The EASY COURSE in HOME RADIO

MAJ. GEN. GEO. O. SQUIER, EDITOR-IN-CHIEF

LESSON IV - THE ALADDIN'S LAMP OF RADIO

BY PROFESSOR J.M. MORECROFT
OF COLUMBIA UNIVERSITY

ONE OF THE FOLLOWING SET OF SEVEN LESSONS
1. A GUIDE FOR LISTENERS IN. 2. RADIO SIMPLY EXPLAINED. 3. TUNING AND WHAT IT MEANS. 4. THE ALADDIN'S LAMP OF RADIO. 5. BRINGING THE MUSIC TO THE EAR. 6. HOW TO MAKE YOUR OWN PARTS. 7. INSTALLING THE HOME SET.

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The Easy Course in Home Radio

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CHIEF OF THE SIGNAL CORPS U.S.A.

LESSON FOUR

The Aladdin's Lamp of Radio

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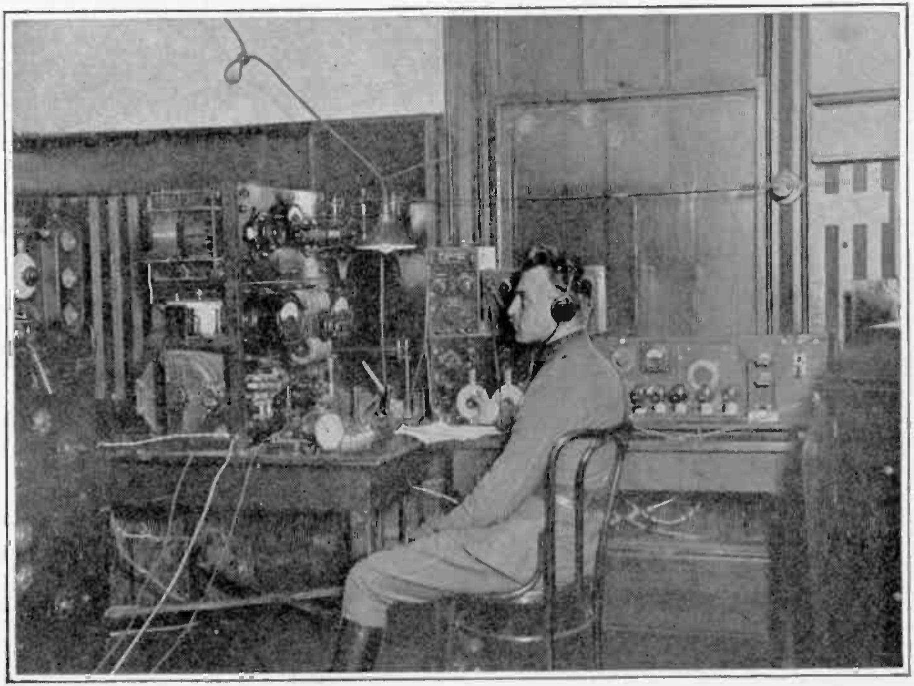


This instrument is a combination of the old and the new. At the left is an old-fashioned spark-transmitting set and on the table at the right a modern receiving set with vacuum-tubes.

LESSON FOUR

What is Matter? What is Electricity?

IN studying the action of the vacuum tube it is very necessary to get a clear idea of the modern scientific concept of the constitution of matter. What does a piece of metal, such as the filament of a vacuum tube, consist of? Is it as dense and solid as it appears? A piece of tungsten wire such as is used for the filament of most vacuum tubes, is made up of a tremendous number of separate particles called atoms, or molecules, and there is much empty space between, and in, these atoms.

Each atom consists of a central portion, called a nucleus or *proton,* and around this proton are grouped many smaller particles called *electrons.* A simple atom may be much like our solar system, the sun corresponding to the proton and the planets, whirling around the sun, to the electrons of the atom.

Many atoms are much more complex than this picture would lead one to believe. Thus the tungsten atom has seventy-four negative electrons grouped about a cluster of nearly two hundred positive protons, together with over one hundred other electrons tightly held together. A solar system to be similar to such an atom would have to have about twenty-five times as many planets revolving about the sun, as has our present system. The hydrogen atom, however, has only one electron revolving about its proton, so that it is very much like the combination of our earth and the moon. The electrons are probably in no closer contact with the proton than are the planets with the sun.

If we imagine a piece of tungsten, the size of a ball, like those used in the ordinary ball bearing, magnified to the size of the earth then the atom would be as large as a baseball, and an electron would be less than one thousandth of an inch in diameter. That is, the whole group of electrons and proton making up the atom would occupy as much space as a baseball, but most of this space would be empty as there would be situated in this space, besides the small central nucleus, nearly one hundred small particles much less than one thousandth of an inch in diameter.

Insulators and Conductors.—In general the electrons that belong to a certain atom stick to it very tightly and cannot be taken away by another atom; in the same way none of the planets which revolve around the sun are taken away by other systems in the stellar universe. In certain substances, however, principally the metals, it seems that one electron per atom is more or less free to leave the atom and wander about at will among the other atoms and electrons, sometimes attaching itself to one atom and sometimes to another. In other substances such as glass, rubber, bakelite, and porcelain, all the electrons are rigidly attached to their atoms and cannot move about. These substances we call *insulators,* whereas the others, like the metals, are called *conductors.*

The Electric Current.—If a wire is connected with a battery, so that one end becomes positive with respect to the other, the free electrons, really negative electricity, will be attracted towards the positive end of the wire, and they will gradually drift along through the crowd of atoms from one end of the wire to the other. This drift of the free electrons through the substance of the wire is called an *electric current*. This motion of the electrons much resembles that of a troop of men advancing through a woods; the individual men go in very irregular fashion, going sideways, and backwards even, to avoid rocks and trees, but on the whole the troop moves slowly forwards. The electrons drift in much the same manner; they bump into the atoms and into one another, sometimes going sideways and sometimes being bumped backwards, but on the whole drifting from one end of the wire to the other.

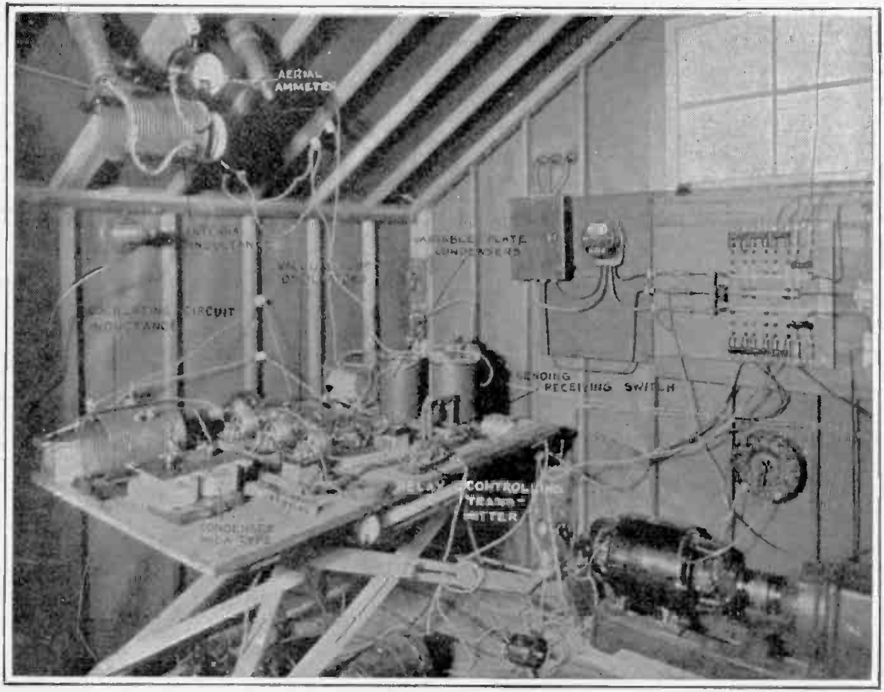
We can apply this idea of current to the ordinary electric lighting system. An individual electron starting out from the generator in the power station may take a month or more to make a circuit of the system and get back to the generator; in the meantime it has been bumping its way along through the wires hung on poles in the street, through the house wiring, then through perhaps an electric iron or lamp, and so back through the wires to the station.

Motion of Atoms and Electrons.—At ordinary temperatures the atoms of which a body is composed are not stationary but have a very rapid to and fro motion, going zigzag fashion in all directions. They bump into one another and bound away much as would a lot of tennis balls shaken about in a big box. Between the atoms, the free electrons, if there are any, bound back and forth with even greater velocity. It is this velocity of the atoms and electrons that gives the body its temperature; at absolute zero temperature (about 460 degrees below zero on the Fahrenheit scale) all the atoms of a body are at rest.

At ordinary temperature the average velocity of the atoms is several hundred feet a second. There is a fundamental law of physics which says that the free electrons in a metal must have the same amount of energy of motion as do the atoms. As the electrons are so small and light when compared to the atoms, the average velocity of the electrons must be correspondingly high. This average velocity of the electrons at ordinary temperatures proves to be about fifty miles a second.

Why Things Get Hot.—Although we cannot attempt to prove it in a non-mathematical pamphlet of this kind it is a fact that the temperature of a body is measured directly by the amount of energy of motion of the atoms of which it is made up; the greater the motion of the atoms and electrons the hotter is the body. Anything that increases the average velocity of its atoms will correspondingly raise the temperature of the body; if a piece of iron is hammered vigorously the iron and hammer both heat up, because the average speed of the atoms of which each is composed has been increased by the blows. If two bodies are rubbed together, as in a bearing, the shaft and bearing metal both get hot because the friction between the two has increased the average velocity of the atoms.

Metals Are Porous.—Anyone who has grasped the ideas set forth thus far will have reached the conclusion that what seems to be a hard and dense metal is really nothing of the sort, but a collection of complex particles,

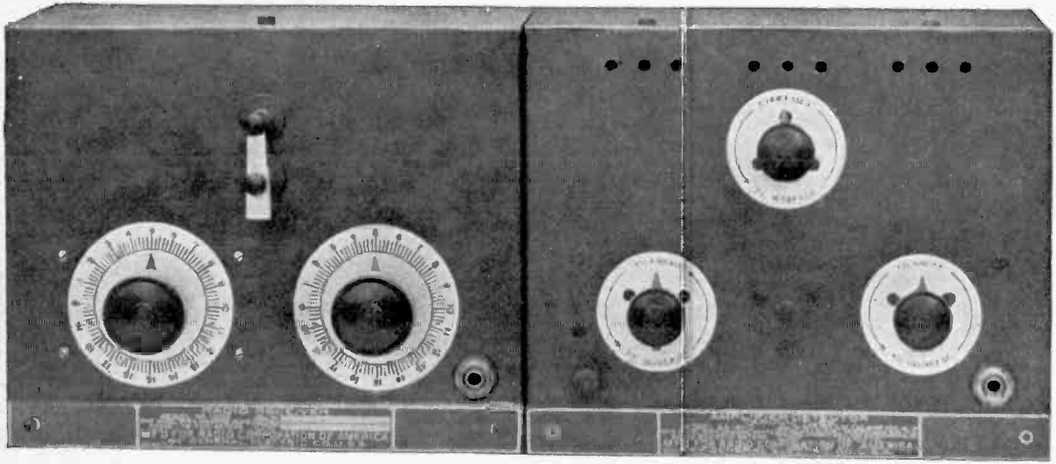


One of the great achievements in radio was the sending across the Atlantic Ocean of signals from American amateur stations. These signals were picked up in Scotland. One of the stations that was heard in Scotland was 1 BCG, and this is a picture of its parts. The four vacuum transmitting tubes can be seen on the bench. Each of these tubes has an energy output of 250 watts. One is used as a master oscillator, the other three as amplifiers of the energy produced by the master oscillator. The total input to the plates of these four tubes was 989 watts. The radiation at this input was 6 amperes, with a total operating efficiency of about 52%, or approximately 558 watts of antenna energy. During the tests 1 BCG operated on a wave length of 230 meters.

each of which in itself resembles a solar system, with the electrons revolving about the proton; there is empty space between the atoms and also in the atoms themselves. From this viewpoint it is reasonable to believe that small particles, such as individual electrons or atoms, might be shot right through a piece of metal if they have sufficient velocity. Such is really the case; atoms and electrons are shot off from radium with tremendous velocities as it decomposes and these high-speed particles go right through sheets of metal a quarter of an inch or more in thickness. They shoot through the spaces between the atoms or perhaps right through the atoms themselves.

Why an Electric Current Heats a Wire

When a wire is carrying current the free electrons are forced to drift along the wire. Hence, in such a conductor, the electrons have an additional velocity as well as the irregular motion due to the temperature of the body. Now, as the electrons crowd their way along the conductor, they bump into the atoms and other electrons more vigorously than they would if there were no current in the conductor; due to this effect the average velocity of the atoms will increase when the conductor carries current and will increase with the amount of the current. This accounts for the heating of a wire carrying current, such as the filament of an incandescent lamp; in such a filament the intense heat is caused merely by the electrons pushing their way along the wire and so bumping the atoms and speeding them up.



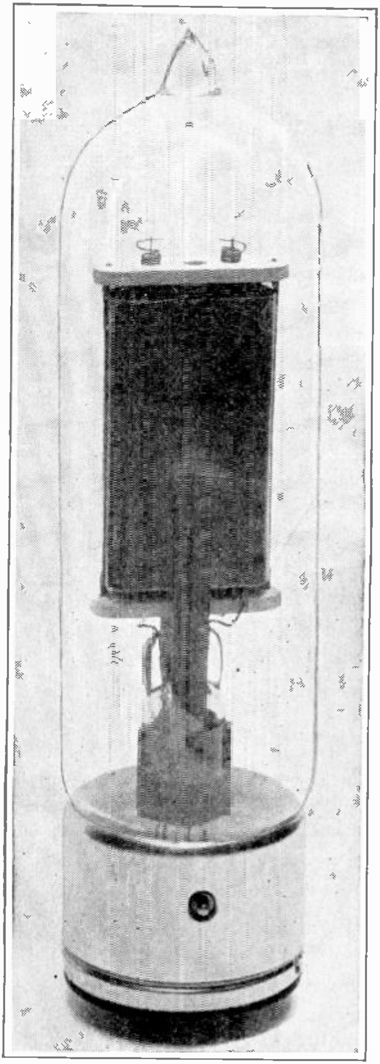
In this set provision is made for both crystal and vacuum-tube detection. The left-half of the apparatus is the crystal detector set, which can be used alone with telephone headsets. The right-half is called a "detector-amplifier" unit. It contains a vacuum-tube detector and tubes to give two stages of audio-frequency amplification. When the right-half (the vacuum-tube half) of this combination is used, the left-half (crystal detector) is switched off. Combinations such as this make it possible to pass from crystal to vacuum-tube detection and audio-frequency amplification as knowledge and experience are acquired.

What is "Evaporation?"

We all know that such substances as water or gasoline will evaporate in an open dish. Just what is evaporation from the viewpoint so far presented? Perhaps you have seen a swarm of bees hanging in a cluster from the limb of a tree; the writer has often cut off such a limb, carried the swarm to the front of a new hive, and shaken the bees off on the ground. They will roll over the ground in a layer perhaps a hundred bees thick, almost like thick molasses and will gradually move into the entrance to the new hive; but if the queen has been lost they will start to fly back into the air. So we have on the ground a mass of bees, perhaps half a bushel, corresponding with a liquid in their motion, and, leaving the surface of this mass, are the individual bees taking wing. We may say that the bees are "evaporating" as they leave the crawling mass on the ground and fly up into the air.

This is a fairly good picture of what happens at the surface of a liquid. Most of the atoms of the liquid stay in the mass of liquid but some of those at the surface, having sufficiently high velocity, will fly away from the liquid all together in spite of the effect of the rest of the atoms of the liquid trying to hold them in. The high speed atoms at the surface do break away and become free individual atoms of the substance floating about among the air atoms at the surface of the liquid, gradually bumping their way through the air atoms and so away from the liquid. It is these individual atoms that break away from the surface of the liquid and that cause it to evaporate.

It is evident that those atoms at the surface with the highest velocity are the most likely to break away from the pull of their companion atoms, and such is always the case. In evaporation it is the fast ones that get away. It follows,



Power vacuum tube as used in the amplifiers associated with loud-speakers.

therefore, that as the high speed atoms get away those left behind will have on the average a lower velocity than before evaporation began to take place; but lower average velocity of the atoms means a lower temperature, and we know that this is just what occurs when a liquid evaporates. Alcohol allowed to evaporate from the hand will cool several degrees; liquid air left free to evaporate will so cool down that what is left behind actually freezes.

Effect of Temperature on Evaporation.—The higher the speed of the atoms the more likely are they to break away from the attraction of their companions and so evaporate; thus hot water evaporates much more rapidly than cold water. Metals evaporate very slowly at ordinary temperatures, but as they are heated the rate of evaporation increases. If the metal is surrounded by air it will generally oxidize before reaching a temperature at which appreciable evaporation takes place; but if the metal is in a vacuum it will actually evaporate or boil away just as do liquids. In the ordinary electric lamp the tungsten is so hot that appreciable evaporation takes place; the metallic vapor condenses when it reaches the comparatively cold walls of the glass bulb. This is the black deposit of tungsten visible in the bulb of any tungsten lamp which has run a thousand hours or more.

Evaporation of Electrons.—About twenty years ago it was predicted by Richardson that if a metal was sufficiently heated not only would the metal evaporate but that *electrons might be made to evaporate from the metal* also. Moreover, it was evident that the electrons would be the same in kind no matter what metal was heated. As the electrons move so much faster than the heavier atoms it was predicted that the electrons would evaporate

4

at a lower temperature than would the atoms of the metal itself, and such proves to be the case. In a good vacuum (space from which practically all air or gas has been pumped out) a glowing piece of tungsten or platinum or similar metal may be maintained at a white heat for thousands of hours without appreciable evaporation of the metal itself; yet in one hour the number of free electrons evaporated is several times as great as the total number of free electrons in the piece of metal. Of course as the free electrons evaporate others must be supplied to take their place, as will be explained later.

Effect of Gas on Evaporation.—In order to get appreciable electron evaporation it is necessary that the space surrounding the hot metal, from which the electrons are being emitted, be very well evacuated not only to prevent the metal from oxidizing but because of the effect of the gas on the electrons that are trying to leave the hot surface. The mass of the electron is so extremely small that if it collides with an atom of any kind it bounds backwards at about the same velocity with which it was rushing forward. This action is the same as when a tennis ball collides with a cannon ball going in the opposite direction; the path of the cannon ball is scarcely disturbed by the collision, but the tennis ball bounds back in about the same way it would have done had it struck against a rigid wall. Thus if there are any atoms of gas surrounding the hot metal the electron bounding out of the surface of the metal strikes against these atoms and so bounds right back into the hot metal from which it just escaped. The gas thus acts as a screen surrounding the hot metal, pushing the electrons back into the metal as fast as they escape.

Effect of Surface Condition.—We know that if the surface of water is covered with a layer of oil the water is effectually prevented from evaporating. A similar effect is often noticed when studying electron evaporation, other things taking the place of the oil layer. Thus if some certain gas sticks to the surface of the hot metal (such gas is said to be "adsorbed") it may practically stop the electron evaporation, whereas certain other gases have no effect at all. Langmuir and his co-workers in the research laboratory of the General Electric Co. have done most thorough work in investigating these effects of different gases in a vacuum tube; those especially interested should consult the scientific journals where such work is reported.

Effect of Oxides.—As noted above certain impurities on the surface of a hot metal prevent electron evaporation, yet Wehnelt discovered that certain oxides, spread over the surface of the hot metal, very much increased the rate of emission. The research laboratories of the Western Electric Co., through van der Bijl and his associates, have developed this phase of the question and have produced an oxide-coated platinum filament that gives profuse electron emission at temperatures much lower than required for pure platinum or tungsten filaments. To get much emission from pure tungsten the metal must be at a dazzling white heat, whereas a properly coated oxide filament will give the same amount of emission at a dull red heat. An oxide-coated filament should never be raised to a temperature hotter than that which gives a dull yellow color; otherwise the oxide coating will be spoiled.

Electron Atmosphere.—The evaporation of electrons from a hot surface is pictured in Fig. 1, the small dots representing electrons, the larger circles *a, a, a,* repre-

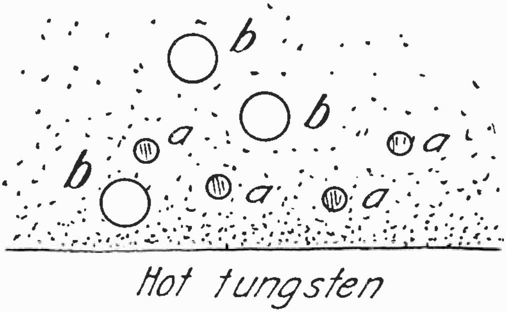


Fig. 1

There is an atmosphere around a hot tungsten filament, in a vacuum, about as indicated here; mixed with the cloud of electrons are atoms of gas, a, a, a, which have not been completely pumped out of the vessel containing the hot tungsten and some few tungsten atoms, b, b, b.

senting some gas atoms, and the still larger circles *b, b, b,* representing some tungsten atoms which have evaporated with the electrons. It must of course be remembered that no matter how well the containing vessel has been pumped there will always be many gas atoms left in the vessel, around the filament. If there is no action pulling the electrons away from the hot surface from which they have come, the height of the electron atmosphere represented in Fig. 1 will be only a few hundredths of an inch. Unless the metal is above a dazzling white temperature but few electrons get more than five hundredths of an inch from the surface before they slow down and then fall back into the hot metal.

The Strange Discovery That Edison Made

The first observer of the effect of electron evaporation was Edison. In the early days of incandescent lamp manufacture he noticed a peculiar action that could not be satisfactorily explained at the time. In an ordinary incandescent lamp bulb he introduced an extra plate, having a connecting wire to the outside of the bulb as shown in Fig. 2. Edison noticed, when the filament was incandescent, that if this plate was connected through a galvanometer to the negative side of the battery heating the filament no current flowed through the galvanometer, but that if the wire *a* was connected to the positive side

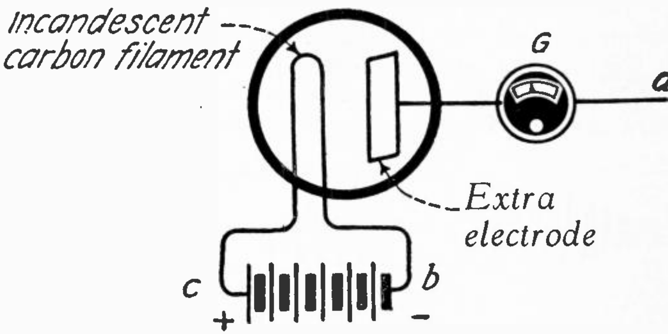


Fig. 2

Edison first noticed the effect of electron evaporation. In an evacuated glass bulb, containing a hot carbon filament an extra plate, or electrode, was sealed. If a wire was connected to "C" current flowed through the galvanometer; if connected to "B" no current flowed.

of the battery the galvanometer showed that a current was flowing. This current stopped as soon as the filament cooled down, showing that it was an effect depending upon the temperature of the filament. Although the phenomenon could not be explained at that time we know that it was due to the electrons evaporated from the carbon filament. When the plate was connected to the negative end of the battery it offered no attraction to the electrons coming off the filament, but when made positive by being connected to the positive end of the filament it did attract the electrons and so caused current to flow.

It is to be noticed that this current is due to the electrons evaporating from the filament, streaming across the vacuous space between the filament and plate, entering the plate, then drifting along through the wire and galvanometer, back into the filament (*a* being connected to *c* in Fig. 2) and so re-evaporating and starting on their course once more. The same electrons will evaporate many times if the filament is kept heated long enough.

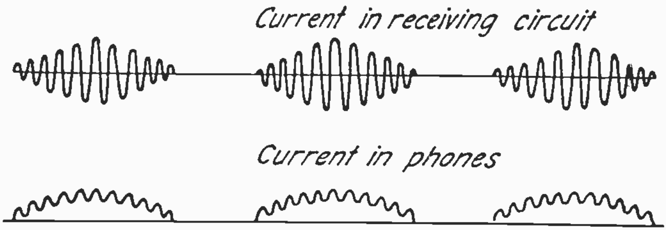


Fig. 3

If a rectifier is connected in series with the telephones, high frequency voltages, such as shown in the upper curves, will give, through the telephones, pulses of current as shown in the lower curves.

For twenty years the "Edison effect" was known but not used until Fleming, working with Marconi in his early radio experiments, got the idea of using it in place of the coherer, as a detector, or rather a rectifier, of the high frequency signals.

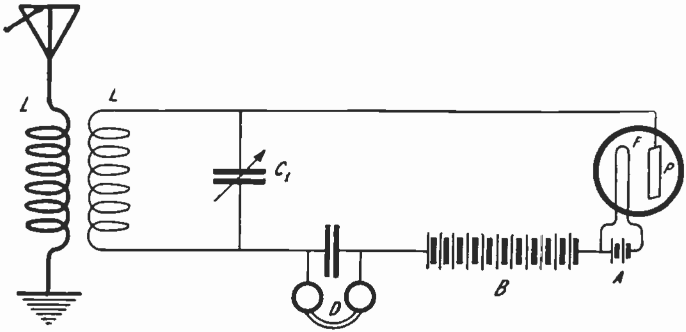


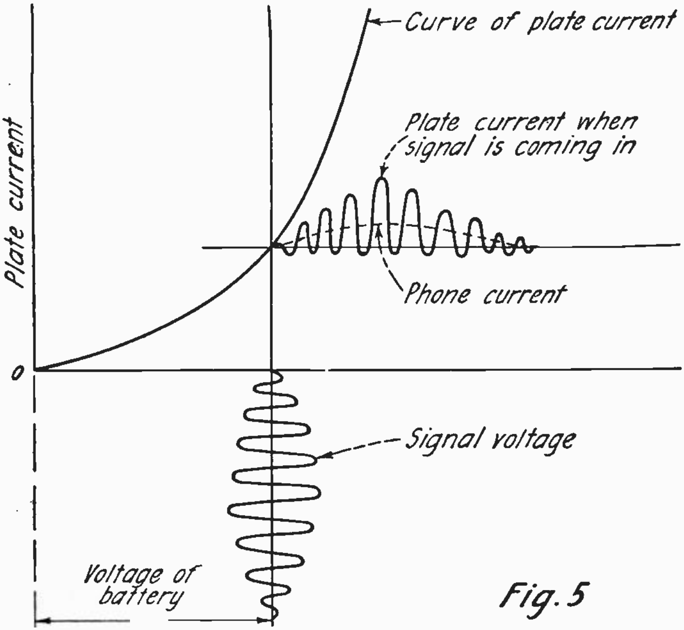
Fig. 4

Showing how Fleming used the Edison effect to make a useful piece of radio apparatus, the Fleming valve or rectifier.

How Fleming Applied Edison's Discovery in Radio

In the upper part of Fig. 3 are shown three groups of high frequency waves such as would be sent out by three spark discharges at a transmitting station sending out spark-wave telegraph signals. The frequency, or number of reversals per second, of the current set up in the transmitting antenna, and the corresponding current set up in the receiving antenna, might be a million cycles per second and the number of these groups per second perhaps a thousand. As the ear cannot hear one million vibrations per second, but can hear one thousand vibrations per second it is necessary to use in the receiving circuit some apparatus which will give one impulse to the telephone diaphragm for one group of waves. If in series with the telephones there is some device which permits current to flow only in one direction (a device called a "rectifier") the current in the telephone will look about as shown in the lower curve of Fig. 3. Each of these current pulses consists of a rectified (and smoothed out) group of waves of the upper part of the figure. Each of these current pulses will give one pull to the telephone diaphragm, and so the groups of high frequency waves, through the rectifier, do give in the telephone an audible tone of one thousand vibrations, which is a musical note of that frequency for which the ear is most sensitive. In other words, the Fleming valve passed spurts or gushes of electricity instead of a steady stream, and these gushes came slowly enough to enable a telephone receiver to respond with an audible musical note.

Action of the Fleming Valve.—Fleming used the Edison effect to detect radio signals in the manner shown in Fig. 4. The filament *F*, was heated by battery *A*, the extra electrode *P*, which we shall call the "plate," was held at positive voltage, or potential, by battery *B*. Whatever electrons flowed to the plate returned to the filament by going through the telephones *D*. When a signal (high frequency wave-train as in upper part of Fig. 3) came in, the voltage between *P* and *F* was alternately raised and lowered about the average value maintained by battery *B*.



When a high frequency voltage is received by the antenna, the plate current of the valve alternately rises and falls; the rise is greater than the fall so that the average current through the 'phones is increased by the signal.

The plate current (amount of current from filament to plate caused by electron evaporation from *F*) varies with the plate voltage about as shown in the full line curve of Fig. 5; the signal voltage is shown below and the corresponding plate current shown to the right. It will be noticed that while the plate voltage increases and decreases symmetrically about its average value, which is the voltage of battery *B*, the plate current variation is not symmetrical about its normal value, owing to the curvature of the plate-current curve. The average plate-current, which flows through the 'phones, is indicated by the dotted line and shows an increase during the time the wave train lasts. From this it follows that if a series of wave trains similar to those shown in Fig. 3 is impressed on the antenna circuit of Fig. 4 the 'phone current will show a "hump" for every wave train; hence one thousand humps per second, and this will give a note of 1,000 vibrations per second in the 'phones.

It will be noticed that when using the Fleming valve for a detector there is current flowing through the 'phones all the time, whether there is a signal coming in or not. But if a steady current flows through a telephone receiver no noise is sent off from the diaphragm at all; it is the *changes of current* only that cause the diaphragm to vibrate and sound.

When using a crystal detector no current at all flows through the 'phones until a signal is coming in; so the current through the 'phones will be about as shown in the humps of Fig. 3. When using the Fleming valve the 'phone current looks as shown in Fig. 6. There is always a large current flowing, and on the top of this are the humps of current caused by the signal. The noise given off by the 'phone will be just the same, however, as it is for the current shown in the lower part of Fig. 3.

The foregoing analysis has been made on the assumption that the telegraph signal received was sent out by a spark transmitter, and we have shown that a musical note is heard in the receiving telephones which has a pitch fixed by the number of sparks per second at the transmitter station. In case a radio *telephone* signal is being received the voltage impressed on the plate of the Fleming valve will be a very high frequency current, the amplitude of which follows the shape of the voice-wave acting at the transmitting station. In such a case the current through the 'phones will be somewhat as shown in Fig. 6, but the humps in the current will not be regular and smooth but of a frequency and shape fixed by the pitch and quality of the voice acting at the transmitter.

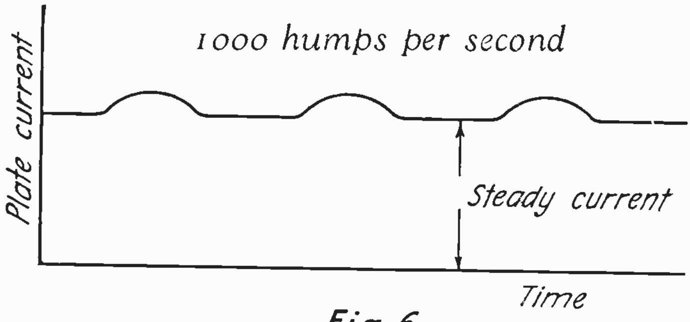
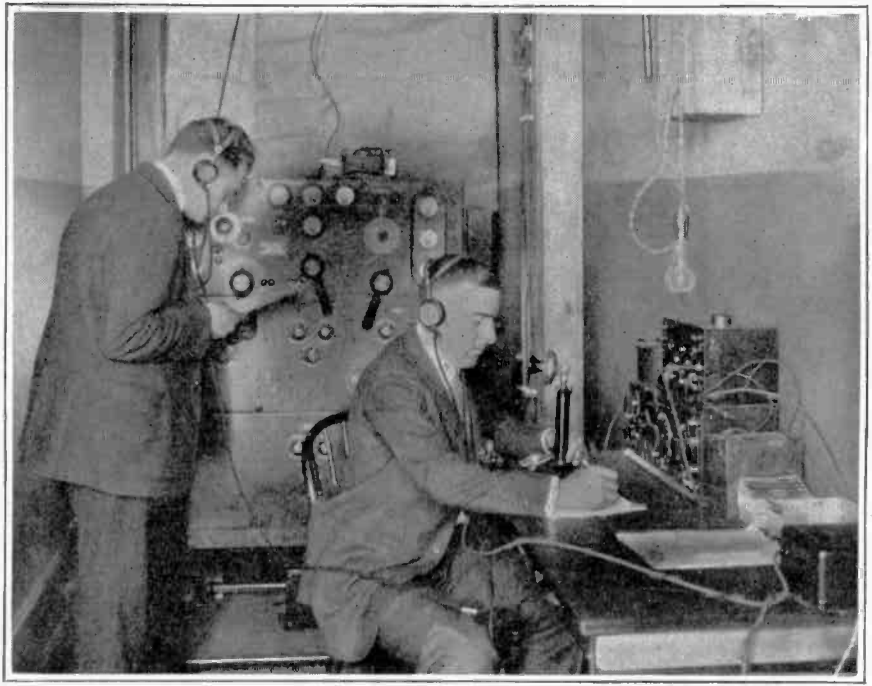


Fig. 6

When a spark signal from a 1000 spark transmitter is received the current through the 'phones has 1000 humps per second, giving 1000 vibrations per second note in the telephones.

De Forest Introduces the Grid

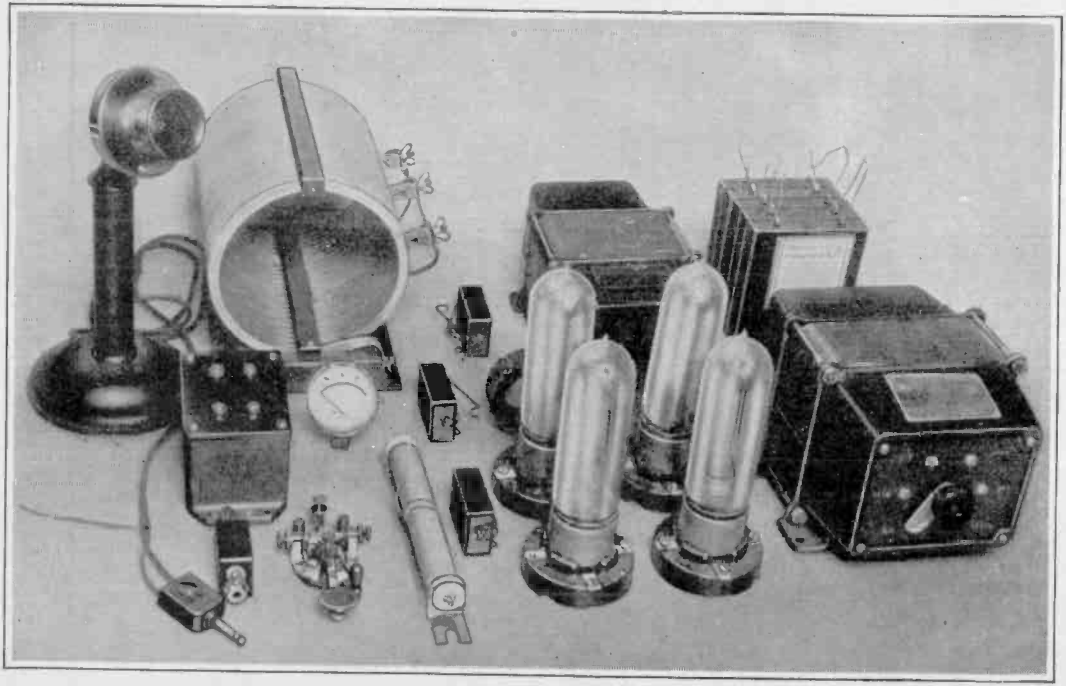
Probably the greatest single step in the advance of radio communication was due to De Forest. He conceived the idea of introducing into the Fleming valve an extra electrode in the form of a lattice or grid, this grid



To judge from this picture, taken within broadcasting station at Roselle Park, N. J., it would never be suspected that tubes played any part in transmission. But the tubes are in the casing in the back.

being so placed that electrons on their way over from the filament to the plate had to pass through it. Other names for this "three electrode valve," in more or less common use, are the *audion* (De Forest's original name) *oscillion, radiotron, pliotron,* and *triode*. The latter seems to be the most applicable of the lot.

In reading the following explanation of the action of the triode the fundamental law of electric charges must be remembered: *Negative* electricity is repelled by a *negatively* charged body and is *attracted* by one which is *positively* charged. The general arrangement of a triode is shown in Fig. 7; the grid is here shown as a zigzag piece of wire, which was the form originally used by De Forest. An electron *a,* having evaporated from the filament is attracted by the plate, which is maintained at a positive potential by the battery *B*. The electron, however, in getting to the plate must pass between the grid wires, and these grid wires may be charged either positively or negatively by the battery *C*. If the grid is charged positively the electrons are attracted and therefore helped on their way over to the plate, but a few of them will go to the grid itself on their way through the spaces of the grid. Thus, making the grid increasingly positive gives greater and greater flow of electrons over to the plate. This increase in plate current with increasing grid voltage, will continue as long as there are plenty of electrons evaporating from the filament. After a certain positive grid potential is reached, however, all the electrons being evaporated are drawn over to the plate or grid, and so no further increase in grid voltage can increase the plate current. This amount of plate current is said to be *saturation current* for the tube; evidently



The component parts of a fifty-watt transmitting set.

the value of this saturation current will depend entirely upon the temperature of the filament, that is, upon the filament current.

Now, if the grid is made negative the electrons can get to the plate only by passing through this *negatively* charged grid and this negative grid *repels* the electrons. What will the electrons do? Many of them will be hurled back into the filament from which they have just evaporated and some will sneak through, keeping as far away from the negative wires as possible. Once through they will travel over to the plate with even greater velocity than they would have if the grid were not there. For once they have passed through the grid and so enter into the space between the grid and plate they are not only attracted towards the plate by its positive potential but are also pushed towards the plate by the negative grid behind them.

One must imagine then, the tremendous crowd of electrons having evaporated from the hot filament, pausing on their way over to the plate because of the repelling influence of this negative grid; some of them, being near the center of the holes in the grid, and perhaps being pushed by some of their companions from behind, do dash through and reach their goal, the positively charged plate, but many of them, apparently less daring or fortunate, cannot run the gauntlet and so fall back into the filament. The more negative the grid the more formidable an obstacle it becomes to the electrons endeavoring to get to the plate, and in the ordinary tube used in radio receiving sets, it takes only a few volts negative on the grid to stop practically all electron flow to the plate.

One may also imagine the grid as a lattice shutter, such

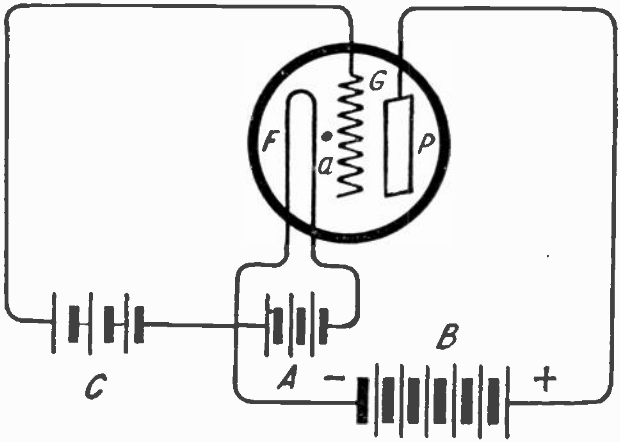


Fig. 7

De Forest conceived the idea of putting a grid between the plate and filament of a Fleming valve and thus produced the wonderful audion or triode.

as were used on house windows a few years ago, or such as are sometimes used in front of the radiator of an automobile. A positive grid corresponds to a wide open shutter that lets all the electrons through, and as the grid becomes more negative we must imagine the shutter more and more tightly closed.

If the plate voltage (determined by the *B* battery of Fig. 7) is held constant and the voltage of the *C* battery is changed in gradual steps, both positive and negative, the variation of plate current with grid voltage will be as shown in Fig. 8, curve *A*. With increasing grid potential the plate current continually increases until saturation current is obtained, and then further increase in grid potention can produce no further increase in plate current. If the same changes in grid voltage are carried but with a lower voltage in the *B* battery, curve *B* of Fig. 8 is obtained, and, if for greater than normal *B* battery, curve

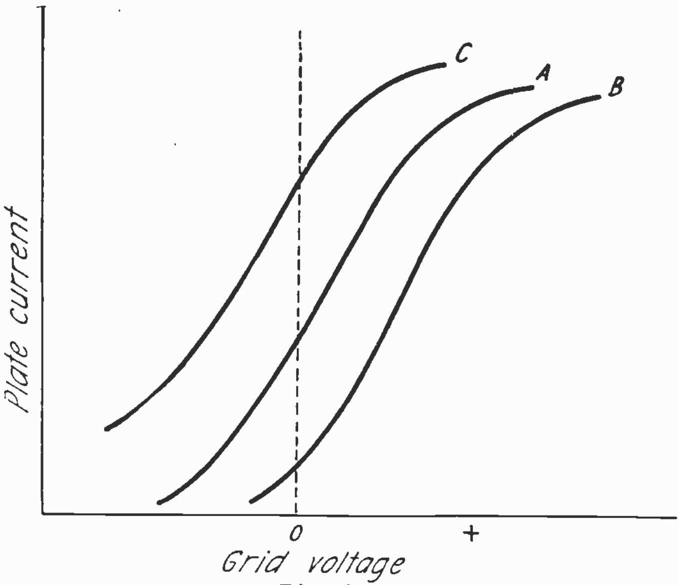


Fig. 8

If the plate voltage of a triode is held constant and the grid voltage varied, both positively and negatively, the plate current will vary about as shown here, the three curves being for different plate voltages.

C is obtained. With the ordinary detector tube curve A might be obtained with a 20-volt B battery, B with a 10-volt battery and C with a 30-volt battery.

We now see that the grid voltage of the triode can control the plate current in the same fashion as it was controlled in the Fleming valve by the plate voltage. Moreover, with a construction of grids as ordinarily used *a variation of grid voltage of one volt will produce from five to a hundred times as much change in plate current as would a change of one volt in the plane voltage.* That is, the grid gives us a very sensitive control over the flow of electrons to the plate, acting as a valve in the plate current circuit. Comparatively weak radio signals impressed on the grid so as to vary its voltage may produce changes in the plate current perhaps 25 times as great as would be produced if a Fleming valve were used and the signal voltage impressed on the plate circuit as shown in Fig. 4. The finer the holes in the grid, that is, the closer the wires are spaced, the more rigid is the control of the grid over the plate current.

How the Vacuum Tube or Triode Detects Telegraph Signals

When the triode is used as a detector in a radio receiving set it is connected to the circuit as shown in Fig. 9. The signal current, coming in the antenna, induces a corresponding current in the tuned circuit, the inductance and capacity of which have been properly chosen for the wave length of the signal being received. The grid of the tube will then be affected by the signal, and as the voltage of the grid goes up and down the plate current must correspondingly go up and down according to the shape of the curves given in Fig. 8. A part of curve *B* of Fig. 8 given in Fig. 10 and drawn downwards in the figure is the form of the voltage impressed on the grid of the triode when one wave train comes in the antenna. For any grid voltage the plate current may be found from the curve of

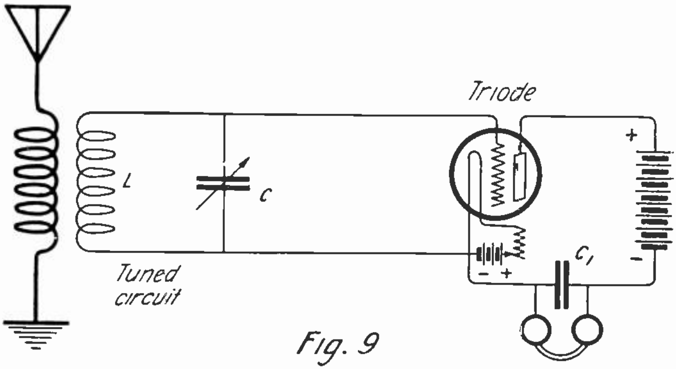


Fig. 9

Showing how the triode is connected for receiving radio signals: signal voltages makes the plate current alternately increase and decrease, resulting in sound in the telephones.

plate current; these values have been picked off the curve and are drawn to the right in Fig. 10. Due to the curvature of the plate current curve the plate current has more of an increase when the grid goes positive than it has decrease when the grid goes equally negative, and this results in an increase in the average plate current while the wave train is acting on the grid. The high frequency fluctuation in the plate current, which is of the same fre-

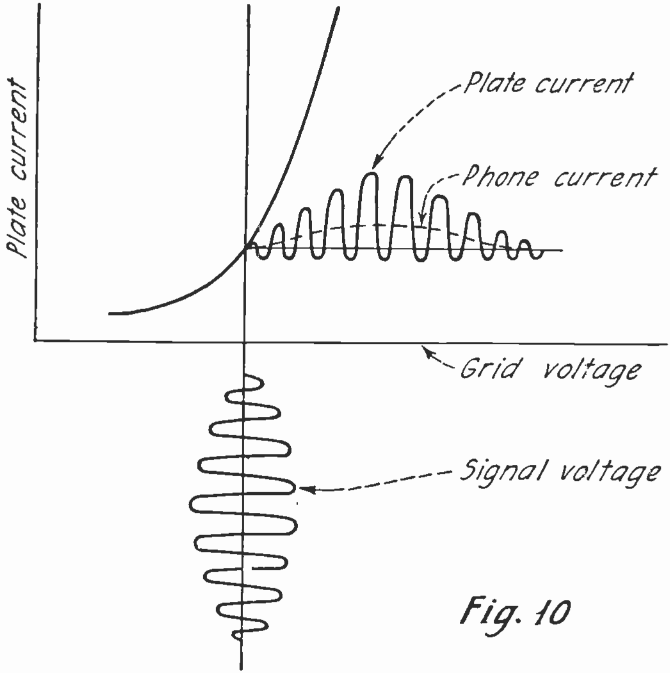


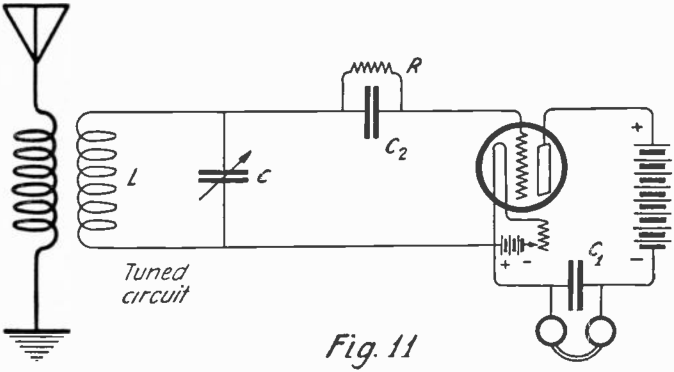
Fig. 10

The action of the triode in detecting a high frequency signal is practically the same as that of the Fleming valve, but owing to the controlling action of the grid, the triode is more sensitive than the valve.

quency as the voltage acting on the grid, passes through the condenser C_1 in Fig. 9, but the average increase shown by the dotted line in Fig. 10 goes through the telephone. So we see that one wave train impressed on the grid of the tube will give a hump in the current through the telephones, just as it did in the Fleming wave. The size of the hump, however, will be much greater in the case of the triode than in the case of the valve. This fact is expressed by saying that the triode is a "more sensitive" detector than is the Fleming valve.

Tube with Gas or Soft Tube.—A tube which has been evacuated as well as modern methods will permit, and therefore has a very high vacuum, is said to be a "hard" tube; on the other hand some gas is actually introduced into the tube in special cases, so that the vacuum is not as good as it is possible to make it and such tubes are said to be "soft" tubes. If an appreciable amount of gas has been put into the tube the plate-current *vs.* grid potential curve is not the smooth curve shown in Fig. 8 but has a small kink in it, where the curvature is much greater than is the case with the hard tube. If the plate voltage is adjusted to just the right value the plate-current, with no signal coming in, will be on the kink in the curve. Now as the curvature is greatest at the kink, and as the size of the hump in the 'phone current of Fig. 10 depends directly upon the curvature of the plate current curve it is evident that the tube with gas may be made a better detector than one without gas. These gas tubes are much used as detectors, but it must be remembered that to give the best results with such tubes the plate-voltage must be regulated to just the right amount and this can only be found out by trial after the set is connected and put in operation.

Action of Tube with Grid Condenser.—The average triode is a somewhat better detector if it is used with a suitable condenser in series with the grid instead of being connected as in Fig. 9. In this case the connection is



The average triode is somewhat more sensitive as a detector if used with a condenser in series with a grid, the condenser being shunted by a grid leak.

made as in Fig. 11; it will be noticed that the connection of the tube is nearly the same as before, but the grid is connected to the tuned circuit through a condenser C_2 which is itself shunted by a resistance R, called the "grid leak resistance."

The action of the tube in this case is somewhat different than that previously analyzed. When the signal gives a voltage across condenser C (Fig. 11), the grid is made to go up and down in potential almost the same as if condenser C_2 was not in the circuit. Now when the grid goes positive it attracts to itself some of the electrons which are flowing through its spaces on their way over to the plate; when the grid goes negative the electrons cannot leave the grid inside the tube, as electrons cannot evaporate from a cold metal. When the grid again goes positive at the beginning of the next cycle electrons are again attracted to the grid and thus as long as the signal is coming in the grid accumulates electrons, and the number it accumulates depends upon how positive the signal causes the grid to become. A strong signal will make the grid swing positive by a large amount, while a weak signal will force it less positive and so accumulate fewer electrons on the grid than will the strong signal.

The accumulation of electrons on the grid would soon make it so negative that the plate current would stay permanently low, and the detecting action of the tube would be very poor if means were not provided to let these accumulated electrons flow back to the filament from which they came. This is the purpose of the leak resistance *R*, Fig. 11. The electrons which accumulate on the grid while it is positive, not being able to get off the grid inside the tube by evaporation (the way they got off the filament) flow back to the filament through the resistance *R* and coil *L*. The values of C_2 and *R* must be properly chosen to make the tube operate at its best; for the average tube about 200 micro-microfarads of capacity and a leak resistance of one million ohms seem best.

From the foregoing it is, therefore, seen that as a signal of varying amplitude is coming into the tuned circuit the grid accumulates more or less electrons, which gradually leak off through *R*; with a strong signal many electrons are caught by the grid, and with a weak signal but few are captured. Now, as electrons are *negative* electricity it follows that the average grid potential, due to this accumulated charge of electrons, will be lowered the stronger the signal. Thus the signal voltage might be of the form shown in curve *a* of Fig. 12, which is part of a word

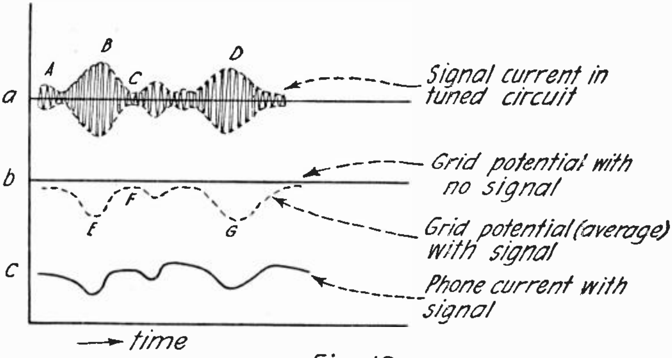


Fig. 12

The form of high frequency current in the circuit of a receiving station resembles in form the voice sound wave at the transmitting station; the triode so acts as to send through the 'phones a current of the same form and frequency as the voice wave.

spoken at a radiophone transmitting station. When the high-frequency current in the tuned circuit is of low amplitude, as at *A*, the electrons are accumulated by the grid at a slow rate and so the average potential of the grid is about the same as when no signal is coming in. But when the signal current increases in intensity, as at *B*, the electrons accumulate more rapidly on the grid, and so its average potential falls, as shown at *E* of curve *b* in Fig. 12. At *C* the signal voltage is again low, and so the average grid potential again approaches its normal value at *F*. In fact the average potential of the grid will follow quite closely the envelope (dotted line through the peaks of the waves of the high-frequency current) of the voltage in *a*, and if the radio transmitting set is working properly this envelope will correspond with the form of the voice wave at the transmitter.

Now as the plate current of the triode, which flows through the 'phones, must go up and down as the average grid potential goes up and down it follows that there will be humps and hollows in the form of the plate current which will have the form of the voice sound as indicated in curve *c* of Fig. 12. But the telephone receivers give off a noise which corresponds to the form of the current flowing through them, and so the sound given off by the receivers will resemble the sound uttered at the transmitter station.

In the previous few pages the action of the three electrode tube has been outlined as a rectifier and detector of high-frequency waves, which we now summarize. Sent off from the antenna of the transmitting station are high-frequency waves the amplitude of which varies. In the case of a radiophone transmitter the variation is such that the amplitude of the waves sent off closely resembles the form of the sound wave of the voice. When these waves strike the receiving antenna they set up currents in it and also in the local tuned circuit. These currents make the grid potential vary with high frequency fluctuations, the amount of this fluctuation varying as does the high frequency current in the antenna of the transmitting station. The variation of grid potential causes corresponding changes in the amount of plate current, which is the current flowing through the telephone receivers. As the sound given off by the 'phones is fixed by the shape of the current flowing through them, it follows that the sound given off by the receiving 'phones will resemble that at the transmitting station.

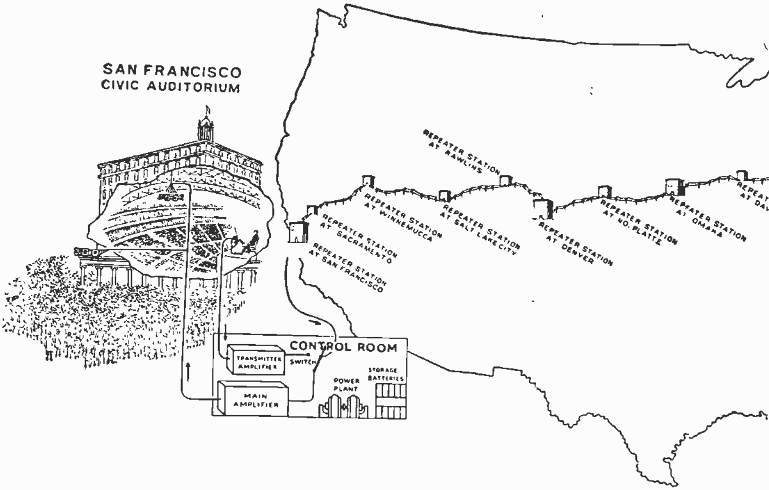
How the Vacuum Tube or Triode Amplifiers Received Signals

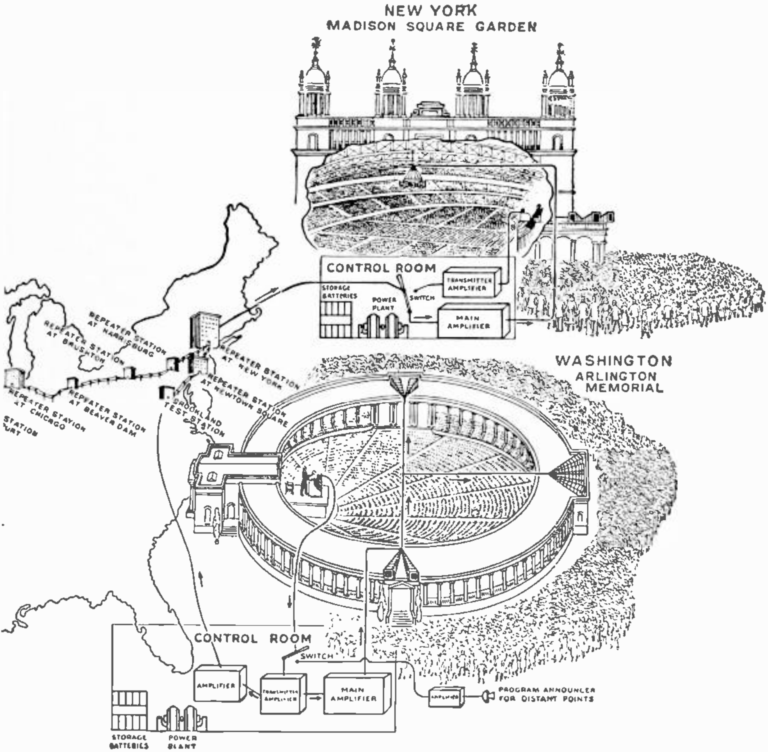
One of the most important roles played by the triode in radio work is that of increasing the signal strength and making audible, signals so weak that without the triode amplifier, they would be entirely inaudible. It is this use of the triode as amplifier which makes it possible to telephone, by wire, from New York to San Francisco. By the use of proper amplifying tubes a speaker in one place may be heard from loud-speaking horns, by thousands of people gathered in halls thousands of miles away. It is perfectly possible today for a political candidate to address at the same time hundreds of meetings, and the people in each of the halls where the loud-speaking horns and vacuum tube amplifiers are located may hear him more distinctly than if the speaker himself were in the hall with them. Actually he may be in his study at home.

By using a very small amount of power to affect the potential of the grid of a tube, large amounts of power may be controlled in the plate circuit. The large amount of energy controlled does not come into the receiving circuit from the receiving antenna but from the *B* battery in the tube circuit. The flow of this large amount of energy through the loud-speaking horns makes no noise as long as the flow is uniform, but if a signal is impressed on the grid of the amplifying tube the flow of energy from the *B* battery is made to fluctuate and the form of the fluctuations resembles the signal voltage, and so the voice which is to be reproduced.

Resistance Amplifier.—In Fig. 13 is given the elementary idea of amplification using a resistance in the

On Armistice Day the President of the United States addressed a vast audience in the Arlington Memorial, Washington, but far vaster was the audience that heard his voice. New York and San Francisco heard him too —thousands who were hundreds and hundreds of miles away. This marvelous performance was made possible by using the vacuum-tube as an amplifier and as a relay. The voice of the President was carried by telephone to New York where it was heard by a throng that filled Madison Square Garden, and from New York was repeated, as shown on this diagram, in cities between the Atlantic and Pacific oceans.





NEW YORK
MADISON SQUARE GARDEN
CONTROL ROOM
STORAGE BATTERIES
POWER PLANT
SWITCH
TRANSMITTER AMPLIFIER
MAIN AMPLIFIER
REPEATER STATION AT HARRISBURG
REPEATER STATION AT BRUSHTON
REPEATER STATION AT NEW YORK
REPEATER STATION AT NEWTOWN SQUARE
BROOKLAND TEST STATION
REPEATER STATION AT BEAVER DAM
REPEATER STATION AT CHICAGO
WASHINGTON
ARLINGTON
MEMORIAL
CONTROL ROOM
SWITCH
AMPLIFIER
TRANSMITTER AMPLIFIER
MAIN AMPLIFIER
PROGRAM ANNOUNCER FOR DISTANT POINTS
STORAGE BATTERIES
POWER PLANT

plate circuit of the tube. The signal voltage to be amplified is impressed between the grid and filament of the tube, and, as we know, the variation in the grid potential will produce a corresponding variation in the value of the plate current. This pulsating plate current flows through the resistance R and so will produce pulsating voltage across the terminals of this resistance.

This variation in voltage drop through the resistance R is very much like the variation in the loss of pressure when water flows through a piece of pipe or hose. If the water system to which the pipe is attached has a pressure of 100 pounds per square inch there will also be this much pressure at the end of the piece of pipe, provided no water is flowing through the pipe; that is, if the valve at the end of the pipe is closed. But if the valve at the end of the pipe is opened, so that water can flow, the pressure at the open end of the pipe will now be less than 100 pounds, because of the loss of pressure in the pipe itself. This loss of pressure will depend directly upon the amount of water which is allowed to flow through the pipe; if the valve is nearly closed so that but little water can flow the pressure at the end will be nearly 100 pounds, but if the valve of the pipe is opened wide so that much water can flow, the pressure at the end of the pipe will be almost nothing. But if the pressure at the end of the pipe is less than 100 pounds the difference must have been used up in forcing water through the pipe. So we get the idea that the drop in pressure through the pipe is proportional to the amount of water flowing through it. In the same way the drop in electrical pressure, or voltage, through the resistance R of Fig. 13 is proportional to the plate current which is flowing through it.

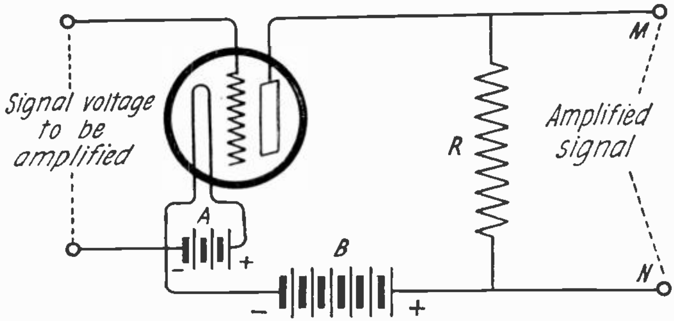


Fig. 13

The elementary idea of an amplifier; the variation of grid voltage makes the plate current, through resistance "R," vary and thus produce at terminals M-N a voltage impressed on the grid, but much larger.

If the tube circuit given in Fig. 13 is operating properly the pulsation in voltage across *R* will be of the same shape as the signal voltage but much larger; with the ordinary tube and suitable resistance, about four times as large. The amount of power used by the grid in changing the plate current, it must be remembered, is practically nothing. Much the same action might be produced with a flow of water instead of a flow of electrons. If a fire hose were equipped with a valve about the same as the ordinary faucet it would be very easy to shut off or start the powerful stream of water. A small child, by vibrating the valve handle, could produce corresponding pulsations in the stream of water, and the power in the pulsations of the water stream would be thousands of times as great as the child could possibly exert. The grid in the triode performs the same function as the valve, permitting weak voltages to control powerful streams of electrons.

Adding Tube to Tube to Obtain Greater Amplifications

Instead of being satisfied with the amount of voltage amplification which can be obtained from one tube it is quite feasible to connect points *M-N* of Fig. 13 to the grid and filament of another tube. The voltage impressed on the grid of the second tube would be then four times as great as the voltage of the signal which was impressed on the grid of the first tube. The points of the resistance of the second tube, corresponding to points *M-N* of the first, may be connected to the grid and filament of a third tube. As the voltage impressed on the grid of the third tube has been increased *four* times by the first tube and then again *four* times by the second tube, the third tube will have impressed on its grid a voltage *sixteen* times as large as the original signal voltage.

Such a scheme is shown in Fig. 14; the whole arrangement is called an *amplifier,* and some such arrangement is used in every good receiving set. An amplifier is said to be "two-stage," or "three-stage," etc., according to the number of tubes used. The one shown in Fig. 14 consists of one detector tube and two amplifying tubes, or we might say of a detector and a two-stage resistance coupled amplifier.

By such an arrangement it is evident that the signals, which, with a one-tube receiving set, are entirely inaudible,

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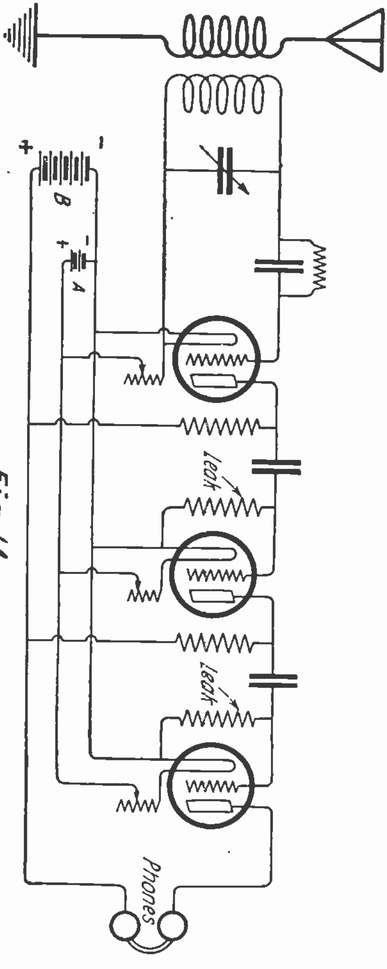


Fig. 14

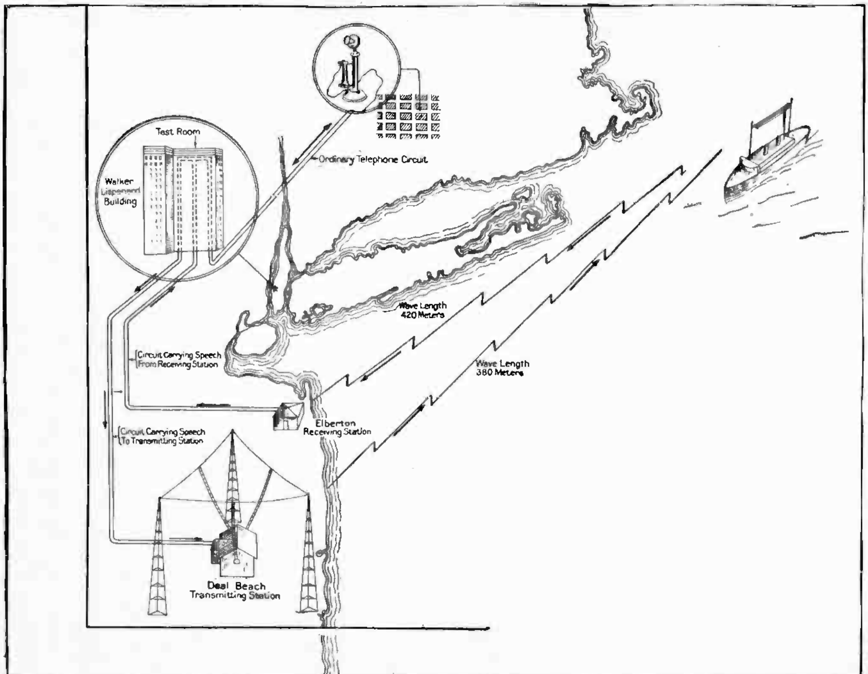
A resistance coupled amplifier, used to increase signal strength; this three tube combination is called a detector and two stage amplifier.

may be made very loud. This question will at once occur to the reader:—If such a connection of tubes will amplify weak signals a hundred times or more why not use more of the same arrangement and amplify signals several million times instead of a few thousand times, as is the practice?

By How Much Can We Amplify?—By means of such an amplifier just described it should be theoretically possible to amplify the sound made by a fly walking on the diaphragm of a telephone receiver, so that it would sound like the blow of a trip hammer, and such is really possible if necessary. In radio receiving sets it does not pay to amplify more than a certain amount because not only is the signal voltage amplified by the tubes but also all similar voltages, from any cause whatever.

There are continually present in the air electrical disturbances which resemble, to some extent, the electromagnetic waves of radio. The wind blowing through the tree tops generates electrical signals and sends them out in all directions. Whenever moisture in the upper atmosphere condenses to form clouds electrical impulses are sent out in all directions. Wherever one wind runs contrary to another, so that there is friction between the two air currents electrical impulses are also generated and sent out. Of course a lightning flash sends out tremendously powerful radio waves, so that even if it is several thousand miles away it may give appreciable currents in a receiving antenna.

All these electrical signals that Nature is continually generating produce noises in the telephone receivers which, if loud enough, will drown out the real radio signal. The currents set up in the ordinary antenna by these natural



How it is possible to telephone to and from a ship at sea partly over land wires and partly through the ether, is here shown. The system permits duplex telephoning, that is, talking and listening at the same time. In order to do this, the voice is transmitted on one wave length and heard on another. Without the marvelous vacuum tube the feat would be impossible.

electrical disturbances, generally called "static," are small compared to those set up by a neighboring transmitting station, so that we only know they exist by a hissing and crackling which can be heard when there is no signal coming in.

But now suppose we want to hear a signal from a distant transmitting station, which, because of the distance, can set up but feeble currents in the receiving antenna. It may well be that these signals are so weak as to be inaudible, and so we have to resort to an amplifier of some kind to make them audible. The noises due to static will also be amplified, and it may be that "static" is so much stronger than the signal that the signal itself remains inaudible no matter how much amplification is used.

The question is often asked:—How much can we usefully amplify? The answer is:—It depends entirely on the amount of static and other disturbing effects present. The writer has an amplifier that can increase the signal strength 2,500,000,000 times and even this is not the limit, by any means. If the amplifier were properly connected to other higher powered tubes and a loud speaking-horn it could be increased thousands of times more.

But such amplification would be of no real value because of the excessive crackling, hissing, etc., which atmospheric disturbances would produce. And even if there were no static at all such a great amplification would result in received signals or speech of poor quality, because of noises due to the irregularity with which the electrons boil off from the filament of the first tube of the amplifier. Yes, it is possible to hear the tumult of electrical activity as the electrons are violently ejected from the surface of the hot filament. Just as soapy water gives off steam in spurts, so the surface of the hot metal gives off electrons in spurts and thus makes the plate current in the first tube vary to a slight extent even though no voltage at all is being impressed on the grid. This slight irregularity will be amplified in the successive stages of the amplifier until it produces audible noises in the telephone receivers at the end of the amplifier. Also, as the electrons move over from the hot filament to the plate of the first tube they bump violently into air molecules that happen to get in their path, and this bumping will also produce irregularities and disturbances that will produce audible noises.

We have spoken about irregularities in the first tube of the amplifier. The same thing is going on in all the tubes, but the effect is amplified more for the first tube. Hence in this first tube most of these "internal noises" originate.

The question might well be asked:—How can the electrons bump into air molecules if the tube has been evacuated, and so freed from air? It must again be pointed out that with the very best evacuation possible today, using the most modern and thorough methods for getting out all the gas, there is still so much gas left that each cubic centimeter of space in the tube still contains about 100,000,000 molecules of air—certainly enough to permit many collisions with the rapidly moving electrons.

How Amplification Sometimes Distorts Received Speech

If a radio broadcasting station is properly adjusted so that the signal being sent out does accurately represent a voice, let us say, then a small crystal receiving set within perhaps 25 miles of the sending station will give remarkably clear reproduction of the voice, much better, for example, than would be the case if the voice were transmitted the 25 miles by ordinary wire telephony. Frequently the writer, when listening to radio signals, has recognized the voice of one of his former students in the first few words of conversation; the enunciation of words and syllables is much clearer than is the case with ordinary telephony.

Now when we use an amplifier and loud speaking horn for giving out the signal the results are generally disappointing. Although much more volume is obtained than when using a crystal receiving set, the quality of the speech is very much poorer. This is due to the fact that the complex shaped electric waves, representing the voice, have their shape changed as they go through the amplifier. Not only is the magnitude of the current increased by the tubes, but the complex forms are so altered (unintentionally of course) that the resulting voice sounds are much modified. This effect is called distortion.

Transformer Amplifier.—The type of amplifier shown in Fig. 14 is called a resistance amplifier because a resistance is used in the plate circuit of each tube, the variation of voltage drop across this resistance being used to supply the exciting voltage of the next tube of the series. Another type, more frequently used, is shown in Fig. 15; in this circuit there is a small transformer between each tube in place of the resistance of Fig. 14. The signal voltage, impressed on the grid of the first tube makes the plate current of this tube vary; this variation of current in the one coil of the transformer (called the primary) will produce a voltage at the terminals of the secondary coil of the transformer. This secondary voltage

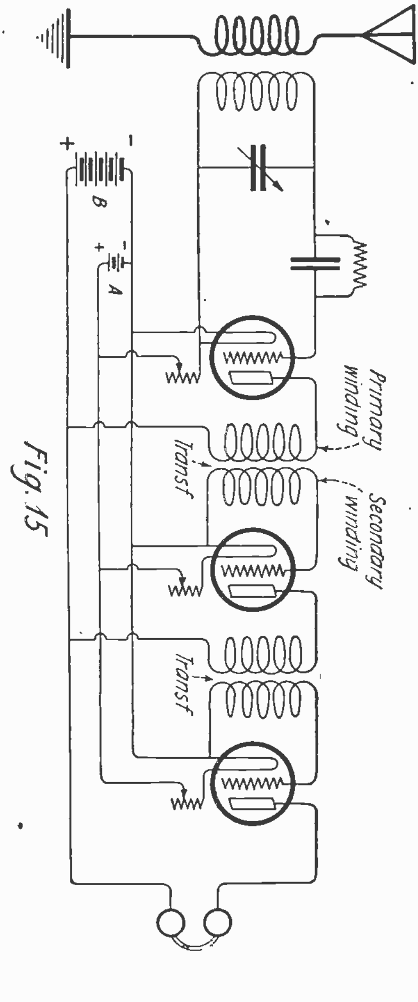


Fig. 15

Instead of coupling the successive tubes by resistances in the plate circuit, transformers are more generally used; such an amplifier (two stage) will make the signal strength increase about 10,000 times, if properly constructed.

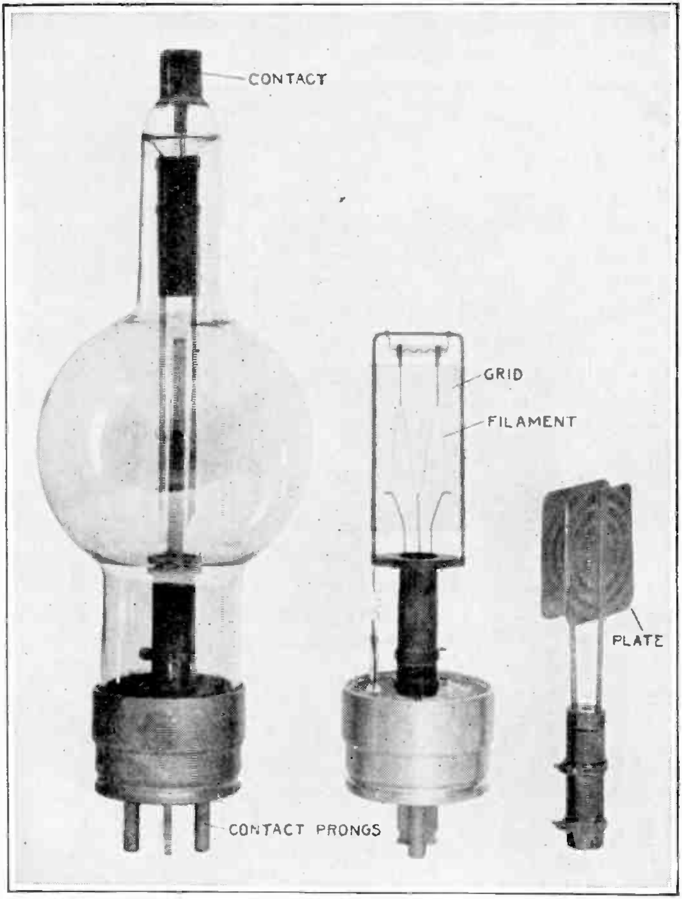
is theoretically of the same form as that impressed on the grid of the first tube, but it may be much larger, using the ordinary transformer sold for such use, with the ordinary amplifying tube, perhaps 10 to 15 times as great.

This secondary winding of the transformer is connected to the grid circuit of the second tube and so causes fluctuation in the plate current of this tube. In the plate circuit of this second tube is another transformer which supplies the voltage for the grid of the third tube, and in the plate circuit of this third tube are placed the telephone receivers.

A transformer amplifier is more effective than a resistance amplifier, two tubes with transformers giving as much increase in signal strength as three or four tubes connected with resistance in their plate circuits. The distortion is generally greater, however, with a transformer amplifier and there is more likelihood of the amplifier's generating internal noises of its own, resulting sometimes in a shrill squealing noise in the telephone receivers even when no signal at all is coming in. If a transformer amplifier is to be much good, care must be taken in getting a transformer suited to the tubes used; a transformer which works well with one type of tube may not amplify at all when used with another.

Radio or Audio Frequency Amplification

As has been pointed out several times the current set up in the receiving antenna by the power from the transmitting antenna is of very high frequency, so high that even if the telephone diaphragm could vibrate at the same speed the note would be so high that no human ear could



A transmitter tube complete and dismembered with the parts named.

detect any sound. Such high frequency currents (from 10,000 to 3,000,000 oscillations per second) are said to be of *radio frequency*. The amplitude, or strength, of the radio frequency current varies at a lower frequency, in fact at the same frequency as the voice sound which actuates the transmitter; such a low audible frequency is said to be of *audio frequency*.

So far, in our discussion of the reception of radio signals, we have shown that the action of the vacuum tube is to rectify the high frequency current in such a manner that the current through the telephones in the plate circuit of the detecting vacuum tube is not of radio frequency but of voice frequency. This voice-frequency or audio-frequency current is then sent through a series of tubes and amplified.

Now it is possible, although not easy, to amplify the radio-frequency current, before rectifying it; such a scheme is said to use *radio frequency amplification*. Radio frequency amplification has at least two great advantages over audio frequency amplification; it is distortionless and it is somewhat selective, amplifying the high frequency signal more than it does atmospheric disturbances. It may then be wondered why radio frequency amplification is not used more extensively than it actually is. All of the reasons cannot be analyzed here but the fact may be taken for granted that to get a certain amount of amplification of the signal voltage requires about three times as many tubes, with their associated apparatus, if the amplification is to be at radio frequency than if it is to be at audio frequency. Certain features of a tube which have a negligible effect at audio frequency limit very much the usefulness of the tube when used at a million cycles. This difficulty in high frequency amplification is so marked that an amplifier may apparently be designed correctly, but so far from failing to increase the high frequency current as much as expected will give actually less signal strength after it has gone through the amplifier than at the beginning!

The best receiver circuit for ordinary radiophone amplification uses about five stages of radio frequency amplification, then a detector, and then two stages of audio frequency amplification. Such a receiver circuit requires eight tubes, rheostats, etc., and is therefore more expensive than the average radio listener cares to obtain. If a loud-speaking horn is to be operated from the set still another tube is advisable, this tube having its characteristics adapted to the horn that it is to operate. The ordinary detector tube cannot furnish enough power to operate a loud-speaking horn without causing considerable distortion.

The Armstrong Regenerative Circuit or "Feed-Back"

It is possible to make a special connection in the ordinary single tube receiver and by proper adjustments to increase its sensitiveness perhaps twenty-five times. In this special connection the plate circuit of the tube is connected to the grid circuit in such a way that the changes in plate current tend to re-inforce the signal itself. The idea was developed and patented by E. H. Armstrong, and is known to all amateurs as the Armstrong "feed-back" circuit.

One of the easiest ways of using Armstrong's idea is given in the connection scheme of Fig. 16. It will be seen

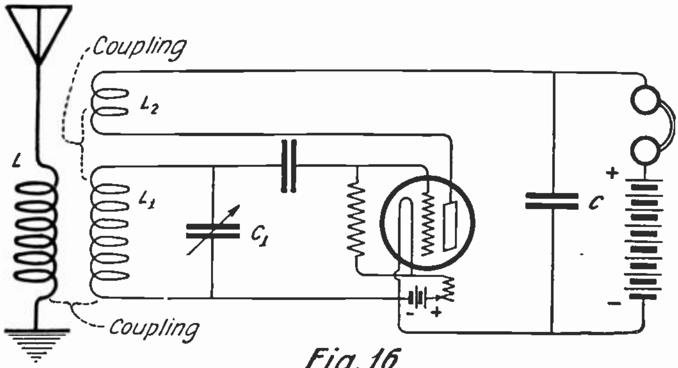


Fig. 16

A simple way of using Armstrong's "feed-back" idea; the tickler coil, L, by re-acting back in the grid circuit, gives a very large amplification to the signal.

that this connection is practically the same as has been previously given with the exception that there an extra coil is now placed in the plate circuit. This coil, known as the "tickler" coil, is connected magnetically to the coil in the local tuned circuit. By "connected magnetically" we mean that the two coils are placed in such positions with respect to each other that when the magnetic field of one changes, it induces a voltage in the other.

It will be noticed that this tickler coil is connected in the plate circuit directly next to the plate. In many home made sets using tickler coils this coil is put between the filament and the telephone, so that either the *B* battery or the telephone is connected directly next to the plate. This should not be done because it makes the tuning of the set much more erratic. It is because of this connection that peculiarities of tuning are noted. A friend of the writer reported that to get the best tuning in his receiving circuit he had to place his feet a certain distance from the radiator! The effect he reported was not a fake effect but one which will always be obtained if the tickler coil is not placed directly next to the plate. The effect is due to the electrostatic capacity of the operator's body. With the telephone connected next to the plate the capacity of the operator's body has an appreciable effect in tuning the circuit, so that getting closer or more distant from the radiator the circuit was actually being tuned. If the circuit is connected as shown in Fig. 16 no such peculiarity in the tuning of the circuit will be found.

How the Tickler Coil Works

A simple explanation of the action of the tickler coil is as follows. Signal currents flowing in the antenna induce voltages in the local tuned circuit L_1-C_1, which is tuned to the signal frequency. Current is thus caused to flow in the L_1-C_1 circuit and it is to be remembered that this current is really caused to flow because of the effect of the changing magnetic field, set up in L by the signal current, acting on coil L_1 to produce voltage in L_1. The grid potential will go up and down at the same frequency as the signal current and so will cause the plate current to rise and fall correspondingly. This changing plate current, flowing through coil L_2 will give here a correspondingly changing magnetic field which reaches out from L_2 into L_1 because of their proximity. This changing magnetic field in L_1, from L_2, will so act as to give a voltage in L_1 which helps out the voltage induced in L_1 by the signal current in

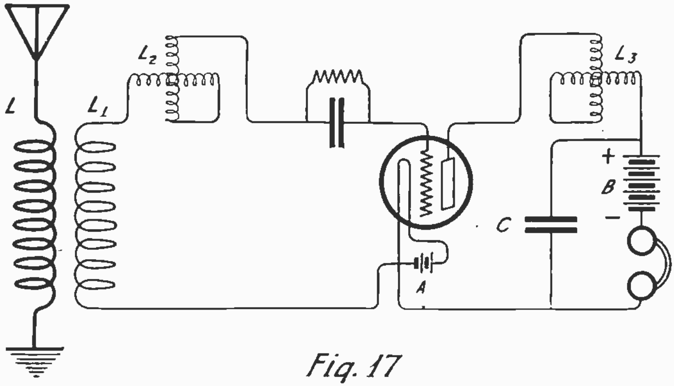


Fig. 17

Another scheme using the feed-back, or regenerative, idea of Armstrong; in this connection the capacity between the grid and plate, inside of the tube, gives an effect equivalent to that of the tickler coil of Fig. 16.

the antenna. In other words, the changing plate current, caused indirectly by the signal current in the antenna, so acts as to help the signal current in the antenna to produce bigger currents in L_1-C_1! It is the amount of current in L_1-C_1 which determines the strength of signal heard in the telephones.

The "regenerative action," as it is called, is controlled in amount by the proximity, or relative positions, of coil L_1 and the tickler coil L_2. The closer these two coils are together the greater is the regenerative action and the louder is the signal, up to a certain limit. If the magnetic coupling of L_1 and L_2 is made too tight the tube circuit may give all kinds of queer noises, sometimes a series of "clucks" at the rate of one or more per second, or singing, or squealing noises, depending principally upon the size of the grid condenser and grid leak. If such noises are obtained the coupling between the tickler coil and L_1 should be reduced until they disappear.

Another scheme which uses Armstrong's idea, which is an extremely sensitive circuit for receiving short waves, is given in Fig. 17. Besides the coil L_1 for coupling the tube circuit to the antenna two variometers are used, L_2 and L_3; one in the grid circuit and one in the plate circuit. When these variometers are each adjusted to just the right amount the signal is increased to a wonderful degree. This is a rather more difficult circuit to adjust than that given in Fig. 16, but is generally a more sensitive one for short wave receivers.

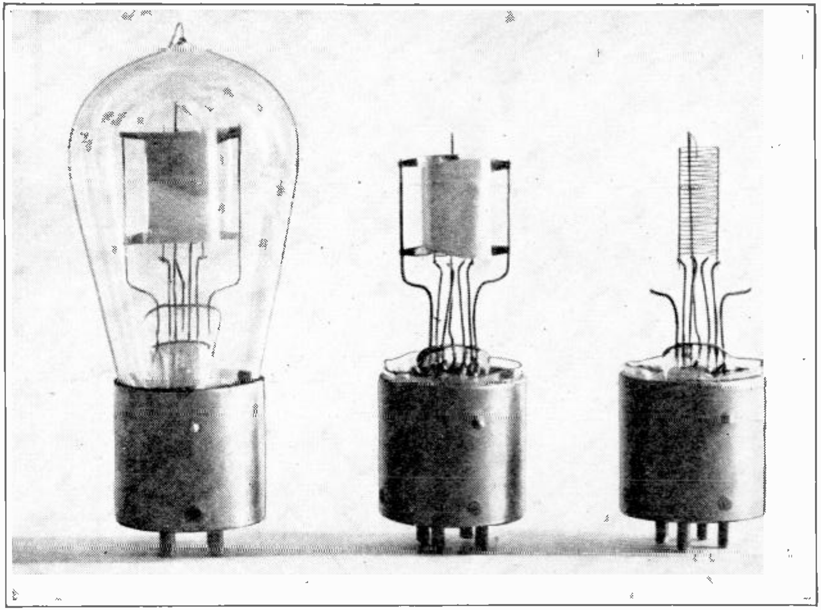
A suitable regenerative connection, properly adjusted, will give an amount of amplification equal to that obtained by between one and two steps of a transformer repeating, audio-frequency, amplifier.

Receiving Continuous Waves

The connection schemes shown in Figs. 16 and 17 are both useful for receiving continuous wave (generally abbreviated *CW*) telegraph signals. In such transmission there may be sent out from the transmitting station a high frequency current of continuous strength as long as the key is held down. It will be noticed that this is different from spark telegraphy (or *damped wave* telegraphy) which sends out a series of high-frequency wave-trains as the key is held down, the number of wave trains per second being fixed by the number of sparks per second at the transmitter, generally about one thousand. The ordinary vacuum-tube receiver, when used for spark reception gives a musical note in the telephones, the pitch being determined by the number of transmitter sparks per second.

Now if such a receiver is used in listening for straight *CW* signals (sometimes another scheme for *CW* than that assumed above is used) nothing will be heard because there is no such thing as spark frequency to determine the pitch of the received signal; the current in the receiver is one of constant amplitude high frequency and therefore inaudible. To make it audible its amplitude (or strength) must change at regular intervals so that its changes will give in the telephones an audible note.

The Heterodyne Effect.—This can be done by a scheme due to R. A. Fessenden, known as the heterodyne, or beat, method of reception. If the incoming signal has a frequency of 1,000,000 cycles per second and if there is continually in the receiver circuit another current of frequency either 1,001,000 cycles or 999,000 cycles per second, this local high frequency current and the current set up by the signal will act together to give a combination high frequency current, the amplitude of which changes 1,000 times per second. But if there is in the local tuned circuit a high-frequency current the amplitude of which is changing at audible frequency the tube so acts, (as previously explained) that there is heard in the telephones a musical note the pitch of which is fixed by the frequency of the amplitude variation. Hence in the above case the continuous wave signal of 1,000,000 cycles would, with the assistance of the other high-frequency current, produce a musical note in the telephone of 1,000 cycles per second. As soon as the signal stopped coming in there would be present only one high frequency current, beats



It is difficult to tell a transmitting from a receiving tube. This is a five-watt transmitting tube; in its complete and dismembered forms.

could not be formed, and so nothing would be audible in the telephone.

By those who have studied the operation of the ordinary pipe organ it will be recalled that the low notes are produced in a manner similar to that just described for the continuous wave receiver. To get a musical note of pitch 32 (that is 32 vibrations a second) two other notes are sounded in unison, say 64 and 96; the combination of these two gives a beat note, the pitch of which is equal to the difference between the two notes sounded, in this case the desired pitch of 32 vibrations per second.

The local high-frequency current required for *CW* reception is obtained by using a scheme like that of Fig. 16, increasing the magnetic coupling between L_1 and L_2 somewhat more than usual. In such a case the tube, when acting properly, will generate high frequency currents in circuit L_1-C_1, the frequency of these currents being fixed by the natural period of the circuit. The tube is said to be "oscillating."

By changing the setting of condenser C_1 the frequency of the local oscillations can be changed at will, and hence the pitch of the musical note heard in the 'phones will correspondingly change. This interaction of the incoming signal and the local oscillation gives rise to a peculiar whistling noise as C_1 is continually changed, if some radio station is sending out continuous wave radiation at the time.

As C_1 is varied, from very small value up, a very high note is heard which, as C_1 is changed very slowly, comes down the whole musical scale and below it, passing below the audible range. As the increase in the value of C_1 is slowly continued the note again appears, very low in

4

pitch, and then ascends through the whole musical scale, finally disappearing into the inaudible range of frequencies above 15,000 vibrations per second. This whole change in the pitch of the note will generally take place as C_1 is changed over perhaps only two or three of the smallest divisions on its scale.

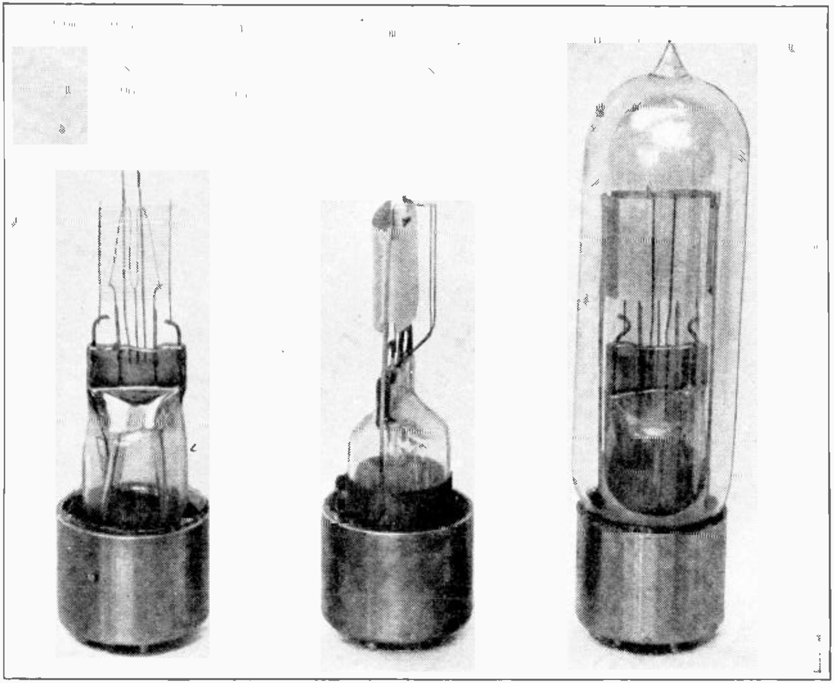
Zero Beat Frequency.—If the value of C_1 is set to be in the middle of the region where the beat note is below audibility the local frequency is the same as the incoming frequency. Hence there are no beat notes; this is said to be the condition for "zero beat frequency." The detecting tube is generating high frequency currents but they are inaudible as they have the same frequency as the signal. If, with this condition, the coupling between L_2 and L_1 is decreased as much as possible, still keeping the tube in the oscillating condition, the detector is set in its most sensitive condition for reception of radiophone signals. To determine whether or not the tube is oscillating with the coupling used, C_1 should be increased a very little; if a low note is heard from the radiophone transmitting station, besides the music or conversation, the tube is oscillating and C_1 can be safely decreased to make the beat note go below audibility with the tube still oscillating.

If the receiving station is close by the transmitting station from which the beat notes are being obtained, low-pitched beat notes are in general impossible; as C_1 is changed, the beat note decreasing from high values, there will be found a value of C_1 below which no beat note is audible. Thus a certain setting of C_1 gives a beat note of 1,000; somewhat less given a note of 400 and if C_1 is further decreased the note suddenly disappears completely. This is because the powerful, near-by station is trying to make the little receiver tube oscillate at the same frequency as itself and when the frequency of the little tube gets too close to that of the transmitter station it is able to do it; the frequency of the current in the L_1-C_1 circuit suddenly changes from that fixed by L_1 and C_1 to that of the transmitter station, and so the beat note at the same time disappears.

Using the Tube to Generate Electromagnetic Waves

As has been mentioned in the previous section, if the plate circuit of a tube is suitably coupled to the grid circuit, there will be set up in the grid circuit high-frequency alternating currents, the frequency of which is fixed by the natural period of the grid circuit, that is, by the L and C in this circuit. To the student who has mastered the first principles of electrical engineering it seems very strange that a source of continuous current power, the B battery, can generate alternating current power, and indeed a really accurate explanation requires a fairly exhaustive analysis.

It is possible to point out, however, instances of common occurrence in which a nearly similar phenomenon is taking place. What makes a violin string vibrate? How does the continuous steady drawing of the bow across the string make it oscillate back and forth (the mechanical equivalent of an alternating current) a thousand or more times a second? Certainly the violinist is not actually pulling the string back and forth with that frequency. He merely gives a uniform, steady pull to the bow, and this steady pull of the bow corresponds to the steady, continu-



The elements of a transmitting tube At the left, the filament and grid are shown, the grid controlling the flow of electrons; in the middle, the "plate," which surrounds the grid and to which the electrons flow; at the right, the completely assembled tube.

ous current power supplied to the vacuum tube by the *B* battery. Analysis of the action of the violin string shows that the changing of the steady pull of the bow into the vibratory motion of the string is due to the peculiar friction between the resin-covered bow and the stretched string. The string, it will be noticed, vibrates at its natural frequency, that is, at the frequency with which it vibrates when plucked and left free to vibrate by itself. This corresponds exactly to the fact that the frequency of the alternating current generated by an oscillating vacuum tube is fixed by the natural frequency of the oscillating circuit.

Another instance from every-day life is the motion of the balance wheel of a watch. The mainspring can evidently push the balance wheel in only one direction, yet the wheel continually works back and forth—oscillates. In this case the essential feature in the problem is the action of the escapement; this allows the mainspring to push the balance wheel in one direction and then prevents it from pushing against the balance wheel when it is on the other part of its swing.

A flexible stick in a smoothly running stream of water provides another illustration. When canoeing in a swift, smoothly running river the writer has often noticed sticks, anchored at the lower end in the bed of the stream with the top projecting above the surface, continually oscillating back and forth, for hours at a time. In this case the peculiar friction between the smoothly flowing water and the stick permits the uni-directional push of the river water to maintain the stick in its oscillatory motion.

A uni-directional flow of steam through a whistle sets the air into vibratory motion, the frequency of the vibration being fixed by the length of the whistle tube. The wind, blowing through tightly stretched telegraph wires, give the humming noise with which we are all familiar.

So we see that there are many cases in every-day life in which a source of continuous power is able to maintain a body in vibratory motion. These cases differ from that of the oscillating triode only in the fact that they are more difficult, to the trained scientist, to explain and solve accurately; to one skilled in the art the operation of an oscillating tube is an exact and predictable phenomenon.

The Triode as a Power Generator.—The amount of alternating current power developed by the small detecting tube used to receive continuous wave signals, is only a small fraction of one watt. To develop much alternating current the tube must be supplied with more power than the ordinary *B* battery can give and be able to absorb this greater power without overheating, or suffering other injurious effects. So, tubes designed to give enough power to operate a transmitting station are much larger and better evacuated than are the tubes used for detectors and amplifiers. The filaments are much larger, use much more power for heating and evaporate a much greater number of electrons. The plate circuit is supplied with power, not from a few small dry cells, but from a small direct current generator, to give an appreciable fraction of an ampere at from 300 to 1,000 volts. These figures are for the small tubes used in amateur stations; the commercial station, using triode oscillators, have tubes using as much as 100 watts or more to heat the filament, and in the plate circuit are used direct current generators which give many amperes of current at as high as 15,000 volts or more. The amount of power generated by a small tube at an amateur station is about five watts, whereas the large tubes mentioned can each generate a kilowatt (one thousand watts) or more. Tubes now being developed will probably generate as much as 100 kilowatts each.

Efficiency of Tubes as Generators.—The efficiency of the small tube is about 25%; that is, of the amount of power supplied by the generator in the plate circuit about one quarter is changed into high frequency, alternating current, power. If we allow also for the power used in heating the filament of the tube, generally supplied by a storage battery, the efficiency of the small tube is only about 10%. The larger tubes, using much higher plate voltage, have efficiencies as much as 60% to 80%, depending upon the voltage used; the higher the voltage of the plate circuit machine the more efficient is the tube as a converter of the continuous current power into alternating current power.

Heating of the Plates.—Anyone who has worked with transmitting tubes knows that the plates of the tubes are likely to get red hot, when in operation. What causes this heat? We have previously said that the temperature of a body is fixed entirely by the amount of agitation of its molecules. The more rapidly they are bumping back and forth the hotter is the body. Now if several hundred volts are used in the plate circuit of a vacuum tube oscillator the attraction of the plates for the electrons evaporating from the filament is so great that when they arrive at the plate they are moving with an almost inconceivable velocity, measured in many thousands of miles per second.

These high-speed electrons are stopped when they bump into the plate, and in stopping they naturally stir up the molecules of the plate with which they collide. The col-

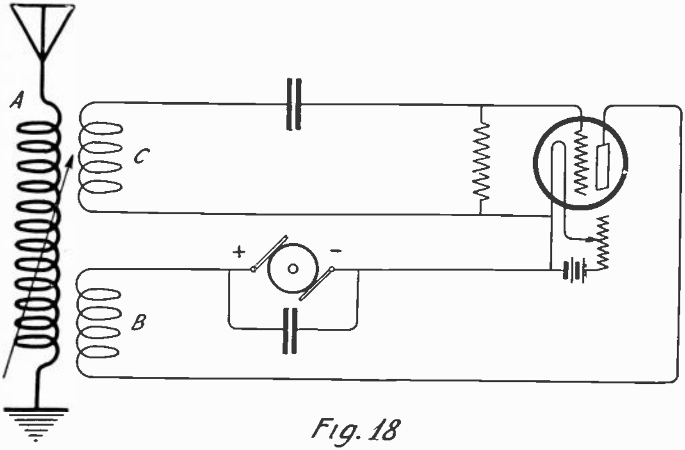


Fig. 18

A commonly used scheme for making a triode generate sufficient high frequency power to excite a transmitting antenna.

lisions result in an increase in the zig-zag motion of the molecules of the plate. Hence the plate is heated. It is perfectly possible to get a metal so hot by this bombardment of electrons that it melts.

Typical Circuits Used.—Various circuits have been used to excite an antenna by an oscillating triode. They are all nearly equally good if the proper adjustments are made for each case. Fig. 18 shows one in which the tube is not directly connected to the antenna at all. Both plate and grid circuits are coupled magnetically to the loading coil of the antenna. The grid is excited through a grid condenser and grid leak, the values of which must be suitably chosen for the type of tube used. It is well to use such a grid connection with transmitter tubes because there is less likelihood of the plates being overheated during use. If the plates do get too hot, gas comes out of them, lessens the vacuum, and the tube may be completely spoiled.

In Fig. 19 one coil is used in the antenna circuit and another is coupled magnetically to it for exciting the grid. In this circuit the wave length sent out from the antenna is controlled by the position of contact *A*, while contact *B* has to be properly adjusted to get maximum output from the tube. The key by which signals are sent out is shown in the grid circuit. Because of the extremely small power taken by the grid this is always the best circuit in which to introduce the sending key; with the smaller tubes, however, it is possible to open the main oscillating circuit it-

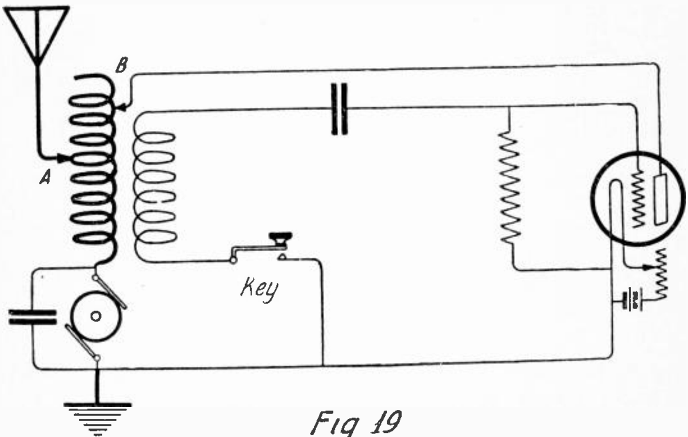


Fig 19

Another typical transmitting circuit; the frequency is fixed by the capacity of the antenna and inductance of the loading coil while the excitation for the grid is furnished by the coil in the grid, circuit magnetically coupled to the antenna coil.

self by a small hand key, if desired. A small Morse key in the grid circuit of a large power tube may safely be used to control several kilowatts of power.

A scheme used extensively by amateurs for short-wave generation is that shown in Fig. 20. The plate is supplied with power from the *B* machine through an iron-core choke-coil, the function of which is to maintain the cur-

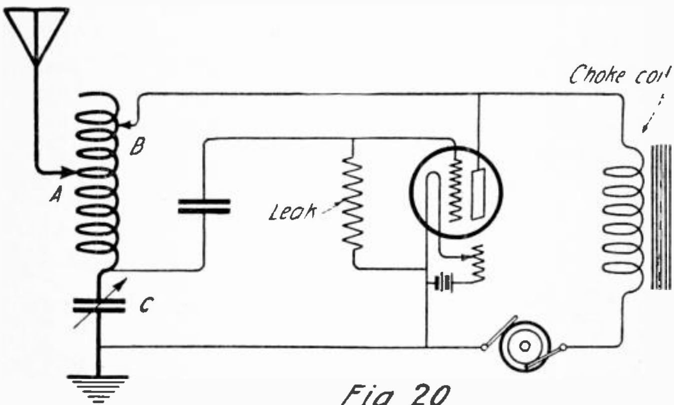


Fig 20

When the power generated is to be used for radio telephony this circuit is frequently used; the choke coil in the plate circuit serves to keep the plate current essentially constant, a requirement in certain radio telephone outfits.

rent furnished by the *B* machine as uniform as possible (hence called "choke" as it chokes out variations in this current). The wave length is controlled primarily by the position of contact *A*, and the maximum output of the tube is obtained by changing both the capacity of condenser *C* and the position of contact *B*. The condenser *C*, should, for the average tube, be about twice the capacity of the antenna itself.

Master Oscillator.—In Figs. 19 and 20 the frequency of oscillation is controlled directly by the capacity of the antenna; if this changes so does the wave length radiated by the station. Now as an antenna swings in the wind its capacity does actually change, and hence the wave length of the station will vary as the wind blows. This has a very serious effect in limiting the transmission range of the station. To cover much distance with a low powered station the receiving circuit must be very sensitively tuned and if the frequency of the transmitting station is varying this cannot be done.

The best stations set their frequency by a small oscillating tube connected to a closed tuned circuit, which has a frequency entirely independent of any changes in the antenna capacity. The grids of the tubes furnishing power to the antenna get their excitation by magnetic coupling to this closed oscillating circuit. Both the antenna circuit and that of the small exciter tube (called the master oscillator) must be accurately tuned to the wave length it is desired to radiate.

Modulating the Voice with the Tube

In radio telephony it is necessary to vary the amplitude of the high frequency current in the antenna according to the voice-frequency which it is desired to transmit. This is best accomplished by using an extra tube as a so-called modulator; the function of the extra tube is really to use up more or less power from the oscillating tube and hence

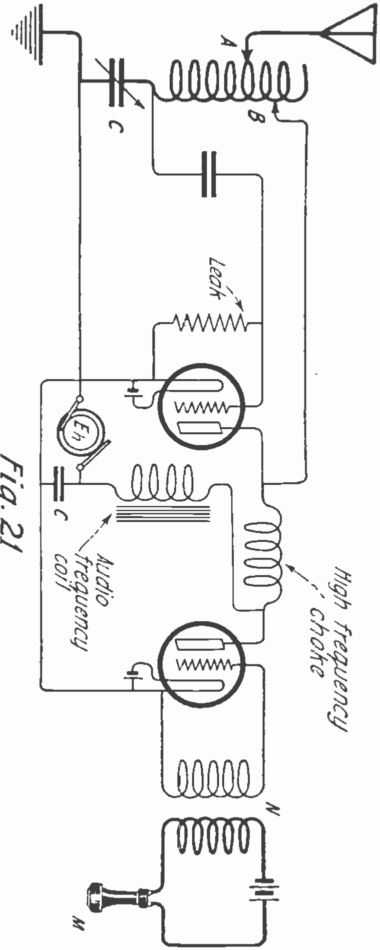


Fig. 21

The Heising scheme of modulation, the one universally employed for good radio telephone transmitting sets. For best results the grid modulator tube should be held negative by a suitable C battery in series with the secondary winding of transformer H.

to make the antenna current vary. The best arrangement for this purpose is that shown in Fig. 21; it is due to Heising and is the well-known Heising scheme for modulation.

Both oscillator and modulator draw their plate-current from the same machine and through the same iron core choke-coil, shown in Fig. 21 connected directly above the plate circuit generator E_h. This choke-coil prevents the current supplied to the combination of two tubes from varying appreciably; that is, they both together draw a constant current from E_h. The telephone microphone M. is used to control the potential of the grid of the modulator tube, through a step-up transformer N. The variation of the potential of this grid will make the plate circuit of the modulator tube take more or less current from the plate circuit of the oscillator tube, as the sum of the two plate circuit currents must be essentially constant. As the amplitude of the high frequency current supplied to the antenna by the oscillator depends directly upon the amount of current supplied to it by the B machine it is evident that the action of the microphone M will control the amplitude of the antenna current, making the envelope follow the voice sounds acting at M.

"Wired Wireless"

A new use of the triode in wire telephony makes it possible to send many telephone conversations over the same pair of wires at the same time. The scheme used is the invention of Major-General G. O. Squier and makes it essentially a radio telephone outfit, both sending and receiving, but instead of broadcasting the waves in all directions they are sent along ordinary telephone wires.

The frequency of the currents used are not as high as those used in radio, being generally between 5,000 and 30,000 cycles per second. A transmitter generating, let us say, 20,000 cycles is connected by two telephone wires to a receiving circuit tuned to receive 20,000 cycles, and regular communication is established by the same electrical circuits and actions as though the two stations were using actual radio waves. A detector and amplifier are necessary at the receiving station just as they are in a radio receiving station.

Such "carrier telephony" or "wired wireless," as it is variously called, will probably never have the vacuum tube apparatus located on the subscriber's premises; it will be installed only in the telephone exchanges, as at present. The carrier current is sent out only between exchanges, that is, over trunk lines. Thus, when subscriber *A* talks into his microphone, ordinary audio frequency currents are sent to the exchange with which he is connected. Here a carrier frequency oscillator is operating and the voice of subscriber *A* modulates (varies the amplitude of) this carrier frequency wave, whereupon the modulated wave is sent to the next exchange with which subscriber is connected. In this second exchange are installed a detector and amplifier and the detected current is sent out from the exchange to subscriber *B* as ordinary audio frequency current, just as though *A* had been talking directly to *B* by ordinary telephone currents.

It is feasible, commercially, to send over a trunk telephone line about five carrier frequencies as well as one audio frequency current at the same time without interference. This increases the possible number of calls handled between exchanges by six times as many as would be possible without the scheme, and without installing any more telephone cables.

Radio Telephony and Wire Telephony Combined

It will also be seen by the imaginative reader that he may, while sitting at home, carry on a telephone conversation with a friend in Europe, or anywhere else in the world, by such apparatus as we have described. He may, for example, talk into his microphone in Chicago; the current started in his microphone will be transmitted by wire to a large radio central station. In going the thousand miles from Chicago to the sea coast, where the radio central would be located, however, it would be necessary for the voice current to be amplified several times, by vacuum tubes used as amplifiers at various points in the wire telephone system. These are called "vacuum tube repeaters," or merely "repeaters." Probably four repeaters would be used to take the current from Chicago to New York. At the radio central station the voice current would control the grid potential of a small vacuum tube, this resulting in corresponding changes in the plate current. This would be successively amplified by tubes until it was powerful enough to control the output of a hundred kilowatt tube oscillator. This modulated, powerful, high frequency, wave would be hurled into space for thousands of miles in all directions. It could be picked up by an antenna in Europe, changed from a modulated high frequency current to audio frequency current, put on the ordinary telephone wires and thus transmitted to the friend in question. And even after the tremendous changes which would have been imposed upon the weak current generated in the microphone at Chicago the received speech in Europe would very likely be clearer than if it had been transmitted over only a few miles of poor telephone line.

It will be noticed that at every step of this miraculous accomplishment, today possible even though expensive, the ubiquitous three electrode tube, first built by DeForest, then perfected by the workers in the research laboratories of the General Electric Company and the Western Electric Company and finally fitted with the remarkably functioning circuit connections of Armstrong, is quietly playing the all-important parts. Even a Jules Verne with all his wonderful imagination, would find it difficult to predict all the feats which this device will undoubtedly be carrying out at the end of the next decade.