that the class can see it, and is illuminated by light emerging from the end of the rod. Most glass absorbs violet much more than it does red, so that even with white light as a source the light that emerges is yellowish.

L-35. Critical Angle and Total Internal Reflection. In Fig. 297 is shown a convenient arrangement for demonstrating refraction and total internal reflection. A large glass jar with parallel sides is filled with water containing a little fluorescein. A plane mirror $M_1$ reflects a slightly convergent beam upon the water surface where it is refracted at $A$. At $B$ it is totally reflected to a second plane mirror $M_2$ mounted on a spindle so that it can
be turned about a horizontal axis by a handle projecting upward. By changing the position of \( M_2 \), the angle of incidence of the beam at the water-air surface can be changed, and critical angle and total internal reflection demonstrated. The path of the beam, both in the water and in the air, is made more visible by placing a sheet of flashed opal glass vertically in the tank, so as to make a small acute angle with the direction of the beam. The beam emerging from the surface of the water can be seen to be colored on account of dispersion by the water.

**L-36. Illuminated Fountain.**

A cone or funnel-shaped vessel (Fig. 298) with a watertight window \( W \), an entrance tube \( A \), and an exit tube \( B \), is arranged to throw a stream of water into the sink. A strong beam of light is focused by lenses through the window to the exit tube. This light is carried by internal reflection along the curved stream of water until it breaks up into drops. The demonstration is enhanced by placing color filters in the path of the light to color the jet. Red, green, and amber filters are especially effective. If no color filters are available, a carbon arc can be used close to the window \( W \), and the light focused by means of the heavy condensing lenses only. On account of the chromatic aberration of the lens, the color of the stream may be changed by moving the arc back and forth through a small distance. Screens should be interposed to cut out stray light.

**L-37. Total Internal Reflection at Glass-air Interface.** Two sheets of thin glass (lantern or microscope slides) separated by strips of paper are fastened together with waterproof cement, so that they have an air space between them. When the plates are immersed in water in an optical tank (L-7) and turned at the proper angle to an incident light beam, they will exhibit total internal reflection.
L-38. Transmission and Reflection near Critical Angle. The image of a brightly illuminated slit is projected on a screen. In the path of the light is placed a rectangular glass container of water in which is immersed the slide with the air film described in the preceding paragraph. When this slide is set so that the angle of incidence is about 49°, part of the light incident on it will be transmitted, and part will be totally reflected off to the side where it may be caught on a second screen. The colors of the two images are complementary in the region of the critical angle. The experiment is most satisfactory if the entire beam falls on the slide and if the light is nearly parallel. In another arrangement, two 90° prisms are placed with their hypotenuses together, the entrapped air film producing the results described. In either case, the resulting beams may, if desired, be dispersed by other prisms and lenses to show two spectra whose colors are complementary. As the device is turned in the neighborhood of the critical angle, the colors are transferred from one spectrum to the other.

L-39. "Mystery Ball." Coat a ball heavily with soot. Immerse it in a jar of water. The soot serves to keep an air film around the ball. It appears bright and silvery when submerged because of reflection of light at the water-air interface.

L-40. Comparison of Total Internal and Metallic Reflection. A test tube is partly filled with mercury, closed with a stopper, and immersed in a jar of clear water in the path of a beam of light from a lantern. When viewed from an angle of about 100° from the incident beam, the light reflected from the mercury appears quite dull in comparison with the light totally reflected at the glass-air surface just above the mercury.

L-41. Reflections from Diamond. A pencil of light is projected toward the class through a small hole in a large sheet of white cardboard. In the beam is placed as large a diamond as procurable, and the reflections, both internal and external, produce a beautiful pattern on the cardboard.

L-42. Dispersion by a Prism. Since index of refraction is a function of frequency, it is possible to break up white light into the familiar colors of the spectrum. Light from a straight-filament source or a strongly illuminated slit $S$ is focused on a screen by a projection lens $P$ (Fig. 299). A prism of glass or a hollow prism filled with carbon disulfide is introduced into the
beam beyond the projection lens. A continuous spectrum is thus formed on the screen.

L-43. Rainbow. A vertical slit is illuminated by a beam of parallel light from the lantern as in the preceding experiment. In the beam from the slit is placed a glass beaker filled with water. Two spectra may be seen on a screen placed between the slit and the beaker and to one side.

The projection lens is removed from an arc lantern, and the position of the arc with respect to the condenser is adjusted to produce a parallel beam which is directed toward the class. The beam passes through a 4-in. hole in the middle of a white cardboard screen 3 ft square and falls on a spherical flask of water 4 in. in diameter, set 2 ft from the screen. A black disk is placed just beyond the flask to prevent glare. On the screen there appears a circular spectrum, with the red outermost, representing a primary rainbow.

L-44. Rainbow Droplets. Coat a sheet of glass with soot from burning turpentine. Spray the surface with water droplets from an atomizer, and illuminate the surface by a strong parallel beam of light. The water droplets do not wet the plate; hence they are spherical because of surface tension. When they are viewed from an angle of about 41°, the droplets glisten like individual colored jewels. Drops about 0.5 mm in diameter show best. They should be allowed to fall on the plate perpendicularly, as they will otherwise bounce off.

L-45. Artificial Rainbow. Form a horizontal spectrum as in L-42. Place a tube of water 1.5 in. in diameter between prism and screen so that the tube is perpendicular to one edge of the prism. A “rainbow” in the form of a vertical circle is cast upon the screen or the walls of the room.

L-46. Scattering of Light—“Sunset Experiment.” A circular opening in a sheet of metal is strongly illuminated with the light from a projection lantern and an enlarged image of the opening,
the “sun,” is projected on a screen. The room should be darkened and stray light eliminated. Between the circular opening and the projection lens is placed a glass vessel with parallel sides 5 in. apart, which is nearly filled with a measured quantity of clear water (distilled if necessary). The clear water scatters very little light, so that the “sun” is white or perhaps yellow. Then 10 ml of concentrated solution of photographic hypo (sodium thiosulfate) and 3 to 8 ml of 5-normal solution of either hydrochloric or sulfuric acid are added for each 500 ml of water. The exact amount and concentration of the acid are not critical. In about a minute, colloidal sulfur will begin to form, and the beam passing through the liquid will look bright blue by scattered light. The number and size of the scattering particles increase so that in from 2 to 8 min, depending on the temperature, even red light will no longer be transmitted. The temperature of the water should be between 20 and 30°C for most satisfactory results.

LENSES

L-47. Image Formation by Lenses. A number of fundamental experiments showing the relation between image and object distances and focal length may be performed by casting the real image of a lamp filament upon a screen, using various distances and various converging lenses of different focal lengths. Images of different size are cast by different lenses, keeping lamp-to-screen distance constant. Conjugate foci may be shown for constant lamp-to-screen distance by setting a given lens successively at two predetermined points. Finally, after casting a sharp image of the lamp filament (or other object) upon the screen, move the lens away from the object until the image is blurred. Then pick up a sharp image between lens and screen, by moving a piece of white cardboard or opal glass along the light path to the correct image position.

L-48. Action of a Lens. Enclose a bright source (automobile or clear-glass incandescent lamp) in a tubular housing with aperture the size of a converging lens. Adjust the lens to cast an image (not too large) of the filament on a screen. Move the lens aside, and close the end of the housing with a metal foil containing many pinholes. Many images of the filament will thus be
formed on the screen (L-16). Now move the lens back to its former position, and show how it collects the many images into a single image.

L-49. Chromatic and Spherical Aberration. A large thick spherical lens, preferably plano-convex, is most satisfactory for demonstrating aberrations. The lens should be provided with several diaphragms, one allowing only the central portion of the beam to pass, a second allowing only an annular portion near the edge of the lens to pass, and a third having two pairs of small round or various-shaped openings, one pair nearer the center than the other pair. A small opening at the focus of the condensing lenses of a projection lantern is the light source. The lens $L$ to be studied is placed far enough from this opening to be illuminated all over and so that it forms a real image of the opening. The beam of light after leaving the lens may be made visible by the trough, the gauze screen, or the smokebox (L-7, 8, 9). The gauze screen will probably show the colors best. Another method is to have the beam from the lens pointed toward the class, interrupting it with a movable translucent screen or a sheet of ground or flashed opal glass or a smooth white paper that is not too heavy. By moving the screen, the changing cross section of the beam may be shown in a manner that enables the student to grasp the idea of image formation. The distance between the focus of the rays passing through the center of the lens (first diaphragm) and that of the rays passing through the annular diaphragm near the edge of the lens (second diaphragm) is a measure of the spherical aberration. With the latter diaphragm, a ring of light is formed on the screen and is clearly seen to be fringed with color, red when the screen is on the side of the focus toward the lens and blue when it is on the opposite side. Tipping the lens seems to tie this ring into a bowknot. The central beam and the four-opening diaphragm help to show the formation of aberrations. By turning the lens with first one side and then the other toward the light, the effect of relative position on aberrations can be demonstrated. With a plano-convex lens, the difference is marked if the object and the image distances are very different. By using large magnification (source placed only very slightly beyond the principal focus), the distance between the foci for the rim rays and for the central rays can be made as great as 2 ft, using an ordinary lantern condensing lens.
Instead of an illuminated opening, a small concentrated-filament automobile or flashlight bulb run at rated voltage or slightly over may be used. No diaphragm is then needed except to limit the beam so that stray light will not blind the class. Another satisfactory source is a 200-w clear-glass incandescent lamp, with the plane of its filament perpendicular to the optical axis of the system. The lamp should be enclosed to reduce stray light.

L-50. **Effect of Medium on Focal Length.** Place a lens in a parallel beam of light, and determine its focal length. Then immerse the lens in a tank of water (L-7), and find the new focal length. Since the focal length of a lens immersed in water is approximately four times that of the same lens in air, it is important to use a lens of short focal length. If a long tank is not available, the experiment may be performed with the lens in a small vessel, such as a projection cell, with parallel sides.

L-51. **Astigmatism and Distortion.** A coarse wire mesh or a lantern slide ruled with a rectangular network of horizontal and vertical lines is used as an object and is illuminated by light from the condenser lens of a lantern. Large condenser lenses of rather short focal length are then used to form a much enlarged image of the mesh on the screen. If the lens is turned about an axis parallel to either set of wires or rulings, there will be found two positions of the screen, for one of which only the horizontal lines are in focus; for the other, only the vertical lines are in focus. A concave mirror will show a similar effect. A set of radial lines may be used instead of the rectangular mesh.

L-52. **Distortion.** A piece of wire gauze or a glass plate ruled with a rectangular network is placed in the beam of light from a lantern, perhaps 5 cm from the condenser lenses. An image of the mesh is cast on a distant screen by a double convex lens. When a diaphragm is placed in front of the lens, as in Fig. 300a,
barrel-shaped distortion of the image results. If the diaphragm is placed on the other side of the lens (Fig. 300b), and several times its focal length away, pincushion distortion of the image will be seen. The size and location of the diaphragm must be determined by trial. In the first case, the hole should be less than 1 cm in diameter; in the second case, a somewhat larger hole works better. The sheet in which the hole is made should be large enough to shield the screen from stray light from the lantern.

The single lens may be replaced by two lenses, 6 to 10 cm apart, whose combined focal length is about the equivalent of the single lens. The two types of distortion can be shown as before, but if the diaphragm is placed between the two lenses, there is no distortion.

OPTICAL INSTRUMENTS

L-53. Microscope. The action of a microscope can be explained with the aid of wall charts published by the makers of microscopes to illustrate the formation of the image in their respective instruments.

L-54. Model Microscope. The essential optical parts of a microscope may be demonstrated on a moderately large scale by using a good-quality lens of short focal length and a large reading glass. The first lens (objective) is placed close to some small brightly illuminated object so as to produce an enlarged real image of it. The reading glass (eyepiece) is set a short distance above this image. A mirror above the second lens inclined at 45° enables those looking at the system to see a greatly enlarged virtual image of the illuminated object.

The whole system may be mounted on a rotating stand so that the mirror may be turned toward each member of the class. It is possible to make a number of minute effects visible to several students at once by use of this optical arrangement, e.g., Brownian movements (A-51), Newton’s rings (L-71), etc.

L-55. Telescope. Astronomical, terrestrial, and Galilean telescopes can be shown diagrammatically. They may also be set up for demonstration by suitable combinations of lenses mounted on an optical bench. Each student may look through the lenses individually; but if projection is used and an image is formed on a screen so that the whole class can see it, the rays of light entering
the objective and leaving the eyepiece are no longer parallel, and this point in the operation of the telescope is lost.

**L-56. Telephoto Lens.** The simple camera lens is easily demonstrated by forming a real image of some object on a screen; telephoto or other special camera lenses can be demonstrated also. The object, illuminated with the condenser system of a projection lantern, may be a wire mesh or crosshatch ruling \( R \) (Fig. 301). A circular hole in a diaphragm \( D \) limits the area utilized. The lens \( L_1 \) is placed at its focal distance in front of the object, thus giving a parallel beam, so that the lens \( L_2 \) can be at any distance from \( L_1 \). It forms an image of the mesh and diaphragm in its own focal plane; this image is formed on a screen, and the diameter of the image of the diaphragm opening and the distance from \( L_2 \) to the screen are measured. When a concave lens \( L_3 \) is inserted in the light path between \( L_2 \) and the screen, the screen must be moved farther back to focus the image, but the magnification is much greater. The diameter of the image and the distance from \( L_2 \) to the screen are again measured; it is found that the magnification ratio greatly exceeds the lens-to-screen ratio, which is the purpose of a telephoto lens. The wire mesh used as object helps to secure a sharp focus, while the diaphragm provides an easily visible image.

**L-57. Lens Combinations.** Several fundamental principles of lens combinations can be illustrated by a pair of lenses so mounted that principal foci, principal planes (magnification of +1), and the symmetrical conjugate planes (magnification of −1) of the system are outside of the combination. Such a system can be constructed by mounting two projection-lantern condensing lenses of about 18-cm focal length in a 10-cm stovepipe about 60
cm apart, plane sides out. A lamp filament placed about 70 cm from one end produces an erect real image of the same size at the same distance from the other end. If placed 20 cm from one end, an inverted real image of the same size will appear at the same distance from the other end. The principal foci of the system are, of course, midway between the two positions of the object and of the image respectively.

THE EYE

L-58. Blind Spot. Every human eye has one spot that is blind—the portion where the optic nerve enters the eye. To demonstrate this fact, a white circle is mounted on the blackboard, and a white cross of about the same size is moved slowly across the board toward the circle. The student closes one eye and fixes his gaze on the circle, seeing the cross out of the corner of his eye. In the position where the image of the cross falls on the blind spot, it disappears. Alternatively, each student may locate his own blind spot by moving about a card held 10 in. from his eye and marked with a black circle and black cross. If his attention is fixed on the circle, he will find a spot where the cross disappears. Circle and cross should be 3 in. apart.

L-59. Inversion of Image on Retina. Three holes are drilled in a brass plate with a No. 60 drill at the corners of a small triangle 2 mm on each edge. The plate covers one end of a tube 1 in. long; the other end is closed with a similar plate having a single hole through it. If the three holes are held close to the eye, with the triangle standing on its base, the pattern on the retina will be three circular patches of light in a triangle standing on its vertex. The system of holes limits the light entering the eye to three pencils originating so close to the eye that they cannot be inverted by the lens. Hence distant objects viewed through the instrument will appear “right side up,” whereas the orientation of the triangular pattern demonstrates conclusively that the image on the retina is inverted.

L-60. Fluorescence of Retina. Turn toward the class in a dark room a strong ultraviolet source (quartz mercury lamp or arc) screened to exclude all visible light (L-114). Call attention to the luminous haze that covers the field of view of each individual.
L-61. **Visual Fatigue.** The eye quickly becomes fatigued after looking steadily for a few seconds at a single color. It is possible to produce the effect in a fully lighted room by projecting a bright spot of color on a screen. After the spot has been observed steadily for a few seconds, it is extinguished, and a spot of the complementary color appears in its place. It is important not to shift the eyes during the progress of the experiment. Red, green, yellow, and blue filters give the best effects.

L-62. **Color Blindness.** Slides with a large number of colored rectangles are obtainable by which the usual types of color blindness may be tested. Directions are provided with the slides. Each member of the class is asked to write down the numbers of those rectangles which resemble a test color; the numbers may then be quickly checked against the correct numbers. In many cases, students discover color blindness of which they were unaware prior to the test. Color-blindness test charts are also available but are better suited to individual than to class use.

L-63. **Chromatic Aberration of the Eye.** A purple filter is mounted in front of a clear-glass tungsten lamp having straight filaments. The eye has difficulty in focusing simultaneously on both the red and the blue images. The effect cannot be seen well from a distance; nor is it the same for all individuals.

L-64. **Astigmatism.** Astigmatism is usually tested by observing a chart bearing a set of radial black lines. To the normal eye, these lines appear equal in intensity, but to an astigmatic eye they appear in varying degrees of sharpness, depending upon the direction of the axis of astigmatism.

L-65. **Eye Models.** A spherical flask is filled with slightly milky water to represent the eyeball. A large lens is placed near the flask so as to bring the image of a bright light to a focus on the far side of the flask. Vertical motion of the light shows that the image on the “retina” is inverted. Motion of the source toward the “eye” shows the necessity for accommodation, and adjustment of the lens position shows such accommodation. Moving the lens so that the focus is beyond or in front of the “retina” shows near- and far-sightedness, and these defects can be corrected by proper selection and combination of lenses.

Several apparatus companies make a model of the eye that can be shown in the lecture, but it is more valuable as a laboratory apparatus where the student himself can work with it.
L-66. Eyeglasses. A study of lenses and the defects of the eye may be made more vivid by borrowing the glasses of members of the class and testing them in the light from the lantern. The lenses are held near the screen and drawn back from it to locate the position of best effect. The type of lens can be inferred from the image formed.

Using the projection lens, throw on the screen an image of a slide showing concentric circles crossed by radial lines, making this original image very sharp. Now place over the projection lens another lens, say a diverging one. The image becomes blurred, as it would look to a person with faulty vision. Correct it by placing in front of the diverging lens a converging lens of the same power. Repeat, using converging, diverging, and cylindrical lenses, each time bringing the image back to sharp focus with a lens of the opposite kind. Spectacle lenses of 1 or 2 diopters power are rather inexpensive and can be secured in matched pairs either from a local optician or direct from the manufacturers. As a by-product of this demonstration, some students may be induced to have their eyes examined and secure much needed glasses.

INTERFERENCE AND DIFFRACTION

L-67. Interference—Color of Thin Films. Interference colors in a thin film can be projected so that a large class may see them. A Gooch funnel or a flat metal ring is dipped in a soap solution and is then held in a clamp so that the film formed across its mouth is vertical. It is more convenient to clamp the funnel or ring in the proper position and then to form a soap film upon it by drawing across its mouth a piece of paper dipped in soap solution. A beam of light from an arc or projection lantern is brought to a focus just beyond the film, and a greatly enlarged image of the film is then projected on the screen with a fast lens \( L \) (Fig. 302) of short focal length, placed so that the angle between its axis and the normal to the film is equal to the angle between the normal and the axis of the incident beam. As the water runs out of the film, the film grows thinner at the top (which is the bottom of the image on the screen). New spectral orders appear until the film is so thin that it becomes black at the top. Soon after the top of the film turns black, it generally breaks. The durability of the film may be increased by decreasing its diameter, so that one should
use as small a funnel as is consistent with visibility on the screen. To diminish convection currents in the funnel, the end of it may be closed with a cork through which a small hole is cut to preserve pressure equilibrium. The number of visible spectral orders is increased by interposing a red filter between the light source and the film. If a gentle air jet is played on the film, the colors are mixed in a beautiful manner.

**L-68.** The colors produced by interference of light in a soap bubble may be shown by holding the bubble in front of an extended source of light in a darkened room. The source is provided by housing a 100-w lamp inside a box in one end of which a piece of flashed opal or ground glass is fitted. The bubble should be held near the ground glass but should have as dark a background as possible. Under a strong monochromatic source of light or a mercury vapor lamp (L-4), the colors are replaced by alternate light and dark rings.

**L-69.** The Boys rainbow cup is a hemispherical shell that can be rotated about a vertical axis. When a soap film is formed across the open top of the cup and the latter is turned rapidly, the film becomes thinner toward the center on account of centrifugal force, and circular colored fringes are formed. Rotation may be continued until the black spot appears at the center. If the motion is quickly stopped, the black spot may break up into several irregular pieces. The film should be protected from air currents by a transparent cover. The color pattern may be projected as previously described (L-67).

**L-70. Interference in Thin Air Films.** Two large pieces of plate glass are laid on top of one another on the table. A broad

![Fig. 302.—Method of projecting interference colors in thin films.](image-url)
sodium flame or a mercury arc is placed so that it may be seen reflected in the glass. The interference fringes are generally separated well enough to be seen easily.

If an optical flat or its equivalent is available, pieces of glass may be laid on it, and from the contour of the fringes observed, the character of the irregularities of the glass surface may be inferred. If some of the test pieces are also optically flat, their straight even fringes may be compared with the crooked ones of the other samples to show the optical method of testing surfaces.

**L-71. Newton's Rings.** When a plano-convex lens of very small curvature is held with its convex side against a plane piece of glass, a thin film of air is included between the two pieces of glass, the thickness of the film increasing with increasing distance from the point of contact. The colored rings formed in this way may be projected by the same optical arrangement as that shown in Fig. 302, by placing the lens and plane glass in the position occupied by the soap film (L-67). When a red and a blue filter are alternately placed in the incident light beam, it is very easy for the class to see the change in size of the rings due to change of wave length.

A more elegant but more elaborate way of illuminating the ring system is that shown in Fig. 303. A strong arc or 1000-w projection lamp $S$ is focused by the condensing lens $L$ on a variable slit. The light from this slit passes through a lens $L_2$ and a large carbon disulfide prism $P$ to form a strong spectrum at $ABC$. The Newton's-rings apparatus is placed at $N$ near the center of this spectrum, and by means of a fast lens $L_3$ a magnified image of the ring system is formed on the screen. Now by turning the prism $P$ back and forth, different colors will fall on $N$ so that the rings will change color and size. By not making the spectrum too large, and by using a fairly wide slit, fast lenses and a large liquid
prism the effect will be bright enough for a fairly large class to see.

**L-72. Michelson Interferometer.** The Michelson interferometer can be demonstrated to large classes. The interferometer is first adjusted for monochromatic fringes and then for white-light fringes by getting the light paths equal. The beam from a strong source (carbon arc) is focused on the first mirror, using a water cell to reduce the heat. With a rather short focal length, high speed lens (4 in., f 4.5) from a camera, the fringes may be projected on a screen. In case the direction of the beam emerging from the interferometer is not that desired for projection, a plane mirror of good quality may be interposed. The fringes may be easily seen if they are projected on a flashed-opal screen facing the class. If a hot wire or the hot stick of a match that has been lighted and blown out is placed in one arm of the interferometer, the distortion produced by change of index of refraction of the air due to heating will be evident (L-30).

**L-73. Single-slit Diffraction.** Each student in the class may observe the diffraction of light through a narrow slit by simply holding two adjacent fingers directly in front of one eye and observing a straight-filament lamp through the narrow aperture thus produced. The fingers must be held parallel to the filament and very close together (see also L-82).

**L-74. Diffraction by Straight Edge.** Pieces of razor blade are cemented between sheets of cellophane to eliminate danger of injury and are distributed to the members of the class. An enclosed carbon arc is set in the front of the room pointing toward the class. If the edge of a blade is held close to the eye so as to cut off part of the light from the arc, interference fringes due to diffraction will be observed far into the shadow. Screening the arc with red glass may improve the visibility of the fringes. In this case, stray light should be eliminated, since the intensity is reduced by the glass.

**L-75. Diffraction by a Feather.** A bright source is focused by a condensing lens $L_1$ (Fig. 304) on a vertical slit. The lens $L_2$ forms an image of the slit at $A$, where a vertical obstacle like a tripod rod intercepts the light. A feather or other similar object is placed at such a position $O$ that the lens $L_2$ forms an enlarged image of it on the screen. This image will be formed by light diffracted by the feather and hence deflected so as to pass the
rod, which intercepts all of the light in the direct beam so that without the feather in position the field is dark. A 1000-watt lantern bulb will give sufficient light so that a large class can see the effect. The slit may be 1/4 to 1/3 in. wide and the obstacle 1/8 in. wide. The slit is put at the place where the condensing lens of the lantern forms the image of the filament. The lens $L_2$ should be achromatic. The finer the texture of the object at $O$ the more striking the result; feathers are especially good, but fine waste or a coarse transmission grating will serve.

Small feathers mounted between microscope slides may be passed around the class so that each student may look through a feather at a bright point source to observe diffraction.

![Fig. 301.—Projection of image by diffracted light.](image)

**L-76. Diffraction Box.** Many diffraction demonstrations are greatly facilitated by a permanent, though semiportable, diffraction box (peep show) 30 cm square and some 5 m long. At one end is a door, through which the source, lens, and a color screen may be adjusted. About 75 cm from this end is a partition in which the small aperture is mounted; it is accessible through a door in the side of the box. A holder for diffraction specimens and masking screen is mounted on a small tripod that is movable to any part of the box. The other end of the box is provided with an interchangeable holder for an eyepiece or viewing screen. Distances that have been used with good results are the following: slit to diffracting object, 202 cm; object to eyepiece, 237 cm; width of object, 0.55 cm; this gives 1.2 cm for the width of the diffracted image when light of wave length 5461 (mercury arc) is used.

**L-77. Fresnel Diffraction.** A bright light $A$ (Fig. 305) is focused by means of lens $B$ on a pinhole at $C$. The light spreads out, illuminating the screen $G$. At some intermediate point are placed such objects as pins, screws, fine wires, and small slits. Their shadows on the screen show striking diffraction patterns. A slit at $C$ will give more light than a pinhole and is satisfactory
for pins, slits, and edges but does not give two-dimensional diffraction and so is not good for screw threads, holes, and round objects. A masking screen to eliminate unnecessary light is advisable.

**L-78. Diffraction about Circular Object.** A bright light A is focused on the pinhole C (Fig. 306). A small round object such as a coin or steel ball is held at N; it may be hung by fine wires, or it may be fastened to a sheet of clear glass. At S is a card with a small hole in it. The light diffracted around the edge of the object will make it look as if it were surrounded with a ring of light when S is at the proper place. If a large hole is cut in the card at S and covered with thin paper with a small hole in its center, the observer can see the geometrical shadow of the object and so is all the more surprised to see the ring of light. This shadow also helps when lining up the parts. Red and blue glass filters may be used to show the effect of change of wave length. The distances are variable over a wide range. Thus CN may be 10 ft, and NS 2 ft. With a steel ball or a coin as object, CN may be 3 ft, and NS 10 ft. A telescope or magnifying eyepiece may improve the results. If the object is viewed from the proper distance along the axis of its geometrical shadow, its center appears bright as if light actually passed through it.

**L-79. Crossed Gratings.** Each student as he comes into the room is given a small square of silk, through which to view an automobile headlight lamp, to observe two-dimensional diffraction by crossed gratings. Certain feathers show the effect. Fine-mesh wire screen also serves well. A refinement is described in A-109.

**L-80. Diffraction by Red Blood Corpuscles.** Smear a drop of blood uniformly on a microscope slide, and protect it with a cover glass. Place the slide close to the eye, and look at a bright point.
source of light. Beautiful diffraction rings are observed. To project the pattern, place the slide 5 to 10 cm away from a point source, and form its image on a screen by a projection lens of 30-cm focal length. In pernicious anemia, it is important to know the average size of blood corpuscles, which can be determined by measuring the diffraction rings.\(^1\)

**L-81. Halos.** A 3-in. hole is cut in the center of a piece of white cardboard about 2 ft square. A beam from a well-shielded point source of light is converged on this hole, so that it disappears within it. If necessary, to reduce stray light, the beam can be absorbed in a black box or by black cloth placed behind the screen. In the beam is held a glass plate 1 ft square, which has been allowed to collect a thin layer of fine dust but which is otherwise clean. Its distance from the cardboard screen is adjusted until circular halos appear on the cardboard screen around the hole. The distance from plate to screen is several feet. The effect may be temporarily enhanced by breathing on the plate. Instead of dust, a very thin sprinkling of lycopodium powder may be used, and the plate covered with another sheet of glass, the two being bound together.

Several of the previous experiments may be combined so that students may observe them one after another as they enter the classroom. The setup is that for diffraction around a circular object (L-78). On one side is a silk handkerchief on a frame, on the other the dusty sheet of glass. The same source of light serves for all. The halos contrast strikingly with the crossed-grating effect; they help to illustrate the powder as contrasted with the crystal type of x-ray pattern. This contrast may also be shown by the rotating crossed grating (A-109).

**L-82. Diffraction by Single and Double Slits.** Each student is provided with a small piece of photographic plate, on the fogged emulsion of which have been ruled a single line and a pair of

\[^1\text{Piper, A., Med. J. S. Africa, August, 1918.}\]**
parallel scratches, the latter 0.2 to 0.5 mm apart. A very bright straight-filament lamp is set in view of the whole class, who can then individually observe single-slit diffraction and the colored interference fringes from double slits. If the upper half of the filament is covered by a red filter and the lower half by a blue one, the variation in diffraction patterns and in fringe widths is very marked. The filters should be as close to the light as safety will permit. Very good filters for this and other experiments can be made from one or two thicknesses of colored cellophane. The cellophane is clear enough to see through easily, and it can be bent around the source so that the straight filament can be viewed from all directions.

The ruling of the double slits is greatly facilitated by the use of a tool made for the purpose. A brass rod is drilled with two holes in the end, into which steel phonograph needles are fastened. The rod is then flattened in such a way that the distances of the needles from the flat side differ by the desired separation between slits (Fig. 307). With this tool and a straightedge, it is a simple matter to rule equally spaced double slits on an old exposed plate. If the rulings are made about \(\frac{1}{2}\) in. apart, the plate can, after ruling, be turned over, marked into squares with a glass cutter, and broken up so that each student can have a section.

**L-83. Projection of Single- and Double-slit Patterns.** With the exception of grating spectra, most diffraction experiments are too faint to project so that a large class can see them. In the grating, the light is increased by having many slits, and the effects of all are brought together by the projection lens. The same result may be attained for single and double slits as follows. On a fogged photographic plate (lantern-slide size is convenient) is ruled a large number of parallel but unevenly spaced slits. On another plate is ruled a large number of pairs of slits, the spacing of each pair being constant.\(^1\) For protection, these plates may be covered with a clear glass and bound like lantern slides. A bright source is focused on a slit (Fig. 308), and by means of an achromatic lens a sharp enlarged image of the slit is

\(^{1}\)But like the previous plate, the successive pairs of rulings are separated in random fashion.
thrown on a screen. If now the ruled plates are introduced at $P$ near the lens with their rulings parallel to the illuminated slit, the image on the screen will be that of a single slit for the first plate and that of a double slit for the second plate. Knowing the double-slit spacing, the distance between lens and screen, and the distance between fringes on the screen, the wave length of the light may be calculated roughly. Frequently the red and the blue edges of the pattern are distinct enough to permit the computation of both wave lengths. The relation between the single- and the double-slit patterns is clearly shown, especially if the plates are held so that as they are moved up and down first one and then the other is before the lens.

The intentional inequality of the spacing of the lines on the first plate destroys the regularity of the pattern due to $n$ slits within the single-slit envelope sufficiently to wipe it out without affecting the width of the single-slit pattern produced and superposed by the individual slits. The same cause operates in the second plate through inequality of the spacing between the successive pairs of equally spaced lines.

**L-84. Fresnel Biprism.** A Fresnel biprism may be used in a spectrometer for a “peep-show” type of demonstration or in a carbon-arc projection lantern for projection on a screen. In the latter case, the arc should be retracted, and the slide holder pushed forward until a slit in the slide holder is illuminated by the image of the arc formed by the condenser lens. The image of the slit is focused on the screen by the projection lens; the biprism is placed between the slit and this lens and adjusted until the best pattern is obtained on the screen. The pattern is similar to that of a double slit.

**L-85. Diffraction Grating.** By means of an achromatic lens, an enlarged image of a brightly illuminated single slit is projected on a screen (Fig. 308). Near the lens on the side toward the slit is inserted a coarse grating. Fine copper screen of 100 to 200

![Fig. 308.—Projection of diffraction patterns from slits or gratings.](image)
wires per inch is satisfactory; finer mesh is still better. Such coarse gratings can also be made by photographing a drawing of equally spaced lines. The spectrum will be visible for several orders on each side. If a grating having several thousand lines per inch is used, it cannot be placed near the lens but can be placed in the converging beam of light not too far from the screen. The spectrum will show up clearly if a fairly large replica grating is used so that it transmits plenty of light through the ruled area. Wave length of light can be calculated approximately from the known grating space, the measured grating-to-screen distance, and the distance from the central image of the slit to any particular color in any order of the spectrum.

L-86. Resolving Power. The two filaments of a double-filament automobile headlight lamp are so spaced as to be at the limit of resolution of a normal eye, when somewhat dark-adapted, at a distance of about 25 to 30 ft. Hence, students in the front half of an average classroom will be able to see both filaments, those in the rear half will see only one. Both filaments are lighted simultaneously, and the brightness for best seeing is adjusted with a rheostat.

One way to help students to see what is meant by resolving power is to show slides of the “Navicula” made with the ultraviolet microscope in green (5461) and then in the ultraviolet light of the mercury-arc line 3650.1

COLOR AND RADIATION

L-87. Color. When an object appears colored (barring psychological or physiological tricks like those described in L-61 and L-94), three conditions must be fulfilled: the color must be in the illuminating source; the object viewed must be capable of reflecting or transmitting the color; the detecting device—eye, photocell, photographic plate—must be sensitive to the color. The following demonstration illustrates the first and second conditions; it can be modified to demonstrate all three (see also color blindness, L-62). Arrange where they will not conflict with one another the following sources or their equivalents: a mercury arc, a sodium flame or arc, a deep-red (not orange) lamp like those used for photographic work, a white desk light. A real blue-violet light is good if available; it can sometimes be made by

1 These slides are made by A. P. H. Trivelli of Eastman Kodak Co.
using filters. As the class comes into the room, have them examine colored cardboard, colored yarns, or anything else under the several lights, the white one last of all. If the class is told beforehand to come wearing gaudy ties or to bring other brightly colored objects, so much the better. For the uninitiated, the effects are surprising. The room must be darkened, and the lights must not interfere with one another. However, this is easily accomplished by screening the sources in separate stalls or by putting some on the floor under tables and the others on the tables.

The preceding method may be modified by using the projection lantern as a spotlight with colored filters. On a large piece of beaverboard are arranged a number of squares of colored paper, cloth, or other material such as flowers or green leaves. If one wishes to take the trouble to cut large letters out of construction paper and spell out in their appropriate colors the words red, orange, blue, green, black, and white, it is easier for the class to remember the colors of the different letters in white light. Inexpensive filters may be made by mounting colored cellophane between sheets of glass like lantern slides. Two or three thicknesses of a given color may be required to give the best results.

Another modification is to project on a white screen a large bright spectrum (L-106), in the various colored regions of which are held pieces of colored paper, flowers, etc. The effects are striking, and with a little practice the component colors of such things as leaves may be quickly identified. The strong red in many green plants is a surprise to most persons.

L-88. Combination of Colors by Addition. Arrangement is made to illuminate a white screen with several colors of light simultaneously. The sources should be capable of motion so as to cause the different colors to overlap or not as desired.

A simple arrangement consists in mounting electric lamps and color filters at the corners of an equilateral triangle having a white surface (Fig. 309). The filters give the primary colors, red, green, and blue, and the lamps and filters are chosen so that the combination of all three colors at the center of the triangular screen produces white, while any possible combination of the primaries will be found at some point on the screen. If a rod is mounted at the center of the screen, the colors of the three shadows radiating from the center will be the complements of the
primary colors. With two rods set up so that their shadows cross, the third primary color will show at the point of intersection. When a triangular pyramid is attached at the center of the screen so that one edge faces each of the lamps, each surface will show a mixture of two primary colors.

**L-89.** Apparatus is commercially available for attachment to a projection lantern so as to produce three independent light beams, which may be colored with filters. The three spots of colored light so formed on a screen may be made to overlap in any desired manner to show combinations of two or three colors. A simple substitute for this apparatus is the following¹ (Fig. 310). Three Wratten filters, Nos. 19, 47, and 61, are cut in the shape of sectors of a circle with an angle of $120^\circ$ at the center of each. They are laid on a sheet of clear glass so that they fit accurately at the center, cemented around the outside edges, and covered with another sheet of glass, which is then bound to the first like a lantern slide. If such filters are not available, colored cellophane

may be used—two thicknesses each of red and of dark blue and two or three of green. The light from a projection lantern passes through a 1-in. hole H cut in a screen held in the slide holder. The condenser C of the lantern is arranged so as to bring the image of the filament just beyond the projection lens P when the image of the hole is on the screen. The color-filter slide is held in front of this projection lens, exactly at the location of the image of the source, thereby coloring the spot of light on the screen in a manner depending upon the ratios of the illuminated areas of the three filters. To show how the light is divided among separate colors, a piece of plate glass may be inserted in the beam at an angle of 45° to its axis. The portion of the light thus removed from the beam is reflected by a plane mirror M parallel to the plate glass through a second projection lens, which focuses an image of the filter on the screen close to the spot of colored light, i.e., the image of the hole.

**L-90. Combination of Colors by Subtraction.** Instead of adding colors as in L-89, they may be combined by subtraction. A strong beam of light from a slit S (Fig. 311) is arranged so that part of it passes through a prism and is spread out in a spectrum on a screen and part goes past the edge of the prism to another screen. A color filter is inserted in the beam near the slit. The
transmitted color and its components in terms of the parts of the spectrum transmitted are both seen. If now different filters that have been examined separately are put into the beam together, the results are evident. By holding them near the slit and partly overlapping, the separate and combined effects can be seen on both screens.

**L-91. Color Due to Absorption.** Light from a lantern is reflected to the ceiling by pieces of red, green, and blue glass. The color of the reflected light is nearly the same in all cases, but the light that goes through the glass to a screen is decidedly colored by absorption. By using a plane mirror, the reflected light may be thrown on the screen beside the transmitted light.

**L-92. Complementary Colors.** White light from an arc is focused on a slit (Fig. 312) and passes through the lens $L_2$ and prism $P$ to form a spectrum on the plane mirror $M$. This mirror reflects the light through a large lens $L_3$, which forms an enlarged image of the face of the prism on the screen. This image will be white if the lens catches all the light from the prism reflected by the mirror $M$. But if a small strip of mirror $M_2$ is inserted in the spectrum near $M$ and tipped slightly, the image formed by the light reflected from $M_2$ will reach a different place on the screen, say $B$, and will be colored; and since part of the light is thus removed from the original image at $A$, this image will also be colored. The colors of these two images are complementary since they add to produce white, as can be shown by removing $M_2$ or by making it parallel to $M$. The mirror $M_2$ should be thin, as otherwise light will be lost on account of obstruction by its edges.

A similar result may be obtained by putting the lens $L_3$ in the dispersed beam from the prism $P$ so as to catch all the light from it, with $M$ just beyond the lens. The light is then reflected by $M$ back through $L_3$, which forms an image of $P$ on a screen. $M_2$ is
inserted in front of $M$ as before. In this case, however, in order to secure enough dispersion, the lens and mirror may have to be so far from the prism that the image produced on the screen is small. In either case, the lens $L_3$ must be large enough to receive all the light dispersed by the prism, since otherwise a white image cannot be formed.

**L-93. Color Disks.** A disk may be made or purchased having colored sectors of such proportions that when the disk is spun rapidly the eye perceives a grayish white instead of the individual colors. Two disks of solid color, with one radial slot in each, may be slipped through one another and fastened to the same rotor. When the rotor turns rapidly, the effect is a color whose hue, brightness, and saturation depend on the combinations used. By rotating one disk with respect to the other, the colored sections may be varied.

An interesting “rainbow top” is now on the market, in which four small disks each bearing 120° sectors of red, yellow, and blue are slowly turned while the top spins, so that continual changes of color occur.

**L-94. Complementary Colors Produced Subjectively.** A disk of heavy cardboard or beaverboard 20 in. in diameter is painted dull black on one half and glossy white on the other (Fig. 313). An opening, half in the white and half in the black, is cut at one edge of the disk. The piece removed is cut in two and glued to the back of the disk, near the edges of the opening, to balance it. The disk is mounted on a rotator, either hand or motor driven, so that it faces the class. A red light is placed behind it so as to be seen through the opening for an instant during each revolution of the disk, and the front is brightly illuminated. Two desk lamps, each with a photoflood lamp whose direct light is properly shielded from the class, are satisfactory. The observer watches for the red light as the disk turns.

![Diagram](image-url)
If the direction of rotation is such that immediately after the light is seen it is obscured by the white section of the disk, a speed of rotation can be found that will make the red light appear green. If the rotation is in the other sense, the eye rests while it looks at the black immediately after the red, and no green color is seen. If a clear-glass bulb is used, the filament may reverse at a slightly different speed from the rest of the light bulb. The effect is subjective, depending upon retinal fatigue (see L-61).

L-95. Dichromatism. A sheet of green cellophane transmits about 50 per cent of the green in the visible spectrum, but its transmission rises to 80 per cent in the extreme red, where the visibility is low. On looking at a white light through an increasing number of sheets, up to 12 or more, the transmitted color changes from green to a deep red. This phenomenon may be discussed in terms of the exponential law of transmission for the two colors. Most cellophane of other colors shows the same effect, though not so strikingly. Deep blue changes to purple and then to red with increasing thickness. The light transmitted by a dozen thicknesses of cellophane is too faint to be projected on a screen; hence the class must look through the cellophane directly at a bright enclosed source. At a certain thickness, the cellophane appears gray, since red and green are complementary.

L-96. Absorption and Transmission—Metals and Dyes. The body color of a pigment is the same whether seen by transmitted or reflected light. The color of a metal, however, is different in the two cases. A thin film of gold (gold leaf or sputtered film) transmits green but looks reddish yellow by reflected light. The latter effect is enhanced if two gilded pieces of glass are set parallel to one another and the light successively reflected from the two surfaces. A colloidal suspension of gold shows a similar effect. Sheets of glass coated with aniline dyes exhibit one color by reflected light and the complementary color by transmitted light, much like gold leaf. The best dye to use is "brilliant green," which appears green by transmitted light but red by reflected light. Light reflected from the dye side of the glass (Fig. 314)
looks yellow, while light reflected from the front glass surface is white.

**L-97. Kirchhoff's Law of Radiation.** A Globar electric element (E-171) is heated to a yellow heat by connecting it across a 110-v line, using no external resistances. White markings (chalk) on the element radiate much less intensely than the natural black surface. The room should be quite dark. The contrast in appearance of the glowing element when a desk lamp is flashed on and off demonstrates that the best absorbers are likewise the best radiators.

A piece of decorated china is heated in a blast lamp. The design emits much more light than the white background, owing to its greater radiating power. If the spectrum of a carbon arc is watched for a few seconds after the current to the arc is cut off, the rapid disappearance of blue and lingering of red radiation will be observed.

**L-98. Radiation Intensity Curve.** Project the continuous spectrum of a carbon arc (L-42). With the aid of a thermopile and a sensitive galvanometer, show the energy distribution throughout the visible spectrum and on each side of it. If the optical system by which the spectrum is projected is of glass, absorption will interfere with the demonstration, particularly at the violet end. It may be possible to demonstrate the maximum at the long wave-length end, though the demonstration will be much better if quartz or rock-salt lenses and prisms are available.

**L-99. Dependence of Color on Temperature.** A clear-glass tungsten lamp is arranged so that the voltage across it can be varied from zero to considerably above the rated value. As the voltage is gradually increased, the filament begins to glow a dull red, then becomes yellow, and at 50 per cent overload is very much whiter than at normal voltage. If the intensity of the radiation (as measured by a photocell) is plotted against the power used by the lamp, it is easy to show that the efficiency of the lamp increases rapidly with the temperature of the filament.

**L-100. Color Due to Scattering.** Smoke rising from the end of a cigarette is blue, while after exhalation it is white. In the first case, the particles are so small that they scatter mostly blue light like that of the sky, but after being in the mouth they collect moisture and are much larger (see also L-46).
SPECTRA

L-101. Spectroscopes. For projection of spectra in the lecture room probably the most convenient instrument is the one-lens prism spectroscope (L-42). The source (Fig. 315) is focused on a vertical slit. The image of this slit is formed on a screen by the projection lens $L$. In the beam just beyond the lens is placed the prism $P$. While large glass prisms will work, they are expensive and will not give so much dispersion as a hollow prism filled with carbon disulfide or monochlorobenzene. The prism will give sharper lines if used near minimum deviation. The best focus can be obtained either by using a bright-line source or by placing over the slit a didymium glass filter, whose sharp absorption lines are very convenient for focusing. This simple spectroscope can be used to produce continuous spectra, bright-line arc spectra, and absorption spectra based on the continuous one. It is generally not suitable for projecting gas discharge spectra or other faint types. However, if the slit is replaced by the capillary of a brilliant discharge tube like neon or mercury, the spectrum can be seen satisfactorily, although the resolving power will be low. A large direct-vision prism, if available, can be used in place of the usual 60° prism. Such a prism can be made by combining a glass prism with a hollow one filled with carbon disulfide, benzene, bromoform, or other liquid of high dispersion.

L-102. For the observation of gas discharge tubes, inexpensive replica transmission gratings can be passed around the class. They are not recommended for projection work. The straight capillary type of tube is best; several tubes can be arranged above one another in a vertical line so that as the student looks at them through the grating he may readily compare their spectra. If all of the tubes are connected in series with an induction coil, they will all glow together; if connected in parallel, some may be quite brilliant while others are scarcely visible.
L-103. **Imitation Line Spectra.** If the demonstrator possesses a colored lantern slide of a continuous spectrum, line spectra can be imitated by drawing lines with the point of a knife at proper intervals on a photographic plate, which can then be used to mask out all portions of the continuous spectrum except those representative of the gas whose spectrum is to be imitated.\(^1\)

L-104. **Bright Line Spectrum.** With the single-lens prism spectroscope (L-101), a bright line spectrum from copper, zinc, iron, or other metal of high melting point can be projected by using electrodes of the metal in an arc lamp. The spectra of metals such as lithium, sodium, and others of low melting point can be projected by using bored carbon electrodes loaded with salts of the desired metal. For gases like hydrogen, helium, neon, or nitrogen, the best form of discharge tube is one having a straight capillary section. If the intensity of the source is great enough, it may be placed near the slit or substituted for it; otherwise it may be viewed by the class individually through replica gratings (L-102). Helium, neon, and mercury are especially good for atomic lines; the nitrogen tube is likely to show molecular bands as well as atomic lines, and so may the hydrogen tube. Sodium and other flame spectra are best viewed individually.

L-105. **Band Emission Spectra.** The most convenient sources of band spectra for demonstration are capillary discharge tubes containing nitrogen, cyanogen, water vapor, and hydrogen. They may be viewed individually either by means of replica gratings held to the eye or through a spectroscope.

L-106. **Continuous Emission Spectra.** Either a carbon arc or a concentrated-filament lamp may be used as source. The lamp in the projection lantern is satisfactory. It is a moot question whether better results are secured with the slit in the position of the slide and the projection lens in its regular place or with the projection lens removed and the slit put at the image of the source produced by the condensers, the projection lens being placed far enough ahead of the slit to throw its image on the screen. Using

\(^1\) A lantern slide (Misc. 20) showing a diagram of a prism spectroscope together with a hand-colored spectrum as if produced by it is obtainable from Yerkes Observatory. A set of hand-colored slides of emission line spectra of the principal gases may be secured of E. Leybold's Nachfolger, A. G., Cologne, Germany.
the single lens and carbon disulfide prism, a brilliant spectrum 2 or 3 ft long is easily produced (L-101).

**L-107. Dark-line Absorption Spectrum.** A mirror (heliostat) is arranged to reflect sunlight on the slit of a spectroscope. By means of a small right-angle reflecting prism or a mirror, light from a sodium flame is used to illuminate half the slit, the other half being illuminated by sunlight. The bright sodium lines from the flame will match the D lines in the solar spectrum, indicating that the latter are due to absorption by sodium vapor in the sun. The sodium flame may be produced by soaking a strip of asbestos in salt water and wrapping or wiring it around the top of a Bunsen burner, with the asbestos projecting well above the metal tube of the burner. Another method is to heat in a flame one end of an iron or platinum wire, bent into a loop or hook, and then to dip it into borax. Some of the borax will stick to the wire and in a hot flame will fuse and form a drop. By repeating this process, a bead of considerable size can be formed, which will emit a bright sodium yellow. This demonstration is suitable only for individual observation. The observer should, of course, be shielded from direct sunlight.

**L-108.** For a demonstration that can be seen by the whole class at once, one of the following methods may be used.

1. The projection arc carbons may be boiled in a concentrated salt solution and allowed to dry thoroughly before using.

2. Another method is to bore the carbons and fill the holes with fused sodium chloride. The arc should be run on direct current with the vertical carbon positive. A large, deep hole is bored in this carbon and filled with fused salt or borax, melted into place with a blowtorch. If ordinary salt is used, its water of crystallization will evaporate so violently in the arc as to blow most of the salt out of the carbon. Either of these methods will generate sufficient sodium vapor to produce a cooler envelope around the arc, so as to show a strong absorption line down the middle of a wide sodium line.
3. The most satisfactory method is to make a furnace of fire clay, furnace cement, or other refractory material (Fig. 316), in the form of a rectangular block with two diametrically opposite horizontal holes into which the carbons fit loosely. Two other holes project as far as the center, one from the top and one from the side. If the top hole is left open and an image of the center front hole is projected on the slit of the spectroscope, the ordinary arc spectrum will be produced. When some metallic sodium is dropped through the hole in the top, a brilliant sodium spectrum will appear. The upper hole is then closed so that the vapor of sodium can escape only through the hole in the side. In doing so, it cools and produces an excellent absorption line (A-70).

The furnace may be cast from Portland cement and sand. A metal plate threaded to take a laboratory support rod is set into the bottom of the mold box. Thus the finished furnace may be mounted conveniently in any optical setup.

L-109. Band Absorption Spectrum. A spherical flask is filled with nitrous oxide, which is a reddish-brown gas. When the flask is placed in a beam of light before it is dispersed by the prism of a spectroscope, it produces an excellent absorption spectrum. Didymium glass is also good, but its absorption spectrum is not so interesting as the fluted spectrum produced by nitrous oxide. Dilute blood, either healthy or poisoned with carbon dioxide, is suggested.

L-110. Absorption Spectrum of Chlorophyll. Extract some chlorophyll by macerating green leaves in methyl alcohol for several hours. Stinging nettle and pine needles are among the richest bearers of chlorophyll. The former, dried and powdered, can be secured from chemical supply houses under the name stinging nettle meal and has the advantage of accessibility in all weathers. Filter, and adjust the concentration until, when the absorption spectrum is projected (as in L-109), the transmission band in the extreme red has maximum visibility. The green transmission is, of course, its principal characteristic. Correlate with the white appearance of foliage in infrared landscape photographs contrasted with its dark appearance in ordinary photographs. The solution also fluoresces (L-114).

L-111. Ultraviolet Spectrum Shown by Fluorescence. That the spectrum extends beyond the visible on the short wave-length side is shown by using a screen painted with quinine sulfate or by
holding any other fluorescent material against the regular screen on which a continuous spectrum is allowed to fall. It is first held in the violet so that its action can be seen and is then moved farther and farther out into the ultraviolet. Using quartz lenses and prisms with an iron or carbon arc, the ultraviolet can be followed for a considerable distance. Using a quartz optical system, a good fluorescent screen, and strong sunlight, atmospheric absorption bands may be seen in the ultraviolet. That it is ultraviolet and not visible light can be shown by sliding a white paper in front of the screen. With such a system, the transmission limit of glass can be shown by introducing a sheet of glass anywhere in the light path.

A quartz mercury arc with quartz lens and prism will show prominent lines in the ultraviolet. Detection of radiation may be by photocell instead of fluorescent screen (A-91).

**L-112. Infrared Shown by Thermopile or Radiometer.** That the spectrum extends to longer wave lengths than those visible can be shown by using a sensitive thermopile and lecture galvanometer or a sensitive radiometer. Starting with the thermopile in the yellow region of the spectrum, it is gradually moved toward the red. The galvanometer deflection will probably reach its maximum value a little beyond the visible region. By using a carbon arc and carbon disulfide lenses and prism (rock salt is better), the spectrum may be followed well beyond the visible. That the energy is really coming through the optical train can be shown by inserting a water cell in the path of the light, to absorb most of the infrared. Place a thermopile in the red-orange region of the spectrum about 18 in. from the prism, and when the deflection becomes steady, interpose a parallel-sided water cell about 1 cm thick. The deflection is somewhat decreased. Now move the thermopile to the region just beyond the red. The maximum deflection will probably be greater than before, but the water cell will produce a very marked decrease. Good results can be obtained with a single glass condensing lens and carbon disulfide prism. No slit is necessary.

**L-113. Infrared.** Iodine dissolved in alcohol or carbon disulfide (3 g iodine in 100 ml CS₂) produces a filter that cuts out the visible but transmits the infrared. The light from a carbon arc is focused to a point. A match or a piece of black paper held at the focus will be ignited or charred. When a parallel-sided cell
containing the iodine solution is placed in the convergent beam, visible radiation is stopped, but the match is ignited or the paper charred as before. A radiometer or thermopile may be used beyond the focus to show the effect, care being taken not to damage the instrument or the galvanometer. Water in a test tube may be boiled by holding it at the focus of the infrared. Caution: As both alcohol and carbon disulfide catch fire easily, the first with sometimes explosive violence, they should be used in closed containers with every precaution to avoid accident.

A corked spherical flask filled with iodine dissolved in carbon disulfide acts as a condensing lens as well as a filter (H-151). A similar flask filled with water also acts as a lens but passes only the visible; its absorption of infrared is increased by the addition of alum. A single element of the condenser lens forms a nearly parallel beam that can be brought to a visible focus by the flask of water. While this focus is hot, it is not nearly so hot as the invisible focus produced by the flask containing the iodine solution. Infrared may also be detected with a caesium photocell.

**L-114. Fluorescence and Phosphorescence.** A carbon arc or a quartz mercury arc with an ultraviolet filter\(^1\) is an excellent source of ultraviolet for fluorescence demonstrations. An argon glow bulb that fits an ordinary lamp socket is very convenient for showing many effects. A battery of 16 2-w argon glow bulbs works very well. If a powerful source is available, it is interesting to turn the source toward the class in a darkened room so that they may observe fluorescence effects on teeth, eyeballs, clothing, etc. Live teeth fluoresce brightly, but dead or false teeth do not shine. When one looks at a bright ultraviolet source, the entire room appears to glow on account of fluorescence within the eye itself (L-60). Caution: Prolonged exposures are dangerous.

Many things show bright colors under ultraviolet light; \textit{e.g.}, fluorescein, dilute mercuriochrome, quinine sulfate, vaseline, motor oil, petroleum, and many aniline dyes.\(^2\) A solution of

\(^1\)Such as Corning red-purple Corex A.

\(^2\)Special collections of fluorescent and phosphorescent materials can be secured from scientific supply houses; \textit{e.g.}, zinc sulfide; barium platino-cyanide; anthracene, dissolved in benzene for writing; eosin in water; esculin; rhodamine; uranium nitrate; uranium glass, solid or powdered; uranium in gelatin; kerosene. The argon bulb will make many of these substances show up well.
chlorophyll obtained by macerating green leaves in alcohol fluoresces (L-110). Zinc sulfide will phosphoresce brightly for a long time after exposure to ultraviolet. A design can be painted on white paper with a solution of anthracene in benzene that is invisible in ordinary light but is visible in ultraviolet light. A cheesecloth robe, soaked in this solution and then dried, has "stunt" possibilities, especially if used as a shroud for a skull painted with the same solution.

**L-115. Transmission by Filters—Photoelectric Cell.** A photoelectric cell, either emission or voltaic type, can be used very easily to measure absorption by filters or solutions. The cell is arranged so that the light is incident on the sensitive surface only through the blackened tube T (Fig. 317). The cell and tube are covered with a black cloth after adjustments and electrical connections are completed. A diaphragm D limits the beam to a cross section slightly smaller than that of the tube. With the filter removed, the light is adjusted to give a conveniently large deflection of the galvanometer. The filter or test solution is interposed, and the new deflection noted. If the response of the cell is linear, the percentage of light transmitted is found from the ratio of the two deflections. The principles involved have been incorporated in a colorimeter that will detect more minute traces of certain substances in solution than the visual colorimeter or any purely chemical method of analysis. By using suitable sources, filters, and cells, the ultraviolet transmission or absorption of such substances as protein and amino acid may be measured.

**POLARIZATION**

**L-116. Polarization—Mechanical Model.** A rubber tube or cord or a rather stiff helical spring is stretched across the lecture table and 6 in. above it between two rigid supports. The cord or spring passes through a "polarizer" and an "analyzer," which are conveniently made in the form of cubical boxes, 1 ft on each edge, open at two opposite faces. Each box has two partitions (Fig. 317).
separated by slightly more than the diameter of the cord, thus providing a central slot that permits longitudinal waves to pass through unimpeded but effectively prevents the passage of transverse waves, except in the plane of the slot. By turning a box through 90°, its slot may be set either vertical or horizontal without changing its height at the center. One box may be marked $P$ for polarizer, and the other $A$ for analyzer. Longitudinal waves, made evident by tying ribbons to the cord at a number of points, can pass through both slots whatever their relative positions, but transverse waves that pass one slot will pass the second only if it is parallel to the first and will be stopped by it if it is turned at right angles, illustrating the action of crossed Nicols.

**L-117.** The mechanical device illustrated in Fig. 319 shows how one component of a transverse vibration can be absorbed and the other not. A weight of a pound or so is hung as a pendulum from the end of a light wooden strut, which projects from the wall some 4 ft and is stayed by cords $A, B,$ and $C$. The cords $B$ and $C$ are somewhat slack and are tied to a loop of cord 3 or 4 in. long which can slip across the end of the strut and is kept in position by three small nails, one above, one below, and one passing through the loop to limit the amount of sidewise slip. When the weight is set swinging in the direction $DE$, it imparts motion to the strut and soon comes to rest; while if it swings in the direction $FG$, the strut is not disturbed, and the motion of the pendulum persists. If now the pendulum is set swinging diagonally or in a circle, the sidewise component of the vibration is soon suppressed, and the weight is left swinging in the direction $FG$.

**L-118. Linear and Circular Polarization—Pendulum Model.** Suspend a weight by a string, and strike the weight a blow in any direction; a linear vibration results. Strike a second (equal) blow,
at right angles to the first, and a quarter period later, i.e., when the weight has reached its position of greatest displacement, and the linear vibration will be replaced by a circular one. If the second blow is delayed until a half period has elapsed, the resultant motion will be linear but in a direction making an angle of 45° with the original direction, while if the delay is three-quarters of a period the resultant motion is again a circular vibration but in the opposite direction. Such aspects of circularly and elliptically polarized light as phase and amplitude may be illustrated with this model.

**L-119. Double-pendulum Model of Double Refraction.** The double pendulum (S-43) consists of a weight suspended by strings as shown in Fig. 320. If the weight is displaced either in or perpendicular to the plane of the paper, it will oscillate in a straight line, the period being greater for vibrations perpendicular to this plane than for those parallel to it. If, however, it is displaced in an oblique direction, the force acting upon it will no longer be directed toward the position of equilibrium, and the weight will move in a curved orbit. In the case of crystals, a particle displaced parallel to any one of the axes of elasticity will be acted upon by a force directed toward the equilibrium position, and the vibration will be plane-polarized; if displaced in any other direction, the force is not directed toward its original position, and so the particle moves in a curved path in a manner analogous to that of the pendulum bob.

**L-120. Double Refraction.** Double refraction is shown most clearly by calcite crystals. Place a crystal over a printed page or some similar object and allow the students to view the effect individually.

Calcite crystals may also be used to show double refraction to the whole class at once. A small hole (1 to 3 mm in diameter) in a sheet of cardboard or metal is illuminated strongly, and its image projected on a screen. When a calcite crystal is held over the hole, two spots of light appear on the screen. As the crystal is rotated, one spot appears to stay fixed while the other moves around it. When a second crystal or a double-image prism is added, four spots appear, and these disappear in pairs as the
second crystal is rotated. Instead of the second crystal, a Nicol prism or polarizing plate may be interposed as an analyzer in the path of the light; by rotating it, the two images may be made to disappear alternately, thus showing that they are produced by light polarized in planes perpendicular to one another. Of course a large double-image prism could be substituted for the first calcite crystal and tested in the same way. If a Wollaston prism is used, it must be held a considerable distance away from the illuminated aperture. For convenience, it may be held in a cap that fits over the projection lens, so that the prism can be rotated.

L-121. Polarizing Crystals. The action of tourmaline crystals is most easily explained by the aid of mechanical models. When the crystals are parallel, they transmit; but when crossed, i.e., at right angles to each other, they stop all light. By analogy with the rope and slots (Fig. 318), it may be concluded that light is a transverse wave motion and can be polarized.

Because of its universal use, the Nicol prism should be demonstrated and explained. Large-scale models visible to the entire class are often helpful in the explanation.

L-122. Polarizing Plates. There are now commercially available polarizing plates that consist of two sheets of clear glass between which is cemented a thin film containing a large number of minute polarizing crystals all oriented in the same way. These plates are much cheaper than Nicol prisms of comparable aperture; in fact, they can be made with apertures far larger than the largest obtainable Nicol. For polarization demonstrations in visible light, they are excellent. On the long wave-length side of 7000 Å, they transmit whether crossed or uncrossed; on the short wave-length side of 5000 Å, they transmit approximately 1 per cent of the light when crossed.

L-123. Polarization by Reflection—Nörrenberg's Polariscope. Reflected light is in general partially polarized, as can be seen by viewing it through a Nicol or a polarizing plate. The principle of Nörrenberg's polarscope is that of polarization by reflection from glass (Fig. 321). Two glass plates made of black glass or of ordinary sheet glass painted black on the back with, say, asphaltum varnish, can be so arranged that light incident upon the first (polarizer) at an angle of about 57° will after reflection fall upon the second plate (analyzer) at the same angle of incidence. When
the second is in a plane parallel to the first, light is reflected, but if the second is rotated (keeping the angle of incidence constant), no light is reflected when the planes of incidence are at right angles. The brightness of the image in this case is very sensitive to small changes of angle of incidence. If the second reflecting surface is a silvered mirror, it will not polarize by reflection, and consequently the image appears bright for all positions. The analyzer may have black glass on one side and a silvered mirror on the other, so that turning the plate over will change the reflection from one type to the other for quick comparison.

As ordinarily set up, the source of light is stationary, and the second reflecting sheet turns. This means that the image moves over angular distances that may carry it completely off the screen. A simple modification keeps the second reflector $B$ (Fig. 321) stationary and with it the spot of light. The source of light is mounted on a horizontal arm, which also carries the reflector $A$ and rotates about a vertical pivot whose axis passes through $B$. The source may be a flashlight, which can be conveniently attached to the movable arm.

**L-124. Polarization by Reflection—Pyramid Method.** A square pyramid is constructed from four triangles of black glass so that each face makes an angle of $57^\circ$ with the base. The pyramid is mounted at the center of a white screen so that both screen and pyramid may be rotated about the axis of the pyramid. A broad beam of plane-polarized light is directed axially upon the vertex of the pyramid. When the plane of polarization is parallel to one edge of the square base of the pyramid, reflection of light to the white screen takes place from only two faces although all four faces are equally illuminated. When the pyramid is rotated $45^\circ$, all four faces reflect equally; when the pyramid is rotated $90^\circ$ from its original position, the two faces that originally reflected light no longer do so, whereas the other two faces now reflect brightly.

**L-125.** A large-scale polarizer using two black-glass plates mounted parallel to one another at opposite ends of a box 1 by 1 by 3 ft (Fig. 322) gives an extended source of plane-polarized light. Large celluloid models may be placed between the plates.
to show stresses (L-134). The source is a brightly lighted ground-glass diffusing screen giving illumination over a large field. If the light is sufficiently bright, projection through an analyzer plate may be possible. Otherwise it will be necessary to view the objects through some type of analyzer. This polarizer is like the louver type of strain tester (Fig. 323) available commercially for the production of polarized light.

Fig. 322.—Large-scale reflection polarizer. Fig. 323.—Louver type of strain tester.

**L-126. Polarization by Reflection—Stack of Plates.** Instead of black-painted glass, which absorbs the transmitted light, a large number of sheets of glass all held at the proper angle may be used to give not only polarized light by reflection but almost completely polarized light by transmission. A wooden box (Fig. 324) 20 in. long and 6 in. square made of plywood will easily accommodate 16 or more 5- by 11-in. glass plates at the proper angle (57°). Two wooden strips on the sides of the box hold the lowest plate at the right inclination, and the others are laid on it. Old photographic plates that have been carefully cleaned without scratching work very well. The ends of the box are open; the top is removable so that the reflected beam may be used or not as desired. The whole box is painted a dull black inside. That the reflected and transmitted beams are polarized in planes perpendicular to one another is easily shown by testing with a tourmaline crystal, Nicol prism, or polarizing plate. If a silvered mirror is used at A, both beams may be projected side by side on the screen.
L-127. Polarization by Scattering. The beam from a bright source of light $S$ (Fig. 325) is rendered parallel or slightly convergent by the condensers $L$. It then is reflected downward by the mirror $M$ into a glass cylinder of water containing a small amount of scattering material such as gum mastic, sulfur from hypo solution (L-46), a drop or two of milk, denatured alcohol, resin in alcohol, or liquor carbonis detergens (coal tar in alcohol). (One-half milliliter of milk in 1500 ml of water is very good.) The path of the light should be confined by a diaphragm $D$ to a beam smaller than the diameter of the cylinder so that it will not strike the sides. Scattered light will be seen in all horizontal directions. If a large polarizing sheet $P$ is placed in front of the cylinder and rotated, it will show that the scattered light is polarized.

With a polarizer in the beam above the diaphragm, the scattered light is brighter in the direction perpendicular to the plane of polarization and very faint or absent in the direction parallel to it. If the polarizer is rotated, these directions of maximum and minimum intensity will rotate with it. Two mirrors set behind the jar at an angle of 100° to each other will enable the class to see the two directions at once. Covering the diaphragm with a quartz plate produces colors.

L-128. A different arrangement of L-127 is illustrated in Fig. 326. An intense beam of light is directed through a long rectangular glass trough $G$. The trough is filled with water having a small amount of scattering material in it, as in the preceding experiment. A diaphragm $D$ of black paper is used to limit the beam to a cross section considerably smaller than that of the trough. Above the trough is a mirror so tipped that the class can look down on the top of the liquid. In the beam is a polarizer $P$. 
that can be rotated. A polarizing plate held in a lens holder is very convenient. As the polarizer is rotated, first the side of the trough and then the top is bright. When the side is brightest, the top is dimmest, and vice versa. This experiment can easily be combined with the "sunset" experiment on scattering (L-46).

L-129. Rotation of Plane of Polarization by Sugar Solution.
A very bright beam of light is made parallel or slightly convergent, polarized, and limited by a diaphragm so as to remain wholly within the liquid in a cylinder or a trough as previously described (L-128). A saturated sugar solution (300 g of sugar to 400 ml of hot water) is filtered through cotton in a funnel and poured into the cylinder. Clear white corn syrup may also be used. One of the scattering materials mentioned previously (L-127) is added, but the amount must be very small, as otherwise the beam becomes too dim to be seen before it reaches the end of the container. The cylinder or trough should be at least 1 ft long.

The plane of polarization of the light entering the solution is rotated by it through an angle that depends upon both the concentration and the thickness of the liquid traversed. Since the rotation is different for different wave lengths, there is rotational dispersion, and different colors are seen along the tube, producing a spiral appearance, the reds and blues being most noticeable. As the polarizer is turned, the whole spiral rotates like a barber pole. The separation of the colors is more pronounced if a plate of quartz with sides cut perpendicular to the optic axis is inserted in the beam before it reaches the sugar solution. This separates the colors from the start, while without it the separation is effected only by the sugar itself.

L-130. Rotation of the plane of polarization by a sugar solution may be shown by the arrangement of Fig. 327. The image of the analyzer $A$ is focused on the screen, and the polarizer and analyzer are crossed with the tube of solution $T$ out of the beam. The tube is then inserted in the beam, and rotation of the analyzer will show colors due to rotatory dispersion. The amount of rotation is made evident by a large indicator attached to the Nicol or polarizing plate.

L-131. Rotation of Plane of Polarization Measured by Quartz "Biplate." When polarized light is sent along the optic axis of crystalline quartz, the plane of polarization is rotated, the amount of rotation depending on the wave length of the light and the
thickness of the crystal. A quartz "biplate" is frequently used in measuring rotation. Its use can be demonstrated to the whole class if it is shown in connection with a glass-ended tube of medium-strength sugar solution, the transmitted beam being thrown on the screen. The light from a bright source $S$ (Fig. 327) is passed through the condensing lenses $L$ so that it is parallel or slightly convergent. In this beam are placed the polarizer $P$, the tube of sugar solution $T$, the biplate $B$, and the analyzer $A$. The last two must be capable of rotation. An image of the biplate is thrown by lens $L_2$ on the screen. With the tube out of the line, the biplate is set so that the edge between the two quartz pieces makes an angle of $45^\circ$ with the plane of vibration of the polarized light from $P$. Then the analyzer is adjusted so that the two halves of the biplate match in color and intensity. The sugar solution is then put back in the optical path, and the two halves of the biplate are decidedly different in appearance but may be made equal again by rotating the analyzer. A pointer should be attached to the analyzer so that the class can see the amount of its rotation required to balance the fields. The sugar solution may be replaced by pieces of quartz showing right- and left-hand rotation.

**L-132. Faraday Effect.** When a beam of plane-polarized light passes through a material medium parallel to the lines of force of a magnetic field, the plane of polarization is rotated. The pole pieces of an electromagnet are bored with holes parallel to the field. A strong beam of parallel light passes through a polarizer, the holes in the pole pieces, and an analyzer, and thence to a screen where it is focused in a spot. Between the poles of the magnet is placed the specimen to be examined—a piece of heavy glass (lead silicate) with ends cut off square and polished, or a glass tube with plane parallel ends containing carbon disulfide.
With the magnetic field off, the analyzer is turned until the spot on the screen is extinguished. When the electromagnet is turned on, the spot reappears. Rotation of the analyzer will show the amount and direction of rotation of the plane of polarization and sometimes rotational dispersion as well. Reversal of the magnetic field reverses the direction of rotation.

**L-133.** Into the hole in a solenoid from a large electromagnet, insert a glass container partially filled with halowax oil or carbon tetrachloride. Cross the polarizer $P$ and analyzer $A$ (Fig. 328) for extinction when there is no current in the solenoid. Focus an image of the analyzer on the screen with a projection lens $L_2$; a thread stretched across the analyzer serves to indicate its plane of minimum transmission. Now turn current on in the solenoid; part of the image turns bright because of rotation of the plane of polarization within the dispersive medium. The amount of this rotation may be determined by rotating the analyzer until this portion of the field is again dark. The solenoid may be operated on 110-v direct current with protective resistances.

**L-134. Induced Double Refraction—Photoelasticity.** The use of polarized light for stress analysis is of considerable engineering interest. Specimens for study are cut from clear celluloid or other plastic $\frac{1}{2}$ in. thick and mounted in a frame (Fig. 329) to fit the slide holder of the projection lantern. Stresses are applied by turning wing nuts on the bolts holding the specimens. Models of bridges, bell-crank connectors, and gear trains are especially interest-

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1 Halowax oil 1007 is a chloronaphthalene obtainable from the Halowax Corp., Wyandotte, Mich. It can be removed with gasoline or benzene.

2 An excellent plastic for photoelasticity is supplied by the Marbette Co., Long Island City, N. Y.
ing. The specimen is inserted in a beam of plane-polarized light, which then passes through an analyzer. A lens focuses the light on a screen. When a stress is set up in the celluloid, the material becomes doubly refracting. If polarizer and analyzer were initially crossed, the neutral axes of the specimens will remain dark, but the image of the specimen will brighten and show colors where the stresses are greatest. Stresses can also be applied by hand. Thus the type of stress in a loaded beam may be shown by applying bending moments to a rectangular rod of clear glass. The axis of the rod should make an angle of 45° with the plane of the polarized light.

When a long flat strip of glass clamped at its center is stroked longitudinally with a wet rubber or rosin cloth, the longitudinal standing waves set up cause standing-wave stresses in the glass, which become apparent when it is viewed by polarized light. Scratches on the glass or celluloid should be avoided, since they scatter light and tend to spoil the effect.

L-135. Kerr Effect. The Kerr effect is easily shown if carbon disulfide or, better, halowax oil, is used between the plates of a condenser. A parallel beam of light is polarized in a plane making an angle of 45° with the vertical. It then passes between the metal plates of the condenser in a rectangular glass cell and through an analyzer. An image of the region between the plates is formed on the screen by a lens. With the plates discharged, the analyzer is set for extinction. If now the two metal plates are connected to the terminals of an electrostatic machine and the plates are slowly charged, the field on the screen will begin to brighten. A safety spark gap should be connected in parallel with the plates so that the condenser cannot be overcharged, as a spark through carbon disulfide may set it on fire and cause an explosion. Halowax oil is safer. With the safety gap set, the condenser may be charged until the gap breaks down. This removes the field, and the spot, which has been growing brighter, suddenly goes black. The operation may, of course, be repeated. The cell constitutes an electrostatic shutter that can be used for producing bright flashes of light of extremely sharp termination. The rectangular glass cell (Fig. 330) is 2 by 2 by 6 in. The top is brown bakelite. To it are fastened the two brass plates $M$, $M$, each $\frac{1}{2}$ by 5 in. These are held in place by $\frac{1}{4}$-in. brass rods, one at each end of each plate, bent as shown. At one end of the cell,
the rods come through the top and have thumbscrew terminals for connection to the source of emf. At the other end, they project farther above the top. One terminates in a small brass ball, and the other has an arm with a ball on its end. This ball spark gap is adjustable by rotating the arm. A lock nut holds it at any desired gap setting. The distance between the plates is \( \frac{3}{16} \) in. The liquids must be clean and pure and free from all moisture. In summer or after prolonged use, the halowax oil may not stand up under the slow charging of the electrostatic machine but will still work if a 60-cycle, 10,000-v transformer is placed across the condenser plates. In this case, the outside safety gap must be wide enough to avoid breakdown.

**L-136. Doubly Refracting Materials in Polarized Light.**

Many doubly refracting crystals when placed between crossed Nicols show colors due to interference. If the crystal is held stationary and either the analyzer or the polarizer is rotated through 90°, each color changes into its complement. Unannealed glass and other materials show colors in regions of strain when placed between crossed Nicols (L-134). Two very convenient substances that exhibit the effect are mica and cellophane (that which is striated during manufacture); the latter is particularly useful because the thickness can be changed so easily by folding. It can be shown that cellophane is optically anisotropic so that every 90°, as it is turned between crossed Nicols, transmission is cut off. At all other positions, light passes the combination, and maximum transmission occurs when the mechanical striae due to manufacture are at 45° to the planes of the crossed Nicols.

As the thickness of cellophane traversed by the polarized light is increased, the color changes. These colors can be shown by the following arrangement. Light from a bright source is focused on a vertical slit by a lens. Before reaching the slit, it passes through two Nicol prisms or polarizing plates—a polarizer and an analyzer. It is then projected on a screen through a direct-vision prism or other dispersion piece so as to form a spectrum (Fig. 331). The material to be examined is placed between polarizer and analyzer. Black bands in the spectrum demonstrate the occurrence of selective interference. Too great thickness of the
material may give so many bands in the red, green, and violet that the color of the transmitted light (without dispersion prism) is white. Smaller thicknesses have only one or two absorption bands and show considerable color in the undispersed image. When one of the Nicols is rotated through 90°, the dark and bright bands in the channeled spectrum are interchanged, and the resulting color is therefore the complement of the previous one.

![Fig. 331.—Optical arrangement for demonstrating the behavior of doubly refracting materials in polarized light.](image)

For best effects and purest colors, the vibration planes of the cellophane should be at 45° to the planes of the polarizer, and the polarizer and analyzer should be parallel or crossed. It should be noted that in all these experiments clear, uncolored cellophane is used. Patterns may be made by using different thicknesses and orientations of clear cellophane or mica. When ordinary light passes through them, they show nothing striking, but in polarized light they exhibit beautiful colors.