AWA Review

Professor David Edward Hughes

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ABSTRACT

Our society and technology is built on the pioneering work of the Victorian scientists. Unfortunately, with the passage of time, only the popular names are remembered. If we peel away this top layer though, we can discover a host of scientists that not only made important discoveries but also led fascinating lives. One of these scientists was Professor David Edward Hughes FRS. His printing type telegraph instrument invented and used in America was also instrumental in the growth and success of the communications network of Europe. His work on suppression of electrical interference and discovery of the carbon microphone led to improved telephone communications and experiments with his induction balance led to the metal detector. His wireless experiments, for which he had invented a unique detector enabling him to receive a transmission over distance of 500 yards with his mobile receiver in 1879-1880, are a tribute to his ingenuity.

In the earlier part of the1800's, electricity was a novelty - a scientific orphan. Then suddenly, (in historic terms), all that changed. A number of clever experimenters observed that electricity could actually travel vast distances instantaneously along wires, and sought to put this phenomenon to good use. When these pioneers cracked open Pandora's box, they had no idea that it would lead to such a diverse and all encompassing communications industry that we all rely on today. The technologies that we now take for granted, can be traced back to the pioneering work of the industrious Victorian scientists.

One of these was Professor David Edward Hughes. Hughes was a brilliant inventor and practical experimenter as well as a gifted musician, ever inquisitive and a true lover of science. He was born when Michael Faraday and Joseph Henry were still uncovering the mysteries of "electricity", a time when they and others were wrestling with the observations that electricity could create magnetism, and magnetism could be used to create electricity. He lived through a period rich in famous names that are still familiar today, such as William Thomson (Lord Kelvin), Cyrus Field, Samuel Morse, Thomas Edison and Alexander Graham Bell.

Hughes was to leave his mark through his inventions and discoveries in the fields of telegraphy, telephony, wireless, metal detection, and audiology. He was an international scientist whose life was spent between America, Britain, and Continental Europe, and became one of the most decorated scientists, receiving high honors from no less than nine countries. Hughes was one of the few self-made scientists who were able to amass a substantial sum of money over their lifetime, which upon his death he generously donated to the London Hospitals. However, like many of the early scientific foot soldiers that laid down the foundations of our communications industry his name has tended to sink below the history horizon. (Fig. 1)

Fig. 1. Prof. David Edward Hughes

David Hughes according to his tomb inscription was born in 1830. His father, originally from Wales, and a boot maker by trade, was a gifted musician who moved to London, married and had four children. David Hughes and his two brothers and sister appeared to have inherited their father's gift and also turned out to be natural musicians.[1] This talent wasn't wasted, as an infant musical troupe was formed and toured the music halls of London and the provinces. They were billed as the "Child Prodigies" and went on to perform for the Royal Family and other notables. (Fig. 2). Buoyed by their success, the child prodigies musical show was taken on tour to America, which opened its arms to the child performers. Their popularity and novelty led to the honor of performing at the White House. After several years of show business they had acquired significant wealth and the family retired from the entertainment business to take up touring for pleasure. Their travels were extensive, covering North America from Nova Scotia to New Orleans. Any thoughts of returning to the old country appear to have slipped away.

During this period of adventure, Hughes' father became interested in geology and mineralogy. Probably like so many of the early pioneers, he dreamt of striking it rich and succumbed to "gold fever". Virginia was then the gold hot spot and this is where the family settled down, buying a farm there in the 1840 s. Here they set about farming and mining for the elusive ore. [2]

During their travels, the children's education was not neglected and a private tutor traveled with them. David Hughes showed the same flare for the sciences as he had for music. He was both inquisitive and inventive and his father built a laboratory next to the farm. Here, Hughes spent his time carrying out chemistry experiments, taking mechanisms apart, building new ones, and making improvements to their mining equipment. Hughes was living in an interesting time that would see the birth of many new technologies throughout his lifetime. One of these was the transition of electricity from a poorly understood phenomenon into a technological powerhouse. This occurred when it was applied to the electric telegraph introduced during the 1840's by William Fothergill Cooke and Charles Wheatstone in England and Samuel F.B. Morse and Alfred Vail in America. Overnight, almost, it seems that communication time shrank from months, weeks or days to a matter of minutes.

THE TELEGRAPH ERA

It was while Hughes was a teenager that he first saw a Morse telegraph system in operation. Always inquisitive when he saw new mechanisms, he questioned the operator as to how it worked. Whilst simple and practical in its operation, it must have set his innovative mind to ponder how such a system could be improved. Over the following few years, he was to bring his ideas to fruition by inventing his own telegraph instrument.

As Hughes came to the end of his teen years, he became restless and tired of the limited amenities of rural Virginian farm life. People were starting to look to the west for new opportunities and he decided to join the migration. He applied, and was accepted for a post as a professor of philosophy and music at a college in Kentucky. This was somewhat of an accomplishment at his young age but Hughes was proud of becoming a professor, a title he maintained throughout his life. The move to Kentucky in 1850 turned out to be a tough period for him as he had limited money and had to juggle his time to accommodate teaching, taking on private music students and experimenting with his ideas for a new telegraph instrument.[3]

Fig. 2. The “Child Prodigees”

During this period, Hughes started to formulate how he could implement the telegraph instrument he had in his mind. He decided that instead of using codes that required operator training as well as requiring multiple pulses to be transmitted, it would be better if one could just type in the message directly as alphabetical characters and print them out at the receiving station. Hughes was not alone in attempting to invent a better telegraph instrument and a number of systems had or were appearing, using a variety of operating principles and vying for their place either in the European or the American market. These used a variety of signaling methods such as a multitude of short and long pulses as in the Morse system, or a long stream of pulses as in the step by step systems, or signals of different polarity as in the needle or dial systems.

In America, at the time there were only two serious competitors to the Morse system, the Alexander Bain electrochemical telegraph and the Royal Earl House printing instrument patented in 1846 and in operation by 1847.[4] Whilst these instruments were used by some of the telegraph companies, Morse was by far the dominant system and they constantly fought to keep it that way by challenging any attempts by patentees of other systems. Hughes's idea of typing in letters and either displaying or printing them at the receiver was not new, and had been used by Paul Gustave Froment in France and Royal Earl House in America.[5] However, his ideas and approach would result in an instrument that would both look and operate differently.

Hughes is renowned for buying old clocks, dismantling them and carrying out experiments with the parts. Somewhere in this experimentation, his ideas started to gel as to how he could implement a printing telegraph. His concept was to provide a keyboard so that the letters could be typed in directly, and at the receiving end print out the letters and words onto a paper tape. (Sounds familiar and taken for granted today). One of the most ingenious parts of his telegraph, though, was in its method of transmitting the information from transmitter to receiver. Up to that time, telegraph systems were based on transmitting voltage pulses and used only three parameters: amplitude, polarity and duration in their method of signaling.

Hughes introduced a time element to his scheme. His notes indicate he conceived of a one wave system, (waves were often used to refer to pulses).[6] He had figured out how to transmit all 26 letters of the alphabet using a single pulse. To accomplish this he constructed a keyboard not unlike a manual typewriter, except the keys were arranged in alphabetical order. Next, he constructed a mechanical scanning device that could scan the keyboard to determine when a key had been pressed. This was implemented by using a rotating cylinder that had a helical pattern of 26 protruding pins (not unlike a musical box cylinder), and driven by a clockwork mechanism. (Fig 3).

When a letter key was pressed down, it pushed forward a contact that was struck by a pin of the helix on the rotating cylinder. By connecting a battery across the cylinder and keys, a voltage pulse would be generated whenever a contact was made. The cylinder was rotated at a constant speed in which time it scanned all 26 let-

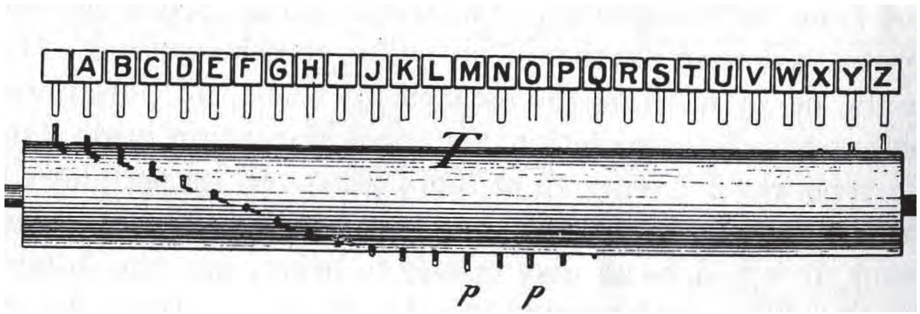

Fig. 3. Helix Scan

ters once each revolution.[7] For example if the "A" key was pressed the first pin on the rotating cylinder would make contact and if "E" was pressed then the fifth pin was struck (but displaced in time by 5/26 of a revolution). Thus, he had set up a repetitive time base (equal to the rotation of the cylinder) that was in turn subdivided into 26 time slices. Each time slice could transmit a one or a zero represented by a pulse or no pulse. (In actual practice, Hughes used 28 keys and ran at 120 rpm). Depending at what position the pulse occurred within the time base indicated which letter had been transmitted. What he had conceived of was a pulse position modulation system that would find many future applications and would later evolve into time division multiplexing. (Fig. 4.)

At the receiver, he arranged for a print wheel (with 26 letters plus the two extra positions - a period and a blank) to rotate at a constant speed and in phase with the scanning cylinder in the transmitter. Below the print wheel was a platen that could be rapidly raised against it. A continuous paper strip was fed over the platen. When a pulse was received, it triggered the platen to be rapidly lifted

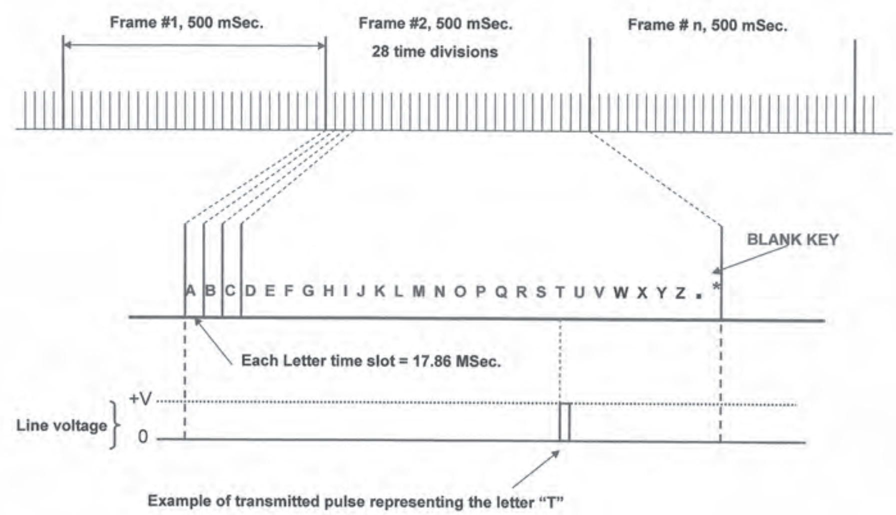

Fig. 4. Pulse Position Modulation

and briefly contact the print wheel and print a letter on the paper tape. Other mechanisms advanced the paper and inked the print wheel. (Fig. 5).

Hughes' challenge was how to get two telegraph instruments to run in perfect synchronism and phase separated by tens or hundreds of miles. Here all his experimenting with clocks came into play. They were at the time the most precise mechanism available. He solved the problem by using a vibrating spring strip to provide the precision timing instead of a pendulum, which would have proved far too slow. The oscillating spring strip drove a typical clock mechanism of an anchor and escapement wheel. The power for the mechanisms was provided by a falling weight drive similar to that used in grandfather clocks. In return, the vibrating spring received a nudge from the escapement wheel each period to keep it oscillating. The vibrating spring was also fitted with a temperature compensating mechanism to keep the vibrating frequency constant.

Hughes took an approach to the electrical signaling that required minimum power. This was in contrast to other telegraphs such as the Morse instruments. For these, hefty batteries were needed, as all the power to drive the receiver register relay had to be supplied from the transmitting end (although later a local relay was introduced to reconstitute weak signals).

Hughes's approach was based on transmitting lower voltage pulses and using a sensitive detector in the receiver. The detector was a smart piece of design. Hughes used a permanent horseshoe magnet with soft iron pole pieces onto which were wound coils. He then arranged an armature to close across the gap, held by the force of the magnet. The armature had a spring attached that could be tensioned such that it was just about to pull the arma-

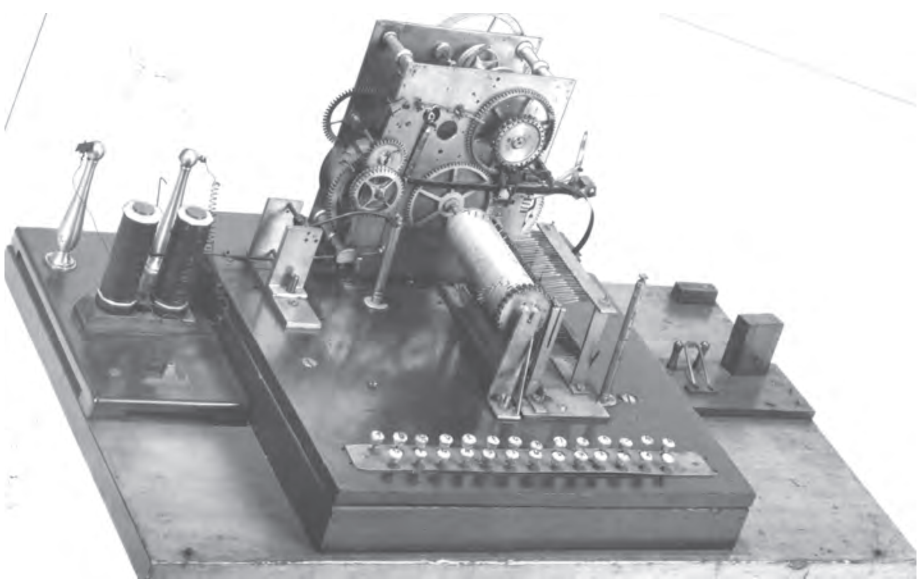

Fig. 5. Hughes' original telegraph instrument

ture clear. When a pulse was received, it was routed through the coils. The resulting magnetic field generated was in opposition to that of the permanent magnet thus weakening it. This caused the armature to release and to fly off under the influence of the tensioned spring. Not only did this need a lot less electrical power to operate but also the response of the detector was very rapid. The release of the armature triggered the platen to rise against the print wheel. The actuation power for the receiver was also provided by a falling weight drive. As the printing was able to take place without stopping the print wheel, it contributed to its overall higher operating speed than other systems. Once the platen had operated, it also reset the armature of the detector.

Hughes' design actually integrated a transmitter and receiver into one instrument and it was designed from the start to operate in a duplex mode (able to transmit and receive simultaneously). It was also possible to actually send more than one letter per revolution of the scanning cylinder providing they were spaced a number of letters apart (equal to the time to recycle the receiving relay). For example, the word "fly" could all be transmitted within one revolution, again further contributing to the speed of transmission. The usual quoted average was three letters per revolution, and five was the maximum.

To synchronize instruments there was a procedure to be accomplished. Instruments could initially be accurately set to run at close to the same frequency after manufacture. Then, installed instruments say in New York and Philadelphia were first set to start in phase. The transmitting instrument and receiving instrument were first latched in the "blank" position. In both instruments, the mechanisms were all running except the print wheel which was declutched from its rotating shaft and held at the blank position and in a wait mode. The transmitting operator then pressed down the blank key on the keyboard. When the receiver detected the blank signal, it unlatched the print wheel setting both instruments to run in synchrony. This clever arrangement also took care of instrument time lags and transmission line lags by automatically offsetting the print wheel equal to the time difference. As these time lags would remain constant, the instruments would remain in synchrony. Time lags up to one revolution of the print wheel could be accommodated (0.5 sec for a rotation of 120 rpm).

Next, to ensure that both instruments were running at the same frequency, the following procedure was used. The transmitting instrument sent out a string of the letter "A". If the receiver printed out a series of A's then they were running at the same frequency. However if the receiver printed out letters that were running away say B, C, D, etc., then the receiver was running too fast or if it was printing Z, X, Y, etc., then it was running too slow. Thus, the frequency of the receiver was adjusted until a series of A's was printed.

The electromagnet arrangement Hughes used in his detector became known as the "Hughes quick acting electromagnet". This component was adopted for use by many other inventors and applications. One of these applications was with railway signaling and safety systems used by Henry

Latique in France and by Sykes' in Britain.

Hughes finally managed to complete his prototype instruments and get them to successfully operate over telegraph lines in 1855 with an average speed of 44 words per minute. Hughes' next move was to patent his instruments and see if he could get the telegraph companies interested in buying the rights. At the time, there were many competing telegraph companies with fragmented operation covering the Eastern part of America. One of their big customers was the newspapers, and in particular, the Associated Press (AP), who had an ongoing battle to reduce the cost of sending their dispatches over the Morse dominated telegraph lines.

It was also a time when Cyrus W. Field had entered the telegraph arena with his grand plan to span the Atlantic with an undersea telegraph cable.[8] However, he and his associates realized that to make their plan work they needed to pull the fragmented telegraph companies into a cohesive operation to be able to provide for smooth message flow to and from their Atlantic cable if it was to be an economic success.

When Hughes had barely completed his prototypes, the AP got wind of his invention and summoned him to New York. If they could acquire Hughes's telegraph, they could put pressure on the Morse telegraph companies by threatening competition to force reduced rates and possibly bring about some cohesion in the industry. AP's common objective with Cyrus Field and the availability of Hughes' new instrument provided the impetus for the New York businessmen to move forward with some bold plans and form the "American Telegraph Company" (ATC) with Peter Cooper as president and Cyrus Field, David Hughes and others as corporate executives.[9]

The AP played a prominent role in bringing this about. Hughes was offered $100,000 for his telegraph system - a sum that must have been beyond his wildest dreams. This was to set a pattern for his life, as he always seemed to be just in the right place at the right time with the right product. He was however unaware that his invention was to be a pawn in the American Telegraph Company business dealings. The AP and ATC now had a competing telegraph system and some clout to use against the Morse companies to start forcing them to amalgamate with the ATC and reduce their costs.

Hughes' instrument was assessed as not being robust enough to survive the daily use by telegraph operators. To solve this, the ATC put their experienced machinist, George Phelps to work with Hughes in upgrading the instrument.[10] A relationship that was not always harmonious. The young Hughes protective of his invention and the more senior Phelps - an experienced machinist and familiar with the telegraph instruments of the day was probably full of ideas as to how to improve the mechanisms.

The eventual outcome however was an instrument that was more robust and incorporated various changes and improvements. These were replacing the typewriter type letter keys with a piano style keyboard, changing the mechanical scanning mechanism to a rotating commutator, beefing up the clockwork mechanism, adding a corrector mechanism to keep the instruments in tight synchronism and combining the transmitter and receiver weight drive mechanism. Manufacturing commenced and the instruments started to be put into service. Hughes patented his original telegraph in England in 1855 and America in 1856.[11] (Fig. 6).

By 1857 Cyrus Field was ready to make another attempt to lay a cable across the Atlantic and invited Hughes to England to join him. Hughes couldn't refuse the challenge and was drawn into the project. The fact that there was insufficient knowledge at the time to know if an electrical signal could be sent through 2000 miles of wire lying under great pressure two miles below the ocean hadn't, so far, deterred Field! The Atlantic telegraph cable is a story unto its self that ended up spanning several years before finally succeeding.[12]

Hughes' involvement briefly spanned the summer and fall of 1858. He traveled to England where he attempted to make his instrument operate over the cable while it was in storage in tanks at the shipyard. Undersea cables had different characteristics to the traditional telegraph lines strung above ground on poles. The difference being its significantly higher capacitance that had the effect of almost swallowing electrical pulses, which became known as the "embarrassment" of the cable. Hughes was to meet William Thomson (later to become Lord Kelvin) in England, who was a few years older than himself and who had taken the time to devise a formula for the propagation of electrical signals in submarine cables.[13] His telegraph equation or law of squares indicated electrical pulses would experience an increasing time delay as they traversed the cable, known as retardation. A delay in

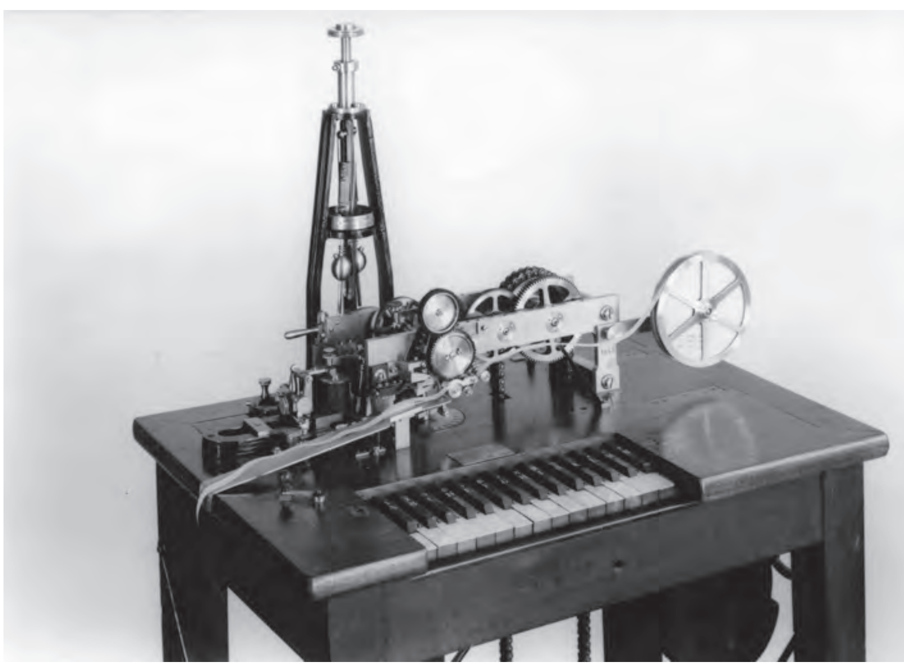

Fig. 6. Later model of Hughes' telegraph instrument

a 100 mile cable would not just increase by a factor of 10 in a 1000 mile cable (if it was linearly proportional) but would increase by a factor of 100. Along with this effect, the signal would also experience attenuation. Thus, sending signals over the cable presented a significant challenge to the instrument technology of the day. The speed that messages could be transmitted was an all-important parameter as the operating economics of the transatlantic cable were dependent upon it.

Unfortunately the electrician for the transatlantic cable, W.W. Whitehouse did not agree with Thomson (an unpaid advisor) and had his own ideas as to how to send signals through the cable. Hughes was caught in between conflicting views and at the same time tried to modify his instrument to run significantly slower to work over the cable. His effort however came to a sudden stop in the fall of 1858 as the cable that had operated for a couple of months went dead.

After the cable failure, Hughes tried to break into the British market dominated by the established "Cooke and Wheatstone" telegraph system, with no success. He contributed to the government's board of enquiry into the transatlantic cable failure. He believed one of the problems was the failure of the insulation. To address this he invented a self-sealing semi- fluid insulation. The idea was that if the gutta percha insulation became punctured the fluid would ooze into the void and reseal it.[14]

Hughes had decided that there wasn't much point in returning to America since ATC owned the rights to his instrument and the telegraph industry was starting to become monopolized by them, and eventually, Western Union. His instrument was subsequently further modified by Phelps who combined some of the features from the Hughes and House instrument with his own to construct an instrument that became known as the "Combination Instrument" that remained in service for many years.

Somewhat disillusioned in Britain, Hughes headed for France which was using a fairly old system of their own invention. It turned out they were about ready for an upgrade and open to evaluating new systems. After a successful trial period, his telegraph system was adopted in 1861 - again he just happened to be in the right place at the right time. The French put his system into use on the heavily used telegraph lines and were happy enough with the system and Hughes' performance that they presented him with the Imperial Order of the Legion of Honor by Emperor Napoleon III in 1864. Unlike America, (and initially Britain), where the telegraph companies were private or publicly traded, the continental telegraph companies were all state run.

Adoption of his system then spread to Italy, Russia, Germany, Turkey, Holland, Switzerland, Belgium, Spain and Serbia until it was in operation throughout Europe. It became the standard for all international lines specified by the International Telegraphic Union.[15]

Whilst England initially had given Hughes the "not invented here" treatment when he had tried to introduce his telegraph previously, they eventually had to adopt his instruments to be compatible with the rest of Europe. (Although there was some rumor that they removed his name from the instrument to avoid embarrassment!). His instruments were put in to use by the United Kingdom Electric Telegraph Company of which Hughes also became a director. By 1869, his instruments were in routine service on many of the cross channel undersea cables.[16]

By the 1870's Hughes' telegraph, system was in widespread use throughout Europe as well as in South America. As a tribute to its design, it continued in service for nearly 100 years finally ending its service in the 1940's. Hughes spent most of the 1860's and early 1870's based in Paris, travelling widely on the continent in support of his telegraph systems where he had licensed a number of manufacturers. During this time he continued to make upgrades and improvements. These included adding numbers and symbols providing up to 56 characters, providing tactile feedback to the operator so as to know when a character had been transmitted, improvements to the timing mechanism and changing over to electric motor drive.

He became known as one of the expert telegraph engineers of the day who was not just in the business of selling instruments but in the business of promoting a communication system. He was also called on to investigate the growing problems of electrical interference and lightning strikes on telegraph installations. He was recognized for his service as he became one of the most decorated scientists of the day receiving honors from all the countries he had systems in. He also received the Gold Medal at the Paris Exhibition in 1867, along with Cyrus Field.

THE TELEPHONE ERA

In 1877, Hughes decided to move to London, then considered the scientific epicenter. His telegraph system had been so successful that he had become relatively wealthy, allowing him to become financially independent. He was now regarded as one of the pre-eminent telegraph men in Europe and was about to take his place in the scientific circle as an independent researcher.

Alexander Graham Bell had just introduced his telephone, and it was the talk of the town.[17] Whilst it was a wonderful invention, it had its limitations. Hughes, along with others, was quick to recognize this. Bell's telephone used the same electromagnetic component and diaphragm both as a receiver and transmitter. While it worked well for the former, it lacked power as a transmitter and therefore was limited in its signal output, and hence its range of transmission. Hughes decided it would make a good research project.

While he recognized the components as functioning pieces of the telephone he saw them also as splendid pieces of test equipment. The telephone receiver, for him, was a device that enabled the amplitude and frequency range of signals to be easily measured for the first time over a wide dynamic range. He constructed a number of receivers for his own use as pieces of laboratory equipment. Next, he turned his attention to the transmitter. Hughes had actually used and demonstrated an earlier version of a telephone in 1865, when he borrowed a "Telephon" from Prof. Philipp Reis the German scientist. At the time he had been in Russia installing his telegraph system when he was requested to give a lecture to the

Czar and notables on the telegraph and other electrical devices. He included Reis's telephone in the presentation. The Reis telephone had actually been the starting point for many of the early telephone experimenters such as Bell and Edison. Hughes made some experiments trying to improve on Reis's approach but they were unsuccessful.

He next started his enquiry by pondering if there was a material or substance that could convert sound directly into electricity. This line of reasoning was based on the fact that it had been discovered that selenium altered its electrical characteristics when exposed to light. William Thomson had also shown that placing a wire under strain resulted in a change to its resistance.[18] Hughes decided to pursue this approach. He set up a stretched wire to see if he could get it to vibrate when exposed to sound waves, believing that if it did then the strains experienced by the wire would change its resistance which in turn could be detected.

His circuit consisted of a battery, the stretched wire and the telephone receiver, all connected in series. Fortunately, the experiment failed, but it was a failure that set him on a path of discovery. Hughes was a great experimentalist and seemed to be able to sniff out which way to proceed. In the failed experiment, which resulted in the wire being so extended that it broke, he noticed at the point of failure that he could hear in the telephone receiver a rushing sound and then a final crackle. Too many a broken wire or loose connection would be an annoyance but he was intrigued by the sounds he heard when the wire broke, it was something to be investigated. He tried holding the wires together and found that noises could be heard, he then laid the wires down on the table one on top of the other slightly weighted to hold them together and was surprised that he could hear sound.

He embellished this experiment by laying three nails down to form a letter "H" and connected them into his circuit. Now he could hear even better – but not with much fidelity. He had discovered the loose contact effect as a means of detecting sound. His basic apparatus relied on being able to modulate a current by the loose or poor contact. It was a device whose resistance changed in accordance with the sound waves, just what he had been looking for. He went on to try many different arrangements and materials in a quest to improve the quality of the sounds he could hear. Some of these were glass tubes filled with metal filings, with charcoal pieces or charcoal powder as well as charcoal that had been impregnated with mercury. (Fig. 7).

He tried many types of material contacts and found that metals that oxidized became unusable. Materials that didn't oxidize were platinum and carbon – and he chose the more economical of the two. As he refined his devices he found the most successful were based on a carbon pencil loosely supported between two carbon supports mounted on a piece of wood or sounding board. These he connected in series with a battery and the Bell receiver. He named it a "microphone" - a magnifier of sound (in keeping with the microscope that magnified light). It was a true microphone in that it had many more applications other than just as a telephone transmitter.

He had discovered a true microphone that could be made so sensitive that a fly could be heard walking about on it. He declined to patent the microphone declaring that he was giving the technology away free to be used by anyone. His experiments were published by the technical societies and in many of the technical journals.[19] The floodgates soon opened and within months, others were repeating his experiments and working on their own versions. Variations of the carbon pencil microphone were extensively used in conjunction with an electromagnetic receiver in Europe for many years by several companies. A later variation, based on Hughes's demonstration of the use of particles in loose surface contact, resulted in the carbon granule microphone of Henry Hunnings.

In America this technology was further developed by A. White into what became known as the solid back transmitter and in the UK as the Post Office insert number 13 microphone. The carbon granule transmitter was not su-

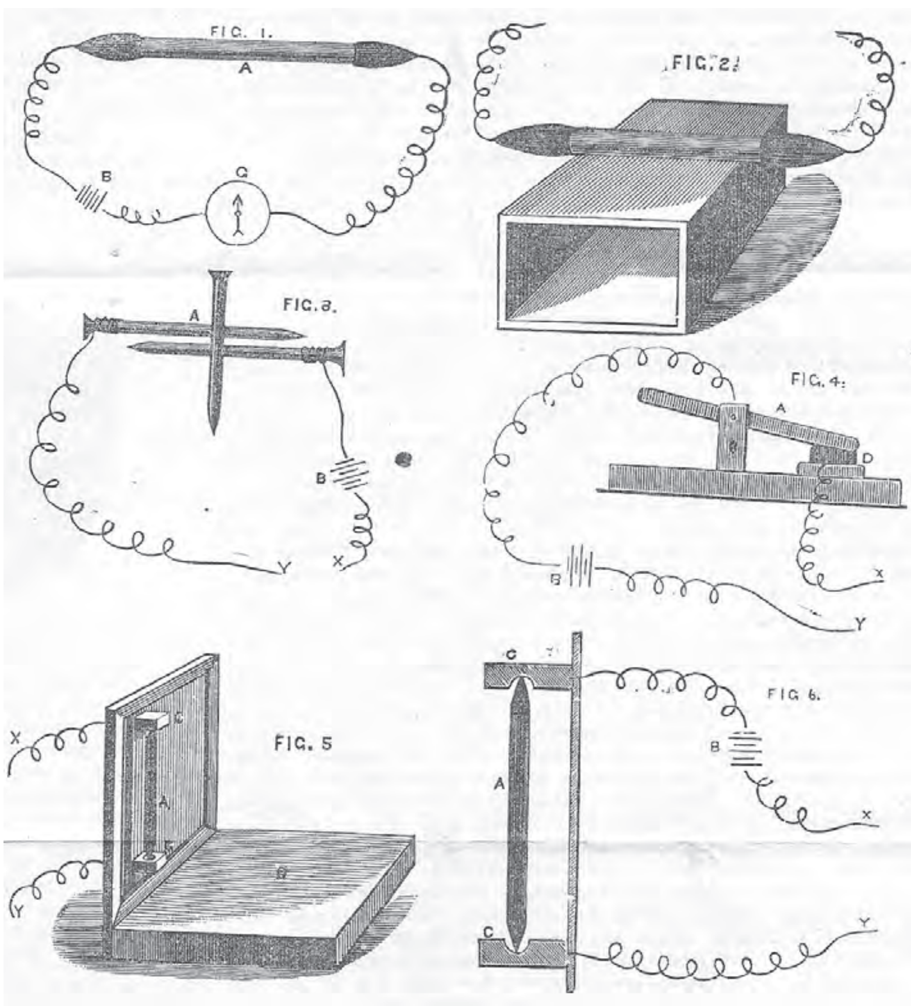

Fig. 7. Various Hughes microphones.

perseded by any other technologies for use in telephones until the 1980's (and in some parts of the world they are still in use!). Hughes's theory as to how the microphone worked was that it was a surface effect due to the number of points in contact that varied in sympathy with the sound waves.

Hughes was a man of short stature, blue eyes deeply set under bushy eyebrows, flowing chevelure and walrus moustache. He was mild mannered, independent, sometimes stubborn, but genial and sympathetic. He was said to be always full of interesting experiences and of a light heartedness that made him excellent company. However at times he become a catalyst (or as some viewed it a lightning rod) for stimulating great debates within the scientific community, either on the theory of electrical phenomena or on his experimental results.

One of these instances came about with his discovery of the carbon microphone when he crossed swords with Thomas Edison. Edison believed he had invented the carbon microphone first and suspected one of the English government officials (William Preece), whom he had confided in, of leaking his secrets to Hughes. Hughes's decision to give away his invention freely to the world only further infuriated Edison, who intended to capitalize on this invention. Unfortunately, the "Wizard of Menlo Park", as Edison was known, had misunderstood the circumstances, and before checking and discussing with Hughes, or others that he was accusing, immediately took the dispute public in the newspapers. Therefore, an affair that could have been settled amiably became a nasty war of words and accusations and counter accusations dragged out in the major technical journals and newspapers.

The dispute drew in the who's who of the scientific world, who waded in with their opinions and in support of their respective champion. The dispute eventually became nationalistic pitting the much larger scientific community of Europe against the smaller one of America. In the end, it was concluded that each had carried out their research independently and there had been no leaks. Hughes, having discovered in the microphone a device that had wide applications and Edison having concentrated specifically on the telephone transmitter. The chief scientist of the day in Britain, Sir William Thomson (Lord Kelvin) scolded Edison in the press over the affair and requested an apology from him for his unfounded accusations - Edison never did reply.

THE INDUCTION BALANCE

Hughes recovered from the assault on his character, and in Europe, at any rate, he was lauded as the inventor of the microphone. The months of publicity had also elevated his name and status amongst the scientific community and the public. Hughes was next to turn his attention to a vexing problem, that of interference on telegraph wires. He had investigated the problems some years earlier while in France, and now the problem had taken on a new urgency with the introduction of the telephone. When the telephone was introduced, it made use of the single iron wire telegraph lines with an earth return, which was far from ideal. In the cities, the telegraph caused significant interference for the telephone. Hughes set to work experimenting to understand the nature of the interference.

He set up a simulation in his lab of telegraph lines using wire coils to simulate lines of many miles in length and whose proximity could be varied to simulate the coupling. The outcome of the research was a solution for suppression of interference on multiple lines. The research also yielded the use of twisted wire pairs for telephone use and the use of shielded wire (coax). However, it would be many years before these techniques were put into use.[20]

In doing research with the induction coils that canceled out unwanted signals, he noticed that they were also sensitive to the presence of small amounts of metal. This led him to further experiments, resulting in the Induction Balance.[21] The device consisted of four coils (two primary and two secondary) that were connected and carefully positioned so as to be in opposition to each other, so that when the primary was excited by a pulsed source and the secondary connected to a telephone receiver no sound could be heard. Hughes' pulsed source consisting of his microphone in close proximity to a loud ticking clock and the newfound sensitive detector, the "telephone receiver", turned the arrangement into a useful device. [22] If a small piece of metal was introduced into one set of coils the arrangement would become unbalanced and this could be detected in the receiver. (Fig 8.)

The apparatus was extremely sensitive, being able to detect minute quantities of metal or alternatively was able to compare two like samples. The device found use at the Royal Mint to compare and check metal alloys used for coinage. Whilst the device proved

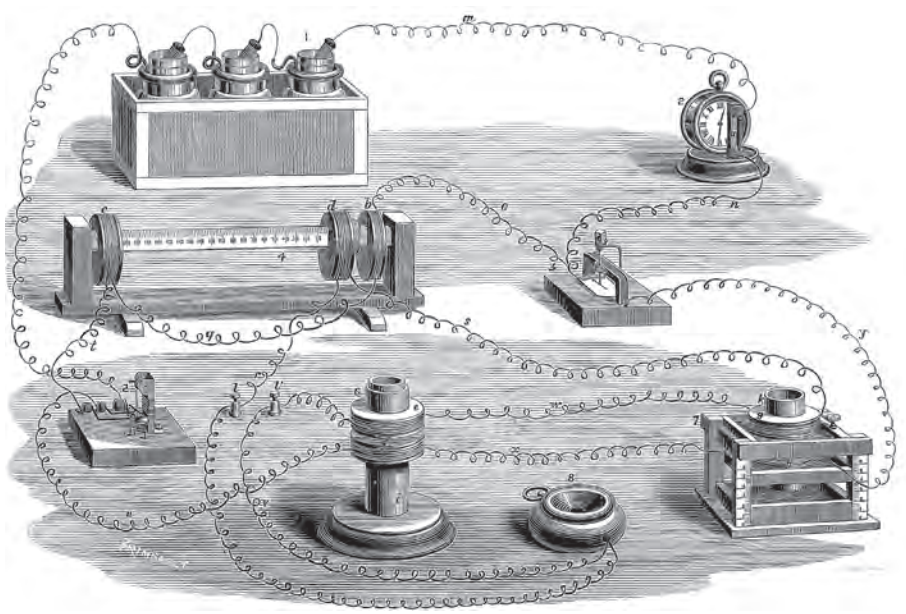

Fig. 8. Hughes' Induction Balance and Sonometer

useful, there was still much to be understood about induction in metals, such as eddy currents, that were still unknown. Hughes' induction balance was the forerunner of today's "metal detector", now in wide use as a recreation device to look for buried treasure on the shore, in the process industry for detecting metal fragments in fluids, etc., and standard equipment at security checkpoints. Out of this research came a number of interesting off shoots.

One was a device he called a "Sonometer" that consisted of two coils mounted on either end of a graduated ruler. A third coil was mounted between these coils and was free to slide along the ruler. (see fig. 8). The end coils wired in opposition and were excited by the pulsed source. The sliding coil was connected to the telephone receiver. When the sliding coil was at midpoint along the ruler it experienced a null and no sound could be heard in the receiver. Sliding the coil towards one end increased the volume of the signal whose value could be correlated with the scale on the ruler. Hughes used this in conjunction with his induction balance as a means of making relative measurements. This was done by switching the telephone receiver back and forth between the induction balance and the sonometer until the relative volume of the two signals was judged the same. The reading was then taken off the ruler scale. The sonometer was also adopted by the medical profession and used extensively for testing hearing.

One of the more famous uses of Hughes' induction balance was Alexander Graham Bell's application of it in 1881 in the desperate attempt to try to determine where the bullet had lodged in President Garfield, while he clung to life after being shot by an assassin. Bell consulted with Hughes but despite his best efforts, he was unable to locate it before President Garfield succumbed.

WIRELESS DISCOVERY IN 1879?

Hughes was a great experimenter, and nowhere is it more apparent than when reading his notebooks.[23] Here the experiments come alive as the reader follows the scrawled handwriting from one page to the next. He was methodical and innovative, his peers saw him as a gifted experimenter as he seemed to have the ability to be able to hit on the right approach or combination of experiments that brought about success. His next discovery was probably his most innovative, but was to be a bittersweet story. His experimentation, resulting in the discovery of wireless, became virtually hidden for many years and his discoveries only became known in the waning years of his life. His experiments took place a number of years before Hertz and Marconi. History finally credited him with the discovery but over time it has slipped off the pages of history.

It all came about when Hughes was experimenting with his induction balance in the fall of 1879. He had started with a primary circuit consisting of a set of coils being pulsed from a battery by clockwork driven contactor. A secondary circuit consisted of a second set of coils inductively coupled to the first that were connected to a telephone receiver. When he rearranged this configuration, it gave him some unexpected results – in that he could still hear the make and break signal even when he thought he shouldn't. He suspected it was either due to an effect called the "extra current" (the current induced in an inductor when its magnetic field rises or collapses) or the breakdown in the insulation of one of the coils.

However, it turned out to be a loose connection between some wires. As the effect was puzzling, he pursued it, substituting one loose connection for another by inserting one of his loose connection microphonic joints from his microphone experiments. Still he continued to hear the signal in his telephone receiver. The mystery grew as he separated the primary circuit from the secondary by some distance and only connected by a single wire. He was struggling to understand how the signal could be heard with a circuit that was apparently incomplete - that is an open circuit.

He also experimented by removing the coils from the secondary part of the circuit and he could still hear the signal of the make and break in the telephone receiver. He then proceeded to the next inevitable step. He cut the connecting wire and still could hear the signal. He was baffled and rationalized that the signal must be traveling between the two circuits by "conduction" through the building structure. Initially the gap between the two circuits was only six feet. He then moved the receiver (although Hughes didn't use this term until much later) to the next room, and eventually some 60 feet of separation.

What was significant was that he was detecting the make and break with a receiver in which the secondary coils had been removed and consisted only of a telephone receiver in parallel with his microphonic joint. In these experiments, he had started to ground one side of the circuit to either a gas pipe or water pipe (not unusual for a telegraph engineer). He also took the receiver a couple of floors down in his house to his basement where he could still plainly hear. He grounded the receiver to one of the pipes and believed the signal grew louder and put this down to the fact that the different metals were creating a battery effect. This led him to add a small low voltage battery to the receiver circuit with the microphonic joint.

To solve the mystery as to how signals were traveling between the transmitter and receiver he suspended the receiver by nonconducting cords from the ceiling and concluded that it could no longer be conduction through the house structure but the signal was coming through the ether (the air was considered to be more complex in the Victorian period). He concluded it was traveling by lines of force and the more of them he intercepted the louder he could hear the signal. It is surmised he came to this conclusion by comparing it to the invisible lines of force that surround a magnet or current carrying conductor.

Although he continued to call the device a microphonic joint it had become a detector and through extensive experimentation it had taken on a much different form and characteristics. His experiments revolved around trying to improve this device so that he could hear signals louder. He settled finally on two configurations for the detector: one of oxidized copper wires looped together, and the other a steel needle resting on a piece of coke. He encapsulated these detectors into small bottles for protection. In arriving at these he had also tried many other forms of his microphone components with mixed results such as a glass tube filled with metal filings and iron wires dipped into mercury.

Hughes next took his receiver and walked out into the street and continued walking, and was still able to hear the signal until by 500 yards it had faded away. This was an embryonic “wireless” experiment but the phenomenon of creating the invisible electromagnetic waves and being able to detect their presence was unknown at the time. It is interesting to note that his previous inventions of the microphone and induction balance and his use of the telephone receiver were all necessary prerequisites and essential ingredients leading up to this discovery. (Fig 9).

Hughes was a scientist of the school that was called “the practical men” whereby discoveries were made by experimenting. Any supporting theory or formula was a rarity and quite often regarded as suspect by these “practical men”. However there was a new breed of scientist surfacing. These were mathematicians and physicists who tackled problems first from a theoretical point of view. One such person was James Clerk Maxwell, a brilliant Scottish mathematician and physicist working at Cambridge University. In the 1870’s he predicted mathematically the theory of electromagnetic radiation, (the basis of wireless signals), a theory he amazingly developed without any experimental evidence or indication of how electromagnetic waves might be produced or detected. Looking back, this was profound, and its impact wasn’t fully understood at the time.

Meanwhile, just over 50 miles away in London, Hughes had experimentally demonstrated just what Maxwell had predicted and had produced electromagnetic waves and detected them – which was the experimental validation of his theory and the missing link. Unfortunately, fate was to intervene, Maxwell died young in 1879, the year Hughes made his discoveries, and Hughes, who was not a mathematician, would not have been able to decipher Maxwell’s complex mathematical equations.

Hughes, however, was so ex-

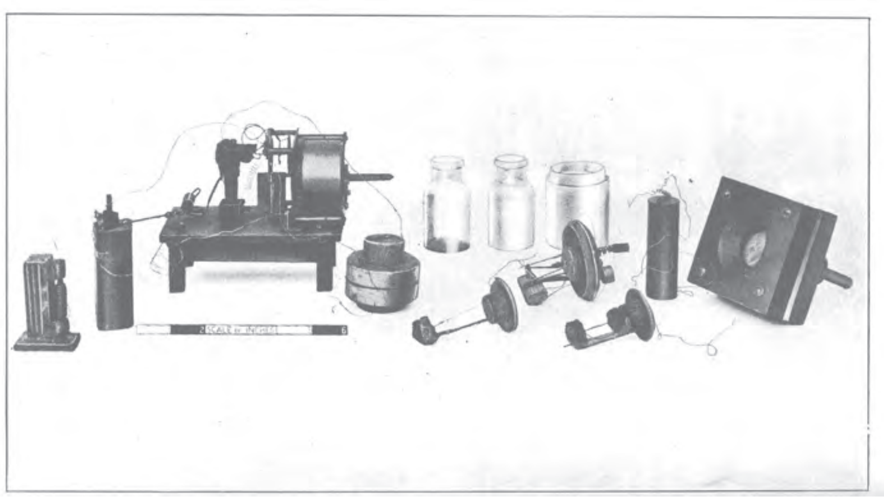

Fig. 9. Hughes wireless components.

cited by what he had discovered that he repeated his experiments in 1880 to important members of the Royal Society, the premier scientific organization of the day that included Professor Gabriel Stokes. Stokes was also from Cambridge University and a mathematician who knew Maxwell and was aware of his work. Could he possibly make the connection between Maxwell's theories and Hughes experiments? However, it all unraveled, and what could have been the start to a brilliant discovery, possibly Hughes greatest, and the verification of Maxwell's work was stopped dead. Stokes observed the experiment and stated that it was not a new phenomenon and could be explained by already known facts of electromagnetic induction. He failed to make any connection with Maxwell's theories or recognize it as a new phenomenon. It was just like pricking a balloon, dashing Hughes's hopes and swaying the opinion of the other observers in the process. Thus, a promising discovery, instead of being encouraged, was scuttled. Hughes was frustrated and angry after the meeting. For some reason, though, Hughes did not appear to have talked about his theory of the signals being transmitted by lines of force, but talked about conduction, probably confusing the issue.

Hughes was, however, reluctant to cross Professor Stokes, a man whose opinion was so widely influential. It is unfortunate that these experiments were not disclosed to scientists with a better understanding such as Oliver Lodge or George Francis FitzGerald. These two young scientists had become fascinated by Maxwell's work and could have perhaps grasped the significance of Hughes experiments, and so could have advised him accordingly.

Hughes by this time had probably become aware that he was to be proposed for membership to the Royal Society, a status that he deeply sought. This provided a further reason not to strike any discord with Stokes or the other members of the Royal Society for fear of jeopardizing his election. Had Hughes' work been recognized at the time it would have pre-dated Hertz by nearly a decade and Marconi by two decades.

As it was, his wireless experiments were not to come to the attention of the general scientific community for another twenty years when Sir William Crookes made some remarks about witnessing some of Hughes wireless experiments many years earlier. The author J.J. Fahie, who was close to completing a book on the "History of Wireless Telegraphy 1839-1899", was, like many others taken completely unaware. [24] He immediately contacted Hughes to follow up on Crookes remarks. Hughes at first was reluctant to divulge the information, unwilling to upstage the work of Hertz and Marconi that had occurred in the intervening years. A generous gesture. Fahie was eventually successful in persuading Hughes to relate to him the experiments and included them into his book. They were also recounted in a number of technical journals.

Hughes did become a "Fellow" of the prestigious Royal Society in 1880 and continued research and experimentation. He had always been interested in the molecular aspect of materials and magnetic properties of metals and it is to this that he next turned his attention . During the early 1880's, he presented many papers on such topics as "Molecular Rigidity of Tempered Steel", and "The Cause of Evident Magnetism in Iron, Steel, and other magnetic Metals". He, like other scientists, was deeply interested in what magnetism was. He presented papers on "Molecular Magnetism" and "Theory of Magnetism based upon New Experimental Researches". During the course of the experiments, he devised a new instrument called a "Magnetic Balance" that enabled magnetic strengths to be measured.[25]

It was during this period in the 1880s that it seems Hughes finally managed to find time to marry his long time friend from Paris - Anna Chadbourne in 1882. She was an accomplished artist, a resident of Paris and also an American citizen. She had been widowed a number of years earlier when her husband, Charles Morey, a promoter of Goodyear's vulcanizing rubber process, was unfortunately, due to a misunderstanding, put in debtors prison, where he was accidentally and tragically shot by a prison guard.[26]

For Hughes his wife was a great supporter of his work and a great help with the many social requirements and engagements of the various societies that he belonged to. It is due to his wife that we have some documentation on his life, as it was she who made copies of his letters and made small notes of his memories of his early life.

In 1886, Hughes was elected President of the Society of Telegraph Engineers (later to become the Institute of Electrical Engineers). Ducking the usual formal acceptance speech Hughes decided instead to share with the society some of his resent researches. The subject was: "The Self Inductance of an Electric Current in Relation to the Nature and Form of its Conductor".[27] He was aware that he had obtained some unexplained results and hoped that by sharing them with the members of the society it would result in some discussion and possible explanation which he certainly got. He probably wasn't ready for the torrent of comments and depth of discussion that followed.

The experiments he presented had been conducted to investigate the interference on telegraph lines during the transient switching period such that occur with the leading and falling edges of pulses. It was an area that had received little attention, but was believed to be the cause of many of the problems that still plagued the industry. The results he presented stimulated an interesting outcome. Hughes like many of the members of the Society was one of what were called the practical men – those who had come about their knowledge via hands-on experimentation and years of experience. There were also members of the society who were academics and who had risen through their university training. They were, however, in the minority and were viewed with suspicion by the practical men, whose attitude was, if they hadn't been "field tested", how could they have anywhere near the knowledge of the practical men.

There was also the matter of terminology that led to miscommunication between the practical men and the theoreticians. Standardization of electrical terms was still in its infancy and it was not uncommon therefore for terms to be invented, especially by the practical men.

When Hughes presented his experiments and results they were totally contrary to what the academics would have expected. This time they couldn't sit by and not challenge them. Lord Rayleigh became their spokesman and believed that Hughes's equipment was in fact not measuring what he believed it was.[28] Hughes had made his experiments based on a modification of his induction balance. Rayleigh was an excellent spokesman working with Hughes in a non combative manner to delve into his experiments and ending up devoting a year of his time to help sort it all out. The dissection of Hughes experiments and discussion in the technical journals ranged far and wide.

It turned out that Hughes experimental apparatus was flawed and thus the majority of his results were incorrect. Nevertheless, there was one set of experiments in which the academics saw some merit. On the recommendation of Rayleigh and others Hughes modified his apparatus and reran the experiments, this time obtaining less controversial results. However in the one area that had previously shown some merit, Hughes obtained additional important data.

For one scientist though, the whole episode had proved too much. This was the reclusive scientist Oliver Heaviside who never ventured out to any of the scientific meetings but communicated via letters and through the technical journals.[29] He had been publishing highly mathematical papers for some time in the journal *The Electrician* which had drawn little attention. Now he saw in Hughes' experiments some results that appeared to verify a mathematical analysis he had made the previous year. Not wanting to lose out on the credit he also joined the discussion. It turned out what Hughes had demonstrated was an increase in a conductor's resistance with an increase in a signal's frequency. This was to become known later as the skin effect, whereby the higher the frequency the more the current crowded to the surface of the conductor resulting in an increasing resistance. At RF frequencies the current flows only in the skin of the conductor. Oliver Heaviside had mathematically proven this, which he called the thick wire effect and took Hughes' experiments as the practical verification of his formula.

For the theoreticians it was verification of their worth, that theory could predict a practical outcome and was starting to explain many of the mysteries that surrounded electricity and magnetism. Oliver Heaviside's work finally started to get the recognition it deserved. Hughes' experiments had finally provided the opportunity for him to shine and it was to be the turning point from where the theoreticians or the "new school" as Hughes called them, started to come into prominence and the old school practical men's influence started to fade.

Hughes continued to be recognized for his scientific contributions and in 1885 was awarded the Royal Medal from the Royal Society. He was also active with the Royal Institution becoming their Vice President in 1891. The Royal Institution had had such prestigious past presidents as Sir Humphrey Davy and his protégé Michael Faraday.

Hughes realized as time went on that his breakthrough invention period was probably over. He still continued to receive money from the success of his telegraph systems and he had judiciously invested it providing him with a sound financial base. He and his wife, while enjoying a comfortable lifestyle, were not extravagant, and elected to live in an apartment on Great Portland Street and later around the corner in Langham Street. They enjoyed an extended tour of Europe each summer.

Hughes started to redirect his energies in other ways such as helping younger prospective engineers and scientists on their way. He was keen on seeing them get ahead with an education especially if they showed initiative in helping themselves. To be in a better position to promote and influence them, he became associated with the London Polytechnic School of Engineering and became their President. He took the job seriously and often stayed up late at night writing letters of encouragement and advice to students, giving them hints and opinions on their inventions or experiments.

He continued to be recognized for his work and was awarded the Albert Medal in 1897. A medal that Faraday, William Thomson (Lord Kelvin), Louis Pasteur and Sir Joseph Lister had previously received. As the century came to a close his health started to deteriorate and he barely saw the New Year in as he died on 22 January 1900 and was laid to rest in Highgate cemetery.

Always generous in life he was also generous after his death. Hughes' estate was valued at £472,704, ($2,268,979). [30] Hughes was in the minority, being a self-made scientist who actually was a financial success. After providing for his wife and relatives he left a substantial amount of his wealth to the London hospitals in the form of "The David Edward Hughes Hospital Fund". This fund is still in operation today and still providing benefits to the hospitals.

To the professional organizations he left sums of money to establish medals, awarded annually in recognition of original scientific research. The Hughes medal continues to be awarded annually at the Royal Society and has been awarded to such notables as Stephen Hawking in 1976 and Alexander Graham Bell in 1913, as well as: Max Born, Robert Watson Watt (Radar), H. Geiger, Neils Bohr, Edward Appleton, Ambrose Fleming and Augusto Righi.

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This article was peer-reviewed.

PHOTO CREDITS

Fig. 1 DEH Papers
Fig. 2 DEH Papers
Fig. 3 American Telegraph, W.Maver.
Fig. 4 I. Hughes
Fig. 5 - Smithsonian Museum, Wshington
Fig. 6 - Archive de France Telecom, Paris
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Fig. 9 - Sciences Museum, London

ABOUT THE AUTHOR

Ivor Hughes spent his early years in the UK and has had a life long fascination with electronics. He initially served as an apprentice in the telephone industry where he received a great practical education that ranged from the basic telephone through to RF group carrier systems. After receiving his BSEE he went into R & D, working on Navigation and Attack electronic systems for aircraft for the British Aircraft Corporation. In the late 1960's, he was recruited by United Technologies in the United States to work in their Electronic Avionics Division as a systems engineer. Here he was involved in electronic systems design of jet engine propulsion controls and flight controls.

In the 1970's, he moved employment to Goodrich Aerospace to work as a system designer of avionics systems. As the work also included flight testing in helicopters it was both an exhilarating and exciting experience on which to end a career.

During his employment, Ivor was awarded a number of patents. His career spanned the wide technology transition that started with analog circuits through the mixed analog/digital period into the digital and software driven designs of today.

Since his retirement, he has had more time to devote to experimenting and researching the history of technology of telegraph and early wireless. For the last few years, he has focused in on his namesake David Edward Hughes. The results of this research are to be published in book form next year (2010) as a biography of Hughes.

Ivor Hughes