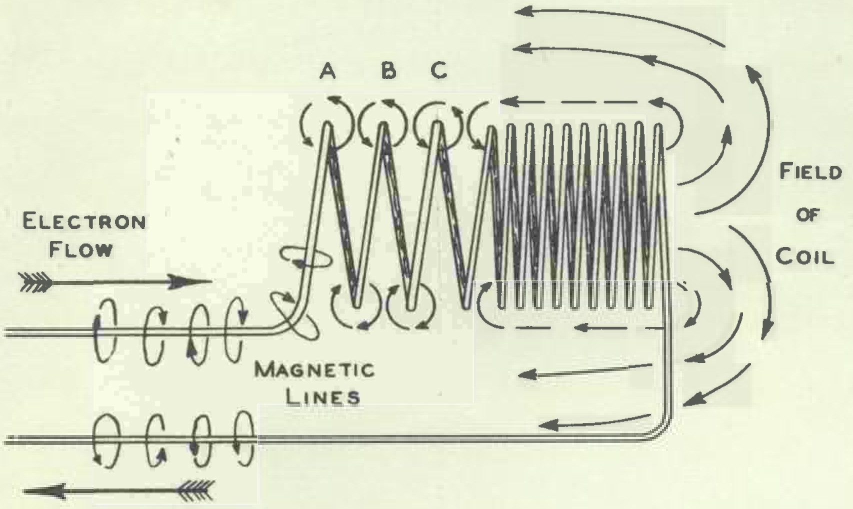

LESSON

7 R

# RADIO COILS OR INDUCTORS

RADIO-TELEVISION TRAINING SCHOOL, INC.

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# RADIO COILS OR INDUCTORS

Now that we are familiar with capacitance, as well as with resistance, we may turn to the third element in our basic radio circuit, this third element being inductance. First, we wish to answer the question: "What is inductance?" Well, when there is any change in the rate of electron flow in any circuit, there is induced in that circuit an electromotive force that opposes the change in rate of electron flow. Furthermore, if there is any other closed circuit near by, the change in rate of electron flow in the first circuit induces also an emf in that nearby circuit, even though there is no conductive connection between the two circuits. This property of a circuit which enables it to induce emf's in itself and also in other nearby circuits, when there are changes in rate of electron flow in the first circuit, is called inductance.

It is the ability of a circuit to induce emf's that is called <u>inductance</u>. A circuit may have this ability or property without actually performing the act. When emf's actually are induced, the action is called induction. The <u>action</u> is <u>induction</u>; the ability or <u>property</u> is <u>inductance</u>.

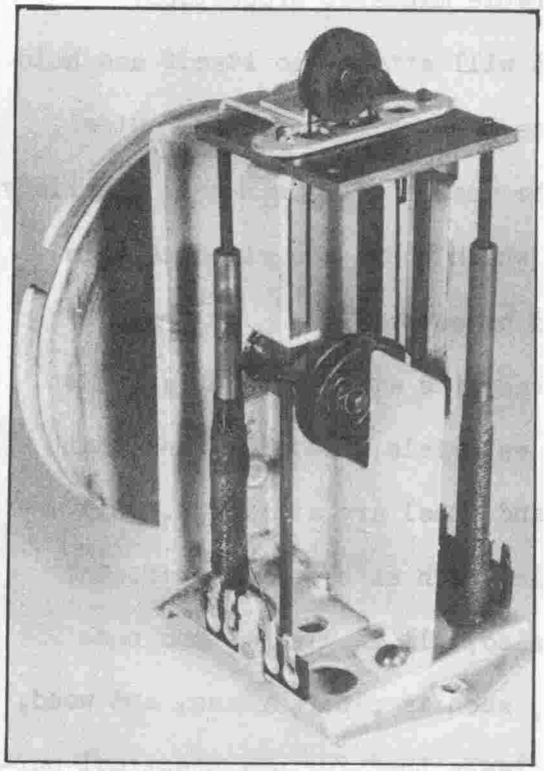

FIG. 1.
This is a receiver tuning unit using adjustable cores of powdered iron to vary the inductances of the coils.

Inductance is a property of every circuit and of every conductor, even though the conductors are straight wires. However, if we take a straight wire and wind it into a coil, the inductance of the coil becomes many, many times as great as that of the straight wire. Consequently, when we need any considerable inductance in small space, we use a coil. This explains why coils often are called <u>inductors</u>.

Surrounding every conductor, and every coil, in which there is electron flow we find a magnetic field. When there is a change in rate of electron flow, there is an accompanying change in the strength of this magnetic field. It is the changes of magnetic field strength that induce emf's in the conductor and in other nearby conductors. Therefore, in order to understand inductance and induction we must first get acquainted with magnetic fields. The easiest way to get acquainted with magnetic fields is to examine the action of magnets, which possess such fields.

## MAGNETS

All of us are more or less familiar with permanent magnets, such as the toy magnet shown holding a piece of steel rod in Fig. 2. These are called permanent magnets, because they retain their magnetic properties for long periods. All permanent magnets are made of steel, usually alloyed with other substances to give the steel desirable magnetic properties.

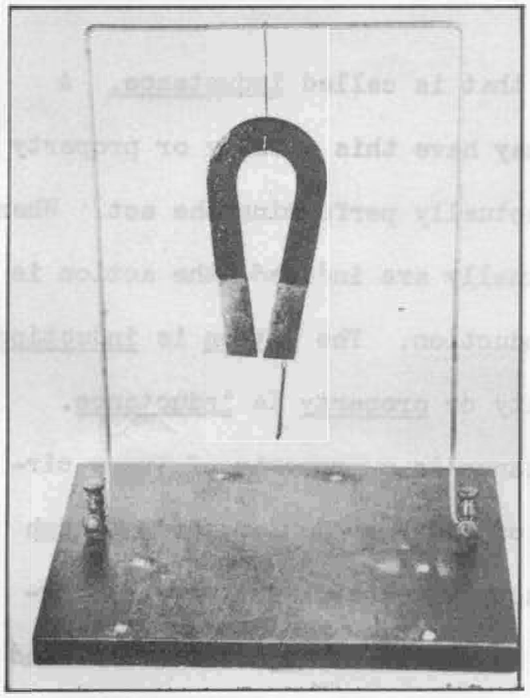

FIG.2.
A magnet attracts and holds pieces of iron or steel.

A magnet will attract to itself and hold other pieces of steel or of iron. Steel, it should be understood, is merely a variety of iron in which there are mixed certain proportions of carbon.

If you test the attraction of a magnet on various materials, you will find that only iron and steel are attracted. All other metals, such as brass, copper, and aluminum, also, all insulators and non-conductors, such as paper, glass, and wood, are not entirely affected by the magnet. This we learn that for all practical purposes, it is only iron and its variety called <u>steel</u> that have magnetic properties.

Nickel, cobalt, and certain metallic mixtures or alloys are weakly magnetic, but they do not interest us in radio work.

A magnet attracts iron and steel because of a magnetic force of attraction which exists near the ends or "poles" of the magnet, and in the space between the poles. The space in which this force acts is called the magnetic field.

For a further test with a permanent magnet, hold the poles of the magnet underneath a sheet of cardboard or glass or anything else which is not iron or steel. On top of the sheet lay a steel sewing needle. When you move the magnet about underneath the sheet of non-magnetic material, the needle will follow the poles of the magnet. Thus we learn that the magnetic field is entirely unaffected by the presence of any substances other than iron or steel. The field acts through all these other non-magnetic materials just as though they were not present, or as though the space were occupied by the same thickness of air or by a vacuum. There is no such thing as an insulator for magnetic fields.

## MAGNETIC FIELDS

In radio we seldom are interested in the attractive force of magnets, but we are greatly interested in the magnetic fields. An easy way to examine magnetic fields is to use some very small particles of iron or steel, such as iron filings, letting the filings fall into the field of a magnet.

For such an experiment we shall use the permanent magnet shown in Fig. 3. The U-shaped magnet itself is of hard steel, which is the kind of steel that retains its magnetic properties. On the ends or poles of this magnet are extensions made of very soft iron. These are called "pole pieces". The magnetic force goes from the magnet poles through the pole pieces, and the magnetic field then extends from pole piece to pole piece just as formerly it extended from pole to pole. The pole pieces are used here to give us a longer field,

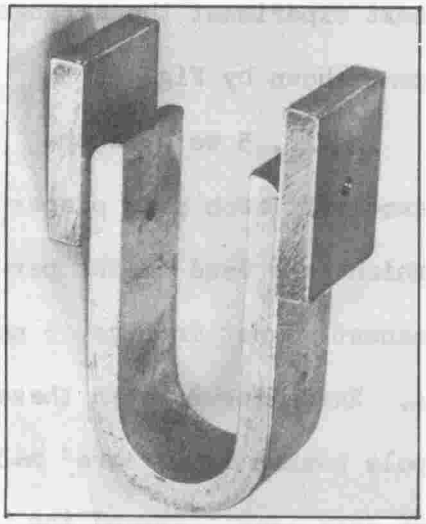

FIG.3.
A permanent magnet with extended pole pieces.

more easily examined.

The pole pieces were held so that they pointed upward, and a sheet of paper was laid on top of them. Then iron filings were allowed to drop onto the paper, which means that they were dropped into the magnetic field. The result is shown by Fig. 4, where the pattern formed by the filings shows exactly how the magnetic force extends outward around the magnetic poles, and how it is concentrated in the space between the poles.

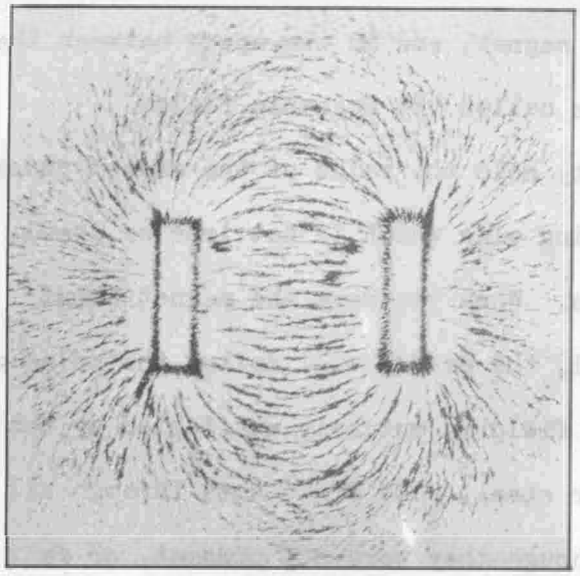

FIG. 4.
The field pattern of the permanent magnet.

Here we have observed the effect of the magnetic field and the magnetic forces between the poles of a permanent magnet. Earlier it was stated that there are magnetic fields around conductors, in which there is electron flow, and of course, there are magnetic fields in and around coils in which there is electron flow. To observe what happens with a coil we shall use for our next experiment the arrangement shown by Fig. 5.

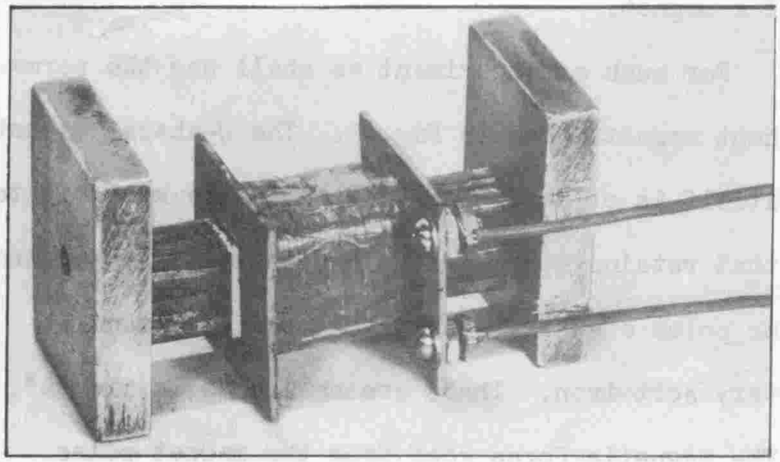

FIG. 5.
An electromagnet with core and pole pieces of iron.

In Fig. 5 we have the same soft iron pole pieces which were used on the permanent magnet in Figs. 3 and 4. Extending between these pole pieces is a "core" made of soft iron. Around the center of the core is a coil made by winding many turns of insulated wire on a form. Electron flow enters and leaves the coil through the wires extending toward the right.

When there is electron flow around the turns of the coil, there is a magnetic field produced in and around the coil. The magnetic force concentrates itself in the core and in the pole pieces, so that most of the field which is outside of the core extends across from the top of one pole piece to the top of the other one. To observe the magnetic field which results from electron flow in the coil, we shall lay on top of the pole pieces a sheet of paper, and sprinkle onto the paper a quantity of iron filings. The result is shown by Fig. 6. Here we have exactly the same kind of magnetic field pattern which we had in Fig. 4. Magnetic fields have the same general properties whether the fields are produced by permanent magnets or by forces due to electron flow in coils. The magnet of Fig. 5 may be called an electromagnet.

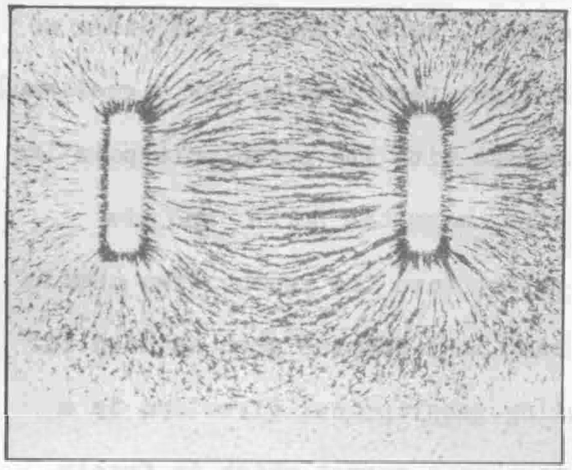

FIG.6.
The field pattern of the electromagnet.

From Figs. 4 and 6 it is apparent that the magnetic forces in the fields are acting along curved and straight lines extending outward from the poles and extending from pole to pole. These lines along which the force appears to act are called magnetic lines of force. It is assumed that the lines of force extend not only through the field but also through the steel of a permanent magnet or through the core and the center of a coil. It is assumed that lines of force are continuous, that they are without beginning or end, that they are "closed loops" forming a sort of magnetic path that often is referred to as a magnetic circuit.

The poles of any magnet are identified as a north pole and a south pole. It is assumed that the magnetic lines of force come out of the north pole, go from north pole to south pole through the field, enter the south pole, and go through the magnet back to the north pole. We say that all of these things are "assumed", because the lines of force are not anything real, like wires, but are merely the paths or directions along which the force acts. Saying that the lines issue from a north pole and go into a south pole is simply a matter of convenience when talking about the lines, it is a convention which has been adopted in the science of electricity.

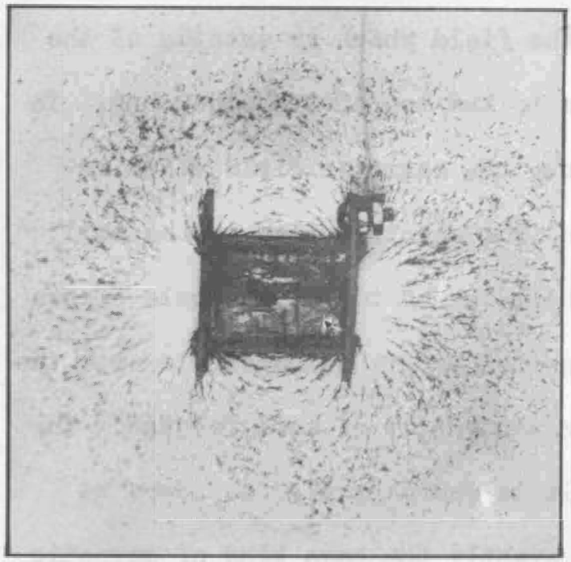

FIG.7
The field pattern of the coil with no iron core.

We speak of a north pole and of a south pole because, were a magnet suspended so that it might turn freely, the magnet would come to rest with its north pole pointing toward the magnetic north and its south pole toward the south. The needle or pointer in a compass such as used for indicating geographical direction is a small permanent magnet which is freely suspended or pivoted and which points north and south. The north pole of the compass needle points toward the north and the south pole toward the south.

Now returning to our experiments with magnetic fields, we may look at Fig. 7. Here the pole pieces and the central iron core of Fig. 5 have been removed from the coil, a sheet of paper has been put through the center of the coil, along the coil axis, and filings have been dropped while there is electron flow in the coil. The field pattern is plainly visible.

With the coil alone the magnetic lines issue from the ends, at first traveling in line with the coil axis. Then the lines curve around the outside of the winding and extend all the way from one end or pole to the other end or pole. It is plain that the magnetic lines of the field do not originate in the iron or steel of a core, nor in the iron pole pieces, but rather in the coil itself.

When there is iron or steel in part of the magnetic field or magnetic circuit, the field is many times stronger than when it extends through air for its entire distance. This is because it is many times easier for the magnetic force to act in iron or steel than in air, or in anything at all other than iron or steel, and the field strength is much greater than in the portion of the field that does pass through air.

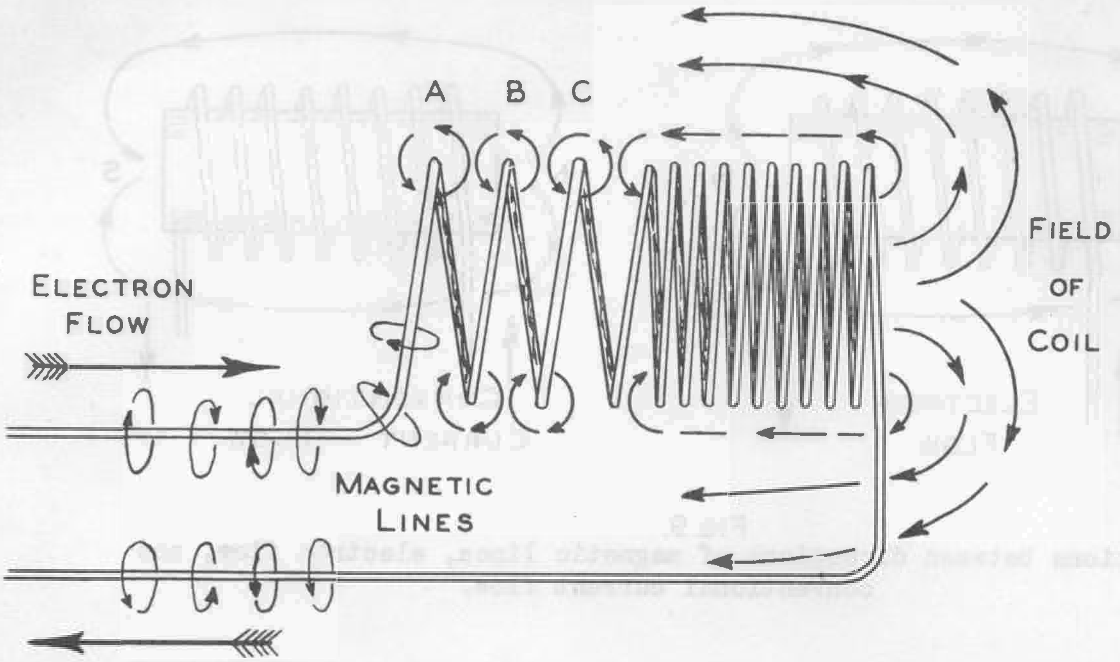

FIG.8.

Magnetic lines around the conductors join together in a coil.

It would be possible to continue the experiments by using a straight wire, and we should then find that magnetic lines of force encircle the wire. Such circular lines of force, which are in the magnetic field around a straight wire, are represented at the left in Fig. 8 by the small circles with arrows indicating the directions of the lines, and where the directions of electron flow in the wires are indicated by the large arrows.

Were the wire made into a coil with turns very widely separated, as at A, B, and C in the diagram, the magnetic lines still would encircle the turns as shown by the small circles with arrowheads. But when the turns of the coil are closer together, as at the right, all of the lines which are in one direction on the outside of the winding join together and form the magnetic field which became evident around the outside of the coil in Fig. 7. All of the magnetic lines which are in the opposite direction inside of the winding join together and become the portion of the magnetic field which is inside the winding.

The greater the rate of electron flow in a straight conductor or in a coil, the stronger becomes the magnetic field around the conductor or coil, and the farther the field extends outward from the conductor or coil. The direction of the field lines in and around a coil depends on the direction of electron flow around the winding. The relations are shown by Fig. 9. At the left are shown the directions of electron flow into and out of the winding, also the accompanying directions of magnetic lines of force and the resulting magnetic poles. The poles are marked "N" for the north pole and "S" for the south pole.

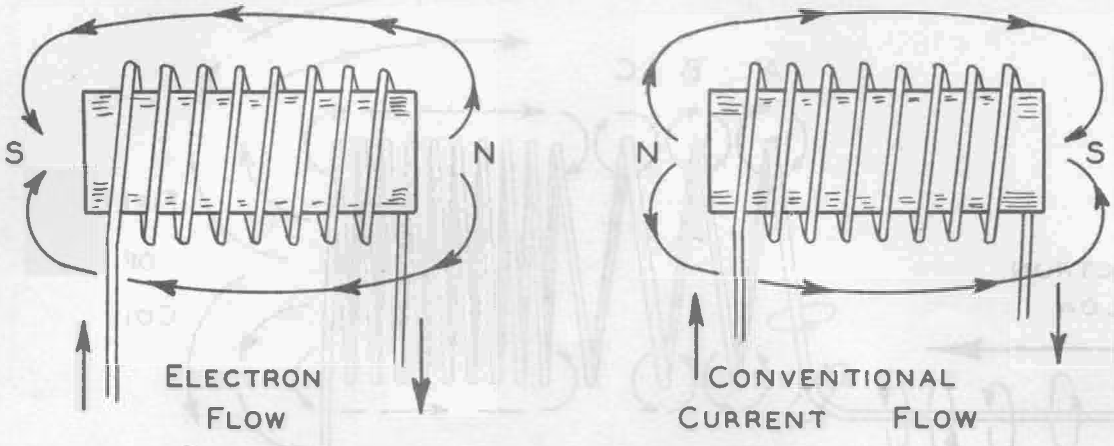

FIG.9.
Relations between directions of magnetic lines, electron flow, and conventional current flow.

Note this in relation to the polarity and direction of electron flow in a coil: if, when you look at either end of the coil, the direction of electron flow in the winding is clockwise or right-handed, you are looking at the north pole and magnetic lines issuing from inside the coil are coming toward you. If electron flow is counter-clockwise or left-handed, you are looking at the south pole and the lines are going away from you into the center of the coil. These rules hold good whether the coil has an iron or steel core, or has a core of air or some other non-magnetic material.

Were we to consider the direction of conventional current flow, which is opposite to actual electron flow, the relations between direction of current and winding polarity would be as shown at the right in Fig. 9.

## ELECTROMAGNETIC INDUCTION

The action by which an electromotive force is induced by a magnetic field is correctly called electromagnetic induction. When an electric charge is induced by an electric field,the action is called electrostatic induction. When iron or steel is made to become a magnet by means of a magnetic field, the action is called magnetic induction. Of these three kinds of induction the electromagnetic kind is employed so much more than the others that when we use the word <u>induction</u> alone, it may be assumed to mean electromagnetic induction.

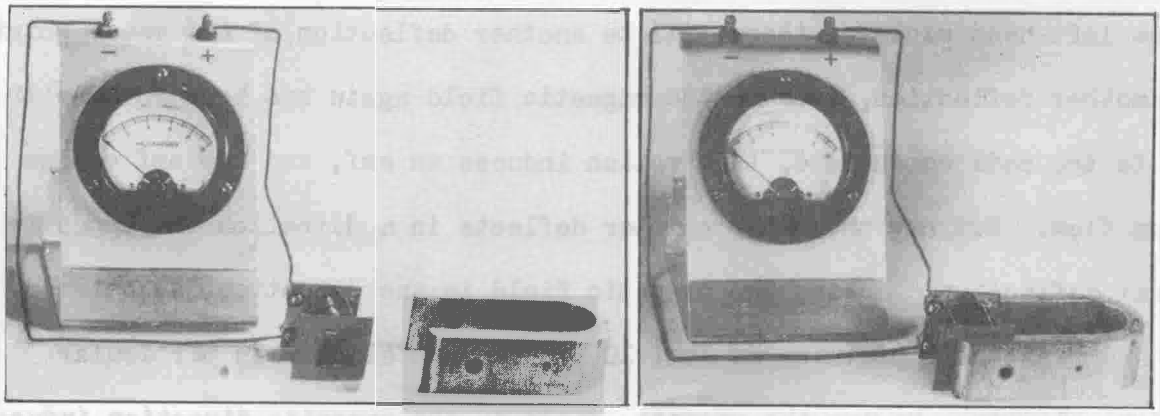

FIG.10.

When the magnet, with its field, is moved toward or away from the coil,there is induction and an induced current.

Electromagnetic induction may be observed with the simple setup pictured in Fig. 10. We have a current-indicating meter, a coil, and a permanent magnet. The meter is a milliammeter used in many earlier experiments. The coil is the same one used for preceding experiments in this lesson: first with an iron core and then with an "air core". The permanent magnet is the one used in those preceding experiments.

If you move the magnet from its position in the left-hand picture of Fig. 10 into its position in the right-hand picture, the pointer of the current-meter will move away from its zero position and then return to zero. When moving the magnet, you have moved its magnetic field. The magnetic lines of force in the magnetic field have been moved across the conductors which are the turns of the coil winding. We may say that the conductors have been "cut" by the lines of force.

While the moving magnetic field is cutting through the conductors of the coil, there is an emf induced in these conductors. The emf causes an electron flow or current to flow in the coil winding and in the connected meter -- and the meter indicates the electron flow. But as soon as the magnet and its field lines come to rest, the meter pointer drops back to zero. It is not the fact that the magnetic field is in the space occupied by the coil which accounts for the emf being produced; it is the motion of the field through the conductors of the coil that induces the emf.

If now you pull the magnet away from the coil, returning the magnet to its position in the left-hand picture, there will be another deflection of the meter pointer. There is another deflection, because the magnetic field again has been moved with reference to the coil conductors, this motion induces an emf, and the emf causes an electron flow. But now the meter pointer deflects in a direction the opposite of its first deflection. Moving the magnetic field in one direction, as between left-hand and right-hand pictures of Fig. 10, induces an emf in one particular direction or polarity. Moving the magnetic field in the opposite direction induces an emf in the opposite direction or polarity.

There will be emf's induced in the coil winding, no matter in what direction you move the magnet with reference to the coil, just so long as the magnetic lines of force cut across the conductors or turns of the coil. The magnet, with its field, may be moved up and down, or sideways, or it may even be waved back and forth above the coil or on either side of the coil, and in every case the induction of emf's will be shown by deflections of the meter pointer.

It is fairly obvious that were the magnet and its magnetic field to be held stationary while the coil is moved into and out of the magnetic field, or through the magnetic field, we should have exactly the same actions as with the moving magnetic field and stationary coil -- so far as induction of emf's in the coil is concerned.

We may say that when there is relative motion between a magnetic field and conductors in any direction which causes the magnetic lines to cut the conductors, emf's will be induced in the conductors. If the conductors so cut by magnetic lines happen to be part of a closed circuit, the emf's will cause electron flows or currents in the circuit.

While the apparatus of Fig. 10 is set up, there is one more thing to observe. It is this: if you move the magnet slowly toward and away from the coil winding, the meter pointer moves only a little ways from its zero position, but if you move the magnet quickly, the meter pointer deflects much farther. This illustrates the fact that the strength of the induced emf, as measured in volts, is directly proportional to the rate at which magnetic lines cut conductors, or is directly proportional to the number of such cuttings per second.

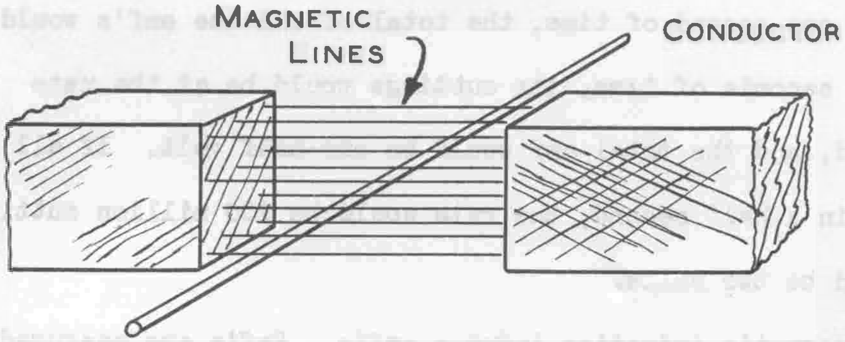

FIG. 11
Movement of the conductor or the field causes "cuttings".

The idea of magnetic lines cutting across a conductor, or of a conductor cutting magnetic lines, may be made clearer by examination of Fig. 11. Here we represent magnetic lines as extending through the magnetic field space between two magnetic poles, with a straight conductor in the field and at right angles to the lines. If this conductor is moved either upward or downward, it will cut across field lines. If the magnet poles and the field were moved either upward or downward, with the conductor stationary, the lines of force would cut across the conductor. If both the conductor and the field were in motion, at different speeds or in different directions, there would be cuttings.

In Fig. 11 we have represented only a few lines of force. One measure of the strength of magnetic fields is in accordance with the number of assumed lines per square inch of cross section of the field. When using such measurements, we speak of the magnetic lines as the "magnetic flux", and we speak of the number of lines per square inch as the "flux density". Flux densities of 50,000 to 100,000 lines per square inch of cross section are employed in radio apparatus. Were the cross section of the field in Fig. 11 to be one square inch, and were the flux density what we call 50,000 lines per square inch, a conductor would cut through 50,000 lines in moving through this field. If two conductors were side by side, each would cut 50,000 lines, and the total number of cuttings would be 100,000 lines.

Supposing that we had 2,000 conductors, each cutting 50,000 magnetic lines in passing through a magnetic field. The total cuttings would be 100 million. Supposing too that all of these conductors were so connected electrically that the emf's induced in all of them would add together. This could be done by having the conductors form the turns in a coil. If all these conductors, or coil sides, were to pass through the field in one second of time, the total of all the emf's would be one volt. If it took two seconds of time, the cuttings would be at the rate of only 50 million per second, and the total emf would be one-half volt. If all the cuttings were completed in a half second, the rate would be 200 million cuttings per second, and the emf would be two volts.

The action called electromagnetic induction induces emf's. Emf's are measured in volts or fractions of a volt. Therefore, the effect of induction may be measured in volts. There are several ways of increasing the induction and the volts of emf. 1, we may form the conductors into a coil, thus permitting many side by side conductors in small space. 2, we may increase the number of turns in the coil, thus increasing the number of cuttings with any given motion. 3, we may increase the relative speed of the coil and the magnetic field, thus increasing the number of cuttings per second of time.

## MUTUAL INDUCTION

Although it is possible to induce emf's in a coil winding by using the magnetic field of a permanent magnet, as in preceding experiments, this is not the way in which induction is used in radio apparatus. The permanent magnet and its field allowed simple demonstrations of important principles which we now shall proceed to use in other ways.

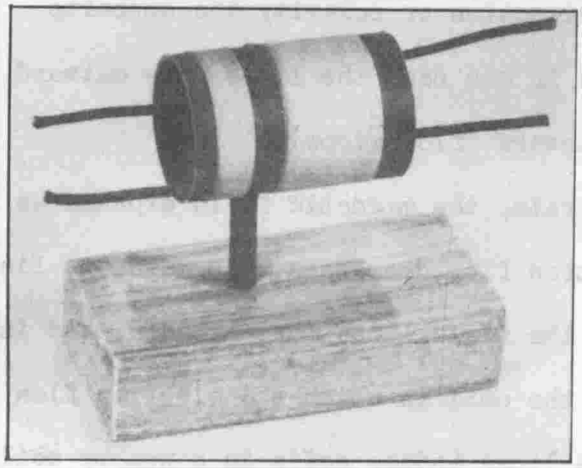

FIG.12.

A simple type of air-core transformer.

In Fig. 12 two windings are on a piece of insulating tubing. Terminal leads for the windings are brought out from the ends of the tubing. If there should be any change of rate of electron flow in the left-hand winding, there would be induced in the right-hand winding an emf, and were the right-hand winding in a closed circuit, there would be caused an electron flow in that circuit. Should there be any change in the rate of electron flow in the right-hand winding, there would be induced in the left-hand winding an emf, and there would be an accompanying electron flow in any closed circuit of which the left-hand winding formed a part.

The two windings or two coils have <u>mutual induction</u>, meaning that a change in rate of electron flow in either one will induce an emf in the other. When we speak of a change of electron flow, we mean any one of four things: 1, a flow may commence when, to begin with, there is no flow. 2, a flow already in existence may increase in rate. 3, a flow already in existence may decrease in rate. 4, a flow may cease. Induction will occur with any one of these changes.

An emf is induced in one coil when there is a change in rate of electron flow in the other winding for the following reasons. If there is no flow to begin with, and a flow commences, there is no magnetic field to begin with and then the field spreads out around the winding. The field and the magnetic lines of force move outward, and in doing so the lines cut through the conductors forming the turns in the other coil. This cutting induces an emf in the conductors of the other coil, just as any relative movement and cutting of lines of force and conductors results in an induced emf. If an electron flow stops, the magnetic field and lines which existed around the winding collapse as the flow stops, and in collapsing they shrink back into the coil. Again there is movement of these lines of force through the conductors of the nearby coil, and an emf is induced in that coil. The emf induced by stopping the electron flow is in a direction or polarity the opposite of that induced by starting the flow, because in one case the lines move outward (flow commences) and in the other they move inward (flow stops).

If an existing electron flow increases in rate, the magnetic field expands as it becomes stronger, and if an existing electron flow decreases, the magnetic field contracts as it becomes weaker. In one case the field lines move outward, and in the other they move inward with reference to the coil in which the electron flow exists. These movements of the field and the lines induce emf's in a nearby coil. The induced emf's will be in one polarity when electron flow is increasing, and in the opposite polarity while the electron flow is decreasing.

The strength of the magnetic field, and the distance which the field and lines of force extend outward from a coil, depend on the rate of electron flow in the coil. The greater the rate of flow or current, the larger is the field, and the less the rate of flow the smaller is the field. But no matter how great or small is the magnetic field, there will be no induction unless the field is moving. So long as the coil having the magnetic field is stationary, the only way to make its magnetic field move is to have a change in rate of electron flow. With stationary coils there is induction and induced emf only while the rate of electron flow is changing in one of the coils.

The two coils or sindings of Fig. 12 form a very simple <u>transformer</u>. A transformer may be defined as a device in which energy is transferred from one circuit to another circuit by means of mutual induction. When electrons flow through one of the windings, energy which is in the electrons is used to build up the force which is the magnetic field, and then the energy, or most of it, is in the magnetic field. As the field moves through the conductors of a nearby winding, energy from the magnetic field produces electromotive force in the nearby winding. The electromotive force causes electrons to flow in this winding, and the moving electrons possess energy. Thus there is transfer of energy from the circuit containing the first winding over into the circuit containing the second winding, although there is no electron flow from the first into the second circuit.

The winding of a transformer to which energy is first delivered is called the primary winding. The other winding, from which the transformer delivers energy, is called the secondary winding.

At the left in Fig. 13 are two coils mounted one above the other. These two coils would act as the primary and secondary windings of a transformer. The manner in which these coils are wound is called a duolateral winding. This is one method of winding a coil with many turns in small space, the object being to provide a considerable induction effect or considerable inductance in small space.

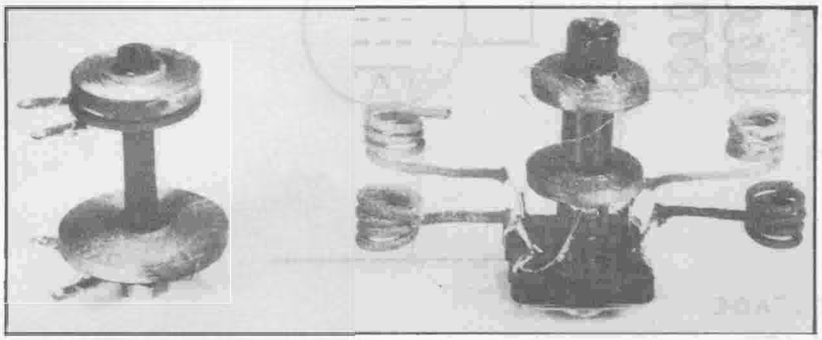

FIG.13.

Two duolateral coils, at the left, and at the right, an i-f transformer made with such coils.

At the right in Fig. 13 is shown the inside of an intermediate-frequency transformer whose primary and secondary windings are duolateral coils mounted some distance apart on an insulating tube. The primary winding would be connected into the plate circuit of one of the tubes in a receiver, and the secondary winding connected to another circuit, which may be the control grid circuit of a following tube. The transformer then provides means for transferring energy from the plate circuit of the first tube into the grid circuit or other kind of input circuit for the following tube.

The connection of the primary and secondary windings of an intermediate-frequency transformer between the plate circuit of one tube and the control grid circuit of a following tube is shown by the diagram of Fig. 14. In practice there is a capacitor connected across the primary and another capacitor connected across the secondary. The purpose and operation of these capacitors will become clear when we come to a study of resonant circuits. There is also a capacitor between the lower end of the primary winding and the cathode of the first tube. This capacitor allows the rapidly alternating currents at the intermediate frequency to go from the primary winding back to the cathode to complete the circuit for these high-frequency currents without making them go through other parts.

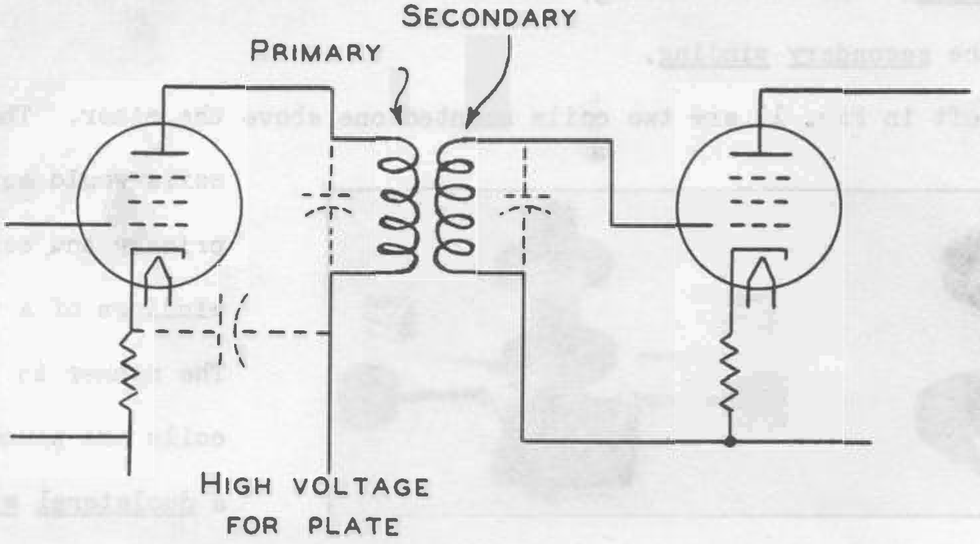

FIG. 14.
How a transformer provides coupling for energy transfer between tubes.

The great advantage of a transformer between tubes is that we may have high voltages in the plate circuit and low voltages in the following grid circuit at the same time, because the primary and secondary windings are insulated from each other. Yet, in spite of the insulation, there is energy transfer from the plate or one tube to the control grid of the following tube.

With the arrangement of Fig. 14 we say that the first tube is "coupled" to the second one by the transformer, or we say that there is "transformer coupling" between the two tubes. The word <u>coupling</u> refers to any means for transferring energy from one circuit to another. Transformers provide one means for coupling. Transformer coupling sometimes is called coupling by mutual induction, and sometimes it is called merely by the name <u>inductive coupling</u>.

The transformers pictured and represented in Figs. 12 to 14 may be called air-core transformers. The core of a coil or winding is whatever is inside the turns. Because everything that is not iron or steel acts like air so far as magnetic and induction effects are concerned, all coils or windings which do not have cores of iron or steel may be spoken of as air-core types. There may be various metals and various non-conductors and insulators in the core space, but we still speak of air cores.

Earlier we observed that the presence of iron or steel in the core space of a coil greatly increases the strength of the magnetic field and, of course, increases the induction effects. The inductance of a given coil with an iron or steel core is many times greater than that of the same coil with an air core.

To increase the induction and inductance of the windings in transformers they may be so constructed that the entire path for the lines of force is through iron of a core such as illustrated by Fig. 15. This core has two openings, called windows, through which pass the turns of the windings. There are three "legs": one large one in the center and two smaller ones on the outsides of the windows. Both the primary and secondary windings are around the center leg, with one winding right outside of the other one. Thus nearly all of the changes of flux that occur in one winding pass through the other winding as the field of one winding expands and contracts with changes of rate of electron flow.

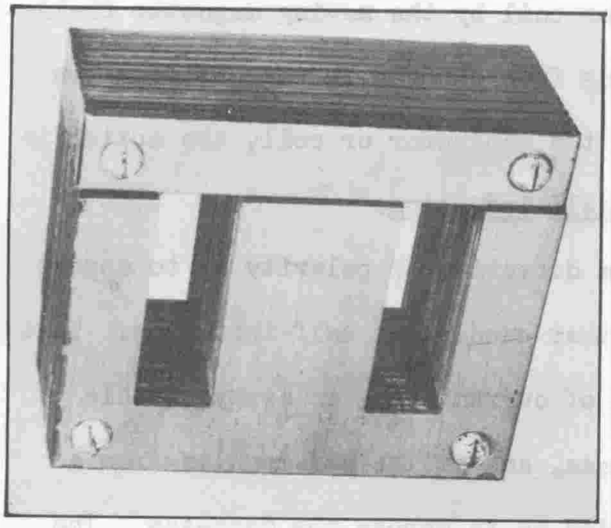

FIG.15.

A transformer core made with many thin pieces of steel.

## SELF-INDUCTION

We have learned that when magnetic lines of force expand and contract around a coil, and cut through the turns of another coil, there is an emf induced in the other coil. We know that the magnetic lines originate in the conductors which form the turns of a coil, and that all the lines around all the turns join together to form the magnetic field of the coil. When you stop to think about it, it is quite apparent that the lines of force which expand and contract around any one turn of a coil must cut through the adjacent turns, and if the field around the turn extends far enough, the lines will cut through every other turn of the coil, since any cuttings of magnetic lines through conductors induce emf's in the turns of the same coil as well as in the turns of any other nearby coil. When emf's are induced in a conductor or coil by the moving magnetic fields resulting from changes in rate of electron flow in the conductor or coil, the action is called <u>self-induction</u>.

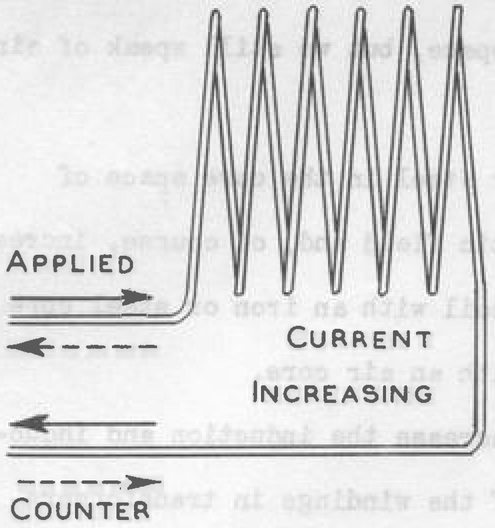

FIG.16. LEFT

Relative directions of counter-emf and applied potential difference.

The emf of self induction always is in such a direction or polarity as to oppose the change in rate of electron flow or current that causes the self-induction. That is, if the induced emf results from an increase of current, the polarity of this emf is in such direction as to oppose the increase, and if the emf results from a decrease of current, this emf is in such direction as to oppose the decrease. The emf of self-induction may be called counter-electromotive force, because this emf always is counter to or against the changes of current. The name <u>counter-electromotive force</u> usually is abbreviated to <u>counter-emf</u>.

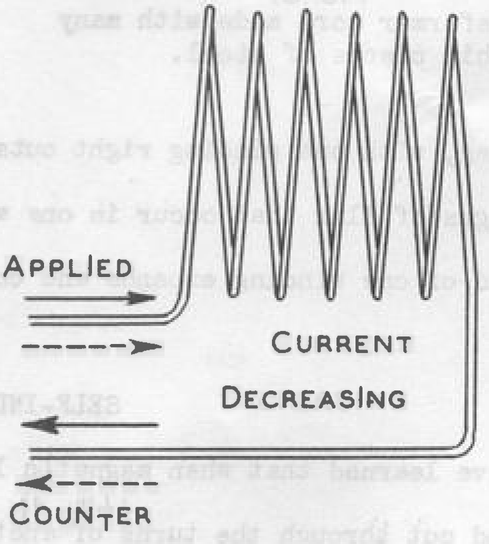

FIG.16 RIGHT

Relative directions of counter-emf and applied potential difference.

While counter-emf always opposes every change of current, it does not always oppose the applied potential difference that is causing the current. This fact may be explained with the help of Fig. 16, where the direction of the applied potential difference is shown by full-line arrows and the direction of polarity of the counter-emf by broken-line arrows. Current flows in a direction which depends on the applied potential difference, and even though the current is increasing and decreasing, it continues to flow in the same direction.

When current is increasing, as represented at the left in Fig. 16, the counter-emf is trying to prevent the increase. Therefore, with increasing current, the counter-emf must be in a direction opposite to that of the applied potential difference. When current is decreasing, as represented at the right, the counter-emf is trying to prevent the decrease. Therefore, with decreasing current the counter-emf must act in the same direction as the applied potential difference.

If you connect a coil, a switch, and a source of direct or one-way potential in series with one another and then close the switch, the current cannot instantly increase to the value which is proportional to the applied potential difference and the resistance of the coil. Upon closing the switch there tends to be a very rapid increase of current. But this means a high rate of change of current, there is induced a proportionately high counter-emf, and the rate of current change is slowed down by the counter-emf. But the current will increase and finally reach its full value, whereupon there is no further change of current and no counter-emf. Then there is a direct current proportional to the potential difference and the coil resistance.

When you open the switch, there tends to be a very rapid decrease of current. But this means a high counter-emf which tends to keep the current flowing. The result may be a small arc or spark at the switch contacts while the high counter-emf forces the current to continue flowing across the gap between the contacts as they separate. Incidentally, if we wished to prevent the sparking, we might connect across the switch contacts a capacitor, as at C in Fig. 17. Then the counter-emf would cause an electron flow which would charge the capacitor until voltage across the capacitor reached the same value as the counter-emf. Thereafter the capacitor would discharge through the circuit consisting of the coil and the source.

If you apply an alternating potential to a coil, the potential is continually changing the rate of electron flow or current in the coil. There are continual

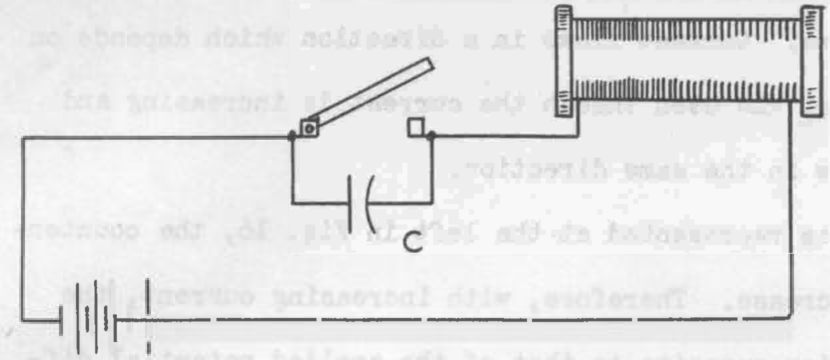

FIG.17

A capacitor will take current caused by counter-emf.

counter-emf's which oppose every rise, fall, and change of direction of the alternating current flowing in the coil. The opposition due to the counter-emf's is in addition to the opposition due to resistance of the wire in the coil. A little later we shall have more to do with the opposition of self-induction to flow of alternating currents.

## INDUCTANCE

To continue our discussion of coils, whose mose useful property is inductance, we must have a unit in which to measure inductance. Remember that inductance is the ability of a coil or of any circuit to produce the action called induction. Inductance would measure the ability to cause mutual induction, which induces emf's in nearby coils and circuits, and it would measure the ability to produce counter-emf's in the coil wherein occur changes of current.

The unit of inductance is called the <u>henry</u>, named for Joseph Henry who was an American physicist. Here is the definition of a henry of inductance. If the induced emf has a value of one volt when current is changing at the rate of one ampere per second, the coil or circuit has inductance of one henry. When we speak of a current change of one ampere per second, we mean, for example, that the current would change from two amperes to three amperes, or from three amperes to two amperes, within one second of time.

The henry is a unit used for measuring either self-inductance or mutual inductance. So many henrys of self-inductance are a measure of the ability of a circuit or coil to induce emf's in itself. A certain number of henrys of mutual inductance would measure the ability of two circuits or coils to induce emf's in each other.

An inductance of one henry is a rather large value, suitable for measurement of inductances of iron-cored transformers and chokes where we commonly find inductances between three or four and several hundred henrys, with usual values in the range of five to thirty henrys. For air-core coils having many turns in small space, such as the duolaterally-wound high-frequency choke coil of Fig. 18, inductances may be measured in millihenrys. One <u>millihenry</u> is one one-thousandths of one henry.

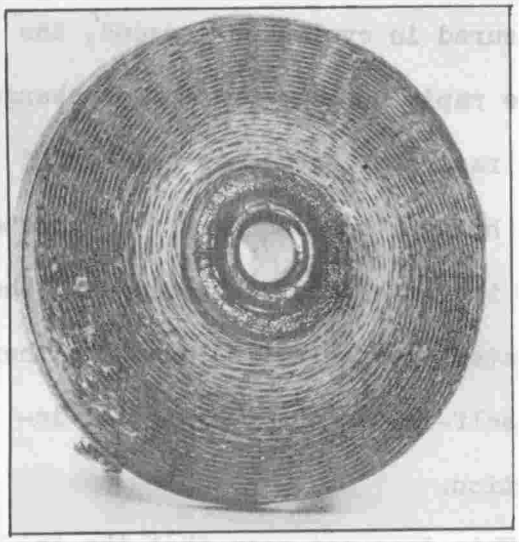

FIG.18.

One style of duolateral coil.

For air-core tuning coils such as those shown in Fig. 12, and also for the high-frequency air-core transformer of Fig. 19, the inductance is measured in microhenrys. One <u>microhenry</u> is one one-millionth of one henry. The transformer of Fig. 19 has for its primary winding two turns around the outside of the secondary winding, which has 20 turns. Connections to the primary and secondary windings are made through the pins mounted on an insulating bar across the bottom of the transformer. These pins or plugs fit into "jacks" somewhat as the pins of radio tubes fit into the socket openings.

## CIRCUIT INDUCTANCES

Emf's which result from the action called induction are caused by changes of current. The greater the rate of change of current, in amperes per second, the stronger will be the induced emf's. Supposing that we consider an alternating current, which is continually changing. Alternating current flows first in one direction and then in the opposite direction. At the end of the flow in one direction the flow must reverse, and at the instant of reversal the electrons must stand still. At this instant there is no current, for current means electron flow. Then the electrons gain speed in the reverse direction, reach a maximum speed in this direction, and then slow down preparatory to stopping and reversing their direction once more.

It is apparent that the higher the frequency of the alternating current, as measured in cycles per second, the more rapidly the current must change its rate of flow. This means that the higher the frequency, the greater are the effects of induction and the greater are the emf's induced either by self-induction or by mutual induction.

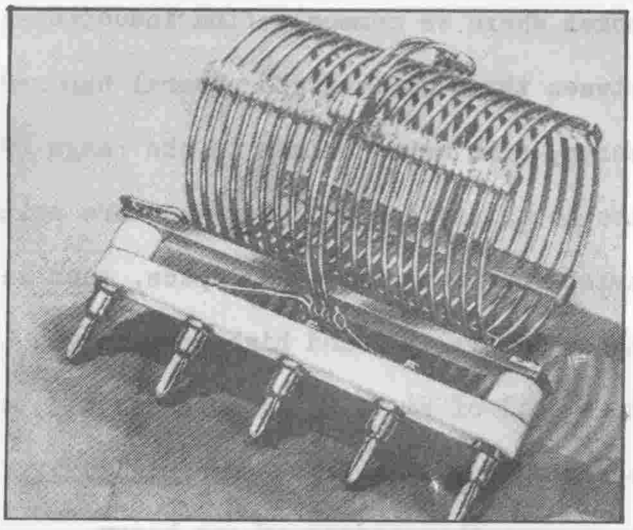

FIG. 19.
A high-frequency transformer with spaced turns.

This does not mean that the inductance of a coil or circuit changes with change of frequency; it means only that with any given inductance there is more induction and greater induced emf's at high frequencies than at lower frequencies. Inductance is the property of a coil or circuit to cause induction. The inductance of a coil or circuit depends entirely on the construction and dimensions. In this respect inductance is like capacitance, for the capacitance of a capacitor depends entirely on the construction and dimensions of the capacitor, not on the applied voltage nor on the electron flow into and out of the capacitor.

If current in a coil or circuit having small inductance is at high frequency, we may have the same induction effect and the same induced emf's as with a coil or circuit of large inductance when the frequency is low. The induced emf's are proportional to inductance and to frequency. More inductance or more frequency or both will result in greater induced emf's, while less of either or both of these factors will result in smaller induced emf's. At very high frequencies even small inductances have important effects, because there are strong induced emf's.

Since there are magnetic lines of force and a magnetic field around a straight wire that is carrying electron flow, and because the lines of force expand and

and contract with changes in rate of flow, emf's are induced in straight wires, and straight wires have inductance. The moving magnetic field around one straight wire may pass through any other wires in the vicinity. Then emf's are induced in the other wires; we have mutual induction as the action, and the wires have mutual inductance.

In every part of every radio circuit there are self-inductances in all of the individual conductors, and there are mutual inductances between every pair of conductors. These inductances are small. At power-line frequencies, such as 60 cycles, and even at most audio frequencies, the inductances of wiring have little effect on performance. But at intermediate frequencies and at radio frequencies the small inductances may cause relatively great induced emf's, and unless the wiring is carefully laid out we get into much trouble.

## SELF-INDUCTANCE OF COILS

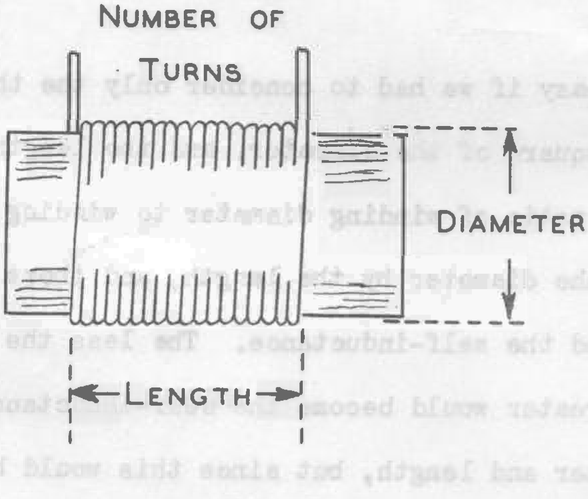

FIG.20.
Factors in self-inductance of a single-layer coil.

The self-inductance of a single-layer coil depends on the three factors shown by Fig. 20: number of turns, length of winding, and diameter of winding. A single-layer coil is one having all the turns side by side from one end to the other. Single-layer coils are pictured in Figs. 12 and 19. When turns are more than one layer deep, we have a multi-layer coil, of which one type is shown in Fig. 18. The length of winding is supposed to be the distance from the center of the turn at one end to the center of the turn at the other end. The turns may be close together, or else we have "spaced turns" as in the windings of Fig. 19. If the coil is wound on a form made of insulation or other material, the length of the form has nothing to do with the inductance of the coil; it is the length of the winding that counts. The diameter is supposed to be the distance, through the coil axis, from the center of one side of a turn to the center of the other side of this turn.

Self-inductance is directly proportional to the square of the number of turns. Doubling the number of turns gives four times the inductance, because the square of 2 is 4, and halving the numbef gives one-fourth the inductance, because the square of 1/2 is 1/4. If you had a coil of 20 turns, fof which the square is 400, and could add 10 more turns without changing the winding length or the diameter, you would have 30 turns, for which the square is 900. Then the inductance of the rebuilt coil would compare with that of the ofiginal coil in the ratio of 900 to 400, meaning that it would be 2 1/4 times as great.

Self-inductance is directly proportional also to the square of the winding diameter. Double the diameter means four times the inductance, and half the diameter means one-fourth the inductance, and so on. Other factors must remain unchanged.

Self-inductance is inversely proportional to the length of winding. That is, doubling the length will mean half of the inductance, while halving the length will mean twice the inductance — so long as the number of turns and the diametef remain unchanged.

Calculation of self-inductance would be easy if we had to consider only the three items just mentioned: square of the turns, square of the diameter, and the length. But self-inductance is affected also by the ratio of winding diameter to winding length, or to the numbef found by dividing the diameter by the length, and there is no constant proportion between this ratio and the self-inductance. The less the diameter in proportion to the length, the greater would become the self-inductance were it possible to maintain the same diameter and length, but since this would be wholly impossible, we find that in actual practice long, small diameter coils have less self-inductance than short ones of lafge diameter.

At A in Fig. 21 is represented a winding 5 inches long and 1 inch in diameter. If this winding were to have 50 turns, the self-inductance would be 11.5 microhenrys. At B the length and diameter both have been made 2½ inches. With 50 turns this coil would have self-inductance of 107.5 microhenrys. At C the length has been made 1 inch and the diameter 5 inches. With 50 turns we now would have self-inductance

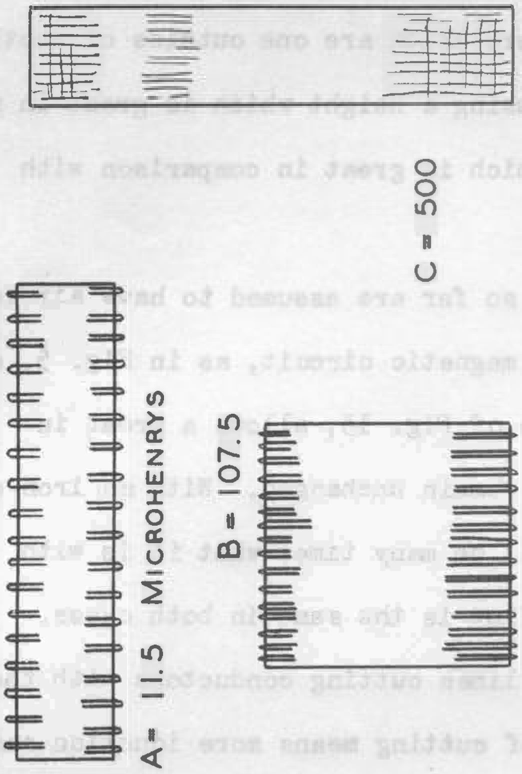

FIG.21.
Self-inductance varies with dimensions and proportions of coils.

of 500 microhenrys. The great differences in self-inductance are due largely to two facts: one being that the self-inductance is proportional to the square of the diameter, which is 25 times as great at C as at A, and the other being that the turns are close together at C and far apart at A when we use the same number of turns in both cases.

Were we to put the turns as close together at A and B as at C, we would have 50 turns at C, 125 at B and 250 at A. Now the fact that the square of the number of turns is proportional to the inductance takes effect, and we have self-inductances of 287.5 microhenrys at A, 672 microhenrys at B, and 500 microhenrys at C.

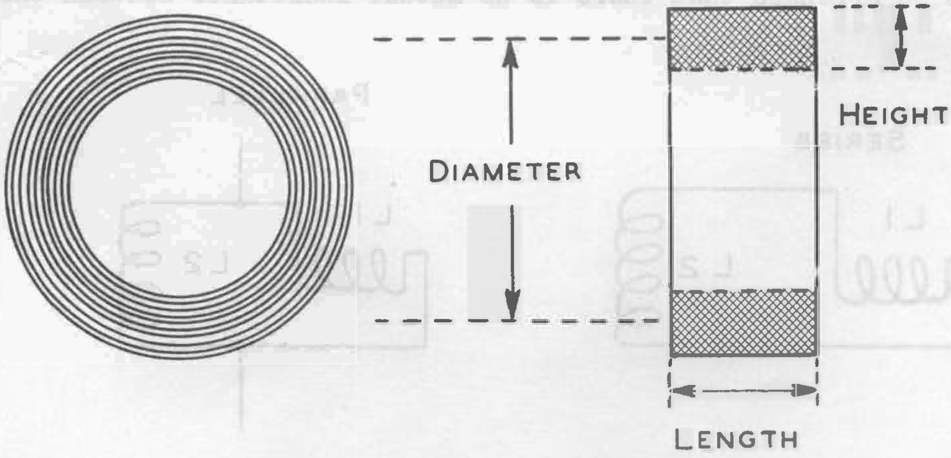

FIG.22.
Factors in self-inductance of multi-layer coils.

In the case of multi-layer coils the number of turns and length of winding have the same effects as with single-layer coils, as has also the diameter, but the diameter is measured between the centers of the opposite sides of the winding, as shown by Fig. 22. In such coils we have an additional dimension, which is the height of the winding through the successive layers which are one outside of another. In general, the self-inductance is increased by using a height which is great in relation to the diameter, also by using a length which is great in comparison with the height.

Single-layer and multi-layer coils considered so far are assumed to have air cores. An iron or steel core forming either part of the magnetic circuit, as in Fig. 5, or else a complete magnetic circuit as with the core of Fig. 15, allows a great increase in self-inductance when all other factors remain unchanged. With an iron or steel core the rate of change of flux density will be many times what it is with an air core when the rate of change of electron flow is the same in both cases. This means that there will be many times as many lines cutting conductors with the iron core as with the air core. A greater rate of cutting means more iduction and stronger induced emf's, and when these occur, we have more self-inductance.

## INDUCTANCES IN SERIES AND IN PARALLEL

When two self-inductances are connected together in series, as at the left in Fig. 23, the inductances add, provided the coils or other inductance units are so far apart or are so arranged that there is no mutual inductance between them. For example, if the self-inductance of unit L1 is 150 microhenrys and that of unit L2 is 200 microhenrys, the total inductance is 350 microhenrys. If there is mutual inductance, and if the emf's induced by the mutual induction act in the same directions as the self-induced emf's in the units, then the mutual inductance is added

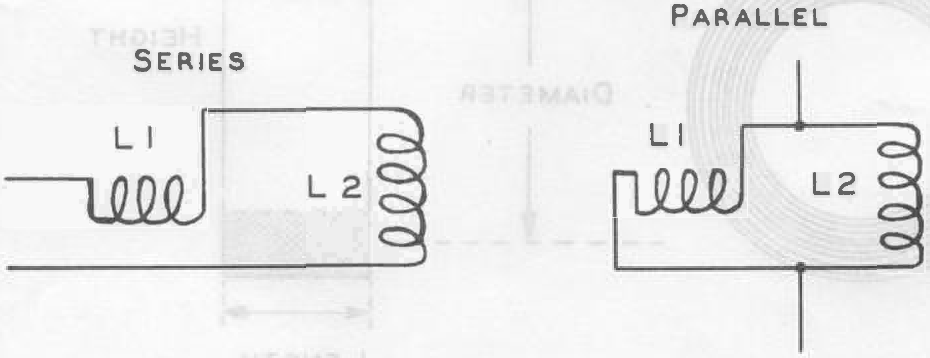

FIG.23.
Self-inductances or coils in series and in parallel.

to the total self-inductance in the circuit. If the emf of mutual induction acts oppositely to the self-induced emf's, then the value of mutual inductance is subtracted from the sum of the self-inductances.

When self-inductances are connected together in parallel, as at the right in Fig. 23, we have the familiar rule of dividing the product by the sum to find the total or effective parallel self-inductance, as an example, supposing that we have separate self-inductances of 20 and 30 microhenrys. The product of 20 times 30 is 600. The sum is 50. Dividing 600 by 50 gives 12 as the parallel self-inductance. This is the way to determine the parallel self-inductance when there is no mutual inductance between the units. If there is mutual inductance, the parallel inductance is increased if the induction emf's aid each other, and the parallel inductance is lessened if the induction emf's (self- and mutual) oppose each other. There is not exact addition or subtraction of the self- and mutual inductances in this case, rather we subtract from the product of self-inductances the square of the mutual, and subtract from the sum of the self-inductances twice the mutual when the emf's aid each other. If they oppose each other, we add to the sum of the self-inductances twice the mutual. These rules are not used often enough to make them worth remembering, but they will be interesting in case you want to work out effects of mutual and self-inductances.

## COIL POSITIONS FOR COUPLING

It has been mentioned before that when there is transfer of energy by means of mutual induction, the circuits between which is the transfer are said to be coupled. The mutual induction and inductance, and the degree of coupling, are affected by the relative positions and sizes of the two coils which provide the coupling.

The "closest" coupling, which means greatest mutual inductance and energy transfer, would be obtained when both coils were of the same dimensions and occupied the same space. Since two solid objects cannot be in the same place at the same time, the closest practicable coupling is obtained with one coil around the outside of the other and with their centers in line, as at A in Fig. 24.

If, as at B, the coils are separated endwise, with their axes still in line,