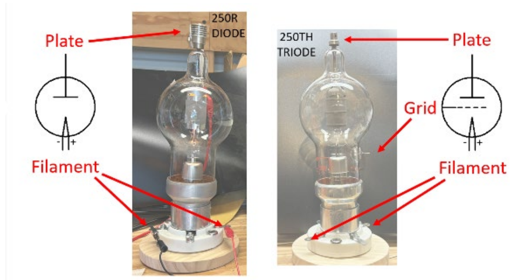
Broadcast Radio[1]

Howard J. Fisher

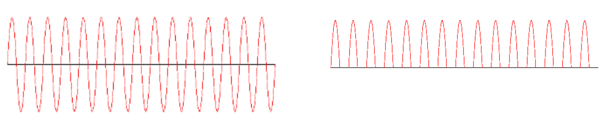
Thank you, everyone, for coming to this talk on *broadcast radio*, the final talk in this series of lectures. Last time we investigated *vacuum tubes* and their distinctive capabilities, which made possible tremendous improvements in wireless telegraphy. This talk will recount the paths by which the basic techniques of wireless signaling were adapted to make possible the wireless transmission of voice and sound—the technology we now call *radio*.

In the last lecture I showed you some measurements I had made on two vacuum tubes: a *diode*—named from its two electrodes, the filament and the plate—and a *triode*, which featured a third electrode, the grid. Both tubes are shown here, along with their



corresponding symbols used in circuit diagrams. Our measurements enabled us to define the functions of electromagnetic wave *detection*, which had been the province of the diode, and electrical *amplification*, which was a new and distinctive contribution of the triode. Let me briefly review both of these functions.

Wireless telegraphy employed the diode, with its ability to conduct current in one direction only, for the purpose of detecting the "dots" and "dashes" of Morse code. When the receiving station took in a signal, the antenna would develop a high-frequency alternating current, as depicted at the top left. That current could not be sent directly to a

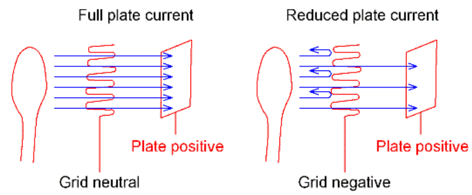


sounding device like the telephone receiver pictured at the bottom, for the rapidly alternating positive and negative peaks would have become blended together and nullified one another. But once the current passed through the diode, only its positive peaks would remain, as shown at the top right. Since these peaks were all in the same direction, they would *reinforce* one another to produce an audible "click" in the telephone earpiece.

[1] Lecture given 29 April 2026 at St. John's College, Santa Fe.

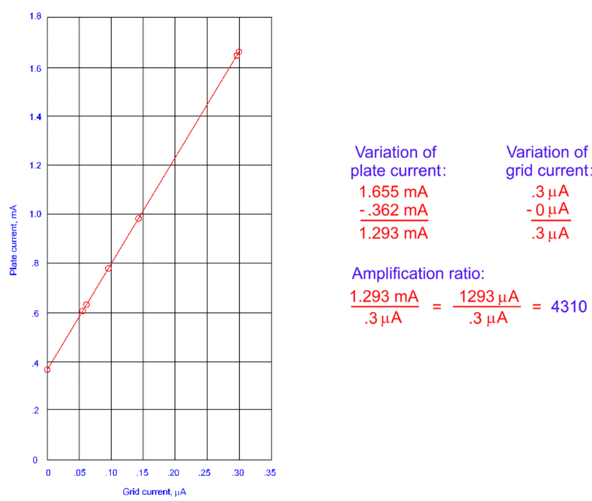
The incoming electromagnetic wave was thereby *detected*—that is, its presence was made known. But, as I noted last time, the pulses received by the telephone could be no stronger than the original current that developed in the antenna. You could not expect a strong "click" in the telephone earpiece unless the received signal were itself quite strong.

That is what led us to appreciate the triode's unique capability for *amplification*. We discussed the principle of the triode's operation last time. So long as the grid bears no



electrical charge, a current of negative ions will stream freely from the hot filament to the positive plate, as depicted in the sketch on the left. But when the grid is made negative it repels some or all of these ions, as sketched on the right, thereby reducing current flow to the plate. *A negative grid* is the usual condition under which the triode operates, because if the grid ever became positive it would begin to compete with the plate for ions. The simplest way to keep the grid negative is by use of a separate battery; and we will see examples of that practice later on.

In the last talk we saw for ourselves how the triode's plate current depends on its grid current. Our measurements enabled us to construct a graph like this one.[2] As you see, the



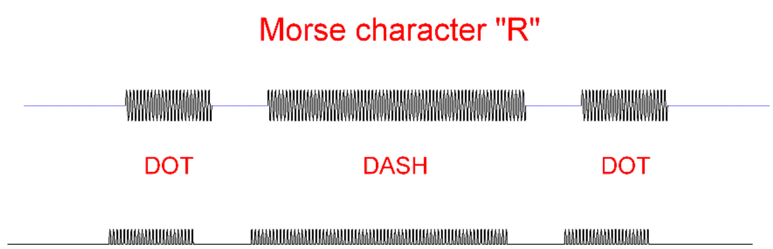
change in plate current is more than *4300 times greater* than that of the grid current! And since the graph is a straight line, we understand that the changes in plate current are proportional to the changes in grid current. Thus any signal sent to the grid will be replicated by the current in the plate, but at a much greater scale. It will be "writ large" by a factor of thousands. That enlargement is called "amplification," although, as I noted last time, the term is not strictly accurate. The triode does not actually make a weak current strong; but it allows a weak current to act as though it were strong. It is like Tennyson's Sir

[2] Here, positive values on the *x*-axis represent negative current sent to the grid. This reverses the graph displayed in the previous lecture, in which positive values on *x*-axis represented negative current *exiting from* the grid.

Galahad: "My stréngth is as the stréngth of tén, because my héart is púre." From which we may deduce that a pure heart gets you *ten*, but a triode gets you *four thousand three hundred*.[3]

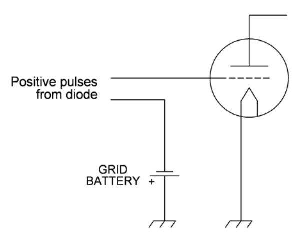
The possibility of *amplification* obviously opens up a very exciting prospect for wireless telegraphy. If we utilize the diode and the triode *in sequence* we should expect a great improvement in signal reception. For example, we might let the diode reduce the incoming alternating current to positive pulses only, then let the triode amplify those pulses to obtain a vigorous response at the telephone receiver, just as though the received signal had been stronger than it actually was.[4] Let us follow the progress of the received electromagnetic wave in such a system.

The Morse character "R" is *dot-dash-dot*. When that character is sent by the transmitter it will produce a wave having this shape; and when that wave reaches the receiving



antenna, it will induce in it an oscillating current having the very same form. But after passing through the diode it will have lost its negative phases and look like this: [SLIDE 10]

These positive pulses are then sent to the grid of the triode, but as I noted earlier, we need to keep the grid negative. That purpose is served by the battery shown here, so long



as its negative voltage is greater than the positive pulses from the diode. In practice, though, it will be advantageous to use a battery of even greater voltage. If we apply enough negative voltage to the grid to cut off the plate current completely,[5] then every *positive* pulse will make the grid less negative, allowing a pulse of plate current to flow. The plate circuit

[3] Soon after the introduction of the triode, Irving Langmuir and others added additional grids having various specialized functions, so giving rise to the tetrode and, eventually, the pentode.

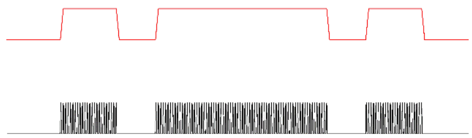
[4] Why not amplify the signal *first*, so as *actually* to make it stronger? Early triodes had difficulty amplifying radio frequencies because of the capacitance that existed between grid and plate (Miller effect); but with development of the tetrode and other means of mitigation, *amplification followed by detection* would eventually become the norm.

[5] In radio circles an initial negative voltage applied to the grid is called "grid bias," and the technique described here is called "biasing to cutoff."

of the triode will therefore develop a current-pattern identical to the sequence of pulses received at the grid—but, of course, much stronger, like this:

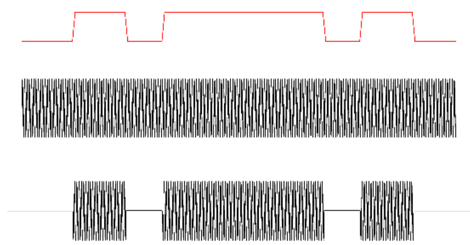
The pulses will have been *amplified*.

Now, what happens when these amplified pulses are sent to, say, a telephone receiver, or a pair of headphones? A headphone's diaphragm cannot vibrate as quickly as the rapidly-succeeding pulses that make up each dot and dash; it will be able to respond to no more than the beginning and end of each dot or dash. It will act, therefore, as though it had actually received a current like this one, drawn in red at the top of the slide, and producing a



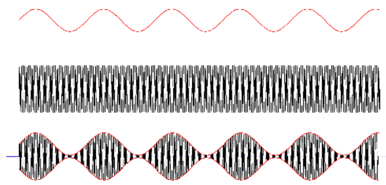
sound like the one you are hearing now. You see what has happened here: the headphone, incapable of reproducing the complex waveform at the bottom—the one it actually received—executed instead the mere outline or "envelope" of that waveform.

Distinguishing the wave from its "envelope" implies a different view of the transmitted telegraphic signal. Instead of thinking of it as a wave that is alternately turned "on" and "off," think of it instead as a wave that is shaped by the pattern of Morse "dots" and "dashes."

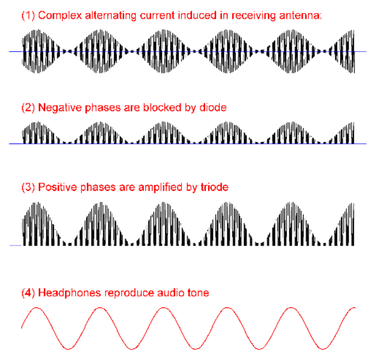


The envelope, or form, drawn in red, is what bears meaning or information—in this case, the Morse letter "R." The process of wireless transmission may then be seen as a process of *imposing this envelope* on the wave proper, shown in the center, to yield the *composite* waveform shown at the bottom: the wave that is actually transmitted. Moreover, if "transmission" is understood as the process of *imposing an envelope* to produce a composite wave, then "detection" ought to be understood as the process of *extracting the envelope* from the composite wave. Whatever the shape of the envelope that was imposed during transmission, that is the shape of the current-pattern that will be extracted when the received signal is routed through the diode. Do you see what this implies? If the transmitting station could impart to the outgoing wave an envelope that represents *sound*, a diode at the receiving station would be capable of extracting that envelope just as effectively as it extracts a telegraphic one.

Suppose, for example, that the envelope has a sinusoidal shape rather than a rectilinear one—the shape of a *pure tone*, such as you are hearing now, and which is depicted at the top



of this slide. If that envelope can be imposed on the continuous wave shown in the center, it will produce the composite waveform drawn at the bottom. If then, at the receiving station, it undergoes the operations we described before, realized by the diode and the triode respectively, you can readily anticipate the stages it will go through; they are these:



First, the complex alternating current arises in the receiving antenna. Next, the diode blocks the negative portions of the signal. Third, the triode amplifies the positive residue; and finally, headphones fail to respond to the high-frequency pulses, but they easily reproduce the audio tone which had been the envelope. This is, of course, a most rudimentary account, but it serves to illustrate the principles of wireless telephony—the original name for *radio*.[6]

But all this assumes that we have been able to produce and transmit the composite wave shown at the top of the slide. We must now inquire how that is possible; and we shall see that the triode is even more essential to this—the transmitting side of the picture—than it was advantageous on the receiving side.

How, then, may we carry out each of the steps listed here, which are necessary to achieve radio transmission of sound?

1. Produce a smooth, continuous wave
2. Obtain a signal that represents the sound in question
3. Impose that signal on the wave as an envelope

Let us address each of these undertakings in turn.

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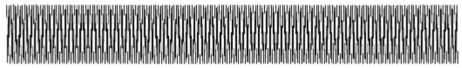
[6] The term "radio" is thought to have been abstracted from "radio-" (compare *radiotelegraphy* and *radiotelephony*) as a combining form of Latin *radius* ("ray"). The term is dated from 1903 by the Oxford English Dictionary.

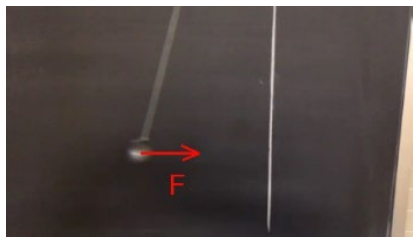
Step 1. The Continuous Wave

In our first talk I recounted various attempts to smooth out the intermittent wave pulses produced by a spark transmitter. But these had only limited effectiveness; they could not achieve a truly uniform wave like the one represented here:



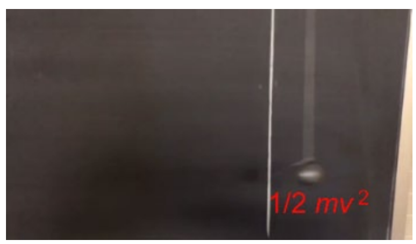
The triode, however, made generation of this kind of wave possible; for such a wave represents simple harmonic *oscillation*; and anything that can amplify can also oscillate. To see why this is so, we need to identify the conditions which produce oscillation. What, for example, makes a *pendulum* oscillate?

Juniors know one answer to that question, a very consequential principle: Any



displacement of the pendulum subjects it to a restoring force that is both proportional to the displacement and opposite to it in direction.

But there is also another way to look at the pendulum. Notice that when the mass swings

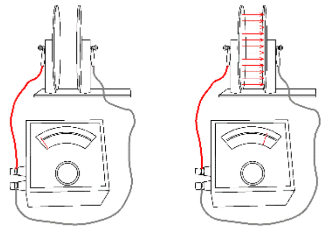


through its central (and therefore lowest) position, all of its energy is *kinetic*—it is energy of motion, $\frac{1}{2}\,mv^2$.

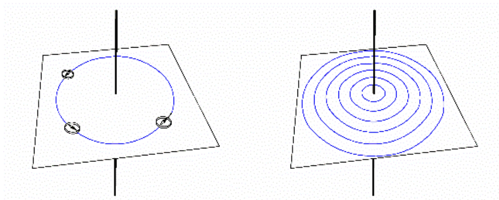
But when it comes to a momentary halt at the limit of its swing, all of its energy is

potential, mgh. So another way to think of an oscillator is as a device in which energy repeatedly alternates between the potential and the kinetic forms. But can these mechanical categories, potential energy and kinetic energy, apply to an electrical oscillator?

Maxwell, in the *Treatise*, repeatedly points out that the energy of a charged capacitor resides in the *electric field* between its plates; it is an instance of *potential* energy;[7] in fact,



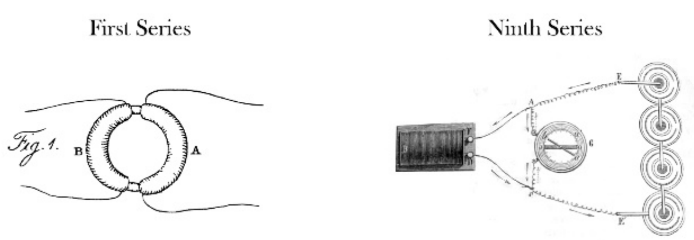
electric potential—potential energy per unit charge—is what the voltmeter measures when we connect it across the capacitor's plates. On the other hand, the energy of an electric current resides in the *magnetic field* that encircles it; and many of you have probably traced



the magnetic lines of force that constitute that field. Maxwell did not hesitate to identify the energy of an electric current as a species of *kinetic energy*.

This is a strain on some readers, and it was too much for some of Maxwell's own contemporaries. What could possibly be "kinetic" about the magnetic field? Was Maxwell relying on the conventional notion of current as being "electricity in motion"? If so (it was objected), he was resorting to a play on words rather than an argument. But Maxwell was not making a pun; he was making an analogy—an analogy based on a fundamental electromagnetic property that resembles *inertia*.

Recall that Faraday, in the First series, showed that a changing magnetic field will induce



a reaction-current[8] in a neighboring conductor. In the Ninth series he went further, showing that a conductor that carries a changing current—and which therefore produces a changing magnetic field—will induce such a current *in itself*.[9] The induced current, moreover, arises in a direction *opposing* the change.

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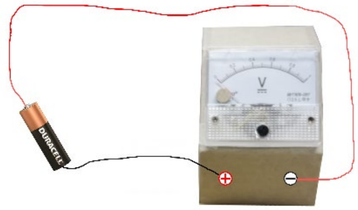
[7] See, for example, Art. 84.

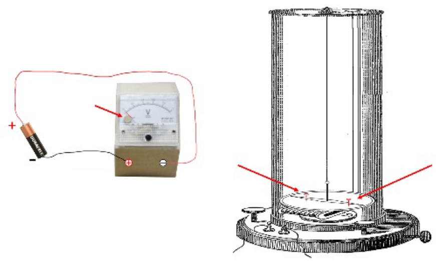
[8] Not Faraday's term.

[9] Paras. 1049–1050. Faraday did not provide a diagram; the one shown here is from *Ganot's Physics*, tr. Atkinson (1884)

We can see this in an experiment based one of Faraday's narratives in the Ninth Series.[10] I am going to connect this voltmeter *backwards*: its positive terminal will be connected to the negative pole of the battery, its negative terminal to the positive pole of the battery. It



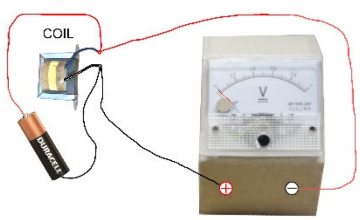
should therefore read backwards when I connect the battery; but I want to limit its pointer's freedom of movement to the forward direction only. When Faraday wished to do that for his galvanometer, he placed small pins, like the ones colored red in this drawing, to prevent



its clockwise rotation, while leaving it free to swing counter-clockwise. I have done the same with my voltmeter by gluing a small wooden post on its face so as to block the needle. Now let's connect the battery.

You see how the meter attempts to read backwards when I close the circuit. And each time I disconnect the battery, the meter simply returns to its zero position, just as we would expect.

But now let me add a coil to the circuit, like Faraday's. Our coil consists of hundreds of turns of wire wound about a steel core; and you can see that when the battery is connected,



current will be flowing through the coil as well as through the meter—which again should attempt to read backwards, just as before. I connect the battery . . . and that is exactly what happens. But what will the meter do when I disconnect the battery this time?

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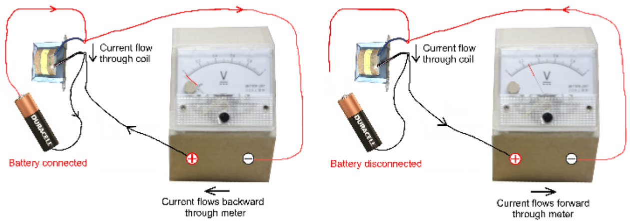
[10] Para. 1087.

The meter *jumps* at the moment of disconnection! It does not simply return to zero but clearly experiences a pulse of current *in the forward direction* at the moment the original current is stopped. Do you see the significance of that direction? On the left I have drawn

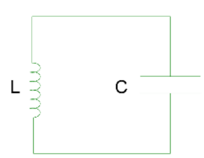


the circuit with the battery connected. Current is flowing downward through the coil; and it is flowing from right to left through the meter, which makes the meter read backwards.

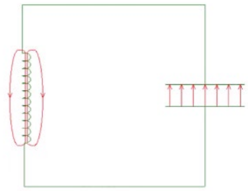
But when the battery is disconnected, as shown on the right, any current that passes through the meter must have been passing through the coil too; and since we saw that a pulse of current actually passed forward through the meter—from left to right—that current must have passed downwards through the coil: *the same direction as before*, that is, in the same direction as *when the battery was connected.* Thus when we *stopped* the battery current, a reaction current developed in a direction to *keep it going*! In other words, the reaction current *opposed* the decrease of current through the coil.

The current in a coil, therefore, tends to *maintain itself*; for if the current (along with its magnetic field) begins to increase, a counter-current will arise to oppose that increase; while, similarly, if the current (again, along with its magnetic field) begins to diminish, a reaction-current arises to augment it. Maxwell compared a current's tendency to maintain its strength to the *inertia of a moving body*, which, similarly, tends to maintain its state of motion or rest—Newton's First Law. So if Maxwell was offering a pun when he characterized magnetic energy as "kinetic," it was a pun on *inertia*—the "*m*" in $\frac{1}{2}\,mv^2$, rather than on the *velocity*, "*v*."

Then let a charged capacitor be connected to a coil, as in this slide. The capacitor will



immediately begin to discharge through the coil. The electrostatic field in the capacitor will be losing energy, but the magnetic field of the coil will be gaining energy; in Maxwell's analogy, energy will be passing from potential to kinetic form. But when the capacitor is fully discharged, the current through coil *does not cease*; for at the first moment of diminution, the reaction-current will augment it and begin to recharge the capacitor in the opposite direction—increasing the potential energy again. The energy of the circuit will thus continually oscillate between the electric and the magnetic forms. If there were no loss of energy, that exchange would go on indefinitely. I have tried to illustrate the process in



this video clip. Here the electric and magnetic forms of energy are represented by Faraday's lines of force.

The pressing question for radio technology was therefore not how to *obtain* electrical oscillations—for that was well known—but *how to keep them going*. And thinking about the pendulum is helpful here too. For the pendulum *doesn't* keep going—at least, not without assistance. A pendulum is constantly losing energy: to friction in its suspension, to the viscosity of the air, and in other ways too.[11] Parents know this; and thus they judge how much of a push to give their child's swing, and when, exactly, to apply it. And we ourselves, as children, probably discovered pretty quickly how, and when, to give ourselves a push by kicking out our legs and leaning backward or forward. An oscillator, then, will keep on oscillating if the energy it loses can be repeatedly restored, in just the right amount, and at just the right time in each cycle of oscillation. In the playground swing, the amount and timing is left to the judgement of a living being. But in a true oscillator, these factors are integral to the mechanism itself. The way this happens is through the technique called "feedback."

Most of us have experienced one variety of "feedback" when, in a lecture or similar event, someone inadvertently brought a microphone within range of a loudspeaker. The awful howling that ensued is a clear case of oscillation; let's see how it arises.

When the microphone picks up any random sound, it sends a current to the amplifier, which reproduces it at the loudspeaker at a much higher level. When, a fraction of a second

later, the sound wave from the loudspeaker reaches the microphone, a duplicate of the original sound will be striking the microphone again—but very likely louder than before, resulting in a still louder reproduction at the speaker. With each iteration the total sound energy in the room increases.

Now enclosed spaces, and even many *partially*-enclosed spaces, feature a multitude of natural modes of vibration of the air they contain. The air in a pipe open at both ends—for example, a flute, a pennywhistle, or a recorder—enjoys the same modes of vibration as does a stretched string: integral multiples of a lowest, or *fundamental*, frequency. The same is true for rooms and auditoriums; but since no single dimension there predominates, the natural modes are more numerous, and their relations more complex. Each mode still has

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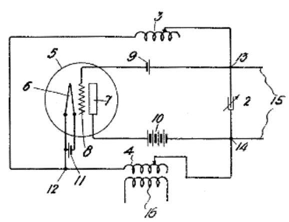
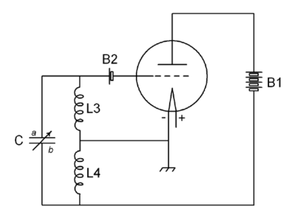
[11] See Paolo Palmieri, "*A Phenomenology of Galileo's Experiments with Pendulums,*" BJHS 2009, esp. page 21.

its corresponding frequency, however. So in the case of microphone feedback, as the level of sound energy in the room continues to grow, one of the room's natural modes of vibration will soon be stimulated; and it is the *frequency of that mode* which we hear as a tormenting howl or excruciating squeal.

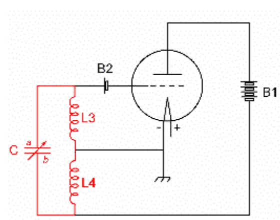
Once this happens, it is the sound of the *modal vibration*, rather than the original disturbance, that is repeatedly fed back into the microphone. So it is not quite accurate to say, as I did a moment ago, that whatever can amplify can also oscillate. It is *the air in the room* that is oscillating; the amplifier is merely *replenishing the energy* of that oscillation to keep it going.

The amplifier in a feedback situation is thus configured in a distinctive way. Whereas in normal operation the amplifier's input is isolated from its output, "feedback" ensues when the input is *coupled* to the output by some means which, like the air in a room, has a natural frequency of its own.

In 1915, R. V. L. Hartley, an American engineer and researcher, applied the principle of feedback coupling to the triode. His original circuit diagram[12] is shown on the left; I have redrawn it on the right in a form I hope you will find easier to interpret.

Let us begin with the oscillating circuit itself, highlighted in red. It is just what we saw a little while ago, a capacitor connected to a coil. The only difference is that Hartley divided



the coil into two parts, L3 and L4; but they function just like a single coil and, indeed, they are often wound as a single coil with a tap affixed to define their junction. In this replica of a

1929 Hartley transmitter, you can see the tapped coil on the left. (The smaller coil next to it links the transmitter to the antenna.)[13]

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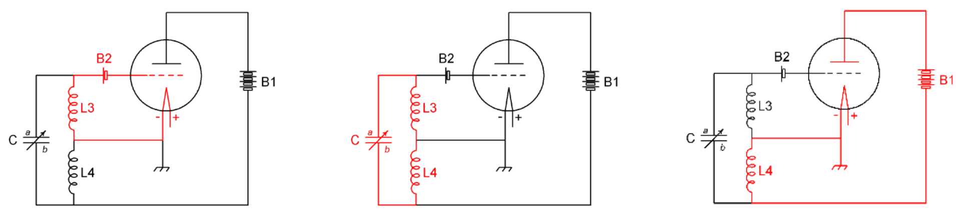
[12] United States Patent Office no. 1,356,763; filed June 1, 1915, granted Oct. 26, 1920.

[13] Hartley's diagram shows a single variable capacitor. The transmitter pictured in the slide uses two capacitors which, nevertheless, function as one: a large capacitor for coarse frequency adjustment and a smaller one for fine adjustment.

How does it work? Since the 1920s, the Hartley oscillator, along with many similar circuits, has become so commonplace that few electronics textbooks bother to explain the logic of its operation in much detail. But in 1915, when Hartley applied for a patent, continuous oscillation was still a novel achievement; and his patent application is wonderfully instructive in its details. You might think this surprising, for the patent process does not require applicants to state, or even to know, how their invention works; nevertheless, inventors often specify operational details in order to claim the widest variety of features as their own. Hartley did exactly that—and more clearly than many of the instructional materials I have come across. I have given a résumé of his analysis in these handouts,[14] and you are welcome to take one after the talk. But for our present purposes, it will be sufficient to see how Hartley's circuit utilizes the principles of *coupling*.

In his patent application Hartley identifies the *input circuit* highlighted in red on the left, the *output circuit*, highlighted on the right, and the *oscillating circuit* in the middle. You can



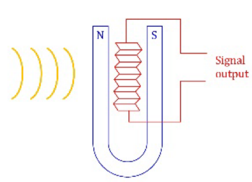
see how the oscillating circuit serves as a kind of bridge between the output and input circuits; and since, as we saw, it has a definite natural frequency of its own, it acts just like the auditorium did in our example of microphone feedback.

Here, then, is an excellent source of the primary wave needed for radio sound transmission. It is far superior to the spark transmitter, for it produces a continuous wave, with a single well-defined frequency. The triode oscillator may be connected directly to the transmitting antenna; or we can boost the signal's power by feeding it to a second triode, this one configured as an amplifier. Our triode, the Eimac 250TH, was in fact designed to serve as either an oscillator or an amplifier in commercial broadcast transmitters of 1000 watts or more.

Step 2. The Audio Signal

Most of you know already that a microphone generates an electrical signal proportional to the sound waves it is exposed to. In the 1930s, the most common type of microphone in broadcasting was the *ribbon* microphone. It works on Faraday's principle, that when a conductor cuts magnetic lines of force, a current tends to arise in it.

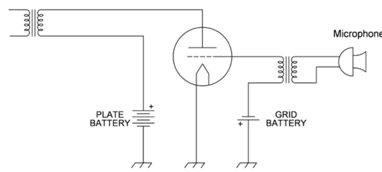
In the microphone shown here, the ribbon—a corrugated aluminum strip—is drawn in red. It is placed between the poles of a magnet, drawn in blue, such that when it vibrates



[14] The handout for this lecture appears on page 00.

under pressure of an incoming sound wave, an alternating voltage is developed in the ribbon, accurately reflecting the vibrations. But microphones generate only very small voltages—much less than what will be needed. How may we increase the microphone's voltage? With—of course!—an amplifier.

You can see it diagrammed here; it is the very same amplifier circuit we employed earlier for enhancing the Morse signal extracted by the diode; as before, a battery keeps the grid

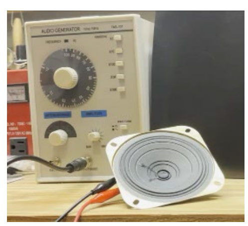


negative.[15] But notice that I have added two pairs of coils: one each in the grid and plate circuits. They are called "transformers," and here their chief function is to separate the oscillating audio signal from the constant battery voltage; I'll say more about that function shortly.

Step 3. Imposition of the Sound Signal as an Envelope

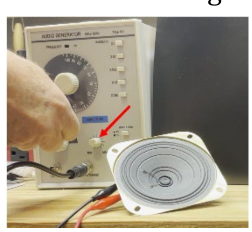
In radio circles, the process of imposing our audio signal on the continuous wave is called "amplitude modulation." The methods for achieving modulation are even more numerous than are the methods for achieving oscillation. We will look at only one of them, but it will serve to illustrate a general principle.

Recall, therefore, what the "envelope" of a wave is: it is a pattern that constrains the strength, or *amplitude*, of an otherwise constant oscillation. For example, with an audio



oscillator I can generate a pure tone having a frequency of 1000 cycles per second, which you are hearing now.

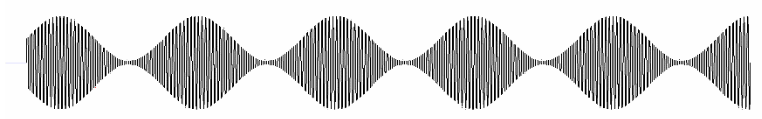
This control allows me to adjust the level of the signal—it is like the volume control on a



radio. Watch as I turn it up and down *twice per second* (a frequency of two cycles per second).

[15] Unlike the previous case which amplified only positive pulses, we here use only as much grid bias as needed to keep the grid negative, not enough to cut off plate current entirely.

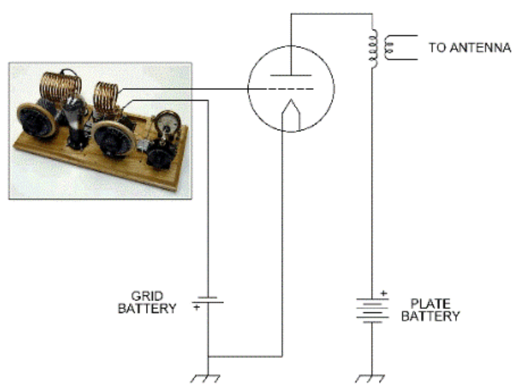
A graph of the resulting wave would look like this:



But this is exactly what we earlier described as *a wave contained by an envelope*. In technical circles it is also termed a *modulated* wave; but in a modulated radio wave the frequency would be not *one thousand*, but *hundreds of thousands*, or even *millions* of cycles per second. And the frequency of the envelope would be not *two* cycles per second, but *twenty* to *twenty thousand*—the range of human hearing. Let's see what kind of apparatus might achieve this.

Look again at the Hartley transmitter:

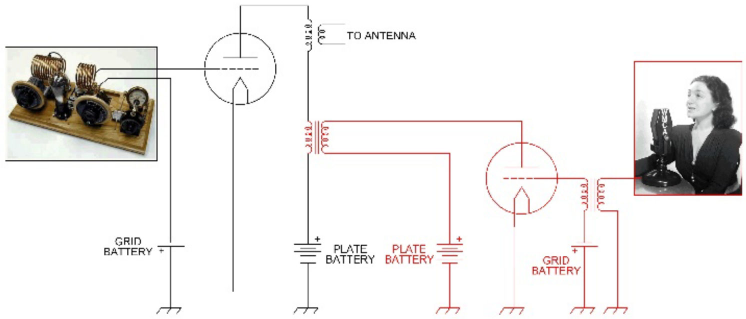
This one generates an electromagnetic wave with frequency about 14 million cycles per second—14 *megacycles*. But now instead of sending its signal directly to the antenna, let us imagine sending it instead to a triode amplifier, like this. Again you see the standard



amplifier circuit, only now the signal to be amplified is being supplied by the smaller transmitter coil, which previously fed the antenna directly. That coil is connected in series with a grid battery having sufficient voltage to keep the grid negative.

There is no "volume control" in this amplifier; but the tube's amplifying ability is strongly dependent on its plate voltage. *Varying the plate voltage*, then, will vary the amplification of the radio wave; and the pattern of that variation will constitute an *envelope* that constrains the wave. Now the plate voltage supplied by the plate battery is fixed. But we can effectively vary it by connecting it in series with a voltage that does vary—the so-called *modulating voltage*—so as to add them together, just as we did in the grid circuit when we connected the grid battery in series with the Hartley oscillator.

Let us therefore break the radio amplifier's plate circuit and insert the signal from the audio amplifier we developed a moment ago. At the microphone is Molly Picon, a

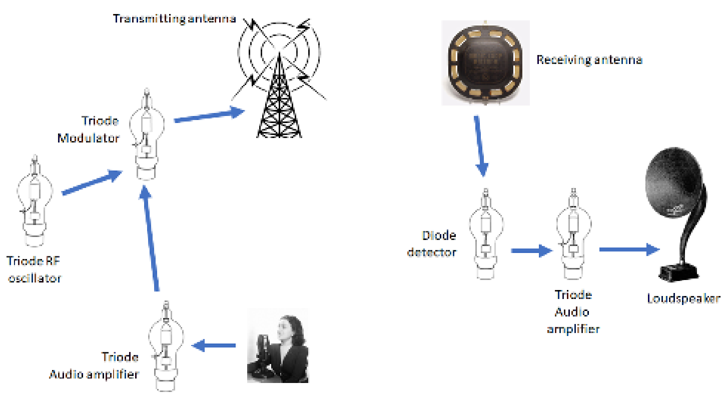


celebrated actress of the 1930s. The transformer labeled "input" protects her microphone from the fixed voltage of the grid battery. If that voltage were applied to a ribbon microphone it would damage or even destroy the delicate ribbon.

The "modulation" transformer is what adds the varying voltage representing Molly's amplified voice to the fixed voltage of the black plate battery, while isolating it from the voltage of the red plate battery; both transformers pass only the changing portion of the current from coil to coil. To appreciate why coils are suited to this purpose, recall once more Faraday's discovery in the First Series that current in one coil could induce a current in an adjacent coil—but only in proportion as the first current was *changing*; a steady current had no such effect. So too, each transformer passes only the *changing* portion of the current applied to it. And it is the *changing* current which in each case represents the voice signal we intend first to amplify and then to transmit. The two transformers wind their coils about an iron core, which, as Faraday found, greatly increases the strength of the induced current.

In order to transfer the modulated radio wave to the antenna we use still another pair of coils, drawn at the very top. But these coils do not employ an iron core, since iron is slow to change its magnetic polarity and cannot do so at the high frequencies of radio. These coils are wound in air, just like the coils of the Hartley transmitter.

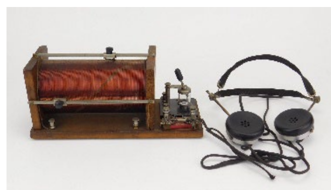
Here, then is a schematic outline of the overall broadcasting pattern—for which I must ask your forbearance, since it is unrealistically simple, even for the 1930s.



Begin at the transmitting station. At the far left, a triode configured as an oscillator generates the radio frequency wave, the so-called *carrier*. At the bottom we see Molly Picon at the microphone; her voice is amplified by another triode. Both the carrier wave and Molly's amplified voice are combined in the modulating triode, the one drawn in red. The modulated signal is sent to the antenna, from which it radiates into the atmosphere and to our homes.

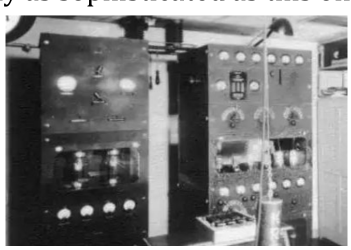
If we live in a strong signal area, the receiving antenna can be indoors, and might even be built in to the receiver itself; the "loop" antenna illustrated here was common in household radios until the 1960s. The signal it receives is conducted to the diode, which extracts the envelope representing Molly's voice. That audio signal is amplified by a triode, which develops sufficient power to drive a loudspeaker. The very early speaker shown here is really an earphone mounted at the base of a tapering horn, but by 1930, most loudspeakers incorporated conical paper diaphragms capable of vibrating with generous amplitudes and moving substantial volumes of air, which made the horn unnecessary.

My treatment of broadcast radio has been confined to the barest essentials. Regarding radio receivers, such abridgement is perhaps not too misleading, because receivers can be remarkably minimal. Vacuum tube receivers do not even require the two individual tubes displayed in the slide; a single triode can actually both detect and amplify. And simpler even than the one-tube receiver was the crystal radio, to which I have given very little



attention, although its simplicity and ready availability helped build a wide audience for broadcasting in radio's earliest days, the decade of the 1920s. But vacuum tube sets, with their superior performance, soon began to predominate. Crystal radios nevertheless enjoyed a resurgence in the 1930s, when tubes were prohibitively expensive for many depression-era families. My mother used to recount wonderful childhood memories of her parents' crystal radio, with its headphones placed at the bottom of an enormous mixing bowl to enable family listening.

But broadcast transmitters could never be as austere as the circuits I have discussed. Even the earliest broadcast facilities involved many features I have had to pass over; and by 1935, transmitters were typically as sophisticated as this one, built for station KRE,



Berkeley. The two—yes, *two*—power tubes are visible at the lower left. I would suppose them to be triodes like ours, but I have not been able to confirm that.

❖

Permit me now to conclude with a question which is a little embarrassing to be asking in retrospect: what has been the aim of this three-lecture study? But I don't think I could have stated the aim in advance—unlike Herodotus, who could proclaim at the outset his intention in writing, namely,

> "that things done by man not be forgotten in time, and that great and marvelous deeds . . . not lose their glory."[16]

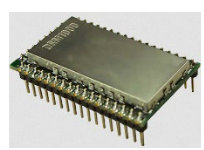
Is it important that human accomplishments "not be forgotten"? Or does such a wish merely betray a futile attachment to things, methods, and practices that are inherently fleeting and transitory? And what can it mean to have a care that great deeds "not lose their glory"?

But since we are at the end of our study, perhaps we may ask: Have any of Herodotus' intentions been advanced by our inquiry? With respect at least to technological exploits, I think we can identify two qualities that might contribute to whatever it is that constitutes their "glory." These are closely related but are, nevertheless, worth distinguishing. The first is *visibility*.

On the left is a modern bridge,[17] completed in 1989. It is without doubt an exceptionally

beautiful creation; but bridges have to be more essentially concerned with strength and stability. We can *see* the bridge's beauty; can we *see* the grounds of its strength? Except for the two supporting pillars, it presents itself as a single, continuous, homogeneous whole. It displays nothing concerning the causes of its strength, which was made possible only by the development of modern *prestressed concrete*. Contrast it with the truss bridge on the right,[18] from the 1880s, a complex of steel members. It freely displays its elements, which in turn make almost obvious the patterns of stress, in the resistance to which its stability consists.

In the field of radio, the photograph on the left is an under-chassis view of a Philco



receiver from 1934. Even if you don't know what the individual components do, you can see that there *are* individual components. Their functions are known, at least by those who cultivate the electronic arts; and their wired connections are fully open to view. Contrast that architecture with the present-day integrated circuit on the right, which performs all the functions of the 1934 radio and lacks only the controls, power supply, and speaker. If it incorporates elements or components, they are certainly not evident to the eye. In fact, the spatial structures of such modern processors are sized on the order of about five

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[16] Herodotus, *Histories*, Book I. Tr. A. D. Godley (1920). Walter Benjamin has perhaps stated the sentiment more concisely with his admonition, "Never forget the best!" See "Franz Kafka" in *Illuminations*, (Schocken 1969), page 136. The phrase "lose their glory" is Godley's rendition of ἀκλεᾶ (without fame).

[17] Storseisundet Bridge, Norway.

[18] "Old Southern Railroad Bridge" by J. M. Bailey, located in Murphy, North Carolina.

nanometers—50 times smaller than an optical microscope could resolve. These miniaturized devices have many virtues—but not that of visibility.

A second estimable quality we typically find in early technology is *approachability*. I think that is what Maxwell had in mind when he wrote, in the *Treatise on Electricity and Magnetism*,

> For science is always most completely assimilated when it is in the nascent state.[19]

Maxwell made this remark in connection with Faraday's scientific work, but what he said of science is, I think, equally true of many other branches of knowledge; for in the earliest stages of development of any field, the gap between the expert and the inquirer is at a minimum. Certainly that is true in Faraday's experimental narratives, which are as free of prerequisite assumptions and implicit erudition as any exposition can be. No body of settled doctrine has yet become the standard for Faraday; everything, or almost everything, is up for question—which means that almost all is open to us. We, as readers, can place ourselves very nearly where Faraday is. As Maxwell states later in the *Treatise*, the reader of Faraday is—I quote—"tempted to believe that, if he had the opportunity, he too would be a discoverer."[20]

Herodotus seems to identify a third aspect of "glory" with his phrase "great and *marvelous*"—the word is *θωμαστά*. By this I suppose he meant to single out doings *so unexpected and extraordinary* as to elicit astonishment. But astonishment seems to be conspicuously rare in the radio story we have followed. I can think of only two instances: Edison's discovery of the mysterious current that could not be reversed—the so-called *Edison effect*—and Pickard's baffling realization that his improvised "detector" must somehow be converting alternating current to direct current. Most of the other developments we have attended to involved well-defined problems and more or less deliberate and systematic efforts to solve them: *how to generate a continuous wave*; *how to vary its amplitude*—little surprise or wonderment seemed to be involved.

But do we perhaps tend to overvalue the "marvelous"? Should we not allow a measure of admiration also for the everyday questions, in which little spectacle is involved? I am thinking of questions like, "How does it work?" "What would happen if we change this or that?" A very young James Clerk Maxwell, it is reported, would constantly ask, "What's the *go* of that?" about anything that "moved, shone, or made a noise".[21] Lives that embrace everyday inquiry would seem to find, if not glory, then at least color in the world. In fact, David Grene translates Herodotus' word *κλέος* as "color" rather than "glory."[22] And *color* is something, I am sure, we do not wish to vanish from our awareness.

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[19] *Treatise on Electricity and Magnetism*, Preface to the First Edition.

[20] *Treatise*, Art. 528

[21] Campbell & Garnett, *Life of James Clerk Maxwell* (1888), p. 28; Mahon, *The Man Who Changed Everything—the Life of James Clerk Maxwell* (2003)

[22] Grene's rendering: "I, Herodotus of Halicarnassus, am here setting forth my history, that time may not draw the color from what man has brought into being, nor...."

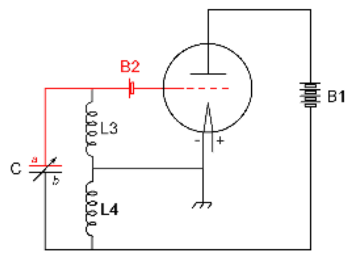
What, then, constitutes the *κλέος* of past deeds? Whether we regard it as "glory" or "color," I am suggesting that this valued quality may be found not only in heroic greatness but sometimes, to the contrary, in the unassuming "nascent" state which Maxwell praised in Faraday's work. In our thinking, too, the surpassingly brilliant need not perpetually blot out the merely luminous. The celestial Sun does not always eclipse the stars, nor the Platonic Sun totally humiliate the fire in Plato's Cave. Indeed, were it not for our experience of the Cave's subterranean fire, would it ever even occur to us to seek the Sun?

The Hartley Oscillator

Handout for the lecture "Broadcast Radio"

When Hartley applied for a patent on his oscillator circuit in 1915, continuous electronic oscillation was still a novel achievement; accordingly, his patent application is wonderfully instructive in its details. He analyzes the circuit this way:

Let the oscillating circuit be in an active state; and suppose the capacitor C is at this moment in the process of being charged, its terminal *a* growing increasingly positive,



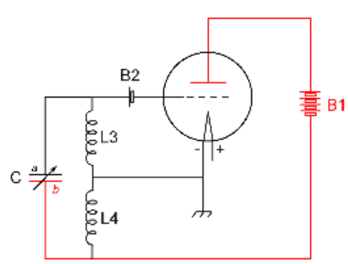
terminal *b* increasingly negative. Now terminal *a* is connected to the grid through battery B2; and since the battery has a fixed voltage, the potential difference between terminal *a* and the grid must be *constant*. Then since *a* is becoming more positive, the grid too must be becoming more positive—that is, less negative—by the same amount.

In our earlier discussion of the triode, we saw that when the grid becomes less negative it repels fewer ions, so the plate current will increase. Hartley, though, has an interestingly different point of view. He states that decreasing the negative charge on the grid

> will have the effect of lessening the electrical obstruction which the grid ... offers to the stream of ions flowing from filament to plate.

The term "obstruction" here refers to the grid's repulsion of negative ions. Since that repulsion is effectively a form of *electrical resistance*, there will now be *less resistance* between the plate and the filament. But for a given current, less resistance means *less difference of potential* between the plate and the filament.[23] With respect to the filament, then, *the plate becomes less positive*.

Now we saw in the lecture how the triode's ability to amplify means that when a change at the grid causes a change at the plate, the change at the plate is by far the greater of the two. But the plate is connected to capacitor terminal *b* through battery B1. Here too, then,

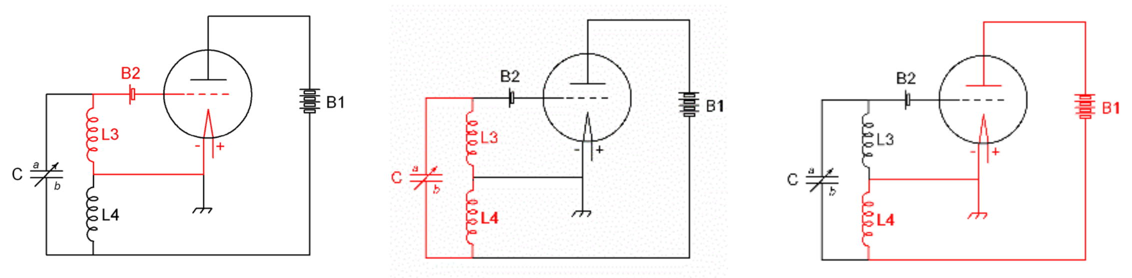


since the battery has a fixed voltage, the potential difference between the plate and terminal

[23] This is a consequence of Ohm's Law.

b must be *constant*. Terminal *b* will then undergo the same change in potential as does the plate: it will become less positive—that is, *more negative*. And as we just affirmed, the increase in *b*'s negativity due to the plate will be greater than its original increase in negativity from merely being in the charging phase of oscillation. The capacitor will thus have received a *boost* of potential energy, delivered moreover at just the right time—a time when its potential energy was already increasing.

We can also see how this circuit utilizes the principles of *coupling*. In his patent application Hartley identifies the *input circuit* highlighted in red on the left, the *output*



circuit, highlighted on the right, and the *oscillating circuit* in the middle. You can see how the oscillating circuit serves as a kind of bridge between the other two circuits; and since, as we saw, it has a definite natural frequency of its own, it acts just like the auditorium did in our example of microphone feedback.

H. Fisher