THE GENESIS OF ELECTRICAL ENGINEERING

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by

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THE medieval university conceived of its role as being to prepare men for lives of service in the great professions, the Church, the Law and Medicine. Modern institutions of higher learning take a broader view of their purpose than to identify it simply with professional training, but even so the traditional task is not overlooked. Preparation for the professions is still an important part of our concern, and to the original triad new professions have been added, amongst which is engineering.

The entry of engineering to the university world was recent and not unopposed. Indeed, in continental Europe it is even now not wholly conceded, but so far as the Celtic and Anglo-Saxon communities are concerned, this privilege has been won. Hephaestos may approach Athene's temple despite his limp. It must not be thought, however, that because engineering is a newcomer to the university it is necessarily a young profession. Indeed the first professional man of whom there is a written record was one of the architect-engineers who designed a pyramid for a Pharaoh.

Even so, engineering is not itself homogeneous and that part of it which is my personal concern, electrical engineering, is of course a newcomer. It is generally accepted that to the ancients only static electrical effects were known and that even these were put to no useful end, but were regarded as mere philosophical curiosities. With the sole exception of the use of the compass in navigation, electromagnetic phenomena were unexploited for practical ends until the 19th century. Now evidently, a mere concern with scientific phenomena is by no means to be identified with engineering. If the word "engineering" means anything at all it specifies the activity of one of the major human professions concerned with the satisfaction of human needs, and cannot be synonymous with the accumulation of knowledge for no more than its own sake. Although electrical science, specifically electrostatics, can be traced back to antiquity, electrical engineering is, by this criterion, new. For the beginnings of my profession, as distinct from the beginnings of the scientific knowledge which it uses, one must come to a relatively late date, in fact to the nineteenth century. It was in 1816 that the first serious attempt was made to use the potential advantages of electricity in the solution of an important problem of human affairs. Thus, the year 1966 might well have been regarded as the one hundred and fiftieth anniversary of the beginning of electrical engineering.

Communication at a distance had always been a major concern of civilized human societies. In ancient times it was solved in many different ways; for example, by the use of human runners, by relays of horse messengers, or, less directly, by the heliograph or other methods of visual signalling. The climax of all these developments was the Chappe semaphore system (Figure 1), which gained currency at the end of the eighteenth century and survived well into the nineteenth. This system relied upon visual communication and used a series of towers, spaced about the countryside, on which large, articulated, arm-like structures were mounted. The configuration of the arms could be varied by a system of simple mechanical linkages operated from within the tower. A remote observer, using a telescope, could translate a particular configuration into an equivalent letter of the alphabet and in this way messages could be transmitted for as far as the eye could reach. A chain of towers could convey messages over hundreds of miles in an hour or so by a simple system of relay operation.

Such methods were highly successful because they permitted a speed of cross-country communication far beyond anything which could be achieved by the horse rider, but they suffered from the disadvantage that a relay station was needed every few tens of miles, the distance depending upon the lie of the land and prevailing climatic conditions. In hilly country the cost of the system could

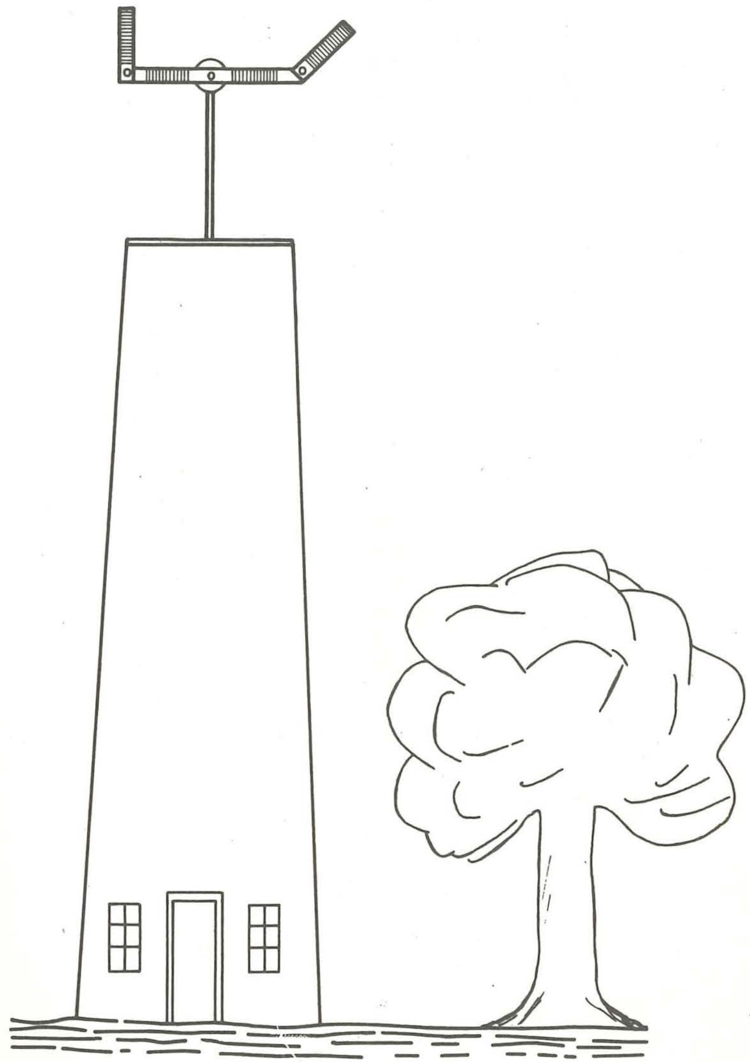

Fig. 1. The Chappe semaphore system

be relatively high and it would be entirely disabled by fog or heavy rain. The British Admiralty had, before the beginning of the nineteenth century, a system of visual telegraphy, invented by Murray, for communication with the Royal Dockyards at Chatham. The Kent coast, however, is misty country and it was said that, particularly in autumn, their Lordships were not infrequently entirely out of communication with their dockyards. Commanders of ships probably thought this no bad thing. Even so, it is a weak point of a communication system that it should be so dependent upon weather, and to this problem a solution was offered in 1816 by the son of a City merchant.

Francis Ronalds was born in London in 1788. His father was able to afford a good education for his son, by the standards of the day, but insisted that the boy should join him in the family business. Although this was a flourishing concern, it was not able permanently to retain Ronald's enthusiasm, and he devoted an increasing share of his time to experiments in science. His interest in electricity was stimulated by an association with de Luc, a well-known Swiss natural philosopher. De Luc was in royal employment in London at that time, and his main claim to fame is the invention of the so-called dry voltaic pile, which was able to produce a small but usable electrical output for a matter of years, in sharp contrast to the earlier wet piles (due to Volta), which generally produced an output for only a week or two, after which they had to be reconstructed. There is a record that Ronalds himself built a pile containing one thousand pairs of elements. To his pile he connected a ratchet and pawl mechanism by means of which a pointer could be driven around a clock face, so that perhaps it is to him that we must attribute the invention of the electric clock.

Why Ronalds should have been drawn to attempt to apply electricity to a telegraph is not now known. However, we do know with certainty that he was by no means the first to be led in this direction. The famous *History of the Electric Telegraph to 1837*, published by J. J. Fahie in 1884, records a long list of early experiments in this field.

Most of the early inventers described only an outline of the methods they proposed to use, and few indeed constructed any experimental apparatus. The earliest suggestion of all, however, can be claimed for the United Kingdom, since it appeared over the initials C.M. in the *Scot's Magazine* for the year 1753, eight years after the second Jacobite rising. This system of electric telegraphy relied upon the use of a separate wire for each letter of the alphabet and the letter signalled was indicated by electrostatic attraction. The sending operator would apply the output of an electrostatic machine to one of the wires and at the receiving end a small fragment of paper marked with the appropriate letter was to be attracted towards the electrified wire. Thus, provided that one wire was available for each letter, a true 'speaking telegraph' would result capable of sending any required message.

It cannot be said with certainty who 'C.M.' was, although various names have been fitted to these initials. Certainly, his invention was ingenious and it might have been made to work. The letter which describes it, however, is cast entirely in hypothetical terms. There is no suggestion at all that the apparatus had been or would be constructed.

Many other electric telegraphs, often closely similar, were proposed in the course of the next sixty years. After the invention of the voltaic pile in 1800, an alternative source of electricity was available, and with the discovery in the same year of electrolysis by Nicholson and Carlisle the methods of detection could now include the electrolytic production of gases in water. So it was that Sommerring in 1809, unaware like the rest of the European scientific community that an electrolytic telegraph had five years previously been fully described by Francisco Salva Campilo, proposed a system which subsequently became famous. Like Salva's, it was similar in general principle to that due to C.M., but with the electricity derived from a voltaic pile and the receiving instrument consisting of a vessel containing water into which the wires from the transmitting station were introduced. When a wire was introduced to the voltatic pile gas bubbles could be seen to be evolved from the same wire at the receiving end. In its final form Sommerring's telegraph was quite sophisticated, containing a system for attracting the attention of the operator by means of an alarm as well as other refinements. However, it was complicated and relatively slow in operation, and, although it attracted a great deal of attention at the time and afterwards for a number of years, it did not lead to any useful exploitation. The cost of laying 26 wires between each station, when considered in conjunction with the relatively poor signalling rate and, therefore the low rate of revenue which the system would have been capable of earning, made it a poor competitor on economic grounds with the semaphore telegraphs already widely used.

The early electrostatic and electrolytic telegraphs, although interesting, were impracticable for a variety of reasons. The electrostatic systems invariably suffered from problems of insulation on the connecting wires between transmitter and receiver, and these were made the more acute and economically intractable because of the large number of wires which most experimenters used. Much the same could be said of the electrolytic systems, where the situation was only slightly eased by the use of somewhat lower voltages, and they had the added disadvantage of very slow operation. The genius of Francis Ronalds overcame these difficulties so convincingly that there is little doubt that, had the circumstances of the time been more favourable to technical innovation, his system of telegraphy could have been applied at once on the widest scale.

The problem of multiplicity of wires Ronalds solved completely by inventing a synchronous system of telegraphy. Although not entirely without precendent, this was, without doubt, a major contribution. At each end of the proposed telegraph link (Figure 2) a rotating clockwork dial was arranged on which the various letters of the alpha-

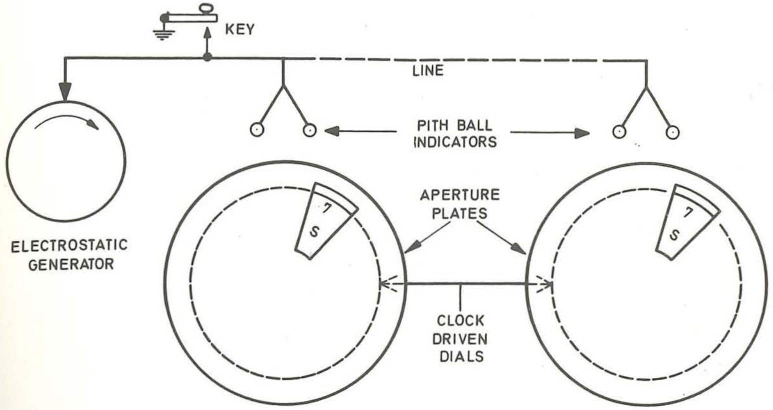

Fig. 2. The synchronous system of telegraphy developed by Francis Ronalds

bet were inscribed. The dial rotated behind a small window so that the letters were presented in turn at the rate of one per second. Provided that the two clockwork mechanisms ran at the same rate, the same letter would appear at each end at the same time. Between the two stations Ronalds arranged a single wire, to which was attached the indicating instrument, a pair of pith balls. Normally these balls of light material hung in contact with each other but they would be driven apart by electrostatic repulsion when the line was electrified. In the system proposed the line was kept permanently electrified by an electrostatic machine, but means were provided by which it could be short-circuited to earth. The process of signalling then simply involved earthing the line momentarily when the required letter appeared behind the window of the clockwork mechanism.

The fundamental idea of the system of telegraphy is a very simple one, although the signalling rate would be rather low. Due to the limited speed of the clock mechnism typically just under one word could be sent per minute, but the use of only a single wire between transmitter and receiver was obviously a great advance. Further-more, Ronalds was not satisfied merely to indicate how a system of this kind could be made to operate, but went on to work out in the most minute detail every aspect of the design, construction and utilization of the system of telegraphy in practical and realistic working conditions. A monograph published by Ronalds in 1823 gives an excellent description of the proposed system and even now, accepting the technology available to him at that time, one cannot fault the design in any detail. Indeed, as so often when one considers the work of early engineers, one can but marvel at the perfection with which he adapted to his purpose the means available to him.

A point of note is that Ronalds was conservative: he used components within his telegraphic system which were already available, had some history of development behind them and were therefore of proven utility. The two main components were the electrostatic generating machine, which had undergone continuous and fruitful development since the invention of the sulphur ball machine by Otto Guericke in 1671, and a clock-like mechanism to carry the alphabetic dial, the design of which was able to draw upon the immense advances in horology which had occurred during the late seventeenth and eighteenth centuries. By bringing these two already existing devices together in his system, Ronalds left himself with only one major technical problem to solve, namely, the construction of a suitable insulated line or cable between the transmitting and receiving stations. This he achieved by insulating his copper wire with glass tubing. The tubing was available in lengths of a few feet and the jointing was done by passing a sleeve, consisting of a glass tube of slightly larger internal dimensions, over the joint and sealing it with wax. In this way a well-insulated line could be produced at a relatively modest cost. The glass-sleeved line was mounted inside a trough of wood which was then filled with pitch. Thus insulated, the conductor was designed for underground burial, and by way of trial Ronalds erected in his garden a line of little

under 600 feet, over which he was able to demonstrate satisfactory telegraphic signalling, despite all the vagaries of the English weather and the high soil humidity one would expect to encounter in a Thames-side garden.

As well as working out in the most meticulous detail the design of the apparatus, this remarkable man also considered the operating procedures and arrangements that would be necessary, and was able to provide completely satisfactory solutions to such problems as calling operators to attend to their instrument, synchronizing the clocks to ensure correct decoding of the signals, and detecting faults on the line. Thus, unlike his predecessors, Ronalds produced a practical and workable telegraph instrument, a usable means of interconnection, and a completely thought out system of operation. The demonstration of the telegraph in his own garden was seen by many distinguished people and operated for some years. With more patriotism than wisdom, Ronalds offered his invention to the Admiralty, feeling perhaps that it would wish to be able to communicate with its dockyards in all weathers and might see in his invention the means by which to do so.

Alas, for such sanguine hopes. Ronalds' letter to Lord Melville, the First Lord, was dated July 11th, 1816. On August 5th, after sending a further communication, he received a reply from Mr. Barrow, the secretary of the Admiralty, in the following terms: 'Mr. Barrow presents his compliments to Mr. Ronalds and acquaints him with reference to his note of the 3rd inst. that telegraphs of any kind are wholly unnecessary and that no other than the one in use will be adopted.' Ronalds said of this correspondence: 'I feel very little disappointment and not a shadow of resentment on the occasion because everyone knows telegraphs have long been great bores at the Admiralty.'

The reason why Ronalds' telegraph was not taken up at the time is a matter of great historical interest. It is clear that, unlike all the earlier proposals, Ronalds' telegraph was an entirely worked-out and practical system. We can, therefore, justifiably claim that he, of all men, deserves the right to the title of the first electrical engineer. It is interesting that our profession begins with a project brilliantly carried through but frustrated in its purpose for want of government support. I shall refrain from commenting or drawing a moral from this circumstance.

The next development in electric telegraphy was the direct outcome of the discovery made by Oersted in 1820. This was the celebrated experiment in which a magnetic needle was deflected by an electric current flowing in a wire near by. In the very same year two subsidiary inventions were made which gave the electric telegraph a more immediate prospect of success. Schweigger discovered that by bending the wire into a loop or a succession of loops around the magnetic needle, the effect of the current would be multiplied roughly in proportion to the number of turns. Thus was invented Schweigger's multiplier or, as we could call it today, the galvanometer. In the same year Ampère, whose contributions to electrodynamic theory are of the highest order, invented the astatic needle. This was an ingenious means of reducing the restraining effect of the earth's magnetic field on the magnetic needle in the galvanometer. Ampère proposed the use of two magnetic needles parallel to each other but oppositely aligned, joined by a length of stiff rod or wire. This astatic pair would ideally receive no mechanical torque from the earth's magnetic field whatever its orientation, provided that the two needles were of exactly equal strength. Further, if one of the needles was contained within the coil of Schweigger's multilplier a most sensitive galvanometer would result. Ampère himself proposed a telegraph in the year 1820, based upon the electrodynamic effect. It used 26 wires rather in the same manner as proposed by Sommerring, but simply replacing the electrolytic detectors by wires and compass needles. It is strange that he did not think of applying either the multiplier or his own astatic needle to this purpose. It is also very unfortunate since it may have led to some delay in the development of the electromagnetic telegraph, at least in Britain.

It is a notable fact of scientific history that men whose names are now hardly remembered often had, in their own day, the very highest reputation. One such was Peter Barlow, who conducted many experiments in physics in the early part of the nineteenth century and whose influence on the English scientific community was considerable. In 1824 he utilized the recently discovered Oersted effect in a rather ill-conceived experiment which aimed at deciding whether electricity consisted, as some thought, of a single fluid flowing through the electrical circuit or, as others argued, of two distinct fluids flowing in the circuit in opposite directions. Certain it is that the experiment which Barlow proposed would have been far too insensitive to distinguish between the consequences of the two hypotheses. Part of the experiment, however, consisted of passing the electric current through a circuit of considerable length, in one set of experiments varying between 98 and 838 feet. A great opportunity to discover the law relating intensity of current to the resistance in the circuit in which it was flowing presented itself, but was unfortunately missed because of the difficulty that Barlow had in interpreting his results. In fact, of course, this law was discovered later by G. S. Ohm and published in his monograph of 1827.

Barlow contented himself with observing that the increase in length of the circuit greatly reduced the deflection of the magnetic needle, and therefore, concluded that an electric telegraph as proposed by Ampère was impossible. Fahie quotes him as saying, 'In a very early stage of electromagnetic experiments it has been suggested that an instantaneous telegraph might be constructed by means of conducting wires and compasses; the details of this contrivance are so obvious and the principles on which it is founded so well understood that there was only one question which could render the result doubtful and this was: is there any diminution of effect by lengthening the conducting wire? It had been said that the electric fluid from a common electrical battery had been transmitted through a wire four miles in length without any sensible diminution of effect and to every appearance instantaneously and if this should be found to be the case with a galvanic circuit then no question could be entertained of the practicability and utility of the suggestion above adverted to.

I was therefore induced to make the trial, but I found such a sensible diminution with only 200 feet of wire as at once to convince me of the impracticability of the scheme.'

A similar result was obtained by Dr. Jacob Green at Jefferson College, Philadelphia, in 1827, and there can be no doubt that the reputations of these two men were sufficient to make their words carry great weight with their contemporaries. For a while the future of the electric telegraph using Oersted's effect seemed doubtful. Yet, in fact, the experimental technique which Barlow had chosen was inadequate even by the standards of his day. Had he adopted Schweigger's multiplier with astatic needles as his detector of electric current, his experimental arrangement would have yielded easily detectable signals over distances two or three orders of magnitude greater than those which he employed. Even so, in Britain it was largely left to men who were not prepared to heed accepted scientific opinion, or to those who were ignorant of it, to pursue further the development of the electromagnetic telegraph.

Considerations of time prevent description of the important contributions to the telegraph made in Germany by Gauss and Weber with their telegraph of 1833, which was subsequently much improved by Steinheil over the years up to 1836. Another pioneer of the electromagnetic telegraph whose work I must necessarily omit to review is Schilling von Canstatt, who built an entirely practical

telegraph using the Schweigger galvanometer in the year 1825. Schilling von Canstatt, a man of greatly original mind who was employed in the diplomatic service of the Czar, developed an instrument which could well have been widely adopted. His early death came at a time when the Czar had already given orders for quite a large-scale experiment, in the form of a telegraph to connect Kronstadt with the capital, St. Petersburg by means of a cable laid along the bottom of the Gulf of Finland. Without the inventor the scheme was not further pursued. Important though these continental developments were, the invention upon which the commercial development of the telegraph was based was the electromagnetic telegraph proposed by Cooke and Wheatstone and described in their joint patent of 1837.

William Fothergill Cooke was a man of negligible scientific education who had served for a time in the army in India, and had later utilized a modest skill in the art of sculpture to secure an income by the preparation of anatomical models. He became interested in the electromagnetic telegraph after seeing a demonstration in Germany of a telegraph derived from the work of Schilling. His first thoughts were of a chronometric telegraph, bearing in some respects a marked resemblance to Francis Ronald's system. The basis of the idea was the use of mechanism somewhat like that of a musical box, with an electromagnetically operated detent so that the mechanism could not normally run but would do so when an electrical signal was received. Thus, two such instruments, provided they ran at exactly the same speed and were connected together over a landline, would begin to rotate simultaneously when an electrical signal was sent. A simple alphabet inscribed on the rotating drum of the instrument would permit telegraphic signalling.

An immediately obvious weakness of the system is the need precisely to synchronize the sending and receiving instruments. The difficulty is much greater than in Ronald's telegraph, because the instruments do not run continuously. Ronald's telegraph could be synchronized like a clock by careful adjustment of an oscillating escarpment, and since running was continuous very small deviations from synchronism could be observed over substantial periods. The discontinuous operation characteristic of Cooke's system would make synchronism much more difficult to achieve, and the repeated starting and stopping would tend to disorder the mechanism and cause differences in running speeds. These problems of synchronization, however, although they might well have made the system finally unworkable, did not present themselves to Cooke as the major problem facing his proposed telegraph. Instead, he was much concerned, although unaware of Barlow's results, about the diminution in strength of the electrical signal as the length of circuit between the transmitter and receiver was extended. Innocent of Ohm's Law, he attempted to conduct an experimental investigation with somewhat discouraging results. The relatively large mechanical force required to operate the mechanism of his telegraph and the poor efficiency of design of the electromagnet must be blamed for this. In his difficulties Cooke wisely sought the counsel of others more learned in electrical science than he, and first addressed his enquiries to Michael Faraday, who was, however, not particularly helpful. Probably at Faraday's suggestion, Cooke later applied to Charles Wheatstone, who was at that time professor of experimental philosophy at King's College, London.

Charles Wheatstone began as a musical instrument maker, and it was in that trade that he learned those manual skills which were to stand him in such good stead during his subsequent career as an experimentalist. His early interest in the physical principles underlying the instruments with which he was concerned led him to a study of acoustics and thence to other topics in the physical sciences. Although largely self-taught, like many of his contemporaries, he early acquired a substantial scientific reputation on which he managed to put the seal by his

ingenious measurement of the velocity of propagation of electricity through wires, which involved the measurement of extremely short time intervals, for that date. Although it is known that he was tolerably fluent in German, and was familiar with Ohm's work on the resistance of conductors to the flow of electric current, certainly he did not at first appreciate how it could be applied in the telegraph system. Thus, when Cooke approached him it was still to some extent a matter of the half-sighted leading the blind.

Wheatstone's experiments on the velocity of electric current had convinced him that substantial electrical effects could be obtained through very extended conductors, and, what is more, he was fully familiar with the very sensitive galvanometers which could be made by combining Schweigger's multiplier with the astatic needle. He was thus able to receive Cooke's proposals for an electromagnetic telegraph in a rather optimistic spirit. The chronometric telegraph was quickly dropped and a far more sensitive instrument using astatic galvanometers was designed. This was the celebrated Wheatstone five-needle telegraph (Figure 3). Its principle of operation is quite simple. A series of five astatic galvanometers was arranged with the axis of rotation of the magnetic needle horizontal, a small gravitational couple being introduced by unbalance of the needle to keep it in a vertical orientation. The electrical signals from a commutating keyboard of five keys could deflect the needles either to the right or to the left, and the five needles were mounted upon a backplate marked in a hatchment in such a way that if any two needles were deflected the instrument gave an unambiguous indication of a single alphabetical letter. The elegance of this system lies in its simplicity combined with its sensitivity, and in the fact that the instrument could be used and read by any unskilled person, provided only that he were literate.

At this point it may be permissible to digress and discuss an interesting feature of the early telegraphs. For reasons

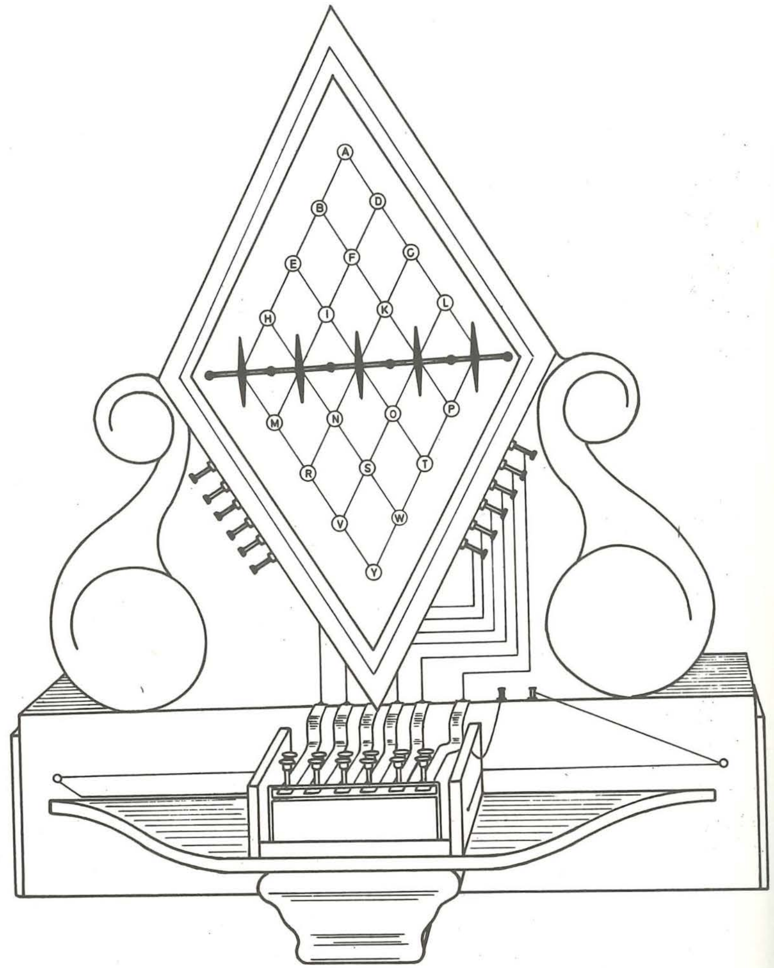

Fig. 3. The Wheatstone five-needle telegraph

which are perhaps not now obvious, most of the early telegraph inventors strove to develop a system which could be read by untrained persons. We today, are very familiar with the idea of a coded telegraph, particularly with the Morse code, in which the operator must learn to recognise a series of sounds or visual signals and to interpret them instantaneously as a letter. Generally this did not commend itself to the early experimenters, who felt instead that some system such as a chronometric or hatchment dial telegraph which gave a direct indication of the letter, was essential. The exceptions to this were in the German series of telegraphs deriving from the work of Gauss and Weber, which did employ a code, and in Schilling von Canstatt's telegraph. Gauss and Weber, and later Steinheil who continued their work, envisaged the telegraph as a means of communication between an observatory and a scientific laboratory. It would be operated either by the experimenters themselves or by highly-trained technicians who worked for them. Thus a coded system of transmission probably seemed unobjectionable and no efforts were made to alter this aspect of the system. The only non-coded telegraphs of the day were Sommerring's electrolytic telegraph or others like it which used 26 wires between transmitting and receiving stations and consequently paid a high price for simplicity of reading.

Schilling von Canstatt also envisaged a telegraph used by expert operators. As a diplomatist he was quite used to employing cipher clerks to deal with messages, and the process of coding for transmission and the subsequent decoding after reception was a matter of well-established routine. Thus, a transmission code using one or more galvanometers with only one or a few lines must have seemed a natural and reasonable approach to the problem, with the added advantage from the diplomatic point of view that secrecy of messages would be helped by frequent changes of code. However, those inventors, in particular Cooke and Wheatstone, Edward Davey and (in the United

States) Morse and Vaile, who envisaged the telegraph as a common carrier of messages, do not seem at first to have felt that a coded system of transmission would be acceptable. They dealt with this problem in different ways. The English inventors devised telegraphs capable of instantaneously and unambiguously signalling single letters, such as Wheatstone's hatchment dial; whilst the Americans, although using a code, went to great lengths to design recording instruments. In Morse's first instrument the incoming coded signal was recorded by means of indentations on a continuous roll of paper tape. There was, therefore, no need for the operator to learn the code by heart; instead, it was possible for the paper tape record to be compared with a code book, permitting decoding at leisure. At the transmitting end Morse designed a primitive automatic instrument in which the signals could be sent by passing a metal stylus across a board on which were mounted alternately insulated and conducting segments, thereby permitting a pattern of currents and interruptions to be transmitted, corresponding to the code for the letter. This device, which required that a metal stylus should be moved over a track with great uniformity of speed if well-formed characters were to be transmitted, never came into general use, and the recording receiver, although used for a time, rapidly became obsolete when the telegraph operators discovered that simply by listening to the sound which the receiving instrument made they could decode the signal directly without reference to the indented paper tape. Soon Morse's system became a fully coded telegraph with operators trained for directly transmitting and receiving coded messages. However, the great care that Morse took to provide recording receivers and automatic transmitters shows that he anticipated that the problem of coding would be a stumbling-block of his system.

It is fair to say that instead of devoting a major part of their attention to the principal problem of the telegraph, which was that of obtaining adequate range, the early

experimenters devoted a great deal of time and ingenuity to devising direct reading telegraphs in order to avoid coding. This ingenuity was, apparently, misplaced, in that within a few years coded telegraphs had quite supplanted all others by virtue of their simplicity. Was the effort therefore entirely wasted? Perhaps not, since it is necessary not only to have an invention which will work and provide the service required of it, but also to attract capital investment, and this is only likely to happen if the system will work in the social environment in which it is to be introduced. In early 19th-century England and America there was still a considerable amount of illiteracy and even to learn to read plain English was something of an accomplishment. To expect operators to learn another and far more exotic alphabet may have seemed too much. It must also be remembered that in the beginning of the telegraph system it was unlikely that, in English conditions at least, the operators would be able to give undivided attention to the telegraph; indeed, in railway use it was virtually certain that they would have to divide their attention between telegraphy and other duties. This meant that the employment of specially trained labour for telegraphic work looked impracticable.

Wheatstone's hatchment dial telegraph was so much more sensitive than Cooke's chronometric instrument that it could at once be operated over lines of considerable extent. It appeared, therefore, that a commercially viable telegraph was to hand. One remaining problem was the design of an alarm system which would call the attention of the operator to the telegraph when a message was to be received. That this should have been considered so important was, once again, an outcome of the fact that an operator giving his undivided attention to the telegraph was not at this time envisaged. The use of a detent mechanism which would release a clockwork alarm had already been pioneered by Sommerring, but using an unsatisfactory electrolytic system of actuation. To use an electromagnetic detent release would have placed serious limitations of sensitivity on the system, with consequent restrictions of range, and thus would have nullified the advantages obtained by the use of the astatic galvanometer – or so Wheatstone supposed, drawing on his and Cooke's experience with the chronometric telegraph. It was this difficulty which led him to invent an electromagnetic relay, in which the needle of an astatic galvanometer also carried a small U-shaped contact wire which joined two mercury cups when the galvanometer was deflected. By this simple means, and without any serious loss of sensitivity, a local battery circuit could be closed allowing a relatively large current to operate the electromagnetic detent. It was only after all this work had been completed, and a practicable electromagnetic telegraph had been developed as a result, that Wheatstone, as a consequence of discussions during a visit by Joseph Henry in the April of 1837, realised that a properly designed electromagnet could operate a detent mechanism directly even at a considerable range. Thus was Ohm's law at last introduced, even in a disguised form, into the operation of the telegraph.

The Cooke and Wheatstone telegraph, with the alarm circuit re-designed to avoid the need for a relay, was a workable system and was demonstrated successfully (using a simplified four-needle instrument) to the directors of the London and Birmingham Railway in 1837. In 1839 a line was completed alongside the Great Western Railway from Paddington to West Drayton for the five-needle system and was later extended to Slough. The subsequent development of the telegraph as the major communications system of the 19th century springs, in Europe at least, from this beginning.

Laymen generally incline to the opinion that the purpose of history is that we may draw some conclusions from it, a moral, perhaps, which has a bearing on the decisions we are obliged to make in our everyday affairs. This is a proposition about which a professional historian might be dubious, however we need not be shackled on this occasion

by an excess of this kind of academic caution. What moral can we draw from the development of the electrical telegraph which could possibly have an application in our time?

It is tempting to suggest that the century or so which separates the development of the electric telegraph from our own time is so large a gulf, in scientific and technological terms, that human experience cannot bridge it. This conclusion I cannot follow. Certainly, the electrical engineer today must have a far larger stock of scientific knowledge than his predecessor at that time. However, the institutional means for acquiring that stock of knowledge, through our universities and other institutions of higher learning, have developed to an extent which Wheatstone, university professor though he was, might have thought almost impossible. It is not necessary now to crusade for a good scientific background for the young engineer; we take this as a matter of course.

The argument for relating present engineering practice to past history is essentially, perhaps, a subjective one. It is legitimate because engineers will readily appreciate that the way in which the early engineers set about their work, and the experience which they had in the course of it, chime impressively with what we know today. The human situations remain almost the same. Capitalists and government officials still react to the engineer much as they did then. All that is changed is the science, and this is no more than the tool that we use: it does not lie at the heart of the matter. All worthwhile engineering innovation occurs just beyond the boderline of what the science of the day confidently knows, and great engineers of the twentieth century, as of the nineteenth, are still in this sense men of the frontier. In considering the experiences of Ronalds, Morse, Cooke and Wheatstone, engineers today can find something which speaks to their condition. The truly engineering problems which faced them can easily be distinguished from the merely scientific; with the passage of time the latter have now become trivial.

When we consider, then, the circumstances in which the great innovations were made, we see an interesting phenomenon. Ronald's electrostatic telegraph was not carried out in terms of the best available scientific knowledge of his day. He chose not the newest electrical energy source, Volta's pile, but a rather older one, the electrostatic machine. Similarly, Wheatstone and Cooke did not utilize all the science then available to them in designing their system of electromagnetic telegraphy. It is very doubtful whether Wheatstone used anything of the very elegant theories of electrodynamics which Ampére and his successors had contributed to electrical science in the decade before the telegraph appeared. Certainly, if Wheatstone did not use these scientific advances nobody else did.

Even Ohm's law, that beautiful generalization which alone could give the answers to the problems of limited range which dogged the early telegraph pioneers, was used only in the simplified and specialized forms in which Joseph Henry expressed it.

Innovative engineering is, at its best, a mixture of conservatism and radical invention. An engineering advance is counted a success if it works, in the sense of providing a needed service and earning its keep. Nobody thanks the engineer for an unsuccessful design, and in engineering it is doubtful whether there are such things as glorious failures. Thus, where he can be so the engineer is conservative, staying cautiously with the tried and tested and eschewing the uncertain, just as Ronalds preferred the known and perfected electrostatic machine to the doubtful voltaic pile. But conservatism will carry one only part way, and innovative engineering at some point necessarily demands originality and invention, perhaps of the most radical kind – a true 'leap in the dark.' Ronald's design for his cable was just this. For the engineer, to invent needlessly is wrong, because it endangers the success of the project. Equally, to baulk at necessary invention is unacceptable because it precludes technical

advance. The true genius of the engineer lies in a nice balance of radical and conservative sentiment.

To describe how the engineer goes about his work is not, however, to come upon the central mystery of the art. Our profession is a vital component of the executive arm of the society in which we live. Design and innovation by the individual engineer is but a small part of a whole which consists, in sum, of modifying the properties of the material universe in order more perfectly to satisfy the needs of human kind. Pediatricians speak of the importance of a facilitating environment to the development of a child. The engineers are charged with providing a facilitating material environment for all humanity. What we see about us bears witness that this is a task by no means yet fully accomplished. A world in which millions starve and millions more lead lives of unrelieved and brute servility needs its engineers still. Even more it needs engineers who can be much more than merely able exponents of well-known skills, who can, in fact, create a new technology again and again ever more perfectly to match the evolving needs of the society they serve. Creativity is the heart of engineering, and it is inventiveness and ability to innovate which we must nurture in our engineering students, and to the study of which we in the universities ought to devote particular attention.

A common image of the process of engineering innovation is that the scientist makes a discovery and the engineer, following diligently in his footsetps, invents a use for the new knowledge that is revealed. There may sometimes be cases where it can plausibly be argued that this is the truth, but most major advances in technology seem to have come about in a way which is rather less simple. A more typical picture is of a discovery at a purely empirical level, perhaps of one or more important physical effects. Simultaneously the pure scientist seeks to relate the new effects to the body of existing knowledge (and thereby to extend that knowledge), whilst the engineer seeks to exploit them. His aim is to make possible either the satisfaction of human needs in some way better than had been known before, or even the satisfaction of a need which could not have been satisfied at all before. The twin processes of comprehension and of exploitation for human and social ends go on side by side. They stimulate each other: the scientist achieving new and valuable insights for use by the engineer, but also the engineer posing questions to the scientist which tend to focus attention on areas of imperfect understanding.

Thus, Oersted discovered the deflection of the magnetic needle by a current. The invention of the galvanometer by Schweigger and its exploitation in telegraphy by Schilling von Canstatt and by Steinheil, and then later by Cooke and Wheatstone, all proceeded without benefit from further scientific discovery. The theoretical formulation of the laws of interaction between magnets and electrical currents, which was being worked out with such brilliance at the same time, played no part in that development. Telegraphy called science to its aid only when it encountered later problems, particularly when the problem of the slow speed of signalling on submerged ocean cables became serious and resisted all attempts at an empirical solution. It was then that the transient response of the cable system had to be investigated in a rigorous manner, and this investigstion can quite properly be called an example of technology demanding a solution to its problems from science, and in due course receiving it.

The point of growth in engineering is, in fact, in the acute perception of a social need and its relation in the mind of the inventor to some means of satisfying it by the exploitation of known properties of the material universe. If we popularly remember, in Europe at least, Cooke and Wheatstone rather than Steinheil, or indeed Ronalds, as the inventors of the electric telegraph, this is because their instrument was in fact taken up, was used, and became a part of the socioeconomic fabric of nineteenth century society. In doing so it changed, modified, evolved so as more perfectly to satisfy the social need which its presence served more fully to reveal.

It has been said that Wheatstone's original five-needle telegraph was really a quite impractical design. Hubbard makes this point in his recent excellent monograph on Cooke and Wheatstone. But this would leave it a mystery why Wheatstone and Cooke achieved success with their system when so many other purveyors of practical systems failed. Did they perhaps manifest an unusual flexibility of mind that enabled them to change very rapidly from a poor system to a better?

As Hubbard wisely observes, the five-needle telegraph succeded because it impressed railway directors. It was a machine which could be used by any literate person with little or no training. A railway director could use it. And the so-called fault of the system, namely the high cost of laying five wires between transmitter and receiver, was no great disadvantage in the actual situation envisaged for its use. Let us not forget that Cooke proposed the employment of the telegraph in the first instance in connection with railway working on inclined planes, using cable haulage from stationary winding engines. Thus the length of line envisaged was quite short, and the cost was not disproportionate compared with the remaining capital cost of the system.

Because this telegraph was operationally very near to their requirements, the railway directors came very near to accepting it. That they hesitated to do so resulted from the fact that, for the simple purpose of stationary engine working, a true 'speaking telegraph' capable of an infinite variety of different messages was not really needed. Satisfactory results could be obtained with a simple 'train-on-line' indicator and this could be achieved (for example, by means of a power whistle operated pneumatically) at lower cost and perhaps with greater reliability than by using the electric telegraph. The railway directors were neither fools nor reactioniares. Indeed, as the success of their enterprises serves to indicate, they were often highly able men who were probably more willing than we commonly are today to gamble large sums of risk capital on innovation. Properly considered, their rejection of the electric telegraph for the specific purpose for which it was proposed must be seen as a right decision. The situation was that their need, which Cooke and Wheatstone identified, was not quite the need which the electric telegraph was uniquely fitted to satisfy. These were considerations that led to the decision not to use the electric telegraph on the London to Birmingham railway for working over the Euston to Camden Town inclined plane, as proposed by Cooke.

This difficulty was, however, countered in two ways. First of all, it was necessary to persuade railway directors that the advantage of a speaking telegraph went far beyond its utility for stationary engine working. Cooke wrote a pamphlet to this effect. The operational flexibility which could be achieved in a railway system when a means of almost instantaneous communication between the various important points was available seems so obvious to us, but had to be made plausible to railwaymen at the time. With ingenuity they had devised means of working which could be operated successfully without the telegraph, and therefore this instrument was not indispensable. A convincing case had to be made that it would be highly advantageous. The other part of the development, which was also vigorously pursued by Cooke, was to perfect the telegraph system so that its cost might be reduced and its reliability improved, at the same time bringing forward simplified one-needle instruments, similar to that used on the London and Blackwall Railway, which were adequate for elementary cable hauled working.

There have been many arguments about the true authorship of the electric telegraph, including a particularly bitter dispute between Wheatstone and Cooke in the years after their initial success; but it can hardly be doubted that what Cooke contributed was an eclectic willingness to modify, alter and adapt the system to any required extent in order to meet the operational needs of a potential user. At times this brought him into conflict

with Wheatstone, who had a designer's natural pride in the elegance of his original five-needle system, but undoubtedly it helped to explain the relatively rapid adoption of the Cooke and Wheatstone electric telegraph. That the 'train-on-line' indicator was a single needle telegraph and that the speaking telegraph for use by trained telegraphists was also ultimately either a single or a double-needle instrument, must not be seen simply as the triumph of the single needle over the five-needle design. Far more it was the triumph of an essentially engineering approach, which adjusts the properties of machines to the needs and capabilities of those human beings who will use them.

The role of Cooke in the history of the telegraph has often been questioned. He wished to be thought of as an inventor, and that he undoubtedly was. But his role was also entrepreneurial. He was able to discover, as a man of affairs, those unsatisfied human needs which the telegraph was able to fulfil. Without the entrepreneur there can be no engineering, for it is this interpretation of needs into technologically satisfiable forms which is an indispensable link in the nexus of engineering innovation. The moral of this, at least, is plain. The engineer cannot but gain by a visit to the market place. We in the Universities must welcome all the contacts with industry and commerce that we can achieve, since the quality of our engineering is dependent upon them and without them our work is doomed to sterility and pointlessness.

The patent granted to Cooke and Wheatstone was sealed in 1837. Within ten years inland telegraphs were in widespread use, and in the next decade the spanning of the Channel and then of the Atlantic became the tasks which seemed inevitably to present themselves to the telegraph engineers. How that was accomplished, however, is another and far longer story.

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