TELEGRAPHY, SUBMARINE

Experiments to send electrical signals along insulated conductors submerged in rivers and lakes began during the 1800s and were successful, but commercial subaqueous telegraph lines were not feasible in the absence of a sufficiently reliable insulating material. However, with the introduction of gutta-percha, a rubberlike substance derived from trees that was a good insulator and could be worked and applied to wires, submarine telegraph lines became possible. Terrestrial telegraphs had proved popular and profitable, with governments and businesses quickly realizing the value of rapid communication. However, by the middle of the 19th century London, the foremost commercial capital of the major manufacturing nation, was not in telegraphic contact with other important centers. To remedy this shortcoming, Jacob and John Brett, British entrepreneurs, determined to lay a telegraph line from Dover in England to Cap Gris Nez in northern France. The first attempt was made in 1850. The line was about twenty-five miles long and consisted of a copper core covered in layers of hemp and gutta-percha and armored with iron wire. The structure of subsequent submarine cables followed this basic form, although the details changed a little from line to line (see Fig. 1 for examples of some cables). The first cable was broken, but not before signals had been exchanged between the two countries. It was not possible to recover the cable but, encouraged by this success, a second attempt was made in 1851. The new cable was more heavily constructed than that of 1850, but its weight caused it to be paid out rather quickly, resulting in insufficient length to reach the French shore. This was only a temporary setback.

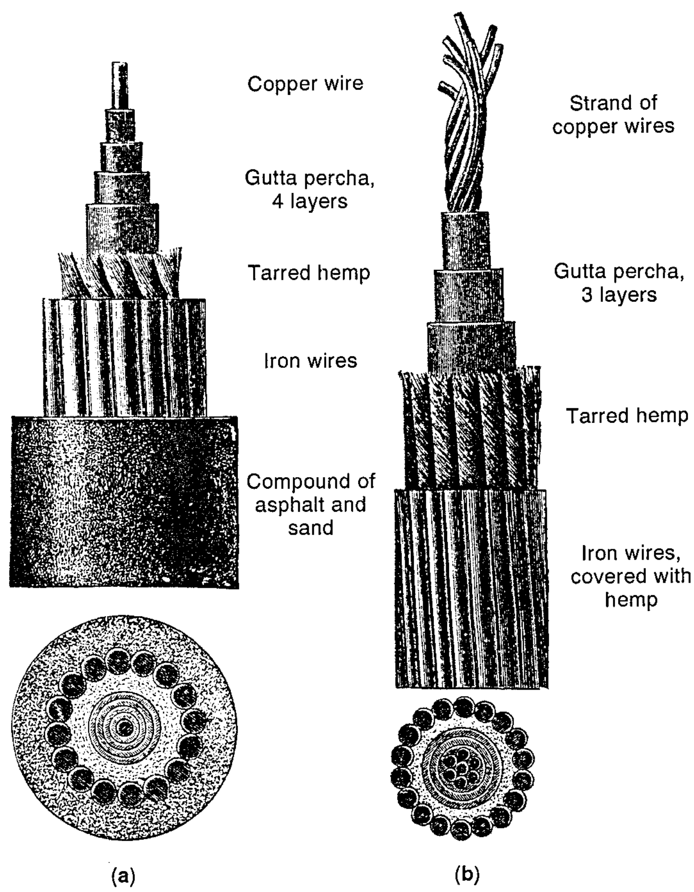

Figure 1. Two cables are shown; (a) is the 1865 Persian Gulf cable, (b) the 1868 Malta to Alexandria cable. Although the form of deep-sea cables were more or less unchanged from those used for the Dover-Calais link of 1851, there were changes in detail from one to the other. To an extent, these variations represented the different likes and dislikes of individual engineers and companies. Later, the standard tended to include multistranded, or multicored copper conductors.

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Table 1. Cables Laid to 1870[a]

Date	Route	Length (miles)
1811	River Isar near Munich	Unknown
1811	In pond, unknown location	Unknown
1838	Unknown, at Chatham	Unknown
1839	Hugli River	Unknown
1842	New York Harbor	Unknown
1844	Lighthouse to boat, Swansea Bay	Unknown
1845	New York to Fort Lee, Hudson River	12
1846	Portsmouth Harbour,	Unknown
1848	Hudson River	Unknown
1848	Kiel Harbour, to fire mines	Unknown
1849	Folkestone Harbour	Unknown
1850	Dover to Cap Gris Nez	27
1851	North Foreland to Cape Sangatte	25
1852	Holyhead to Houth	58
1852	Portpatrick and Donaghadee	22
1852	Portpatrick and Donaghadee	22
1853	Orfordness to The Hague	115
1853	Portpatrick to Donaghadee	22
1854	Bona to Chia (Sardinia)	10
1854	Spezia to Corsica	110
1855	Varna to Balaclava	300
1857	Genoa to Spartivento	Unknown
1857	Valentia to Heart's Content, Newfoundland	1900
1858	Valentia to Heart's Content, Newfoundland	1900
1859	Suez to Aden, in three sections	1600, (270, 477, 645)
1860	Ivica to San Antonio, Spain	90
1860	Aden to Karachee, three sections	1700 (720, 490, 480)
1860	Minorca to Majorca	40
1860	Barcelona to Port Mahon, Minorca	210
1860	Majorca to Ivica	85
1861	Malta to Alexandria, three sections	1300
1861	Toulon to Algiers	450
1864	Oran to Cartegena	130
1865	Fao on River Shatt-al-Arab, three sections	1500 (total)
1865	Valentia to Heart's Content	1900
1866	Valentia to Heart's Content	1900
1868	Malta to Alexandria to replace earlier cable that had failed	900
1869	Brest to Sydney, Nova Scotia via St. Pierre off Newfoundland	3100

[a] This list is not exhaustive; more than 150 cables were laid between 1850 and 1870. Not all of these were particularly significant, and many were second or third attempts at the same route. However, the cables got longer and more reliable as the engineers gained experience and the cable manufacturers improved the design and quality of their product. Almost all cables laid in the period were produced by British manufacturers and laid by British engineers.

Some more cable was attached, and the electric connection was firmly established and opened to public use on November 13th, 1851.

During the first years of the 1850s the length and the geographic spread of the submarine systems were extended so that soon there were many lines running out of England and Scotland to continental Europe and to Ireland, and cables were being laid across the Mediterranean (see Table 1). Engineers were gaining in confidence and experience, and the cables were beginning to prove themselves politically and economically. Spurred by the apparent success of these projects, US entrepreneur, Cyrus Field, decided the time was ripe to make an attempt on the Atlantic. The idea had been broached by several men in the 1840s. Samuel Morse and Jacob Brett were two of these, and there had been an attempt to combine fast sea transport with submarine and terrestrial telegraphs to speed up communications between North America and Europe. In 1852 an Englishman, F. N. Gisborne, in association with Cyrus Field attempted to take a telegraph line across Newfoundland to link with a submarine line across the Gulf of Saint Lawrence on the west and with fast mail steamers at St. John's, Newfoundland. The scheme was not successful; the task of carrying a telegraph line across unknown and difficult terrain was beyond Gisborne's resources. However, Cyrus Field began raising interest and money to lay a cable from Newfoundland to Ireland. Making many voyages across the Atlantic, he courted financiers and governments to raise sufficient capital to construct and lay the cable. He succeeded in raising the money; the British and United States governments guaranteed the enterprise and offered HMS *Agamemnon* and the USS *Niagara* to be adapted to lay the cable. British engineers and cable companies were engaged to design, manufacture, and lay the cables; they had gained considerable experience in putting lines down around Europe and were judged adequately qualified to carry out the project of laying a transatlantic submarine telegraph cable.

In the summer of 1857 everything was ready. Each naval vessel had been loaded with half the cable. Signaling protocols had been agreed upon, and engineers and operators were in place. In August the *Agamemnon* sailed from Valentia in Ireland, sinking the cable behind it. In the mid-Atlantic, when the *Agamemnon* had laid all its cable, the cable on board the *Niagara* would be spliced on and laying would continue to Newfoundland. Electric signals were exchanged between ship and shore, but the cable broke a few hundred miles from land. Subsequently, it was decided that while the electrical properties of the cable were fine, the laying machinery required redesigning to meet the tough conditions of the North Atlantic, where storms were frequent and fierce. Engineers and entrepreneurs expected success, and in the summer of 1858 the second attempt began. This time, a cable was laid connecting Valentia in Ireland with Heart's Content on Trinity Bay in Newfoundland. From there landlines and short submarine stretches completed the link between the continents of North America and Europe. The President of the United States and Queen Victoria exchanged greetings and celebrations were mounted—exuberant in the United States, more muted in the United Kingdom, reflective, some thought, of different national characteristics. The political value of the cable was illustrated by the countermanding of an order to move troops from Canada to England. They were bound for India to quell uprisings against British rule, but the telegraphic messages kept them in Canada, saving money and unnecessary journeys. Signaling speeds were very low indeed, in modern terms no more than 0.2 bits to 0.4 bits per second, but the cable did not last long enough to determine its commercial value. Within a few weeks signals began to fade, until it was evident that there was a break in the insulator 300 miles to the west of Ireland, which rendered the cable useless.

While the Atlantic telegraph cable was being laid, engineers were building a telegraph line from the United Kingdom to India. Important parts of this link were a series of cables already laid on the bed of the Mediterranean and a line laid in the Red Sea making landfalls every few hundred miles or so. Although portions of this cable transmitted messages, the whole never operated successfully. The British government was unhappy: it had assisted the Atlantic cable and had lost a lot of money through underwriting the Red Sea project, and would not consider subsidizing other schemes. Yet it recognized the potential of submarine telegraphs, especially as a tool for governing the British Empire and assisting commerce. It had become clear that the laying and operating of deep-sea cables was a complex process, utilizing phenomena that were not particularly well understood, and placing man-made objects in unexplored environments at great depths where they had to perform reliably with little or no maintenance. The 1857 Atlantic cable had failed mechanically, but that of 1858 had failed electrically. The shortcomings of the Red Sea cable were less clearly defined, although later it emerged that the failures were electrical and arose from poor cable design. To clarify the situation the British government and the Atlantic Telegraph Company set up an enquiry known as the Galton committee, whose brief was to examine all aspects of submarine telegraphy and to identify shortcomings and good practices. On behalf of the committee a number of engineers carried out an exhaustive study of the science, technology, and management of submarine telegraphy, and the committee's report contained, *inter alia,* five conclusions:

1. The need for careful quality control in the construction of cables
2. The need for electrical units and standards to be defined and realized
3. The need for the general adoption of best practices validated by experience
4. The need for careful attention to the management of the laying operations
5. The need for standard signaling and receiving methods

For a time attempts to lay long cables in deep oceans were suspended, but there was no moratorium on submarine telegraphy. Lines, such as those which connected the United Kingdom with continental Europe, were well used and were proving economically sound. In addition, Great Britain, with its international trade and growing Empire, accepted the importance of long-distance, rapid communications. During the first years of the 1860s more and longer cables were laid (see Table 1), and there was continuing interest in a transatlantic telegraph. There had been rivals to the direct path across the ocean all aimed at reducing the oceanic lengths. One option was to take the transatlantic cable from northern Scotland via the Faroe Islands, Iceland, and Greenland to Newfoundland and thence to the United States. Another possibility envisioned an eastward (from the United Kingdom) connection. Land telegraphs were proposed across Europe and Asia to the eastern shore of China. A submarine cable was to carry the signals to the Kamchatka peninsula, which was to be crossed by land lines. A series of submarine cables were to direct the signals from island to island in the Aleutians to Alaska. From there submarine and land lines would carry messages to California to join up with the recently completed trans-continental telegraph line. This was a technologically, politically, and geographically desperate measure. Technologically, the nature of the ocean depths around Alaska were unknown. Politically, so many nations and empires were involved in the eastward line from the North Sea to the Sea of Japan that international rivalries and enmities would render the line practically impossible. Geographically, from the viewpoints of the engineers, eastern Asia, the Kamchatka peninsula, and Alaska were unknown territories. Yet the fact that such suggestions were made and entertained for a while at least indicates the importance attached to an electric connection between North America and Europe.

These extreme ideas were rejected by most engineers who were working to build up their experience and knowledge with increasingly more challenging projects. A continuing effort was made to connect London with India. For the British, India was a symbol of their political and economic power. But messages were slow in transmission, a fact that had been emphasized during the so-called Indian Mutiny. The unsuccessful Red Sea cable had had its rivals—in particular, a line that would go by land across Europe, southward through the Russian Empire, then into the Ottoman Empire, eventually to reach Karachi, thus linking London with the extensive terrestrial system then in place on the subcontinent. The line was completed in 1865, and its last section was a lengthy submarine cable laid on the bed of the Persian Gulf without incident and operated without serious problems.

The failure of the 1858 Atlantic cable had depressed the value of shares in the company, and there was little interest in supporting another attempt immediately. However, the report of the Galton committee and the increasing reliability of the cables laid during the early 1860s acted as encouragements. Cyrus Field resumed his search for finance, crossing and recrossing the Atlantic to maintain the interest of financiers and to obtain their capital. Again, he was successful. By 1865 all was ready to try again. In the first efforts the adapted naval vessels were not entirely up to the task, but fortunately the *Great Eastern*—Brunel's great ship—was available. This large vessel of about 22,000 tons was launched in 1858 but had been unable to find a market. However, it was ideal for conversion into a cable layer. It was large enough to carry the laying and grappling machinery. Its holds were sufficiently capacious to store well more than the 2200 miles of cable required. It had accommodation for the numbers of engineers, telegraphers, clerks, and tradespeople who were needed on the voyage. It had screws and paddles that gave it more than enough driving power, coupled with the maneuverability that experience had shown necessary for successful cable laying. In the summer of 1865 suitably modified and loaded with the cable, it set sail from Valentia in western Ireland bound for Heart's Content. The conclusions of the Galton committee of inquiry had been accepted and put into practice. Cables had been carefully considered, designed, and manufactured. Laying machinery was beyond doubt. Sensitive yet robust, well-tested instruments were on board. Signaling protocols had been agreed upon, and the workers, from engineers to artisans and laborers, were expert in their duties and were well managed. Indeed, although the cable parted about 600 miles from Newfoundland, this was not considered disastrous, merely unfortunate. Finally, in the summer of 1866 the *Great Eastern* laid a cable that connected the Old and New Worlds. The ship returned to where the 1865 cable had snapped and grappled and hauled it to the surface, where it was repaired to provide a second route for telegraphs from Europe to America.

Initially little use was made of long distance submarine cables. Telegrams were expensive (about $100 for a short message in 1866) and the speed of signaling was very slow (perhaps 10 words per minute, or about 1 bit/s). However, particularly on the North Atlantic, it became necessary to increase the carrying capacity of the cables. Three solutions were available. First, signaling speeds could be increased; second, additional cables could be laid; and third, duplexing—or the simultaneous use of a cable in both directions—could be applied. The electrical properties of the cables imposed "natural" limits on signaling rates but William Thomson had demonstrated that these could be enhanced by decreasing the conductor resistance, and by controlling the shape and timing of the pulses; cost and weight considerations militated against increasing the size of conductors and "pulse shaping" demanded complicated sending and receiving instruments. The expensive option of additional cables was one that the companies tried to avoid, although on the busy North Atlantic route extra cables were necessary. There was some nationalistic pressure for non-British lines, for example the Brest–St. Pierre cable of 1869, but this "French" link used cables and instruments made in England, and was laid by British engineers in British ships for a British telegraph company. By the end of the century a combination of automatic senders, recorders, "curbing" capacitors (see below), and duplexing allowed up to 100 words/min to be transmitted through several thousand miles of submarine cable.

In 1902 the final link in the chain around the earth was forged with the completion of a Pacific cable from Vancouver to Australia and New Zealand. The submarine cable system had more or less reached its final form. Lines were added from time to time throughout the first half of the twentieth century. The telegraph system was an important complement to radio telegraphy introduced in the early twentieth century and later to long-distance radio telephony first used across the Atlantic in the 1920s. In 1956, however, transatlantic cables incorporating repeater amplifiers were laid. In a few years the international, global submarine telegraph became obsolete, and its stations and cables were abandoned.

THEORETICAL AND INSTRUMENTAL CONSIDERATIONS

Three elements make up a submarine telegraph line: senders, cables, and receivers. Senders and receivers included operators and instruments. Cables were composites of copper wire, gutta-percha insulation, waterproofing, and armoring. Together they formed an interlinked system. No one part was most important, and changes in one tended to affect the others.

In 1851 when Dover and Calais were connected, mechanical problems had been expected, but electrical were not anticipated, for by that time terrestrial telegraphy was well established. Signaling rates were high as Wheatstone, Hughes, and other engineers developed automatic equipment that could be operated at very high speed. Yet, even with well-tried instruments, messages transmitted from Dover were unintelligible by the time they arrived at Calais, and vice versa. It seemed that intelligibility could be obtained only at the cost of slowing down the transmission rate. Thus arose the problem of "retardation of the signals." Earlier hints of this problem had arisen in Prussia where the habit grew up of burying insulated cables, but repeater relays on land were sufficient to solve the problem. Under the seas this solution was not possible. Before the connection of Ireland and Newfoundland in 1858 the longest submarine line was about 200 miles. Extending this by a factor of 10 was not simply a matter of mechanical scale, for the problem was electrical with its seat in lengthy, insulated cables. For they formed a cylindrical capacitor of several thousand microfarads, which, added to the resistance offered by a very long conductor, of a few thousand ohms, had profound effects on the signals. In particular, the more or less rectangular pulses produced by standard Morse-type keys were rounded by the cables, so that although clear, separated signals were sent into the cables, the outputs were not faithful reproductions of the originals.

Michael Faraday became interested in the phenomenon and recognized that, in effect, the transmission of a pulse along such a construction was not simply a matter of electrical conduction, but involved electric charge and discharge. Faraday concluded that it was necessary to understand the processes involved, but in the mid-1850s there was no electrical theory available that would allow the effects of the insulator to be evaluated. However, William Thomson took a phe-

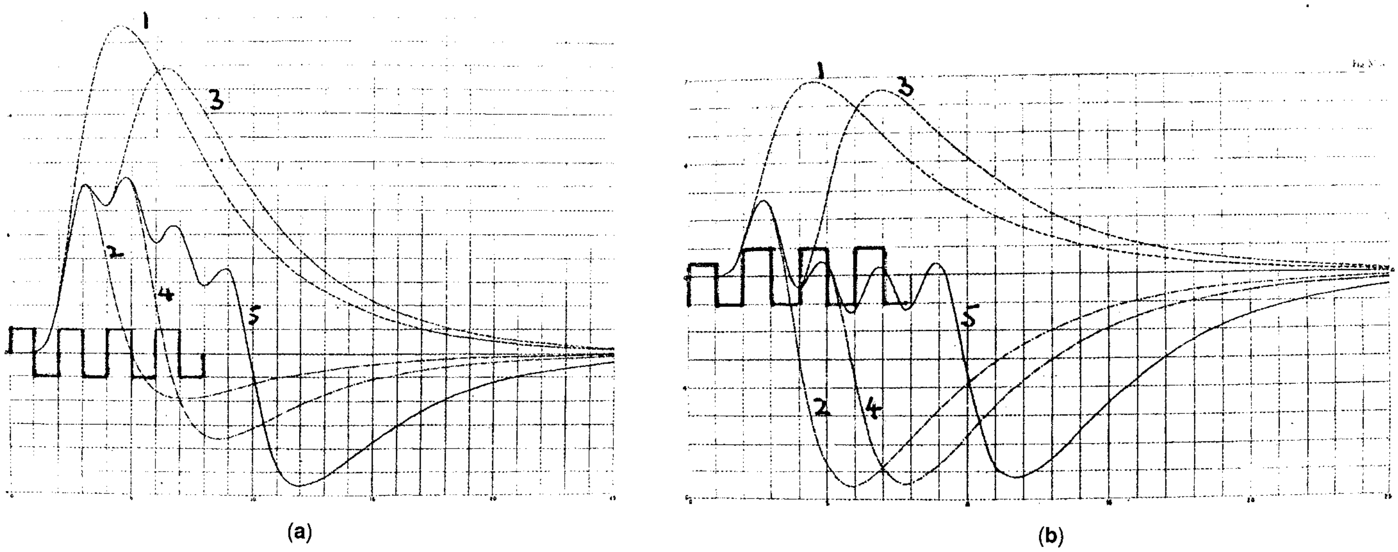


Figure 2. These two graphs were calculated by William Thomson and reproduced in the Galton report. They are essentially the same, except that the first pulse in (b) is half the amplitude of that in (a). Curves 1, 2, 3, 4 and 5 in both graphs represent the appearance of successive pulses at the distant end of a cable. Thomson's colleague, Jenkin, verified the theoretical findings and showed how successive dots and dashes could be rendered intelligible by varying the length of positive and negative pulses according to a strict protocol.

nomenological approach to the problem. He was well acquainted with Fourier analysis, and by drawing an analogy between the flow of electricity through a cable and heat conduction in an insulated metal bar he analyzed the effect of the cables on the pulse shapes. He demonstrated that a sharp, rectangular pulse transmitted into a submarine cable would emerge in an elongated, rounded form, such that successive pulses would merge. If the separation between pulses was too small, no intelligible signals could be received. Some of Thomson's results, first published in 1855, were enlarged in a continuation of his analysis and published in 1861. He demonstrated that signaling speeds could be increased if dots and dashes, instead of being produced by simple positive and negative swings of voltage, were compounded of positive and negative pulses of different but determined lengths. Messages would be more readable and could be sent more swiftly. Some of his results are reproduced in Fig. 2. Others, again working phenomenologically, had reached similar results but from different directions. Cromwell Varley, later a close associate of Thomson, visualized several stages in the charging and discharging of a cable and argued that the output pulses could be made sharper if the input end of the cable were grounded or had a negative pulse applied to it when the cable was about half charged. In effect, this was similar to Thomson's theoretical conclusion.

Thomson's treatment, in which he ignored the effects of magnetic induction, produced three significant conclusions: first, that if carefully controlled sequences of pulses were sent into the cables, more or less readable signals would result, even at considerable distances from the sender; second, that the speed of signaling was inversely proportional to the square of the length of a cable, all other variables being constant; and third, that the conductivity of the copper core had to be as high as possible. The first of these encouraged Thomson and some of his associates to develop automatic sending devices that would produce the required pulses. The second result, at first the subject of dispute, had been verified by 1860 and was a vital factor in assessing the economic viability of long cables. The third led to detailed studies of the electrical properties of copper, which revealed poor quality control in the refining of the metal and which demonstrated, for the first time, the large effects that impurities could have on the electrical properties of solid materials.

The results were particularly important for long cables, such as those in the Red Sea and the Atlantic, and they enabled a controlled approach to intercontinental submarine telegraphy. In 1857–58 terrestrial experience had been translated to the oceanic scene and was found wanting. Two approaches to sending signals across the Atlantic were adopted. A surgeon turned engineer, Wildman Whitehouse electrician to the Atlantic Telegraph Company, visualized the solution in terms of pressure. He decided to apply hundreds, if not thousands of volts to the cable, hoping, thereby, to ensure an economically rapid signal transmission; he thought that with large input voltages, currents sufficient to operate existing instruments would reach Newfoundland. Thomson had calculated that the speed of signaling would be more or less independent of the applied potentials. His approach was to design a very sensitive galvanometer, capable, it is now claimed, of detecting currents of the order of 10^{-9} amps (Fig. 3). The instrument, an astatic moving magnet galvanometer, indicated the passage of current by the movement of a spot of light on a distant screen. An ingenious modification of this mirror galvanometer allowed it to be used at sea. The mirror galvanometer served the submarine telegraph system for about 15 years until replaced by Thomson's siphon recorder in the early 1870s. This complex, sensitive, yet reliable instrument produced a permanent trace on a moving paper

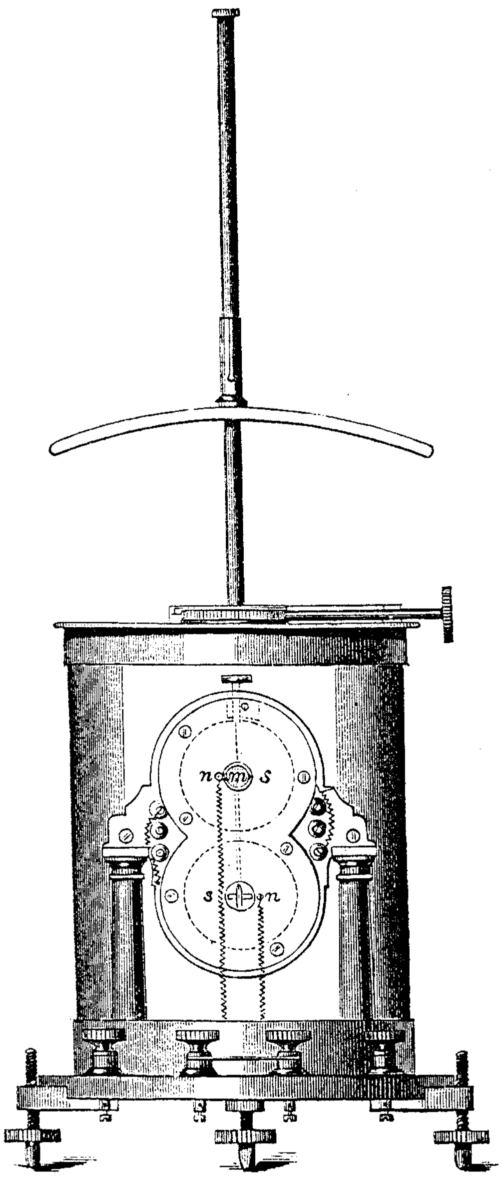


Figure 3. Thomson's mirror galvanometer. The two small magnets were suspended by a silk thread in the center of coils of wire. A concave mirror on the upper magnet allowed a spot of light to be reflected on to a distant scale. It is claimed that these instruments could detect currents as small as 10^{-9} A. A modification of this instrument allowed it to be used at sea. It became the standard method of receiving signals until it was replaced by the siphon recorder.

tape, thereby obviating the need for tedious viewing of a moving spot of light whose track on a screen represented dots, dashes, and words. In essence the siphon recorder was a moving coil galvanometer. A light coil swung in the field produced by a powerful magnet, and its motion was communicated to a very light glass siphon with the aid of thin cords and delicate levers. One end of the siphon rested in ink, the other was near a moving paper tape. A high potential difference was maintained between the siphon and the paper so that a fine jet of ink wrote a trace on the paper. To reduce friction and to improve the sensitivity, the siphon was vibrated at a relatively high frequency.

In the early years of submarine telegraphy, signals, positive for dots and negative for dashes, were generated with standard Morse keys by human operators. The feeble traces were displayed by Thomson's mirror galvanometers by spots of light. Two operators read the messages. One would read the letters, the other would record them. This was a slow, tedious business, and one susceptible to errors. Yet in the first few years of submarine telegraphy it was sufficient. Ultimately, commercial success demanded that signaling be both reliable and speedy. Two factors, however, impeded achieving these goals. First, because caution required restricting applied voltages to a few tens of volts and the resistance of a cable could reach several thousand ohms currents were of the order of a few milliamps. Therefore sensitive detectors were absolutely necessary. Second, the effect of a distributed capacitance effectively grounding a high resistance was to modify the shape of the input pulses (see Fig. 2). Thomson's theory had shown that if dots and dashes, rather than being represented by simple positive or negative pulse, were replaced by strings of pulses of fixed mark/space ratios, then relative rapid, intelligible signals could be transmitted along very long cables. This process of transmitting a series of pulses became known as curbing, and it is interesting to note that although Thomson had arrived at his solution theoretically by analogy and provided a mechanical solution, Cromwell Varley, arguing from a view of the charging and discharging process, arrived a solution that interposed a capacitor between the sending key and the cable. The addition of capacitors at both ends of submarine cable became common, effectively decoupling the cables from the effects of direct currents.

Thomson and his associates began to design automatic senders in the early 1860s and by 1873 they had designed a fully automatic, clockwork-driven, electromechanical device, comprising four components:

1. A drive train, clockwork-driven and mechanically governed
2. A paper tape "reader," carrying holes on either side of a center line of driving/timing holes and deriving from Bain's and Wheatstone's automatic senders of the 1840s and 1850s
3. A signal generator, whose pulses were formed and defined by cams and levers
4. A curb generator whose pulses opposite in sign to those of the signals and of the correct length were generated by electrical contacts controlled by cams

The sender's purpose was to generate positive and negative pulses corresponding to the dots and dashes of the submarine Morse code, to add "curbing" pulses of the correct sign, and to define accurately both the lengths of the composite pulses and their separations. The paper tape moved at a controlled rate under two levers or "prickers," of which one end could engage with the left or right holes. The other ends of the levers engaged in one of two signaling cams which determined the length of the pulse, for the pricker disengaged at a preset point. As this occurred, the curb cams operated to apply a pulse of opposite sign to the line, and of a length that met the theoretical requirements. For signals to be both rapid and intelligible it was vital that the shapes of the output pulses be constant and uniform. In general, a message consisted of

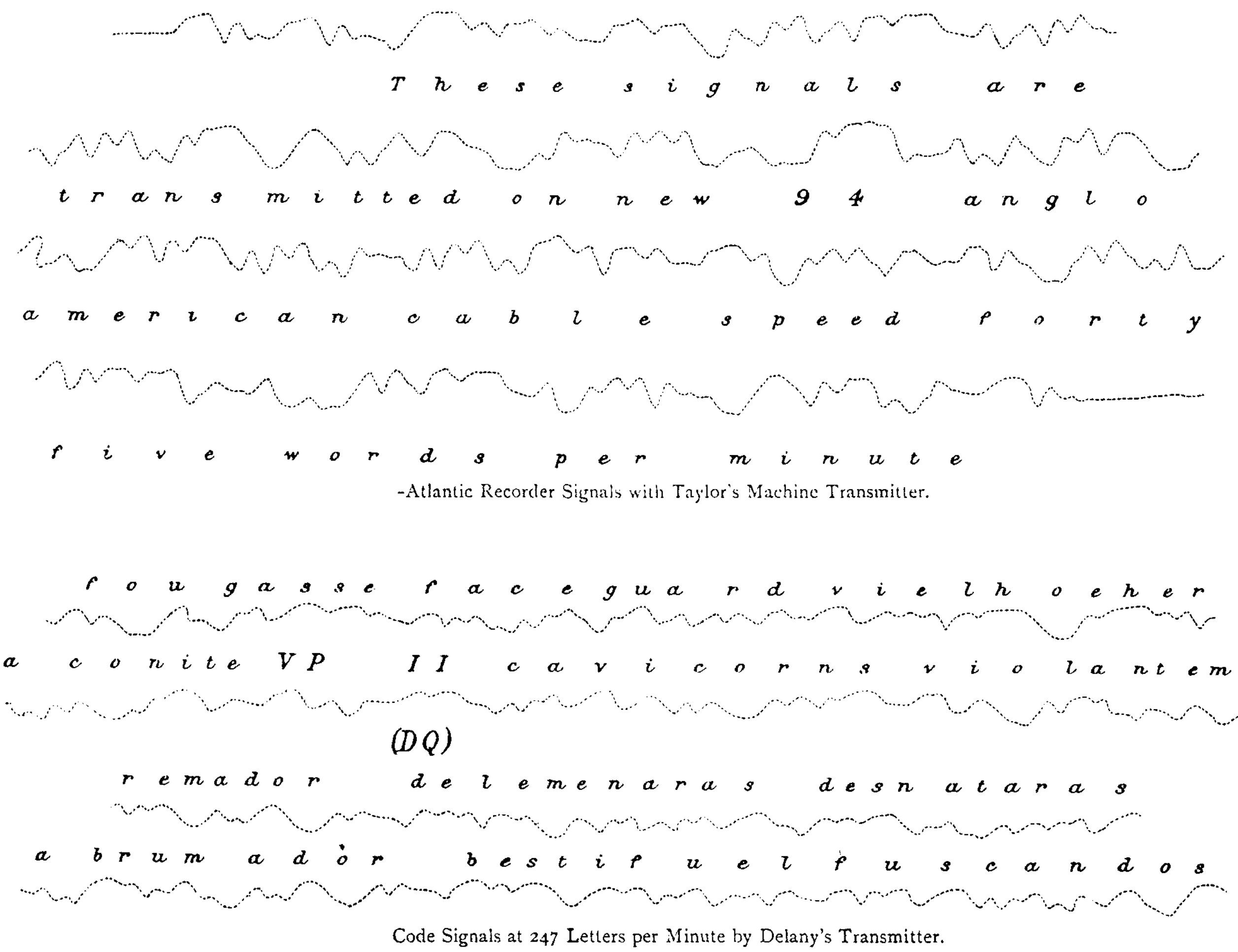


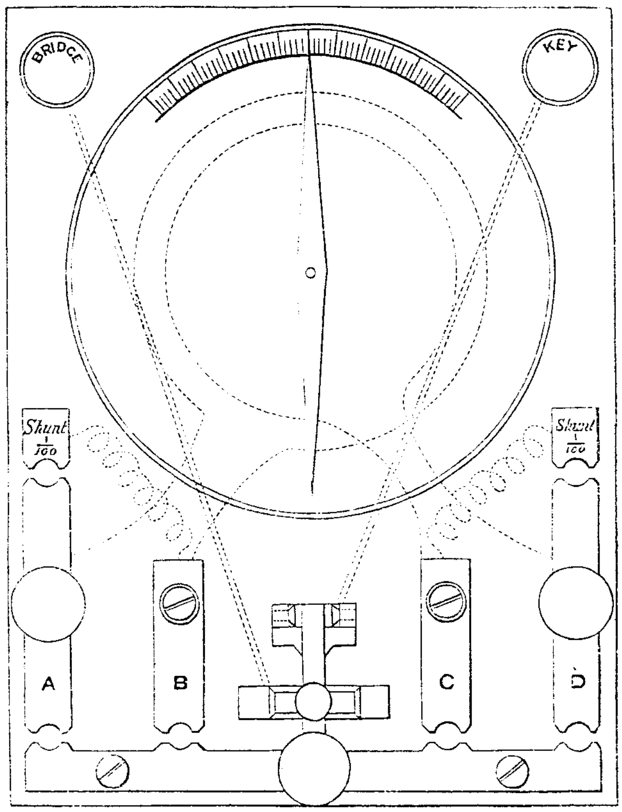
Figure 4. Examples of traces produced by siphon recorders from signals provided by automatic senders. The instruments were similar in principle to the first automatic device developed by Thomson and his associates. Notice that the first set of traces claim a speed of 45 words/minute, while the second set claim a speed of 247 letters/minute, using code signals. It was not unusual for users of the lines, businesses and governments, to employ codes. This not only served security interests, but also allowed more words/minute to be transmitted. 247 letters/minute could equate to a speed of about 50 words/minute uncoded.

a train of words, each word consisted of a train of letters, each letter was composed of a train of dots and dashes, and each dot or dash comprised two pulses. Words, letters, and dots and dashes were separated by predetermined, different, and constant time intervals. The lengths of dots and dashes and the various separations had to be maintained accurately. The sender was capable of providing sufficient precision, but although it formed the model for subsequent automatic devices, at the time of its introduction traffic was not sufficient to warrant its use. However, as submarine telegraphic traffic increased toward the end of the century automatic senders began to be used on more lines. Some typical traces received on siphon recorders are shown in Fig. 4.

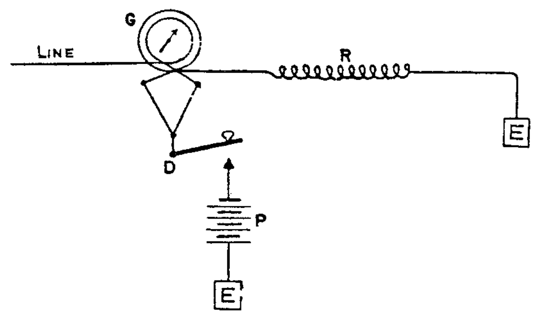
As noted in the previous section, automatic senders coupled with Thomson's siphon recorders greatly increased the rate of information flow through long cables, but as traffic grew other means were employed. Duplexing was perhaps the most important of these. As noted previously, duplexing allows two messages to be transmitted in opposite directions at the same time along a single cable. There were many different systems, but they can be grouped into two basic forms:

1. Those that relied on differential galvanometers
2. Those that employed the principle of the Wheatstone bridge

The differential galvanometer [Figure 5(a)], of which there were many models, was a common and versatile instrument. It consisted of magnets moving in the fields generated by two coils wound in opposite senses. Its use in a duplex circuit is illustrated in Fig. 5(b). R was a resistance equivalent to the cable so that when the key was depressed to dispatch a pulse to a distant receiver, equal currents flowed through the oppositely wound coils. Thus there was no net current and no deflection. However, signals from a distant source went to ground through R, affecting only one coil and giving a deflection. Evidently, this circuit could be used to send and receive at the same time.



(a)



(b)

Figure 5. In (a) an outline of a typical differential galvanometer is illustrated. It was a moving magnet device, and uncalibrated. The example shown was intended for use within a bridge circuit, and had provision for connections to the bridge and to keys, and contained internal shunts that could act as resistance dividers. There were many types of this instrument. A schematic diagram is given in (b) and shows how a differential galvanometer could be used as a component in a duplex circuit. In practice, a good match would have to be present between the resistance R and the line itself. This device was not sensitive enough to be used on long submarine cables.

Duplex systems relying on the principles of resistance bridges operated with a basic circuit shown in Fig. 6(a), in essence a modification of a Wheatstone bridge. The cable was matched by a similar artificial line. Signals proceeding from one end of the cable would affect the galvanometer only at the distant end, but those arriving from the opposite end would produce readable deflections. In practice, the presence of stray currents and unbalanced components led to increasingly complex circuits, a late nineteenth century example of which is shown in Fig. 6(b).

Tests were developed to ensure quality in production and to maintain continuity of signaling. During manufacture and laying it was essential to maintain a close watch on the quality of the copper, the integrity of the insulator, and the effectiveness of any joints in the cable. Joints had to be tested for electrical continuity and for leakage. Bridge or substitution methods were commonly employed to measure continuity and insulation resistance. For example, Fig. 7(a) shows a bridge method of determining core resistance (core, in nineteenth century parlance, referred to the copper conductor in its gutta-percha envelope), and Fig. 7(b) shows the use of a differential galvanometer in a substitution circuit. An ingenious use of a good cable as a large capacitor in a test for a leaky joints is illustrated in Fig. 7(c).

Broken cables and leaky insulation were continuing problems. Grappling techniques were sufficiently well developed by the middle 1860s to allow the *Great Eastern* to recover the broken cable of 1865, but the positions of faults, in general, were unknown. Almost without exception, faults were either internal short circuits within multicored cables or to ground. Because the electrical characteristics were known, the position of a fault was readily found by using modifications of the Wheatstone bridge.

Tests such as these remained standard throughout most of the period of submarine telegraphy, although commercial forms of bridges and potentiometers bore little outward resemblance to experimental setups, and specialist equipment was designed for and installed in the cable stations. Until the advent of modern electronic devices, bridges and their modifications were reliable, sensitive, and very accurate. They needed very little maintenance, and they were robust. They possessed versatility and had wide ranges. As a result, they

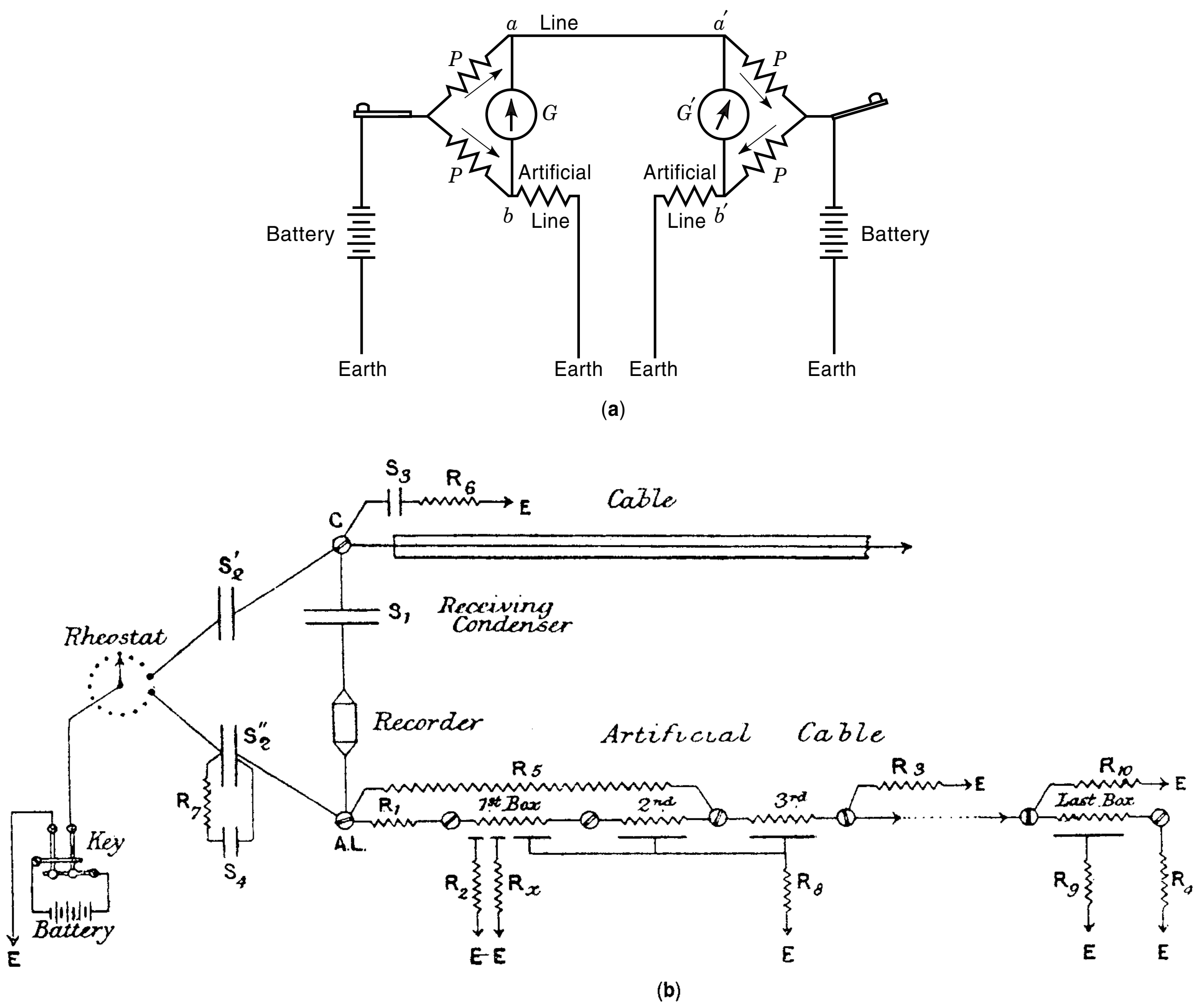


Figure 6. Duplex circuits. When left key is depressed since P + resistance of line = P + resistance of artificial line, then no current flows through G. However at the other end of the line there is a potential difference between a′ and b′ since the current flows to earth through P and P. (a) The basic form of a bridge circuit. (b) A late 19th century version. This circuit refers to a duplex instrument manufactured by the Muirhead Company of the United Kingdom. Although it is evidently similar to the circuit shown in (a), it was a great deal more complicated. It needed some skill to set up and to keep in balance, so that the two signals were kept separated.

could be used to determine all of the parameters associated with electric circuits, resistance, capacitance, potential, current, inductance, and so on. For example, in the case of resistance they could be adapted to determine resistances of fractions to many millions of ohms. In later years of the nineteenth century, two British physicists, Ayrton and Perry, developed robust, moving-coil galvanometers, ammeters, and voltmeters, which gradually replaced other sorts of detecting and measuring devices, except for very accurate or delicate purposes.

COLLATERAL CONSEQUENCES

Those who developed the technology of submarine telegraphy and its instruments and tests were also concerned with the science of electricity. The practical problems of controlling the network and maintaining the cables and the instruments drove the engineers to develop electrical standards that would be reproducible and usable anywhere in the world. The difficulties associated with the definition and realization of standards gave rise to studies of the conduction of electricity through solids, and the knotty problem of units and dimensions had to be solved.

The need for universally agreed standards had been recognized by the Galton committee in 1859–60, and in response the British Association for the Advancement of Science set up a standards committee initially charged with defining a resistance unit and a means of realizing a standard. In a short report to the Committee published in 1873, Fleeming Jenkin, Professor of Engineering in the University of Edinburgh, considered that the installation of telegraph lines from

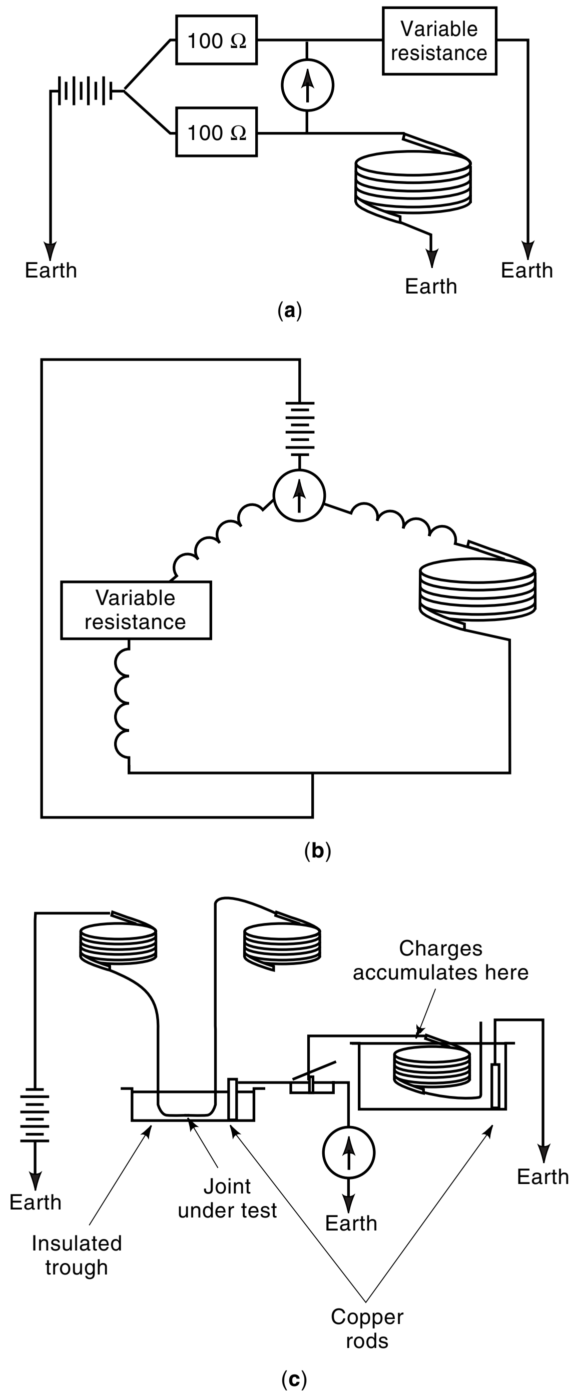


Figure 7. Three tests commonly in use in the late 19th century. In (a) and (b) methods of measuring the core resistance are shown. This was an important piece of knowledge, for the parameter resistance/unit length was significant if breaks were to be found, and indications could be obtained of the quality of the joints between different sections of the cables. Leaky joints could affect the performance of the cables to a marked extent. In the worst case, direct shorts to earth could occur, rendering the cable useless; but even leaks would diminish the strength of the signals received. The method is particularly interesting for it shows an "engineering" solution to an important problem. (a) Bridge method of measuring core resistance. (b) Differential method of measuring core resistance. (c) Accumulation method of detecting leaky joints.

1850 stimulated the definition and production of standard resistance coils. He pointed out that the idea of resistance was implicit in Ohm's law, and that the earliest referential standards were reductions to unit lengths of particular wires. Indeed by the latter half of the 1840s a multiplicity of standards existed, leading the German physicist Jacobi to suggest that only one should be used. However, simply to possess a particular resistance was not enough; the standard had to be accurately reproducible, reliable, and constant.

Precise knowledge of the resistance of conductors and insulators was important both for controlling the processes of manufacture and laying the cables, and for the detection and location of faults. Telegraph engineers and companies developed their own metrics, as did the various nations, so that by the time the British Association committee first met in 1862 many different standards were in existence: Jenkin referred to some ten varieties in his report. His writings make it evident that the problem fell into two classes: first, what absolute system should be used; and second, what should serve as practical units. This problem, the divide between absolute and practical units, ceased to exist with the adoption of the MKSI System, but in the mid-nineteenth century the difficulties presented were both empirical and theoretical.

The definition and realization of the practical units was more or less straightforward, for fundamental theoretical considerations were not involved. It was clear that a standard could be easily defined, for example, in terms of a fixed resistance of precisely determined composition and dimensions. However, there were considerable difficulties in the choice of materials. Stimulated by Thomson's study of pulse transmission through insulated cables, a series of careful, exhaustive researches were instituted on the electrical conductivity of various substances. Surprising but irritating results were reported. It was found that the electrical properties of metals were very sensitive to their composition and to the mechanical working to which they had been subjected. Small concentrations of impurities resulted in very large variations in conductivity, and there was no clear relation between the composition of a conductor and its conductivity. The resistance of some metals was found to be markedly temperature dependent, and some materials that appeared to be conductors behaved in deviant ways. Evidently the search for a suitable standard resistance material was not going to be straightforward, particularly as easily available metals, such as copper, proved unsuitable.

There were advocates of two standards. One, favored by Siemens, used very pure, liquid mercury in a column 1 m in length, and 1 mm^2 in cross section. The other, favored by Jenkin, made use of alloys of the noble metals, for they were found to give some degree of certainty. In the end, it was agreed that the primary resistance standard, the *Ohm,* should be based on mercury, and that it should also be realized in three other materials: alloys of gold-silver, platinum-silver and platinum-iridium, which became secondary standards.

While the resistance was the prime interest of the committee they did consider other electrical entities, and in due course defined voltage, current, power, and capacitance standards that were adopted internationally in 1881. Along with the physical definitions of the standards went the measurement methods and protocols that would allow accurate measurements to be made wherever there was suitable equipment.

The practical units of electricity that the Committee defined were a matter of choice. They had to be reliable and reproducible and they had to be of a reasonable magnitude; but, while they had significance in the operation of the telegraph system, to be consistent it was necessary that they were conformable with the centimeter, gram, second system that formed the absolute system of units then in use. These units had their ontological base in the existence of the three fundamental dimensions of length, mass, and time, and were defined in terms of what were considered to be well-known and reproducible "natural" metrics—for example, the density of water, the length of the line of longitude through Paris, and so on. Thus there were three fundamental units, leaving all the others to have the status of "derived units." Studies of electricity and magnetism during the eighteenth and early nineteenth centuries had shown, *inter alia,* that an inverse square law of force existed between charges and that a similar rule linked the forces between (presumed) magnetic poles. Hence units such as charge, magnetic pole strength, field strength, electric and magnetic potential and so on could be derived, and dimensions of the physical quantities could be expressed in terms of mass, length, and time (MLT). Before the unification of electricity and magnetism implicit in the work of Oersted and Faraday there were two sets of electrical units: those based on electrostatics and those based on magnetism, known respectively as the "electrostatic system" (esu) and the "electromagnetic system" (emu). The various units differed greatly in magnitude, but more seriously there were dimensional differences. The esu unit of conductivity, for example, had the dimensions of a velocity, while the emu unit had the dimensions of the inverse of velocity. These difficulties were recognized by the Standards Committee, but their final resolution was deferred for nearly 100 years.

The relationship between submarine telegraphy and electrical science ranged beyond the pragmatic and the practical, but historians have not yet clarified completely how telegraphy affected electrical theories, or was affected by them in its turn. However, some historians have argued that Maxwell's interest in submarine telegraphy and the significance of the insulator focused his attention on the relationships between electricity and the properties of space. The insulator was not simply a passive guard against leakage, but was an integral part of the electric circuit, at least under changing current conditions. It has been suggested that the strong, almost unique British interest in the cables gave a characteristic flavor to field theories, and it is indeed the case that Maxwell worked on electromagnetism while engaged with the work of the standards committee. However, although telegraphy had a considerable effect on the development of the science of electricity, if only at the instrumental and practical level, whether there was any feedback from electrical theories to engineering practice is less clear. Up to 1902 at least, the development of submarine telegraphy in all its complexity seems to have been based on operationally defined, phenomenological theories. These were needed only as "calculating devices" and required no connection with an underlying physical reality, except in enabling working cables and systems to be constructed. Neither Thomson nor Varley with their different approaches to the problems of "retardation of the signals" paid much attention to contemporary thinking in electricity. As if to underline this point, Heaviside's work on distortionless cables, although dealing with the effects of both electrostatic and electromagnetic induction, made no use of Maxwell's ideas, although it is certain that Heaviside was well acquainted with them. Thus although it can be argued that telegraphy acted as a catalyst in the development of electromagnetism, it seems that electromagnetism had little to do with telegraphy. Rather, the technology was developed in its own right, by engineers concerned more with practice than theory, and driven by economic as well as technical considerations.

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