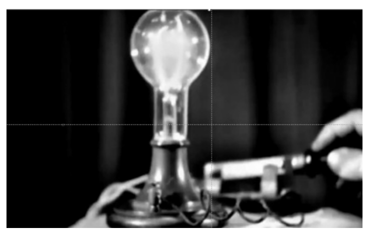
The Vacuum Tube[1]

Howard J.Fisher

Good afternoon, everyone, and thank you for coming to this second of three lectures on early radio technology. Our topic is the vacuum tube—I chose the two examples on display here for their large size, which allows us to see their construction. The vacuum tube made possible the age of *radio*—that is, wireless transmission and broadcast of sound—as opposed to *radiotelegraphy*, which was limited to sending wireless messages in the dots and dashes of Morse code. What did the vacuum tube do, that made it such a consequential device? And what are the principles of its operation?

The vacuum tube finds its beginnings in *Edison's light bulb*. Here is one of Edison's later

designs. The hair-like filament is heated to incandescence by a strong electric current, producing a very creditable glow, as you see here. But at temperatures high enough to



achieve incandescence, almost any filament material would soon burn up in the presence of air; the glass bulb therefore had to be evacuated.

Edison's light bulb was by no means the first. Earlier researchers had crafted similar incandescent devices; but the limited capability of early vacuum pumps achieved only mediocre vacuums, in which the glowing elements would burn up quickly. Edison benefited from the development of highly effective pumps such as Sprengel's and Geissler's, which could achieve pressures as low as a tenth of a millimeter of mercury.[2] The ability to obtain such low pressures enabled Edison to develop by 1880 a carbonized bamboo filament capable of lasting hundreds of hours; but very soon another difficulty emerged. Early versions of this filament tended to throw off some of their carbon, which would then be deposited on the interior of the glass, gradually blackening it, which, of course, defeated the very purpose of a lighting device.

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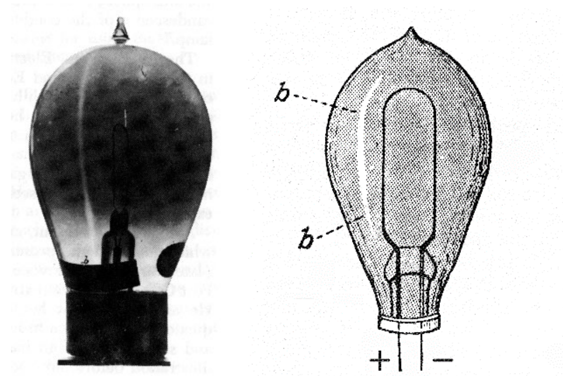
[1] This lecture was given 15 April 2026 at St. John's College, Santa Fe. It is the second of a series of three talks on early radio technology.

[2] Andrade, E. N. da C. (1953). "The history of the vacuum pump." *Vacuum* **9** (1): 41–47.

Interestingly, though, the pattern of carbon deposit was not uniform. Edison noted a peculiar "reverse shadow" of the filament—a line of *less darkening*, as you can see in the photograph on the left.[3] Curiously, this lighter line appeared only on the side of the bulb adjacent to the *positive arm* of the filament—the line labeled *b b* in the diagram on the right.



For, indeed, there *was* a definite positive and a definite negative arm of the filament, as the diagram indicates. That is because Edison powered his lamp with *direct current*, for which the positive extremity of the source remains positive, and the negative remains negative, throughout the current's duration. In contrast, the common household current of today is *alternating* current, in which the positive and negative polarities exchange places 60 times each second.

Evidently, in Edison's bulb, many of the carbon particles traveling in the direction from negative to positive were being blocked before reaching the glass, but particles traveling in the opposite direction were not so impeded. What could cause this asymmetry?

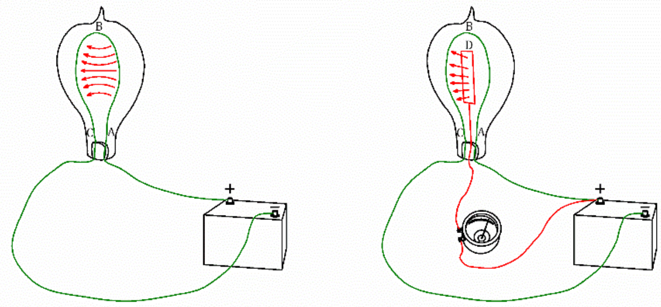
Well, if the carbon particles escaping from the filament carried a *negative charge*, then at least some of the particles originating from the negative arm of the filament would be attracted by the positive arm and might be captured by it before reaching the glass, while those escaping from the positive arm would be repelled from the negative arm; they would be less susceptible to capture and would continue beyond it, and would at last deposit themselves on the glass. But *did* these roving carbon particles carry an electric charge? Edison investigated that question by mounting a metal plate between the filament arms, as shown in this photograph. On their way from the negative arm to the positive, some

particles, at least, would presumably strike the plate and give up their charge to it. Then, if that plate were connected back to the filament, the circulating charge would constitute a

[3] Left: from Tyne, Gerald F. J., *Saga of the Vacuum Tube*, Howard W. Sams & Co. (1977). Right: adapted from Fleming, J. A., *The Thermionic Valve and its Developments in Radiotelegraphy and Telephony.* London, The Wireless Press (1919).

current and should be detected by a galvanometer. Edison began a series of experiments with this special bulb in 1882. When he connected the plate to the positive end of the filament, a current did indeed pass; but *no current passed* when it was connected to the negative end. Let us see if we can understand this.

Figure (1) is a diagram of Edison's original light bulb. The righthand filament arm, AB, is connected to the positive terminal of the battery; the lefthand arm, BC, is connected to the



Standard Edison bulb
(1)

Current flows when plate is positive
(2)

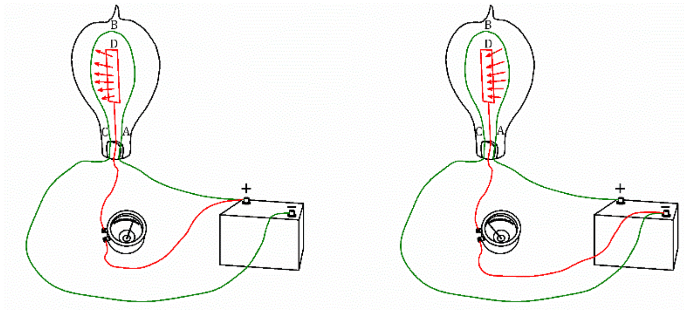
negative terminal. Thus there is a potential difference between the two extremities of the filament; and since the filament is a conductor, a current will flow through it. But the same potential difference exists *in the space between the two arms*, since the filament is bent in a horseshoe shape. Thus there is an electric field between AB and BC, represented by the curved red arrows. If, then, electrically-charged particles are emitted from the filament, they will be urged in the direction of the arrows if they are positive, and in the opposite direction if they are negative.

Now consider Figure (2). With the addition of plate D connected (through the meter) to the positive battery terminal, plate D and arm AB are effectively connected together. They are therefore at the same electric potential and no electric field exists between them. But the full battery voltage now obtains between plate D and arm BC, connected to the negative terminal. An electric field therefore exists between them, having direction from D to BC, as indicated by the little red arrows.

If, then, as Edison suspected, negatively-charged particles of carbon were being emitted from the filament, they would be urged in the direction opposite to the electric field, that is, in the direction from BC to D; particles emitted from BC would thus carry negative electricity from filament to plate, producing the current that Edison witnessed.

What about negative particles emitted from the other arm of the filament, AB? They are exposed to no field at all and therefore are not urged toward the plate; they would not reach it and so would play no part in the measured current.

But now consider Figure (3), where the plate is connected to the *negative* terminal of the battery. Here plate D and arm BC are effectively joined together; they must therefore have



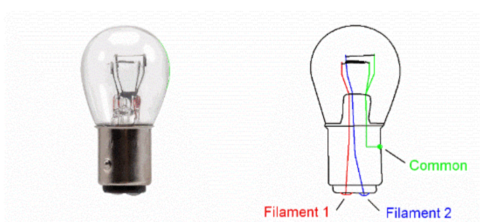
Current flows when plate is positive (2)

No current flows when plate is negative (3)

the same electric potential, and there will no longer be any electric field between them. Instead, a field exists between arm AB and plate D, in the direction from AB to D. Negative particles emitted from the filament now have nowhere to go! Particles emitted from BC are exposed to no field at all and so are not drawn to the plate, as I mentioned before. Particles emitted from AB *are* exposed to a field; but if they are negatively charged, they are urged in the opposite direction, that is, *away from the plate*. Negative particles thus cannot form a current no matter what part of the filament they originate from, which explains why Edison observed no current when the plate was connected to the negative battery terminal. This asymmetric current—a current that flows to one end of the filament but not to the other, came to be known as the "Edison Effect."[4]

Edison's experiments thus confirmed that the carbon particles thrown off from his light bulb filaments were negatively-charged. But that knowledge proved of little value for preventing the original problem—the progressive blackening of his bulbs with use.[5] In fact that blackening could not be averted so long as carbon was the filament material; eventually carbon gave way to *thoriated tungsten wire*, which today is the material used almost universally for incandescent lamp filaments.[6]

We can witness the Edison Effect for ourselves.[7] An automotive taillight bulb, such as the number 1157 bulb shown here, has *two* filaments: one for the taillight, and a brighter



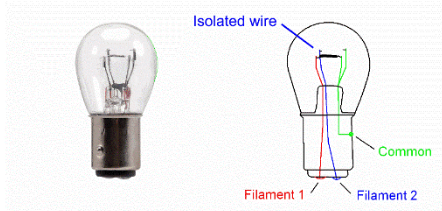
[4] Preece, W. H., "On a Peculiar Behaviour of Glow Lamps when Raised to High Incandescence," *Proc. Roy. Soc.* (1885) *38*: 219–230.

[5] Edison did, however, envision a different application for his specially-equipped bulb, its use as a kind of sensitive voltmeter. He took out a patent on the device in 1884.

[6] Even bulbs with tungsten filaments exhibit a long-term blackening, though at far slower rates than do those with carbon filaments. The problem is a serious one only in lamps of very high wattage, such lamps control this by filling the bulb with a gas such as nitrogen, argon, krypton, or xenon, which do not readily react with tungsten, at a pressure great enough to reduce filament evaporation.

[7] This clever procedure is described in an article by ZhiQi Lin, Wei Zhang, and HuiJie Li: "Using car taillights as an experimental device to demonstrate the Edison effect" in *The Physics Teacher*, 56, pp. 410–411 (2018).

one for the brake light. They have a terminal in common, as the diagram indicates; so they are not isolated from one another the way Edison's plate was isolated from his filament. But if we deliberately *burn out* one filament, as this slide shows, one fragment of the



destroyed filament *will* be isolated from the filament that is still intact, and so should play the role of Edison's plate. Let us try.

The intact filament is being heated with 11 volts, and I connect the isolated element, through the milliammeter, to the positive end of the filament. The meter shows an Edison

current of 0.5 microamperes. But when I connect it to the negative end, we find *no* current, just as Edison had observed.

Now since currents require a closed circuit, whatever current I measure in the wire *outside* the bulb must also be flowing in the space *within* the bulb. What, then, is the nature of this internal current? It obviously does not consist of carbon particles, as did Edison's; for our filament is tungsten. But neither is it likely to consist of charged tungsten particles, since the very advantages that make tungsten a superior filament material—lack of "blackening" and long lifetime—indicate that the filament is not losing tungsten at a sufficient rate to be carrying the Edison current.[8]

Perhaps, then, the current within the bulb does not consist of charged *material* particles at all—perhaps it is a flow of *electricity itself!* But what does that even mean? We are accustomed to thinking that electricity requires a *conductor* in order to "flow"; and *vacuum* is not a conductor! The engineer Edwin Houston expressed this puzzlement in a paper he presented at the International Electrical Exhibition at Philadelphia in 1884.[9] Speaking of the Edison Effect, he wrote:

> The question is, what is the origin of this current? How is it produced? Since we have within the globe a nearly perfect vacuum, we cannot conceive the current as flowing across the vacuous space, as this is not in accordance with our preconceived ideas connected with high vacua.

Houston went on to muse further:

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[8] This inference was conclusively demonstrated by O. W. Richardson; see "The Emission of Electrons from Tungsten at High Temperatures," *Science* **38**, 967 (1913).

[9] Houston, E. J.: "Notes on phenomena in incandescent lamps," *Transactions of the American Institute of Electrical Engineers*, I, 1 (1884).

It may be electricity flowing through empty space, which I don't think probable.

Even if we set aside the perplexity as to how electricity can possibly move through empty space, we are confronted anew with Edison's question: whether the current is positive or negative. But we cannot answer it as definitively as he did. For in the absence of occurrences like "blackening" we no longer have physical evidence that something is traveling from filament to plate; and therefore we can no longer know whether we have a current of *negative electricity* passing from the filament to the plate or a current of *positive electricity* from the plate to the filament.

One piece of evidence, at least, does certainly implicate the *filament* as the source; watch what happens when I start with a cold filament and gradually raise its temperature by increasing the heating voltage. As before, the meter will measure the Edison current. I started with no filament voltage at all, and of course no plate current either; but we're still seeing no current, even as I continue to raise the voltage enough to make the filament glow… Ah! We're getting tenth of a microampere with about 8.6 volts on the filament… As

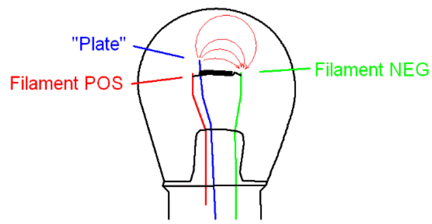
I continue to raise the filament voltage, the plate current rises… and we reach a full microampere when the voltage is a little over eleven volts.

Now why would the current depend on the temperature of the filament? If the current is "electricity flowing through empty space"—the case Edwin Houston thought "not probable"—it is hard to see why there should be such a connection, since no theory of electricity implies any inherent relation between it and heat. But that dependency would make sense if the electricity traveled in the form of *material particles*, inasmuch as the temperature of a body indicates the kinetic energy of the particles which compose it; and the more agitated those particles are, the greater the number that may escape the forces which bind them to their host—just as a liquid will evaporate more quickly when it is hot than when it is cold.

But wait! Did we not conclude earlier that the current could not consist of charged particles of tungsten—the material of the filament? If the charged particles are not tungsten, *what possible material* could they be? That is the very question seniors take up in the first semester
lab when they study cathode rays, and the answer is startling: it appears that current in the evacuated tube is carried by charged particles whose material *belongs to no known species* of matter![10]

[10] Thomson, J. J., "Cathode Rays," *Philosophical Magazine. 5. **44** (269): 293* (7 August 1897); "On Bodies Smaller Than Atoms," *Popular Science Monthly* (August 1901)

Shall we then affirm that the *heated filament* is the source of charged particles of some as-yet-unknown material, and that these constitute the Edison current? Unfortunately, the mere association of current strength with filament temperature overlooks a subtle but crucial factor. The problem is that our power supply does two things at once: it both heats the filament *and* establishes the electric field between the plate and the filament. This diagram shows the interior of our taillight bulb. The isolated fragment of the burned-out



filament is our "plate," as I mentioned before. And, as before, both the "plate" and one end of the surviving filament are connected to the positive terminal of the power supply; the other end of the filament is connected to the negative terminal. *The full potential difference of the supply therefore exists between the plate and the negative end of the filament*. I have drawn Faradayan lines of force—they are the curved red arrows—to represent the electric field associated with this potential difference. But this field is what furnishes the very force that would propel charged particles along their paths—from plate to filament if they are positive, from filament to plate if they are negative. These charged particles, whatever their source, will be subject to a greater electric force if the voltage is raised; they will be accelerated more quickly and will attain a higher velocity. More charge, whether negative or positive, will be transferred in a shorter time; and this will result in a greater Edison current, *wholly apart from any increase in filament temperature*.

You see, then, the weakness in our former reasoning. In raising the voltage of our power supply we both raise the filament temperature *and* increase the electric field; and a stronger electric field would tend to increase the rate of particle transfer, *whether they are negative particles emitted from the filament or positive particles emitted from the plate*.

It is clear, then, that we cannot definitively identify the filament as the source of charged particles so long as we rely on a single electrical source. But if we were to use *separate supplies* for the plate and the filament, we could control their voltages independently, and so distinguish the influence of filament temperature from that of electrostatic attraction.

That is what the British engineer John Ambrose Fleming[11] did in 1896. Using samples of Edison's special bulbs that had been made specifically for him, Fleming connected separate batteries to the filament and the plate. A variable resistance, or *rheostat*, controlled the voltage at the filament, and hence the filament's temperature. With a fixed voltage between the plate and filament, Fleming obtained a current through the plate that rose rapidly with

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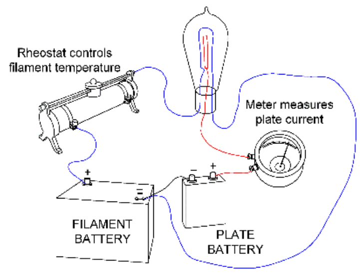
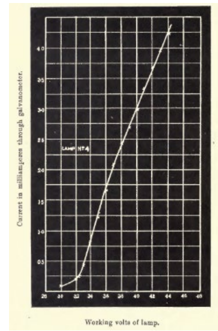
[11] In addition to the researches to be described here, Fleming is known for having originated one of the many "right-hand rules" used in physics, and for designing the transmitter that sent the first transatlantic radiotelegraphy message. He studied under Maxwell at Cambridge in 1878 and 1879, and was by his own account one of *only two or three students* who attended Maxwell's final lectures. See Fleming, Ambrose, "Some Memories of Professor James Clerk Maxwell" in *James Clerk Maxwell, A Commemoration Volume 1831–1931*, Cambridge University Press (1931).

increasing filament voltage. That rise is depicted in Fleming's graph, on the right.[12] And since he kept the plate voltage *constant* while varying the filament voltage, the plate current's dependence on the filament voltage means that we can now point confidently to the *heated filament* as the source of electrified particles.[13] The current must therefore





consist of *negatively-charged particles* that were liberated from the filament by heat in the manner we described a moment ago. Once freed from the filament they will be accelerated towards the plate by the electric field between plate and filament, thereby constituting the Edison current.

In 1904 Fleming constructed the device shown on the left; it was essentially Edison's bulb, with a flat plate like his. The one on the right was a later design employing a

cylindrical plate to surround the filament completely. Fleming's "valve," as he called it—we will soon see why that name is appropriate—launched decades of commercially manufactured devices having essentially the same design. One of them is *this* elegant creation, an Eimac model 250R, introduced in the late 1940s; you can see how like it is to

[12] Fleming, J. A., *The Thermionic Valve and its Developments in Radiotelegraphy and Telephony.* London, The Wireless Press (1919). The graph records measurements he had made in 1896.

[13] This conclusion is valid provided the filament voltage is small compared to the potential difference between plate and filament. That was true for Fleming's devices and will be true in our adaptations of his experiments.

Fleming's. And if you wonder what possible commercial application could have supported such a product as this one, 40 years after Fleming patented his apparatus, I invite you to take one of these handouts[14] after the talk; they deal with the topic of current *rectification*. We, however, will employ the Eimac tube to continue our own investigation of the role of the heated filament.

In his initial work with the special Edison bulb, Fleming kept the plate voltage constant while varying the filament voltage. Later he examined the complementary case: varying the *plate* voltage while keeping the *filament* voltage constant.[15] We can replicate these experiments, using variable power supplies in place of Fleming's batteries. Here is our setup. I am applying 2 volts to the filament. The plate voltage is zero; and as you see, the plate current is also zero.

But keep your eye on the plate current as I apply more and more voltage to the plate. . . . You see how the plate current increased to one milliampere right away, but its growth seems to have stopped . . . No, it has grown to 2 milliamperes, but it is not increasing any further, even as I continue to raise the plate voltage . . . The plate current appears to have

reached a maximum—at least for this degree of heating the filament. Let's do the same thing using a higher filament voltage, and therefore a higher filament temperature.

The filament voltage is now 2.3. As before, I am gradually applying voltage to the plate, and the plate current has risen to 2 milliamperes . . . and now 3 milliamperes . . . Now it has risen to 4 milliamperes . . . But it is definitely holding there . . . It is still 4 milliamperes, even at the maximum voltage of 118.7 volts.

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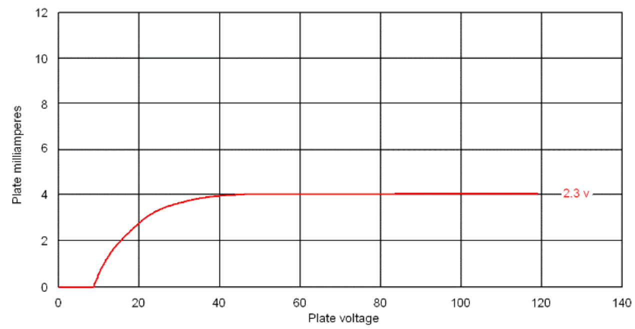
[14] The handout for this lecture begins on page 21 below.

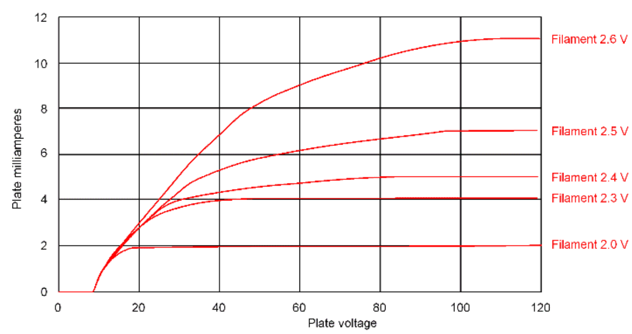
[15] Fleming, J. A., *Principles of Electric Wave Telegraphy and Telephony* (1916), page 533.

Here is a graph of the measurements we just made. Just as in our first trial, when we raise the plate voltage, the plate current increases rapidly at first; but it once again levels off



to a plateau. But notice that the plateau attained with 2.3 volts on the filament is higher than when the filament was being heated with only 2.0 volts. The plateau is now 4 milliamperes, while before it was only 2 milliamperes.

I made several other sets of measurements using higher and higher filament voltages. Let us append those results to our initial graph and produce a composite presentation of all the trials:



The interpretation of these curves is clear: once charged particles are emitted from the filament, they become subject to acceleration towards the plate by the electric field that exists between the filament and the plate. At low plate voltages, for which the electric field is weak, particles are emitted in greater numbers than they can be swept away. But as the plate voltage rises, more and more of the emitted particles are drawn to the plate. Finally the plate voltage reaches a value at which particles are being removed at the same rate as they are emitted; the measured current cannot then undergo any further increase, no matter how much more the plate voltage is raised. The value of this current maximum, or "plateau," is therefore a measure of the rate at which particles are being emitted from the filament; and since the plateau rises when the filament voltage rises—and hence when the filament temperature rises—it should now be clear that the rate at which negative particles are emitted depends essentially on the *filament temperature*. Because these charged particles, or *ions*,[16] are released by the action of *heat*, Owen Richardson of Cambridge

[16] Ion, from ιέναι, *go*, since charged particles undergo motion when placed in an electric field. Like so many other electrochemical terms, it was introduced by Faraday at the suggestion of William Whewell.

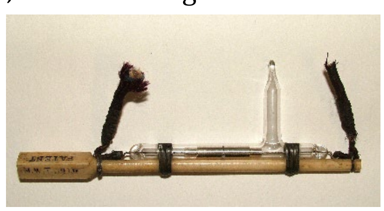
University called them "thermions," and their travel to the plate he called the "thermionic current."[17]

With the aid of a vacuum tube essentially identical to Fleming's we have finally, I think, been able to appreciate the role of the heated filament. But that was not the question which had excited Fleming's interest. His chief concern was the asymmetric character of the conduction—the same asymmetry we noted in the Edison Effect.

Here the power supply is connected so as to make the plate positive; and we are obtaining a generous 37 milliamperes of plate current. It is much higher than what we obtained a moment ago, because I am heating the filament with a much higher voltage—4.0

volts. But if I reverse the connections to make the plate negative… there is no current, even though I am applying a very strong voltage to the plate. To Fleming this meant that current could flow through the tube in *only one direction*—a feature that, he realized, would have immediate application to *wireless telegraphy*. To help us see why, let me revisit a topic I raised in February's talk.

At the time of Fleming's researches, the standard device for detecting an incoming radiotelegraphy signal—that is, an electromagnetic wave—was still the enigmatic *coherer*,

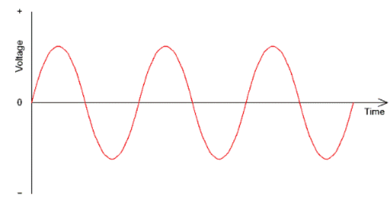


which we discussed last time; but as I noted then, that apparatus's principle of operation was poorly understood; and it had many deficiencies, concerning which I quoted some choice words from several disgruntled engineers.

Why not, then, simply send the current from the receiving antenna to one of the more ordinary current indicators: a galvanometer, a telephone receiver, or some other electromechanical device? The reason is that the current induced by an incoming

[17] "Here we have two currents: the current used to heat the wire and the thermionic current away from the surface of the latter." O. W. Richardson *in London, Edinburgh & Dublin Philosophical Magazine* 6th Series vol. 17, 814 (1909)

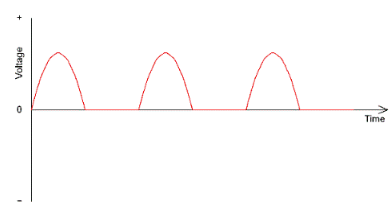
electromagnetic wave is oscillatory, or *alternating*. A graph of that current with respect to time would look like this:



The current swings regularly between positive and negative; and the number of complete swings per second is the frequency of the current. But in wireless telegraphy the frequencies are so high that no ordinary mechanical responder—neither the needle of a galvanometer, nor the diaphragm of a telephone receiver—could possibly vibrate at those rates; the alternating pulses would simply end up nullifying one another and would produce no response at all.

Now it had been known since the 1870s that certain crystals, when brought into electrical contact with a metal probe, could somehow make these radio-frequency alternating currents compatible with indicators like the telephone receiver.[18] In February's talk I singled out the work of G. W. Pickard in this connection; his contact devices would soon become practical "crystal detectors" for radiotelegraphy and would remain in use well into the broadcast radio era. But at the time of Fleming's work, these contrivances were temperamental and delicate; and because their operation was poorly understood, improvements in their design could be pursued only by trial and error, not by systematic analysis. In contrast, Fleming's vacuum tube excelled in all these areas. It was mechanically sturdy, its electrical characteristics were stable and reliable; and, most importantly, its principle of operation—"one-way" conduction—was understood.[19]

By conducting electric current in one direction only, Fleming's vacuum tube could prevent the mutual nullification of positive and negative wave phases by *blocking* the negative phases. It would then send onward a pulsating current whose graph would look like this:

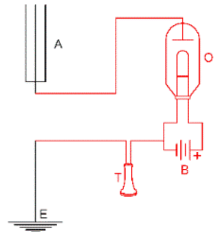


To be sure, those pulses would still be arriving at a rate too high for either a galvanometer needle or a telephone receiver to reproduce; but they would be *in the same direction*! They would not nullify one another, as a train of alternating pulses must do. On the contrary, if sent to a galvanometer, they would reinforce one another to displace the needle by a clearly visible amount. If sent to a telephone receiver, they would produce a definite *click*.

[18] Carl Ferdinand Braun studied the properties of such junctions in 1874 and Jagadish Chandra Bose employed crystals as microwave radio detectors in 1894.

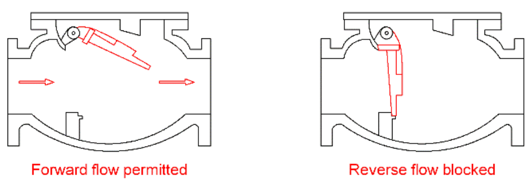
[19] The crystal detector, too, exhibited "one-way" conduction, though this was not recognized at first. Even after that behavior was established, the physical principles underlying it were not understood until the 1930s and 1940s; the researches of that period would provide the basis for modern solid-state electronics.

Fleming proposed a circuit like this one for the detection of electromagnetic wave



signals. I have reduced his circuit[20] to its essentials for clarity. When an electromagnetic wave is intercepted by the antenna, it induces an oscillating current. If the red portion of the circuit were absent, that current would simply flow between the antenna A and the earth, E. But in Fleming's circuit, it must first pass through the vacuum tube O, then through the telephone receiver T, and finally to earth. And so long as the incoming wave makes the antenna *positive* with respect to the earth, the plate of the tube will likewise be positive, and current will flow. But in the next phase of oscillation, the antenna will be negative; the plate too will therefore be negative; and we saw that current cannot flow through the tube under those conditions. Only *positive* current pulses will pass through to the telephone; and together these will produce the "click" that announces the commencement of a "dot" or "dash," followed by a slightly different "click" when it releases at the end of the train of pulses.

You can see, then, why Fleming called his device a "valve"—a term which British usage retains to this day. By permitting flow in one direction only, it functions like the "check valve" used in plumbing and other applications. In the mechanism depicted here, a hinged



flap opens to permit liquid flow from left to right, but any flow from right to left bears on the flap to close it and halt the flow.

Fleming's explicit adoption of the terminology of plumbing suggests that he had in mind the "fluid flow" image of electric current. Indeed, to the extent that we seem to have demonstrated the existence of a stream of charged material particles in the vacuum tube, flowing from filament to plate, it may appear that we have confirmed the fluid image quite literally. Yet I hesitate to say that, for there are some vital differences. What, exactly, constitutes a "fluid"? For Archimedes, a fluid is a *continuous whole*, capable of sustaining *pressure*; and when it moves, it is driven by a difference of pressure between one region and another. Recall his definition at the opening of *On Floating Bodies*:

[20] Fleming, J. A., *Principles of Electric Wave Telegraphy and Telephony*, 3rd ed. (1916), p. 531. The diagram in my slide is highly idealized; an actual receiver circuit would incorporate additional coils and capacitors to utilize the incoming current more efficiently.

> Let it be assumed that a fluid is of such a nature that if its parts lie evenly and are continuous, that part which is pressed the less is thrust out by that which is pressed the more…[21]

But in the vacuum tube we have a multiplicity of individual charged particles; they do not seem to form a "whole" in any obvious sense; and their motion is by no means the result of anything like Archimedean pressure, for-we envisioned each of the particles as being accelerated independently by the electric field. In an Archimedean fluid, every portion moves in virtue of being part of a moving whole; but in the vacuum tube, each particle enjoys its own private treaty[22] with the field. So it is not at all clear that we ought to call this stream of particles a "fluid." Furthermore, what kind of relation do these particles have to the electricity which distinguishes them? Is electricity itself an immaterial substance, which just happens to be embellishing each of these particles like a coat of paint? Or is electricity *these very particles*—not a fluid at all, even though they seem to resemble a fluid when they are confined to a "conductor"?

No doubt Fleming meant his "check valve" allusion to convey only *what* the vacuum tube does, not to explain *how* it does it. Despite any resemblance between a stream of charged particles and the flow of a fluid, we will not expect to find a mechanical "flap" anywhere in the vacuum tube. How, then, shall we understand the halting of current when it is applied in the forbidden direction? We may find some guidance in another example of "one-way" flow, one that does not rely on mechanical contrivance; that is the *waterfall*. Water (or any material) can fall *down*, but it does not fall *up*. If you tried to swim up the falls you would be "blocked," so to speak—not by a hinged flap, but by the gravitational field. Nevertheless, a field can be overcome with a sufficiently great store of kinetic energy—as salmon do when they ascend waterfalls in order to reach their ancestral breeding grounds:

When we try to direct a *reverse* current through the vacuum tube, we have the equivalent of a salmon run; for instead of the kinetic energy of the fish being converted to gravitational potential energy, we have the kinetic energy of the emitted particles—Richardson's *thermions*—being expended through conversion to electrical potential energy due to the reversed electric field. But whereas most salmon have enough kinetic energy to overcome the potential-barrier, in a well-functioning vacuum tube the ions do not.

We have seen how Fleming's vacuum tube blocked half of each cycle of the alternating current induced in the antenna; thus the remaining half-cycles, having a common direction, could exert a cumulative effect upon a telephone receiver or a galvanometer. A disadvantage, of course, is that since the incoming wave current is very weak, only a weak current was available to energize the telephone or galvanometer.

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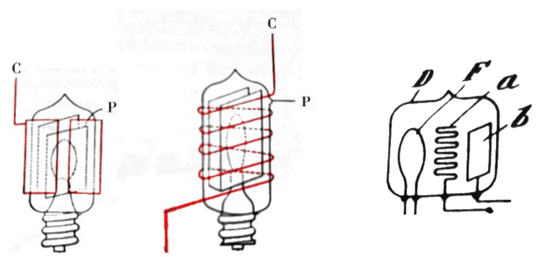
[21] Archimedes, *On Floating Bodies*, Book I.

[22] "Private treaty" was the *bon mot* used by Clinton J. Davisson in his paper, "Are Electrons Waves?" Franklin Institute Journal, **205** (1928).

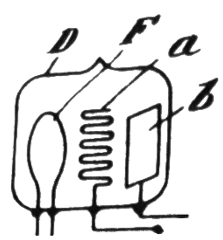
But not long after Fleming introduced his vacuum valve, the American inventor Lee De Forest dramatically altered the technical possibilities by adding a *third electrode*. Fleming, offended by what he saw as a trespass upon his specialty, regarded the new electrode as a merely gratuitous embellishment of his own invention; and there ensued a 37-year succession of court battles over patent rights—a real-life *Jarndyce v. Jarndyce*, that celebrated legal saga immortalized in Dickens' *Bleak House*.[23]

Do we know *why* De Forest added the third element? That is not clear from his initial efforts, since he originally positioned the additional electrode *outside* the tube, first in the form of parallel foil sheets, shown on the left, and later as a wire coil wound around the



glass tube, in the middle sketch; in both drawings the third element is highlighted in red.[24] Eventually, however, he located the added structure *within* the tube, between the filament and the plate, as drawn on the right. De Forest named these devices *Audions*;[25] but since his definitive version included three electrodes within the glass, it quickly acquired the informal name "triode," distinguishing it from Fleming's two-element tube, which (despite Fleming's objections) won the name "diode."[26] Let us see what De Forest's third element accomplished; for I think we will find that the triode, even more than the diode, implicitly draws upon the imagery of a *stream of particles* rather than a flowing fluid.

In this diagram of one of De Forest's triodes, taken from an early patent application, *F* represents the filament and *b* the plate, just as in the Fleming diode—although De Forest



preferred the term "wing" rather than "plate." Between them is the third electrode—not an impenetrable *plate*, but a *wire* bent into the serpentine shape drawn here. It was thought to resemble a cooking grate or griddle; and on that basis the third electrode acquired the name "grid."

As I mentioned before, it isn't clear whether De Forest adopted this configuration with any specific expectation in mind. About its operation, he is reported to have said, "I don't

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[23] "The Radio Tube Goes to Court," *The New York Times*, 23 November 1930. The ongoing cases described in the article would finally be resolved in 1943.

[24] Adapted from Gerald F. J. Tyne, *Saga of the Vacuum Tube* (1977), p. 59.

[25] Considering the wide range of designs upon which De Forest bestowed the name "Audion," it would seem that he regarded that title as a the name of a brand more than as the name of a device.

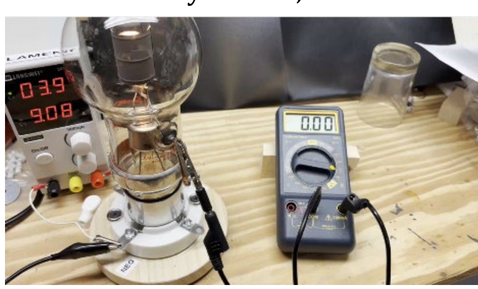
[26] Fleming insisted that the name of a device ought to convey its essential function, as his epithet "valve" did. "Diode," which expressed only the number of elements in the tube, would fail to meet that criterion.

know how it works, it just does!" That is rather hard to believe, since I think that even *we* can anticipate some of the effects of mounting *any element whatsoever* within the tube itself. Nevertheless, the grid does exhibit some behavior that is bound to seem odd at first sight. Let us study that initial puzzle in a triode of our own, before going on to the "working" that De Forest would have had chiefly in mind if he really did say, "it just works."

This lovely objet d'art is an Eimac 250TH triode, first introduced in 1938. It is practically the twin of the diode we have been experimenting with, except for the added grid; you can see the grid connection at the side of the glass envelope.

I am applying 3.9 volts to the filament, which heats it to glowing; and I am making no connection to the plate. Now when I connect a meter between the grid and the positive end of the filament, we measure a negative current; it is 1.29 milliamperes. No doubt this is our

old friend the Edison current; and if so, we should expect zero current between the grid and the negative end of the filament. Let us try . . . Yes, we are reading zero milliamperes. But I

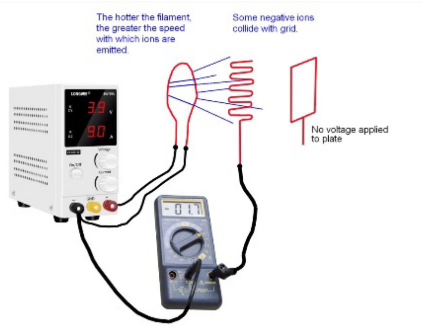


am not using the most sensitive range of my meter; let's see what happens when we switch to the *microampere* range . . .

Well, it is not zero! Instead, we have a negative current of 1.7 microamperes. True, this is a very small value—only about one thousandth of what we measured for the Edison

current—but the account we gave earlier implied that there should be *no current whatsoever* to the negative end of the filament; because if the Edison current really consists of a stream of negative ions, they should be *repelled* by the negative end of the filament, and therefore repelled by the grid which is connected to it through the meter; they should not be flowing *to* the grid! What on earth can be causing this "maverick" current?

Our earlier explanation of the Edison Effect appealed solely to the *electric field* that exists between the positive and negative ends of the filament. We did not consider any source for the ions' motion other than their acceleration by that field. But remember that the charged particles were emitted from a *heated* filament. They will therefore have acquired kinetic energy by *heat*, wholly apart from experiencing any electrical attraction. So it is not at all



far-fetched to suppose that some of them might have enough energy to strike the grid and adhere to it, making the grid slightly negative. Thus when we connect the ammeter, negative electricity will migrate from the grid to the rest of the circuit, constituting the current that seemed at first so surprising.[27]

We can test this conjecture. If this "maverick" current to the negative end of the filament is indeed powered by thermal energy, it should diminish when I reduce the filament heating. Let us do that . . . Yes; you see I am lowering the filament voltage, and the current

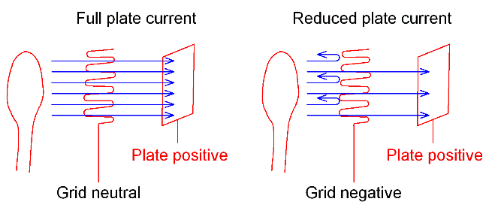
has already dropped by about half. With a further reduction it drops to 4/10ths of a

[27] This well-known phenomenon is called "grid leak" in radio circles.

microampere. So this constitutes additional confirmation, if we still needed any, that the current within the vacuum tube is constituted by a stream of *material* particles—Richardson's *thermions.*

The thermionic current, then, makes itself evident at De Forest's third electrode. But that could scarcely have been any part of De Forest's thinking when he introduced the grid. For the chief function of the diode was to conduct or block *current through the plate*. Surely when De Forest added a third electrode, he would have been looking for some result bearing on the plate current. Let us try to envision what such an effect might be.

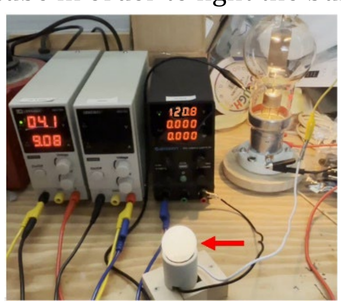
Imagine, then, a current of negative ions departing from the heated filament and streaming towards the positive plate under the influence of the electric field between the



filament and the plate. If the grid is electrically neutral, it should have no effect on the stream of ions. But what will happen if the grid is made negative? It will then *repel* negative ions; and some of the less energetic among them will be brought to rest, or even turned back toward the filament, with a consequent reduction in plate current.

This resembles the operation of two devices that I mentioned in February's talk: the relay and the coherer. In both of those contrivances a weak current controlled a second, much stronger current. That is exactly what happens in the triode: a negative current supplied to the grid controls a completely separate current to the plate, whose strength can be far greater, since it is powered by its own battery. No wonder De Forest was convinced that his alleged trespass against the integrity of the diode was in fact a spectacular advance! Let us see for ourselves this remarkable capability in action.

I am applying 120 volts to this light bulb—not directly, but through the triode, so that the current has to pass through the tube in order to light the bulb. The grid supply is off, so the

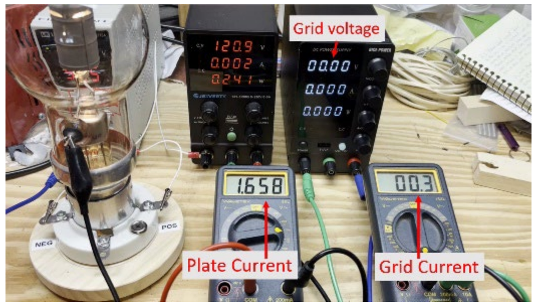


grid is neutral; and as you see, the tube is passing enough current to light the bulb fully.

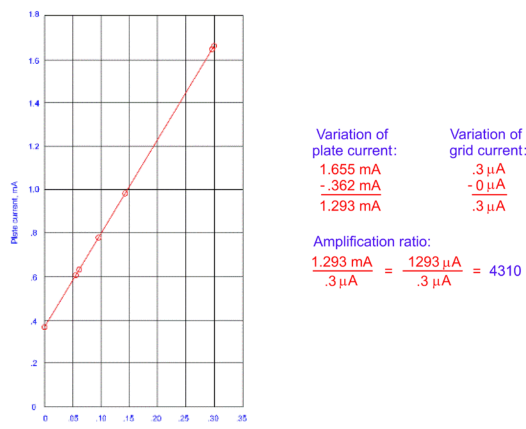
But watch the light bulb when I turn on the grid supply to place a negative voltage on the grid. The current is blocked, and the bulb is extinguished. When I remove that negative voltage, current flows again and the bulb lights once more. You see how a mere two or three volts applied to the grid is able to control a 120-volt lamp.

We can carry out a more quantitative study of the triode's action by measuring both the plate and the grid currents.

Here I am applying positive 120 volts to the triode's plate, but zero volts to the grid. As you see, the plate is carrying a current of 1.658 milliamperes; and the grid current is (negative) 0.3 microamperes.



I begin increasing the grid voltage (that is, making it more and more negative), and the plate current decreases, just as we expected. *But so does the grid current*. That might have seemed surprising earlier, but now we know what is going on: the grid power supply is sending negative current *to* the grid, thus opposing the thermionic current that was coming *from* the grid; that's why the grid current decreases when the grid voltage rises. Finally, when the grid current has been brought to zero, the plate current has diminished to .362 milliamperes. When we graph these measurements, the results show plainly how the plate current depends on the grid current.



The graph is *a straight line*; thus changes in the plate current are proportional to changes in the grid current. Do you see what this means? If I send to the grid of the triode a signal which causes the current to vary between 0 and .3 microamperes *according to any pattern whatsoever*, the plate current will reproduce *that very same pattern*—but at a larger scale: a .3 microampere variation of grid current will produce a plate current variation of 1.293 milliamperes, that is, a signal *more than 4300 times greater*!

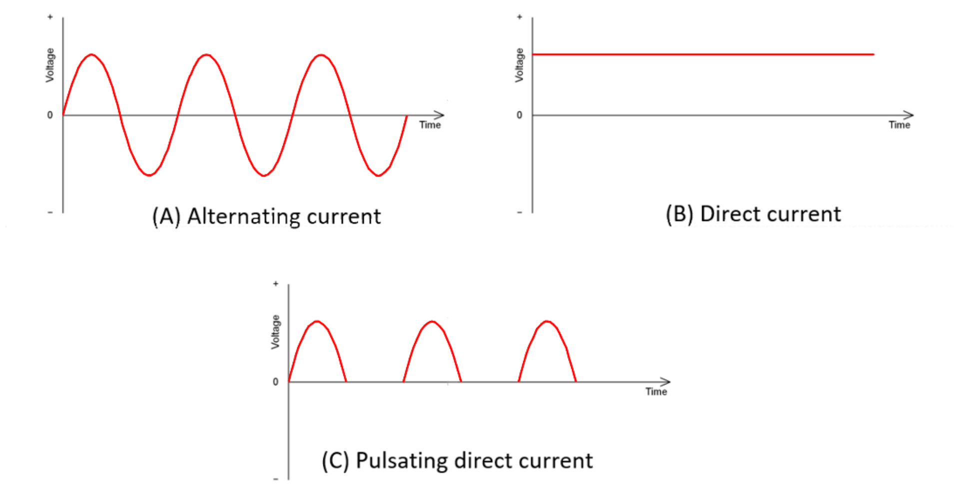
This has implications of great consequence for electromagnetic wave detection. It means that even if the received signal current is merely a *microampere*, it will be able to initiate a current greater than 4.3 *milliamperes*—enough to operate a telephone receiver, a meter, or some other indicator. De Forest boasted that this, in effect, *amplifies* the tiny incoming signal—since even though the triode does not actually make a small current *larger*, the result is the same as if it did.

I will have much more to say about amplification in the next lecture. For one thing, we can combine the *detection* function of the diode and the *amplification* function of the triode to make a far more sensitive wireless telegraphy receiver. But the triode's capability for amplification will do much more; it will also become the basis for a new method of electromagnetic wave *generation*, far superior to the spark transmitter. This in turn opens up the first truly practical prospects for transmission and reception of *sound*—the heart of what we now call "radio." That will be the topic of my next talk, the final lecture in this series. I hope many of you will be able to join me then.

"Rectification"

Handout to accompany the lecture "The Vacuum Tube"

As the distinctive capabilities of the diode became more perfectly understood, one technical term came into particularly prominent use. "Rectify," to *put right* or *correct*, but literally *to make straight*, became the standard term for the conversion of alternating current to direct current. If the diode really had been capable of converting a current from the profile (A) to profile (B)—making "the crooked straight, the rough places



(A) Alternating current

(B) Direct current

(C) Pulsating direct current

plain,"[28] the term would indeed have been well-chosen; but as I noted in the lecture, the vacuum diode does not produce current having the rectilinear profile (B) but the pulsing profile (C). It is "direct current" only in the sense of having a *single direction*, not in the original sense of being *constant* or *straight*; it ought really to be called "pulsating" current. Nevertheless the term "rectify" quickly acquired the meaning "to make unidirectional"—with no regard whatsoever to straightness or constancy.

Alternating current had been the standard power source in the United States since 1892; and alternating current was very well suited to applications such as incandescent electric lighting and many kinds of electric machinery. But tasks like *arc lighting* and *electric welding* still for the most part required direct current; and this either had to be generated by dynamos or obtained from the standard power system by rectification. Long after incandescent bulbs became the dominant light source, electric arcs remained standard in high-intensity instruments such as searchlights, theatrical follow-spots, and cinema film projectors. As late as 1959, my high school's movie projectors employed

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[28] Handel's adaptation, in *The Messiah*, of Isaiah 40:4.

electric arc units like the AmproArc model shown here. The arc housing is the large grey cylindrical structure. The rectifier is on the floor at the right.

Storage batteries were another source of demand for direct current. Unlike the batteries of Faraday's time, which were recharged *literally*[29] by discarding the used acid solution and replacing it with new, storage batteries are recharged by passing direct current through them in reverse. Such batteries became standard automotive equipment with the advent of electric starting; and rectifying battery chargers like the Tungar model pictured here were

found in nearly every service garage and even some households. The large glass bulb on the right is the rectifying diode. (The bulb on the left is an ordinary light bulb, used to regulate the current.)

A third area demanding direct current was that of *vacuum-tube electronics*, especially for radio receivers and transmitters. I will be discussing this technology further in the next lecture, and we shall see why these devices required direct-current power sources.

The diode I experimented with for this lecture, the Eimac 250-R, was designed to supply direct current for high-powered radio transmitters.

H. Fisher
5 December 2025

[29] The root meaning of "charge" is *to load or fill*.