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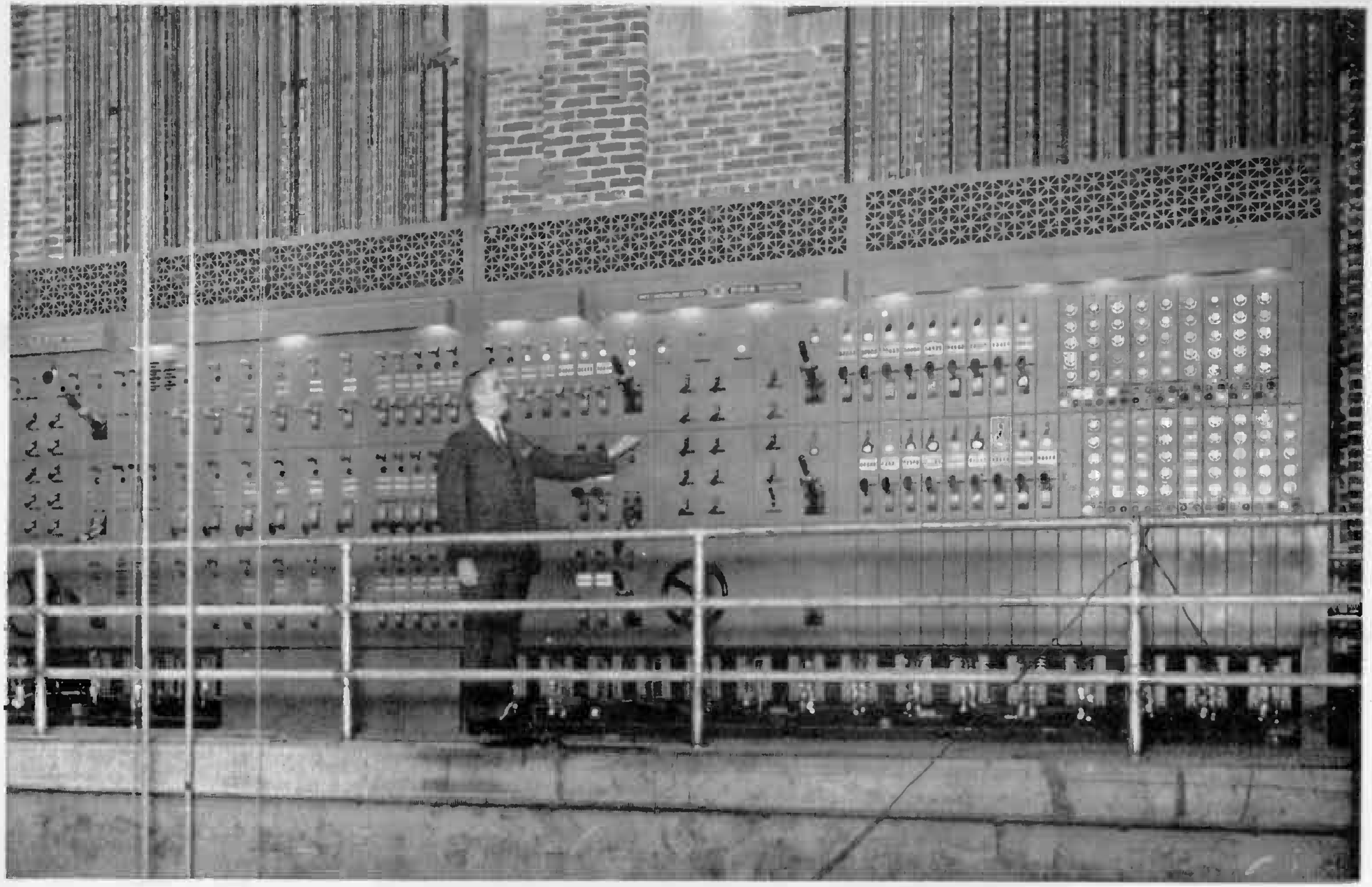
The dynamic speaker being assembled depends on electromagnetic forces for its operation.

Faraday's Discovery of Electromagnetic Induction. The Relation of Electric Current to Magnetism.

VOL. 10, No. 3 *Dewey Classification* R100



Electromagnets operate the switches and relays on this convention hall control panel.
These units distribute the sound currents to broadcast hook-ups.

Courtesy Westinghouse Elec. & Mfg. Co.

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ELECTROMAGNETISM — ELECTROMAGNETIC INDUCTION

A FLOW OF CURRENT PRODUCES MAGNETIC EFFECTS. With the invention of the magnetic compass man made use of a natural force about which he knew little. Since that time, however, steady progress has been made in finding practical uses for magnetic properties. Although the exact nature of magnetism and the medium through which it acts is still unknown we are able to produce magnetism and control its forces as this lesson will explain. From a study of the subject of "magnetism" one learns about the inherent properties of magnets and their effects. The same fundamental laws and characteristics governing magnetic lines of force of a permanent magnet are applied to all cases where electromagnetic lines of force are set up by a movement of electric current.

MAGNETIC EFFECTS ARE ALWAYS SET UP IN THE SPACE MEDIUM SURROUNDING A FLOW OF CURRENT. A stream of negative electrons moving from one place to another through any path which acts as a conducting medium is considered to be a flow of current. This is in accordance with the "Electron Theory." Therefore, a movement of electrons or current flow through a conductor (for example a wire) sets up in the region about that conductor electromagnetic lines of force which are in the form of a magnetic whirl beginning at the center of the wire and extending an infinite distance outward into space.

A review of the terms by which magnetic units are known and the origin of these terms are presented in the following paragraphs. You will notice from the explanations that magnetic units are named after some of the earlier investigators of electricity and magnetism. Two of these terms, the "Oersted" and the "Maxwell," have not as yet been officially recognized by scientific societies.

The MAXWELL, named after James Clerk Maxwell, a Scotch physicist, who expounded a mathematical theory of the existence of electromagnetic waves in the spectrum, is the unit of magnetic flux and represents the number of lines of force passing through each square centimeter of a field of unit density.

The total number of magnetic lines of force or flux in any given area is represented by Φ, or Phi, a letter taken from the Greek alphabet and pronounced "fe" as in feet, or "fi" as in fine.

The OERSTED, named for Hans Christian Oersted, a Danish scientist, is the unit of magnetic resistance and is defined as the reluctance offered by a cubic centimeter of vacuum.

$$\text{Reluctance} = \frac{\text{length in centimeters}}{\text{permeability x cross section in square cm.}}$$

The GILBERT, named after the English physicist, William Gilbert, is the unit of magnetomotive force or magnetic pressure. One ampere-turn produces 1.2566 units of magnetic pressure (0.4π). One unit divided by 1.2566 ampere-turns = .7958 ampere-turn, or one Gilbert.

Magnetic pressure = 1.2566 x turns x amperes, or

$$\mathcal{F}\text{ (m.m.f.)} = 1.2566 \times N \times I$$

The GAUSS, named after Karl Friedrich Gauss, a German mathematician, is the unit of magnetic field strength, and is equal to one line of force per square centimeter. It represents the intensity of a field which acts on a unit pole with a force of one dyne.

In electricity Ohm's law states that the

$$\text{Current} = \frac{\text{Electromotive Force}}{\text{Resistance}}, \text{or } I = \frac{E}{R}.$$

Expressed in electrical units:

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}$$

With electromagnetism we have a relation of quantities similar to Ohm's law. This relation between magnetomotive force, magnetic flux, and reluctance is expressed as follows:

$$\text{Magnetic Flux} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}}, \text{or } \frac{\mathcal{F}}{\mathcal{R}}$$

In magnetic terms it is expressed as follows:

$$\text{Maxwells} = \frac{\text{Gilberts}}{\text{Oersteds}}$$

The magnetic field, or whirl, can be detected easily by means of a magnetic compass, or with the aid of iron filings, as shown by the experiment in Figure 1. It shows that a wire of suitable length (either insulated or bare wire) is thrust vertically through the center of a sheet of cardboard upon which is sprinkled a thin uniform layer of soft iron filings. The opposite ends of the wire are connected respectively to the positive (+) and negative (—) terminals of a dry cell which furnishes the electromotive force necessary to send current through the wire. The direction of current flow is indicated by arrows. With current flowing the cardboard is tapped lightly which causes the fillings to move and arrange themselves in concentric circles, each circle being a line of force. Of course, the filings cannot clearly map out all of the lines because of their vast numbers. An important fact to be remembered is that the lines of force exert their effort in a certain direction around the wire and at right angles to it.

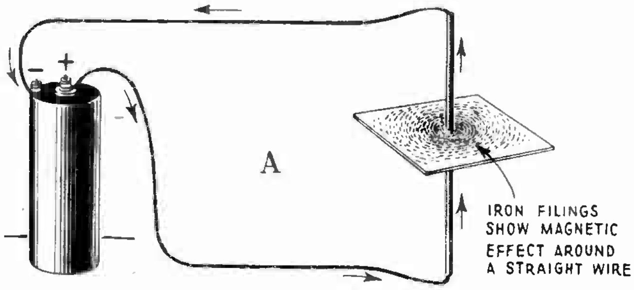


Figure 1

Our experiment offers a convenient means for indirectly observing how the passage of current through a wire sets up magnetic effects. Although these whirls of magnetic lines exist along the entire length of the wire circuit (whenever current flows) we are only visualizing them at one location on the wire, i.e., at the point where our cardboard is placed. To prove that the magnetism exists all along the wire move the cardboard up and down at the same time observing the behavior of the filings. The total number of lines encircling the wire is an indication of the magnetic field strength, or density, and in this case is chiefly dependent upon the number of amperes of current flowing. A current of low value will produce a comparatively weak field, whereas, a current of larger value will produce a relatively stronger field. The magnetic lines (or flux) around the wire have precisely every quality possessed by lines existing about a steel magnet. The lines act upon the space medium about the wire to place it under a strain as any magnetic flux would do.

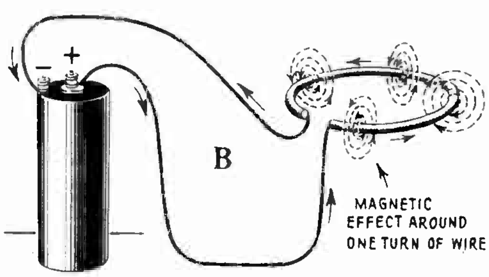


Figure 2

<u>THE MAGNETIC EFFECT ABOUT A "LOOP" OF WIRE WHEN CURRENT FLOWS.</u> Now let us bend the straight wire in Figure 1 into a loop as in Figure 2. It is seen that the magnetic lines are present but that by forming a loop we have obtained a condition where the direction of the lines are all upward inside the loop and all downward outside the loop. Stating this in a different way we could say that all of the lines set up by the current emerge from one end of the loop, surround the loop and re-enter at the opposite end, with the result

that a continuous magnetic flux encircles the single turn of wire. Figure 3 shows the magnetic flux set up by current flowing through a coil. The magnetic whirl around each turn is similar to the single turn in Figure 2, but by the coil arrangement the lines around one turn combine with those of an adjacent turn, and so on, throughout the length of the coil. This results in the lines assuming a similar direction around the coil and through the core, that is they emerge at one end and after continuing around the coil re-enter at the opposite end. Thus, a coil can be made to produce strong magnetic effects because the lines set up by each of its turns add up collectively.

You now see from the drawing in Figure 3 that a coil through which current is flowing is similar to a steel magnet insofar as each produces a magnetic flux and, consequently, each has "N" and "S" poles at its opposite ends. Since magnetic lines of force have similar characteristics, regardless of how they are produced, then any effects or work which a bar or other type magnet is capable of doing could likewise be done by any suitable coil of wire when current flows through its turns. The following important facts concerning a current-carrying coil should be remembered: (1) The current produces a magnetic flux; (2) the coil has definite "N" and "S" poles; (3) the end of the coil from which the lines of force leave is the "N" pole and the opposite end where they re-enter is the "S" pole.

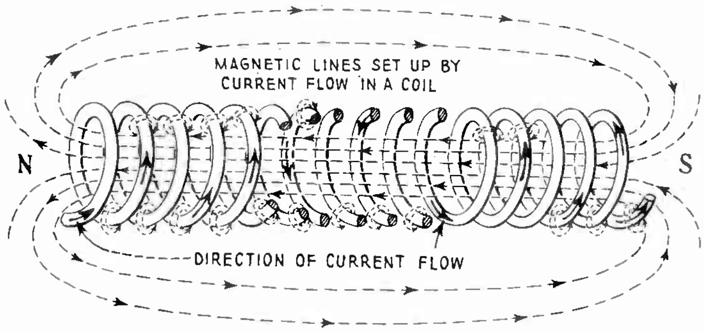


Figure 3

<u>RELATION BETWEEN DIRECTION OF CURRENT FLOW AND MAGNETIC LINES AROUND A WIRE.</u> The relation between the direction of current flow through a straight wire and the direction of the lines as they encircle it at right angles can be easily understood by the student after examining the diagram in Figure 4 and applying the following right-hand thumb rule:

<u>FIRST RIGHT-HAND THUMB RULE:</u> If a conductor is grasped with the right hand, with the thumb pointing in the direction of the current flow the fingers will encircle the wire in a direction similar to that taken by the lines of force. In other words, the fingers coincide with the direction of tension which the lines set up in space.

By placing a compass first above and then below a wire when current is flowing the direction of the force lines can be determined since they exist entirely around the wire in concentric circles. We have shown in Figure 4 how the compass needle points in a certain direction when it occupies a position over the wire, but, when under the wire, the needle points in the opposite direction. If we were to reverse the connections at the dry cell and cause current to flow through the wire in an opposite direction to that shown by the arrows the compass needle would indicate this change since it would point in directions just the contrary to those indicated for positions above and below the wire during the original connection.

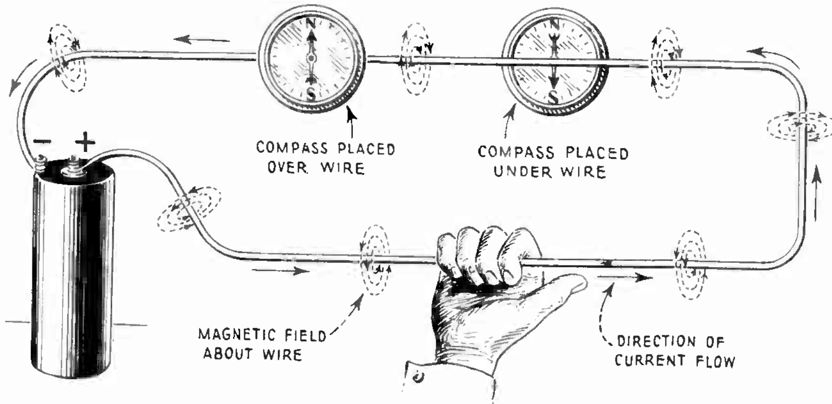


Figure 4

The drawings in Figures 5 and 6 are almost self-explanatory. Figure 5 shows the end view of a wire with the current flowing through it in a direction away from the reader (indicated by a cross) and the lines of force are in a clockwise direction about the wire. Figure 6 shows the same wire with the current reversed and flowing toward the reader (indicated by a heavy dot) and the lines are in a counter-clockwise direction about the wire. Figure 3 illustrates a coil with a cut-away section permitting you to readily visualize the magnetic effects around each turn and the total flux in and around a coil when current flows.

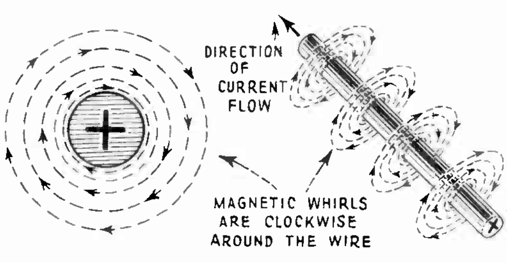


Figure 5

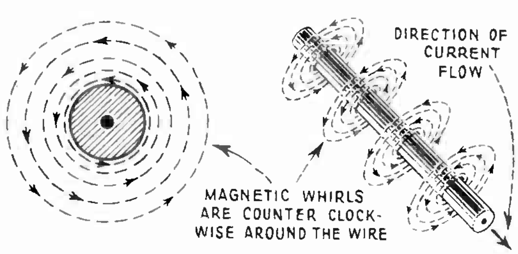


Figure 6

The attraction between the magnetic fields set by two parallel wires when the current flows through each one in the same direction is shown in Figure 7. The repulsion between two such fields when current flows in each wire in opposite directions is shown in Figure 8.

RELATION BETWEEN DIRECTION OF CURRENT FLOW AND POLARITY OF A COIL. The purpose of Figure 9 is to demonstrate how you could find the "N" and "S" poles of a coil providing you knew the direction of the current flow. This could be stated otherwise by saying that if you knew the polarity of a coil you could find the direction in which the current passes through its turns. The polarity is determined by applying what is popularly known as the second right-hand thumb rule, as follows:

SECOND RIGHT-HAND THUMB RULE: TO DETERMINE POLARITY OF A CURRENT-CARRYING COIL. Grasp the coil with the right hand, place the fingers parallel with the turns, point them in the direction of the current flow and the thumb will point toward the "N" pole of the coil.

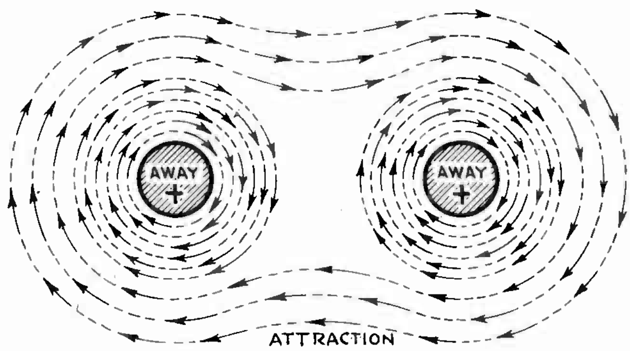


Figure 7

SOLENOID - HELIX. If a coil consists of but a few turns of wire it is usually called a helix (meaning spiral shaped) but a coil wound with a considerable number of turns is more often called a solenoid. In ordinary conversation coils are frequently referred to as "windings."

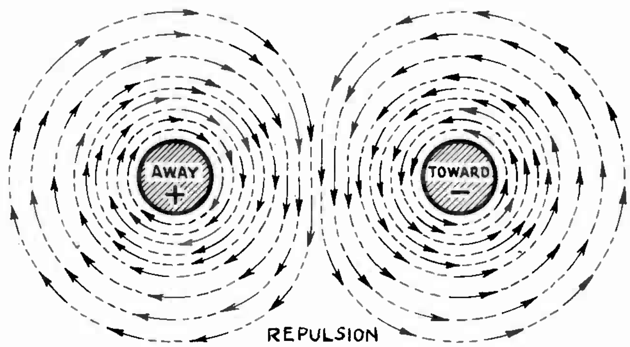


Figure 8

AIR CORE AND IRON CORE. When the inside of any coil consists merely of an air space the coil is said to have an air core, like the one in Figure 9. But, if we insert a bar of soft iron into the coil to fill the air space, as in Figure 10, the coil is then said to have an iron core and the whole unit is given the name "electromagnet."

ELECTROMAGNET. When current flows through the windings of an electromagnet the iron used in the core becomes magnetized by induction the same as would any mass of iron if brought into the presence of a magnetizing force. When the iron molecules are arranged in parallel rows the iron core itself sets up its own force lines and the latter are added to the lines established by the current in the coil. Thus, in any electromagnet the magnetic field strength is the sum of the lines set up by the iron core and those set up by the coil. By employing an iron core, as in figure 10, the magnetic flux set up around a particular coil by a certain current is multiplied many times over that of a similar coil with an air core.

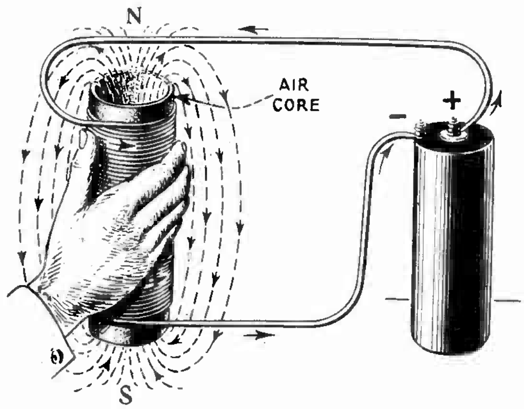


Figure 9

When iron is used and the iron protrudes beyond the ends of the coil it will be noticed that most of the lines pass entirely through the iron before they emerge and act upon the surrounding space medium. However, in the case of a coil with an air core the lines begin to spread out into space at the opposite ends of the coil itself, or where the turns end. This is due to the fact that iron has a higher permeability than air. See Figures 9 and 10.

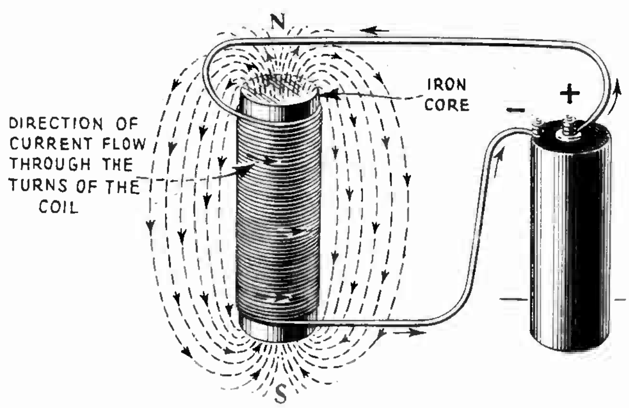


Figure 10

An example of how powerful an electromagnet can be made is given in the drawing in Figure 11 showing a modern lifting magnet moving large pieces of iron. The large pieces of iron are lifted by means of the strong magnetism produced when a very high current, perhaps 50 amperes or more, flows through coils consisting of a few thousand turns. A magnet of this kind often weighs over 5000 lbs. itself, has over 100,000 ampere-turns, and is capable of lifting iron pieces weighing thousands of pounds. By discontinuing the current in the coils the magnetism disappears due to the magnetic field collapsing inwardly to the center of each turn of wire making up the coil.

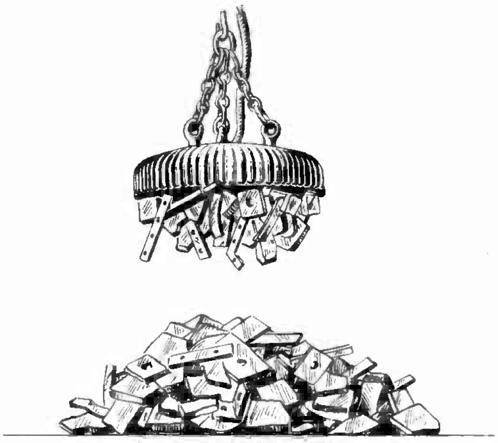


Figure 11

The fader relay in Figures 12-A and 12-B is another example of how the properties of an electromagnet are utilized to actuate an iron armature which moves the contact arms that switch the connections of the

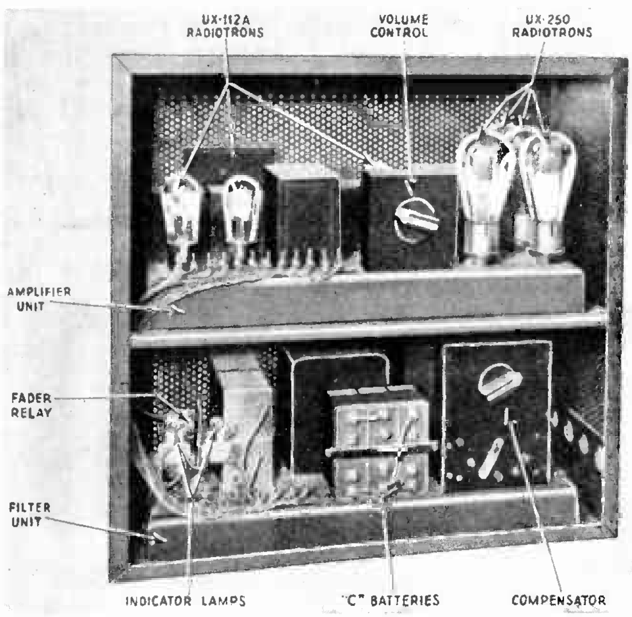


Figure 12-A

amplifier from one motion picture projector to the other, when the "changeover" switch is thrown. Figure 12-A shows the location of the fader relay in the amplifier housing of equipment for use in small theatres. Figure 12-B shows the wiring details of the relay. In operation current flowing through the magnet winding produces a magnetic field, the lines of force of which are greatly concentrated due to the soft iron core, thus forming an electromagnet. The magnetism attracts the armature, pulling it toward the magnet and by pivot action disengages the two long contact arms from the output connections of one projector which were shorted

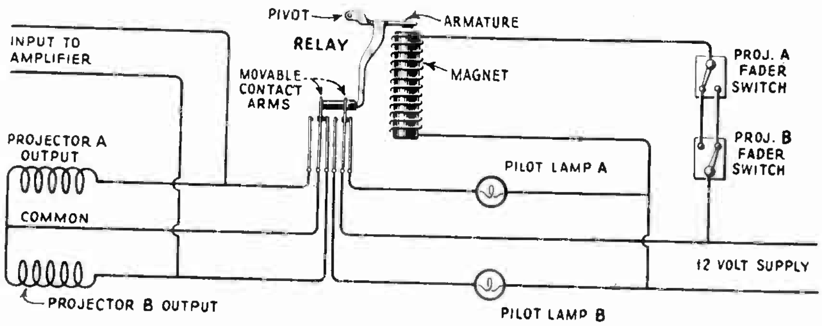


Figure 12-B

and moves them with the result that the connections to the other projector are shorted. It is known as the short-circuiting type of a fader relay. Keep in mind that the strength of an electromagnet or any current carrying coil depends mainly upon its ampere turns.

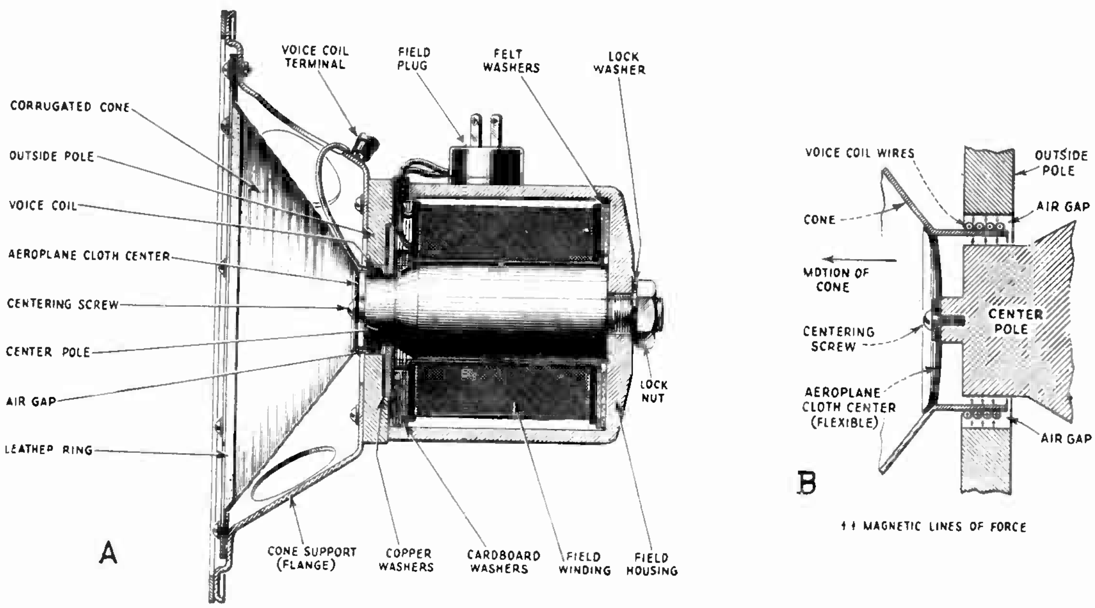


Figure 13

Another illustration of the use of an electromagnet is given in Figure 13, A and B, which is that of an electrodynamic speaker. Here the magnet or center pole is energized by a field winding receiving current from a direct current source. The magnet attracts and repels the voice coil, which is located at the neck of the cone, because of the alternating sound currents flowing through the voice coil from the output of the amplifier. In this manner the sound currents are converted into physical vibrations producing speech or music.

MEANING OF "AMPERE-TURNS." The magnetizing effect of a solenoid, or the number of lines of force produced by a given solenoid, are expressions which mean practically the same thing. The number of lines depend mainly upon two factors, namely: (1) the value of the current in amperes flowing through a winding and (2) the number of turns of wire comprising a winding. Hence, the term "ampere-turns" represents the product of the number of turns of wire on a coil and the number of amperes flowing in each turn. We can set down this relation for ampere-turns in a formula, thus:

AMPERE-TURNS = NUMBER OF TURNS x AMPERES

According to this formula a current of 0.2 amperes flowing through a coil consisting of 500 turns will produce exactly the same amount of magnetic strength as will a current of 20 amperes flowing through a similarly formed coil but which has only 5 turns. In both cases we have 100 ampere turns.

MAGNETOMOTIVE FORCE. (Abbreviated m.m.f.) This is the name given to the unseen force which is fundamentally the cause of setting up the magnetic flux in a magnetic circuit. It is essentially the same as electromotive force, meaning it is magnetic pressure. This force is an indispensable requirement for the establishment of magnetism in just the identical way that electromotive force is required before current will flow in an electric circuit. There is a definite relation between flux and magnetomotive force. For example, when iron is magnetized, demagnetized, and magnetized to an opposite polarity as is the case when alternating current flows through the magnet winding, part of the energy necessary to arrange the molecules in a polar alignment is converted into heat, due to friction between the molecules. The movement of the molecules either when magnetizing or demagnetizing, however, lags behind the magnetizing force. This lag of molecular arrangement is known as "hysteresis." In other words hysteresis is that property of the iron which helps the iron to maintain the magnetism it has acquired. The energy used in demagnetizing the iron to a zero point before it can be magnetized in the opposite direction to the other polarity is known as "hysteresis losses."

To exemplify this fact Figure 14 is given showing a hysteresis loop. Whenever iron is magnetized to the point of saturation, or a little beyond this point the magnetization curve flattens out as will be observed from the line OXA. If we remove this magnetizing force H the flux density does not follow the identical line it did during magnetization which marked its rise, but takes a different course as indicated by the line ALMP. Upon examination it will be noted that at point M the force H is zero but the flux density B is 10,000 gausses, represented in the ordinate from O to M. This value is termed the "remanence". To remove this remanence from the iron we are compelled to apply a magnetizing force H in the opposite direction of 9 gilberts per centimeter, represented by the line OP termed the "coercive force." By increasing the magnetizing force, minus H, (-H), a flux density, minus B, (-B), will be produced in the opposite direction. The magnetization curve of this operation is shown as line OC indicating a negative value at C equal in amplitude to A which is positive. (+). Going through the process of again diminishing the force minus H it will be noted from the course taken by curve CNA, that at N the density minus B, is 10,000 gausses and the force minus H is zero. In order to remove the remanence from the iron a coercive force Z must be applied in the positive direction which if continued will bring the curve up again to A. This cycle of events in the magnetization of iron is known as the "hysteresis loop."

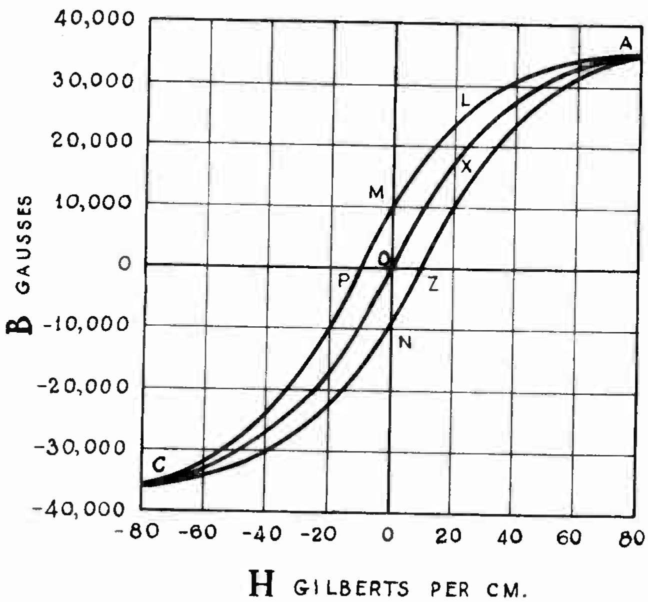


Figure 14

SUMMARY. The important facts to be remembered from the subject of "Electromagnetism," besides the two "right-hand thumb rules," are as follows:

(1) A magnetic field is always established in the region around a wire carrying a current of electricity.
(2) When current passes through a coil of wire each turn produces lines of force which extend outward into space and combine with the lines of neighboring turns to set up a magnetic flux encircling the entire coil. This effect is clearly shown in Figures 3 and 7.
(3) A coil carrying current exhibits "N" and "S" poles at its opposite ends, since a magnetic field is established in the surrounding space.
(4) Both a bar magnet and a coil through which current is passing produce similar magnetic effects.

ELECTROMAGNETIC INDUCTION

ELECTROMOTIVE FORCE AND CURRENT INDUCED IN WIRES BY LINES OF MAGNETIC FORCE. We learned in the earlier part of this lesson that an electric current moving through a wire, or any conductor, sets up a magnetic field surrounding the wire and, also, the lines of force comprising the field reach cut a considerable distance into space. The extent or magnitude (called density) of the field about a current carrying wire depends mainly upon the strength of the current for which the lines are responsible and, also, upon the material of the magnetic circuit, i.e., whether it be all air or partly iron. Other facts brought out were that if a conductor is wound in the form of a coil (helix or solenoid) it produces a magnetic field similar to that of a permanent bar magnet when current passes through the turns of the coil and that the coil will exhibit north and south poles at its opposite ends according to the direction of the current in the turns. We will repeatedly make use of these facts throughout our present discussion. However, we must now become familiar with principles which are the converse of the above statements, that is, magnetic lines of force are capable of producing a movement of electric current in conductors under certain conditions.

It was Michael Faraday who made this discovery in 1831 which is one of the most important in the entire electrical science because, from the application of these principles have sprung many forms of radio, sound picture equipment and power apparatus, such as generators transformers and so on. He noticed during one of his experiments that when a conductor was moved through a magnetic field in such a way that it cut across the lines of force an electrical pressure (e.m.f.) would be set up along the conductor, that is, induced in the conductor. That an e.m.f. or electric charge was made available was proved by attaching the conductor to the gold leaves of an electroscope and observing the movement of the leaves while the conductor was being moved. He also observed that if a conductor in which an e.m.f. was induced formed part of a closed electric circuit the induced e.m.f. would cause a movement of current through the entire circuit. "Induced e.m.f." is often called "induced voltage." Let us explain in regard to the latter statements that an e.m.f. is induced in an open conductor (this means a conductor whose ends are left free or disconnected) when acted upon by lines of magnetic force, whereas, an e.m.f. is induced and current flows in a closed conductor under similar conditions. When discussing the action occurring in a closed conductor we refer sometimes only to the induced current, keeping in mind, however, that we must first have the induced electromotive force.

Among several effects observed by Faraday one was that if a conductor after being placed in a magnetic field, remained at rest (that is, the conductor was not moved with respect to the lines of force) no induced e.m.f. could be obtained. Nor could an induced e.m.f. be obtained if the conductor was moved in the magnetic field in such a way that its direction of motion was parallel to the direction of the lines of force. In other words, in the latter motion the conductor would not cut or pass through the field, it would merely travel along and coincide with the direction of the lines. But, he found that if a conductor remained in a stationary position and the magnetic lines were made to move so that they passed through or cut across the conductor an e.m.f. would be induced in the wire under such conditions.

Notice particularly that in all cases involving induced e.m.f. and current we have to consider the relative motion of the conductor and the magnetic lines since either may remain stationary. That is, we must take into account the following conditions, namely: (1) Whether a conductor is moved through a stationary field, or (2) Whether magnetic lines move past or cut across a stationary conductor.

The foregoing statements form the basis of the study of "Electromagnetic Induction." As we now see, this subject deals with the production of electrical pressures and currents in conductors by making practical use of the invisible force that is always present in the space where a magnetic field exists.

CURRENT INDUCED IN A CONDUCTOR BY A MAGNET AND AN ELECTROMAGNET. In the following explanations it will be shown that the principles of electromagnetic induction remain the same regardless of the source of the flux. The flux may be obtained from the use of a permanent magnet, as in Figure 15, or from an electromagnet, as in Figure 16. In our practical work we find coils of both the air-core and iron-core type in use. The design of a coil is governed by its particular function in the circuit. We do know, however, that when iron is used for the core material it sets up a magnetic flux which is hundreds of times greater than could be obtained from a given coil when operated with only an air core.

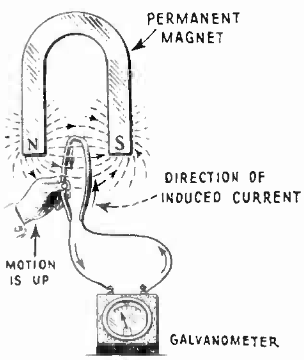


Figure 15

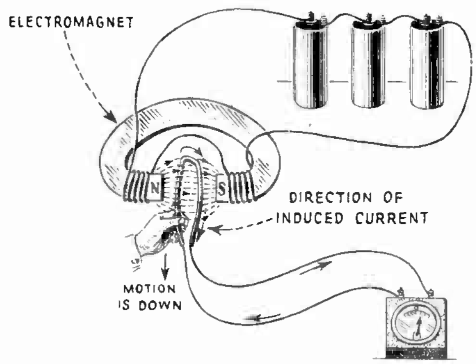


Figure 16

In the experiment in Figure 15 the induced e.m.f.'s and currents for movements of the loop of wire will be detected by the deflections of the pointer of a sensitive galvanometer. Before continuing with our subject let us first give a brief explanation of this instrument. It consists of a small movable coil carrying a pointer, the coil being mounted on a bearing and placed in the magnetic field of a horseshoe type magnet, and it operates on the principle that a passage of current through the coil causes it to rotate, one way or the other, due to the force of the magnetism set up by the current in the coil acting upon the force of the magnetism of the magnet. A spring holds the coil and pointer in a zero, or center position. The pointer will move right or left of the zero mark according to the direction of the current supplied to the coil through the connections at the two binding posts on the top of the meter case. The amount of the pointer deflection is taken as the measure of the strength of the current induced in the circuit when the loop of wire moves across the lines of force as illustrated.

Let us know proceed with the experiment. If the loop is suddenly moved vertically downward a deflection of the galvanometer pointer will be seen, indicating that current momentarily flows through the closed circuit consisting of the loop, the coil in the galvanometer, and the connecting wires. The pointer will move a certain distance across the scale and immediately drop back to its natural position of rest. Assume that the pointer moves to the right. If the loop is suddenly moved upward the pointer will momentarily deflect in a direction opposite to its first movement and, accordingly, it will move a certain distance across the scale to the left of zero. It is evident that when the loop stops cutting the lines the induced current dies out. Bear in mind that the induced electromotive force is generated only momentarily, or while the conductor is actually moving and cutting lines.

The galvanometer readings indicate that the induced current in the loop alternates with each reversal of its movement through the field. If the loop is moved quickly across the lines a higher deflection will be read on the galvanometer than if only moved slowly. Also, if instead of moving the loop perpendicular to the direction of the lines we now move it from left to right, or right to left, either way (that is, parallel to the direction of the lines) no lines will be cut and, therefore, no e.m.f. or current will be obtained. A person performing an experiment of this kind could easily move the loop up and down so rapidly that the pointer, due to its weight, could not follow the variations or reversals of the induced current and, therefore, the pointer would remain at zero, or possibly it might make a slight quivering motion without giving any definite reading.

There are two more important points to be mentioned in regard to Figures 15 and 16. If the loop is held stationary and either the magnet or electromagnet is moved up and down so that the lines are made to cut through the loop the same results will be obtained as for conditions outlined in the foregoing paragraphs where the loop is made to cut through the lines. And if the magnetic fields were reversed, with "N" to the right and "S" to the left, the induced pressures would then be set up in the reverse directions for the same motions of the loop relative to the field.

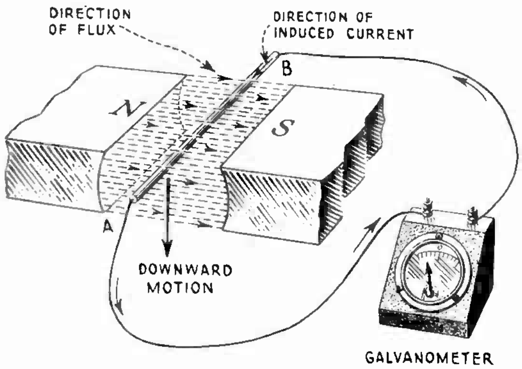


Figure 17

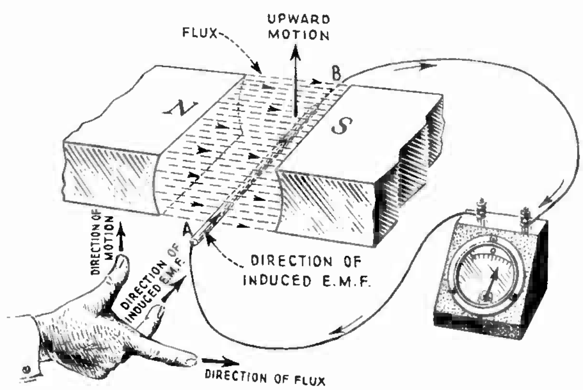


Figure 18

<u>FLEMING'S RULE FOR DETERMINING THE DIRECTION OF INDUCED E.M.F. IN A CONDUCTOR.</u> To explain the rule it is best to perform the experiments in Figures 17 and 18 with a straight copper rod. It is easy to understand the inductive effects set up in a rod and then later you can apply the same rule to any number of conductors, or turns of wire. A galvanometer is again used to indicate the strength and direction of the induced current, the instrument being shown connected to the ends of rod AB.

The laws relating to the direction of the e.m.f. induced in a conductor when it cuts through a magnetic field must be learned in order to understand the principles of the electric generator, which will be dealt with in one of our forthcoming lessons. The diagrams in Figures 17 and 18 are drawn expressly to illustrate one method for determining the relation between the direction of the induced current, the direction of the motion of the conductor, and the direction of the lines of force. In the following paragraphs we will consider two cases: (1) The effect when the rod is moving downward, (2) The effect when the rod is moving upward.

Case (1). If rod AB is moved down across the magnetic flux, as in Figure 17, the induced pressure in AB will be in the direction from B to A as indicated by the arrow in the rod. This e.m.f. sends current through the rod and the galvanometer coil and, thus, a momentary deflection of the pointer is seen. Let us assume that the pointer moves to the left of zero and drops back immediately.

Case (2). Now, if rod AB is moved up across the flux, as in Figure 18, the induced e.m.f. will be set up in the opposite direction, or from A to B, as indicated by the arrow drawn in the rod. This reversal of induced pressure with a reversed movement of the rod sends current through the rod and galvanometer coil in the opposite direction to that obtained during the down movement as in case (1) above. During the up movement of the rod the pointer will deflect momentarily to the right and return to zero.

Hence, we find that the direction of the induced electromotive force depends upon the direction of the lines of force and the direction of motion of the conductor with respect to the lines. An easy way for remembering these relative directions and particularly to find the direction of the induced e.m.f. is to apply a rule, known as Fleming's Right-Hand Rule, as shown in the diagram in Figure 18 and explained as follows:

With the THUMB, FOREFINGER, and MIDDLE FINGER of the right hand all held at right angles to one another, let the THUMB point in the direction of the motion, the FOREFINGER in the direction of the lines of force, and the MIDDLE FINGER will point in the direction of the induced e.m.f.

Carefully examine the hands in the diagram in Figure 19 which clearly show the application of Fleming's rule to the effects set up in a rectangular loop of wire when it is being rotated on its axis in a clockwise (or right-hand direction) through a magnetic field. Current will circulate entirely through the loop when it cuts through the lines because the loop forms a closed metallic circuit. It will be noticed, however, that for the set of conditions we have shown in the drawing (that is, with the N pole to the right, and the S pole to the left, and the right side of the loop moving downward through the field, and the left side of the loop moving upward through the field) the induced pressure and current will be in a direction away from the reader on the right side of the loop and toward the reader on the left side.

It will be noticed that whenever the rod is moved in a vertical direction across the lines, either up or down, the galvanometer will deflect a certain amount first to one side and then to the opposite side of zero. If the rod were moved across the lines in such a way that it followed a diagonal path then lesser amounts of current would be obtained as indicated by small deflections of the pointer, providing, of course, that for all cases the same rate of movement of the rod is maintained. Or, if the rod is moved parallel to the lines and, therefore, does not cut through the lines, no induced current will be obtained nor will any deflection of the pointer be observed. The facts just mentioned explain, in general, the results to be expected for various changes in the path which a conductor could be made to take across a magnetic field.

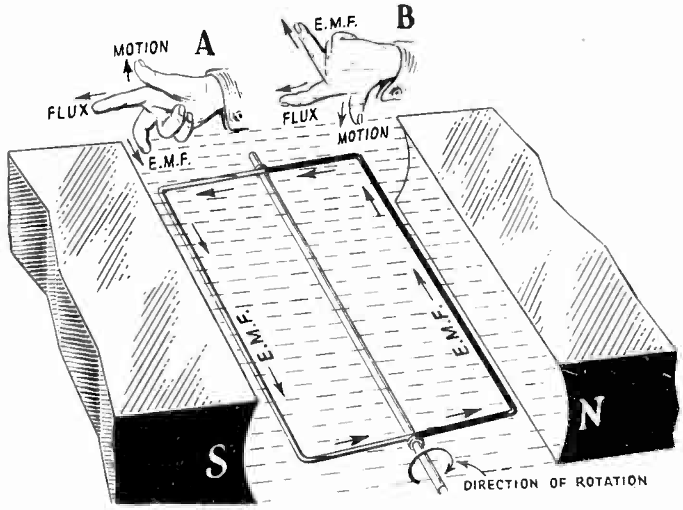


Figure 19

WHEN A CIRCUIT IS "CLOSED" AND "OPENED" THE CURRENT DOES NOT RISE FROM A ZERO TO MAXIMUM VALUE INSTANTLY - NOR DOES THE CURRENT FALL FROM MAXIMUM TO ZERO INSTANTLY - A SHORT INTERVAL OF TIME IS REQUIRED FOR THESE CHANGES TO OCCUR. The purpose of the several views in Figure 20 is to illustrate pictorially three conditions, namely: (1) How current gradually rises in strength on the "make" or closing of a circuit by throwing a switch (views A and B). (2) How the current flows at a steady value an instant or two after a circuit is closed and does not vary in intensity if the circuit remains closed, provided the circuit conditions remain unchanged (view C). (3) How the current gradually decreases in strength from its steady value and drops to zero, on the "break" or opening of a circuit by pulling a switch (views D and E).

Since every change in current strength will produce a corresponding change in the number of lines of force produced by the current then we can assume that while current flows through a wire, and progressively increases in value, the lines of force build up and expand outward into space for some distance.

When the current flow becomes steady or constant the lines remain stationary, i.e., they do not vary in number, or density. A "constant current" is an unvarying current. When current in a wire progressively decreases the lines gradually diminish in number, contract back on the wire and, finally, when the current ceases to flow the lines disappear entirely.

Thus, from Figure 20, we learn that on the "make" and "break" of a direct current circuit the rise and fall in the intensity of the current causes a corresponding change in the magnitude of the magnetic field and, also, that the changes in current strength and variations in flux strength are only momentary.

HOW AN E.M.F. IS INDUCED IN A SECONDARY CIRCUIT BY VARIATIONS OF THE MAGNETIC FLUX SET UP BY A CHANGING CURRENT IN THE PRIMARY. The principles already explained relating to the setting up of a current in a conductor by causing a flux to cut across it will again be used, but this time the results will be obtained without moving either one of the wires. The circuit arrangement is shown in Figures 21 and 22.

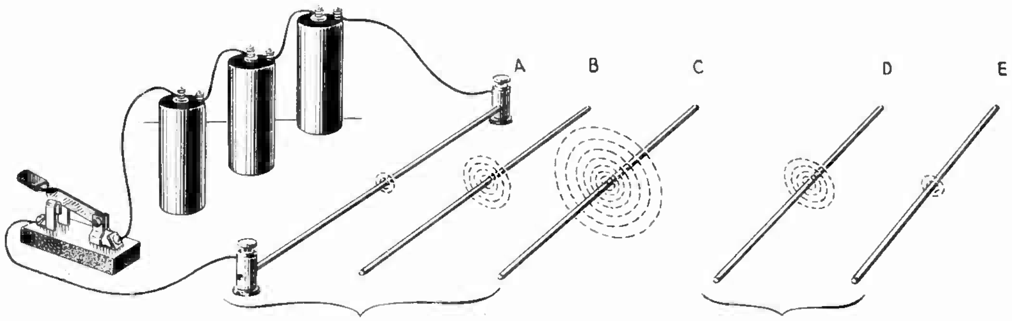


Figure 20

Figure 21 shows the action during the "make" of the primary. At this instant the current begins to rise and the lines of force it produces also increase in numbers and in another instant they will have reached out sufficiently far to cut through the secondary conductor. This effect of the primary on the secondary induces an e.m.f. in the secondary in the direction designated by the arrows, and the lines set up by the momentary flow of current are shown as small magnetic whirls along the secondary.

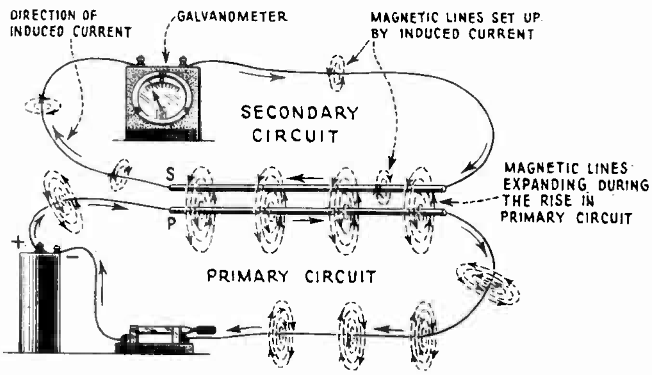
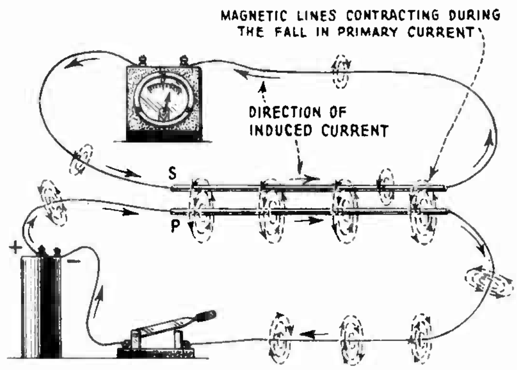


Figure 21

Figure 22 shows the action during the "break" of the primary. At this instant the primary current begins to fall and the lines, as they contract and fall back on the primary, cut through the secondary conductor in a direction opposite to their movement during the "make" of the primary. The cutting action of the lines this time induces an e.m.f. in the secondary in the opposite direction to the previous induction. This change in direction is denoted by arrows. Observe that the secondary e.m.f. and primary e.m.f. are now in the same direction, and also that the magnetic whirls assume similar directions.



ACTION DURING THE "BREAK" OF THE PRIMARY

Figure 22

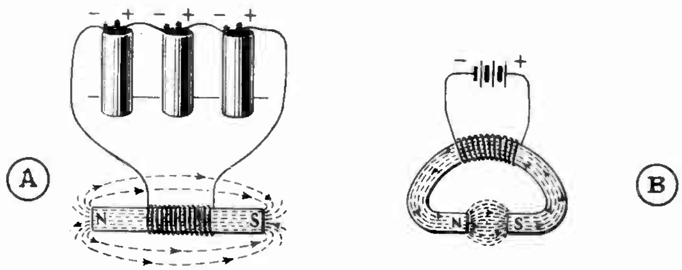
The above two actions illustrate the fact that the secondary opposes the induction of current in it by the direction that its lines take when compared to the primary's field, and the secondary also opposes the stopping of the current induced in it the second time by the change in direction of its magnetic lines. In brief, in one instance the primary and secondary fields are opposed and in another instance they aid each other.

The effect of magnetic lines expanding and contracting for increases and decreases in current through one circuit is made use of to produce an e.m.f. and current in some other circuit. Both circuits, or their parts, although usually independent are in close mechanical relationship, i.e., coupled to each other but with no physical connection between them. Stated in a few words the principle is simply one where a changing magnetic flux set up by the conductors of one circuit reach out and link through, or cut through, the conductors of a neighboring circuit. Coils are employed to provide this coupling between two such circuits so that the proper magnetic effects will be set up by one circuit and the desired amount of voltage will be available from the other circuit. This principle is illustrated in the diagrams in Figures 21 and 22. This is one method for generating an e.m.f. by electromagnetic induction without the necessity of moving wires of coils, as we have heretofore been doing in our experiments.

<u>LAW RELATING TO THE AMOUNT OF INDUCED E.M.F.</u> Suppose in Figure 18 that the magnetic flux consists of 100,000,000 lines of force. It would be found that if rod AB was made to cut these 100,000,000 lines in exactly one second, the pressure set up along the rod (that is, between its opposite ends, or between A and B) would be one volt. This relation between the amount of the induced electromotive force measured in volts, the strength or density of the flux. and the rate of cutting the lines should be learned.

All of the following conditions have a direct bearing on the amount of the pressure induced in a conductor when cutting, or being cut, by lines of force:

(A) The strength or density (number of lines per unit area) of magnetic flux at the point where the conductor is acting at any instant.
(B) The number of turns in the coil or length of the conductor actually being acted upon by the lines.
(C) The angle which the conductor makes with the direction of the lines, as determined by the path through which the conductor moves as it cuts across the lines.
(D) Rate of motion, or the number of lines cut per second.

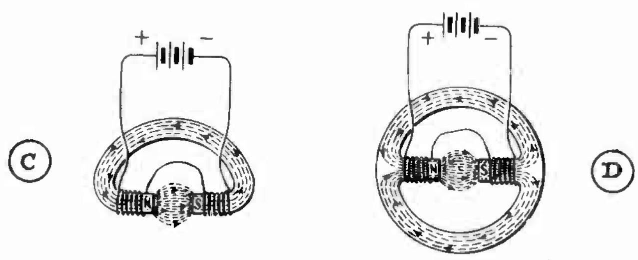


LONG AIR GAP BETWEEN POLES DECREASES FLUX

SHORT AIR GAP BETWEEN POLES INCREASES FLUX

Figure 23-A

THE STRENGTH OF THE INDUCED E.M.F. DEPENDS SOMEWHAT ON THE SHAPE OF THE MAGNETIC CIRCUIT AND ITS MATERIAL. The three electromagnets in sketches B, C, and D in Figures 23-A and 23-B each have a more efficient form of magnetic circuit than the electromagnet in sketch A because the length of the air gap through which the lines must



SERIES MAGNETIC CIRCUIT.

PARALLEL MAGNETIC CIRCUIT FORMED BY A SOLID IRON FRAME AND AIR GAP.

Figure 23-B

pass is longer in A than in the other cases. A short air gap strengthens the magnetic field for a given set of conditions and, thus, for certain movements of a loop of wire through the flux more lines of force will be enclosed or cut by the loop. In some types only one electromagnetic winding is mounted on the iron core while in the other types more than one winding is used, this being done to increase the ampere-turns. The distance between the poles which governs the size of the air gap is carefully considered in practical machinery to keep the reluctance of the magnetic circuit minimum. The coils are connected in series so that current flowing through one must also pass through the other and their turns are so wound as to make the adjacent ends of the windings north and south poles, respectively.

LENZ'S LAW. This law in a condensed manner states that the direction taken by the current caused by the induced e.m.f. is such that the magnetic field produced offers a repelling force to the motion which produced it. Explaining this law further, since we are conversant with the effects occasioned by magnetic lines of force, is that current always flows under pressure of the induced e.m.f. and sets up magnetic lines of force in such a direction, they oppose any change in the initial magnetic lines responsible for the production of the induced e.m.f. The induced e.m.f. is also termed counter electromotive force, meaning the pressure of this force retards the flow of the applied current which produced it. The application of this property is credited with the successful use of alternating current apparatus.

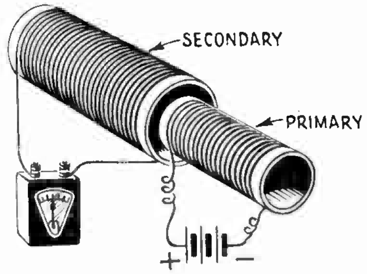


Figure 24

Refer to Figure 24 showing two coils, one a primary and the other a secondary; together they constitute a transformer. A practical explanation of Lenz's law is given below with references made to the diagram: Let us assume that the current in the primary coil is such that it makes the polarity at the left-hand end north. When the primary is moved into the secondary the flow of induced current in the latter coil makes its polarity at the right-hand end also north. Thus, the adjacent ends of both coils when the primary is fully inserted, have opposite polarity and, therefore, the effect set up between them is one of repulsion. However, when the primary is withdrawn from the secondary the induced current in the latter is reversed and reverse polarity will be set up at the right-hand end of the coil. We now have a condition where the left-hand end of the primary is north (note that the polarity of the primary does not change because it is supplied with a steady source of e.m.f. by the dry cells) and the right-hand end of the secondary is of south polarity. A magnetic attraction now exists between the coils that tends to oppose their separation. It is only while the coils are moved with respect to each other and the induced current flows and reversed magnetism is set up about the secondary that we have these effects of attraction and repulsion. It is seen in every case that the magnetic attraction and repulsion tends to oppose the motion of the primary coil.

SELF-INDUCTION. This is the name given to that property of an electric circuit wherein it tends to oppose any change (increase or decrease) in the strength of the current in the circuit. The effects of self-induction are present only at such times as when a current is changing in intensity. The magnetic lines which always accompany a current begin in a wire at the very center of its core. Thus, when current rises the lines build up outward and pass through the very wire which is producing them. On the contrary, when current falls the lines recede inward on the wire and cut the wire in the opposite direction to the first instance cited. This cutting action on a conductor by its own lines induces an e.m.f. in the conductor first in one direction for an increase in current and, secondly, in the opposite direction for a decrease in current. Thus, we see that the induced e.m.f. at one time tends to oppose the establishment of a current in a conductor and at another time it tends to prevent the current from dying out. The induced e.m.f. is known as the induced e.m.f. of self-induction. The student must understand that the e.m.f. of self-induction is another e.m.f. acting on a circuit and separate from the usual e.m.f. which is applied to any conductor in order to make current flow in the first place.

MUTUAL INDUCTION. Current flowing in a secondary circuit, by reason of the induced e.m.f. set up by the varying flux produced by current changes in the primary circuit, establishes a secondary flux which cuts the conductors of the primary and induces in the primary an e.m.f. which exerts a pressure in the same direction as the flow of the applied primary current. Therefore, when two independent circuits are so associated that the effects produced by their respective magnetic fields, results in inducing e.m.f.'s and currents in these circuits, that is, the primary induces an e.m.f. in the secondary and the secondary induces an e.m.f. in the primary. Two such circuits are said to react on each other. This reaction is known as mutual induction and the circuits involved are said to possess the property of mutual inductance.

These effects explain the fundamental action of transformers and illustrates why more current is drawn by the primary when the load on the secondary is increased. Figures 21 and 22 show two independent fields reacting on each other. One magnetic field is due to the applied or inducing current, flowing in the primary (P) and the other is due to the current flowing under pressure of the induced e.m.f. in the secondary (S). The strength of the current flowing in the secondary is determined principally by the load placed upon it.

INDUCTANCE. The unit of inductance, called the "Henry," is designated by the symbol "L." Inductance may be defined as that property possessed by an electric circuit (when current flows) which stores up energy in the form of electromagnetic lines of force. The total lines represent the magnetic flux. Self-induction is the result of inductance in a circuit, and is that property which induces a reverse, bucking or counter voltage, always acting to oppose any change in the value of the current flowing through the circuit. The resulting field when current flows expands outwardly cutting the conductors and induces this reverse or bucking voltage which tends to maintain the dormant state, or the existing conditions before the change from no current flow to current flowing, took place. When the current flow is interrupted the magnetic field collapses but this time it cuts the conductors in an inward direction toward the center of the conductors, and induces a current which takes the same direction as the applied current and, hence, attempts to keep the applied current flowing. This effect can be noticed by the spark which appears at the switch blades whenever a circuit is broken, the spark being the result of self-induction.

The amount of inductance, as measured by the unit henry, is determind by the amount of voltage that will be induced in a coil or circuit by the current changing at a given rate. Thus: "A circuit is said to have an inductance of one henry when a current changing at the rate of one ampere per second will induce therein an electromotive force of one volt."

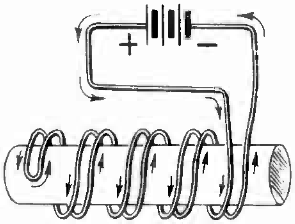


Figure 25

<u>NON-INDUCTIVE CIRCUIT — HOW EFFECTS OF SELF-INDUCTANCE WITHIN A CIRCUIT MAY BE NEUTRALIZED.</u> The fields set up along the turns of a coil can be made to neutralize one another if the turns of the coil are wound so that the field around each turn opposes in direction the field around an adjoining turn. The current in each turn must be equal, and adjacent turns should be close together. A coil wound to produce this result is shown in Figure 25. The coil is said to be non-inductive because practically no field is established around the coil when current flows. Coils of this general type are employed for resistor units in instruments such as Wheatstone bridges, meters and in any circuits where resistance is required but inductive effects are undesired.

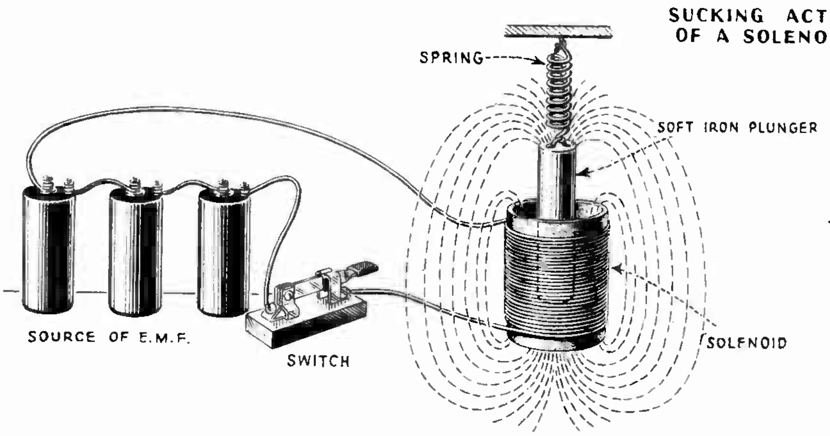


Figure 26

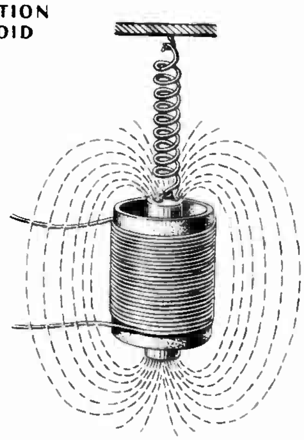


Figure 27

<u>SUCKING ACTION OF A SOLENOID.</u> Since all magnetic fields possess similar properties a solenoid will attract iron when current flows through it in the same way a bar magnet will attract iron as shown in Figures 26 and 27. The flux seeks the path through the iron plunger in preference to passing entirely through air and this magnetizes the plunger, causing it to be attracted by the coil. The plunger is drawn into, or sucked into the coil, and does not stop moving until it centers itself in a position where it will accomodate the greatest amount of flux. It remains unmoved in the coil so long as the current flows at the proper value to provide the requisite amount of

flux to hold the plunger from being pulled back by the spring. This principle is utilized commercially in the operation of protective devices called "circuit breakers." These devices automatically trip, open a circuit and shut off the power when the spring is adjusted to the proper tension so that the plunger is sucked into the coil only under extreme conditions. This idea can be used for relay operation, or any form of tripping device.

PRACTICAL APPLICATIONS. Practical applications of the use of electromagnets are both numerous and varied. The electromagnets in the automatic oscillograph, shown in the photograph in Figure 28, play an important part in the operation of this device which is used to investigate current and voltage conditions in an electrical circuit. Oscillograms may be taken of chance transients, surges and also normal voltage and current characteristics of circuits under observation. The records are traced by means of light directly on a strip

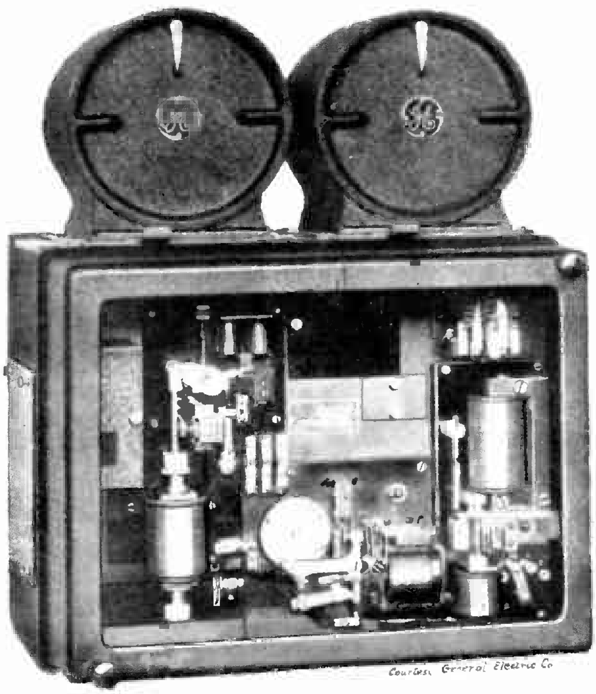


Figure 28

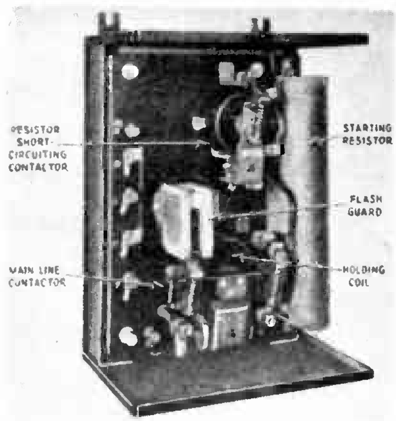


Figure 29

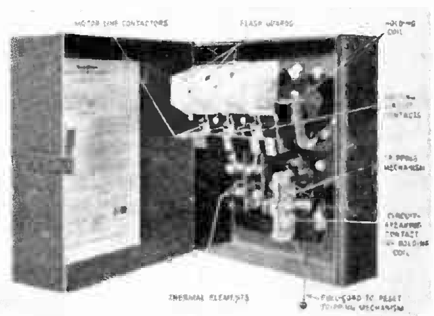


Figure 30

of sensitized paper so after the development process the current and voltage characteristics appear directly as wavy lines on the strip of paper. The records obtained show wave shapes and phase relations instead of merely envelopes of these waves. Two typical examples of the use of electromagnets are given in Figures 29 and 30 which show two types of line switches for motor-generator sets used in motion picture equipment. One type is for d-c operation and the other for a-c operation. The holding coils and electromagnet for the resistor short-circuiting contactor are clearly shown in the photographs. In operation they become energized and attract the iron armature to which the operating mechanism is attached.

EXAMINATION QUESTIONS

1. What phenomenon always exists when current flows?

2. State the right-hand thumb rule for determining the polarity of a solenoid and draw a simple sketch illustrating same.

3. State the right-hand thumb rule for determining the direction of a magnetic flux around a current-carrying wire.

4. What is Fleming's right-hand rule?

5. If an air-core is carrying a current and a bar of soft iron is inserted into the coil what effect will be produced?

6. (a) What happens when an "open" conductor moves across a magnetic field?
   (b) What happens when a "closed" conductor moves across a magnetic field?

7. Explain the principle of the sucking action of a solenoid.

8. Explain briefly what is meant by the following terms: (a) Self-inductance, (b) Mutual inductance, (c) Ampere-turns.

9. What does Lenz's law state?

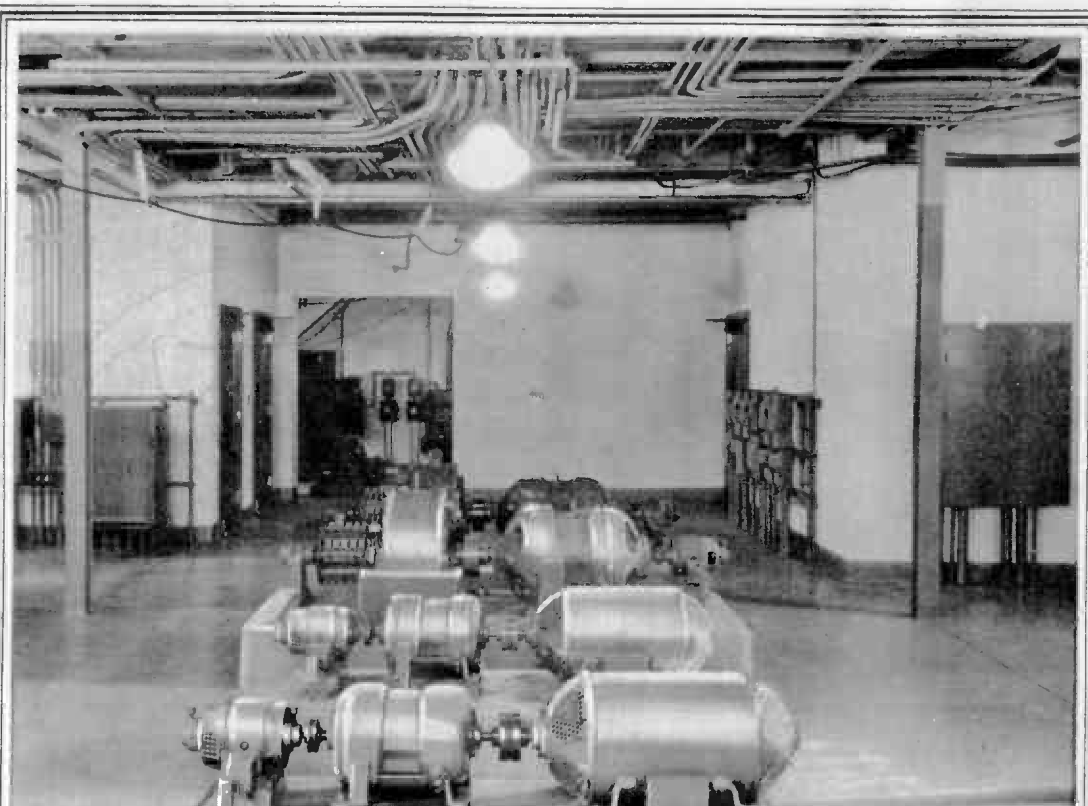
10. (a) Give the definitions of the gauss, gilbert, oersted and maxwell.
    (b) What does the Symbol Φ represent?

11. Either one of two conditions must be satisfied before an e.m.f. can be induced in a wire or circuit. What are these conditions?

12. If 5 amperes circulate through a magnet winding of 30 turns, how many turns are required to produce an equal m.m.f., with only 1.5 amperes flowing?

13. What does the line OXA in Figure 14 represent? The line OM? The line OP?

14. What coercive force is required to remove a remananence of 10,000 gausses? Refer to Figure 14.



Electromagnetic principles are applied in the power plant of WEAF, New York.

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A whistle lights the lamp — a clap of the hands puts it out. Sensitive relays are used in this modern application of electromagnetism.

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