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Electromagnetic waves were first postulated by James Clerk Maxwell (1831–1879) in 1865. To demonstrate their existence 22 years later, Heinrich Hertz (1857–1894) had to design new instrumentation that he used to carry out an experiment than had never been performed before. To detect the waves produced by his oscillating electric circuit, he used a very crude receiver, subsequently known as the Hertz resonator. This was made of a simple wire shaped in a circle with a small gap between the two ends where a spark was caused by the waves [1]. It was a very weak effect that Hertz could hardly observe: a very tiny spark that required a dark room and even a magnifier. Hertz, focused on pure science, asserted, "I do not think that the wireless waves I have discovered will have any practical application" [2].

However, his sensational result triggered the interest of many researchers who, over the following years, explored electromagnetic waves in the direction of practical applications. These trailblazers developed finer devices that allowed more sophisticated experiments. In 1890, the Italian physicist Augusto Righi (1850–1920) built an efficient oscillator that could operate at higher frequencies. He thus extended Hertz's results into the range of short waves with a 2.5-cm wavelength compared to Hertz's 66 cm. Around 1895, Indian polymath Jagadish Chandra Bose (1858–1937) obtained even shorter waves of 5-mm wavelength. Both of these physicists employed different detectors. The former used a small glass plate covered with two metallic layers separated by a thin gap, while the latter used a crystal detector [3].

Soon a different kind of wave detector, considerably more sensitive than Hertz's simple wire loop resonator, became popular among those experimenting with electromagnetic waves. It was developed in 1890 by Désiré-Edouard-Eugène Branly (1844–1940) and consisted of a glass tube containing metal filings placed between two electrodes, as shown in Figure 1. Branly, who was a French physician and physicist and a professor at the Catholic University of Paris, later called the device a *radioconducteur* (radio-conductor) [4]. It exploited an effect identified six years earlier by Temistocle Calzecchi Onesti (1853–1922), an Italian high school teacher. It consisted in the proclivity of metal filings to acquire high electrical conductivity when exposed to electrical effects and to regain high resistivity after receiving a small shock (Figure 2) [5]. Similar effects had been observed even earlier, in 1835 by Peter Samuel Munk at the University of Lund in Rösenschold, Sweden, and in 1879 by American–British inventor David Edward Hughes. To give an idea of the magnitude, resistance could vary from several million ohms to a few hundred ohms or from

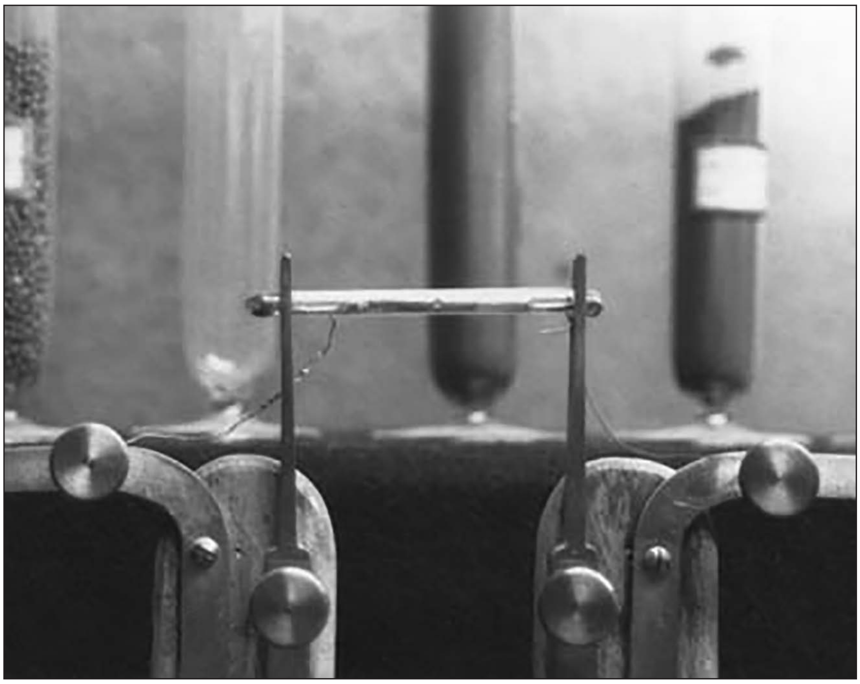

FIGURE 1 – One of Branly's early *radioconducteur*, 1890. (Photo courtesy of Wikimedia Commons.)

tens of kilo-ohms to a few ohms, depending on the metals used.

Calzecchi Onesti had thought he might exploit his invention for detecting lightning or as a seismic detector. On the other hand, Branly conceived the *radioconducteur* while studying the effect of the electrostatic discharges produced by a Wilmshurt machine [6]. He observed that it was activated by an electric discharge nearby and soon noted that it could also react when placed in another room some 20 m away. He focused his research on the electrical conduction instability in inhomogeneous conducting media, and this was named the *Branly effect*. By 1891, he was able to detect discharges at a distance of 80 m. Only some years later, in 1898–1899, did he participate in experiments of long-distance wireless transmission and contribute to identifying the role of the aerial.

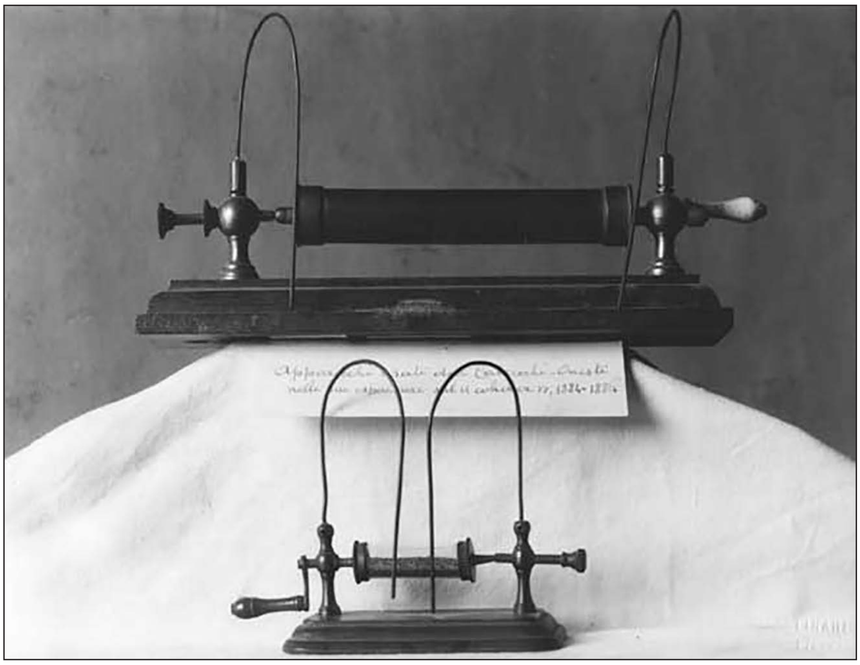

FIGURE 2 – The original tubes by Calzecchi Onesti (1884–1886). (Photo courtesy of Comitato Guglielmo Marconi International.)

Branly's radio-conductor was introduced in the United Kingdom at a scientific meeting in Edinburgh in 1892 [7], and the possibility of using it to detect Hertzian waves was soon suggested. The following year, British physicist Oliver Lodge (1851–1940) of University College Liverpool developed a more advanced version of the device that he called the *coherer*. It was fitted with a decoherer that tapped the tube continuously so as to dislodge the filings after each detection. Lodge used it to investigate the optical properties of electromagnetic waves and reported early results at a scientific meeting in Oxford in 1894. Here he acknowledged the work of Hertz, who had recently passed away [8]. Soon Lodge was able to detect waves produced 55 m away [9]. Lodge had been experimenting with electromagnetic waves (conducted in wires instead of radiated in air) since 1888, or almost as long as Hertz. Like Branly, he failed to foresee the possibility of using his equipment for communication. He later admitted that he had not seen any advantage in telegraphing across the air to replace the well-established wires: "stupidly enough no attempt was made to apply any but the feeblest power so as to test how far the disturbance could really be detected" [10]. Nevertheless, the coherer he had perfected resulted in not only the first sensitive detector of radio waves; it was also capable of two-state operation and therefore well suited for telegraphic binary codes. It had a fundamental role in the development of early wireless communication.

After reading Lodge's 1894 report, Alexander Stepanovich Popov (1859–1906), a teacher at the Russian Navy School in Kronstadt, improved the receiving circuit by adding an antenna connected to one electrode of the coherer, the other connected to ground. In 1895, he used such a circuit to pick up radio waves produced by atmospheric lightning that struck 30 km away. These results, reported in May that year, represented the first long-distance reception ever, albeit that the signals were of natural origin and not man-made messages [11].

At around the same time, Guglielmo Marconi (1874–1937), a young Italian who had worked at Righi's laboratory but did not attend university, was working alone at his country house. A few months after Popov's achievement, Marconi transmitted the first radio signals over a distance of 2.4 km. He used Righi's oscillator for transmission and Lodge's coherer as a receiver. Both had one terminal connected to ground and the other to an antenna. Quarter-wavelength aerials were thus used both in transmission and reception and proved to be surprisingly efficient. The distance covered, greater than the one-half mile maximum transmission limit postulated by Lodge the year before, proved that remote radio transmissions were indeed possible. The way forward for wireless telegraphy, a dream that had been pursued using different technologies for over 50 years, was paved.

British on his mother's side, and in search of financial support and industrial interest, Marconi moved to England. There he patented his wireless telegraph in 1896 and transmitted over a distance of 14 km in 1897. The same year, he founded the first wireless telegraph company, which, in 1900, was renamed Marconi's Wireless Telegraph Company. This allowed him to begin the commercial exploitation of wireless technology and to fund his research. In developing his system, Marconi further improved the coherer, developing it into an autocoherer in which decohering was self-triggered by the detected signal. In an advanced design, he enclosed the metal filings between two slanted electrodes a few millimeters apart (Figure 3). With such improvements the coherer became a reliable device well suited to provide the sensitivity then required.

By 1897, Adolf Karl Heinrich Slaby (1849–1913), a German engineer who was working at AEG and had participated in Marconi's experiments, could radio transmit at a record distance of 21 km. This limit would soon be overcome thanks to another German, physicist Karl Ferdinand Braun (1850–1918), who had, a quarter of a century earlier in 1874, discovered the rectifying properties of a galena crystal provided with point electrodes. After inventing the Braun tube—a single-axis cathode-ray indicator and the forerunner of the oscilloscope and the cathode ray tube [3]—in 1897, Braun became interested in wireless telegraphy, initially for underwater applications. The following year, he developed a syntonic wireless transmission system in which, unlike that of Marconi, the transmitter circuit was connected to the antenna via a mutual inductor. By adapting the circuit impedance, that is, tuning transmitter and receiver, this provided much better transmission efficiency together with higher selectivity. Like Marconi, in 1900 Braun established his own company, Professor Braun's Telegraphie Gesellschaft GmbH, which was backed by Siemens (the system was named *Braun-Siemens*). After that patent litigations started between Braun-Siemens and AEG, and in 1903, at the behest of Kaiser Wilhelm II, they were incorporated into Gesellschaft für drahtlose Telegraphie System Telefunken (Telefunken).

In the same year as Braun, Marconi developed his own syntonic system, by his own admission strongly inspired by Braun's system, and received a patent in 1900. This enabled him to transmit across the channel in 1899 (his first message acknowledged Branly's contribution to radiotelegraphy), and the following year he set further records, arriving to transmit over 135 km. During these experiments, Marconi observed that when the receiving station was on a ship traveling away from the transmitter, detection persisted after the ship had disappeared beyond the horizon. The effect convinced him that he could transmit much farther, despite the scientific belief that electromagnetic waves, like light, only travel in straight lines and cannot follow the earth's curvature. For his 1901–1902 experiments, he set up a transmitting station in Poldhu, Cornwall, and a receiving station first in Newfoundland and then on board the SS *Philadelphia* [12]. At 25 kW the Poldhu station was the most powerful station in existence, transmitting 830-kHz waves. It had been designed by John Ambrose Fleming (1849–1945), who operated it during the experiments [13]. To detect the very feeble signals, Marconi used a mercury coherer, the most sensitive type then available. This was an autocoherer based on a drop of mercury contained between one adjustable plug of iron and one fixed plug of carbon. It was provided with a telephone earpiece to enhance its sensitiveness. With his successful experiment Marconi had demonstrated that very long distance radio transmissions (3,400 km) were possible and that radio signals do indeed bend to follow the earth's curvature. How this could happen was explained the same year (1902) by Oliver Heaviside (1850–1925) and Arthur Edwin Kennelly (1861–1939), who independently proposed the reflection of radio waves by layers of ionized gas in the earth's atmosphere, the ionosphere.

Marconi deemed even the mercury coherer as "not sufficiently reliable for commercial work" over the ocean and started to develop the more sensitive magnetic detector (Figure 4). This was based on a closed iron tape kept in motion between two pulleys that passed through the bore of a coil connected to the aerial. The excitation of this coil in the presence of an arriving signal changed the magnetization of the iron tape. This change was detected by a second pickup coil. Marconi's companies started regular transatlantic radiotelegraph services in 1907 despite the fierce opposition of the transatlantic telegraph cable companies [14]. During these years Marconi also displayed his entrepreneurial talent by consolidating his companies and managing financial and market issues. He

FIGURE 3 – A Marconi advanced filings coherer. (Photo courtesy of Wikimedia Commons.)

FIGURE 4 – A Marconi magnetic detector, developed in 1902. (Photo courtesy of Spark Museum.)

hired the best scientists available, including Charles Samuel Franklin (1879–1964) and Henry Joseph Round (1881–1966), besides Fleming. Branly was offered a position as technical advisor but refused.

While all of this had been happening, Nikola Tesla (1856–1943) was experimenting with wireless transmission in America, with the aim of transmitting power rather than information. His approach was based on continuous waves, i.e., waves that were not dampened, unlike the other researchers who were pursuing pulsed, dampened waves. After several lectures involving spectacular demonstrations of discharge tubes that glowed with no wire connection in 1893, he conducted systematic experiments from 1894 onward. For example, he transmitted a signal to a ship in the Hudson River in 1896 and gave a sensational demonstration of a radio-controlled boat at Madison Square Garden, New York, in 1898. He continued his research in Colorado Springs, Colorado, after 1899, developing alternators at 10–25 kHz and systems consisting of four tuned circuits with oscillatory sparks. A similar four-circuit tuning system was also patented in 1900 by American telephone engineer John Stone Stone (1869–1943).

Within a few years, the vast research effort had produced simpler and more sensitive detectors. Notable among these were electrolytic detectors from 1903 (Figure 5) and crystal detectors. The most important of the latter was the galena detector, first used in wireless by Braun in 1901. This had point contacts and was known as the *cat's-whisker galena detector*. Simple and efficient, it gained popularity in the following years, particularly after 1906. In 1904, Fleming had introduced the vacuum diode, and two years later De Forest invented the Audion, the vacuum triode. These tubes provided superior performance as radio detectors and by 1912 had replaced the magnetic detector throughout Marconi's companies [9]. With the spread of these much more efficient detectors the coherer fell into disuse. Nevertheless, its role in the development of radio communication had been enormous, even though, at the time, the underlying physics had not been understood. Only since the 1960s has the research on granular media cast new light on the basic principles.

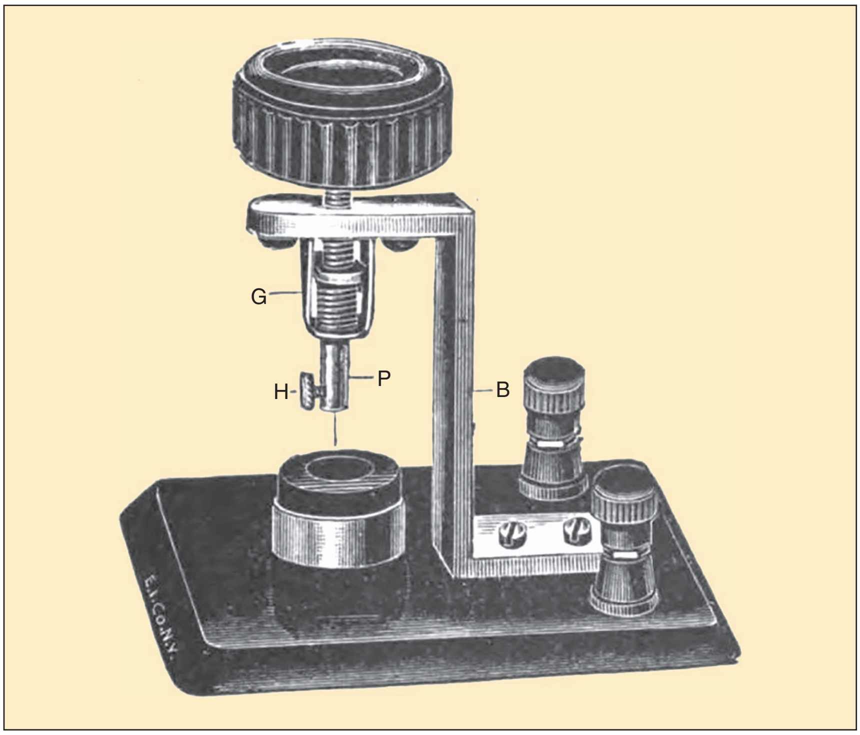

FIGURE 5 – An electrolytic detector. (Photo courtesy of Wikimedia Commons.)

After Marconi's transatlantic success the intense interest in wireless inventions unleashed a hornet's nest of controversy, and several patent trials ensued involving, among others, Marconi, Lodge, Stone Stone, and Tesla. They took years to conclude. The litigation in relation to syntonic tuning that set Marconi against Lodge, who also had invented such a system in 1898, was only concluded in 1912 when Marconi purchased Lodge's patent and offered him an honorary position as scientific adviser. Tesla sued Marconi for the infringement of 12 patents, mainly regarding the syntonic system. Early judgments were in favor of Marconi, but the last one in 1943, after the deaths of both inventors, overturned the previous one.

One famous dispute regarded the mercury coherer that Marconi had patented in the summer of 1901. He actually had it presented to him by Luigi Solari (1873–1957), his schoolmate and right-hand man. It transpired that a number of Italian scientists and technicians had been involved in the invention, notably Swiss–Italian physicist Professor Thomas Tommasina of the University of Geneva, who had worked on it since 1899, signalman Paolo Caselli, and other officers of the Italian Navy [12]. The controversy was settled on the Italian side in 1903 with the declaration that the mercury coherer was the result of the efforts of several persons in the service in the Italian Navy, hence the name *Italian Navy coherer*. Marconi soon gave credit to Tommasina too.

At that time, and up until recently, a development reported by Jagadish Chandra Bose in a lecture at a meeting of the Royal Society in London in March 1899 was completely overlooked [15]. Had it been noticed, the priority of Bose's contribution would have been clear. The only difference between Bose's and the disputed mercury coherer was that Bose's device had a U-shaped tube as opposed to the straight one used by Marconi a couple of years later in his transatlantic experiments. The role of Bose was credited only in 1997 [16].

There is an aspect of this story that deserves further attention. Radio communication, since its early days, was the result of work carried out in different countries by a number of scientists and inventors. As we have seen, the major contributions were from Hertz and Braun in Germany; Branly in France; Lodge, Marconi, and Fleming in the United Kingdom; Popov in Russia; Bose in India; Tesla and Stone Stone in the United States; and Calzecchi Onesti, Righi, and Marconi in Italy. Each country has later claimed the title father of radio for its own national: Branly in France (indeed, Branly denied the title), Tesla in the United States, Popov in Russia, Marconi in Italy and the United Kingdom, and Bose in India. However, it makes little sense to try to identify the true inventor of radio. It is more meaningful to consider the booming evolution of this technology in the last decade of the nineteenth century and the very first years of the twentieth century as the result of a collective effort, albeit played amid harsh competition. Similar considerations apply to the telegraph, telephone, solid-state electronics, and digital computing, to mention but a few [17]. In fact, technologies ripen in due time. Men and women can only outpace others in seizing the opportunities as they arise and in selecting and applying the knowledge needed to develop them. Had Hertz not existed, someone else among the enthusiastic followers of Maxwell's theory would sooner or later have performed an experiment like Hertz's. Lodge was very close to doing so.

MORE FARSIGHTED THAN OTHER LEARNED SCHOLARS OF THE DAY, MARCONI CONCEIVED WHAT SEEMED TO BE UNATTAINABLE GOALS: WIRELESS TELEGRAPHY AND VERY LONG DISTANCE RADIO COMMUNICATION.

Most of the people who contributed to making radio communication a reality, with the exception of Marconi, were born within a few years of each other between 1850 and 1860 (Fleming in 1949; Braun, Righi, and Heaviside in 1850; Calzecchi Onesti in 1853; Tesla in 1856; Hertz in 1857; Bose in 1858; Popov in 1859; and Kennelly in 1861). This may not have been by chance. The most creative phases of their careers coincided with the boom in the knowledge of electromagnetic waves, and their brilliant minds rose to the challenge. Arguably something similar happened more recently with information and communication technology, and possibly on an even more condensed timescale, with Bill Gates, Paul Allen, Steve Jobs, Steve Wozniak, and Tim Berners-Lee all born within a few years around 1955.

Hertz died prematurely, before he reached 37, possibly following cancer of his nose. Had he lived longer he would certainly have been a strong candidate for the Nobel Prize in Physics, which was first awarded in 1901. Both Righi and Branly were long-standing candidates for the prize but never won it. Branly may have defeated Marie Skolodowska Curie in the election to the French Académie des Sciences in 1911, but she became the first woman to win a Nobel Prize (Physics, 1903) and the first ever person to win two of them (Chemistry, 1911). The researchers who were awarded Nobel Prizes for their work on radio waves were Marconi and Braun in 1909. Both men, independently, played major roles in the practical exploitation of radio waves in wireless telegraph.

What made the difference with Marconi, who had never graduated from university? More farsighted than other learned scholars of the day, he conceived what seemed to be unattainable goals: wireless telegraphy and very long distance radio communication. He collected the best skills and technology available to pursue these goals. In 1895 and in 1901 he succeeded. He was visionary. In recent years we have seen shining examples of other visionaries who have grasped the best available knowledge to develop revolutionary technological systems. Perhaps the most outstanding example is Steve Jobs. In many ways Marconi appears as the forerunner of today's leaders of technology, one century in advance. These are the kind of people who, more than any others, change the world.

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