PART IV

ELECTRICITY AND MAGNETISM

ELECTROSTATICS

E-1. Electric Charges on Solids Separated after Contact. A hard rubber rod or a stick of sealing wax is rubbed with fur and then placed in a stiff aluminum-wire stirrup hung by a silk thread. The suspended rod will move away from another rod that has been rubbed with fur but toward a glass rod that has been rubbed with silk. This behavior is interpreted in terms of two kinds of charge and the forces exerted between them. Positive electricity is defined (arbitrarily) as that which appears on glass when rubbed with silk.

Another method of supporting a charged rod so that it is free to turn is shown in Fig. 207. The rod is laid on a metal trough to which is attached a pivot supported by a vertical rod. The trough also carries a wire framework that forms a collar surrounding the charged rod and so prevents the charged rod from falling.

A 10-ft plank (well dried) is suspended by a wire or strong cord at the middle so that it hangs horizontally. An ebonite rod is rubbed with fur and one end of the plank also brushed with the fur. The plank is set into rotation by repulsion when the charged rod is brought near to its charged end.

E-2. Large-scale Electroscopes. There are many ways of detecting the presence of a charge on a body; all depend on the forces exerted between charges. In this sense, small bits of paper or pith, cork filings, sawdust, and other light objects attracted toward charged bodies are electroscopes, as are also the torsion pendulums described in E-1.

An "electrical pendulum" consists simply of a small ball of pith or a ping-pong ball, coated with metallic paint and suspended by a long silk thread. It is a more sensitive detector of charge than the torsion pendulum. An inverted electrical pendulum is
made by tying a gas-filled balloon to the table top or to the floor by a thread 3 or 4 ft long. The balloon is charged by rubbing on the demonstrator's hair, or by stroking with cat's fur.

Two gilded ping-pong balls are hung from the same point on a sealing-wax rod by fine wires. When the system is charged, the balls fly apart, and the magnitude of their separation may be made an indication of the amount of the charge, on an arbitrary scale. Two similarly treated rubber balloons separate in the same way.

A simple and sensitive electroscope is provided by suspending a gilded ping-pong ball by a No. 40 copper wire, which passes over a piece of sealing wax for insulation and is connected to an insulated plate of brass or aluminum mounted vertically so as to be tangent to the ball when the system is uncharged (Fig. 208). This arrangement permits many electrostatic experiments to be performed before a large class without the use of projection apparatus.

**E-3. Projection Electroscopes.** In the gold-leaf electroscope, electric charge is detected either by motion of two gold leaves hanging vertically beside one another or by the motion of one leaf hanging beside a fixed plate. In either case, the charge to be detected is communicated to the leaves from an external knob, insulated from the protecting case of the instrument. Students may be encouraged to make their own electroscopes. A glass jar with a tin top, a rubber stopper for insulation, a long nail, and a piece of aluminum foil (chewing-gum or candy wrapper) are sufficient. The rubber stopper is set in a hole cut in the top of the jar, and the nail is pushed through a hole in the stopper. The aluminum foil is fastened to the nail by wrapping it with a piece of fine wire.

In using the gold-leaf electroscope before a large class, place it near the condensing lens of a projection lantern, and cast an image of the leaves upon the screen (L-1). An erecting prism is useful but not necessary. Shadow projection of the whole electroscope has the advantage of showing the class both the motion of the leaves and the operator's manipulations. The electroscope may safely be charged by contact with a proof plan-
that has been touched to a charged rod. (Charging by induction is described in E-23.)

A simple projection electroscope is made with a cylinder of thin paper in place of the gold leaf. This cylinder, made conducting with India ink, is attached to a metal rod projecting through the top of the case and insulated from it with sulfur or other dielectric. A convenient case may be made of a 3-in. length of brass tubing 4 in. in diameter, with glass windows cemented on the ends, and mounted on a suitable stand to fit the lantern. The instrument may be made into a vibrating electroscope of the Zeleny type by including in the case a metal block placed so that the leaf will strike it when sufficiently deflected. This block is grounded to the case, so that when the cylinder strikes it, its charge is lost and it falls back. If charge is being continuously supplied to the electroscope knob, the cylinder will vibrate at a rate proportional to the rate of supply of charge, i.e., to the current.

Caution: When an electroscope is connected to a battery or other source of potential capable of giving a relatively large current, a high resistance should be put in series with the electroscope for its protection in case the leaf should strike the case or a plate attached to the other terminal of the source. A resistance that limits the maximum current to 1 ma will in general suffice.

**E-4. Electrosopes and Electrometers.** For many purposes, the large-scale and sturdy electrosopes previously described (E-2 and 3) are adequate. Other more sensitive types of electrostatic instrument are useful for experiments where voltages, minute charges, or ion currents must be measured.

The electrostatic voltmeter (Braun) consists of an aluminum vane balanced in a vertical position near a fixed vertical metal rod mounted on an insulator. When rod and vane are charged, the vane rotates under repulsive forces of electrostatic origin, and its new equilibrium position depends upon the charge and hence upon the potential of the system. The instrument may be calibrated directly in volts from, say, 0 to 2000 v. The moving-vane-and-rod assembly may be used separately from the case to serve as an indicator of charge wherever a leaf electroscope is needed (Fig. 209). (Shadow projection.)

The oscillating-leaf electroscope (Zeleny\(^1\)) is useful for indicating ion currents. It consists of a wide leaf suspended from an

insulated support close to an insulated stationary plate (Fig. 210). When a potential is applied to the plate, the leaf is charged by contact and is repelled. As the leaf loses charge, it again comes in contact with the plate, and the process repeats itself. The rapidity with which the leaf oscillates is proportional to the current reaching the exterior terminal connected to the leaf. Motion of the leaf is shown by shadow or image projection.

Fig. 209.—Braun electroscope.

Fig. 210.—Zeleny electroscope.

For the measurement of very minute charges and potential differences, the demonstrator may use a quadrant or a string electrometer. Inasmuch as these instruments are rarely used except in advanced electrical or research laboratories, the reader is directed to any text on experimental atomic physics for details of their adjustment and calibration.

**E-5. Conductors and Insulators.** By means of a wire, connect the electroscope to a conductor mounted on an insulating stand. If necessary, support the wire by pieces of glass tubing fitted into wooden bases. Charge the conductor by means of a proof plane and charged rod. The consequent divergence of the electroscope leaves shows that the wire conducts charge. If a silk thread is
used in place of the wire, the insulating property of silk is demonstrated. If a dry cotton thread is used, it will ordinarily be sufficiently nonconducting to prevent flow of electricity to the electroscope. If, however, the moistened fingers are run along the thread, it becomes a poor conductor; a thread moistened with salt water shows some conductivity even after it has dried.

Although the subject of capacitance has not usually been discussed at the time this demonstration is used, it is nevertheless interesting at this point to show poor conductivity by connecting one insulated conductor $A$ (Fig. 211) to the electroscope $E$ with a wire $W$, at the same time connecting $A$ to a second insulated conductor $B$ by a cotton thread $T$ that has been wet with salt water and then allowed to dry. If the conductor $B$ is given a charge, the divergence of the electroscope leaves is gradual because of the time required for sufficient charge to flow along the cotton thread to charge both $A$ and $E$. (The rate of charging $E$ is greater if $B$ is connected directly to $E$ without the presence of $A$.)

Then, after the electroscope has reached its full deflection, $B$ may be grounded, and the electroscope leaves come together slowly. The time required for these effects can be shortened by running the moistened fingers along the cotton thread, if the latter is not already a sufficiently good conductor.

**E-6. Attraction and Repulsion.** When a rubbed ebonite rod is dipped into a container filled with dry cork filings, a surprisingly large mass attaches itself to the rod. After a short interval of time, one may notice some of the particles of cork being forcibly ejected because of the repulsive forces between them and the rod. At first, the attraction between the negative charge on the rod and the induced positive charge on the cork particle predominates; but when the cork particle becomes charged by conduction from the rod, the force of repulsion between similar charges is shown. “Familiarity breeds contempt!” If the demonstration is carried out with strong illumination against a black background, the trajectories are visible at a distance.

**E-7. Force between Charges—Coulomb’s Law.** Two pith balls of equal mass are aluminum painted to improve their
conductivities and are suspended by silk threads, the upper ends of which are attached to a common point on a horizontal support rod as in E-2. The pith balls are charged by contact with a hard rubber or a glass rod, and after the first contact their efforts to keep away from the rod are amusing and instructive. The distance between the pith balls, their masses, and the lengths of the supporting threads may be given to the class as data for computing the charge on each ball, provided that the charges on the two balls are assumed to be equal. This demonstration assumes Coulomb's law and furnishes a link between Mechanics and Electrostatics.

**E-8. Electrostatic Induction.** A cylindrical conductor with hemispherical ends, mounted on an insulating stand, is provided with two wire supports, one above each end, from which metalized pith balls are hung by silk threads so as just to touch the ends of the conductor when it is uncharged. When a charged rod is brought up toward one end of the conductor, the pith balls are both deflected away from the ends, showing that charges are now present there. A third similar pith ball charged by contact with the charging rod is brought near each of the other balls in turn to show that the charges on the ends of the conductor are of opposite sign and to determine their signs with respect to that of the charge on the rod.

**E-9.** A charged rod is held by a wooden support near a conductor on an insulating standard. Using the electroscope and proof plane, demonstrate that the conductor was uncharged before the charged rod was brought near; that there are charges on the conductor separated by induction; and that the conductor is uncharged after the inducing charge has been removed, provided that only small and nearly equal amounts of the induced charges have been removed for testing purposes. The fact that there are induced charges on the conductor may be demonstrated by bringing the proof plane into contact with the conductor and then transferring the charge received by the proof plane to the electroscope. The fact that the charges induced on opposite ends of the conductor are opposite in sign is shown by giving the electroscope a charge and then conveying a sample charge from each end of the conductor to the electroscope by using the proof plane. In one case, the divergence of the leaves increases; in the other, it decreases. By similarly testing the inducing charge, it can
be shown that the charge induced on the nearer end of the conductor is of opposite sign.

**E-10. Electrophorus.** The electrophorus, described in all elementary textbooks, is easy to make. Melt a layer of sealing wax in a pie plate, and let it harden. Provide a flat metal disk, slightly smaller than the surface of the wax, with an insulating handle of pyrex or ebonite. Give a negative charge to the wax by rubbing it with fur. Place the disk in contact with the charged wax, which induces a positive charge on the lower side and a negative charge on the upper side of the disk. The usual method of removing the induced negative charge is for the demonstrator to touch the disk with his finger. A variation of this method is to use a neon-discharge-tube "wand," which is held so that the hand makes contact with one electrode. Touch the electrophorus disk with the other electrode of the tube. When the negative charge flows to ground through the demonstrator's body, the neon tube flashes brilliantly. A second flash is obtained by similarly touching the wand to the charged disk after it is removed from the wax plate. For best results, the metal disk should be at least \( \frac{1}{8} \) in. thick, with its edge smoothly rounded.

**E-11. Mechanical Work and Energy of Charge.** Work is required to separate the unlike charges in the electrophorus. Suspend an electrophorus disk by its insulating handle from a sufficiently sensitive helical spring. With the disk initially uncharged, lower it onto a hard rubber plate. Without touching the upper plate to any conducting material, slowly raise it again. The extension of the spring remains unchanged. Now with the plates again in contact, remove the charge induced on the upper surface of the upper plate by touching it with the finger. The force now needed to separate the plates is more than the weight of the disk, as shown by the increased stretch in the spring. Thus work must be done in separating the unlike charges.

**E-12. Electret.** An electret is an interesting variation of the usual electrophorus. Essentially, an electret is a sheet of dielectric that retains an electric moment after the externally applied electric field has been reduced to zero. It is somewhat analogous to a permanent magnetic sheet, but the analogy is not very close, as will appear presently.

To prepare an electret, it is necessary to produce an electric field strength of about 10,000 V per cm in a molten dielectric and
to maintain this field while the dielectric is solidifying. A pyrex pie plate makes a good container for casting the dielectric. A sheet of tin foil is spread evenly on the bottom of the plate so as to extend over the edges of the plate to serve as connection for one terminal of the high-voltage source. A few short pieces of pyrex tubing are placed on the surface of the tin foil, to support at the proper distance above it a brass disk that serves as the other electrode. The separation of electrodes should be such that the high potential source to be used will produce a field of about 10,000 v per cm. A full-wave rectified a.c. source, unfiltered by condensers or inductors, may be used. A potential difference of 2200 v average value with a distance of 2 mm between electrodes is satisfactory.

A tin pie plate may be substituted for the pyrex as a mold for the dielectric, the wax poured in, and a second pie plate floated on it in place of the brass disk. The upper plate must be kept from touching the lower one at the edges by insulating stops.

As a dielectric, one may use a mixture of two parts Carnauba wax, two parts rosin, and one part beeswax, the last to make the casting less brittle. These ingredients should be melted and mixed in a separate dish, then strained through cheesecloth into the pie plate. The plate may be placed over a wire screen on a tripod stand to allow application of a little heat in case the mixture has solidified after it has been poured into the plate and the upper electrode has been lowered into position. A piece of pyrex tubing attached at the center of the upper disk provides a handle. The bottom surface of this disk should be covered with tin foil, to prevent the mixture from sticking to the disk on cooling. The electric field is maintained until the mixture is cool. It is well to record the polarities of the electrodes. After the mixture has solidified and the high-voltage source has been disconnected, the tin foil may be removed from the upper disk. To keep moisture off the surface of the electret, it should be stored in a dry place, and the bottom tin foil should be connected to the brass disk when not in use, to prevent a layer of ions from gathering on the surface of the electret.

In use, the brass disk is operated exactly like the disk of an electrophorus. During the first few days after preparation, the upper surface of the electret has a charge of electricity opposite in sign to that given the brass disk by the high-voltage source. In
one or two weeks, this charge will reduce to zero and then reverse. The magnitude of charge will increase for several days, until after a period of about four weeks it reaches a maximum. The potential of the brass disk, after it has first been grounded and then removed from an electret such as this (2 mm thick) is sufficient to pass a fair-sized spark a distance of 1 cm to a grounded conductor. It is probable that the electret will retain its electric moment for several years provided that it is kept in a dry place. During the summer months, it may be necessary to keep it in a calcium chloride drying chamber.¹

E-13. Electrostatic Induction—Faraday's Ice-pail Experiment. This well-known experiment proves the equality of the induced and the inducing charges. A hollow conductor open at the top (a tin can will do) is mounted on an insulating stand and connected to an electroscope. A metal ball hanging by a silk thread is given a charge of known sign by contact with a charged rod or electrophorus disk. The ball is then lowered into the hollow conductor without touching it. The divergence of the electroscope leaves demonstrates the presence of an induced charge on the outside of the conductor. The demonstrator may call attention to the fact that the divergence of the leaves does not change as the inducing charge is moved about inside the conductor, thus showing that all of the lines of force from the inducing charge end on the inside of the conductor, regardless of the location of the inducing charge, provided that it is not too near the opening. If the ball is removed without touching the conductor, the electroscope leaves collapse, showing that no charge was transferred to the conductor. But if the ball is allowed to touch the bottom of the hollow conductor, the fact that there is no further change in the divergence of the leaves indicates that there must have been a charge induced on the inside of the hollow conductor exactly equal to that on the ball. This equality is further proved if the ball is withdrawn, the electroscope then discharged, and the ball returned to its original position within the hollow conductor without having been in contact with any body outside the conductor. The electroscope now shows no divergence, demonstrating that the ball was completely discharged by contact with

the inside of the hollow conductor and establishing the equality between the inducing and the induced charges.

**E-14. Equality of Charges on Solids Charged by Contact.** The simple Faraday ice-pail apparatus (E-13) allows one to show that the two charges produced by contact between dissimilar bodies are equal and opposite in sign. A hard rubber rod has a piece of woolen cloth wrapped around one end and securely tied. This rod and another one having nothing attached to it are held inside a hollow conductor connected by a wire to an electroscope. When the end of the plain rod is rubbed against the woolen cloth, the electroscope leaves do not diverge; but if either rod is withdrawn, there will be a divergence of the leaves, of the same amount. The experiment may be varied by rubbing the two rods together outside the conductor, then inserting one after the other separately, then both together (see also E-52).

**E-15. Charging Paper on Slate.** It is well to show that the materials so far used in the production of electric charges are not exceptional in this respect. If a sheet of paper is held against a slate blackboard and rubbed with the hand or struck with fur, the paper becomes charged and will stick to the board because of the induced opposite charge on the board. It is of interest to remove the paper and to watch it return to the board when released nearby. The sign of the charge on the paper may be determined by carrying it to the vicinity of a charged electroscope (E-24).

**E-16. Electrically Charged Student.** If a student stands on an insulated platform—an inverted battery jar will do—and is struck several times on the back with a piece of fur, his body becomes charged to a potential of several thousand volts above ground, and a 2-cm spark can be drawn from knuckles or ear, greatly to the amusement of the class. If the student holds a key tightly in his hand, sparks may be drawn from the key without causing him discomfort. The instructor may present to him a grounded Bunsen burner and let him ignite the gas by the spark. The sign of the charge on the student may be tested by a proof plane and an electroscope to which a known charge has been given (E-24).

**E-17. Charging Metals by Contact.** The charging of metals by contact may be shown and the signs of the charges determined. It is only necessary that the metal be held by an insulating handle
and be rubbed with wool. If a hard rubber rod with woolen cloth attached (E-14) is used, then the sign of the charge on each body is easily determined by placing it within the ice pail (E-13), provided that the electroscope has been given a charge of known sign; in this case, increased or decreased divergence of the electroscope leaves indicates the sign of the unknown charge (E-24). If a substance in the following list of materials is rubbed with one below it in the list, it becomes charged positively, the other substance negatively: fur, wool, quartz, glass, silk, wood, metals, hard rubber, sealing wax, rosin, sulfur, guncotton. Surface conditions may change the above order to some extent.

E-18. Neon Discharge from Rug Scuffing. Charges may also be separated by several other means, such as rubbing dry paper with the hand, passing a rubber or bakelite comb or fountain pen through the hair or rubbing it on the sleeve, drawing a rubber band across the edge of a board or desk. Charging the human body by scuffing the feet across a rug is a familiar parlor trick that may be varied by discharging the accumulated charge through a neon discharge tube. The operator holds one end of the tube and, after scuffing his feet on a rug, presents the other end of the tube to an uncharged person or, better still, to a radiator or other grounded conductor.

E-19. Electric Charges from a Stretched Rubber Band—Charging Electroscope by Contact. A piece of stiff wire is bent into the form of a miniature violin bow, and rubber stoppers are fitted over its ends. An ordinary rubber band becomes charged positively when stretched across the ends of this frame. This charge may be conducted to an electroscope by sliding the band along the knob. The device is convenient because any desired quantity of charge may be obtained by sliding a suitable length along the knob. If the stretched rubber band is rubbed along a grounded conductor, the positive charge will be removed; after the band has been allowed to contract to its original length, it will be charged negatively, thus enabling one to conduct a negative charge to the electroscope.

E-20. Charging by Contact between Glass and Mercury. The charging of a solid and a liquid may be shown with an evacuated glass tube containing a small quantity of mercury. A glass tube about 2 cm in inside diameter and 60 cm long is drawn down to a capillary at one end. The mercury is introduced into the
bottom of the tube. Connection is made to a pump, and the tube is evacuated. During evacuation, the tube may be heated with a flame, and the mercury boiled to expel air. The tube is then sealed off at the capillary. When the tube is shaken, potential differences are developed sufficient to cause a luminous discharge, but the luminosity is not great enough to make the demonstration effective in a large auditorium unless it is quite dark. It is well to hold the tube in a horizontal position while shaking to avoid the mercury-hammer effect.

If facilities are available, the experiment may be varied by the introduction of neon. A glass tube 5 mm in diameter and 25 cm long is sealed at one end, and a small quantity of clean mercury put in it. It is evacuated thoroughly, and neon gas is admitted to a pressure of a few millimeters, after which the tube is sealed off. Upon shaking the tube, the characteristic neon discharge may be observed in a dark room. The effect is enhanced if the tube is constricted at a number of places along its length so as to increase the contact of mercury with glass as it is shaken from one end of the tube to the other. The neon must be pure, otherwise the color is muddy.

**E-21. Mercury-glass Charging Wand.** The effect described in E-20 is employed in a simple charging rod to replace the more usual rubber or glass ones. A glass tube 30 cm long and 1 cm in diameter containing a little mercury is evacuated and sealed. One end is covered with tin foil or platinized. When mercury is allowed to run from one end of the tube to the other, it acquires a positive charge; when it is run into the platinized end, a negative charge is induced on the glass, and a positive charge appears on the metallic coating. A negative charge may likewise be obtained by grounding the metallic coating and then allowing the mercury to run back to the other end of the tube. The rod may be used to obtain either positive or negative charge for charging an electroscope by contact or induction; the potential of the charge on the metal coating is sufficiently high to produce a flash in a neon bulb.¹

**E-22. Charging by Change of State.** Many substances become charged upon solidification. Sulfur is melted in a glass dish, and some of it is taken up on the end of a glass rod where it is

allowed to solidify. If it is held near an electroscope, it can be shown to acquire a negative charge.

**E-23. Charging Electroscope by Induction.** Hold a charged rod near the knob of an electroscope. A charge of opposite sign is induced on the knob, while a charge of the same sign is induced on the electroscope leaves. Charge on the leaves is conducted away by touching the knob ( grounding) while the inducing charge is near. Break the ground connection, and remove the inducing charge. The electroscope is thus left with a permanent charge of sign opposite to that of the inducing charge. Any insulated body may be similarly charged by induction, giving a resultant charge opposite to that brought near it.

**E-24. Identifying Positive and Negative Charges.** The electroscope charged with electricity of known sign, either by contact (E-19) or by induction (E-23), may be used for testing the sign of an unknown charge. A charge of the same sign as that on the electroscope, when brought near the knob, will cause increased divergence of the leaves, while a charge of opposite sign will cause decreased divergence. It is instructive to bring a charge of opposite sign so close that the leaves not only collapse but begin to diverge again. In determining the sign of an unknown charge, one must remember that the approach of any grounded conductor, for example, the demonstrator's hand, toward the electroscope knob, will cause decreased divergence of the leaves since some of the charge on the leaves flows to the knob as a result of the attraction caused by the charge induced on the grounded conductor (condenser effect). This difficulty is largely avoided if the charge being tested is brought up on a proof plane attached to the end of a long pyrex rod. Another source of trouble is the charging of the demonstrator's body, especially in dry weather and on dry wood floors. This charge can be removed by touching a gas or water pipe.

**E-25. Kelvin Water Dropper.** Two tin cans $A$ and $B$ (Fig. 212), with tops and bottoms removed, are mounted on insulating supports above two other cans $C$ and $D$ with perforated bottoms, also insulated. The cans are connected electrically as shown, with one pair connected to a vibrating-leaf electroscope (E-4) with case grounded. The arms of a glass T-tube are bent at right angles, and the tube is mounted so that water may drip from both arms through the upper cans without touching them.
and may then be caught in the lower cans, whence the water runs off to the sink; the flow of water is regulated with a pinchcock. As they leave the glass, the water drops are charged, and charges build up by induction and contact so that the electroscope leaf is deflected until it strikes the grounded stop in the case. As dropping continues, the leaf oscillates, about twice a second. The sign of the charge on each of the conductors should be tested by presenting the electroscope to each in turn. A large potential difference can be generated by this simple electrostatic machine.

A "dry water dropper" has been constructed, in which \( \frac{1}{2} \)-in. steel balls are dropped instead of water droplets. The balls are dropped over and over again as they are returned to their upper elevation either mechanically or by hand.

**E-26. Toepler-Holtz and Wimshurst Machines.** An electrostatic machine (frequently called "influence," "induction," or "static") is really a continuous-action mechanical electrophorus (E-10). Such machines may be shown at any time after the simple experiments on electric induction are performed. They are useful for subsequent demonstrations, since they are more effective charging devices than the electrophorus or electret. By increasing the distance between the two knobs, to delay the spark discharge, higher potential differences can be built up. Much larger charges can be stored before the spark discharge occurs by connecting the knobs to Leyden jars, which are usually component parts of the machines. Proof plane and electroscope may be used to show that the knobs are oppositely charged (E-24). A card or a thin sheet of glass may be punctured by the passage of a spark through it; however, the spark will in general go around the edge of a thick piece of glass.

**E-27. Van de Graaff Generator.** The principle of generating high potentials by the mechanical separation of electric charges, upon which the operation of the Kelvin water dropper (E-25) is based, is likewise shown in the Van de Graaff electrostatic generator. A small model of this generator may be constructed at low cost. The generator consists of one or more endless belts of silk or paper driven at high speed by a motor. The belts become
charged when they pass pointed wires connected to a 10,000-v transformer and kenotron rectifier and carry their charge to the inside of an insulated sphere, where they give it up to other pointed wires connected to the sphere and return "for another load." The insulated sphere thus acquires charge, and its potential builds up to a high value, higher in general than can be obtained by an ordinary rotating-plate static machine. The charging transformer and rectifier can be omitted, and the device can be made self-sustaining when once started by a static charge by using two insulated spheres and two belts, with appropriately arranged points as shown in Fig. 213.¹

DISTRIBUTION OF CHARGE ON CONDUCTORS

E-28. Location of Charge on Insulated Hollow Conductors.
A hollow conductor on an insulating stand is charged by contact with the electrophorus disk. With proof plane and electroscope, show that no charge is given to the proof plane when it is touched to the inside of the conductor, but that a charge is received by contact with the outside.

A cone-shaped linen bag, generally called a "Faraday's bag," has its base attached to a ring on an insulating stand and has two silk threads attached to its apex, by which the bag may be pulled inside out. The bag is given a charge, and the proof plane is used to show that the charge is wholly on the outside. The bag

¹ For further details, see Van de Graaff, Compton, and Van Atta, Phys. Rev., 43, 153, 1933.
is then pulled inside out and the proof plane again used to show that there is still no charge on the inside.

**E-29. Surface Distribution of Charge.** An egg-shaped conductor on an insulating stand is charged. Proof plane and electroscope are used to compare charge densities at various points on the surface of the conductor. It is found that the charge density (and hence the charge acquired by the proof plane) is greatest at the point of greatest curvature. (Care must be exercised that the proof plane itself does not disturb the charge distribution by its presence.)

Instead of the ellipsoidal conductor, an insulated aluminum cooking pan may be charged. The charge density is greatest at the corners and edges and least where the pan is flat, being greater on the outside of the bottom than on the inside of it.

**E-30. Absence of Electric Field within a Closed Conductor.** A cylinder of coarse-mesh screen (galvanized-iron wire of 1/4-in. mesh serves well) about 4 in. in diameter and 8 in. long, open at both ends, is set on an insulated metallic plate connected with one terminal of the electrostatic machine. A metal-coated pith ball is suspended by a fine wire from the top of the cylinder so as to hang against the cylinder on the inside about half-way down, a similar ball being suspended from the top so as to hang about half-way down on the outside. When the machine is started, the outer ball deflects outward, the inner one remaining motionless. In the absence of an electrostatic machine, the electrophorus may be used.

**E-31. Electric Shielding.** Since charges reside on the outside of conductors, an electroscope, whether charged or uncharged, when enclosed within a conducting surface will be unaffected by outside charges. The shield may be a closed metal vessel but need not be continuous. A cage made of heavy wire screening is entirely effective. Charges may be brought near the screen and, if it is grounded, sparks may be passed to it without affecting the electroscope within. Project the image of the electroscope leaves to show the absence of any effect.

**E-32. Discharge of Electricity from a Point.** A thin sheet of metal is rolled into a sharp-pointed cone and attached to a conductor on an insulating support. The hollow conductor used in E-28 is convenient, since the metal sheet may be cut in such a shape that a strip will extend from the base of the cone, the strip
being bent into a hook to hang over the edge of the opening in the hollow conductor. Another conductor, also on an insulating support, is placed about 5 cm from the vertex of the cone and is charged either by use of the electrophorus disk or by the electrostatic machine. Charges are induced on the conductor carrying the cone. If the inducing charge is now removed, it can be shown by proof plane and electroscope that the conductor carrying the cone has acquired a net charge of the same sign as that of the charge on the other conductor, owing to the escape of charge from the conical point. This experiment may be contrasted with E-23, where an opposite sign of charge results.

**E-33.** A charged conductor is connected to an electroscope and contact made with the blunt end of a carefully insulated darning needle, so that the needle projects perpendicularly from the surface of the conductor at the place of contact. The deflection of the electroscope falls to zero.

**E-34.** A tinsel tassel is hung from one knob of a static machine, and the machine is started. The strands of the tassel stand apart because of repulsion, but when the point of a needle held in the hand or otherwise earthed is brought near the tassel, the strands collapse. If the needle is not earthed but is held in an insulated handle, its effect is negligible.

**E-35.** If a point attached to one knob of a static machine is brought near an insulated uncharged conductor, the conductor becomes charged, as may be demonstrated by bringing it near an electroscope.

**E-36.** The lecture-room galvanometer is connected to one knob of the static machine and to a wire suspended from an insulated support so as to hang over the other knob to form a vertical air gap, shorter than that between the knobs (Fig. 214). The galvanometer deflects widely, owing to the invisible brush discharge between the dangling wire and the adjacent knob. With point terminals on the static machine, this brush discharge may be seen in a darkened room. The galvanometer should be protected by using a 0.5-megohm series resistor and disconnecting the condensers of the static machine.

**E-37.** "Electric Wind." A candle flame held near a pointed conductor connected to the positive terminal of a static machine
is strongly repelled from the point as if a breeze of ions were actually issuing from the point. If the flame is held near the negative terminal, it is attracted toward it. The phenomenon is one of electrostatic repulsion and attraction rather than of any strong ion current issuing from the positive point. In the luminous part of the flame, positive ions predominate.

**E-38. Electric Reaction Wheel.** The “electric whirl” is another device illustrating discharge from a point. Two wires are crossed at their midpoints, and their pointed ends are bent at right angles so that they form a swastika. The device is pivoted at the crossing and connected to either terminal of a static machine. Rapid rotation is caused by reaction forces due to the repulsion of ions from the points.

**E-39. “Electric Chimes.”** This is an old demonstration, but still effective. The action depends on attraction and repulsion of charges, involving induction. It may be understood by reference to the case of two bells supported at the same level, with a small metal clapper (ball) suspended by an insulating thread midway between them. One of the bells is connected with one knob of an electrostatic machine or a charged Leyden jar, while the other is earthed. Attraction between the charge on the first bell and that induced by it on the clapper causes the latter to strike the bell. The clapper now becomes charged with the same sign as the bell and is repelled with enough force to strike the earthed bell, to which it loses its charge. The process is repeated indefinitely, as long as the charge is maintained on the first bell.

**E-40. Effect of Intervening Medium on Force between Charges.** Bring a charged insulated conductor near the knob of an uncharged electroscope; the induced free charge on the leaves causes their deflection. Without touching the electroscope or moving the charged conductor, insert successively between the two, without touching either, sheets of equal thickness of glass, paraffin, shellac, hard rubber. When each of these sheets is introduced, the deflection of the electroscope leaves decreases a little, and when the sheet is removed the deflection rises to its former value.

**E-41. Water Jet.** This experiment involves not only induction but surface tension and adhesion. A stream of water flows from a small glass nozzle with a 2-mm orifice, inclined at 10° from
the vertical. The pressure is adjusted until the jet rises upward 2 or 3 ft and falls into the sink. The normal jet is smooth near the orifice but becomes unstable and breaks into drops near the top of the arc. Surface-tension forces predominate. If a charged rod is brought toward the jet, about on a level with the nozzle, forces of adhesion are in part counteracted by electrostatic repulsion of like induced charges on nozzle and water, and the charges induced on the water tend to counteract surface tension along the jet. The form of the stream is then seen to change, until the jet is smoothly continuous from nozzle to sink, with apparently circular cross section at all points. If the rod is moved still closer, the jet bends toward the rod because of electrostatic attraction between the charged rod and the induced charge on the water. If the charged rod is brought very close to the jet, the induced charge is increased to such an extent that the jet breaks up into small droplets which fly away from each other and of which some may even be drawn backward around the rod. This dispersion of the drops is much more pronounced than in the normal jet, because of positive repulsion due to electrostatic charges. (See also A-120.)

**E-42. Movement of Charged Material along Lines of Force.**

Connect the static machine with the handle of a small metal ladle provided with a lip, such as is used to pour Babbitt metal. Hold the ladle by a dry wooden stick attached to its handle, and melt in it some rosin. Hold the ladle a foot or so above a paper spread to cover a large area on the lecture table, and keep it well away from the clothes. Now start the static machine, with condensers attached and spark gap set at 3 in., and slowly pour the molten rosin from the lip. The result is somewhat spectacular. Tiny streams of electrified rosin spurt from the edge of the lip, almost in straight lines, apparently in defiance of gravity. They keep well apart from each other, striking the paper and solidifying into droplets. The jets follow the field, whose lines run quite straight out from the edge of the ladle to an appreciable distance. Gravitational forces are small compared to electrostatic near the ladle. The jets collapse whenever a spark occurs between the knobs of the static machine, but they stiffen again as the charge on the ladle builds up. A synchronous pulsating behavior can be noted in an electroscope placed in the same field (E-52). Solidified remnants of the directed jets may be found...
attached to the edge of the ladle at the conclusion of the experiment. Use shadow projection.

**E-43. Movement of Charged Particles in Electric Field.** Support two small metal plates horizontally on insulating stands, one about 1 cm above the other, and connect them to the terminals of a static machine. Sprinkle aluminum powder on the lower plate. When the machine is operated, the powder acquires the charge of the lower plate and is repelled to the upper plate, where the sign of its charge is reversed and it is driven downward. Thus there is a continual stream of particles in both directions, which may illustrate by analogy the conduction of electricity through a gas by ions. The motion is made visible by shadow projection.

The same effect may be shown on a larger scale. A glass bell jar with a metal terminal in the top rests on a wooden base on which is laid a metal disk. The disk and upper terminal are connected to the terminals of a static machine. When the machine is operated, metallized pith balls inside the jar rise and fall between the terminals.

**E-44. Mapping Field of Force with Epsom Salt Crystals.** Two disks of tin foil 1 cm in diameter are cemented to a glass plate that is set in a lantern arranged for vertical projection. A narrow strip of foil is left attached to each disk for electric contact by fine wires to the terminals of a static machine. When the machine is operated, an electric field is set up between the disks. The lines of force of this field are made "visible" by sprinkling fine epsom salt crystals on the glass plate through a wire sieve. The plate is tapped to assist in the alignment of the crystals.

**E-45. Mapping Field of Force near Electrified Bodies with "Electric Doublet."** Two pith balls are aluminum painted and thrust over the ends of a thin glass rod about 6 cm long. One end of a silk thread about 50 cm long is attached to the middle of the glass rod, and the other end to a short wooden rod. Two conductors on insulating supports are connected to the terminals of a static machine and charged. One of the pith balls is given a positive charge by contact with one of the conductors, and the other is given a negative charge in the same manner. If the "electric doublet" so produced is held in the region of a charged conductor or set of conductors, the doublet will point in a direction tangent to a line of force. By "fishing" in various places,
the electrostatic field can be mapped. If aluminum paint is used on one pith ball and bronze paint on the other, the positive directions of lines of force may be shown more readily.

**E-46. Human Electroscope.** A student (with fine dry hair) stands on an insulating stool and takes hold of one terminal of the static machine (previously discharged to prevent shock). When the machine is run, his hair tends to rise and extend along the lines of force of the field about his head. This hair-raising experience is accentuated by placing a grounded metal plate horizontally above his head at a distance greater than the spark gap. Each time a spark passes, this “hair electroscope” will collapse, then rise again. There is no danger to the student if the terminals of the spark gap are short-circuited before he takes hold. He will have no unpleasant shocks so long as he continues to hold to the terminal, but he may experience sparks if he lets go or touches grounded objects. It is best to cut out the condensers during this experiment.

**E-47. Discharge through the Body.** Two students *A* and *B* stand on two insulated platforms, and each grasps one of the knobs of a static machine (previously short-circuited). (If condensers are used, they should be of small capacitance.) A third student *C* stands on the floor and so is earthed. After the machine is started, *C* touches *A*, and a small spark passes. He removes his hand from contact with *A* and similarly touches *B*, and another small spark passes. Then *C* touches *A* while still in contact with *B*, and a large spark passes, since there now occurs an almost complete neutralization of the charges on the machine. The smaller sparks indicate partial discharges to earth, the rest of the charge in each case being bound by the attraction of the opposite charge on the other terminal.

**E-48.** All the students in the class join hands and form a line around the sides of the lecture room. The student at one end of the line makes contact with one knob of the static machine. At the other end of the line, a spark gap is formed between the other knob of the machine and a metal rod held in the hand of the last student. This student closes the gap. All the class now feel what they previously only saw and heard, the effect of spark-gap length (between knobs of the machine) on the charge and voltage. *Caution:* Keep the charge small by using a small condenser. Remember that even a \( \frac{1}{4} \) in. spark requires about
5000 v. Encourage the students to grasp hands tightly so that sparkling shall occur only at the end of the line.

**E-49. Voltage Measured by Length of Spark.** Connect an electrostatic voltmeter (E-4) to the ball terminals of a static machine with condensers, and note the reading just prior to the spark discharge. Repeat a number of times, varying the spark gap. Compare the observed value with that usually given, viz., 30,000 v per cm in air at atmospheric pressure.

**E-50. Discharge of a Conductor by Surrounding Gaseous Ions.** A charged conductor (positive or negative) is connected with an electroscope. When a flame (candle or lighted match) is brought near it, the deflection of the electroscope falls rapidly to zero, showing that the charge has been dissipated. The electroscope is quickly discharged by blowing the gases of combustion from a flame upon the conductor. A sample of radium gives the same effect (A-112), and so do x-rays (A-103).

**E-51. Ions Formed in Flame.** Two metal plates supported vertically on insulating stands are set parallel and 2 to 3 cm apart and are connected to the terminals of a static machine. A candle flame is held just beneath the plates. The hot gases rising between the plates are made visible by shadow projection (H-137). When the static machine is operated, the gases will be seen to divide into two streams as ions of opposite sign are attracted to the charged plates.

**E-52. Extent of Electric Field.** An unshielded electroscope is set several feet away from a static machine (with condensers) and a 2-in. spark gap. As the machine builds up charge, the electroscope leaves rise; when a spark occurs, they fall, although not completely, as the field immediately begins to build up again. This experiment demonstrates strikingly the existence of an appreciable field at relatively large distances from the charges. (A radio receiving set with loudspeaker may be used as a sensitive detector of sudden changes of field.)

With the condensers out and the spark gap several inches long, test the signs of the charges on the knobs by charging the electroscope, held near one of the knobs, by induction. Then discharge the knobs by contact, and note, by the absence of the deflection of the electroscope brought near them, the absence of charge. This is a simple experiment but fundamental, since it shows that the
two charges, simultaneously produced, are equal in amount and opposite in sign. (Compare E-14.)

**E-53. Energy in the Discharge.** The knobs of the static machine are set a few centimeters apart, and some alcohol in a spoon is held just below the gap. When a spark passes, it ignites the alcohol, directing attention to the heat in the spark and so to the potential energy stored in the charges. Gas flowing from a grounded Bunsen burner may be ignited by a spark from the charged disk of an electrophorus. Powder in a toy cannon may be exploded by passing a spark between terminals buried in the charge.

**E-54. Heat Generated by Spark.** A glass tube with side arm as shown in Fig. 215 is mounted vertically. Ball electrodes project through tight rubber stoppers in each end of the larger tube. Water fills the tube nearly to the level of the lower knob. When a spark from a static machine (with condensers in) is passed between the knobs, the expansion of the air drives the liquid into the side tube.

**E-55. Gas Explosion by Spark.** An insulated terminal or automobile spark plug is mounted in the wall of a metal vessel so that a spark may be made to pass between the terminal and the wall. The vessel is filled with an explosive mixture of hydrogen and oxygen and is corked. The terminals of the spark gap are connected to the knobs of a static machine. When a spark passes, the gases explode and blow the cork out. An explosive mixture of gasoline vapor and air may be more readily obtained (H-182).

**POTENTIAL AND CAPACITANCE**

**E-56. Electric Potential.** As an aid in teaching the idea of potential, one may charge an insulated conductor either with the static machine or with the electrophorus disk. The work done in bringing additional charge of like sign from a distance up to this conductor may be illustrated by bringing up a similarly charged pith ball hanging by a silk thread from any convenient support. As the demonstrator moves the charged pith ball
toward the conductor, it is evident that work must be done against the observed repulsive force between the conductor and the pith ball.

**E-57. Mapping Potential Field.** Charge a large metal sphere, and suspend it by an insulating string as far as possible from other objects. Attach a small metal alcohol lamp or a cigarette lighter to the end of a long, insulating handle (preferably rubber). Run a wire from the metal lighter to one side of an electrostatic voltmeter, and ground the other side of the meter. The flame of the lighter ionizes the surrounding air, and the lighter rapidly acquires the charge necessary to bring it to the potential of the point at which it is held. By moving the lighter about in the field, one may show that the potential is inversely proportional to the distance from the center of the charged sphere. Ions from the flame will in time neutralize the charge on the sphere. It may be recharged from time to time by touching it with the knob of a charged Leyden jar.

**E-58. Model of Potential Field.** Stretch a sheet of rubber dam horizontally midway between the table and a glass plate set 15 in. above it. The plane of the dam represents a region of uniform potential, which may be taken as zero. At some point $Q$ (Fig. 216), push the dam up by a $\frac{1}{2}$-in. dowel rod, rounded at its upper end, to represent an increase of potential due to the presence of a "positive charge." Magnitude of charge is proportional to the length of dowel rod above the zero level of the dam. The potential diminishes on all sides, at a rate roughly proportional to $Q/r$. "Negative charges" may be introduced into the field by inserting dowel rods between the dam and the glass plate, as at $P$, thus introducing depressed regions of negative potential. Positive and negative electrical potentials are here represented by gravitational potentials, positive and negative with respect to the zero level of the dam. The potential difference between any two
points is, of course, represented by the vertical distance between them. The field strength or potential gradient at any point is represented by the slope of the rubber-membrane surface at that point. Gravitational equipotential ("level") surfaces intersect the dam in contour lines, which, when projected on the zero plane, represent the traces on that plane of the electrical equipotential surfaces due to coplanar charges. Combinations of rods or objects of various cross sections may be used to show the potential field about various combinations of charged conductors. The motion of charged particles in electric fields (e.g., as in a triode vacuum tube) may be shown by rolling small balls or shot on such potential models (see A-83).

**E-59. Potential of a Conductor during Discharge—Electroscope as Potential Indicator.** A conductor on an insulating support is connected to a Braun electroscope (E-4) in the lantern field. The conductor is charged by sparks from the electrophorus disk until the electroscope vane stands out at an angle of 45° or more. When the vane has stopped oscillating, connection is made between the charged conductor and one terminal of the electric chime (E-39), the other terminal being grounded. This connection may be made by means of a wire attached to the end of a glass rod and held in contact with both the conductor and the terminal of the chime. The kinetic energy gained by the brass ball in moving from one bell to the other is dependent upon the charge imparted to the ball when in contact with the first bell, which depends upon the potential of the conductor. Since the intensity of the sound is dependent upon this kinetic energy, the gradually decreasing sound intensity shows the slow decrease in potential of the conductor during discharge.

The Braun electroscope is included in the experiment to show that the deflection of an electroscope is an indication of the potential of a conductor. While the potential of the conductor in this experiment decreases, the electroscope vane returns slowly toward its undeflected position.

**E-60. Potential of Charged Sphere.** A conducting sphere is supported on an insulating stand, and three small electroscopes are attached to it at points 90° apart on a horizontal plane through the center. The electroscopes consist of pairs of small pith balls, aluminum painted, hung from the sphere by conducting threads. When the sphere is charged, the three electroscopes show the
same deflection. When the sphere is discharged, the deflections vanish. Now a second charged sphere is brought near the first, but not touching it, with its center on the diameter connecting two of the electroscopes. These two will show equal deflections, on account of the equal, though opposite, charges induced on the first sphere. The third electroscope, which is midway between the other two, will show no deflection. Nevertheless, the sphere is a conductor and must therefore be at the same potential throughout. Since, however, the electroscopes obviously have different deflections, we must conclude that there has been a redistribution of charge on the sphere. If an earthed metal plate is brought near one of the electroscopes showing a deflection, the deflection decreases, while a similar plate brought up to the middle (undelected) electroscope will cause it to deflect. Redistribution of charge on the sphere because of the presence of the earthed plates may make the deflections of the three electroscopes equal.

E-61. Comparison of Charges on Spheres at Same Potential—Capitance. Two conducting spheres of diameter about 2 cm and 4 cm respectively are equipped with pyrex rod handles. The spheres may be made of wood or cork, aluminum painted. They are charged to the same potential by touching them simultaneously to a large charged conductor or to one terminal of a charged Leyden jar. They are then introduced separately within a hollow conductor connected to an electroscope (E-13), without touching the walls of the conductor. The divergences of the leaves of the electroscope serve to compare qualitatively the magnitudes of the charges on the two spheres. The larger sphere will, of course, bear the larger charge, although the potentials of the two spheres are equal.

E-62. Elementary Condenser. Charge an 8-in. insulated metal sphere with several sparks from the electrophorus (E-10). It will be noted that successively weaker sparks pass to the sphere as charging proceeds, for the potential of the sphere rises. Discharge the sphere to ground, and observe the character of the spark. Place near the sphere a conductor, such as a parabolic reflector (H-150). This second conductor is at first insulated. The capacitance of the sphere has now been increased somewhat, and many more strong sparks may be passed to it from the electrophorus. Remove the neighboring conductor, and again dis-
charge the sphere to ground. A more intense spark is observed. Finally, replace the neighboring conductor, but this time ground it, and repeat the previous charging and discharging process. The capacitance is greatly increased, and a large number of sparks may be passed to the sphere because its potential rises slowly with increasing charge.

E-63. Leyden-jar Condenser. A Leyden jar with outer coating grounded is charged by bringing the electrophorus disk close enough to the knob of the jar for a spark to pass. After a number of small charges have been given to the jar by successive applications of the electrophorus disk, the inner and outer coatings of the jar are connected by a pair of discharge tongs, whereupon a noisy, bright spark passes. The tongs are removed, and after a few seconds they are again used. A second, weaker spark will be observed, showing that the condenser coatings have acquired a "residual charge" in the short interval between the first discharge and the second application of the tongs.

The Leyden jar may be discharged through the class as described in E-48. Use discretion! A small charge is sufficient to give the students a jolt.

E-64. Dissectible Leyden Jar. A Leyden jar whose inner and outer coatings can be removed is charged, and the electrodes are then removed from the glass. When they are brought into contact with one another, no spark passes; but if the jar is reassembled, it may be discharged in the usual manner, showing that the energy of the charge resides in the dielectric.

E-65. Bound Charge on Leyden Jar. The two coatings of a charged Leyden jar on an insulating stand can be grounded alternately with only small loss of charge. This process may be repeated a number of times, but when the two coatings are finally connected, a vigorous spark is obtained. Thus either coating of the jar may be put at ground potential (or any other potential) without affecting the potential difference between the coatings.

E-66. Positive and Negative Charges on Dielectric—Lichtenberg Figures. A charged Leyden jar is held in the hand by the outer coating, and with the knob a pattern is traced on a plate of dielectric, such as shellac or hard rubber. The jar is then set on an insulating stand, and the hand is transferred to the knob, without discharging the jar, so that a corner of the outer coating
may be used to trace another pattern on the dielectric. The dielectric plate is then sprinkled with a mixture of litharge (red lead) and flowers of sulfur, well dried and shaken together, so that the litharge particles become charged positively by friction and the sulfur particles negatively. The litharge then adheres to the pattern traced by the negative electrode of the Leyden jar, and the sulfur to that traced by the positive electrode. The two patterns are easily distinguished by the difference in their colors as well as by their character; the yellow pattern has many branching lines, while the red appears in small circular spots. The principle of this experiment has recently been adapted to the measurement of the very high voltages of lightning.

**E-67. Addition of Potentials.** Connect three or four similar Leyden jars in parallel, and charge them by the static machine. Discharge them simultaneously, and note the length and intensity of the spark. Again charge them in parallel, place on individual insulating stands, and connect in series. The potential difference between the end terminals is now the sum of the potential differences of the individual jars, and a much longer but less intense spark will be obtained. This simple method of “multiplying potentials” is frequently used for obtaining high voltages from low.

**E-68. Condensers in Series and Parallel.** Connect four similar Leyden jars in parallel, and charge them by a static machine. Disconnect one of the four and discharge it; then discharge the other three together. Since the potential difference across each jar is the same, the difference in the “fatness” of the sparks comes from a difference in quantity of charge. Now connect the three jars in series and the fourth in parallel with the three, and charge as before. Disconnect the one jar, and discharge it; then discharge the three that are in series. The length of spark is the same in the two cases, but in the latter case the spark is much weaker because of reduced capacitance due to the series connection. Similar to this experiment and to E-67 is another experiment (E-262) performed with a ballistic galvanometer and condensers charged at low voltage.

**E-69. Parallel-plate Condenser.** A convenient demonstration condenser consists of two metal plates mounted parallel to each other on insulating supports, one of the plates being movable. An easily constructed form consists of two rectangular sheets of
metal, about 12 by 20 cm, tacked to two blocks of wood resting on a sheet of glass for insulation. The sides of the two plates facing one another are coated with shellac for insulation. One condenser plate is connected to the knob of an electroscope with grounded case; the other plate is grounded. The plate connected to the electroscope is charged, and the divergence of the electroscope leaves indicates the potential difference between charged plate and ground. If the plates are brought close together, the divergence of the electroscope leaves decreases. If the distance between the plates is increased, the increased potential difference is shown by the electroscope. This experiment emphasizes the fundamental relationship among charge, potential, and capacitance, \( Q = VC \). The charge upon the insulated plate is constant; the potential must therefore increase with decrease of capacitance, and vice versa.

This principle is frequently used in "potential multipliers" to detect small potential differences by electroscopes or electrometers (E-71 and 116). A convenient substitute for the parallel plates described above is a radio condenser with a set of rotating plates. One set of plates is grounded; the other set is connected to the electroscope and charged.

**E-70. Dielectric Constant and Capacitance.** The apparatus described in E-69 may be used to make a rough determination of the dielectric constant of an insulator. The divergence of the electroscope leaves is decreased when a sheet of insulating material is inserted between the plates (E-40). If pieces of plate glass, hard rubber, and paraffin of approximately the same thickness are used separately, with the distance between the condenser plates fixed and only a little more than the thickness of the dielectric sheets, the relative effects of the different materials may be observed. Any charge on the test sheets may be removed by passing a flame quickly over their surfaces before they are inserted between the condenser plates.

**E-71. Condensing Electroscope.** Small electrostatic charges may be detected by an electroscope and variable condenser. One of the plates of a parallel-plate condenser is earthed; the other plate is connected to an electroscope in the lantern field, and a sheet of mica or of paraffined paper is used as a dielectric (Fig. 217). If a charge too small to deflect the electroscope is given to the insulated plate, a deflection is produced when the
upper plate is lifted from the sheet of dielectric, because of a decrease in the capacitance of the condenser. Attention is called to the fact that charges are sometimes developed on the surface of a sheet of mica by slight rotations of the disk. These charges may be removed by holding the mica momentarily over a flame.

The capacitance of the pair of plates may be greatly increased by grinding the disks together with fine emery until the ground surfaces appear uniform, after which the disks are cleaned and dried. One of them is dipped in thin shellac to form an insulating layer on its ground surface. This disk is mounted on the knob of an electroscope, or on an insulating stand with a wire running from disk to electroscope. The other disk is provided with an insulating handle of sealing wax or hard rubber.

**E-72. Contact Difference of Potential.** To demonstrate contact potential difference one needs, in addition to the condensing electroscope (E-71), a plate of copper and one of zinc, both on insulating handles. The copper plate is earthed, and the zinc plate is laid upon it, their surfaces being close together. The potential of the zinc while in contact with the copper is of the order of 1 v above that of the copper, and a positive charge is given to the zinc. The zinc plate is then removed from contact with the copper and touched to the insulated plate of the condenser. Some of the positive charge is conveyed to the insulated condenser plate, but it does not deflect the electroscope because the amount of charge so conveyed is too small. With condenser plates about 15 cm in diameter and zinc and copper plates about 8 cm in diameter, it is necessary to repeat the operation of touching the zinc to the copper plate and to the insulated condenser plate about thirty times to make an ordinary electroscope show a distinct deflection, when the capacitance of the condenser is decreased by the removal of the grounded plate. The sign of the charge given to the electroscope should be tested to show that it is positive. The experiment may then be repeated with the zinc plate grounded and the copper plate used to charge the electroscope, in which case the charge on the electroscope is negative.

Other materials may be used to demonstrate larger contact potential differences. For example, a block of paraffin dipped
into distilled water in an insulated can and removed will be found to have acquired a negative charge, leaving an equal positive charge on the water. Quartz dipped into mercury acquires a positive charge.

E-73. Dependence of Capacitance on Area. An insulated hollow conductor with open top is connected to an electroscope. A piece of brass chain about 1 m long is coiled within the hollow conductor, one end of the chain being attached to a pyrex rod about 50 cm long. The conductor is charged, and the chain slowly lifted out. The electroscope leaves slowly collapse, because of the decreasing potential of the conductor resulting from an increase in its surface area, but return to their original deflection when the chain is lowered into the conductor again. Telescoping metal tubes may be used to produce the same effect.

E-74. Another method is to cement one edge of a long rectangular sheet of tin foil to a horizontal pyrex rod supported in notches cut in the upper ends of two vertical pieces of wood, the lower ends of which are attached to a wooden base. One end of the pyrex rod is bent to form a crank. When the rod is rotated, the tin foil is wound up like a curtain. A small brass rod is cemented to the lower edge of the tin foil, to keep the foil under slight tension, and a fine wire is attached to it to connect the sheet of foil with an electroscope. If the foil is charged, the divergence of the electroscope leaves is an indication of the potential. As the foil is rolled up, the potential increases, showing clearly the dependence of the capacitance on the area. An insulated window-shade roller may be used in place of the glass crank.

E-75. A still simpler method of changing capacitance with change of area is with a plane-plate radio condenser with rotating plates. One set of plates of the condenser is connected to an electroscope, and, when set for maximum capacitance, the condenser is charged by a 45-v B battery. The switch K (Fig. 218) is opened, the plates are rotated toward minimum capacitance, and the divergence of the electroscope leaves indicates an increase of potential. This simple device may be applied to E-71, 116, etc.
MAGNETISM

E-76. Indicator for Magnetic Effects. In showing magnetic experiments, it is important to have some clearly visible indicator whose function is similar to that of an electroscope in electrostatic experiments. A large compass needle swinging in a horizontal plane on a jeweled bearing serves well. Two paper flags of different color will enable students at a distance to distinguish between north and south poles of the needle. For still greater visibility, one may use a large dipping needle swinging in a vertical plane about a horizontal axis mounted in jeweled bearings. If possible, the needle should be placed to swing in an east-west plane perpendicular to the magnetic meridian so that its rest position will be horizontal. Paper flags may be used, or the shadow of the needle may be projected.

E-77. Natural Magnets. Two pieces of magnetite are held in paper stirrups suspended by threads. These natural magnets or lodestones come to rest in the magnetic meridian. If one of them is removed from its paper stirrup and brought near the other, the repulsions between like poles and the attractions between unlike poles will be evident. For large classes, the directional effects may be shown by attaching light paper arrows to the lodestones or by using the magnetic indicator (E-76). A piece of magnetite picks up small tacks. Iron filings cluster about certain regions commonly called “poles.” (Shadow projection.)

E-78. Magnetization by Contact. A steel knitting needle may be magnetized by stroking it with a piece of lodestone (or any permanent magnet). This experiment is of some historic interest, since for centuries the magnetic needles of mariner’s compasses were magnetized by contact with natural magnets. If the steel knitting needle is already magnetized, it may be demagnetized sufficiently for the present purpose by passing it through a solenoid connected to an a.c. line. After such a needle has been magnetized by contact with a piece of lodestone, it too will pick up tacks and iron filings.

E-79. Magnetization by Contact. To induce four poles in a knitting needle, support it horizontally with its ends resting on the north poles, say, of two similar bar magnets, and stroke it with the south pole of a third magnet, beginning at one end of the
needle and lifting the magnet away from it near its center, then repeating, in the reverse direction, on the other half of the needle. The needle will then have a south pole at each end and two north poles close together at the center.

**E-80. Magnetization by Mechanical Disturbance in Earth’s Field.** A magnet may be made by hammering a soft iron bar held parallel to the lines of force of the magnetic field of a solenoid or of the earth. A bar of permalloy is magnetized simply by holding it parallel to the earth’s field, and it will change polarity upon reversal end for end. The polarity may be tested with a compass needle (E-76).

**E-81. Isolated Pole.** The condition of a single “isolated” pole can be approximated by passing a long bar magnet (knitting needle) through a cork and floating it vertically in water, the upper end of the needle being much nearer the cork than the lower, for stability. The lower pole is now so far from the upper that one can lead or propel the magnet about with another isolated pole (a similar needle held in the hand), approximating closely the action of two ideally isolated poles on each other.

**E-82. Induced Magnetic Poles.** A chain of nails or tacks may be supported from a magnet, each in turn becoming a magnet by induction. The polarity of the end of the chain may be tested with a compass needle (E-76).

**E-83. Magnetization by Current.** A solenoid is connected to a source of direct current. A piece of steel, initially unmagnetized, is magnetized by placing it in the solenoid. As a sample of steel, one may use a demagnetized compass needle with a pivot bearing or a steel knitting needle supported in a wire or paper stirrup by a thread. When in the demagnetized state, neither of these needles shows any distinct tendency to align itself in the earth’s magnetic meridian, but after magnetization the needle becomes a magnetic compass.

**E-84. Strong Permanent Magnets.** Strong permanent magnets of cobalt steel may be shown, and their magnetization emphasized by using one of them to pick up a cluster of nails. Two 35 per cent cobalt-steel magnets about 6 by 6 by 35 mm are so strong that one of them may be supported in the air at a distance of 1 or 2 cm above the other by the repulsion between like poles. One magnet is attached to a wooden base; end guides for the second magnet are made of celluloid films bent into half
cylinders and held by large brass pins driven into the base. These guides are necessary to prevent motion of the hovering magnet in a horizontal direction, since it cannot be in stable equilibrium under magnetic and gravitational forces alone. A suggestion of mystery may be added, if desired, by concealing the first magnet. (Project.)

Forces between magnets may be demonstrated with two cylindrical cobalt-steel magnets. They are laid on the table and rolled toward each other. If the magnetic axes agree in sense, the magnets will be repelled as if by an elastic collision; if the axes are opposite in sense, the magnets will be strongly attracted. If they are held together with like poles adjacent and then released, they will roll away from each other. If one is at rest on the table and the other is rolled toward it, so as to repel it, the first starts rolling away, and the second stops. Interchange of momentum may thus take place without actual contact between the magnets.

**E-85. Which Is the Magnet?** Show two similar bars of iron, one magnetized, the other not. Ask the students how to discover (without other equipment) which bar is magnetized. Evidently this question cannot be answered by touching the ends of the bars together, for they invariably show only attraction for one another. But if the end of one bar is presented to the middle of the other, there will be attraction when the magnetized bar touches the middle of the unmagnetized, but not when the two bars are interchanged.

**E-86. Magnetic Balance.** A permanent magnet is balanced on knife-edge bearings. A second magnet is placed below it, in such a position that one pair of like poles is a few centimeters apart, while the other pair is far enough away so that forces due to these poles are negligible (Fig. 219). The balanced magnet is restored to equilibrium by means of a rider. The magnitude of the force of repulsion or attraction may be determined from the position of the rider and its mass. By measuring the distance between the poles, the inverse square law may be roughly verified; it should be noted, however, that the poles are not exactly at the ends of the steel bars.
E-87. Determination of Pole Strength from Law of Force. Two similar steel knitting needles are magnetized equally in the same solenoid. They are suspended by light threads about 25 cm long from each end, so that like poles are adjacent. The magnets hang horizontally and parallel, and the threads from the north ends meet at a common point, as do those from the south ends. The needles then repel each other to a distance of a few centimeters. If the masses of the needles are equal and known, together with the length of the threads and the distance between the magnets, then the pole strengths (assumed equal) may be computed from the inverse square law. This experiment may be made a connecting link between the subjects of Mechanics and Magnetism.

E-88. Magnetic Induction. A bar of soft iron held near a strong permanent magnet becomes a magnet by induction (E-82). Tacks will cling to the ends of the bar as long as the permanent magnet is near enough to magnetize it by induction, but the tacks will fall when the permanent magnet is removed.

The inducing magnet and the piece of soft iron are held with their axes collinear. A compass needle (E-76) shows that the end of the soft-iron bar more distant from the inducing magnet has a polarity of the same sign as the magnetic pole on the nearer end of the permanent magnet. This effect may be compared with that of electrostatic induction (E-8).

E-89. Magnetic Fields Shown by Iron or Permalloy Filings. Strips of magnetized clock spring or other thin steel are sealed between two glass plates, whose edges are bound with gummed tape. The plates are placed horizontally in the field of a lantern arranged for vertical projection. Iron filings sifted over the top plate become magnetic by induction and when the plate is lightly tapped they arrange themselves along the lines of force. In this manner, the fields between like poles, unlike poles, and that produced by induction in soft iron may be shown on the screen. Small letters $N$ and $S$ of black gummed paper may be attached to the inside surface of one of the glass plates near the ends of the steel strips to indicate polarities.1

1 Magnaflux powder is an excellent material for showing magnetic fields in this and similar experiments. It is supplied by Magnaflux Corporation, 25 West 43d St., New York. N. Y.
E-90. Mapping Field of a Magnet. Show the lines of force in
the field of a permanent horseshoe magnet by supporting two
small parallel equal bars of soft iron vertically in a projection cell
in which iron filings are suspended in a mixture of equal parts of
glycerin and alcohol. The upper ends of the iron bars project
equal distances above the liquid, and the poles of the magnet are
placed against them. (Project.)

E-91. Theory of Magnetization. The molecular theory of
magnetization may be illustrated by a model consisting of several
short magnets free to turn about vertical axes on pivots set in a
wooden base. The magnets are first arranged in random oriënta-
tion. A magnetizing field is then produced by means of one or
two strong cobalt-steel magnets, whereupon the short magnets
align themselves with the direction of the magnetizing field.

The experiment as just described is not suitable for showing to
a large class, unless the magnets are mounted on a glass plate for
vertical projection. A modification of the demonstration is
obtained by using several short magnetic needles in random oriëntation on a ground-glass plate a few inches above the poles of
an electromagnet. Steel phonograph needles may be broken into
two pieces, and the pieces magnetized by contact with a strong
electromagnet. The images of the needles are formed on a
screen by the vertical projection lantern. As current in the
electromagnet windings is gradually increased, the short magnetic
needles align themselves discontinuously in a manner suggestive
of the alignment of elementary magnets in the Barkhausen effect
(E-94).

E-92. Elementary-current Model of Magnetization. An
apparatus consisting of coils carrying current, with no iron what-
ever, is used as a magnetization model (Fig. 220). The magnet-
izing field is provided by a current of from 0 to 20 amp flowing in a
large solenoid. The elementary magnets are small coils of wire
supported by pieces of twine. The restoring torques that
produce random orientation of the coils in the absence of a field
are supplied by small helical springs, which also serve as current
leads. A top view of the model is possible with the aid of a 45°
mirror placed above it. The model may be operated on alternating
current if direct is unavailable, since reversal of current in
both the large solenoid and the small coils leaves the direction of
torque on the latter unchanged. This model, which depends
upon the interaction of currents, is in keeping with modern theories of magnetization.\footnote{For further details, see F. W. Warburton, *Am. Phys. Teacher*, 4, 21–3, 1936.}

**E-93. Breaking a Magnet.** If a slender piece of magnetized hard steel is grasped with two pairs of pliers, it may be broken into smaller pieces. The indicator needle (E-76) will show that each piece is a complete magnet and that a pair of opposite poles appears at each break. Bars of steel with transverse cuts to facilitate breaking may be purchased, or knitting needles may be hardened for this purpose and magnetized by an electromagnet prior to use.

![Elementary-current model of magnetization.](image)

**E-94. Barkhausen Effect.** Discontinuities in the magnetization of iron due to sudden realignment of submicroscopic groups of elementary magnets during the growth of the magnetizing field may be demonstrated by placing a soft-iron core within a solenoid having several hundred turns of fine wire. The two ends of the winding are connected to the input of an audio amplifier and loudspeaker (A-85). When a bar magnet is thrust toward the soft-iron core, the elementary magnets align themselves intermittently in the direction of the magnetizing field. As each group of magnets turns over, a feeble emf is induced in the solenoid. There results a rasping sound in the loudspeaker, which may be changed by altering the rapidity of approach of the permanent magnet. There is a difference in the sound when a hard-steel core is used in place of the soft iron. A greater effect
may be obtained if both core and coil are made short so that they can be inserted between the ends of a U-shaped magnet, which may then be rotated through 180° to reverse the polarity.

**E-95. Retentivity.** The retentivity of soft iron may be shown by attracting to the pole pieces of an inverted U-shaped electromagnet a soft-iron bar. When the current is stopped, the bar will continue to cling to the iron core; but if the bar is pulled away, the magnetic induction in it decreases to such an extent that it will no longer be held against the pole pieces when returned to them.

**E-96. "Pulling Magnet."** A piece of demonstration apparatus known as a "pulling magnet" shows the force between two pieces of magnetized iron and the retentivity of iron somewhat better than the electromagnet and iron bar of E-95. The pulling magnet has a soft-iron core in the form of a split toroid with polished contact surfaces. A few turns of wire are wound around one half of the toroid. So long as current is supplied, by a single dry cell, the iron is so strongly magnetized that it is difficult or impossible for two students to pull the two halves of the toroid apart. Handles may be attached to the toroid halves to facilitate pulling. To show retentivity, the two sections are fitted together and magnetized by the current. After the current is stopped, it is still difficult to separate the halves, but once separated and replaced, no appreciable force is needed to separate them a second time. The iron may remain magnetized for months, because of the excellent fit between the two sections of the toroid, which leaves no free poles to cause a demagnetizing effect.

**E-97. Influence of Area of Contact between Pieces of Magnetized Steel on Tractive Force.** When two plane surfaces of magnetized iron are in contact, the force required to separate them is $F = B^2 A / 8\pi$, where $B$ is the magnetic induction and $A$ is the area of contact. Expressing $B$ in terms of flux $\phi$, the equation becomes $F = \phi^2 / 8\pi A$. From this equation, it is evident that the force is inversely proportional to the area of contact, provided $\phi$ is independent of this area. In the experiments to be described, this condition is not strictly fulfilled, but the variation of $\phi$ with area is small enough to enable one to show a large increase in $F$ accompanying a decrease in $A$.

For a demonstration of the effect with a permanent magnet, one may turn a truncated cone on one end of a piece of drill rod
15 cm long and 1 cm in diameter. The diameter of the small end of the cone and its height may each be 0.5 cm. After the rod is machined and the ends lapped, it is glass hardened and permanently magnetized. The large end of such a rod will lift a 200-g piece of iron, whereas the small end will lift a 600-g piece. Another way to show these forces is to hang the magnet from a spring balance and to measure the forces necessary to separate each end of the magnet from a heavy piece of iron.

E-98. In the following demonstrations, an electromagnet (Fig. 221) is used. Its core is a piece of cold-rolled steel 40 cm long and 4.5 cm in diameter. The winding consists of 1500 turns of No. 16 wire wound on a brass form. A magnetizing current of 2.5 amp is used in this experiment and in E-99.

An iron ring 3.3 cm in diameter outside, 2.7 cm in diameter inside, and 0.3 cm thick is shrunk over a brass disk, in the center of which is screwed a brass hook. When the face of the disk is against the core of the electromagnet, the magnetic force between the ring and the core will support a load of 115 g. When the curved edge of the ring is in contact with the core, a load of 800 g may be supported. In this case, a string is passed through a hole drilled near one edge of the brass disk, so that the ring may be pulled away from the core without tipping.

E-99. A soft-iron bar 15 cm long and 1 cm in diameter has a truncated cone turned on one end, as for the bar magnet previously described (E-97). Holes are drilled through the bar near each end for the attachment of strings by which weights may be supported. When the large end of the bar is in contact with the core of the electromagnet (E-98), the mass that can be supported is about 100 g; when the small end is in contact with the magnet, about 3400 g may be supported.

E-100. Magnetization and Hysteresis Curves for Iron by Magnetometer Method. The magnetometer provides a simple and direct means for determining the intensity of magnetization of a sample of iron or steel and its hysteresis curve without using a ballistic galvanometer. The magnetometer is a
short magnetic needle suspended by a fiber of unspun silk, with a small mirror attached. A small damping coil in series with a dry cell and a key is placed near the magnetometer; the needle can be brought to rest by timely tapping of the key.

The iron or steel sample is a rod about 1.5 cm in diameter and 40 cm long. It is magnetized by a solenoid of 850 turns of No. 22 wire wound on a piece of fiber tubing 75 cm long. The sample rod is placed in the center of the solenoid, which is in an east-west position and either east or west of the magnetometer. The distance between magnetometer and center of rod is chosen so that the deflection of the spot of light reflected from the mirror will remain on the scale for the highest value of magnetization.

The arrangement of solenoids and circuit is shown in Fig. 222.

A rheostat and an ammeter are included in the circuit. The demonstrator should mark those positions of the rheostat that give the various currents he expects to use, since it is not possible to decrease the magnetizing current when taking readings on the magnetization curve without introducing errors due to hysteresis.

After the sample is demagnetized (E-127), it is placed in position in the magnetizing solenoid. The switch is closed to give the first of the chosen values of magnetizing current, and the deflection of the magnetometer needle is noted. The rheostat is then
changed to give the next value of current, and so on up to the highest value to be used. From this point, the hysteresis loop may be run by reducing the current in steps to zero, reversing its direction through the solenoids, increasing it in steps in the opposite direction to the same maximum value as before, and returning to the starting point. Since for demonstration purposes, absolute values of magnetization are unimportant, it is sufficient to plot magnetometer deflections against corresponding magnetizing currents. If small-angle deflections of the magnetometer are used, it is permissible to consider magnetization proportional to deflection; actually, the field produced by the magnetized sample is proportional to the tangent of the angle of deflection.

**E-101. Hysteresis of Iron Shown by Cathode-ray Oscilloscope.**

A cathode-ray oscilloscope may be used to show hysteresis of the iron in a transformer core. The connections are shown in Fig. 223. The primary of the transformer is connected in series with a rheostat from which one may pick off a potential difference proportional to the primary current and hence proportional to the magnetizing force $H$ in the iron. This potential difference is applied to the oscilloscope plates producing horizontal deflection of the cathode-ray beam. Hence the abscissae of whatever figure is shown on the fluorescent screen will be proportional to instantaneous values of $H$ in the iron.

The secondary of the transformer is connected to a resistor in series with a condenser. The instantaneous potential drop across the condenser should be small compared with that across the
resistor. When this condition is fulfilled, the potential drop across the condenser is proportional to the instantaneous value of $B$. Hence if the oscilloscope plates producing vertical deflections are connected to the terminals of the condenser, the ordinates of the figure on the fluorescent screen of the tube will be proportional to $B$. This figure is the Lissajous figure resulting from the combination of two shm's at right angles to each other and differing in phase by either 0 or $180^\circ$, depending upon the accidental choice of polarity in connecting one of the two pairs of plates. The phases should be the same to give the hysteresis loop as it is usually plotted. If the phases are not the same, the resultant figure will be a mirror image of the customary loop. By reversing the connections to one of the two pairs of plates, the desired orientation of the loop may be obtained.

A small demonstration transformer that has two low-tension coils and two high-tension coils, with separate terminals for each coil, is convenient. This arrangement permits one to apply to one of the low-tension coils a potential difference larger than that for which the coil is designed; thereby the iron may be magnetically saturated and a hysteresis loop thus obtained that is nearly parallel with the $H$-axis at the two ends of the loop. The capacitive reactance should be negligible compared to the resistance in the secondary circuit; however, a good hysteresis loop is obtained when the former is 10 to 15 per cent of the latter. With 110-v alternating current on the primary and about twice as many secondary as primary turns, one may use about 1000 ohms for $R$ and about 20 $\mu f$ for $C$. A fair hysteresis loop is obtained with only 10 $\mu f$.

E-102. Paramagnetism and Diamagnetism. Many substances are sufficiently affected by a strong magnetic field to show a tendency to set themselves either parallel or perpendicular to it. Samples in the form of small cylinders are hung between the pole pieces of a magnet by suspension threads that are free from twist. For all except the ferromagnetic materials, the forces are so small that it is necessary to have a moderately strong and nonuniform magnetic field. A U-shaped electromagnet with an iron core, 2.5 cm in diameter and 40 cm long, magnetized by about 15,000 ampere turns and provided with pole pieces 2 cm apart, will supply a sufficiently strong field; and if one of the pole pieces is flat while the other is pointed, the field will be sufficiently non-
uniform. For showing the experiment to a large class, the vertical projection lantern may be used to form on the screen images of the pole pieces and of the suspended sample of material. A cylinder of nickel aligns itself parallel to the direction of the field. So does a cylinder of aluminum, though the force on it is much weaker. Diamagnetic substances, such as bismuth and glass, will set themselves across the field. The paramagnetic property of a solution of ferric chloride may be shown by suspending in the field a short sealed glass tube containing the liquid. The tube thus suspended takes a position parallel to the field, although an empty glass tube takes the perpendicular position. Liquid oxygen is paramagnetic (H-111).

One should be careful to distinguish between true paramagnetic and diamagnetic effects and effects due to eddy currents. Samples of copper or aluminum placed in a changing magnetic field show pronounced deflection due to electromagnetic induction.

**E-103. Effect of Temperature on Magnetic Properties of Nickel.** A 3-mm nickel rod slightly longer than the distance between the ends of a strong U-shaped magnet is suspended from a horizontal support in a horizontal position like a pendulum by means of two asbestos strings or fine copper wires (Fig. 224). The rod, when cool, is attracted by the magnet and thus displaced from its lowest position. A Bunsen flame is placed near the magnet and in such a position that the nickel rod becomes heated while it is held aside by the magnet. When heated, the nickel loses its paramagnetic properties, and the magnet no longer holds the rod. The rod therefore breaks away from the magnet and leaves the Bunsen flame. Upon cooling, the permeability of the rod increases, the magnet attracts the rod to its first position, and the cycle is repeated.

It is helpful to have a glass cylinder or a sheet of metal in such a position that the rod will swing against it when it breaks away from the magnet. This makes an audible event in each cycle, and limits the amplitude of swing. It is necessary to protect
the magnet against excessive heating. The ends of the nickel rod should be wound with asbestos, and the poles of the magnet may be protected by using the same material. The asbestos not only protects the magnet, but it also secures a more frequent repetition of the cycle since it prevents the nickel from making contact with the ends of the magnet, thus making it easier for the rod to break away. A still better precaution against overheating is to put the magnet in a shallow aluminum pan containing enough water to cover it. This furnishes perfect protection against overheating, and at the same time demonstrates that magnetic fields are not screened by aluminum.

A U-shaped electromagnet may be used in place of the permanent magnet. The field produced by it is stronger, and the ends of the iron core usually project far enough beyond the windings to eliminate danger of damage from heat.

E-104. Iron Nonmagnetic at High Temperature. Hang a length of No. 16 or 20 soft-iron wire from two rods at opposite ends of the lecture table, connecting it to a 110-v d.c. source with series rheostat for current control. When the wire is heated red hot by current, it expands and sags, showing, incidentally, the phenomenon of recalescence (H-9). If an electromagnet is situated below the lowest point of the wire and slightly to one side, the wire will be drawn aside when magnetic, and its motion can be seen in a mirror set at 45° above the wire. Thus it is possible to show the restoration of magnetic properties as the wire cools through the critical temperature at which recalescence occurs. This temperature varies somewhat for different samples of iron but lies between 690 and 870°C.

E-105. Magnetic Screening. A collection of nails or of iron screws is placed in a shallow crystallizing dish on a box high enough above the lecture table for good visibility. Just over the nails there is a horizontal sheet of glass, then a space of about 1 cm, then another sheet of glass, and finally the poles of an electromagnet in contact with the second sheet of glass. The current in the magnet is adjusted to draw the nails against the first sheet of glass. If a sheet of iron is now inserted in the space between the two sheets of glass, the magnetic field will be screened, and the nails will drop. Magnetic screening cannot be made so complete as electrostatic screening; however, a sheet of iron about 3 mm thick will screen effectively enough for the present purpose.
second sheet of glass is used to facilitate the removal of the iron sheet while the magnet is energized. Except for this purpose, it may be dispensed with. The demonstrator may use sheets of various substances such as brass or fiber, to show that effective screening is exclusively a property of iron.

E-106. By the attraction of a magnet placed above it, hold in mid-air a nail anchored to the table top with a string. When slabs of nonferromagnetic material are placed between nail and magnet, no change in the supporting force is apparent. When, however, a sheet of iron is interposed, the nail falls.

E-107. Magnetic Screening. Suspend a soft-iron bar or rod horizontally by two long threads. A long pointer is attached to the bar. Near one end of the bar and in line with it is placed a bar magnet close enough to displace the soft-iron bar from its equilibrium position. If now a sheet of iron is inserted between the two, the force of attraction is diminished, and the motion of the bar is made evident by the motion of the pointer across a scale. An optical lever may be used if preferred.

E-108. Shunting Magnetic Flux. Pick up a ½-in. steel ball on the end of a strong bar magnet. Then lay a nonmagnetized bar of soft iron against the bar magnet, and slide it toward the suspended ball. As the end of the soft-iron bar approaches the ball, the ball drops off, since much of the magnetic flux is now shunted through the bar to the other pole of the magnet. A bar of permalloy serves admirably for “by-passing” the magnetic flux. Show, by turning the bar end for end, that the effect is independent of its direction.

E-109. Magnetostriction. The length of a rod of nickel or steel changes slightly when the rod is magnetized. Although the change is only of the order of 1 part in 500,000, it is, nevertheless, quite easy to demonstrate this minute effect to a large class. A rod of nickel about 6 mm in diameter and 20 cm long is placed within a short solenoid so that one end of the rod is in contact with a wooden plug inserted into the end of the solenoid. The other end of the rod extends a short distance beyond the open end of the solenoid and touches a brass rod that acts as a lever to magnify the change in length of the nickel rod (Fig. 225). A nail is passed through a hole in the lever and driven into a block of wood to serve as fulcrum. The lever may be 4 mm in diameter and 50 cm long, with the short arm 2 cm. A thread attached to
the end of the long arm is wrapped once around a spindle free to rotate and is kept taut by a small weight. With a spindle of diameter about 2 mm, its rotation may be about 1° when the solenoid is energized. This rotation is best made visible by reflection of a beam of light from a small mirror attached to the spindle.

Nickel decreases in length when magnetized. The cobalt steel developed during the past few years for permanent magnets of high magnetization intensity shows a relatively large magnetostriction effect. This material increases in length when magnetized. A rod of 35 per cent cobalt steel about 20 cm long, when used in the arrangement just described, will lengthen enough to rotate the mirror on the spindle about 2°. When demonstrating an increase in length, it is necessary to show that the effect is not due to heating by the solenoid current. Heating may be reduced by wrapping the rod in paper. The fact that change in length resulting from magnetization is immediate shows that it is not caused by heating.

If alternating current is used in the solenoid, the spot of light becomes a line as the alternate expansion and contraction of the rod cause it to move in periodic motion on the wall. This also shows that the effect cannot be due to heating. If desired, a rotating mirror may be used to spread the light path into a sine curve (S-76).

**E-110. Magnetic Heat Motor.** A piece of magnetic alloy (70 per cent Fe, 30 per cent Ni) in the form of a thin strip is wrapped around the rim of a wheel. The wheel must be well balanced, and its bearings must have very little friction. The rim is placed between the poles of a 17 per cent cobalt-steel U-magnet with pieces of soft iron on the ends of the U to make the air gap just wide enough to allow the passage of the wheel rim. An automobile headlight lamp with a reflector is arranged to heat by radiation the portion of the metal strip just above the magnet. The permeability of this portion of the strip is reduced by rise in temperature, and the unheated portion of the strip is therefore drawn into the gap between the poles. The heating action
continues, and the wheel slowly rotates. The effect will be enhanced if the heat from a small carbon arc is focused on the tape just above the air gap. The wheel must turn very freely, and the magnetic field must be strong, with a steep gradient of field intensity. For a museum exhibit, a further element of mystery may be introduced by concealing the source of radiation behind infrared filters.1

**E-111. Terrestrial Magnetism.** The alignment of a compass needle in the magnetic meridian is easily shown (E-76). To show approximately the declination at any location on the lecture table, a true north-south line should be established and made permanent by marks on two walls of the room. Such a line may be established from a large-scale map that gives the orientation of the building or a street near it; or the line may be established from the shadow cast by the edge of a window at local apparent noon, which can be determined from the longitude of the place and the equation of time as given in a nautical almanac. Draw a chalk line on the lecture table or stretch a piece of light cotton cord across it in the true north-south direction. With the compass needle just over the chalk line or just under the cord, the declination on the lecture table may be determined accurately by using a protractor, and the magnetic meridian may be marked on the table.

The inclination is read directly from the dip-needle apparatus. It may be noted that the direction of the earth's field at a point on the lecture desk is likely to differ from that given by the tables for the place in question, on account of the presence of iron gas and water pipes, radiators, etc.2 The vertical and horizontal components of the earth's field may be determined with the earth-inductor (E-222).

**E-112. Magnetic Induction in Earth's Field.** A 1-m length of ½-in. water pipe, held parallel to the lines of force of the earth's field and struck with a hammer, becomes magnetized by induction (E-80), as can be shown by presenting its ends to a compass needle; in the northern hemisphere, the lower end of the pipe repels the north end of the needle. When the pipe is turned end

2 Maps showing the magnetic elements, declination, dip, and horizontal intensity over the surface of the earth may be purchased from the Hydrographic Office, U. S. Navy Department, Washington, D. C.
for end, it retains its polarity until it is struck again, whereupon
the polarity reverses. If the iron has an objectionable amount of
permanent magnetization, it may be demagnetized and made
magnetically soft by bringing the whole pipe to a dull red heat
and allowing it to cool slowly.

A permalloy rod shows induced magnetization in the earth's
field much more strongly than iron. This material has a high
permeability in weak fields. The lower end of the rod always
repels the north end of a compass needle provided that it is not
held so close to the needle that the latter, rather than the earth's
field, controls the rod's magnetization. A permalloy rod will
pick up pieces of permalloy ribbon when the rod is parallel to the
earth's field and will drop them when it is turned perpendicular
to the earth's field.

**CURRENT ELECTRICITY**

It is important to give the student a clear idea of the close con-
nection between static and current electricity so that he does not
regard them as independent. For that reason, a number of
experiments have been included to enable the instructor to show
clearly the relationship between the two subjects.

**E-113. Potential Drop along a Conductor with Current from a
Static Machine.** One end of a stick of wood about 2 cm square
and 3 m long is held in an earthed metal clamp; the other end is
suspended above the lecture table by a cord. A metal clamp is
attached to the insulated end, and a wire connects the clamp with
one terminal of a static machine, the other terminal of the
machine being grounded. An electroscope serves as an indicator
of potential at various points on the stick between the ground
connection, where the potential is zero, and the insulated end,
where the potential is a maximum. The electroscope case must
be grounded.

If several electroscopes are at hand, the simplest method is
to twist four or five wires tightly around the stick, spacing them
uniformly between the two ends. An electroscope is then con-
ected to each of these wires. A few turns of the static machine
will supply the necessary potential. The electroscopes announce
the arrival of charge at the points on the conductor to which they
are connected. The greater time needed for flow of charge to the
more distant points is clearly shown. If the static machine
has its terminals connected to the condensers usually mounted on the base of the machine, then enough charge will be stored during a few turns of the plates to bring the current in the stick to a steady value and to maintain that value for a considerable time. The various electrosopes then indicate the potentials of the uniformly spaced wires, while the potential drop along the conductor is clearly demonstrated.

If the experiment is shown to a large class, a projection electroscope should be used. One method of procedure is to wrap strips of tin foil about 5 cm wide around the wood at the points where potentials are to be indicated. These strips are tied on by thread or fine wire, and a piece of coarser wire is twisted tightly around each strip near its center. The electroscope is connected to one of the wires to show the time required for the potential to reach a steady value. After the steady value is reached, the electroscope may be connected to each wire in turn, starting at the end joined to the static machine, to show the potential drop along the stick. The tin-foil strips are needed to furnish the necessary contact and to accumulate enough charge so that the deflection in the electroscope is not dependent upon the time during which the contact is made. The wire leading to the electroscope should be attached to an insulating handle to avoid discharging the tin-foil strips.

There is another method of performing this demonstration. Tin-foil strips and wires around the stick are not used, but the fine wire leading from the electroscope is attached to a metallic conductor with an insulating handle. The discharge tongs commonly used with Leyden jars are suitable. The demonstrator moves the conductor along close to the wooden stick, keeping it as nearly as possible at a uniform distance from the stick. The charge induced on the electroscope is then proportional to the potential of the region of the stick just opposite the conductor. The advantage of this method is that the continuously varying potential is shown. The disadvantage lies in the difficulty of keeping the electroscope lead wire away from the top of the lecture table.

With any of the three procedures described, it is well to show that all points on the stick come to the same potential when there is no current, as is the case when both ends are insulated. It is also desirable to show that any two points come to the same
potential when they are connected by a wire. A Zeleny electroscope used as a current indicator shows the effect of putting two sticks in series, then in parallel.

**E-114. Water Analogue of Current and Potential.** The filled reservoir \( J \) (Fig. 226), corresponding to a charged Leyden jar or other condenser, has leading from it as a conductor a 1-mm capillary tube \( C \), placed horizontally. A pivoted spoon \( S \) fills periodically with water, dumps, and repeats, corresponding to the needle of the Zeleny electroscope. The rate of water flow (current) is proportional to the pressure head in the reservoir (potential difference in condenser). A pressure drop exists along the line, as indicated by the gauge \( G \) (voltmeter or electroscope), which should be of at least 5-mm bore to avoid capillary effects.

![Fig. 226.—Water analogue of current and potential.](image)

The rate of flow is affected by the length of the conducting tube and the cross section of its bore. Stopping the flow stops the current and brings the pressure to the same value at all points along the conductor, as indicated by the equality of levels in \( G \) and \( J \) (all points at the same potential). While the water analogue holds in many respects, too much must not be expected from it.

**E-115. Electric Charges from Dry Cells.** An electroscope may be charged by a number of 45-v B batteries in series. By changing the number of batteries, the additive nature of potential may be shown. Use a protective high resistance in series with the batteries to limit current in case of short circuit.

**E-116. Identification of Charge from Dry Cells.** The upper plate of a condensing electroscope is earthed and also connected to one terminal of several dry cells in series. The lower plate is touched momentarily by the other terminal of the dry cells. The condenser is thus charged, but no deflection of the electroscope is observed, since the potential supplied by the dry battery is
much too small. However, as the capacitance of the condenser is decreased by the removal of the upper plate, the potential of the insulated plate increases, and the electroscope leaves show a deflection. The sign of charge on the insulated plate should be determined by bringing a charged glass or rubber rod near the electroscope (E-24). In this way, the demonstrator may prove the charge obtained from the carbon terminal of a dry cell to have the same sign as the charge on glass that has been rubbed with silk, which is, by definition, positive.

The condensing electroscope used in this experiment may be of the horizontal-plate type (E-71), the vertical-plate type (E-69), or the multiple-plate radio-condenser type (E-75).

E-117. Electrostatic Motor. A relatively large static machine is connected to a smaller one. When the larger machine is turned, the energy is sufficient to operate the smaller one as a motor. The drive belt should be removed from the smaller machine to reduce friction. A similar experiment may be performed with a single machine and a battery of about four Leyden jars connected in parallel. The machine is first turned to charge the condensers. The drive belt is then removed, whereupon the machine stops and then reverses its direction of rotation because the stored energy is being given back. (The experiment with one machine used to turn another is analogous to that of a generator operating a motor, while the experiment with a single machine and battery of Leyden jars is analogous to that of a generator used for charging a storage battery, the battery subsequently being used to operate the generator as a motor.)

E-118. Heating Effect of Current from a Static Machine. A piece of wood about 1 cm² in cross section and 20 cm long has several turns of copper wire wrapped tightly around each end. The wire should be tight enough to press firmly into the wood. As a preliminary test, the terminals should be connected to the static machine with a microammeter or galvanometer in the circuit, one terminal of the instrument being earthed. This is to make sure that at least half a watt will be dissipated in heat. The potential drop may be estimated from the sparking distance between the terminals of the machine (30,000 v per cm). It is likely that the resistance of the wood will be too high to develop the necessary amount of heat. In this case, one may decrease
the length of the stick or soak the wood in a salt solution, afterward drying it. If the latter is done, enough moisture will remain in the wood to increase its conductivity far above the former value.

After adjusting the resistance of the wood to a value that will ensure maximum heating with the particular static machine available, the stick is placed within a glass tube not much larger than the wood. Both ends of the tube are closed by tight stoppers through which pass the ends of the stick (Fig. 227). An arm of a U-shaped water manometer is inserted through one stopper. For a small class, the water may be colored to improve visibility; for a large class, the U-tube should be projected.

Provided that the power is half a watt or more, there is no difficulty in showing the heating effect accompanying the operation of the static machine by the rise of water in the open column of the U-tube. It is essential that there be no leaks. The stoppers may be sealed with sealing wax if necessary to prevent the escape of air.

E-119. Electric Currents from Voltaic Cells. Exhibit a few types of voltaic cell, and show the heating and magnetic effects of currents obtained with these cells. The current from a few voltaic cells in series is sufficient to bring a short loop of iron or nichrome wire to the temperature of incandescence. Show the magnetic field near a conductor by holding over a compass needle (E-121) a straight copper wire connected to the terminals of a single cell.

E-120. Elementary Storage Cell. Connect two lead plates in a glass jar containing 30 per cent sulfuric acid to the middle terminals of a d.p.d.t. switch. Connect two of the other terminals of the switch to two or three dry cells in series for charging the storage cell. Connect the two remaining terminals of the switch to a 1.5-v flashlight bulb. After the lead cell has been charged by the dry cells for a few minutes, the switch is thrown over to connect the cell to the flashlight bulb. A center-zero ammeter shows that the direction of current during charge is opposite to that during discharge.
E-121. Oersted’s Experiment. A straight wire is stretched horizontally in the magnetic meridian just above a pivoted compass needle (E-76). When there is current in the wire from several dry cells in series or from a storage cell, the compass needle turns, in a direction that depends upon the direction of the current through the wire, and through an angle that depends upon the current strength. This simple experiment may be made the basis for discussion of the rules of direction of magnetic field with respect to direction of (conventional) current.

It is of interest to show that similar magnetic effects are produced whether the current be in a metallic conductor, in a long tube containing an electrolyte, or in a gaseous discharge tube. Direct current must, of course, be used. All three types of conductor may be connected in series to insure equality of current.

E-122. Magnetic Field Due to Current in a Long Straight Conductor. A simple method of demonstrating the circular field due to current in a long straight conductor is to stretch a long wire vertically above the lecture table. A heavy copper wire may pass through a hole in the table, or it may pass close to the edge of the table. The current needed is 50 amp or more. Such a large current may be supplied by an Edison battery without damage to the battery, or it may be provided (with some risk of damage) by a 6-v lead storage battery. A compass needle with paper flags may be used to show the direction of lines of force due to the current and to show that the magnetic field is concentric with the conductor. A dipping needle may be used to explore the field about a long horizontal conductor. In either case, the needle indicates a field that is the resultant of the field produced by the current and one component of the earth’s magnetic field.

E-123. Magnetic Field about Various Conductors. Three glass plates arranged for vertical projection are convenient for showing magnetic fields about current-carrying conductors. In the first, a vertical wire passes through a hole in the glass plate. Since the lantern lenses limit the length of the vertical portion, the direction of the conductor must change not far below and above the glass plate. The magnetic fields produced by current in the connecting wires will distort to some extent the circular field due to current in the vertical wire. The magnitude of this disturbing effect is reduced by running the two lead-in wires
parallel. Several turns of wire may be used to reduce the current required.

In the second, two parallel wires are arranged with connecting wires extended on opposite sides of the glass plate. They may be used to show the field surrounding two parallel conductors carrying current either in the same or in opposite directions.

In the third, several turns of wire are passed through two holes in the glass plate to form a coil whose plane is perpendicular to the plate while its center lies in the plane of the glass. With it, the field surrounding a circular coil carrying current may be shown.

To show the direction of field at several points, one may use a number of small compass needles. Small compasses about 1 cm in diameter are available but cannot be used for projection without modification because the cases in which the pivots are mounted have opaque bottoms. However, the needles and their pivots may be removed from the cases for mounting on microscope slides. A few of these needles arranged on a circle with the wire or coil at the center show the circular character of the field about such a conductor.

Finally, fine iron filings may be sifted on the glass plate and the plate tapped to facilitate orientation of the filings. Greater current is required in this case.

**E-124. Magnetic Field Produced by Current in a Circular Coil—Tangent Galvanometer.** The field at the center of a circular coil has an important application to the definition of the unit of current strength. A large circular coil placed in the plane of the magnetic meridian is used, and a compass needle with a paper flag is placed at the center of the coil. The current in the coil is proportional to the tangent of the angle through which the needle is deflected. A rheostat should be used for varying the current, and it may be well to have a shunt in the circuit, to which the terminals of the lecture galvanometer or an ammeter may be connected. This experiment establishes a connection between current strength and the horizontal component of the earth’s field. It also introduces the lecture (d’Arsonval) galvanometer as a current-measuring instrument, which may be calibrated in terms of the tangent galvanometer.

**E-125. Field Produced by Current in a Solenoid.** To show that a solenoid is magnetically much like a bar magnet, two layers
of wire are wound on a mailing tube. Beginning at a point about 5 mm from the center, the winding proceeds to the nearer end of the mailing tube; then it extends to the other end of the tube, whence it returns to a point about 5 mm from the center of the tube and 1 cm from the beginning of the winding. Lengths of wire are left at the beginning and end of the winding, to serve both as current leads and as a bifilar suspension by which the solenoid may be hung horizontally. When current is established, the solenoid turns into the magnetic meridian. A reversing switch should be included in the circuit. A compass needle demonstrates the polarity of the solenoid, and a bar magnet shows that forces are exerted on a solenoid by a magnet. The insertion of an iron core in the suspended solenoid makes its magnetic effects much more pronounced.

**E-126. Electromagnet.** An ironclad electromagnet, whose energizing coil is surrounded by iron, may be shown as a model of the large commercial lifting types. It is impressive to lift a large weight by using a few dry cells as source of current. With current from a single dry cell, through some 25 turns of wire, the magnet is able to support a load of over 200 lb.

**E-127. Magnetization and Demagnetization.** With direct current, magnetize a steel rod inside a coil. Then with alternating current, demagnetize the same rod in the same coil, starting the current at a value approximating that of the direct current and reducing it to zero by a potential divider. Iron filings may be used as a detector of magnetization. A d.p.d.t. switch permits rapid change from direct to alternating current (Fig. 228).

**E-128. Force on Core of Solenoid.** A large solenoid capable of carrying a heavy current, such as one of the coils of an electromagnet, is laid horizontally on the lecture table and connected to a d.c. source through a switch. One end of an iron or steel rod, such as a laboratory support rod, is inserted in the solenoid. When the switch is closed, the rod is violently drawn into the coil, as if by suction, and may oscillate several times before coming to rest. This shows that magnetic material tends to move into the part of a magnetic field that is most intense. If
the demonstrator is quick enough, he may be able to open the
switch just as the rod reaches the center of the solenoid, so that its
momentum throws it out the other end.

**E-129. Magnetic Field Due to Current through Coil.** A
cylindrical projection cell is made by cementing flat glass plates
to the ends of a short piece of large-diameter glass tubing, in
which a lateral hole has been made. The cell is filled with a half-
and-half solution of glycerin and alcohol in which iron filings are
suspected by thorough shaking. The cell is wound with a helix
of several layers of wire. A beam of light is passed longitudinally
through the cell. When direct current is sent through the coil,
the iron filings orient themselves parallel to the field and at right
angles to the plane of the coil, thus permitting more light to pass
to the screen. The same cell may be placed between the poles of
a strong electromagnet to show the form of magnetic field
produced (E-89).

**E-130. Resultant of Uniform and Circular Magnetic Fields.**
On either side of the vertical wire used in E-123, place soft-iron
bars backed with strong permanent magnets to produce a uni-
form field (Fig. 229). Show the resultant of this field and that
due to current in the wire by sprinkling iron filings on the glass
plate.

**FORCES ON CONDUCTORS IN MAGNETIC FIELDS**

**E-131. Force on Conductor Carrying Current Perpendicular to
Magnetic Field.** A narrow strip of lead foil hangs vertically
between the poles of a U-shaped permanent magnet. (A length
of Christmas-tree decoration with its ends attached to slender
brass rods makes a good conductor for this purpose. It is flexible
and easily seen by a class of average size.) The foil should be
slack in order that it may move several centimeters at the
moment when current starts. A few dry cells connected in series
with it and to a reversing switch will supply sufficient current to show the force on the conductor.

E-132. Two glass U-tubes filled with mercury are connected by an inverted U-shaped segment of large-diameter aluminum wire (Fig. 230). This wire is set between the poles of an electromagnet perpendicular to the strong magnetic field. When a storage battery is short-circuited through the aluminum wire, the wire hits the ceiling.

E-133. Electromagnetic Swing—Ampère's Experiment. A U-shaped wire is supported by mercury cups or wire loops as shown in Fig. 231. One pole of a vertical bar magnet is placed just below it. When a current passes through the wire, it is moved to one side. By proper timing of current impulses, a pendulum motion is built up.

E-134. Magnetic Grapevine. Suspend a very flexible wire alongside a vertical bar magnet. When there is current in the wire, it wraps itself around the magnet. Reversing the current unwinds the wire and makes it wrap in the opposite direction. Braided Christmas-tree tinsel is suitable.

E-135. Rolling Rod in Field of Magnet. An electromagnet or a strong bar magnet is arranged to produce a vertical magnetic field. Two parallel brass rods are supported horizontally (Fig. 232), one on each side of the poles of the magnet, so as to form a track. A third brass rod laid across the track is free to roll along it between the poles of the magnet. A battery is connected through a reversing switch to the parallel rods. The current in the rolling rod is thus perpendicular to the field, and the rod will roll under the action of a force parallel to the track.
As the direction of the current is periodically reversed, the rod rolls back and forth along the track.

**E-136. Barlow's Wheel.** A copper disk is mounted on pivot bearings so that it can rotate in a vertical plane. The lower edge of the disk dips into a pool of mercury connected to one binding post on the wooden base, and connection is also made between the pivot bearings and another binding post, so that current will be radial through the wheel. The disk is free to rotate between the poles of a U-shaped permanent magnet placed so that the current is approximately perpendicular to the direction of the magnetic field. Current is supplied by a few storage cells connected through a reversing switch. The interaction of magnetic field and current causes a slow rotation of the disk. By tracing the direction of the current along the radius of the disk and by knowing the direction of the magnetic field, one may verify the motor rule. For successful results, the disk must turn freely and both disk and mercury must be clean.

**E-137. Force on Magnet in Field of Conductor—Unipolar Motor.** Suspend from a thread a light frame 10 cm wide, which holds two long, magnetized knitting needles vertically, with both south poles directed downward (Fig. 233). A metal rod projects upward from the table in line with the supporting thread. One terminal of a 6-v storage battery is connected to the lower end of the rod; the other terminal is connected with the upper end of the rod by a flexible wire held in the hand, so that the contact may be broken and the wire drawn aside to permit passage of each needle as it comes around. By proper timing of current impulses, the needles are set into rotation. This experiment likewise shows the circular nature of the magnetic field about a straight conductor (E-123) and its effect on "isolated poles."

**E-138. Electromagnetic Balance.** An open rectangle is formed of heavy aluminum wire (Fig. 234). Holes are drilled part way into the wires forming two opposite sides of the rectangle, and the wire frame is balanced in a horizontal plane on pivots fitting into these holes, the two standards being conductive. The wire may be bent slightly at points over the pivots in order that the frame may be in stable equilibrium. The free ends of the wire are not in contact.
The side of the rectangle opposite the free ends is in the horizontal magnetic field of a U-shaped permanent magnet or an electromagnet. A battery is connected through a reversing switch to the two pivots. Current through that part of the rectangle that is perpendicular to the field will disturb the balance of the frame.

**E-139. Vibrating Lamp Filament.** A long tubular lamp with a straight filament carrying an alternating current is held between the poles of a strong U-shaped magnet. The filament will vibrate with sufficient amplitude to show an apparent widening. For a large class, a magnified image of the filament may be formed on a screen by means of a lens or a concave mirror. The shadow of the magnet may also be seen on the screen, but enough of the filament extends beyond the magnet to show vibration satisfactorily.

**E-140. Vibration of Wire Tuned to Alternating-current Frequency.** A brass sonometer wire (S-131) is stretched horizontally and tuned to resonance with the a.c. frequency. A strong U-shaped permanent magnet or an electromagnet is placed near one end of the wire so that its field is perpendicular to the wire. When there is an alternating current in the wire, the wire will vibrate, and by adjusting either the tension on the wire or its length, the tuning may be improved. The motion of the wire may be shown by stroboscopic illumination (S-49). A long wire may be used, and the current in it may be increased to the point where the wire glows red at its nodal points (S-37).

**E-141. Electromagnetic Circuit Breaker.** A straight vertical copper wire about 25 cm long hangs so that it may swing like a pendulum. The upper end of the wire may be soldered perpendicularly to a slender finishing nail, the two ends of which rest in grooves in wooden supports. The lower end of the vertical wire dips into a small pool of mercury. A U-shaped magnet is placed near the lower end of the wire in such a position that the magnetic field between its poles is approximately perpendicular to the wire. One terminal of a storage battery makes contact with the supporting nail through a flexible lead; the other makes contact with the pool of mercury. When current is sent through
the wire, the electromagnetic force causes it to swing away from the pool of mercury, thus breaking contact. It will then swing back, and the cycle will be repeated.

**E-142. Elementary Motor.** A vertical solenoid or a bar magnet carries at the top a circular trough containing mercury (Fig. 235). A straight copper wire is suspended loosely from a point on the axis of the magnetic field so that its lower end dips into the mercury. When there is current in the oblique copper wire, the wire rotates in the trough, like a conical pendulum.

**E-143. Torque on a Coil.** A wire frame, in the shape either of a rectangle or of a circle, is mounted on bearings so as to be free to rotate about a vertical axis. (This apparatus is sometimes called Ampère's frame.) A magnetic field may be supplied by two strong bar magnets held by wooden clamps in such a manner that the field in the space occupied by the wire frame shall be as strong as possible.

The torque on the coil is demonstrated by connecting it to a few storage cells, preferably through a reversing switch. If the demonstrator is quick enough, he may be able to reverse the direction of current through the coil at suitable times during each revolution and thus obtain a continuous rotation of the coil. This reversal process is carried out automatically by the commutator of a d.c. motor.

**E-144. Floating Coil.** An annular wooden float supports a coil of wire in a vertical plane (Fig. 236). A flashlight cell, also supported by the float supplies current to the coil. The apparatus floats on water in a large glass jar. It is prevented from sticking to the jar by a wire ring slightly larger in diameter than the float and supported by it a short distance below the water surface. This arrangement provides a current-carrying coil free to rotate about a vertical axis, useful for showing torque due to a magnetic field. A soft-iron bar is supported horizontally over the jar near the coil. A bar magnet is then brought into contact
with one end of the soft iron. With the proper orientation of the bar magnet, the coil will float away from the soft iron, turn around, and come back to it.

**E-145. d’Arsonval Galvanometer.** A large model d’Arsonval galvanometer may be constructed from a coil and a U-shaped magnet. The dimensions of the model depends on the size of the magnet, which should be as large as possible to ensure good visibility. The coil is made by winding fine wire on a rectangular frame. The coil is shellacked and removed from the frame, and the turns tightly bound together with silk thread. A cylindrical piece of soft steel fitting loosely inside the coil is mounted midway between the poles of the magnet, which are clearly marked N and S to show the direction of the magnetic field. A mirror is attached to the coil, and the latter is suspended in the magnetic field. Coarse phosphor-bronze ribbon is suitable for the suspension.

An image of a lamp filament is formed on a screen after reflection from the galvanometer mirror. A dry cell in series with a variable resistance may be used as the source of energy. The coil deflection is shown to be inversely proportional to the resistance of the circuit.

**E-146. Simple Direct-current Motor.**
A rectangular coil of wire is mounted on a longitudinal axle running in oiled bearings (Fig. 237). One terminal of the coil is connected to the axle; the other protrudes as a stiff wire T, which makes contact each revolution with the spring brass strip S₁. A single dry cell is connected to S₁ and to a second brass strip S₂, which makes contact with the axle at A. The coil may be made to run continuously in the field of a horseshoe magnet by the periodic impulses given to it by the current whenever T makes contact with S₁. A small flywheel on the axle assures continued motion between impulses. The direction of motion may be reversed by turning the magnet over or by reversing the battery terminals. Simple motors and generators of this type with commutators for a.c. or d.c. operation are available at scientific supply houses.

**E-147.** In a more elaborate model motor, the armature consists of one or more turns of heavy copper wire wound in a circular
coil about 25 cm in diameter (Fig. 238). This is mounted in ball bearings so that it may rotate about a vertical axis with minimum friction. The ends of the coil are soldered to the strips of a two-segment commutator made from a short piece of brass tubing fitted over a piece of fiber tubing, riveted on, and then separated into two segments by cutting with a hack saw. The commutator is more easily seen by the class if it is on the upper side of the armature coil. As brushes, one may use two strips of thin spring brass or copper.

The field is furnished by two solenoids mounted with their axes horizontal. Each solenoid is about 25 cm long and has an iron core 4 cm in diameter. If the solenoids are made of wire of a size nearly the same as that in the armature coil, the model motor may be operated as a series machine. It may be shown that changing the brush connections changes the direction of rotation of the coil. A current of 15 to 20 amp is needed to operate the model.

**E-148. Forces on Parallel Conductors.** Two straight wires 50 cm long are hung vertically by loops at their upper ends, which are supported by two brass pins. The wires are about 1 cm apart, and the loops fit loosely enough to permit the lower ends of the wires to move through horizontal distances of 1 or 2 cm. The lower ends dip into a pool of mercury. The brass pins and the mercury are connected to separate binding posts, so that current can be sent through the wires in the same or in opposite directions.

When currents in the two wires are in the same direction, the attractive force causes the wires to move toward each other. When currents are in opposite directions, repulsion between the currents is shown. The current should be 15 or 20 amp; but the forces are nevertheless small, and for a large class it is advisable to project the wires on a screen.

**E-149.** Four or five feet of flexible copper wire (e.g., No. 36 s.c.c.) is connected to terminals 2 in. apart so as to hang in a long narrow loop. The loop is connected in series with a resistor such as is used with the lecture-room arc lamp. When there is a large current the loop opens.
Two circular coils, suspended in parallel vertical planes by long lead wires, show attraction or repulsion depending upon whether the currents traverse them in the same or in opposite senses.

**E-150. Dancing Spring.** Another device for showing the attractive forces between parallel currents in the same direction is a helix of fine spring brass wire hanging in a vertical position. The lower end of the wire dips into a pool of mercury. When current is sent through the helix, the attractive forces between adjacent turns lift the lower end of the wire out of the mercury, thus breaking the circuit. The lower end then returns to the mercury, and the cycle is repeated, each time with sparking at the lower contact. If the spring fails to start, introduce an iron bar into the top of the helix.

**E-151. Action of Current on Its Conductor.** A thin ribbon of mercury in a horizontal glass tube 1 in. in diameter (Fig. 239) will pinch itself off when there is a heavy current through it. (Vertical projection.)

**E-152. Maxwell's Rule.** An electric circuit tends to change its shape so as to include the maximum possible magnetic flux. This is true even where the magnetic field is due only to the current in the circuit itself. Two horizontal parallel wooden troughs containing mercury form "canals" in which float metal "boats" supporting a copper connecting wire (Fig. 240). When there is current through the wire via the troughs, the wire moves away from the terminals of the troughs, thus increasing the area of the circuit and hence the flux through it. With two d.p.d.t. switches connected as shown, it is possible to demonstrate that reversal of direction of current by switch A does not reverse the motion, whereas reversal of terminals on the troughs by switch B does reverse the motion.

**RESISTANCE**

**E-153. Introductory Experiment on Resistance.** This experiment forms another link between Electrostatics and Electric
Currents. A copper wire is tightly wrapped around each end of a dry pine stick 2 cm square and 75 cm long. The stick and a microammeter, or the lecture galvanometer properly shunted, are connected in series to the terminals of a static machine. Potential drop is measured with an electrostatic voltmeter connected to two potential terminals formed by wrapping copper wires around the wooden stick at any chosen points between the end electrodes.

The resistance of a dry pine stick is generally too high for this experiment; but if a soft lead pencil is rubbed over one edge of the stick, the conductivity may be increased to a suitable value. An ordinary static machine will then produce a current of about 5 μA, and the electrostatic voltmeter will show a potential drop of about 600 V between potential terminals close to the ends of the stick. The relationship between current and potential difference may be shown by varying the resistance with further application of the lead pencil.

E-154. Voltmeter and Electroscope. The model d'Arsonval galvanometer (E-145) may be made into a voltmeter by putting sufficient resistance in series with it. It may be connected to any desired number of cells in series to show that the deflection is proportional to the number of cells. The lecture galvanometer may likewise be made into a voltmeter by connecting it to a shunt and then using enough resistance in series with this parallel combination to make a deflection of one division on the scale correspond with a potential difference of any desired number of volts.

To establish a bond with Electrostatics, several 45-V dry batteries may be connected in series to an electroscope in the lantern field and then to the shunted galvanometer in series with the proper high resistance. An electroscope of the type commonly used for projection requires about 200 V for a deflection of the leaves large enough to be seen.

E-155. Wheatstone-bridge Network. Four 60-W lamps are mounted on a board in the form of a diamond-shaped bridge, with one lamp for each arm of the bridge (Fig. 241). A 10-W lamp is mounted in place of the galvanometer. When the four lamps are operating, the “galvanometer” lamp is dark. If one lamp is turned out or replaced by a lamp of different rating, the 10-W lamp lights. The board should be vertical for showing the experi-
ment effectively. If a 220-v circuit is available, it may be used with a bridge made up with 110-v lamps. Otherwise, if the demonstrator wishes to have the lamps operating at their normal brightness, he may use 32-v lamps and connect the bridge in series with a resistance to a 110-v line. A more sensitive "galvanometer" may be introduced when the bridge is balanced by closing the switch S, thus throwing a 6-v flashlight bulb in shunt with the 10-w bulb.

E-156. Wheatstone Bridge—Slide-wire Form. Two No. 24 nichrome wires are stretched across the lecture table, one above the other. Their ends are joined so that they may be connected in parallel through a rheostat and switch to the d.c. supply. Sliding clips connect the lecture galvanometer to the two wires so that pairs of points at the same potential may be located by bringing the galvanometer to zero deflection. The resistance of either nichrome wire may be varied by shorting any section of it with copper wire.

E-157. Wheatstone Bridge with Human Galvanometer. Stretch a loop of clothesline previously soaked in salt solution from insulating supports so as to form a parallelogram. Connect two diagonally opposite vertices to a 110-v a.c. line. Now touch any point on one branch of the circuit with the left hand, and with the right hand find a point on the other branch where there is no sensation of shock. Let students try the experiment. Various modifications are possible, as, for instance, shunting sections of the rope with copper wire so that balance points are not opposite one another.

E-158. Resistance Measurement Using Voltmeter and Ammeter—Potential Drop along a Wire. The lecture galvanometer is arranged to be used as a voltmeter with any chosen number of volts per scale division of deflection (E-154). Either the same or another lecture galvanometer is arranged for use as an ammeter by connecting the galvanometer terminals in series with a suitable resistance to a shunt designed for a current of a few amperes. A d.p.d.t. switch makes possible the use of one galvanometer for either purpose (Fig. 242).
Several wires of different materials, or of different sizes of the same material, are connected in series and stretched between vertical support rods. The combination is in series with the galvanometer shunt and is connected to a few cells in series with a rheostat. By connecting the voltmeter terminals to two clips, the potential difference between any two points along the stretched wire may be measured. The uniform potential drop along any length of a single kind of wire may be shown by sliding one of the clips along the wire. The resistance of any length of the wire may be measured by using the galvanometer first as an ammeter and next as a voltmeter.

**E-159. IR Drop in a Wire.** The IR drop in a wire carrying a current may be readily shown by clipping the terminals of one or more low-voltage flashlight lamps at various points along the wire. The dependence of potential drop along the wire upon resistance is made evident by the variation of light intensity with the distance between clips. A long iron or nichrome wire carrying 2 to 5 amp, either alternating or direct current, is suitable.

**E-160. Rheostat as Potential Divider.** The common slide-wire rheostat may be used either as a series resistor or as a potential divider. The contrast between these two uses may be shown by connecting a rheostat to a 110-v line as illustrated (Fig. 243), using a 40-w lamp as indicator. The rheostat may be made into a potential divider instead of a simple series resistor by closing switch S. With the potential divider, the voltage across the lamp can be reduced from 110 v to zero, whereas with the series resistor it can be reduced only by the IR drop across the rheostat. The rheostat must be capable of carrying the lamp current plus the current carried by the resistor alone when connected across the line.

**E-161. Potentiometer.** Stretch a 10-ft length of No. 24 nichrome wire above the lecture table, and connect it to a 6-v storage battery through a rheostat. Arrange a lecture galvanometer as a voltmeter to show deflections proportional to the distance
between points on the nichrome wire to which its leads are clipped.

In the galvanometer circuit, insert a cell so that its emf opposes the line drop between the clips. Adjust the clips until the galvanometer gives no deflection. Note that no current is now drawn from the cell, so that it has no internal potential drop, and the true emf of the cell is obtainable by calculation from the line drop in the nichrome wire. The wire may be calibrated with a standard cell or a dry cell whose emf is known. Thereafter the emf's of other cells or combinations may be measured, provided that they do not exceed the $IR$ drop of the potentiometer wire.

**E-162. Fall of Potential—Model Transmission Line.** A model transmission line may be strung along the lecture table, and the decreasing potential difference between points on the two wires at different distances from the input end may be shown. In this experiment, the line loss is purposely made large in order to demonstrate the effect of line potential drop. The line may consist of two parallel wires of No. 28 copper or No. 26 aluminum, each 2 m long. Five 6-v, 6-cp automobile lamps or radio pilot lamps are connected across the line, one at each end and the remaining three equally spaced between the ends. A 6-v storage battery supplies the energy, and a rheostat set at about 0.4 ohm is used as a load at the output end. The lamps will show the potential differences between the various points where they are connected. The lamp at the supply end glows at normal brightness; the lamp at the load end glows just perceptibly. Decreasing the load by increasing the resistance of the load rheostat will increase the brightness of all the lamps.

**E-163. Effect of Temperature on Resistance.** A small helix of nickel wire is connected in series with a few cells and with a low-resistance shunt connected to the lecture galvanometer, which is arranged for use as an ammeter (E-158). The number of cells used should be such that the current does not heat the nickel wire more than about 100°F above room temperature. When the wire is heated by a gas flame until it becomes incandescent, the resistance increases, and the deflection of the galvanometer decreases.

**E-164.** An iron wire is bent into a long narrow U and connected in series with a regulating resistor and an ammeter. The current is increased until the wire is red. When the lower half of the U is
immersed in a beaker of water, the resistance of this cold part of the wire decreases, current through the wire increases, the upper half glows more brightly than before, and the ammeter indicates more current. These effects are most prominent when the power-supply voltage is such that the regulating resistance is low. A similar effect is produced when a coil of copper wire is dipped into liquid air (H-104).

**E-165. Putting Light Out by Heat.** A 1.5-v flashlight bulb is operated in series with two dry cells (3 v emf) and sufficient iron wire to reduce the brightness of the bulb to normal. The iron wire is wound on a porcelain insulator. When the wire is heated in a Bunsen flame, the lamp goes out because of increased resistance in the iron at high temperature.

**E-166. Comparison of Temperature Coefficients of Resistance.**

A slide-wire Wheatstone bridge is arranged as shown in Fig. 244, where the slide wire $AB$ is a 6-ft length of No. 24 nichrome wire. Two coils $C$ and $D$ of different materials having comparable resistances at room temperature are inserted in the bridge, and the bridge is balanced. If either coil is heated, the galvanometer will be disturbed. The temperature coefficients of resistance of the two coils may be compared by comparing galvanometer deflections produced by equal changes of temperature, successively produced in the two coils.

**E-167. Negative Temperature Coefficient of Resistance.** A satisfactory demonstration of negative temperature coefficient of resistance is obtained with a Nernst glower. The resistance of a 0.6-amp, 110-v glower at room temperature is about $10^5$ ohms. The glower must be used in series with a ballast resistor. It may be operated on direct current, and the lecture ammeter and voltmeter may be used to indicate the resistance of the glower. The current through the glower at room temperature and with rated voltage is so feeble that the glower does not become appreciably warmed. When heated by a gas flame or by a match, the resistance of the glower decreases, as is shown.

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by the meters, and finally when heated to a temperature well below dull red heat, the resistance of the glower becomes small enough to permit electrical heating up to the point of rated power consumption and of rated light emission.

Globar electric heating elements (E-171) likewise show a negative temperature coefficient of resistance, as does a carbon-filament incandescent lamp.

**E-168. Conduction in Glass at High Temperature.** A piece of soft-glass capillary tubing or rod about 1 cm in diameter and 10 cm long is provided with electrodes at the ends (Fig. 245), made of strips of sheet copper 6 mm wide, 1 mm thick, and 6 cm long. The copper is bent around the end of the glass, and a fairly snug fit is obtained by crimping with pliers. The glass is then placed on a board covered with asbestos, and the electrodes are connected to a 110-v a.c. line (or d.c. if it is available) in series with a 15-ohm rheostat capable of carrying about 7 amp. One may use in place of a rheostat two or three 110-v, 500-w lamps in parallel. An ammeter may also be included in the circuit.

The glass is heated with a Bunsen flame or blast lamp. It does not conduct electricity to a noticeable extent until it is red hot. Then because of the high negative resistance-temperature coefficient of glass, the conductivity increases rapidly, and at a bright red heat the $I^2R$ loss in the glass is sufficient to maintain the temperature without further use of the flame. The current increases to about 7 amp with the two or three 500-w lamps as described, at which point the glass is white hot. If all lamps but one are disconnected, the remaining lamp glows brightly, and the glass cools. By adjusting the resistance in series with the glass, or simply by opening the switch when the glass becomes white hot and then closing it when the glass cools to a red heat, the experiment may be continued indefinitely. The glass has a tendency to spread out on the asbestos and thus to pull away from the electrodes. Small pieces of cold glass may be dropped into the pool of molten glass to compensate for the effect of spreading out. **Caution:** Because of the high luminosity of incandescent glass, it is suggested that a suitable dark-
glass screen be erected to protect the eyes of the students. The instructor is advised to wear dark glasses.

**E-169. Electric Thermometers.** The use of resistance thermometers for temperature measurements is of sufficient practical importance to warrant a demonstration experiment. A factory-made thermometer and thermometer bridge may be shown, but this equipment is not constructed for teaching purposes; the resistance elements are concealed, and there is an extra lead-wire to eliminate trouble arising from changes in the lead-wire resistances. A simple demonstration resistance thermometer therefore may be made by attaching No. 14 copper wire leads to terminals of a coil of fine platinum wire wound on a mica frame. The resistance of the coil should be large compared to that of the lead-wires. The coil may be in the closed end of a pyrex tube for protection. This results in slower operation, but it has the advantage of enabling the students to see the coil. The slide-wire (E-156) or any other type of Wheatstone bridge may be used for resistance measurement. The apparatus may be calibrated in advance, using two or more standard temperatures, and may then be used to measure any suitable known temperature. (See also the thermoelectric thermometer described in H-6.)

If the laboratory is provided with a Pirani gauge for the measurement of low gas pressures, it may be shown in this connection, since the principle of the gauge is that of change of resistance with change of temperature owing to conductivity of heat by the gas.

**E-170. Selenium Photoconductivity Bridge.** This experiment shows the effect of light in decreasing the resistance of selenium. Drill four small holes in the corners of a piece of glass about 2.5 by 4.5 cm (Fig. 246). Grind the surface of the glass with carborundum to roughen it slightly. Attach two nickel wires (No. 34) at two of the corners of the glass, and wind them approximately parallel to each other as far as the other corners, where they are fastened. There may be about 15 turns of each wire. Place the grid thus made on a block of metal, which is heated slowly by a burner. When the glass is somewhat above the melting point of selenium (217°C), rub a stick of selenium on the ground-glass
surface and on the nickel wires stretched over it. The selenium will melt, and a thin layer can be formed on the glass. This operation should be carried out in a hood, since the compounds of selenium are cumulative poisons. Remove the grid from the block of metal, and allow it to cool rather quickly to room temperature. The selenium will then be in the amorphous form, and if a sufficiently thin layer has been obtained, it will transmit red light.

Selenium in this form is practically a nonconductor. To bring it into the conducting and light-sensitive form, the material is again heated. Support a glass test tube in a beaker of oil, the open end of the tube projecting above the oil. Heat the oil to 180°C, and drop the grid into the test tube, allowing it to remain for 5 min. When the grid is withdrawn, the selenium will be seen to have changed into the gray, partly crystalline form.

The grid after cooling to room temperature will have a resistance of the order of 10 megohms in the dark; its resistance will be about 15 per cent of that value when illuminated with a 60-w lamp at a distance of 20 cm. This ratio of dark resistance to light resistance will decrease if the grid is kept in a damp place, but if it is stored in a desiccator containing a drying agent, the light sensitivity will remain high for a long time.

The experiment may be shown by connecting a suitable source of potential difference in series with the selenium grid and the lecture galvanometer. No rheostat should be in the circuit containing grid and galvanometer, since such a resistance will reduce the ratio of deflections in darkness and under illumination. The deflection under no illumination may be obtained by placing the grid in a cardboard box.

HEATING EFFECT OF CURRENT

E-171. Heating Effects of Electric Current. A loop of No. 18 nichrome wire may be used to show the heating effect of a current. Two Fahnestock connectors screwed to a board are convenient for holding the wire and for making connections to it. A lecture-room ammeter and voltmeter may be used to measure both power and resistance; i.e., volts × amperes = watts; volts ÷ amperes = ohms. A rheostat may be included in the circuit for regulating the current. If desired, the wire may be arranged to illustrate the hot-wire ammeter (H-11).
In a similar way, one may use a Globar electric heating element. These elements may be obtained in various ratings. Contacts with their terminals are easily made. They glow brightly when operated at normal power consumption and have a negative temperature coefficient of resistance (E-167). An ammeter connected to measure current through one of these heaters shows a gradual increase in current after the circuit is closed.

Electric heating devices, such as hot plates, radiant heaters, and immersion heaters, may be shown. Attention may be called to the large amount of heat emitted by a carbon arc.

E-172. Fuses and House-lighting Circuits. The use of fuse wire for protection of electrical circuits may be demonstrated by connecting a short piece of wire between two Fahnestock clips with a rheostat and an ammeter in series to regulate and to measure the current required to melt the wire.

A miniature house-lighting circuit may be constructed by mounting on a board various outlets, switches, and sockets connected in parallel through a fuse block with plug and leads for connecting to a 110-v circuit. When lamps, electric irons, and other accessories are used, the load may be made to exceed the capacity of a fuse of low rating.

E-173. Fuse-wire Problem. If two (or more) fuse wires of the same substance but of different diameters and ratings are connected in parallel between two copper bars, which one will burn out first as the voltage between the bars is increased?

Few students will guess the correct answer. The simple arrangement of Fig. 247 demonstrates that the large wire will burn out first. (The smaller fuses may burn out soon thereafter because of the decreased IR drop in $R$ when the current decreases.)

E-174. Comparison of Heating in Various Conductors. Five or more wires of equal length (e.g., 25 cm each of No. 16 copper, No. 22 copper, No. 22 "advance," No. 16 iron, and No. 23 iron) are connected in series, using soldered joints. The wires are supported horizontally above the lecture table and are connected in series with a rheostat, ammeter, and battery. A strip of paper

1 Globar Corporation, Niagara Falls, N. Y.
or an index card is attached with soft wax to the center of each sample of wire. The current through the wires is gradually increased. The first paper to fall on account of the melting of the wax will be that on the "advance" wire, because of the high resistivity of this material and the consequent large heating effect. The wax holding the paper to the smaller iron wire will melt next, etc., the order of melting and falling being an indication of the relative resistances of the wires. However, the smaller iron wire will become red hot before the advance wire because of the higher resistance-temperature coefficient of iron. It will be noticed that the specifications suggest that this wire be one size smaller than the "advance." In this case, at lower temperatures the resistance of the iron wire is certain to be less than that of the advance, but at higher temperatures the resistance of the iron wire exceeds that of the advance.

**E-175. Dependence of Resistance on Length and Area of Conductor.** Mount in series on a board German silver or "Nisil" wires, of lengths 1, 2, and 3 ft, which are respectively single, double, and triple, with switches arranged so that they may be used singly or in multiple (Fig. 248). Since these three elements of the circuit, \(AB, BC, CD\) are in series, they all carry the same current, whether as single wires or in multiple. Their resistances can be compared by voltmeter readings taken individually over each of the three elements. Thus, when used singly, the voltmeter readings \(AB:BC:CD\) will be as 1:2:3; but when section \(BC\) has two wires and \(CD\) has three, the voltmeter readings will all be equal, showing that the length factor is compensated by increased area.

**E-176. Heating Effect of Current in Organic Material—"Hot Dog" Cooker.** It is well to show that the heating effect of an electric current is not confined to metallic conductors and glowing filaments. Two nails are driven through a piece of wood about 10 cm apart so that their ends project 3 cm beyond the surface of the wood. The nails are connected to a 110-v line with an ammeter in series, and the board is placed on the lecture
table with the pointed ends of the nails upwards. A raw frankfurter is now pressed against the sides of the nails. The current is small since the resistance of the skin of the frankfurter is high. There will be scorching at the contacts if a little pressure is applied, since with small current but high resistance considerable heat may be developed locally. This corresponds to the surface burns suffered when a person receives a severe shock with poor skin contacts. If the frankfurter is now impaled on the nails, contact is improved, and the current increases to 1 or 2 amp. The heating effect is sufficient to start cooking the frankfurter. If the nails fit snugly into the holes that they make in the skin, the steam generated does not escape but soon produces enough pressure to burst the skin of the "hot dog."

E-177. Resistances in Parallel and in Series. Attach six lamp receptacles to a board, three being in parallel and three in series. Insert lamps of the same rating in each socket. Use an ammeter to show that the current through the three in parallel is three times the current through a single lamp, and also that the current through the three lamps in series is (about) one-third the current through a single lamp having the same potential difference between its terminals as exists between the end terminals of the three lamps in series. The current through the three in series will actually be more than one-third, since the filaments of the lamps in series are below their normal operating temperature and hence have a resistance less than the normal operating value. The sum of voltmeter readings taken across the three series lamps individually may be shown to be equal to the total applied voltage.

E-178. Electrocalorimeter. The purpose of this experiment is to obtain an approximate value for the mechanical equivalent of heat by electrical methods. The electrocalorimeter consists of an ordinary calorimeter to which an electrical heating unit, e.g., a 100-w lamp, has been added. The demonstrator puts a known mass of water in the inner calorimeter cup and reads its temperature. An ammeter and a voltmeter measure the power delivered to the heating unit. The class determines the time required for heating the water to a temperature as far above room temperature as the water was below room temperature at the time of closing the switch. The ratio of volts \( \times \) amperes \( \times \) seconds to calories delivered should approximate 4.2 joules per cal. Temperature
change may be shown by the demonstration thermocouple thermometer (H-6).

A 600-w radiant heater element immersed in a beaker of water will bring the water to a boil in less than a minute. The heater should be immersed before the current is turned on.

**THERMO-, PIEZO-, AND PYROELECTRICITY**

**E-179. Thermoelectric Effect—Seebeck Effect.** A piece of copper wire about 75 cm long is attached to each end of a piece of iron wire of the same length by twisting the ends together. The free ends of the copper wires are connected to the lecture galvanometer in series with enough resistance to keep the deflections on scale. One of the copper-iron junctions is kept either in ice water or in water at room temperature, while the other junction is heated with a gas flame. The thermal emf increases as the temperature of the hot junction rises until 275°C (approximately) is reached. For higher temperatures, the emf diminishes, becomes zero at about 550°C (dull red heat), and then increases in the opposite direction.

The lecture-room thermocouple (H-6), thermo electric pyrometers, and thermopiles may be discussed at this time.

**E-180. Peltier Effect.** When current is passed through a thermocouple, one junction is cooled while the other is heated (Peltier effect). This effect is in addition to the $I^2R$ heat generated throughout the circuit by the current. It is important in showing this effect to keep the $I^2R$ heat small compared with the Peltier heat by using a couple consisting of large rods of bismuth and antimony. One end of a piece of pyrex tubing 1.2 cm in diameter and 12 cm long is closed by a plug of alundum cement. The tubing is held vertically, and molten antimony is poured into it until it is about half full. After the antimony has solidified, a short portion of it at the top is remelted, and the tube is filled with molten bismuth. Two such rods are made and removed from the glass. The bismuth ends of the two rods are slipped into a short length of pyrex tubing and welded together. Each antimony-bismuth junction of the composite rod so formed is placed within a piece of pyrex tubing about 1.8 cm in inside diameter, whose ends are closed with rubber stoppers (Fig. 249). Side tubes are connected to a piece of tubing about 0.25 cm in inside diameter in which there is a short thread of colored
water or of mercury. If there is an evolution of heat at one of the antimony-bismuth junctions and an absorption of heat at the other, the water will move away from the first and toward the second. The apparatus is mounted on a wooden base. When a direct current of 20 amp is passed through the rod, the globule of water will move about 0.5 cm in 30 sec. The direction of motion may be reversed by reversing the current, which would not be the case if the $I^2R$ heat were the cause. (Project.)

Fig. 249.—Antimony-bismuth thermocouple for demonstrating the Peltier effect.

E-181. Seebeck and Peltier Effects in One Thermocouple Circuit. The converse nature of the Seebeck and Peltier effects is emphasized by the following experiment. For a period of several seconds, send a current through a copper-iron-copper circuit (Fig. 250). Then disconnect the battery, and immediately connect the thermocouple to the galvanometer. (A d.p.d.t. switch accomplishes this change quickly.) With the initial current from $C$ to $D$ through the iron, the galvanometer deflection indicates that junction $C$ is warmer than junction $D$. Repeat the experiment with the direction of the initial current reversed. The galvanometer now shows that $D$ is warmer than $C$.

E-182. Thermoelectric Magnet. The emf of a thermocouple depends only upon the two metals used and the difference in temperature between their junctions; the current is, by Ohm's law, dependent upon the resistance of the circuit. Very large currents may be generated if the resistance is sufficiently low, as may be shown by the thermocouple magnet. A single loop of heavy copper bar is closed by welded joints with a short section of copper-nickel alloy. Two copper vanes are welded at the junctions for rapid heat conduction. When one vane is cooled in water and the other heated in a Bunsen flame, the current may
even exceed 100 amp. The copper loop fits inside an iron shell to form an electromagnet whose attraction for a soft-iron armature is sufficient to support a load of more than 200 lb. (Fig. 251).

**E-183.** Bars of iron and copper are riveted together with a compass needle mounted between them (Fig. 252). The unit is placed parallel to the magnetic meridian. When one of the junctions is heated, the compass needle deflects. The deflection is reversed by heating the other junction and cooling the first. From electromagnetic principles, the direction of current in each case may be determined (E-121).

**E-184. Thermoelectric Effect in One Metal.** Pass a flame along a piece of soft-iron wire connected to a galvanometer and show that any effect (E-185) is small. The wire must be fresh from the spool and not kinked. Then care-
fully make a single loop near its center, and draw it down quite tightly to make a sharp kink, avoiding kinks elsewhere. Now hold a pointed flame (not too hot) about \( \frac{1}{2} \) in. from one side of the kink, and observe the galvanometer deflection. Remove the flame at once, and allow the wire to cool. Repeat the heating similarly on the other side of the kink, and the galvanometer should deflect in the opposite direction about the same amount. In kinking the wire, its elastic limit has been exceeded, and in effect a new material has been inserted in the circuit.

E-186. Thomson Effect in Single Wire. A single long wire loop is connected to the lecture galvanometer. The flame from a Bunsen burner is passed along the wire, heating it locally as it goes (Fig. 253). The galvanometer shows the existence of a current as if electrons were “pushed ahead” of the advancing flame. The effect was discovered in 1854 by Prof. William Thomson, later Lord Kelvin.

E-186. Piezoelectric Effect in Rochelle Salt Crystals. A properly cut crystal of Rochelle salt\(^1\) develops charges on its faces when the crystal is under stress. In a piezoelectric demonstration unit commercially available, the crystal is mounted on a heavy base with a metallic cap fitted over one end. Tin-foil coatings are cemented to the faces of the crystal, and these are connected to the electrodes of a small neon lamp. When the metallic cap is tapped with a piece of wood or a rubber mallet, the stress developed is sufficient to cause the neon lamp to flash.

If the tin-foil coatings of a large crystal (about 10 cm long with faces about 8 cm wide) are connected to an electrostatic voltmeter, the potential differences developed may be measured. One end of the crystal may be in contact with a pad resting on the table to prevent chipping. The demonstrator applies pressure to another pad on the upper end of the crystal. A moderate pressure develops a potential difference of more than 50 v. If this potential is applied to the grid of a three-electrode tube, the resulting variation in plate current may be shown in several ways that will suggest themselves. One way is to have a neon

\(^1\) Rochelle salt piezoelectric crystals and bar resonators are available from the Brush Development Co., Cleveland, Ohio.
lamp in the plate circuit. The lamp glows until the negative potential developed by the piezoelectric effect stops the plate current.

**E-187. Mechanical Vibration of Crystal under Electric Forces.** The converse piezoelectric effect, in which the application of an electric field to the crystal produces a strain in it, may be shown with the large crystal. Connect two tin foils on the crystal (E-186) to the amplified output of an audio-frequency oscillator (A-27 and 85) to develop mechanical vibrations in the crystal. The sound produced may be heard distinctly in a large lecture room.

**E-188. Piezoelectric Oscillator.** The piezoelectric bar oscillator consists of a steel bar of square cross section with four properly cut Rochelle salt crystals cemented on the flat surfaces of the bar near its center. With the circuit shown in Fig. 254, the bar may be put into oscillation. Since the crystals are all cemented to the bar, it serves as a common plate for all of them. The other sides of the crystals are covered with tin-foil coatings that are connected in pairs to two binding posts. The coatings of one pair of crystals are connected to the high-tension side of an a.f. transformer with a turn ratio of about 1:8, the low-tension side of this transformer being in the plate circuit of a three-element tube. The coatings on the other pair of crystals are connected to the grid of this tube. A slight change in plate current causes a potential difference across one pair of crystals; the resulting slight change in the dimensions of these crystals initiates a longitudinal pulse along the bar. The longitudinal pulse in the bar develops in turn a potential difference across the crystals whose tin foils are connected to the grid of the tube. In this manner, the plate current is further changed, and oscillations are sustained in the bar.
The tin foils on the driving crystals must be connected in the correct sense. If the bar does not oscillate when first set up, reverse one pair of terminals on the transformer. The transformer must be selected to match the tube. Any tendency of the bar to oscillate at double its fundamental frequency may be avoided by using the tuned circuit of Fig. 255.

The sound produced by the oscillator is of sufficient intensity to be heard distinctly in the largest lecture room. The pitch corresponds to the natural frequency of the bar. There is one-half of a standing wave in the length of the bar. With a steel bar 76 cm long, the frequency is about 3400 cycles per sec. The wave length in air is about 10 cm. The students may detect very prominent interference effects due to reflections from the walls of the room by moving their heads from side to side over a distance of a few centimeters.

E-189. Pyroelectric Effect in Tourmaline—Heating. A long thin crystal of tourmaline at least 2 cm long and reasonably clear is held by a wire over a Bunsen burner and heated to about 250°C. The heating should be slow to avoid breaking the crystal. As the temperature increases, pyroelectric charges are developed on the ends of the crystal and are neutralized by ions from the flame. When the crystal is removed from the flame, pyroelectric charges develop upon cooling and are retained on its ends. These charges—positive on one end and negative on the other—may be detected by means of an electroscope. They are sufficient to produce a large deflection. The crystal may be projected in silhouette on a screen.

E-190. Pyroelectric Effect in Tourmaline—Cooling. A long thin crystal of tourmaline is suspended by two silk threads

1 Obtainable from Ward’s Natural Science Establishment, Inc., Rochester, N. Y.
tied a few millimeters apart on either side of the center, forming a bifilar suspension. It is immersed in liquid air or in a mixture of carbon dioxide snow and alcohol (p. 224). When the crystal is withdrawn, frost is formed on it, chiefly at the ends. On close examination, one can see minute frost needles being shot off by electrostatic repulsion. By means of a charged rod brought near the crystal, one can show that the crystal has opposite charges at its two ends and behaves like an electric doublet.

The charges acquired by the crystal may be shown by dusting over it a mixture of powdered sulfur and red lead (E-66). The yellow sulfur adheres to the positively charged end of the crystal, and the red litharge to the negatively charged end.

**ELECTROLYTIC CONDUCTION**

**E-191. Magnetic Field of Current through an Electrolyte.** A piece of glass tubing about 2 cm in inside diameter and 75 cm long has its ends bent at right angles to its length and flared to receive rubber stoppers. A sulfuric acid solution of specific gravity about 1.4 is poured into the tube while the latter is held horizontally in a north-south direction just over a compass needle on a pivot (E-76). Platinum electrodes are provided at the ends, the lead-wires passing through the rubber stoppers. A current of about 2 amp from a d.c. source is sent through the electrolyte. The magnetic field produced by this current is evident from the deflection of the compass needle.

**E-192. Conduction through Electrolytes.** The contrast between the conductivity of pure water and water containing an electrolyte may be shown by immersing two copper plates in a vessel of distilled water. The plates are connected in series with a 25-w lamp to a 110-v line (alternating or direct current). When salt or sulfuric acid is dissolved in the water, the solution becomes conductive, and the lamp glows.

**E-193.** With the apparatus of the preceding experiment, add barium hydroxide to the distilled water until the lamp lights. Then carefully add dilute sulfuric acid, a little at a time, until the lamp goes out. An insoluble precipitate of barium sulfate forms. Further addition of sulfuric acid causes the light to come on again, thus showing the necessity of ions for conduction in an electrolyte.
E-194. Rotation of an Electrolyte Carrying Current Perpendicular to a Magnetic Field. A crystallizing dish 10 cm in diameter contains a solution of zinc chloride having about 20 g of the salt to 100 ml of water. A strip of zinc 2 cm wide is bent into a thin ring 9 cm in diameter. It is placed in the crystallizing dish to serve as the outer electrode. The inner electrode is a hollow cylinder of zinc 1 cm in diameter located at the center of the dish. Some cork filings may be floated on the surface of the solution. The images of these bits of cork may be projected onto a screen by vertical projection.

A strong bar magnet is held vertically over the center of the crystallizing dish, thus producing a magnetic field with a component perpendicular to the surface of the liquid. A solenoid surrounding the dish may be substituted for the bar magnet.

The electrodes are connected in series with a rheostat through a reversing switch to a 60-v source of direct current. When the current is about 10 amp, the positive and negative ions move toward the electrodes with velocities that have components at right angles to the magnetic field. The electromagnetic forces are at right angles to the magnetic field and to the directions of motion of the ions. The result is that the electrolyte is given a rotational motion. The angular speed varies with distance from the central electrode, since the current density is greatest near this electrode and also because the field is greatest at a point just under the end of the bar magnet. A particle of cork floating at a point about one-third the way from the central electrode to the outer electrode will make one revolution in about 2 sec.

E-195. Electroplating—Lead Tree. Two strips of lead or zinc serve as electrodes in a projection electrolytic cell containing a saturated solution of lead acetate, with a few drops of acetic acid added. The electrodes are connected in series with a rheostat, through a reversing switch, to several storage cells in series. When the circuit is closed, the image of the cell projected on the screen shows the rapid deposition of lead in fernlike clusters on the cathode. Reversal of the current causes the lead deposit to disappear from the electrode upon which it has been deposited and to form on the other electrode, which has now become the cathode. The rate of growth of the “lead tree” is controlled by the rheostat.
E-196. Electroplating—Tin Tree. Electrodes of copper and tin are dipped into a projection cell containing an acid solution of stannic chloride. With the copper as cathode, a current causes tin to crystallize on it in long needles. (Project.)

E-197. Electroplating. Copper or silver plating may be demonstrated, but the process is slower and less spectacular than in the preceding experiments. However, the plating may be carried on at low current values throughout the lecture period, and the results shown at the end of the hour. The object to be plated is connected to the negative terminal of the battery. The positive terminal should be connected to a rod or sheet of copper or silver. Copper plating may be done in a copper sulfate solution. Silver nitrate solution is suitable for silver plating.

E-198. Voltaic Cell. A projection cell is filled with an electrolyte consisting of one part sulfuric acid to four parts water. The electrodes are a strip of copper and a strip of amalgamated zinc. When the terminals of the cell are connected to the lecture galvanometer arranged as a voltmeter, the potential difference is shown. If the cell is short-circuited, the evolution of hydrogen bubbles at the cathode (copper) is apparent on the screen. If two lecture galvanometers are available, one may be used as a current-measuring instrument while the other is used for measuring potential difference (E-158). The variation of potential difference as the current is changed by means of a series rheostat may be demonstrated. It is interesting to note the large amount of gas liberated near a piece of unamalgamated zinc (local action) when the cell is on open circuit and to observe the relatively small amount near a piece of amalgamated zinc.

E-199. Cardboard Model to Illustrate Potential Difference and Electromotive Force in a Voltaic-cell Circuit. Cut out of thin white cardboard a right triangle ABC (Fig. 256), with angle $\theta = 20^\circ$. Distances measured parallel to BC are proportional to potential difference; those parallel to the base are proportional to resistance. Then, by Ohm’s law, the slope of the hypotenuse is proportional to the current. Draw on the cardboard two straight lines, DE, EF, parallel respectively to the altitude and the hypotenuse. Draw EG parallel to the base. Then going around
the circuit $BFEDAHB$, the length $BF$ is proportional to the contribution to the emf of the zinc-acid contact; $FG$ is proportional to the $IR$ drop within the cell due to internal resistance; $ED$ is proportional to the contribution to the emf of the acid-copper contact. Now $BF + ED = BF + FC = BC$, which is proportional to the total emf of the cell. Also, $HD = BC - FG$ is the potential difference at the cell terminals, or the useful potential difference over the external circuit $DA$. The distinction is thus clearly brought out between the terms electromotive force and potential difference.

**E-200. Polarization of Voltaic Cell.**—The formation of a layer of hydrogen on the surface of the cathode reduces the emf of a voltaic cell. Using the same arrangement as in E-198, remove the copper cathode, and heat it well in a Bunsen flame so as to oxidize it. After cooling, replace it in the cell, and close the circuit. A large current, steady for about 1 min, results, during which no gas comes from the copper surface, since the oxide is being reduced by the hydrogen. An oily-appearing stream (zinc sulfate) flows off the bottom of the anode. Suddenly, the current begins to decrease, and gas starts to leave the cathode surface. Polarization is complete when the galvanometer shows a new steady lower value of emf.

**E-201. Electromotive Force of Polarization during Electrolysis of Water.**

The projection electrolytic cell may be used for showing the evolution of hydrogen and oxygen to a large class. The electrolyte may be a sulfuric acid solution. Two strips of platinum are used as electrodes. They are connected to the middle terminals of a d.p.d.t. switch (Fig. 257). With the switch in one direction, current through the cell causes evolution of hydrogen at the cathode and of oxygen at the anode. If the switch is then turned so as to connect the cell to the lecture galvanometer, arranged as a voltmeter, the galvanometer shows a momentary current in the opposite direction because of polarization. No emf is developed by the cell unless there are layers of gas on the electrodes.

**E-202. Electrolysis of Water—Quantitative Experiment.** The Hoffman apparatus allows the volumes of hydrogen and oxygen
liberated by the electrolysis of water to be measured. With this apparatus, one may show the volume of hydrogen to be twice that of the oxygen when measured at the same pressure, and one may obtain a sample of either gas by holding an inverted test tube over one of the stopcocks.

The usual Hoffman apparatus is not easily seen by a large class. In this case, one may construct a miniature projection electrolytic cell with two inverted test tubes filled with electrolyte and held vertically, with their lower ends just under the surface of the solution. Electrodes are at the lower ends of the tubes. The whole apparatus is projected on the screen, and the formation of the gases is easily seen by a large class.

**E-203. Explosion of Hydrogen and Oxygen.** An explosive mixture of hydrogen and oxygen is obtained by combining the gases generated on both sides of the Hoffman apparatus. A satisfactory way is to connect rubber tubes to the two stopcocks and to a glass T-tube. A tube from the third arm of the T is then used to blow small bubbles in an open dish of soap solution. Still better, reverse the current after one side of the apparatus is about half full of hydrogen, and allow gas to collect until both tubes contain the same volume. A perfect mixture of two parts hydrogen to one part oxygen is thus assured in both tubes. After the gas has been collected in the soap suds, remove the dish to a safe distance from the apparatus, and ignite the bubbles with a small gas flame on the end of a long glass tube. A loud, startling report results.

**E-204. Secondary or Storage Cells.** Reference has already been made in E-120 to an elementary lead storage cell. A small portable storage cell of the lead electrode type contained in a glass jar may also be shown in a similar manner. This cell may be charged while on the lecture table and subsequently connected to a resistance load. A voltmeter or the lecture galvanometer connected to the terminals shows the potential drop on open circuit (approximately the emf of the cell) and the potential drop both when the cell is being charged and when it is being discharged.

An Edison-type storage battery may be shown, and its potential differences under similar circumstances demonstrated.

**E-205. Large Current from Storage Cell.** To demonstrate the very large current obtainable from a 6-v automobile storage
battery when there is a low external resistance between its terminals, one may use the current to melt an iron nail of about 3.5 mm diameter. The head of the nail is cut off, and each end is soldered into a hole in the end of a short piece of brass rod about 5 mm in diameter. The length of nail between brass rods may be about 3.5 cm. It is essential to keep the resistance of the circuit at a minimum; care must be taken that the joints are good. Regular automobile battery cables are used, and all connections are soldered except those on the battery terminal posts and others made with bolts. If a 500-amp switch is available, it may be used advantageously in the circuit. If such a switch is not available, the following procedure may be used. One of the battery cables is bolted to its terminal post. The terminal of the other cable is adjusted to make a snug fit on the other battery post. When the demonstrator is ready for the experiment, he holds this terminal in one hand just over the battery post that it is to fit and a hammer in the other hand. The terminal is then dropped into place, and an immediate blow with the hammer forces it tightly over the post.

With the specifications given, the nail will come to a white heat and melt in about 2 sec. The experiment is quite spectacular. The initial current may be about 700 amp. This is without question rather severe punishment for a battery. However, the current required to melt the nail does not greatly exceed that needed to operate an automobile starting motor in cold weather.

**E-206. Ionic Speed.** Dip two platinum electrodes into an ammoniated copper sulfate solution, containing some phenolphthalein. A current causes the blue solution to move to the cathode and the red solution to the anode, with a difference in the motions of the two layers that should be noted. (Project.)

**E-207.** A glass tube about 5 mm in inside diameter and 50 cm long is bent into a square U, the base of the U being about 15 cm long (Fig. 258). The base of the U is filled with a hot saturated solution of potassium chloride containing 2 per cent of agar-agar, which is allowed to cool and solidify, forming a gel. A saturated solution of copper sulfate is poured into one of the arms of the U, and a saturated solution of potassium chromate into the other.
arm. Copper electrodes of about 6 cm² surface area are placed in these solutions, that in the copper sulfate being made the anode. The part of the U-tube containing the gel is immersed in cold water, to prevent the gel from liquefying when heated by current.

The potassium chloride in the gel is colorless when put into the tube, but when a potential is applied, the region near the anode soon becomes blue because of the presence of copper ions that are moving toward the cathode. There is a sharp boundary between the blue and the colorless regions. The speed of this boundary can be measured directly. With a potential difference of about 120 v between anode and cathode and with a current path about 18 cm long, the speed of this boundary is about 8 cm per hr or $2.2 \times 10^{-8}$ cm per sec.

A rather faint yellow boundary moves from the cathode end of the tube as chlorine ions progress toward the anode. The line of demarcation is not sufficiently definite to serve for measurement of its speed.

**E-208.** In another experiment, the speeds of hydrogen and hydroxyl ions are measured. Hydrogen ions have a mobility greater than that of any other ions, and hydroxyl ions come next on the list. About 2 per cent of agar-agar is dissolved in a saturated solution of potassium chloride as already described (E-207), and about 0.5 per cent of phenolphthalein is added. The mixture is poured into a U-tube 9 mm in inside diameter and 40 cm long, with a 5-cm base (Fig. 259). The mixture should fill the bottom of the tube and extend up the sides, so that the length it occupies is about 15 cm. Before the mixture has hardened, a few drops of hydrochloric acid are added to one side, and a few drops of potassium hydroxide solution to the other. The potassium hydroxide diffuses down the arm of the U-tube, making the color a bright pink. The hydrochloric acid diffuses down the other arm, hardly changing the color, but if anything making it more nearly white. After the solution has hardened, potassium hydroxide is poured on top of the colorless gel, and hydrochloric acid is poured on the pink gel. Carbon electrodes are introduced, that in the acid being made the anode. The
part of the U-tube containing the gel is surrounded with a beaker of cold water.

When a potential difference is established, the hydroxyl ions move toward the anode. As they enter the gel, the phenolphthalein becomes pink, and the motion of the boundary between the pink and the colorless parts of the gel enables one to measure the speed of these ions directly. The hydrogen ions from the hydrochloric acid move toward the cathode. As they enter the colored gel, it becomes colorless. The speed with which this boundary moves toward the cathode shows the speed of the hydrogen ions.

With a 30-cm length of current path, of which 15 cm is through the gel, and with a total potential difference of 120 v, the speed of the hydroxyl ion is about $3 \times 10^{-3}$ cm per sec, and that of the hydrogen ion about $5 \times 10^{-8}$ cm per sec.

**E-209. Electrolysis of Sodium Sulfate with Purple Cabbage as Indicator.** Crush some purple cabbage in a vessel of water to remove its coloring matter, then strain. Add sodium sulfate to the colored water to make it conductive, and introduce two platinum electrodes. When a current passes, the liquid at one pole turns pink, at the other green, the colors being quite brilliant.

**E-210. Electric Forge.** Fill a battery jar two-thirds full of strong sodium sulfite solution, and lay a lead plate on the bottom for an anode. The cathode is an iron rod with wooden handle, which may be held in the hand. Apply 110-v direct current through a rheostat, and dip the iron terminal into the solution. Sparks fly and droplets of iron melt from the tip of the rod in a spectacular manner, owing to the highly localized generation of heat.

**E-211. Electrolysis of Sodium Ions through Glass.** Put a mixture of about 90 per cent sodium nitrate and 10 per cent sodium chloride (to lower the melting point) in a porcelain beaker or an agateware pan. Support a 60-w clear-glass lamp bulb (*not* gas filled) near the center of the vessel so that it does not touch the bottom (Fig. 260). Let the upper half of the lamp bulb project through a hole in a sheet of asbestos paper, which rests on the rim of the vessel and serves to reduce heat loss from the vessel and to keep the upper part of the lamp bulb cool. Place an anode of nickel in the vessel, but not flat on the bottom.

Melt the sodium nitrate with a Bunsen flame, and raise it to a temperature of about 360°C. Run the lamp filament at normal
brightness from a 110-v source. Connect the nickel anode in series with a rheostat and milliammeter to the positive side of a 110-v d.c. supply, and connect one terminal of the lamp filament to the negative side. There will be a current of about 0.1 amp in the d.c. circuit when the potential drop between anode and filament is about 100 v. This current is carried by sodium ions through the glass lamp bulb; their positive charges are neutralized by thermions emitted from the filament, and the neutral sodium atoms then condense inside the bulb on the cooler parts of the glass.\(^1\)

The apparatus may be used as a rectifier by applying an alternating voltage between the anode and one terminal of the lamp filament. A milliammeter in the circuit will show unidirectional current.

After about half an hour, there will be a mirrorlike deposit on the inside of the bulb near the top and on the glass post supporting the tungsten filament. Because of the time required, the demonstration should be started before the class meets.

**E-212. Sodium Photoelectric Cell.** A sodium photoelectric cell may be constructed by the method of electrolysis described in E-211. A small hole is blown in the bulb with the aid of a fine flame, and a side tube is sealed on. A platinum wire is sealed through the bulb, after which the bulb is carefully exhausted and sealed off. Sodium is deposited on the inside by electrolysis and sublimed to the region surrounding the platinum-wire cathode, by heating the deposit in a Bunsen flame, using a sheet of asbestos

\(^1\) For further details, see R. C. Burt, *Rev. Sci. Instruments*, 11, 87, 1925.
paper to protect the end of the bulb, and cooling the area around the cathode with a stream of air. An opening in the sodium film for the admission of light is made by applying the tip of a flame to the spot where the opening is desired. (See A-91 and related experiments for the use of this cell.)

**E-213. Mass of Sodium Atom Determined by Electrolysis.** A good value of the mass \( m \) of a sodium atom may be obtained from the electronic charge \( e \), the valence \( n \), and the quantity of electricity \( Q \) passed through the sodium electrolytic cell (E-211) if the mass \( M \) of the sodium deposited is determined with care. For the number of atoms passed through the glass is \( N = Q/ne \). Hence the mass of each atom is \( m = M/N = Mne/Q \), where \( e \) and \( Q \) are, of course, expressed in the same kind of unit. The valence \( n \) is 1 in the case of sodium.

The bulb is heated with a flame to remove moisture from the glass and to oxidize any readily oxidizable material on the threaded base of the bulb. It is allowed to cool and is then weighed. It is put into the sodium nitrate, the sodium is deposited by a steady measured current for an hour or more, and the bulb is removed, allowed to cool, then washed and dried. It is weighed again, and the gain in mass is the mass of the sodium deposited.

Other atomic masses may be found by electrolysis in the same manner, but in most experiments great inaccuracy is introduced by loss of electrolyzed metal. In this experiment, the metal is enclosed in a protecting glass envelope.

**E-214. Electrolytic Rectifier.** A saturated solution of sodium bicarbonate fills a glass jar. Electrodes of aluminum and lead, each about 16 cm\(^2\) in area and about 10 cm apart, are connected in series with a d.c. ammeter and an a.c. ammeter to an a.c. line. A potential divider controls the current (Fig. 261). The ratio of average value of unidirectional current to effective value of alternating current is about 0.6. The resistance of the cell to a direct current from lead to aluminum in the electrolyte is about 5 ohms, while the resistance in the opposite direction is about 50,000 ohms, due, probably, to the formation of a layer of hydrogen on the lead.
ELECTROMAGNETIC INDUCTION

E-215. Direction of Induced Electromotive Force. A straight copper wire is connected to the lecture galvanometer and is moved rapidly across the field between the poles of a strong electromagnet. A deflection of the galvanometer results. The relation between direction of motion, direction of field, and direction of induced current may be analyzed in accordance with the well-known rules.

E-216. Induced Current from Relative Motion of Magnet and Coil of Wire. Wind a coil of 100 or more turns of No. 30 copper wire on a wooden spool having a central hole large enough for the introduction of a bar magnet. Determine the relation between galvanometer deflection and direction of current with a dry cell (and protective resistance) in order to verify the direction of induced current when the coil is connected to the galvanometer. Move the north end of the magnet toward and away from the coil, and note that an emf is induced in the coil each time the magnet is moved but not when it is at rest. Repeat the operation with the south end of the magnet. Hold the magnet fixed while the coil is moved (motional emf); turn the coil through 180°, and again move it toward and away from the magnet. Finally pass the magnet through the coil. These experiments will verify the general principle that an emf is induced whenever there is a change in the number of lines of force passing through the coil and that the magnetic field of the current generated opposes the motion producing it.

E-217. Dependence of Induced Electromotive Force on Number of Turns. Coils 5 cm in diameter and having 1, 2, 5, 10, and 15 turns are wound from a single length of No. 18 copper wire, and each coil is bound with thread. When a strong cobalt-steel bar magnet is thrust into the coils successively, with as nearly constant speed as possible in each case, the emf induced is shown to be proportional to the number of turns in the coil. If the magnet is thrust into two coils held face to face, the emf induced is the algebraic sum of the emf’s induced in the separate coils, the signs depending upon the sense of the windings. Thus when the 10-turn and 15-turn coils are used together, they will have the effect of a 5-turn or a 25-turn coil, depending upon the sense of winding.
If both poles of a horseshoe magnet are thrust into a coil connected to a galvanometer, no deflection occurs; thus the equality of poles is shown. However, if the magnet straddles the coil so that only one of its poles enters the loop, a large deflection of the galvanometer results.

**E-218. Motional Electromotive Force.** A motional emf is induced in a wire of length \( l \) moving with velocity \( v \) in a magnetic field \( B \). When both \( l \) and \( v \) are perpendicular to \( B \), this emf is given by \( e = J B \cdot v \cdot dl \). The wire \( A \) (Fig. 262), 6.5 cm long, is perpendicular to the magnetic field of the bar magnet \( NS \). It is attached to a wood or fiber disk \( E \), which is free to rotate about an axis coincident with the axis of the magnet. Strips of spring-temper phosphor bronze are soldered to the ends of \( A \) and make sliding contact with two rings, \( C_1 \) and \( C_2 \), of copper wire soldered to brass screws in the fixed support \( D \). The disk \( E \) and a pulley \( G \) are fastened to a piece of brass tubing that turns on a second tube supported by \( D \) and another support \( F \). Collars of copper wire are soldered near the ends of the inner piece of tubing to prevent end play. The copper rings \( C_1 \) and \( C_2 \) are connected to a galvanometer arranged to measure to about 0.5 mv.\(^1\)

When wire \( A \) revolves about the magnet, a motional emf induced in \( A \) will be shown by the galvanometer. In a trial experiment, the magnet was 38 cm long, and its magnetic moment was \( 42 \times 10^3 \) cgs units. The center of \( A \) was 6 cm from the center of the magnet, and the angular speed of \( A \) was about 820 rpm. In this case, the motional emf was about \( 0.24 \times 10^{-3} \) v.

To demonstrate that the rotation of the magnet has nothing to do with the emf induced in \( A \), the magnet is supported in bearings made by shrinking a brass endpiece \( P \) over each end of the magnet and drilling these endpieces to form cone bearings. Steel screws turned or filed to points at their ends pass through supports attached to the base of the apparatus and fit into cone bearings. One of the endpieces may be grooved to take a belt. Thus both the magnet and the wire may be rotated simultaneously, either in the same or in opposite directions, or either may

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be kept fixed while the other is rotated. In no case does rotation of the magnet affect the emf induced in $A$; i.e., the field of the magnet is fixed whether the magnet itself rotates about its own axis or not.

If a brush (not shown in Fig. 262) is provided for making contact with the magnet while the latter is being rotated, the emf induced in the material of the magnet itself may be demonstrated. One terminal of the galvanometer is connected to the steel pivot at one end, and the other terminal is connected to the brush. The magnitude of the induced emf for a definite speed of rotation of the magnet depends upon the total flux through the magnet at the point of contact with the brush. If the brush is moved along the magnet while the latter is rotating at constant speed, the galvanometer readings will indicate the distribution of magnetization.

**E-219. Current Induced when Change in Magnetic Flux Is Caused by Changing Electric Current—Faraday's Experiment.**

Two coils of wire are wound on an iron ring. The split toroid (E-96) is suitable for the present demonstration. One coil (secondary) is connected to the lecture galvanometer in series with whatever resistance may be necessary to keep deflections on scale. The other coil (primary) is connected to a battery with a key in the circuit. When current is started in the primary winding, a ballistic deflection of the galvanometer is obtained, and when the primary circuit is opened, the ballistic deflection is in the opposite direction. The second deflection is likely to be less than the first because of the large flux remaining in the iron after the magnetizing current has been reduced to zero. That this is the case may be shown by observing the large ballistic deflection obtained when the two halves of the toroid are separated after the magnetizing current has been stopped.

**E-220.** Two similar coils of wire each having several hundred turns are placed side by side. One (the secondary) is connected to the lecture galvanometer, the other (the primary) to a battery controlled by a potential divider, whereby the current through the coil is continuously variable (Fig. 263). A current is induced in the secondary so long as the current in the primary is changing.
If the slider of the potential divider is moved uniformly, a steady galvanometer deflection may be maintained for many seconds. Its magnitude will depend upon the rate of change of current in the primary and not upon the total current. Reversing the motion of the slider of course reverses the direction of induced emf. An iron core increases deflections.

**E-221. Current Induced When Change in Magnetic Flux Is Caused by Change in Magnetic Circuit.** Two similar coils are connected to the galvanometer and battery as in E-220. They are set parallel to one another about 5 cm apart. A steady current is maintained in the coil connected to the battery. When a rod of soft iron is pushed through the centers of the two coils, deflection of the galvanometer shows an induced current. When the soft iron is withdrawn, an induced current occurs in the opposite direction. A rod of copper or of brass produces no effect. When the separation of the coils is changed, by moving them together or apart, a current will be induced in the coil connected to the galvanometer.

**E-222. Earth Inductor.** A rectangular wire loop of a single turn about 1.5 m wide and 6 m long (Fig. 264) is made by attaching the ends of the loop to strips of wood with double-pointed tacks. Its leads are connected to the lecture galvanometer. The demonstrator and a student hold the loop horizontal and then quickly turn it over through 180° so that it cuts the vertical component of the earth’s field. With an ordinary wall galvanometer not designed for ballistic work and in a latitude of 20° or more, the throw may be several scale divisions. If the galvanometer has a damping turn attached to its moving coil, it should be removed for the present experiment.

A large flexible loop of many turns of wire connected to the galvanometer likewise produces a deflection when it is suddenly collapsed in the earth’s magnetic field.

A long flexible wire is connected to the lecture galvanometer and swung like a skipping rope. Its motion in the earth’s
magnetic field induces an alternating current of low frequency, which the galvanometer will follow if its period is short enough.

A commercially available earth inductor may be shown. This device is a coil of known area and known number of turns that can be rotated rather quickly through 180° by a spring. When the coil is connected to a calibrated galvanometer, the ballistic deflection produced by a half turn of the coil may be used to determine the absolute value of the vertical or horizontal components of the earth’s magnetic field. The values of these two components are proportional to the respective galvanometer deflections.

**E-223. Earth-inductor Compass.** A circular coil of several hundred turns of wire may be arranged in bearings so as to turn continuously about a diametral axis. The ends of the coil are connected to two commutator segments on which stationary brushes make contact. Thus the coil is essentially a direct-current generator free to run in the earth’s magnetic field. The brushes are connected to the lecture galvanometer. While the coil is rotating at constant speed (motor driven), its axis is turned to show that when it is in the magnetic meridian no deflection occurs, whereas when the axis is east and west, deflection is maximum. The direction of deflection depends, of course, upon the sense of rotation with respect to the field.

**E-224. Magnetization of Iron Bar in Earth’s Field as Shown by Induction Effects.** Around the center of a soft-iron bar, 1 ft long and 1 in. in diameter, put a coil of about 600 turns, connected to the lecture galvanometer. With the bar in an east-west position, hammer it with a wooden mallet. There is no response in the galvanometer. Then turn the bar parallel to the earth’s field, and hammer again rather gently; a deflection will occur. Pound harder, and get increased deflection, showing increased magnetization. Turn the bar to the east-west direction again, and on repeated taps the magnetism disappears, giving a galvanometer deflection in the opposite direction. Compare with E-80.

**E-225. Induced Current in Metallic Disk—Eddy Currents.** The Barlow’s wheel apparatus described in E-136 may be used for demonstrating induced current. The axle of the copper disk and the pool of mercury are connected to the lecture galvanometer. The disk is rotated by hand, and the galvanometer deflection shows the presence of an induced emf. The direction
of this emf should be determined from the galvanometer deflec-
tion and used to check the dynamo rule. Some models of this
apparatus are so designed that the disk may be lifted from its
position between the poles of the permanent magnet. In this
case, the galvanometer is disconnected, the axle and pool of
mercury are connected by a wire of low resistance, and the disk is
set into rotation while out of the magnetic field and is then
lowered into contact with the mercury to show the magnetic
braking effect resulting from induced eddy currents.

E-226. Arago's Disk. A magnet is suspended by a thread with
its center above the center of a copper disk on a vertical shaft.
When the disk is rotated in the field of the magnet, the induced
eddy currents exert a torque on the magnet, causing it to rotate.
A sheet of glass inserted between disk and magnet prevents
spurious effects from air currents. Conversely, a rotating
magnet causes a torque on a copper disk—the principle of the
automobile speedometer.

E-227. Magnetic Brake. The damping effect of eddy currents
may be shown by arranging a heavy copper disk so as to swing
as a pendulum between the poles of an electromagnet. With no
current in the windings of the magnet, the pendulum swings
freely. If the switch is closed just before the edge of the disk
enters the field, the pendulum is stopped abruptly by the damping
effect of the eddy currents. If a similar disk in which several
parallel slots have been cut is swung through the magnetic
field, the effect of the slots in reducing the eddy currents is shown by
the decreased damping.

A silver half dollar released between the poles of a strong
electromagnet falls through the field with surprisingly low
acceleration. (Project.)

A ring of heavy copper on a bifilar suspension may be swung
through the magnetic field. When the plane of the ring is per-
pendicular to the field and parallel to the direction of motion,
damping takes place in the nonuniform regions of the field.
When the plane of the ring is parallel to the field, no perceptible
damping occurs.

ALTERNATING CURRENT

E-228. Wave Form of Alternating Current. The type of
model generator provided with an escapement whereby the arma
ture is rotated only 10° at a time may be used to obtain a graph of generated emf as a function of angular position of the coil and hence of time. The armature is connected to a ballistic galvanometer whose successive throws are plotted in rapid succession on the blackboard, giving a sine wave that takes shape before the students’ eyes. Thirty-six observations can be taken and plotted in a very few minutes. The wave form can be compared with that shown by a cathode-ray oscilloscope, when the vertical deflection plates are connected to the a.c. supply. The horizontal deflection plates are connected to the sweep circuit.

**E-229. Alternating- and Direct-current Generators.** There are several model generators and motors commercially available,

![Fig. 265.—Model generator. The generator N may be run as a synchronous motor on alternating current of low frequency produced by the commutator C driven by the auxiliary motor M.](image)

but none of them is large enough to be seen by any but a small class. The demonstrator may use the small models in spite of this obvious fault, or he may have a sizable piece of apparatus constructed. The model illustrated in Fig. 265 is a versatile piece of apparatus suitable for showing the principles of generators and motors.

The iron cores for both field and armature consist of 17 laminations of transformer iron, separated by spaces so that the total thickness perpendicular to the planes of the iron sheets is about 5 cm. This arrangement makes the apparatus large enough to be seen easily by the class; it also makes the proportions of the apparatus similar to those in a real machine and reduces the
weight. The over-all height is 28 cm. The field has two shunt coils, each consisting of 2400 turns of No. 25 wire, and two series windings, each having 152 turns of No. 13 wire. The terminals of these coils lead to four binding posts on the fiber end of each frame. When the two shunt coils are connected in series to a 110-v d.c. supply, the current is 0.65 amp, which is more than sufficient for most experiments. The magnetic flux produced by the shunt field on 110 v is estimated at about 35,000 maxwells.

The armature bearings, mounted on a sliding piece of wood, are made to open quickly and easily. Thus the armature, complete with its slip rings and commutator, may be removed from its position between the pole pieces, and another substituted, so that one may show how the various characteristics of the machine depend upon the armature winding.

The armatures are 15 cm in diameter. An armature winding consisting of a single coil of 270 turns of No. 18 wire is suitable for many experiments. A crank on the end of the shaft is provided for turning the armature by hand. When the shunt field winding is connected to a d.c. source and the armature rotated at a speed of 4 or 5 rps, the output is sufficient to light two 4.5-v lamps in parallel. The commutator brushes or the slip-ring brushes may be connected to a galvanometer with the proper combination of resistances for showing the directions and magnitudes of the induced emf's as functions of the angular position of the armature when it is turned slowly. To indicate angular position, a pointer traveling over a circular scale may be fixed to one end of the shaft.

Each armature is provided with slip rings for use as an a.c. generator and with commutator segments for use as a d.c. generator. Hand rotation may be used during the demonstration of the a.c. and d.c. emf's generated. If the armature is driven by a motor at a higher speed, some change in the combination of resistances used with the galvanometer may be necessary.

The effect of changing the position of the brushes on the operation of both motors and generators may be demonstrated.

With either the small commercially manufactured model machine or the larger specially constructed model described, the wave form of the alternating current may be shown by an oscilloscope. A phonoscope (S-77) driven with a standard telephone receiver makes a good demonstration oscilloscope. The receiver
Electromagnet is connected to the slip rings of the model generator, and a suitable series resistance is included if necessary.

The machine may also be run as a low-speed synchronous motor. The field is then excited by direct current. A low-frequency alternating current is obtained from a d.c. source using a commutator $C$ that may be rotated at low speed by an auxiliary motor $M$ (Fig. 265). The commutator reverses the direction of current once each half revolution (see also A-23).

**E-230. Counter Electromotive Force in a Motor.** A lamp or a bank of lamps in parallel is connected in series with a motor. Either a d.c. or an a.c. motor may be used, and the number of lamps depends upon the no-load current required by the motor for operation at nearly normal speed. With no load on the motor, the lamps do not glow, on account of the counter emf generated by the motor itself. When a friction clamp is applied to the motor pulley, the counter emf is decreased because the speed of the armature is decreased, and the lamp filaments glow.

**E-231.** In another method for showing counter emf, the armature of a shunt-wound d.c. motor is disconnected from the line while running at full speed and quickly connected to a voltmeter or to the lecture galvanometer arranged as a voltmeter (E-154). The motor field is left connected to the supply line. A d.p.d.t. switch is useful for accomplishing the change quickly. The voltmeter indicates the counter emf, which decreases as the motor slows down. If braking action takes place too rapidly, a flywheel may be added.

**E-232. Simple Speed Control for Small Direct-current Motors.** In many lecture experiments, as, for example, the siren disk (S-120) and the mechanical stroboscope (S-49 and S-81), it is desirable to control the speed of a motor over a wide range. The arrangement shown in Fig. 266 is simple and effective. The field and armature terminals of a $\frac{1}{2}$-hp, d.c. motor are connected at $F$ and $A$ respectively by means of a four-prong radio socket and base from an old tube. The direction of rotation may be reversed by turning the d.p.d.t. switch $R$. The speed of rotation is decreased.

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controlled between 0 and 100 rps by turning the d.p.d.t. switch S and by moving the contact K on V, a rheostat of 200 ohms resistance that serves as a potential divider. The motor runs at normal speed when K is at the left; it runs at higher than normal speed when K is moved toward the right and S is in the position shown. When S is reversed, then moving K toward the right reduces the speed below normal. If the motor is to be run only at normal speed, the switch C may be opened to stop loss of power in V.

E-233. Synchronous Motor. If an a.c. dynamo is available, it may be run in either direction as a synchronous motor by supplying alternating current to the armature coils while the field magnets are being excited with direct current. The motor will run at only one speed, namely, that at which it would have to be run as a generator to deliver a current of the same frequency as that supplied to it. The armature must be brought up to synchronous speed by external means; for example, by pulling on a cord wrapped several times around its pulley.

E-234. Exploring an Alternating Magnetic Field. An exploring coil of many turns of No. 30 wire is wound on a small frame and connected to a 6-v automobile lamp. An electromagnet with a laminated iron core and an open magnetic circuit, like that described in E-229, is operated on alternating current. The exploring coil is held in various locations in the open part of the magnetic circuit. The brightness of the lamp filament depends upon the induced emf and therefore indicates the effective value of the magnetic field in the region in which it is placed. Mystifying effects may be produced by concealing the a.c. magnet under the lecture table.

E-235. Transformer. A demonstration transformer can be built up from materials easily obtainable. A bundle of iron wires 6 cm in diameter and 30 cm long is wrapped with friction tape and mounted vertically on a wooden base. The primary winding is a circular coil 8 cm in diameter with 200 turns of No. 14 wire, held together with tape. It is slipped over the core and held about 10 cm above the base on a wooden support. It may be connected directly to the 110-v, 60-cycle line without danger of overload. Several secondary coils are provided, having different numbers of turns wound on annular wooden frames. The ends of the coils may be connected to binding posts on the frames. A 40-w, 110-v
lamp will be lighted if it is connected to the terminals of a secondary consisting of 200 turns of No. 24 wire. When the secondary is brought near the end of the iron core, the lamp filament will begin to glow; and when the secondary is slipped over the core near the primary, the lamp will operate at nearly normal brightness. A step-down transformer can be illustrated with a secondary of 12 turns of No. 18 wire in series with a 6-v lamp. A secondary of 400 turns of No. 24 wire connected to a 220-v lamp illustrates a step-up transformer.

E-236. Jumping Ring. An aluminum ring about 7.5 cm in inside diameter, 14 cm outside, and 0.4 cm thick is laid on top of the primary (E-235). When the switch is closed, the electromagnetic repulsion is enough to throw the ring high into the air, giving the demonstrator an opportunity to show his ability as a catcher. A student may be invited to attempt to hold the ring over the core. It is evident to the class that considerable force

![Image](image-url)
is required; and it is soon evident to the student that the ring grows uncomfortably hot. A split ring shows no effect. A ring cooled in liquid air shows an augmented effect due to increased conductivity (H-104).

**E-237. Large Currents in Step-down Transformer.** The heating effect of the large currents induced in a secondary of a single turn may also be shown by causing water to boil in a ring-shaped trough (Fig. 267) resting on the primary. The cross section of the trough is about 1 by 1 cm; it is made of sheet copper about 1.5 mm thick. The trough is enclosed, and a small steam vent is provided, which may be closed with a cork if the element of surprise is desired. The water in the trough should not be allowed to boil away, since the soldered joints would then quickly melt.

**E-238. Autotransformer.** A single coil of 400 turns of No. 18 wire, tapped at every 50 turns, may be used on the same iron core (E-235) to illustrate an autotransformer. The 110-v supply is connected across 200 turns. One terminal of a 110-v lamp is then connected to the beginning of the winding; when the other terminal is connected to the second tap, the lamp will be provided with 55 v; the fourth tap will furnish 110 v, and the lamp will glow normally. The higher taps give voltages in excess of 110 in steps of 27.5 v. These higher voltages may be shown by overloading the lamp or (more economically) by connecting two lamps in series.

Autotransformers are now available in sizes suitable for laboratory purposes. In one of these, the potential difference is 0.5 v between successive turns, and a sliding contact enables one to control the output voltage to the same degree as with a potential-dividing resistance. The losses in the autotransformer are very much less than in a resistance-type voltage-regulating device. With such a transformer designed for an input a.c. voltage of 110 v, the output voltage may be controlled between 0 and 260 v. A 110-v lamp may be used as the load, and it may be operated at various voltages from 0 to 125 v. The single lamp may then be replaced by two such lamps in series, this combination being operated at voltages up to 260 v. A 10-w, 110-v lamp may be operated for a short time at the full voltage of such an autotransformer with obvious increase in brilliance. The life of the lamp is short at such overloads, but the experiment is of value
in showing not only the change in brightness but also the change of spectral distribution of energy (with consequent change of color) at the higher temperature of the filament (L-99).

**E-239. Dissectible Transformer—Electric Welding.** A transformer is more efficient if it has a closed magnetic circuit. Such a transformer, which can be used for the experiments described in E-233 and E-234 and for others as well, consists of two L-shaped laminated iron cores with interchangeable coils. The production of large currents as in the step-down electric-welding transformer may be demonstrated by using a secondary of only one or two turns of heavy copper cable connected to a short piece of heavy galvanized iron wire, about No. 6. When 110-v or 220-v alternating current is applied to the primary, the iron wire quickly becomes white hot, the zinc coating takes fire, and the wire burns in two.

**E-240. Toy Transformer.** Many types of small step-down transformer are commercially available. These usually have several separate windings from which wires lead to binding posts, thus making it possible to use different transformation ratios. Their design is more like that of commercial transformers than of those described in the preceding sections. To show the voltage transformation ratio, one may attach a 110-v lamp in parallel with the input line and a 6-v automobile lamp to the proper output terminals. Both lamps will operate at nearly normal brightness. To show the relation between the currents in the two windings, one may put a low-candle-power automobile-taillight lamp, which operates on about 0.5 amp, in series with the input side and connect across the 6-v terminals a piece of fuse wire that melts at about 10 amp. The input voltage is gradually increased by a potential divider or variable autotransformer. The fuse wire melts when the small lamp bulb is not much above normal brightness; thus an indication is given of the ratio of the currents in the two windings. At the moment when the fuse wire melts, the brightness of the small bulb decreases because of increased impedance of the primary in the absence of the large secondary current (see E-241 and 242).

**E-241. Reaction of Secondary Circuit on Primary.** Connect a 100-w lamp in series with the primary of a transformer, and show that when the a.c. supply is connected, the current is limited by the reactance of the primary when the secondary circuit is
opened, so that the lamp does not light. However, if the secondary circuit is closed through a variable resistance, the reactance of the primary diminishes, and the lamp increases in brightness as current in the secondary circuit increases.

**E-242.** A step-down transformer is made with a primary of 320 turns and a secondary of 200 turns. The coils are placed coaxially with the primary connected to a 110-v a.c. line with a 110-v lamp in series; the secondary circuit has a 6-v lamp with a shunting switch (Fig. 268). With the shunting switch open, the circuit is closed through the primary, and the 110-v lamp lights. A bundle of iron wire is then inserted through the two coils as a core; the 110-v lamp goes out, and the 6-v lamp lights. But when the shunting switch is closed, the 6-v lamp is short-circuited, and the 110-v lamp comes on again, because of the reaction of the large secondary current upon the impedance of the primary.

**E-243. Magnetic Shunt.** An E-shaped laminated iron core has coils of equal numbers of turns around two adjacent legs. A laminated iron yoke is provided to bridge either two or three of the legs (Fig. 269). The coil on the outer leg is connected to a source of alternating current, and the center coil to a lamp that glows normally when the yoke covers only the first two legs. But when the yoke is pushed across to make contact with all three legs, there is a pronounced drop in brilliancy because a large fraction of the magnetic flux now passes through the third leg, which is a magnetic shunt. The magnetic circuit is analogous to the electric circuit: the terms magnetomotive force (mmf), flux, and reluctance correspond respectively to emf, current, and resistance.

**E-244. Use of Transformers for Transmission of Energy at High Voltage.** The most extensive commercial use of transformers is in the transmission of energy over great distances at high voltages for the purpose of reducing line losses. To demon-
strate this use, a model transmission line may be arranged as in Fig. 270. A line made of No. 30 nichrome wire 2 m long has a resistance of about 80 ohms. At each end of the line there is a 110-v, 60-w lamp, $R_1$ and $R_2$. When both d.p.d.t. switches $A$ and $B$ are closed in position 2, the lamp at the output end of the line will operate at about 80 v, because of $IR$ drop in the line. Voltages may be checked with a voltmeter. When both switches $A$ and $B$ are closed in position 1, the 110-v supply is stepped up to 750 v by a transformer $T_1$ of about 0.2-kva rating. The energy is transmitted at high voltage to the output end of the line, where a similar transformer $T_2$ steps it down. The lamp at the output end will then operate within 5 v of its normal voltage rating and consequently practically at its normal brightness. Transformers of the rating suggested may generally be purchased at low cost from companies dealing in used electrical equipment. With well-designed transformers, the no-load magnetizing current is so small that current in the high-tension side of the transformer at the output end of the line when switch $B$ is in position 2 is negligible, especially since the potential drop across the high-tension side of $T_1$ is then much less than the rated value for this winding. The demonstrator must take care not to have switch $A$ in position 1 when switch $B$ is in position 2, since lamp $R_2$ would then be burned out.

**E-245. Induction Coil.** One or more induction coils may be exhibited as applications of the transformer principle for the production of high voltage from a d.c. source. If the spark takes place between spheres of about 1-cm diameter, the potential difference may be estimated from the approximate value of 30 kv per cm. If points are used, this value is much less. Sheets of paper or cardboard may be punctured by the spark. Brush discharges from points may be seen in a darkened room. The induction coil may be used for charging an electroscope or a condenser. One of the secondary terminals is connected to one plate of a parallel-plate air condenser. A spark is passed to the
other plate by bringing the other high-tension wire within sparking distance. The sign of the charge may be tested with the aid of a proof plane (E-9). Where the induction coil is provided with a condenser across the interrupter, the charge is always of one sign. Reversing the terminals on either primary or secondary changes the sign of charge.

The unidirectional nature of the discharge may be demonstrated by comparing the appearance of a glow discharge tube (A-12) when operated first on the induction coil, then on a high-voltage a.c. transformer (with protective series resistance in the secondary circuit). Transfer from one source of potential to the other may be made quickly by a d.p.d.t. switch.

An automobile spark coil may be used to produce a spark across the gap of an automobile spark plug. The primary circuit may be made and broken with a single-pole switch, as is done in the distributor of an automobile.

If an old induction coil is available, it may be possible to show the students more about its construction by taking it apart. The condenser, interrupter, iron in the open magnetic circuit, and the two windings are of interest.

**E-246, Telephone and Radio Transformers.** The extensive use of transformers for technical, industrial, and laboratory purposes makes it desirable to show some of the commercial designs. Telephone transformers usually have rather low transformation ratios, 1:1 and 1:3 being common. Radio transformers (audio-frequency) may have transformation ratios up to 1:28, this value obtaining in one designed to have its primary in a single-button microphone circuit with its secondary connected to the grid of a triode.

If the secondary of such a transformer is connected to the case and leaves of an electroscope, while its primary is operated on about 20 v alternating current, the secondary voltage is sufficient to deflect the leaves of the electroscope.

An alternative demonstration is to connect the secondary of an audio-frequency transformer to the terminals of a high-impedance loudspeaker with the primary in series with a telephone transmitter and a 3-v source of direct current. The handle of a tuning fork is held against the transmitter case or the diaphragm. The loudspeaker reproduces the sound of the tuning fork. The operation may be improved if a vacuum-tube amplifier is used, in
which case a dynamic loudspeaker whose impedance is matched to the output stage of the amplifier may be used.

**E-247. Speed of Alternating-current Motors.** Mount on the end of the shaft of an induction motor a white paper disk with a radial India-ink arrow. Illuminate the disk with stroboscopic light from a neon lamp on 110-v alternating current, and observe its increased "slip speed" as the load upon the motor is increased by means of a friction clamp. A synchronous motor observed in the same way shows only a phase shift.

**E-248. Rotating Magnetic Fields.** A three-pole rotating-field magnet for use on three-phase alternating current may be constructed from stock transformer punchings (Fig. 271). The magnetic circuit is about 36 cm² in cross-sectional area, and the distance from one pole through the iron to either of the other poles is about 62 cm, while the air gap is 10 cm. About 150 turns of No. 14 wire are required for each winding. The three coils are delta-connected and used on a 110-v, three-phase a.c. line, in which case the current in each of the three wires of the line is about 8 amp.

To show the rotation of the field, the rotor from a small squirrel-cage induction motor is mounted on pivots in the field. It should not be allowed to operate at an angular speed more than twice that for which it was designed. The direction of rotation may be reversed by interchanging any two phases. A saucer or a watch glass may be laid on the pole pieces, and a silver dollar or a disk of copper or aluminum stood on edge in it. If the coin or disk is started spinning about its vertical diameter, it will continue to rotate. A metal cylinder or tin can hung by a thread between the poles will also rotate. A blown egg, electroplated for strength and filled with iron filings, will start spinning in the field and will stand on end.
E-249. Remove the rotor from a three-phase induction motor of about \( \frac{1}{2} \) hp. Place a small steel ball inside the field winding. When the motor is connected with the three-phase supply mains, the ball will travel around a vertical circle. The speed is rather low compared with any speed approaching synchronism with the rotating field, so that the motion is easily observed. (Project.)

E-250. A simpler device for demonstrating a rotating magnetic field is illustrated in Fig. 272. A circular coil of 200 turns of No. 18 wire is wound on a wooden form 25 cm in diameter; after winding, it is slipped off the form and wrapped with friction tape to hold the turns in place. The wooden form is then turned down so that its radius is less than that of the first coil by the thickness of that coil. A second coil is wound with the same number of turns, of such a diameter as to fit inside the first. A third coil is similarly made to fit inside the second. The three coils are then mounted on a wooden base, the planes of the coils being vertical and making angles of 120° with each other. The coils are delta-connected to a 110-v three-phase line. The rotor is an empty tin can 12 cm in diameter and 12 cm high (a 1-lb tobacco can is satisfactory). The top is soldered on the can, and brass disks are soldered to the center of the top and the bottom. These disks are drilled to provide cup bearings. Steel pins held by a wood or fiber frame are sharpened to points to serve as cone bearings. The axis of the can is set vertical so as to coincide with the common diameter of the three coils. A rheostat should be included in each of the supply lines so as to limit the current through each coil to 8 amp; with this current, the coils will not overheat. The speed of the rotor will be high.

E-251. A rotating magnetic field may likewise be made from a two-phase a.c. supply by using two coils with their planes at right angles to each other. Three-phase current may be transformed into two-phase, or vice versa, by two T-connected autotransformers. If three-phase current is supplied to the points A, B,
and C (Fig. 273), then one phase of a two-phase output is obtained from A and B, and the other from D and E. The number of turns between A and B equals the number between D and E, but the ratio of the number of turns between D and C to the number between D and E is 0.87 (more accurately \( \frac{1}{\sqrt{3}} \)).

Two-phase alternating current may be obtained from single-phase alternating current by running the two coils in parallel from the single-phase supply and inserting a large inductance in series with one of them.\(^1\)

**COILS AND CONDENSERS**

**E-252. Self-inductance.** A large electromagnet is connected in parallel with a lamp. When this combination is connected to a source of direct current, the lamp glows. The lamp should be operated somewhat below its normal voltage. When the switch is opened quickly, the self-induced emf in the coil will be larger than was the potential drop across the lamp while the switch was closed. The lamp will therefore flash brightly before going out. The lower the power rating of the lamp, the greater the contrast. With a sufficiently large magnet, it is even possible to burn out a 10-w lamp by this inductive pulse. Slow opening of the switch makes the effect less pronounced.

**E-253.** The coils of an electromagnet, for example the shunt-field winding of a motor or generator operating on a potential drop greater than 75 v, are connected in parallel with a neon lamp having two semicircular plane electrodes, again in series with a d.c. supply. When the switch is closed, the lamp glows, but the glow surrounds only one of the electrodes. When the switch is opened, the induced emf makes the lamp glow for a short time, but the glow surrounds the electrode that was formerly dark. This is because the terminal of the coil that was at the higher potential during steady current will be at the lower potential when the switch is opened. The demonstrator may substitute a rheostat for the inductive winding to show that in this case no induced emf is detectable.

**E-254. High Voltage from Low by Self-induction.** A 4.5-v battery, neon lamp N, and iron-cored choke coil L are connected

\(^1\) For a simple arrangement for showing a rotating magnetic field and the principle of the synchronous motor, see J. J. Coop, *Am. Phys. Teacher*, 6, 37, 1938.
in series (Fig. 274). The choke coil is of the type used in radio power-supply filters, or it may be the primary or secondary of an audio-frequency transformer. When the switch $S$ is closed, a small direct current is established in the choke coil; when $S$ is opened, a momentary flash of one plate of the neon lamp occurs, thus showing that an emf much greater than the applied emf is generated by the decaying current. The whole circuit may be mounted on a small board for student operation, with a push button serving for the switch $S$.

**E-255. Effect of Inductance on Wheatstone-bridge Measurement.** A Wheatstone bridge of any type is used to measure the resistance of a coil having large inductance. Almost any electromagnet is suitable. Two keys are provided—one for the battery and the other for the galvanometer circuit. The battery circuit is closed first; and after the current has had time to reach a steady value, the galvanometer circuit is closed, and the bridge balanced. The galvanometer circuit is opened first, then the battery circuit. Next the battery and galvanometer circuits are closed at the same time. The galvanometer will show a large deflection because of the counter emf of self-inductance in the coil while the current through it is increasing. If after the current has reached its steady value the battery circuit is opened, the galvanometer circuit remaining closed, the galvanometer will be deflected in the opposite direction. This behavior may be contrasted with that of a bridge containing only resistance. A shunt should be used to protect the galvanometer from damage.

**E-256. Electromagnetic Inertia.** Bend a copper wire to form an $\Omega$-shaped loop, almost closed (Fig. 275). Discharge a Leyden jar through the loop. The discharge jumps the air gap rather than pass through the low-resistance copper conductors, because the impedance of the loop to a current surge is great compared to the impedance of the air gap.

**E-257. Time Required for Rise of Current in a Circuit Containing Self-inductance.** For this experiment, an electromagnet with a ratio of self-inductance in henrys to resistance in ohms
greater than 2 is required. Almost any large electromagnet with closed magnetic circuit meets this requirement. \( L_1 \) and \( R_1 \) represent the self-inductance and resistance of the coil (Fig. 276). \( R_2 \) is a rheostat arranged for fine regulation of the current. In parallel with the fixed resistor \( R_3 \), there are a neon lamp and sufficient dry batteries B (radio B batteries) to furnish about 1 v less than the potential difference needed to make the lamp glow. A neon lamp requires a very definite minimum potential difference to initiate the discharge, but once started it will continue to operate at a potential difference much below this minimum starting value. Since the dry batteries furnish almost enough potential difference, it follows that a small additional \( IR_3 \) drop will cause the lamp to operate. It also follows that \( R_3 \) may be made small relative to \( R_1 \) with the result that the rate of increase of \( I \) will thereby be kept as low as possible. A three-pole switch is provided to stop the current through the neon lamp when the main circuit is opened.

The switch is closed, and \( R_2 \) is adjusted carefully until the lamp glows. The switch is then opened. The next time the switch is closed, the neon lamp will not immediately glow because of the time required for the increase of \( I \). An adjustment of battery voltage and \( R_2 \) may easily be made so that the additional \( IR_3 \) drop required to start the lamp will not be sufficient until \( I \) has risen to within 0.5 per cent of its final value. The lag between the closing of the switch and the flashing of the lamp may be made as much as 5 sec.

An approximately noninductive resistor having a value equal to \( R_1 \) should be substituted for the coils with the aid of a d.p.d.t. switch. When this substitution is made, the neon lamp glows as soon as the switch is closed. If the demonstrator does not wish to use the sound of the switch to indicate the zero time or if the switch is not visible to the class, he may connect a lamp of suitable voltage rating across the d.c. terminals of the three-pole switch to flash on when the switch is closed.
E-258. Inductive Reactance. A solenoid 40 cm long and 3.5 cm in diameter is wound with 1800 turns of No. 18 wire. The terminals of the coil are connected to the 110-v a.c. supply in series with a 200-w lamp. The lamp operates at nearly normal brightness until a bundle of iron wires about 60 cm long and 3 cm in diameter is put into the solenoid as a core. The reactance is increased by the iron to such an extent that the lamp filament is reduced to a dull red. Paradoxically, the brightness of a 10-w lamp is not changed so much, because its resistance is large in comparison with the reactance. The contrast between d.c. resistance and a.c. impedance is readily shown by connecting the lamp and coil to the middle pair of terminals of a d.p.d.t. switch. The outer pairs of terminals are connected respectively to the 110-v a.c. and d.c. supplies. Attention may be called to the bright flash occurring at the switch when the d.c. circuit is broken, showing evidence of the large emf of self-inductance (E-252 and 254).

E-259. Current as Rate of Change of Charge. The relationship between the charge on a condenser and the applied voltage is given by $Q = CV$. If the applied voltage $V$ changes (while the capacitance $C$ remains constant), a current is set up proportional to the rate of change of $V$; or $i = \frac{dQ}{dt} = CdV/dt$. This dependence of current upon rate of change of charge of a condenser may be shown by the simple circuit of Fig. 277. The rheostat $R$ is connected across the battery $E$ as a voltage divider. The condenser $C$ (say 4 $\mu$) is connected in series with the lecture-room galvanometer $G$. Whenever the voltage applied to the condenser is changed, a current is indicated by the galvanometer. It is easy to show that this current depends upon the rate of change of $V$, that it reverses in direction when the direction of change of $V$ reverses, and that it is independent of the magnitude of $V$ itself. A radio potentiometer is a convenient substitute for a slide-wire.

E-260. Capacitive Reactance. A 25-w, 110-v lamp is connected in series with a paper condenser of 6-$\mu$ capacitance. When 110-v direct potential is applied, there is no current; but when 110-v alternating potential is applied, the lamp lights. In this case, a voltmeter will show about 50 v across the lamp and about
82 v across the condenser with a line voltage of 110. Unless an electrostatic voltmeter is used, one cannot expect that the square root of the sum of the squares of the two readings will equal the total reading. When an ordinary voltmeter is used, the impedance of the instrument is not sufficiently high in comparison with the resistance of the lamp and the capacitive reactance of the condenser; hence the voltages read by the meter are less than the actual voltages existing before the voltmeter is connected. A phonelescope used as an oscilloscope (E-229) may be connected in series with a suitable resistor for showing the relative phases of the voltage across the lamp and across the condenser. The voltage across the lamp is in phase with the current, while that across the condenser is 90° out of phase. The oscilloscope may be connected to the lamp and then to the condenser successively by means of a d.p.d.t. switch. If the speed of the rotating mirror is properly adjusted and constant, there is no difficulty in detecting the fact that a phase difference of about 90° exists. If two oscilloscopes are available, the two waves may be shown simultaneously on the same screen. A piece of colored glass may be interposed in the path of the light that enters one of the oscilloscopes.

E-261. Condensers in Series and in Parallel. Two 2-μf condensers and a 40-w lamp are connected in series to the 110-v a.c. line. The current is too small to make the lamp filament glow. When the two condensers are in parallel, however, the lamp glows brightly (see also E-68).

E-262. Laws of Capacitance with Ballistic Galvanometer. The proportionality of quantity of charge to voltage applied to a condenser may be shown by charging a condenser successively to several different known voltages and observing the corresponding deflections when the condenser is discharged through a ballistic galvanometer (Fig. 278). If two or more condensers, not necessarily equal, are used, the additive nature of capacitance when condensers are connected in parallel may likewise be shown (E-68). If they are then connected in series, the deflections will be decreased since the effective capacitance is the reciprocal of the sum of the reciprocals of the individual capaci-
tances. In this latter case of series connection, it is instructive to show that each condenser produces the same galvanometer deflection when discharged individually, since the charge on each condenser is the same regardless of its capacitance. From $Q = CV$, this experiment shows that the greatest potential difference must exist across the condenser of lowest capacitance.

**E-263. Charging Time of a Condenser in Series with a High Resistance—Flasher Circuit.** A 4-µf condenser is connected in series with a variable high resistance that may be adjusted to values between 2 and 8 megohms. Several grid leaks connected in series provide a satisfactory variable resistance. A 2-watt, 110-v neon lamp with plane semicircular electrodes is connected in parallel with the condenser (Fig. 279). Connection is made to a d.c. source (generator or B batteries) through a single-pole switch. The condenser will start charging when the switch is closed; and when the potential difference across the condenser terminals has increased to about 80 v, the neon lamp will flash, thus discharging the condenser to about 60 v, the potential difference at which the neon lamp ceases to operate. The cycle is then repeated. By changing the resistance, the number of flashes per minute may be varied widely. The neon-lamp flash is not brilliant, and the room may have to be darkened.

**E-264. Speed of Rifle Bullet by Condenser Discharge.** The speed of a rifle bullet may be measured by allowing a condenser to discharge through a resistor during the time required for the bullet to pass from a point $A$ to a point $B$ a known distance away, and by determining the time from the charge remaining on the condenser after the bullet has passed the point $B$. A strip of tin foil 3 mm wide and 2 cm long is placed at $A$ (Fig. 280), and a similar strip at $B$. When key $K$ is up, condenser $C$ has a charge $Q_0$. When $K$ is depressed, the ballistic galvanometer shows a deflection $\theta_0$ proportional to $Q_0$. If $K$ is up and a rifle bullet cuts the tin-foil strip $A$, then the condenser will discharge through the resistor $R$ until the bullet cuts the strip $B$, at which time the condenser will stop discharging and will have a residual charge $Q$. If $K$ is then depressed immediately, the ballistic galvanometer deflection $\theta$ will be proportional to
The equation that applies is \( Q = Q_0 e^{-\frac{t}{RC}} \), where \( t \) is the time required for the bullet to travel the distance \( d \). Then 
\[
t = -RC \log_e \left( \frac{Q}{Q_0} \right) = -RC \log_e \left( \frac{\theta}{\theta_0} \right)
\]
where \( t \) is in seconds, when \( R \) is in ohms, and \( C \) in farads. The speed \( V \) of the bullet is given by
\[
V = \frac{d}{\left( RC \log_e \frac{\theta}{\theta_0} \right)} = \frac{d}{\left( RC \log_e \frac{\theta_0}{\theta} \right)}
\]

In any particular experiment, the only variables in the above equation are \( V \) and \( \theta \). For rapid computation, it is desirable to plot on coordinate paper a few values of \( V \) against corresponding values of \( \theta \).

The muzzle speed of a bullet from a certain type of .22-caliber rifle is about \( 3.3 \times 10^4 \) cm per sec. If \( R = 4500 \) ohms, \( C = 2 \mu F \), and \( d = 2.2 \) m, then \( t \) will be about \( 6.7 \times 10^{-3} \) sec, and the condenser will lose slightly more than half its original charge during the time required for the bullet to traverse the distance between the tin-foil strips.

The rifle is held in wooden clamps at one end of a board 3 m long. Each tin-foil strip is held between two ebonite rods by brass clips that also make electrical contact with the strip. The rods fit in holes bored in a narrow vertical board attached to the base by shelf brackets. The rifle is sighted first on strip \( B \); after which strip \( A \) is moved into position, about 10 cm from the muzzle. A large block of soft wood or a sandbag may be located just beyond \( B \) to stop the bullet.

**E-265. Combined Capacitive and Inductive Reactances.** The solenoid described in E-258 has a reactance of about 120 ohms on
60-cycle alternating current. The inductive reactance of this coil will be equalled by the capacitive reactance of a set of condensers of total capacitance about 22 \mu F. If a coil with more self-inductance is available, then the amount of capacitance needed is correspondingly less. If a 40-w lamp is connected in series with an inductive and a capacitive reactor, several striking effects may be shown. When the condensers are short-circuited, increasing the inductance decreases the current through the lamp (E-258). When the inductor is short-circuited, increasing the capacitance increases the current through the lamp. Finally, with the capacitance at maximum value, the inductance is gradually increased. The lamp current then increases—just opposite to its behavior when the condensers are out of the circuit. If sufficient inductance and capacitance \( LC = \frac{1}{4\pi^2 n^2} \) are available, the lamp current may be made to reach a maximum for a definite value of inductance, beyond which it again decreases with increase of inductance. Thus the circuit may be made to pass through resonance, in which condition the current is limited only by the resistance of the circuit.

The potential drops across the condensers, the inductor, the lamp, and the terminals of the whole circuit should be measured. The arithmetic sum of the first three will greatly exceed the fourth because of phase differences (see also E-268).

**E-266. Oscillatory Charge of Condenser through an Inductor.**

If a condenser is charged through an inductor, the potential difference between its plates may rise above the applied emf because the charging sets up oscillation.\(^1\) That this is the case may be shown by the circuit of Fig. 281. The voltmeter \( V \) reads the d.c. voltage applied from the potential divider to the condenser \( C \). If switch \( S \) is in position 1 and key \( K \) is pressed, the condenser is charged only through the resistor \( R \). A neon tube \( N \) shunted across the condenser glows only if the applied voltage as read by \( V \) is high enough to strike an arc. Once the arc strikes, the voltage may be decreased considerably without extinguishing the glow discharge. Having determined the necessary voltage for causing \( N \) to glow when \( K \) is depressed, the potential divider is set so that \( V \) reads 10 to 20 V less than this.

value. Depressing \( K \) no longer causes \( N \) to glow, but if \( S \) is turned to position 2, \( N \) will light when \( K \) is depressed, provided that the condenser has previously been discharged by closing the switch \( D \) momentarily. The circuit has "memory"; for if \( N \) is once lighted by depressing \( K \) when \( S \) is at 2, it will not light a second time until the condenser \( C \) has been discharged. If the

![Circuit diagram](image)

**Fig. 281.**—Circuit for showing oscillatory charging of condenser through an inductor.

series resistance \( R \) is increased, a point is reached where the circuit no longer oscillates as it is charged. Best results are obtained if the capacitance of \( C \) is not too large; 0.1 \( \mu F \) or less is suggested. \( P \) is a lamp or other protective resistance, in case \( D \) is closed when \( S \) is in position 1.

**E-267. Oscillatory Discharge of a Condenser.** A condenser \( C \) of 6- to 8-\( \mu F \) capacitance is charged to 200 or 300 v, by depressing key \( K \) momentarily (Fig. 282). Now with switch \( S \) in position 1, the neon lamp \( N \) glows on only one electrode when switch \( D \) is depressed to discharge the condenser through the 10,000-ohm resistor \( R \). But when \( S \) is moved to position 2 and \( C \) is recharged and again discharged, both electrodes of \( N \) glow. In this case, the discharge occurs through an iron-core radio coil \( L \) of approximately 2 henrys inductance.

**E-268.** The secondary of a high-voltage transformer is shunted with several Leyden jars (connected in parallel) and with a spark gap in series with an inductor made of several turns of heavy copper wire. A projection lens casts an image of the spark gap onto a piece of opal glass by way of a plane mirror which can be turned about an axis parallel to the gap. Whenever a
spark passes across the gap and its image is cast upon the opal glass from the rapidly rotating mirror, there appears a "ladder" of bright flashes from alternate sides of the gap, thus giving visual evidence of the oscillatory nature of the discharge. If the Leyden jars are disconnected, the character of the image changes greatly.

**E-269. Phase Relations of Voltages across Elements of Oscillating Circuits.** The circuit with resistance, inductance, and capacitance in series (E-265) is tuned to resonance on a 110-v a.c. line (Fig. 283). A neon lamp is biased with a radio B battery so that when its terminals are connected to any pair of successive terminals, 1-2, 2-3, or 3-4, only one electrode of the neon lamp glows. The intermittent light from the neon lamp falls upon a black disk with a white paper sector, rotated by a synchronous motor. The apparent position of the white sector will depend upon whether the neon lamp is connected across R, L, or C.

For further experiments on resonant circuits, see A-22 to A-40.