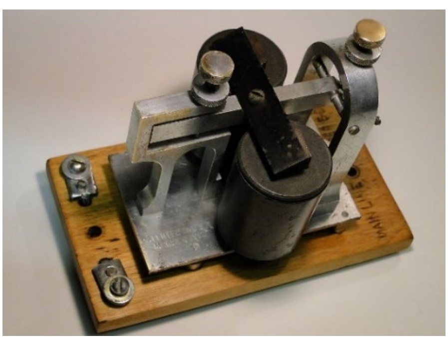
Telegraphy and Radiotelegraphy[1]

Howard J. Fisher

Welcome, everyone, to this first of three talks on early radio technology. The talks are three in number because the history of radio communication may be said to fall into three periods. The first was the era of *signaling*, in which radio transmission was limited to the dots and dashes of Morse code; accordingly, this first talk will be on *telegraphy and radiotelegraphy*. The third period, which dates from about 1920, is that of transmission and reception of voice and sound; so that the final talk in this series will be on *broadcast radio*. Between these periods there appeared one magnificent invention, which alone made it possible to advance from the first era to the third. This was the *vacuum tube*, and that will be the topic of my next talk, to be given in April.

Thus the three periods of radio development are more or less defined by three specific technologies. These bodies of knowledge and practice are highly interesting, both historically and in their own right; but I wish to pay special attention to what we might call their *rhetoric*—because each of them embodies, in its own way, an implicit image of *electric current*. Each of them implies a picture of electric current as some sort of *motion*; but they appear to paint with different palettes when they try to contend with *what*, exactly, is doing the moving.

Let us begin by considering—or, for some of us, *remembering*[2]—the telegraph. If you have ever made an electromagnet from a nail, a length of wire, and a battery, you have already constructed the heart of a potential



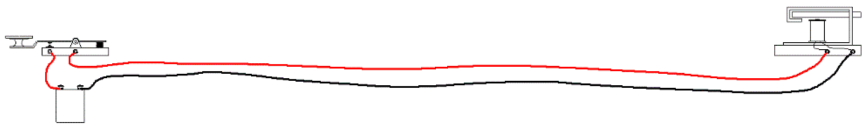
telegraphy system. The telegraph "sounder," on the left, is basically a pair of electromagnets; they pull down the pivoting bar when current flows through the coils, and the bar springs back when the current ceases; both the pull and the release make a distinctive *click*. The telegraph "key," on the right, is

[1] Lecture delivered at St. John's College, Santa Fe, on 18 February 2026.

[2] Western Union sent its last telegram on January 27, 2006.

simply a switch that closes when the knob is pressed. (The shorting switch, marked with a red arrow, keeps the key closed when it is engaged; we will see in a moment why this is useful.) I have connected this battery and key to the sounder at the side of the room; you can hear it respond as I press the key: a short press for a *dot*, a long press for a *dash.* Does anyone here know Morse code? . . . I just sent "S J C": dit dit dit for "S," dit dah dah dah for "J," dah dit dah dit for "C."

Here is a diagram of our wired connections. The battery and key are here

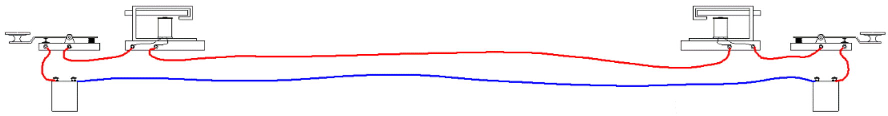


at the table, the electromagnet is part of the sounder, and when the key is closed we have an unbroken pathway, which evidently transports electricity from the battery to the sounder, *and back again*. The "back again" element is crucial. If a break occurs *anywhere* in the path—whether in the red or the black wire in our drawing—the action will cease. We usually speak of this fact as showing the need for "a closed circuit."

The terminology we conventionally use to describe this system is revealing. We say that the wire is a "conductor," and that a "current" of electricity "flows" through it. These are all, clearly, metaphorical terms, drawn from the behavior of water or other liquid. The metaphor portrays electricity as a *mobile substance* which, just like ordinary liquids, requires a source of motive power to maintain its flow.

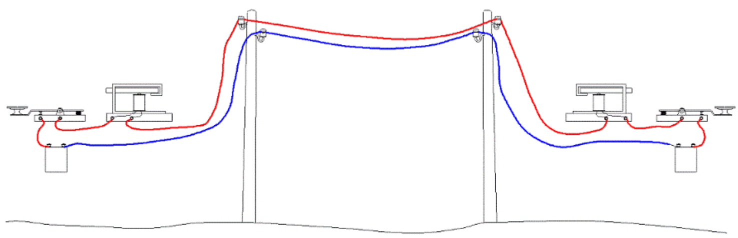
Can we be content with metaphorical imagery? Don't we want a *true* image of electrical action? But I don't see how we can escape metaphor. We cannot observe "electricity itself" (whatever that means); so it is impossible to speak "literally" about electricity, or to imagine it in any terms other than what we had previously gleaned from other realms of experience. But what we *can* do, and should, is to remember that our description *is* metaphorical—and that *other metaphors may be possible,* perhaps even preferable. Our telegraph system, in its present form, gives perfect expression to the fluid-flow metaphor by treating the wires as paths of circulation for electricity. But as familiar systems expand into new settings, new phenomena sometimes appear, which may not be easily accommodated by the received imagery. When that happens, alternative idioms of expression, images which might previously have seemed merely speculative or idiosyncratic, may perhaps take on new persuasive force. I think we will encounter an example of this, as our telegraphic system becomes more refined.

Now, with the apparatus I have assembled, I can send messages to you, but you cannot send back to me. We can fix that by adding a second *key* at your end and a second *sounder* at mine, like this:

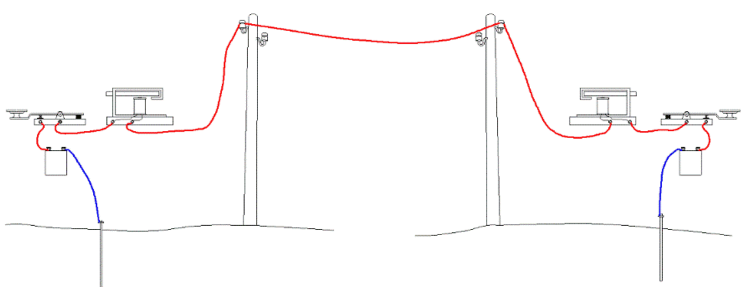


We might also want to add an extra battery, since we will be operating two sounders at once. Now I can send to you and you can send to me. As long as my key is closed, your key is what turns the current on and off; so I can receive the message you send; that was the purpose of the shorting switch I pointed out in our first slide. When it is time for you to receive, you keep your key closed; then my key controls the current, and you can receive the message I send.

But a useful telegraph system must be capable of operating over greater distances than the length of a lecture hall! When the first railroad tracks were laid from Lamy Station to Santa Fe, in 1880, telegraph lines were strung along the right-of-way, a distance of some 17 miles. How would you adapt our telegraph system to that distance? Would you suspend the wires on poles, like this?

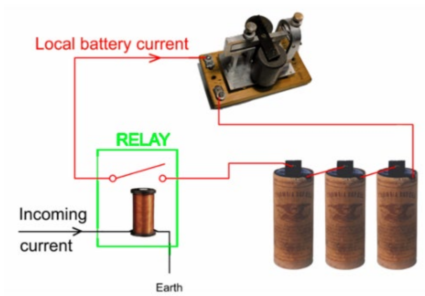


That would work, of course; but it would involve twice as much wire, and nearly twice as much labor, as you really need. For the earth itself can serve as a conductor; in fact, over long distances it is often more effective than a wire would be. So instead of stringing both the red and blue wires on poles, as pictured here, connect the blue wires to the *earth* by driving a long copper rod into the ground at each station; like this:



Now our system seems complete. Is there any reason why it could not in principle be extended to greater and greater distances? True, we find that longer distances require additional batteries; but that presents no great challenge. We understand that the wire in some measure *resists* the flow of current even while conducting it. Longer distances therefore represent more resistance, and that is overcome by using more batteries—sometimes by simply adding to the ones already in use; but more often by another technique, which I want to take note of here because the same principle will come up later in another connection.

To produce a clearly audible signal, a telegraph sounder requires a fairly strong current; mine needs a current of about 375 milliamperes for reliable operation. But the currents which could realistically be maintained in a telegraph wire hundreds of miles long were typically only about one-eighth of this. How then, with a such a small current, could the sounder be activated? That problem was solved by the *relay*: this is an electromagneti-

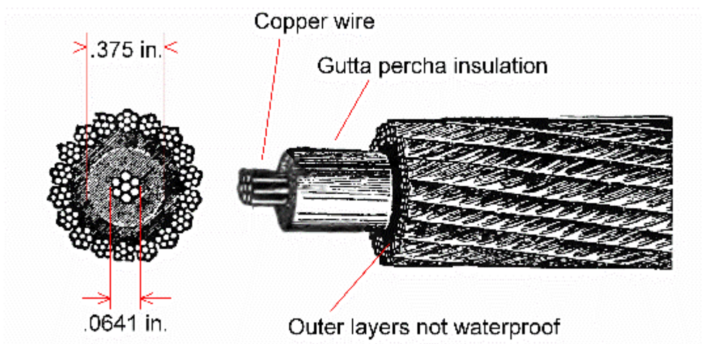


cally operated switch that requires only a weak current to turn it on. As you see here, the incoming current energizes the relay's electromagnet and closes the red contacts. Once these contacts are closed, a much stronger current from the batteries can pass and activate the sounder. It is as though the weak current were able to do the job of a much stronger current. Although telegraphers sometimes spoke of this arrangement as "magnifying" the incoming current, you can see that such a description is misleading. The relay cannot "magnify" anything; it is a control mechanism, not a transforming one. It does not *alter* the incoming current, but only enables it to trigger a more powerful one.

With this latest development, it seems that the only barrier to unlimited expansion of our telegraphic system is the ocean: *you can't erect telegraph poles in the middle of the deep blue sea!* But poles would be unnecessary if a telegraph wire could be laid directly on the seabed itself. In 1850 a telegraph cable was indeed laid along the floor of the English Channel. The first successful transatlantic cable was achieved in 1865.[3] But not only were undersea cables enormously expensive, their transmission speeds proved to be *extremely slow* compared to overland telegraph lines; let's try to see why.

The 1865 transatlantic cable ran 2900 miles from the west coast of Ireland to the shores of Nova Scotia. As we just saw, distance in itself is not a novel problem. 2900 miles happens also to be the distance between New York and San Francisco; and that mileage had already been covered with the completion of the transcontinental telegraph line in 1861. But overland wires are surrounded by air. What happens to such a wire when it is surrounded by *seawater*?

The 1865 cable is reported[4] to have contained a central conductor of about 64 thousandths of an inch in diameter, surrounded by gutta-percha



insulation to a diameter of 3/8 of an inch. Then the wire proper will have had a circumference of .204 inches. The cable was 2900 miles long, or 183 million, 744 thousand inches; so the outer surface of the conductor would have had area of nearly 37 million, 484 thousand square inches. This means that more than 37 million square inches of copper was separated by a little over 1/8 inch from an equal surface of excellently-conducting saltwater. What do we have when these two conductive surfaces are separated by a thin layer of insulating material? *We have the equivalent of a gigantic Leyden jar.*[5]

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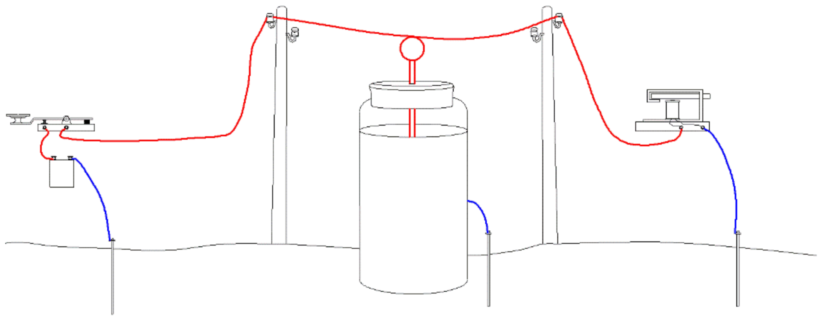
[3] An earlier cable, the first, carried its inaugural message in 1858 but failed within three weeks.

[4] Bright, Charles, *The Story of the Atlantic Cable* (1903), pp. 46, 52.

[5] Faraday observed behavior similar to that of the Leyden jar when very long wires were buried in the earth. See Faraday, Michael, "On Subterraneous Electro-Telegraph Wires," *Philosophical Magazine*, June 1854.

Imagine what would happen if we added such an enormous Leyden jar to our telegraphic line between Lamy and Santa Fe:



For simplicity, we'll consider only a one-way system, with a single battery. When the key is closed, current flows to the Leyden jar as well as to the sounder; the jar becomes charged, and the sounder clicks as its electromagnet is energized. But when the key is released, the Leyden jar *will still be charged*. It will then discharge through the sounder, keeping the electromagnet energized until discharge is complete. This means that after the key is released, there will be a delay before the sounder is released. If the key operator sent a "dot," the receiving operator might hear a "dash!"

We can mimic this effect. Here I have connected the sounder normally;

you can see it respond faithfully when I tap "dots" and "dashes" on the key.

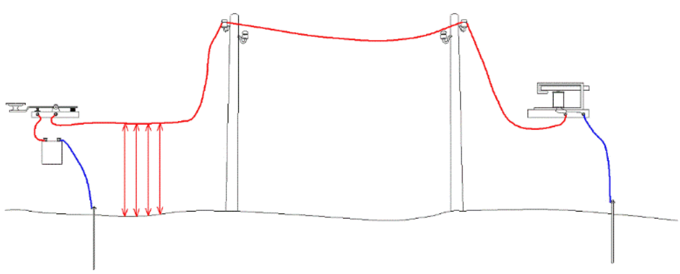
Next I will connect a capacitor—the modern equivalent of a Leyden jar—across the sounder's terminals to represent the result of submerging the

cable. The capacitor is only about an inch in diameter; nevertheless it is electrically equivalent to *many millions* of Leyden jars! Let's see how the sounder responds . . . Did you notice how sluggishly the sounder's armature released? When I tried to send "S J C," the sounder quickly became paralyzed, and the message was completely garbled.

The only way to avoid confusion is for the key operator to allow time for the jar to discharge between each "key up" and the next "key down." But this requires sending *very slowly*. The 1865 undersea cable could not carry more than about 8 words per minute.[6] By comparison, skilled landline telegraphers were expected to send and receive between 20 and 40 words per minute; while the lines themselves could support speeds three times as fast using automated sending and receiving apparatus.

The problem, then, with an undersea cable is not the cable but the *sea!* But doesn't that cast serious doubt on the imagery of electric current as a species of *flow*, with the telegraph wire as its channel or conduit? For the performance of a pipe or channel is ordinarily determined by the conditions *inside it*, not the conditions outside it. To take only the most naive example, water flowing through a pipe is majestically indifferent as to whether that pipe is suspended in air, lying on the ground, or buried in the earth—in stark contrast to the submarine cable's susceptibility to its environment. Moreover, if a telegraph cable immersed in saltwater behaves conspicuously like a Leyden jar, then surely the same cable suspended in air must likewise act like a Leyden jar—but merely to a lesser extent. How, then, can any realistic image of electric current privilege a supposed process of "flow" *within* the wire, while excluding any representation of the conditions *surrounding* the wire? Yet that is just what the conventional "flow" image does.

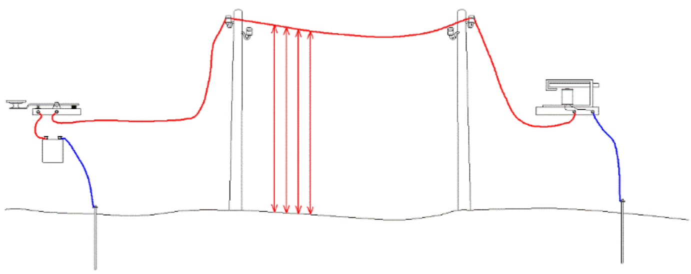
Faraday, in his Eleventh and Twelfth Series, especially, found that for purposes of understanding the Leyden jar, an image of electrification that emphasized *tension in the surrounding dielectric* was far more fruitful than was the image of electricity as residing in or on a conductor. A more Faradayan account of our telegraph system might proceed like this:



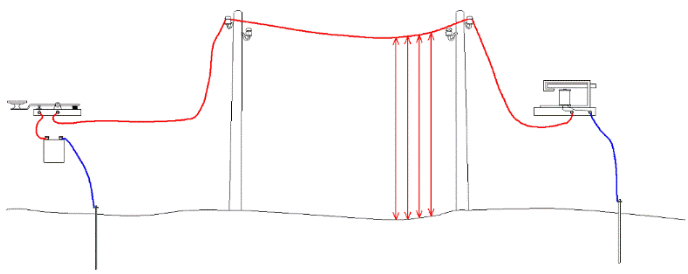
[6] Even this was a vast improvement over the first, 1858, cable, which required 16 hours to transmit a 98-word message from Queen Victoria to President James Buchanan—a speed of 1/10 word per minute!

The telegraph key has just sent a single "dot"—a short pulse. While the key was closed, the battery began to impose tension between the left end of the wire and ground. That tension spread to the right as each region affected the adjacent region. Similarly, when the key was opened, tension at the wire's end returned to zero; and this condition too propagated to the right from region to region. The result is a zone of tension that has moved from the telegraph key about halfway to the first telegraph pole.

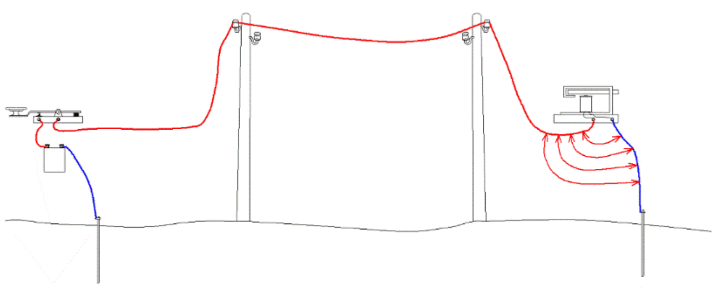
A moment later, that zone of tension will have moved just beyond the first telegraph pole…



And from that point nearly to the second pole…



Finally it will approach the telegraph sounder; and when it reaches that device, the tension will discharge in the sounder's coils, developing the



momentary magnetic field which attracts the armature, thus signaling that a "dot" has been received. Let us view these images as a sequence, to give a better sense of how this wave of tension—for it *is* a wave—travels. Notice that while the wave may be said to be *guided* by the telegraph wire and the earth; it is not travelling *through* either of them. It is traveling through *space*.

You see how the behavior of the transatlantic cable is far more concordant with Faraday's "tension" image than with the image of *flow through a wire*. Moreover, by acknowledging the relevance of action *outside the wire* Faraday's image provides a more natural rhetorical context for the phenomena encountered in submarine cables. But I would not wish to argue that either image is the "true" one. Both of them bear a metaphorical stamp, in that both work to render *unfamiliar* phenomena in *familiar* terms.

Returning, then, to the telegraphic predicament, I had suggested earlier that the problem was not the cable but its submersion in the sea. On the other hand, inasmuch as there is no way to suspend a cable *above* the sea, from a practical point of view the problem *was* the cable; and the solution would be to eliminate the cable altogether.[7] But how is that possible?

Indeed, it is *not* possible if electric current is essentially *flow through a wire*, as the conventional image represents it; for then a wire will be indispensable. But if current is essentially a *wave of tension*, new possibilities for transmission would seem to open up, in imagination if nothing else. I am not sure to what extent Faraday actually contemplated the idea of "separating the current from the wire," so to speak, though some of his later writings are highly suggestive.[8] But Maxwell certainly did—and largely on the basis of Faraday's views on the nature of conduction. As juniors will see for themselves later in the semester, Maxwell's theory implies that every electric current necessarily generates an electromagnetic wave—and although currents cannot travel without wires, *electromagnetic waves travel in space*.

Maxwell's calculations provided compelling reasons for him to believe that *light* was an electromagnetic wave, but he did not conjecture whether there might be other kinds of electromagnetic waves, nor whether such waves could be produced in practice by electrical means. That achievement—the generation of electromagnetic waves—was accomplished by Heinrich Hertz in 1888.

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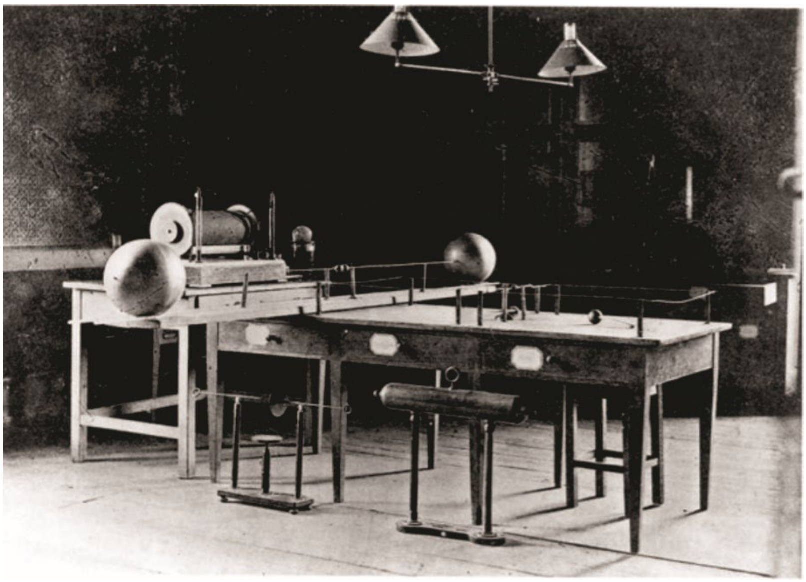
[7] By no means, of course, have submarine communication cables been abandoned! Dramatic improvements have resulted from the use of better insulation, inline repeaters, and, since about the 1980s, transition from electrical to optical cables.

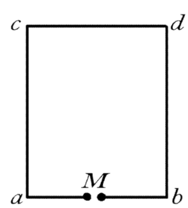
[8] See, for example, "Thoughts on Ray-Vibrations," *Experimental Researches in Electricity*, vol. III, p. 447; "On Subterraneous Electro-Telegraph Wires," ibid., p. 521; "On Electric Induction—Associated cases of current and Static Effects," *Phil. Mag*, Series 4, vol. 7, no. 44 (March 1854), p. 197.

Hertz's apparatus is shown in this haunting photograph—taken, I believe,



by Hertz himself. The pair of long rods with large globes at their ends form the radiating structure—what we now call the "antenna."[9] The large coil at the far left end of the bench produced pulses of very high voltage which discharged through the spark gap at the center of the rod pair, and so initiated in them a rapidly oscillating current. Although a spark discharge inherently produces waves exhibiting a huge range of frequencies, Hertz's rods and spheres were sized to favor waves having a length of about 6 meters and a frequency of about 50 million cycles per second.

Hertz demonstrated the existence of these waves by showing their effect on a separate wire loop, interrupted by a spark gap of its own; here is Hertz's diagram.[10] Whenever the main apparatus sparked, a discernable



spark developed across the gap at M, even when the loop was held twenty or thirty feet away, thus demonstrating that the waves were indeed traveling through the air.

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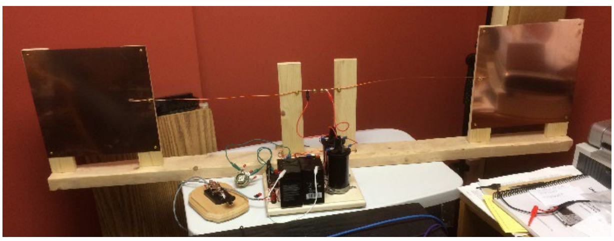
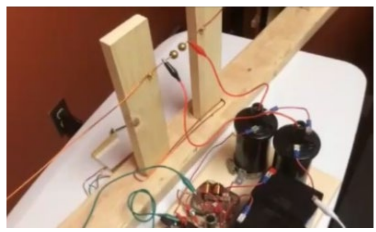
[9] *Antenna*—Latin term for *sailyard*, *yardarm*; later (15th cent.) the long protruding "feeler" of an insect—became the accepted name for such a radiator by 1902.

[10] Redrawn from Hertz, *Electric Waves* (1893).

Hertz's apparatus could not transmit waves over distances useful for practical communication. Nor had Hertz harbored any such intention; his interest was in confirming Maxwell's electromagnetic theory. But a young Guglielmo Marconi saw these "Hertzian waves," as they were then called, as a potential means of wireless communication. Instead of turning an *electric current* on and off in short and long pulses, it was only necessary to turn the *spark generator* on and off. Pulses of electromagnetic waves would then carry messages in the same form as landline telegraphy did; but it would be *wireless telegraphy*. Marconi began experimenting with his own wave apparatus in 1894; he succeeded in transmitting over distances that gradually increased from one-half mile, to 10 miles in 1897, across the English Channel in 1898, and in 1899 to a vessel at sea 66 miles away.[11]

A few years ago I made a spark transmitter from old automotive ignition parts; I even tried to imitate Hertz's antenna:

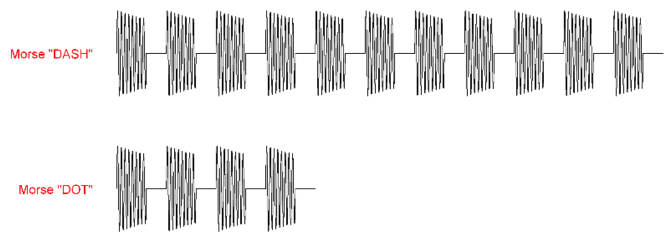
The two copper sheets correspond to Hertz's globes, while the brass spheres at the center form the spark gap. The two cylindrical objects are a pair of automotive ignition coils, wired back-to-back. They take the place of Hertz's enormous induction coil.

Here is the transmitter in operation . . . The buzzing sound you heard is a set of contacts in the battery circuit; each time they open, a spark is generated. With the aid of this Hertzian memorial, Mr. Franks and I were able to send a signal from the portico of Weigle Hall to his office in ESL—a magnificent range of one hundred twenty feet!

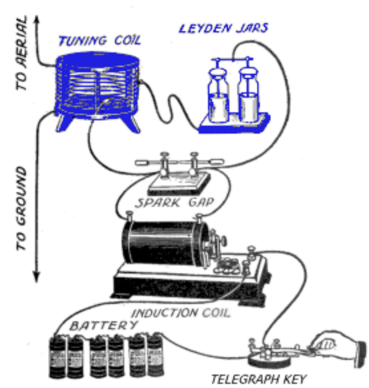
The wave produced by this series of *sparks* is, accordingly, a series of wave *pulses*. A new pulse is produced each time the buzzer contacts open—in my transmitter that is about 500 times per second. But each pulse itself oscillates at a frequency of roughly 50 million times per second, and it also decays slightly in amplitude. So if I hold down the transmitter key for the

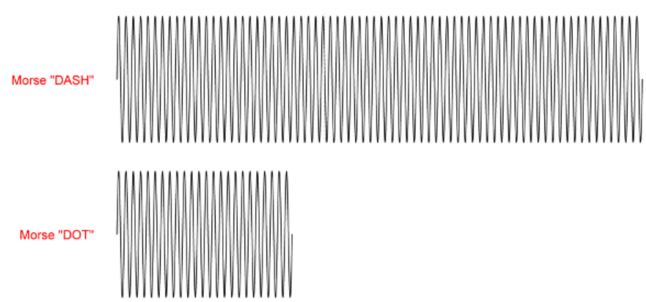
[11] Largely because of Marconi's single-minded pursuit of wireless telegraphy, it is his name that is most prominently associated with its development; but Marconi was by no means the sole originator. In the year when Marconi began his experiments Oliver Lodge, already a scientific luminary, would introduce the "syntonic" (tuned) transmitter in a memorial lecture on Hertz (Royal Institution, June 1894) and transmit wireless Morse messages between two Oxford University buildings (British Association meeting, August 1894).

length of one "dash" (about a third of a second) it produces a wave shape like the one drawn at the top of this slide. A Morse "dot," which should be about a third of the length of a dash, is drawn at the bottom.

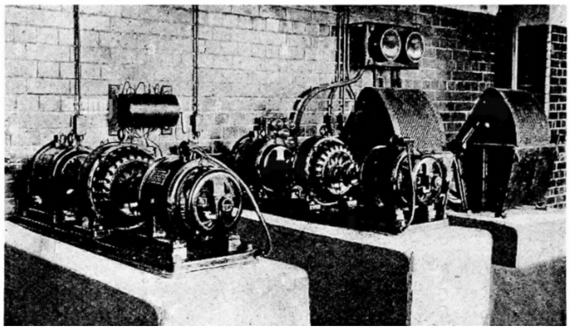


With the steady growth of wireless range it seemed inevitable that wireless transmission would eventually extend from continent to continent; it was only a matter of commandeering more electric power for the spark and building more efficient radiating and receiving structures. But the intermittent character of the spark wave was a serious impediment to transmission power. As the slide shows, only about 50% of the transmission time was actually occupied by a wave! This is deplorably inefficient, and various methods were developed to make the radiated wave more nearly continuous. One of them utilized a Leyden jar and a coil, like the ones highlighted on the right, to prolong oscillations in the antenna. Instead of the intermittent pulses generated by the earliest transmitters, this and other improvements resulted in a wave that was nearly continuous, so that Morse "dashes" and "dots" had waveshapes like these:



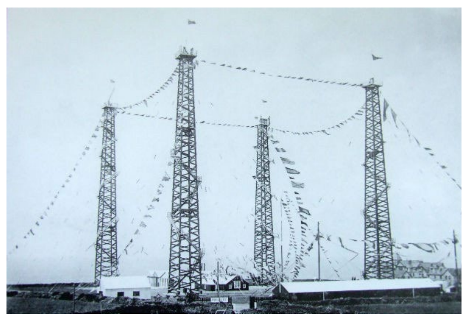


But even with the greater efficiency obtained with improved wave continuity, the power needed for long-distance wireless transmission was far greater than any battery could supply. Marconi's most powerful transmitters employed steam-powered electric generators like these:[12]



As you might imagine, the sparks produced by such enormous machines were distressingly noisy. The residents near one installation[13] complained that the sound of the spark could be heard four miles downwind of the station!

The radiating and receiving antenna structures likewise grew in scale and complexity, as more and more came to be known about the behavior of electromagnetic waves. Here are two of Marconi's transatlantic antenna



arrays, the one on the left was located in Nova Scotia, Canada; the one on the right was constructed in Cornwall, England around 1902. But successful reception of the transmitted electromagnetic wave was not, in itself, sufficient to establish communication; the recipient had to *know* that it was received! The wave had to be *detected*. How was this to be achieved?

When an electromagnetic wave is intercepted by a conductor, an electric current tends to develop in it. Roughly speaking, a conductor will develop a current insofar as it is parallel to the incoming electric field, or perpendicular to the incoming magnetic field. (Recall that Faraday had shown, long before, that a conductor tends to develop a current when it

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[12] Bucher, Elmer. *Practical Wireless Telegraphy* (1917), p. 295.

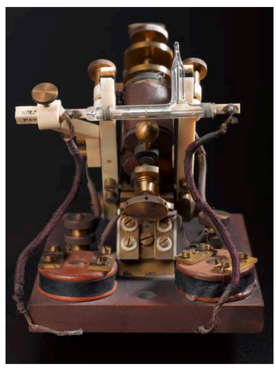
[13] South Wellfleet, Mass. See https://www.nps.gov/caco/learn/historyculture/marconi.htm

"cuts" lines of magnetic force.) Any phenomenon associated with this current will, therefore, signal the reception of an electromagnetic wave.

So long as Hertz's wire loop was within a few dozen feet of the transmitter, the currents that developed in it were strong enough to produce a spark, though a very feeble one (Hertz had to darken the room and use a magnifying lens to see it). But the currents that would develop in a far distant conductor—even in a sophisticated and elaborate array like the ones shown here—would be incomparably weaker. A far more sensitive indicator would be required to discern them.

Numerous such indicators were contrived, several of them truly ingenious; but most were either too delicate or too slow for practical use. The first device to gain widespread adoption was one whose operation no one really understood. This was the "coherer," widely credited in principle to the French physicist Édouard Branly, although many other investigators, including Marconi, contributed to its practical utility.

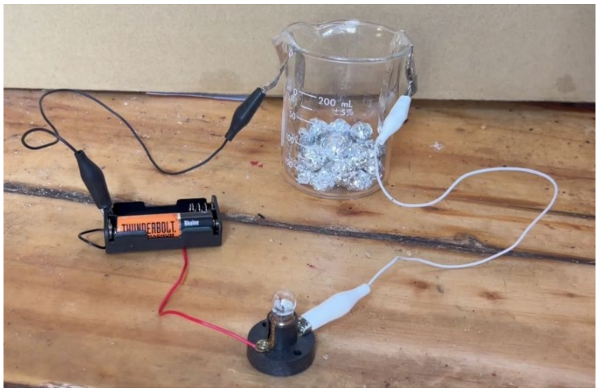
On the left is one of Marconi's coherers; and on the right you see how it would have been incorporated in an actual wireless receiver, mounted in a



mechanism I will explain in a moment. The coherer itself is a length of glass tubing fitted with two electrodes, the space between them filled loosely with metal filings. Although metals are generally good conductors, tiny shards of metal do not contact one another very well, so the coherer does not readily conduct an electric current. But in the presence of a high-frequency electromagnetic wave the metal filings mysteriously "cohere"—hence the name—and the device becomes suddenly conductive.

We can see the "cohering" behavior using little more than a heap of metallic spheres.[14] I have squeezed about a dozen four-inch squares of

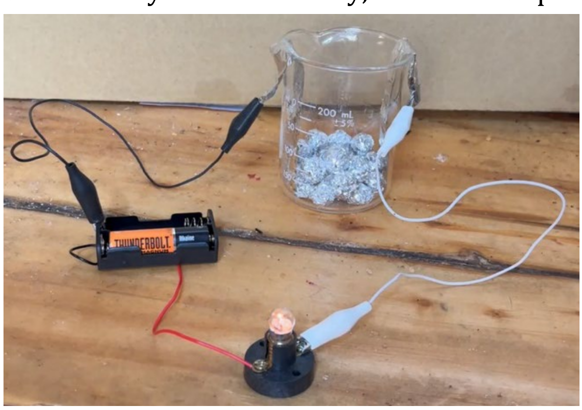
[14] This was one of Branly's early versions; see Fleming, J. A., *Principles of Electric Wave Telegraphy and Telephony*, 3rd ed. (1916), p. 478. My version is adapted from a YouTube video whose presenter identifies himself only as "Mr. Whibley": look for https://youtu.be/ESgoNEH__E8?si=Xw5a7Zzmhb8Q5G6Y—truly a little gem.



aluminum foil into spheres about one-half inch in diameter and placed them loosely in the glass beaker. Strips of foil taped to opposite sides of the beaker connect the pile of spheres in the circuit of a battery and flashlight bulb. As you see, the bulb is not lit, even though aluminum is a good conductor. Evidently the loose contact *between* the spheres cannot pass enough current to light the bulb.

But we know from Hertz that an electric spark generates electromagnetic waves. This battery-operated stove lighter generates a series of electric

sparks when I press the trigger; it's what I use to light my propane stove at home. In a wireless telegraphy receiver, the incoming electromagnetic wave would have been routed to the coherer by means of a wire from the antenna; but since my sparker is only a few feet away, we need no special conductor.



See? When the discharge occurs, the pile of spheres suddenly becomes conductive, and the lamp lights. But you can also see the great deficiency of this device: it *remains conductive*, and the lamp stays lit, even after the spark and its radiated wave have ceased. It cannot distinguish a dot from a dash; indeed, so long as it remains conductive it will not be able to detect the arrival of a subsequent pulse, whether dot *or* dash.

What seems to be happening is that the sudden spike of electromagnetic disturbance generates tiny sparks between the foil surfaces, which momentarily raise the temperature at the discharge points sufficiently high to weld the spheres together. But notice that when I give the cup a sharp tap, *the current ceases*. Evidently a slight disturbance is enough to break the tiny bonds—today they are called "microwelds"—between the foil spheres.

Such was the purpose of the elaborate mechanism in which the coherer was typically mounted. The moment Marconi's coherer became conductive,

it passed a current through an electromagnet; this in turn caused a steel tapper to strike the glass tube and "de-cohere" the particles, opening the circuit. The tapper would immediately spring back; and if the received pulse had been a short "dot," the coherer would now be ready to receive the next pulse. If, however, the pulse had been a long "dash," the wave would still be present; the particles would cohere again, the tapper would strike the glass once more; and this process would repeat, and the tapping would continue, until the cessation of the "dash." This principle—the "switch that turns itself off"—is the principle of the electric buzzer, and when the decoherer was in operation it created a similar buzzing sound.[15]

The coherer was, however, far from satisfactory. One engineer complained, "It was publicized as wonderful, and it was—wonderfully erratic and bad. It would not work when it should, and it worked overtime when it should not have."[16] Another described it as "the *bête noir* of radiotelegraphy," since it could not reliably distinguish between "legitimate signals, static disturbances, a slipping trolley several blocks away, and even

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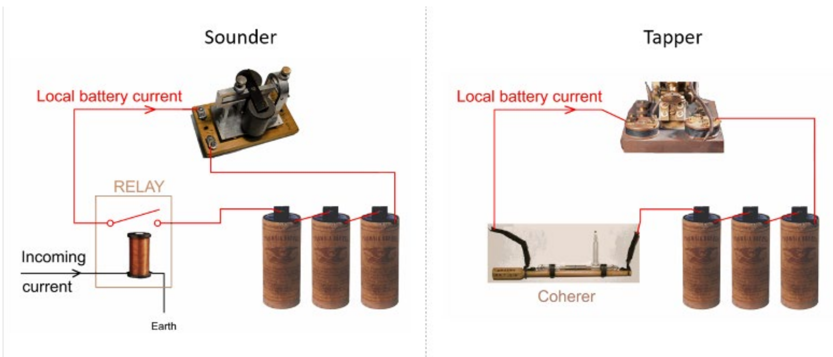
[15] This "buzzer" style of decoherer was only one of many methods that were developed to enable the coherer to control an indicator, or even a recorder.

[16] Robert Marriott, quoted in Lewis Coe, *Wireless Radio, A History*, 2nd ed. (2006), p. 6.

the turning on and off of electric lights in the building."[17] But perhaps the most serious deficiency was its sluggishness; the coherer's cumbersome tapping mechanism limited reception to about 12 or 15 words per minute—barely a third of the standard for landline telegraphers. Still, even with these limitations, the coherer was a tremendous advance over Hertz's spark detector, because it acted *indirectly*. Let me explain what I mean by this.

The spark Hertz observed in his wire loop detector was the direct manifestation of the current induced in it by the intercepted electromagnetic wave. Nothing intervened between the current and the spark; indeed, from Faraday's point of view, the current *was* the spark. Necessarily, then, the perceptible indication of the electromagnetic wave could be no more energetic than was the received wave itself. The coherer, by contrast, allows a weak incoming current to trigger a separate and much stronger current—the same principle we saw earlier in the telegraphic relay, only effected by different means. The relay used *electromagnetic attraction* to close a switch



mechanically, thus completing a battery circuit. In the coherer, *heat* from tiny sparks creates microscopic welds between the metal shards; it completes the battery circuit by fusing conductive fragments together. The coherer, like the relay, makes possible a much more pronounced effect than the wave itself would have been able to produce; and since the wave-current only *triggers* the current which produces the sensible outcome, I call the coherer an *indirect* detector.

Notice that the crucial element in the operation of the coherer is *production of heat*; everything else depends on that. But until about twenty years ago, when research finally confirmed it,[18] the role played by *heat* in the operation of the coherer could at best be only surmised. Nevertheless, to

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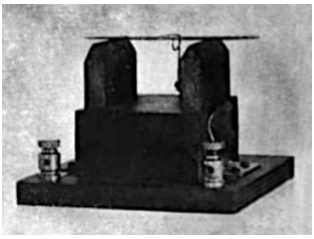
[17] G. W. Pickard, "How I Invented the Crystal Detector," *Electrical Experimenter* (August 1919), p. 325.

[18] Falcon, Eric; Castaing, Bernard. "Electrical conductivity in granular media and Branly's coherer: A simple experiment," *American Journal of Physics* **73** (4): 302–307 (2005).

early twentieth-century investigators, explanations based on *heat* would have seemed the most reasonable and natural among the available candidates. We find a striking example of this in the work of G. W. Pickard, an American engineer.

In 1902 Pickard was experimenting with the detector shown here on the



left, a sewing needle laid across two carbon supports; and perhaps because it involved *loose contact between conducting bodies*, Pickard thought of his detector as a type of coherer. In contrast to Marconi's coherer, though, this one was *self-restoring*; it did not need to be tapped after each received pulse. Nevertheless, Pickard was using it just as he would have employed an ordinary Marconi coherer: the detector was connected to a set of batteries, so that when it became conductive in the presence of an electromagnetic wave, the resulting rush of current from the batteries would produce a distinctive clicking sound in a Bell-style telephone earpiece, pictured on the right.

Pickard's great discovery occurred when he accidentally disconnected the batteries, yet *continued to hear clicks* in the earpiece whenever a wave pulse was received at the antenna. But with the batteries disconnected, the only source of electrical energy was the current from the antenna. Pickard was astonished to realize that

> the telephone diaphragm was being operated *solely by the energy of the receive[d] signals*. [19]

What was astonishing about this? I'm guessing here, because Pickard did not say very much more about the course of his thinking. But everyone knew, and he would have known, that the current coming directly from the antenna should have been *incapable* of activating the telephone.

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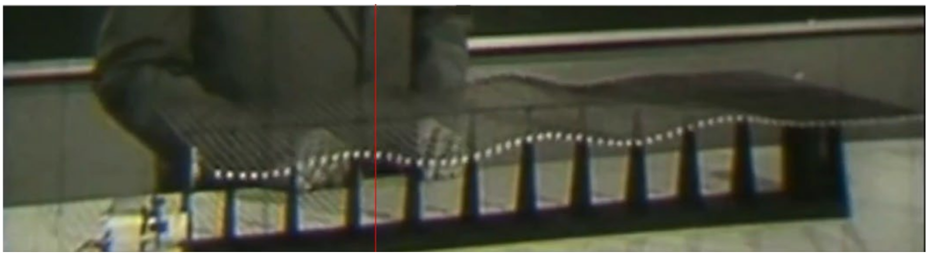
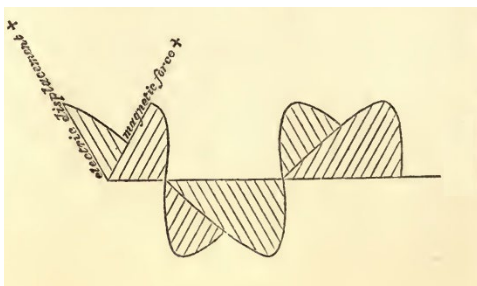
[19] G. W. Pickard, "How I Invented the Crystal Detector," *Electrical Experimenter* (August 1919). Emphasis in the original.

Let us understand why this is so. Remember that every wave has an *oscillatory* or, we might say, *alternating* character. For example, when we send a wave along one of our Bell wave machines, the wave itself travels horizontally; but every point on it moves *vertically*—alternating between *motion up* and *motion down*. Here is a clip from a 1959 instructional film; the presenter is John Shive, who invented the Bell wave device. Keep your



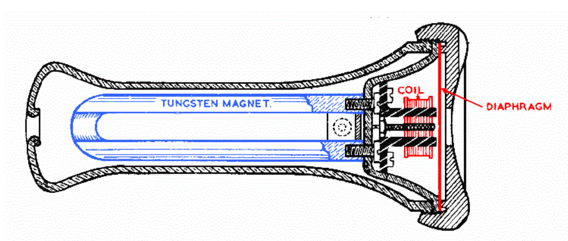
eye on any of the crossbars, and notice their alternating up-and-down displacement. A vertical red line will assist you in this.

Analogously, each of the components of an *electromagnetic* wave—the electric field and the magnetic field—undergoes a similar alternation between positive and negative. Maxwell depicted that alternation in this drawing; it is Figure 66 from his *Treatise on Electricity and Magnetism*.



When the incoming electromagnetic wave is intercepted by the receiving antenna of a radiotelegraphy station, the alternating *fields* induce an alternating *current*. What happens, then, if this current is sent directly to a telephone receiver?

The Bell telephone earpiece of 1900 (and they really haven't changed all



that much, even today) consists of a permanent magnet, shown here in blue, and a coil and a flexible steel diaphragm, shown in red. The diaphragm, being attracted to the magnet, is permanently deflected in the magnet's direction. But when an alternating current is sent through the coil, the coil's magnetic field will alternately reinforce and oppose the magnet's field. As a result, the diaphragm will be deflected now more, and now less; it will attempt to *vibrate* with the frequency at which the current alternates.

But this frequency would have been in excess of *hundreds of thousands of vibrations per second*, for that was typical of the electromagnetic waves used in radiotelegraphy. No telephone diaphragm could sustain such rapid vibrations; and even had it done so, Pickard could never have heard them! For the limit of human hearing is at best about *twenty* thousand vibrations per second.

What Pickard *did* hear in the earpiece was a sequence of *clicks*. What kind of current would cause *that*? The same kind of current that produced the clicks in our telegraph sounder earlier: a *steady* current—what we now call a direct current—turning *on and off*. Just as with the sounder's armature, the telephone's diaphragm is pulled towards the magnet when the current is *on*, then released when the current is *off*.

Here I have an actual Bell receiver mechanism from about 1915; listen in the following video as I repeatedly connect, then disconnect, a battery. In the video I have amplified the sound considerably, and you can also see the diaphragm moving in and out.

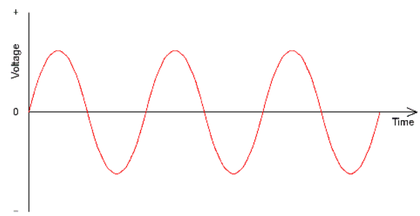
Here, then, is the problem. Pickard's antenna was sending an *alternating* current *to* the detector—but the telephone was receiving a *direct* current *from* the detector! The detector, then, must either be *transforming* an alternating current into a direct current, or it must be *replacing* one current with the other. Pickard assumed the second option: replacement rather than transformation. We know this because in his patent certificate of 1906[20] he states:

> The energy of the received oscillations is converted into heat at the … junction.… This heat energy is then, according to this invention, regenerated or converted into a direct electric current.

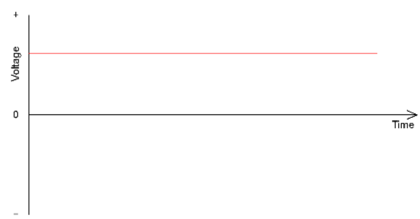
[20] U.S. Patent no. 836,531 issued November 20, 1906.

Pickard is asserting that the process has two stages: first, the alternating current produces *heat*; next, the heated junction between two dissimilar materials produces a direct current. Both of these phenomena were well known. Electrical production of heat had been described by Joule in 1840, and the thermal generation of electricity—Faraday called it "thermo-electricity" in his Third Series—was discovered by Seebeck in 1821.

On what basis did Pickard offer this interpretation?—or, rather, this *conjecture*, since as far as I know, there existed at that time no research confirming the idea that *heat* was really involved. I think his word "regenerated" is telling. In the absence of a clear picture of electric current, he cannot think of "current" as a thing capable of being wrought from a serpentine profile, like this:



into a rectilinear profile, like this:



Current, for him, does not seem to be the sort of thing that can be fashioned "as clay in the hands of the potter."[21] Without a clear picture of its nature, electric current can only be conceived as a manifestation of *the power that generates it*; the only way it can change its character, therefore, is to perish in one form, then be *re*-generated in another.

Pickard's attempt to avoid the idea of "transformation" would prove to be mistaken. His device actually *does* transform the *current as such*—not by converting it to heat and back again, but by a different process altogether.

[21] Jeremiah 18:6

That process would finally reveal itself with the advent of the *vacuum tube*.

That invention will be the topic of my talk in April, and I hope many of you will be able to come. The vacuum tube would not only address the problem of wave *detection* in a much improved way, it would make possible sweeping advances in the production and transmission of electromagnetic waves. It would, above all, enable electromagnetic waves to convey *sound*—giving rise to the fascinating technology we now call “radio.” Additionally, the vacuum tube will raise anew, and perhaps in a more visualizable form, our former question, that of *the nature of electric current*. I hope you will join me for that discussion.