"indirect" group the variations agree in time, but are opposite in character; in the third, the "indifferent" group, there is no regular correspondence. Sir Norman and Dr. W. J. S. Lockyer have shown that a region may for years belong to the "direct" group, then suddenly become "indirect," and later return to the "direct" group. Drs. Helland-Hansen and Nansen accept this frequent inversion, and also their explanation of the phenomenon.

The authors' instructive study of North Atlantic temperatures therefore strengthens the case for solar variations acting through the atmospheric circulation as the main cause of meteorological changes. To what extent the ocean helps by regulating the air temperature and circulation the authors do not discuss in the present memoir; that and other questions are to be dealt with after further investigations in a series of memoirs to which the present is introductory. The usefulness of the promised memoirs would be increased (should they have as many appendices and supplementary notes as the present) if each were provided with an index.

The Thermionic Valve in Wireless Telegraphy and Telephony.[1]

By PROF. J. A. FLEMING, F.R.S.

THE thermionic valve is an invention which has vastly increased the powers and range of wireless telegraphy. Like many other inventions, the telephone, for instance, it is simple in its essential construction. It consists of a little electric lamp comprising a glass bulb, very highly exhausted of its air, containing a filament of carbon, or better tungsten, which can be rendered incandescent by an electric current. Within the bulb and around the filament are fixed certain metal plates or cylinders, and, it may be, spirals of wire or metal networks called the grid. To explain its origin in its simplest form I shall have to take you back in thought to the days when the physical effects taking place in incandescent electric lamps were first beginning to be considered carefully. In 1883 Mr. Edison for some purpose placed in the glass bulb of one of his carbon filament lamps a metal plate which was carried on a platinum wire sealed through the glass. When the filament was rendered incandescent by a current from a battery, he found that if the plate was connected by a wire, external to the lamp, with the positive terminal of the filament, a small electric current flowed through it, but if connected to the negative terminal no current, or at most a very feeble current, flowed. This new and interesting effect became known as the "Edison effect" in glow lamps, but Mr. Edison gave no explanation of it, and made no practical application of it.

Edison supplied some lamps with plates in the bulb to the late Sir William Preece, and the latter found that the current called the Edison effect current increased very rapidly as the filament was heated to higher and higher temperatures, and that the collecting plate could be placed a long way from the filament, even at the end of a side tube, without altogether causing it to vanish. At a little later date I took up the subject, and one of the first things discovered was that the Edison effect was greatly reduced if that side of the carbon loop filament in connection with the negative pole of the battery was enclosed in a glass or metal tube, or if a sheet of mica was interposed between the filament and the collecting plate. This seemed to indicate that the effect was due to some material emission from the hot filament.

Another fact I observed very soon was that the filament was giving off torrents of negative electricity, and could discharge a positively electrified conductor connected to the plate, but not one negatively charged. Furthermore, I found that the vacuous space between the filament and the plate possessed a curious unilateral electric conductivity for low-voltage direct electric currents, and that even a single cell of a battery could pass a current from the hot filament to the collecting plate if the negative pole of the battery was in connection with the hot filament, but not in the opposite direction. This fact had, however, been previously noticed in another manner by W. Hittorf. These experiments were made in 1888 or 1889, and at that time were not satisfactorily explained.

It was not until nearly ten years later that your distinguished professor of natural philosophy, Sir Joseph Thomson, published accounts of his epoch-making and important researches, in which he proved that the agency we call negative electricity is atomic in structure, and exists in indivisible units now named electrons, which carry a certain electric charge and have a certain mass. These negative electrons are constituents of all chemical atoms. An electrically neutral atom which has lost one or more electrons is called a positive ion, and neutral atoms which have lost or gained electrons are said to be ionised. There are arguments in favour of the view that the majority of the atoms in metals and other good conductors of electricity are in a state of intermittent ionisation, and that intermingled with the atoms or positive ions, say in a wire of copper, tungsten, or carbon, there are electrons which are jumping from atom to atom with great velocity. If we apply to the wire an electromotive force, this causes a drift of these electrons at the instant they are free in the opposite direction to the force (on usual conventions), and this drift or unidirectional motion is superimposed on the irregular motion, and constitutes an electric current. The drift velocity may be very slow compared with the velocity of the irregular motion. The drift motion of the electrons superimposed on the irregular

[1] From a discourse delivered at the Royal Institution on Friday, May 21.

motion may be compared with that of a swarm of bees in which each insect is flying hither and thither rapidly, whilst the whole swarm is being blown by a gentle breeze slowly down a road. If the electrons merely surge to and fro, it gives rise to a form of current we describe as an alternating current, and if they execute this motion very rapidly we call it an electric oscillation.

The reason an electric current produces heat in a conductor is because the drift energy of the electrons is then being continually converted into additional irregular-motion energy in the free electrons and atoms by collisions of electrons with the atoms of the conductor. If, then, the temperature becomes very high—that is, if the irregular electronic motion becomes very great—certain electrons may acquire such velocities that they are flung out from the surface of the wire even against the attraction of the positive atomic ions left behind. If there is no electric force tending to make the electrons move away from the neighbourhood of the hot wire, these electrons constitute a *space charge* around it, and the repulsion they exercise on each other tends to keep other electrons from getting out into the space. Suppose, however, that the incandescent wire is placed in the axis of a highly exhausted glass tube, and is surrounded by a metal cylinder which is kept positively electrified, the electrons move to it, and others then make their exit from the wire. Such a tube with incandescent wire cathode and cold metal plate anode is now called a *thermionic tube*. The steady emission of electrons is called a *thermionic current*. In the case of a tungsten wire brilliantly incandescent *in vacuo* and under sufficient electric force, this current may amount to as much as an ampere per square centimetre of surface. This means that electrons are being flung or pulled out at the rate of millions of billions per second per square centimetre. So soon as Sir Joseph Thomson had proved by experiment that this electronic emission was taking place the explanation of the effects observed in incandescent electric lamps by Edison, Preece, and myself became clear. For in the Edison experiment we have a slow drift of electrons through the carbon filament superimposed on a very rapid and erratic motion, and multitudes of these electrons are escaping from the filament on all sides—just like steam escaping from a porous or leaky canvas steam pipe. If the plate in the bulb is connected to the positive pole of the filament-heating battery, it is positively electrified and it attracts these escaped electrons, and they enter it and drift through the external wire, forming the observed Edison current.

Suppose, then, that we connect the collecting plate by a wire external to the bulb with the negative terminal of the filament, and that we insert in this circuit a battery of a number of cells which can be altered so as to vary the potential of the plate, the said battery having its negative terminal connected to the filament, we then find that a thermionic current flows which can be measured by an amperemeter inserted in the circuit. If we vary the voltage from zero upwards we shall find that the thermionic current increases, but not indefinitely. It soon reaches a value at which no further increase of voltage raises the current. The reason the current does not increase indefinitely is because for each particular temperature of the filament there is a certain maximum possible rate of electronic emission. The electrons are drawn away from the filament at a rate which increases with the potential of the plate up to that point at which the maximum emission rate is reached. The thermionic current then becomes stationary and is said to be *saturated*.

It is remarkable that although this emission of electricity from incandescent substances had been studied for more than a quarter of a century, none of them made any practical application of it prior to 1904. At that date I was so fortunate as to discover a totally unexpected application of this thermionic emission in wireless telegraphy. Before 1904 only three kinds of detector were in practical use in wireless telegraphy, viz. the coherer, or metallic filings detector, the magnetic-wire detector, and the electrolytic detector. The coherer and the electrolytic detectors were both rather troublesome to work with on account of the frequent adjustments required. The magnetic detector was far more satisfactory, and in the form given to it by Senator Marconi is still used. It is not, however, very sensitive, and it requires attention at frequent intervals to wind up the clockwork which drives the moving iron-wire band.

In or about 1904 many wireless telegraphists were seeking for new and improved detectors. I was anxious to find one which, while more sensitive and less capricious than the coherer, could be used to record the signals by optical means. Our electrical instruments for detecting feeble direct or unidirectional currents are vastly more sensitive than any we have for detecting alternating currents. Hence it seemed to me that we should gain a great advantage if we could convert the feeble alternating currents in a wireless aerial into unidirectional currents which could then affect a mirror galvanometer or the more sensitive Einthoven galvanometer. There were already in existence appliances for effecting this conversion when the alternations or frequency was low, namely, one hundred or a few hundred per second. After trying numerous devices my old experiments on the Edison effect came to mind, and the question arose whether a lamp with incandescent filament and metal collecting plate would not provide what was required even for extra high frequency currents, in virtue of the fact that the thermionic emission would discharge the collecting plate instantly when positively, but not when negatively, electrified. Accordingly I appealed to the arbitrament of experiment, and the following arrangement was tried.

Two coils of wire were placed at a distance, and in one of them electric oscillations were created by the discharge of a Leyden jar. The other coil had one terminal connected to the filament of a lamp, and the collecting plate to one terminal of a galvanometer, the second terminal of the latter being connected to the second terminal of the coil. I found, to my delight, that my anticipations were correct, and that electric oscillations created in the second coil by induction from the first were rectified or converted into unidirectional gushes of electricity which acted upon and deflected the galvanometer.

I therefore named such a lamp with collecting metal plate used for the above purpose an *oscillation valve*, because it acts towards electric currents as a valve in a water-pipe acts towards a current of water. I soon found that for the purposes of wireless telegraphy quite a small low-voltage lamp with a metal cylinder placed round a carbon or metal loop filament was a very effective rectifier, and could be used for converting the feeble alternating currents in a wireless receiving aerial into unidirectional currents capable of affecting a telephone or galvanometer. It was almost immediately adopted in practical wireless telegraphy as a simple and easily managed detector, and the intermittent rectified currents were passed through a telephone. Some time after the introduction of this oscillation valve I found that another method of employing it as a detector was as follows:

If we connect the plate of the valve with the negative terminal of the filament-heating battery, and insert in that circuit a battery for creating a thermionic current, we can delineate a characteristic curve, as already described, by varying the E.M.F. of the plate circuit battery. That curve has generally some places in it at which the slope changes rather quickly. If we adjust the E.M.F. of the plate battery to work at that point, and then by means of a transformer superimpose a feeble oscillatory E.M.F. derived from a wireless receiving aerial, the thermionic current will oscillate from one value to another, and it is easy to see from the concave form of the characteristic curve that the mean value of this varying thermionic current is greater than the value of the steady thermionic current when the oscillations are not superimposed on the steady or battery voltage. This mode of usage in the case of valves with a certain degree of exhaustion in the bulb gives very great sensitiveness in the detection of radio-signals. It is commonly called the potentiometer method because the extra steady voltage required in the plate circuit is derived by employing a fraction of the voltage of the battery used for incandescing the filament by means of a potentiometer resistance.

This is, perhaps, the place to refer to another view of the mode in which my valve acts even when no additional E.M.F. is placed in the plate circuit. The characteristic curve of a valve is found not to start exactly from the point of zero voltage, but from a point on the negative side about ¾ to 1 volt. This means that if the plate is connected to the negative terminal of a filament battery by a wire, there is found to be in it a small negative electric current flowing from the plate through the external circuit to the negative terminal. The reason probably is that the electrons are shot out of the filament with a certain velocity and accumulate round the plate. The result is a tendency for them to diffuse back through the external circuit, creating a feeble electron current which can be stopped only by introducing a small counter E.M.F. into that circuit. Hence the characteristic curve starts from a negative point on the voltage axis. At the place where it crosses the zero voltage point that curve is concave upwards, and hence, for the reason just explained, the introduction into the external thermionic circuit of a feeble alternating high frequency electromotive force will result in an increase in the mean or average thermionic current. Hence the valve is sensitive to feeble electric oscillations and rectifies them, not by quite suppressing all current in one direction, but because the thermionic current is greater for a given E.M.F. applied in one direction in the thermionic current than when that E.M.F. is applied in the opposite direction, whilst the mean value of the thermionic current throughout the complete cycle is greater than its value when the alternating E.M.F. is not applied.

We must now turn to consider an improvement which was introduced in 1907 into the thermionic valve, for which credit must be given to Dr. Lee de Forest. He placed a grid or zigzag of wire carried on a separate leading-in wire between the plate and the filament of my valve, and thereby made what is now called a three-electrode valve (Fig. 1).

In modern thermionic devices the grid takes the form of either a spiral wire or else a metallic gauze cylinder, which surrounds the filament without touching it, and is in turn surrounded by the plate or cylinder which does not touch the grid. This addition enables the valve to act as an amplifier of electric oscillations as follows:

Suppose we insert in the external plate circuit a battery B_2 (see Fig. 1) giving an E.M.F., say, of 100 volts, and also a current-measuring instrument A. If the battery has its positive terminal connected to the plate, the stream of electrons emitted by the filament will be drawn to the plate and give a thermionic current of three or four milliamperes if the valve is highly exhausted. This stream of electrons will reach the plate by shooting through the holes or interspaces in the mesh or spiral grid G.

Let us now suppose that we give the grid a small negative charge by a battery B_3. This will cause the electrons coming out of the filament to be partly repelled, and therefore the thermionic current in the plate circuit will be reduced perhaps even to zero. Again, let us give the grid G a small positive charge. This will attract the emitted electrons, and they will shoot through the grid with increased velocity. Therefore the thermionic current will be increased. The important point to notice is that, owing to the small electrical capacity of the grid, and also owing to the high voltage acting in the plate circuit, a very small expenditure of power on the grid circuit will vary or modulate a much larger amount of power in the plate circuit. Just as the pressure of a child's finger on the switch may start or stop an electric

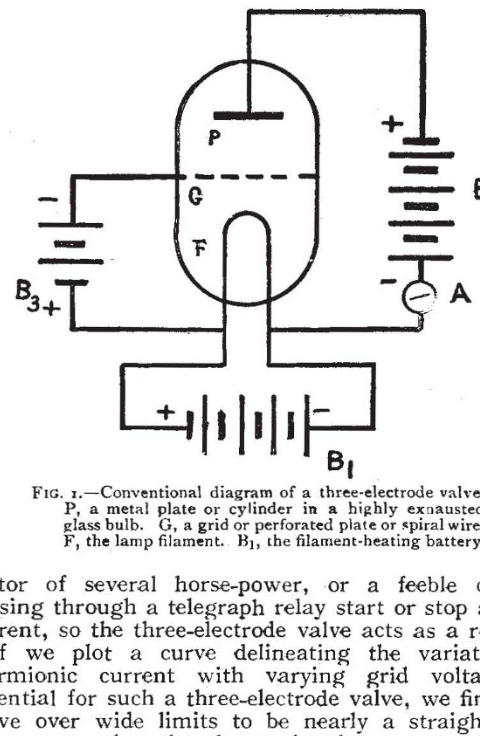

FIG. 1.—Conventional diagram of a three-electrode valve. P, a metal plate or cylinder in a highly exhausted glass bulb. G, a grid or perforated plate or spiral wire. F, the lamp filament. B_1, the filament-heating battery.

motor of several horse-power, or a feeble current passing through a telegraph relay start or stop a large current, so the three-electrode valve acts as a relay.

If we plot a curve delineating the variation of thermionic current with varying grid voltage or potential for such a three-electrode valve, we find that curve over wide limits to be nearly a straight line. This means that the change in plate current is proportional to the change in grid voltage. However rapidly the grid voltage may change, so nimble are these little electrons that the thermionic current copies on a magnified scale the changes of grid potential. Hence the arrangement is called a thermionic amplifier.

We can, however, advance further. If we cause the plate current of one valve to pass through the primary coil of a transformer, and then connect the terminals of the secondary coil of the latter respectively to the grid and filament of a second valve, we find that the fluctuations in the plate current of the first valve can be made to generate exalted potential variations of the second valve, and this again to create magnified variations of the plate current of the second valve. This mode of connection is not limited to two valves; we can thus employ three, four, or more valves *in cascade,* as it is called, and each one multiplies or amplifies the effect of the one before. It is this use of three-electrode valves in cascade that has given us recently such vastly increased powers of detecting wireless waves. The last or final amplifying valve may be made to operate a detecting or rectifying valve, or perhaps a crystal detector.

But there is an additional very valuable power possessed by the thermionic valve, viz. that it can generate electric oscillations as well as detect them. We have already seen that the fundamental property of this valve is that variations of grid potential create similar variations of plate or thermionic current. Supposing, then, that this latter current is passed through a coil over which is wound another secondary coil connecting the grid and filament (Fig. 2). It is possible so to make the connections that any increase in the plate current will give the grid a negative charge and so immediately reduce the plate current. Conversely, any reduction of plate current will give the grid a positive charge which will again increase the plate current. Hence the operations in the plate current when once started will be maintained, the energy required being drawn from the battery B (see Fig 2) in the plate circuit. The action

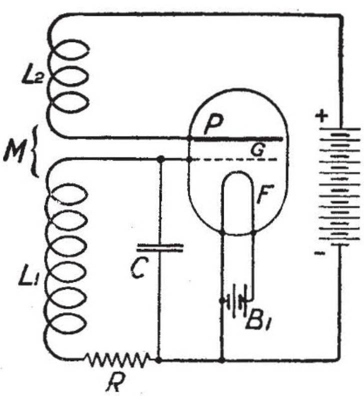

FIG. 2.—Connections for generator valve.

resembles that in the well-known experiment called the singing telephone.

The discovery of the oscillation-producing power of the valve was of great importance, because it at once put it in our power to conduct wireless telephony with simple, easily managed apparatus. The principles of radio-telephony are briefly as follows: At the transmitting station we have to establish in the sending aerial undamped or persistent oscillations and to radiate continuous waves. By means of a carbon microphone we have then to modulate the amplitude or intensity of these waves in accordance with the wave-form of the speaking voice.

The arrangements for a wireless telephone transmitter are, then, as follows: By means of a thermionic valve, with its plate and grid circuit inductively coupled, we set up, as already explained, persistent electric oscillations in the plate circuit, and these are transferred by induction to an aerial wire properly tuned to sympathetic vibration. High frequency electric currents, therefore, flow up and down the aerial. These produce magnetic and electric effects in surrounding space which are propagated outwards as an electromagnetic wave. We have in the next place to vary the amplitude of these radiated electromagnetic waves by a speaking microphone, and this is done by means of a control valve. This latter valve has its grid circuit inductively connected by a transformer with a circuit containing a battery and a telephone transmitter.

Hence, when speech is made to the mouthpiece of the carbon microphone, this varies the electric current through it, and therefore the potential of the grid, in accordance with the wave-form of the speech sound. The plate circuit of this control valve is joined in parallel with that of the generating or power valve, and the result is that speaking to the carbon transmitter modulates the amplitude of the aerial current, and therefore the amplitude of the radiated waves, in accordance with the speech wave-form.

At the receiving station these electromagnetic waves impinge on the receiving aerial and create in it very feeble alternating currents, which are a copy on a reduced scale of those in the transmitting aerial. These are then amplified by valves in cascade, rectified, and sent through a Bell receiving telephone. The result is that the latter emits sounds which closely imitate the speech sounds made to the distant transmitter. We require very high E.M.F. to create a thermionic current of sufficient strength for wireless telephony. This is now obtained by rectifying a high-voltage low-frequency alternating current by a Fleming two-electrode valve.

The whole of the appliances are usually contained in a small cabinet. A $\frac{1}{4}$-kw. radio-telephone set as made by the Marconi Co. will work over 200 miles and transmit speech perfectly. More powerful arrangements on the same principle have telephoned from Chelmsford to Rome.

For aircraft radio-telephony it is usual to provide a small high-tension dynamo driven by a wind-screw to give the requisite direct high plate voltage. The filament-heating currents are provided from small closed storage cells. The aerial wire is a long trailing wire about 250 ft. in length, which is unwound when required from a drum. The actual valve apparatus may be placed at any convenient place in the aeroplane body and yet be controlled by the pilot or observer from his seat. The mere act of taking hold of the microphone transmitter closes a switch which lights up the valves and throws over the aerial wire into connection with the transmitting valve. Such aircraft radio-telephones will operate over a distance of fifty miles or more. So sensitive are these cascaded valve detectors that it is not even necessary to use a long aerial wire at all. A very few turns of insulated wire wound on a wooden frame, called a frame aerial, connected to the receiver suffice to collect and detect the electric wave signals.

Experiments were conducted in March, 1919, by the Marconi Co. to ascertain the minimum power required to transmit by these valve generators articulate speech across the Atlantic during daylight hours. The transmitting plant consisted of two three-electrode generating valves, with a third control valve for speech modulation. A small alternator of 2·5 kw. power supplied an alternating current which was stepped up in potential to 12,000 volts and rectified by a two-electrode or Fleming valve. The reception was by a series of six valves in cascade, with a final detector valve. The speech transmission was perfectly good and clear across the Atlantic, and so loud at Chelmsford, five hundred miles away from Ballybunnion, Co. Kerry, that it could be heard on a simple frame aerial.

Before leaving the subject of radio-telephony it may be remarked that, both in connection with it and with the everyday uses of radio-telegraphy in maritime intercommunication, there is a great demand for an effective wireless call-bell. I have recently devised a form of call-bell which depends upon the use of a new type of four-electrode valve made as follows: A highly exhausted glass bulb contains a straight filament of tungsten, which is rendered incandescent by a 6-volt battery. Around the filament are arranged four narrow curved metal plates having their curved sides facing the filament and very near to it. Each of these plates is carried on a wire sealed through the glass bulb. The plates are arranged round the filament, as shown in Fig. 3.

Two of these plates on opposite sides of the filament, viz. 3 and 4 (see Fig. 3), are called the potential plates, and the other two the collecting plates. The collecting plates are joined together outside the bulb and connected to the positive terminal of the filament-heating battery, and a galvanometer G or telegraphic relay is inserted in that circuit. The electronic emission from the filament then creates a current which flows through the galvanometer or the relay, as in the Edison experiment. If the two other plates have a small potential difference made between them, either of constant direction or else a high-frequency alternating difference, this suddenly reduces the thermionic current. The potential difference of the potential plates introduces a new electric force into the field which deflects away the electrons proceeding from the filament and prevents them from reaching the collecting

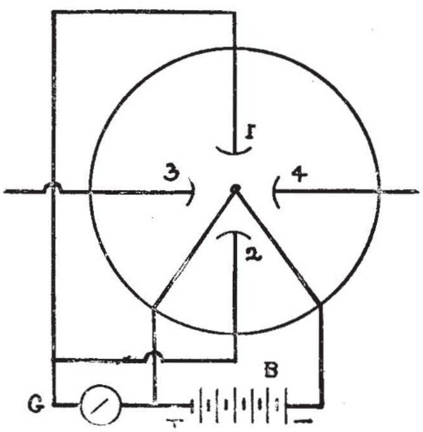

FIG. 3.—Fleming four-anode valve. 1 and 2 are the collecting plates. 3 and 4 are the potential or deflecting plates. B is the filament-heating battery, and the central dot is the end-on view of the straight filament. G is a relay or galvanometer.

plate. If, then, we connect the potential plates to the ends of a resistance of about 15,000 or 20,000 ohms, and include this resistance in the plate circuit of an ordinary three-electrode valve, the thermionic current of the latter flowing through the resistance will create a terminal potential difference which arrests the thermionic current of my new valve. Hence the relay does not operate. If, however, we give an extremely small negative potential to the grid of the three-electrode valve, then this reduces the thermionic current of the latter and increases that of the other valve, which again in turn causes the relay to close contact, and it may be caused thereby to ring a bell. The negative grid potential can be derived from the oscillations in an aerial wire as above described. In this manner I have constructed an arrangement by which the ordinary feeble antenna oscillations can be employed to ring a call-bell. The operator can then switch over the aerial to an ordinary valve receiving set and listen to the telephone.

It remains to say a few words on the methods by which the thermionic valve is employed in the reception of signals made by undamped or continuous waves. By far the best method of receiving signals by these waves is by the so-called beat-reception. If two sets of waves of slightly different wave-length are superimposed, no matter what sort of waves they may be, the result is to produce a compound wave with periodically increasing and decreasing amplitude. These augmentations are called the *beats*.

If a continuous electric wave falls on an aerial it creates on it continuous oscillations. Suppose, then, that we generate also by some local means in the aerial wire undamped oscillations differing in frequency, say by 1000, from the incident waves. The result will be to produce in the aerial electrical beats having a frequency of 1000. These act to a receiver just as do damped trains of waves with a train frequency of 1000. They can be rectified and detected by a valve and telephone, as already explained. It is now quite easy to produce high-frequency oscillations of any required periodicity by coupling a three-electrode valve to the aerial and then coupling the grid and plate circuits of the valve. Sometimes a separate three-electrode valve is used to rectify and detect the beats. Capt. H. J. Round has, however, invented ingenious methods by which one and the same thermionic valve can be used simultaneously to generate and to detect the beats.

We must, in the last place, glance at the uses of the thermionic valve in connection with ordinary telephony with wires. When the rapidly fluctuating electric currents which are propagated when a speaker at one end of a long line converses by telephone with an auditor at the other flow along a copper telephone line, two effects take place which militate against clear and audible speech transmission. First, the current generally is enfeebled as it flows, and this is called the attenuation. Secondly, the different harmonic constituent currents which go to make up the complex wave-form which corresponds to each articulate sound are differently enfeebled.

The vibrations of high pitch are more enfeebled than those of lower pitch. The first effect reduces the loudness of the speech received, and the second its articulate clearness or quality. The cause of the general enfeeblement is the resistance of the line, which fritters away the energy of the speech electric currents. Until lately the only known method of overcoming it was by putting sufficient copper into the line, but this, of course, means cost.

The thermionic valve is, however, able to make a very large economy in copper. It has already been explained that the three-electrode valve can act as an amplifier. Suppose, then, that we cut a long telephone line in the middle and insert on one side a transformer, the secondary terminals of which are connected to the grid and filament of a valve, whilst the plate circuit also contains a battery and a transformer of which the secondary circuit is in connection with the continuation of the line. Feeble telephonic currents arriving at the valve would vary the potential of the grid, and this, as just explained, would fluctuate in like manner, but with increased energy, the plate current. The transformer in the plate circuit would then re-transmit the speech current, but with exalted amplitude. The valve can thus be used to counteract the effect of resistance on the line. In practice, however, the arrangements are a little more complicated, because a telephone line has to be used in both directions.

If our trunk telephone line system in Great Britain had to be laid over again, it is perfectly certain that a very great economy in copper could be made by a widespread use of the thermionic valve as a repeater and relay. It repeats so perfectly that we may certainly say it has completely outclassed all previously invented forms of microphonic relay.