

5. Second case study – the birth of electronics

He [Clerk Maxwell] lived towards the end of the last century and his world was, of course, vastly different from the world of today. There were no motor cars, no telephones, radio valves or aeroplanes, and even insulated copper wires were not available to him; possibly he would not have used them if they had been, as he was a thinker rather than a practical experimenter....

The mathematical formulae which he employed were very complicated and it is only given to a few people to understand them.

RS Elven
Outline of radio, p130

Inventors were few in those earliest years of the century. Invention was easy, the soil exceedingly fertile, and the Patent Office not yet clogged with thousands of pending applications on insignificant, or hardly distinguishable, details. Consequently the incentive to strike out and pioneer on paths radically new, and therefore wondrously attractive, was intense. In rapid succession followed the auto-detector (self-restoring, electrolytic, and crystal types), the telephone receiver, the alternating current transmitter, the two-tuned circuits at sender and receiver, the high frequency spark, the quenched-spark gap, the Poulsen arc and tikker, the direction finder, the series selective circuits of Stone, the heterodyne principle of Fessenden, the Audion as detector and as radio-frequency and telephone amplifier, the Alexanderson high-frequency generator, and the Audion oscillator (first as regenerator for heterodyne reception, then as transmitter for telegraph and telephone). All of these kaleidoscopic changes were accomplished in less than eighteen years – from 1900 onward.

Lee de Forest
Father of radio – the autobiography of Lee de Forest p249

One of the first things that was fully developed in our minds was the necessity of occupying the field; not only that but of surrounding ourselves with everything that would protect the business Just as soon as we started into the district exchange system we found that it would develop a thousand and one little patents and inventions with which to do the business which was necessary and that is what we wanted to control and get possession of.

President of AT&T
FCC investigation of Bell System, 1934

It is a matter of passing historical interest that it is almost fifty years ago to-day that what may be regarded as the greatest invention of the modern age first saw practical expression. It was fifty years ago that Marconi first transmitted a wireless message.

Lord Lucas of Chilworth
introducing the second reading of the Patents and Designs Bill
Hansard (H.L.) 29 March 1949 c752

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

5.1 Introduction

The first case study traced the development of artificial illumination from the early light sources through to the incandescent tungsten filament lamp, which is still the most widespread method of lighting in use today. Although driven by socio-economic considerations, technological innovations were shown frequently to be initiated by serendipity and their development constrained by the physical properties of materials. A second case study, presented in this chapter, follows the evolution of communications and electronics. This technological development was chosen to cover a similar period of history to that of the initial case study. Since they occurred in a similar socio-economic environment, many influences were common to both regimes. A comparison of the mechanics of the paradigm changes with that of those studied in the initial investigation will therefore highlight the effect of the differences. As many of the key events which shaped the evolution of communications were shared with the lighting and electrical industries, the two case studies are built around a common chronology.

Appendix 2

After looking at manually-operated, visual communication systems which were used almost exclusively for military purposes, this case study investigates how the technological innovation of the battery and the discovery of electromagnetism gave rise to different forms of the electric telegraph. It considers how nineteenth century commercial pressures led, first to land-based lines following the wayleaves of the railways, and then to submarine cables which linked continents. Finally, it traces the complementary innovation of radio and some of the inventions which made it feasible.

Although the national economies in which development took place were the very ones which provided the environment for the evolution of the electric light, the global nature of communications meant that international agreement was necessary to regulate the growth and operation of cable and its sister paradigm, wireless. The case study therefore illustrates the effects on innovation of this additional influence.

Due to the underlying military application of communications technology, ordnance procurement and two world wars were also expected to play a significant role. Furthermore, since a temporary suspension of the US patent system took place when the

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Americans entered hostilities in November 1917, an opportunity was presented to review the influence of the presence or absence of this statutory monopoly.

During the growth of these technologies, arrangements were set up for the pooling of patents. It was therefore possible to investigate how this reduction of competition impinged on the development of the industry.

As with the previous case study, the effects of the various determinants are discussed in the concluding section.

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5. Second case study – the birth of electronics

5.2 Early communications

Early long-distance communication was by means of the signal fire, but, towards the end of the eighteenth century, Chappe, in France, invented the semaphore, which was rapidly adopted for military communications.

Girling 1978, 11 p582

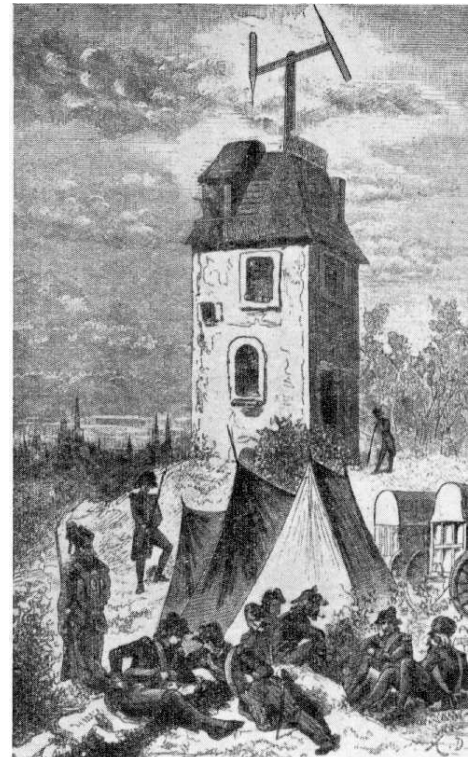
In Britain, the Admiralty erected a chain of semaphore towers between London and Portsmouth and these were used for transmitting messages to the navy. In 1814, Ralph Wedgwood submitted plans to Lord Castlereay at the Admiralty for an electric telegraph to replace the semaphore, but was informed “the war being at an end, and money scarce, the old system was sufficient for the

country.” Jarvis 1956a, p132 Another electric system was proposed two years later by Sir Francis Ronalds, the Honorary Director of Kew, who used a static electric charge to cause two pith balls suspended in front of a dial to diverge so that their position indicated an alpha-numeric character on the dial. Continuous current systems had their origins around 1809 when

von Sömmering constructed a 35-wire telegraph in which 25 characters of the German alphabet plus ten numerals were indicated by electrolytic decomposition of water at the end of selected wires. Jarvis 1956a, p135

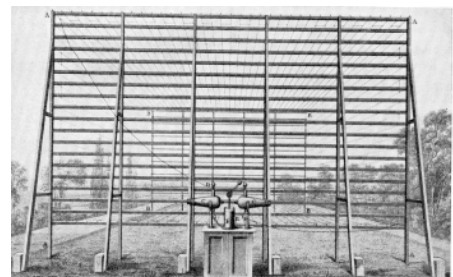
In 1819, Oersted discovered that an electric current deflected a neighbouring magnetic needle Girling 1978, p582 and around 1825 PL Schilling demonstrated first electromagnetic telegraph based on deflection of magnetised needles.

Jarvis 1956a, p136



Jarvis 1956a

Fig. 5.1 Chappe's semaphore at the siege of Condé-sur-l'Escault,



Jarvis 1956a

Fig. 5.2 Ronalds' electrostatic telegraph Upper Mall, Hammersmith (1916)

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5. Second case study – the birth of electronics

5.3 Cable

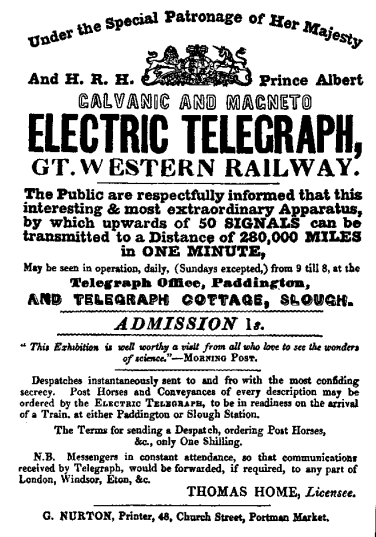
The spread of the railways provided a powerful impetus for the introduction of reliable communications systems and, in 1837, Cooke and Wheatstone produced the first practical electric telegraph, which was based on an idea Cooke had seen demonstrated on 6 March 1836 at Heidelberg. In this system, five magnetic needles were deflected by individual current-carrying lines to point to a character on an indicator panel. A five-bit code later formed the basis of the telex system which persisted for most of the twentieth century.

There was a flurry of activity at this time. Girling 1978, p582 Karl Steinhill (1836) devised an electric telegraph in which two gongs of different pitch were actuated by magnetic needles to give a code of audible signals. In 1837 Morse, in the USA, devised his electromagnetic telegraph, whilst, in Scotland, Edward Davy produced a system which operated along similar lines to that of Cooke and Wheatstone. Eng Pat 7719/1838

Cooke and Wheatstone filed the application for their first English patent for “giving signals and sounding alarums in distant places by means of electric currents transmitted through metallic circuits”, which was sealed on the 12 December 1837. Eng Pat 7390/1837

They subsequently disputed inventorship and submitted to arbitration which credited Cooke with having reduced telegraphy to practice. He later transferred his electric telegraph patents to the newly-formed Electric Telegraph Company Ltd. Jarvis 1956b, p590

In 1839, the first railway telegraph line was installed between Paddington and West Drayton using a five-wire system. Jarvis 1956b, p589 The relationship between telecommunications and the railways was symbiotic. Control of train movements created a demand for rapid passing of messages, whilst the rail track provided a long-distance wayleave for the telegraph cable. (History is currently repeating itself

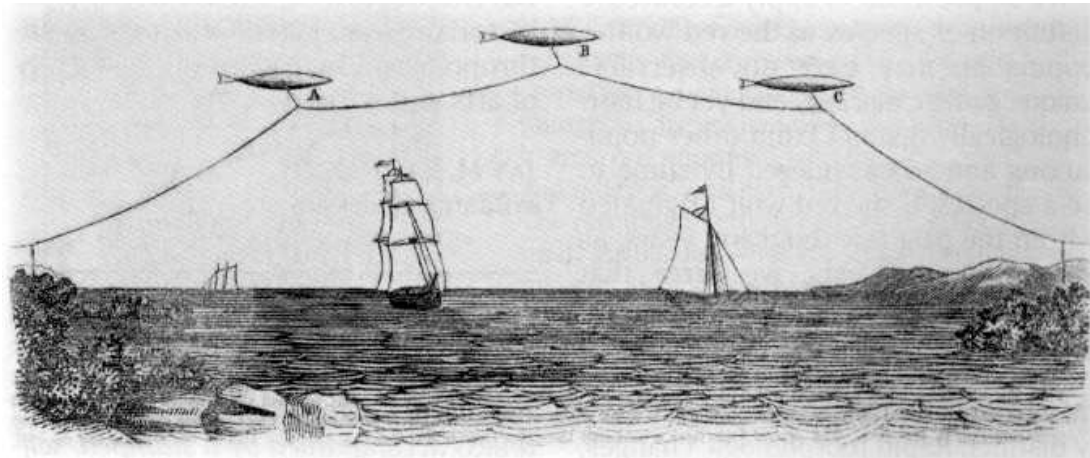


Jarvis 1956b

Fig. 5.3
Leaflet publicising the electric
telegraph installed by Cooke and
Wheatstone

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics



Scientific American, Nov 1845

Fig. 5.4 The magnetic telegraph crossing a river

with the laying of fibre optic cables from railway terminus to railway terminus, city centre to city centre.)

Meanwhile, Cooke and Wheatstone were planning a cable under the Thames.

The Enderbys are a wealthy family who have made most of their money in the South Sea trade. They have a large sail-cloth and rope manufactory at Greenwich, and a great many other undertakings on hand. I am going down to Greenwich tomorrow morning to see their works and arrange a method of covering our wires with yarn and including them in a rope, for our cross-Thames experiment. I sent off the wire yesterday. This rope, 1500ft in length, including 6000ft of wire, is to be ready by the close of the week.

Letter from Sir William Fothergill Cooke, 23 May 1837

The partners' cable was the precursor to the use of submarine cables for international telecommunication services. Most of these cables, with the exception of those across the Atlantic, were British owned. The cable industry sprang up in England, partly due to the British dominance of world trade in gutta percha, a rubber product which was used as an insulator, and partly because the mother country had a need to communicate with the outposts of Empire. In a just over half a century, England acquired control of international communication. *Sturmev 1958, p126*

Great interest in the possibilities of communication across stretches of water led to a variety of techniques being proposed. One of the more fanciful involved supporting the wires by means of elliptic balloons, sixty feet long and costing \$200 each. It was estimated that each balloon would support about 40 pounds besides its own weight. They would be made of thin varnished cloth and inflated with hydrogen gas and would be attached to a small pipe $\frac{1}{4}$ inch in diameter to replenish the gas. *Sci American, Nov 1845*

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

The brothers Jacob and John Brett pioneered cable laying. Between 1845 and 1849 they formed a series of companies to install submarine cables. After experiments in 1849, their third company, the English Channel Submarine Telegraph Company laid a cross-Channel cable from Dover to Cap Gris Nez in 1850. This failed, but a further cable, laid the following year, was still working ten years later. ^{Sturmev 1958, p73}

In 1856, an American, Cyrus W. Field formed the Atlantic Telegraph Company in England with a capital of £350,000, of which he subscribed £88,000. Following two failures, a trans-Atlantic cable was successfully laid and the first messages were transmitted on 5 August 1858. This cable was short-lived and had completely given up the ghost some eleven weeks later. As with many other early cables its failure was due mainly to the lack of experience of the technological problems which were encountered and to consequent unsatisfactory techniques used in the manufacture and operation of cables. In 1865 the company made another attempt to lay a trans-Atlantic cable which was abandoned when the cable broke at a depth of 2,000 fathoms. Before the cable was eventually completed in 1866, the company, which had been re-formed under the name of Anglo-American Telegraph Company, had commissioned another cable which was laid in one operation by the *Great Eastern*. By 1898, there were fifteen cables across the North Atlantic. ^{Sturmev 1958, p74}

In 1864, the cable companies set up a pool to protect rates, which remained at 2s. per word until December, 1884 when it was reduced to 1s. 8d. per word to fight a newly-opened service of the Commercial Cable Company. In June, 1886, the pool companies reduced their rates to 6d. per word in an attempt to force the Commercial Company out of business. Commercial tried unsuccessfully to sell its cables to Western Union so it also reduced its rate to 6d. The 6d. rate was not profitable so, in September 1888, all the companies agreed to increase their rates to 1s. per word and they remained at this level for thirty-five years.

5.4 Communication by induction – a halfway house

Many telegraphic systems used a single wire to carry the signal and relied on a connection to earth to complete the circuit and provide a return path. At a fairly early stage, it was found that communication could be sustained even when there was no

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

direct connection between the transmitting and the receiving circuits. A current flowing in one induced a sympathetic current in the other. Preece, the Engineer to the Post Office, passed messages in this way across the river Tay in 1845. In 1882, when the Isle of Wight cable failed, he managed to signal across the Solent by induction currents. This led him to carry out further experiments. In 1895 he used the method to effect a temporary connection between the Island of Mull and the mainland. In 1899 a permanent inductive telephone was established between Anglesey and the Skerries lighthouse, and a similar installation gave telegraphic communication between Rathlin Island and the Irish coast. *Sturmey 1958, p18*

In America, in the mid-1880s, Edison experimented with induction to provide telegraphic communication between moving trains and trackside cables, but the idea was not a success since the signal was frequently lost due to imperfect coupling between the transmitting and receiving conductors. He merged his United States Railway Telegraph and Telephone Company with Phelps Induction Railway Telegraph Company and quit the business in April 1887.

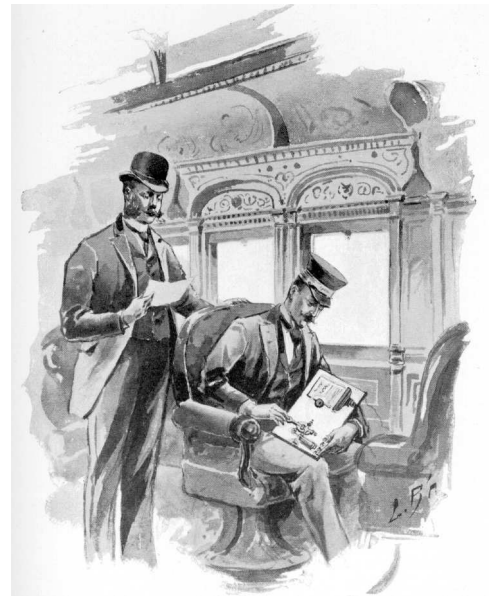


Fig. 5.5 Telegraphing from a Pullman parlour car on a train in motion

5.5 Wireless

In 1865 Maxwell had formulated mathematically the theory that electromagnetic effects travel through space in the form of transverse waves at the speed of light and Hertz confirmed this experimentally in 1887. *Ivall 1996, p461* He created electrical disturbances by means of an induction coil, a spark gap and a dipole aerial. In 1894 Professor Oliver Lodge used Hertzian waves for signalling. Both he and Marconi discovered that the process could be made more efficient by concentrating the signals at

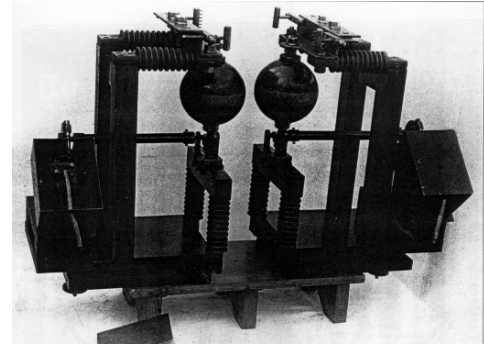
Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

a predetermined frequency by “tuning” them using a combination of induction coils and condensers. In 1897, Lodge employed tuned circuits for transmission and reception.

5.5.1 Early transmitter technology

Marconi’s first transmissions were made using a quenched spark. He later modified his apparatus by employing a rotary disc discharger to produce a regular succession of quenched sparks. These were synchronised with the alternator which supplied the charging potential to generate discharges at regular intervals. The resulting signals had a musical note which made them easier to read. Later examples had motors to rotate the spheres between which the discharge was struck, thereby reducing pitting of the surface.



Ivall 1996
Fig. 5.6 Spark gap for wireless transmitter (1905)

Meanwhile, in Germany, Professor Slaby was also working on wireless communication. In May 1897, he visited Britain and was present at a demonstration by Marconi in South Wales. It is alleged that Slaby was able to correct deficiencies in his system by using the knowledge gained from watching these tests and he became one of the main competitors of the Marconi Company. He describe his techniques in a book, *Spark Telegraphy*, which was published in 1897. Professor Slaby and Count Arco

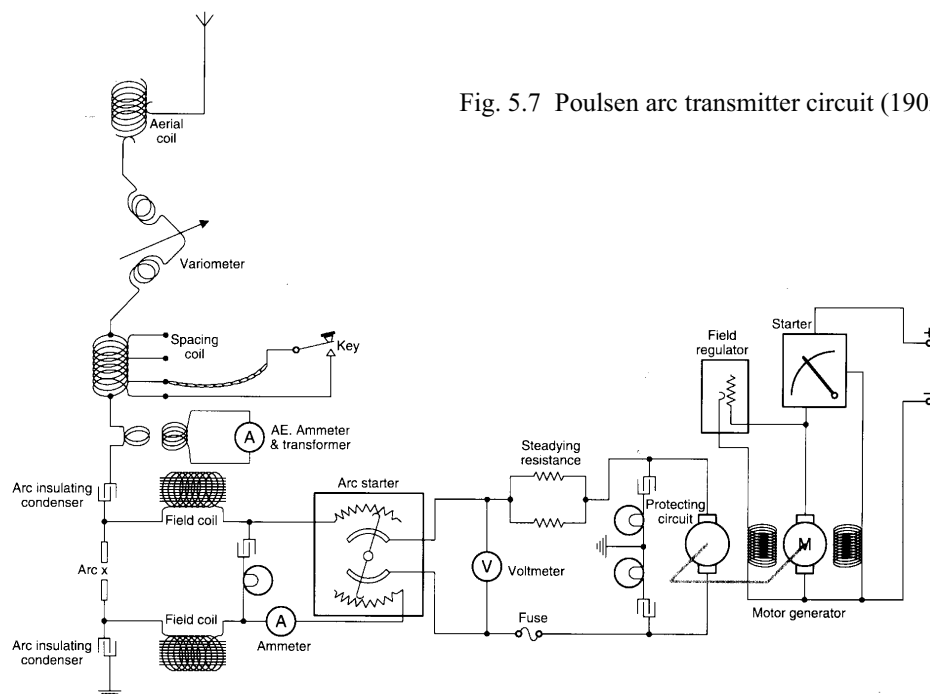


Fig. 5.7 Poulsen arc transmitter circuit (1902)

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

co-operated in producing the Slaby-Arco system and in 1903 amalgamated with Siemens-Halske to form the Telefunken Company.

Dudell, in 1900, created an audible sound from a continuous arc discharge. His ideas were developed by Poulsen, in Denmark to obtain radio frequency oscillations. ^{Ivall 1997} With this method, a continuous arc discharge was coupled to an inductor and capacitor which constrained the oscillations to the characteristic frequency of the tuned circuit, determined by the values of the components. The continuous arc had an advantage over the quenched arc as it could handle large powers and was thus suitable for long distance communication. It was, however, inherently unstable and its frequency tended to drift.

In 1906, RA Fessenden commissioned General Electric to produce an alternator designed to operate at 100kHz. They then assigned EFW Alexanderson the task of developing high power, high frequency alternators. ^{Tyne 1977, p133} He drove a six-hundred-pole-piece alternator at 20,000 rpm to generate a current at a frequency of 100kHz. Goldschmidt, in Germany, worked along similar lines. However, he used a relatively low speed and increased the output frequency by selecting harmonics using resonant circuits across the rotor and stator. At Eilvese, Germany and Tuckerton, USA he constructed 48kHz links in this way. At Nauen in Germany, the non-linear saturation characteristic of the cores of a series of toroidal transformers was harnessed in a quadrupling arrangement which increased the frequency of 200kW alternators to 24kHz. ^{Pickworth 1993} Keying of the signal was achieved by saturation of the core of a transformer. Common to all alternator transmitters was the need for extremely accurate workmanship to overcome the problems of running at such high speeds. The consequent cost limited their use.

5.5.2 Receivers

The first receivers were nonlinear detectors which converted the radio-frequency signal to an audible note. Marconi's initial experiments were based on the coherer, a device, invented by Professor Edouard Branly, which relied on imperfect contact between metal filings in a glass tube. Later he adopted a magnetic detector with two coils wound on a core of soft iron wires in front of which a permanent magnet was

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

rotated by clockwork. An alternative early detector was the semiconducting galena crystal which was first used by Telefunken in 1901. ^{Sturmev 1958, p30} This method became common practice five years later with the invention by Dunwoody and Pierce of detectors based on carborundum and other materials. ^{US Pats 837616, 879061, 879062, 879117} The “cat’s whisker”, as it became known as a result of the appearance of its fine metal contact, was widely used throughout the early days of radio and, indeed, the construction carried over to the first transistors in the late 1940s.

When rectified, the intermittent signal produced by the quenched spark produced a sound in high impedance headphones, but the continuous wave signals generated by the arc gave a dc output which was inaudible without the interposition of some form of interrupter device. The tikker, devised by Poulsen and Pederson for this purpose, consisted of a fine wire resting lightly on a metal cylinder rotating at high speed. The intermittent contact chopped the radio frequency current directly into on/off pulses.

Goldschmidt, who employed rotating machine technology, constructed a “tone wheel” which was essentially a commutator that, at a certain speed, gave half wave rectification of the wireless signal. The resultant direct current gave no audible sound in the headphones, so the speed was varied to permit it to slip in and out of synchronisation, alternately rectifying negative- and positive-going half waves to generate an audible tone.

5.6 The thermionic valve

5.6.1 Early developments

“As soon as Senatore Marconi had perfected and brought into use his admirable magnetic detector its many advantages caused the use of the coherer as a detector to begin to decline. Nevertheless, the magnetic detector had the disadvantage that the signals being audible only and received by telephone the telegraphist had no record of them as in the case of coherers employed with relay and Morse inker. Also the strain on the attention of the observer was greater, because if a code message was being received, the omission of a single *dot* or *dash* might make nonsense of such a word.

Hence the author was desirous, if possible, of finding some method of working a sensitive relay by means of the feeble oscillations or intermittent telephone currents. Furthermore, having become the subject of a progressive deafness, the writer desired to find some instrument to record the radiotelegraphic signals which would appeal the eye and not to the ear.”

J.A. Fleming

The thermionic valve and its developments in radio-telegraphy and telephony

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

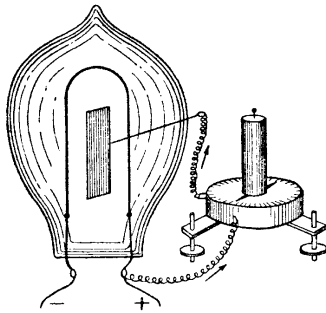


Fig. 5.8 Apparatus demonstrating the Edison Effect
Fleming 1921

On 26 May 1883, Edison and Upton observed a “molecular shadow” in the plane of the filament in incandescent lamps. Fleming 1883, pp283-284 and, six months later, constructed a thermionic diode from an incandescent lamp containing a shielding plate. Tyne 1977, p32

At Edison’s request the lamps were exhibited and a paper presented at the 1884 AIEE International Exhibition and Fall Meeting in Philadelphia. Houston 1884, pp1-8 Samples of these lamps

were taken back to the UK by William Preece, Engineer in Chief of the General Post Office. Preece duplicated Edison’s experiments and confirmed that current flow through vacuum depended on incandescence of the lamp. He coined the terms “Edison effect” and “blue effect” (glow). Preece 1885, pp219-230 J.A. Fleming, who had been appointed electrician to Edison Electric Light Company of London in 1882, carried out further experiments on these lamps and presented a paper on their characteristics to the Physical Society. He re-visited the phenomenon a decade later and showed that, even when energised by alternating current of 80-122 Hz, an incandescent filament lamp will only pass unidirectional or direct current. Fleming 1896, p99

The sensitivity of earlier wireless detectors, such as the tikker and the tone wheel, was determined by the threshold of an audible sound produced by the headphones. However, for Fleming, who at the start of the twentieth century was retained as scientific adviser by Marconi, the techniques which were prevalent at that time presented a major difficulty. He was afflicted by progressive deafness and thus set out to devise a form of detector which did not rely on the sense of hearing. He remembered his experiments on Edison Effect lamps and connected an Edison Effect lamp to a galvanometer to create the first diode detector. Under the terms of his consultancy agreement, Fleming was obliged to assign his invention to Marconi Fleming 1924 and it later became the subject of a conflict with de Forest that shaped attitudes to patents which persisted throughout the twentieth century.

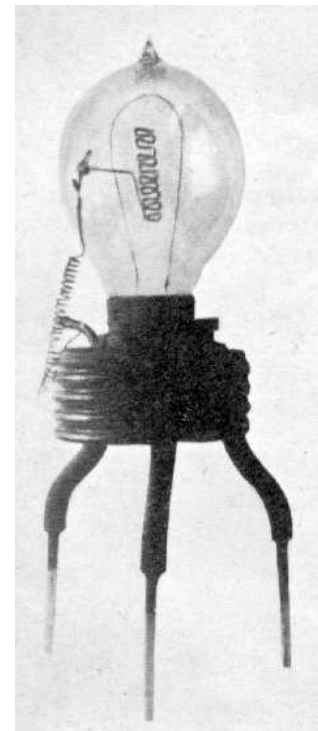
As early as 1851, flames had been shown to exhibit electrical conductivity. Buff 1851, pp1-16 Experiments at low pressure led to construction of a primitive thermionic

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

diode. **Becquerel 1853, pp355-402, Elster 1887, p120** In 1879, Braun used a beam of cathode rays to create a bright spot on fluorescent screen which could be deflected by electrostatic or magnetic fields. **Braun 1897, p552-559** Schuster advanced an hypothesis, that cathode rays comprised high-speed, negatively-charged particles derived by dissociation of gas molecules into positive and negative components. **Schuster 1884, pp317-339**

There was a substantial initiative in Germany to harness thermionic effects. In 1903, Arthur Wehnelt was studying the thermionic emission of platinum, when he noticed that a filament, which had been contaminated by grease, gave a strong electron emission at a temperature of about 1200°K, well



Fleming 1924,

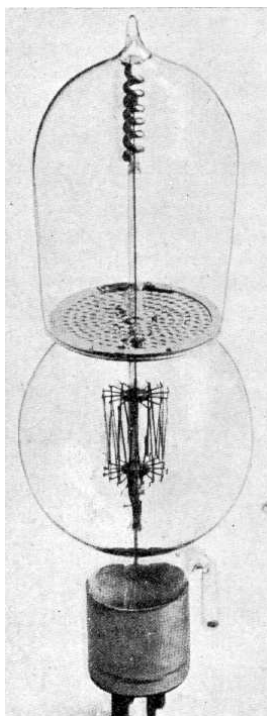
Fig. 5.9
Early Fleming diode (1904)

below that required for the

uncontaminated metal. Surmising that impurities within the grease gave rise to the enhanced emission, he carried out a series of experiments which showed that filaments coated with the oxides of alkaline earth metals, such as calcium and barium, would give an equivalent emission to an uncoated filament, but at a considerably lower temperature. **Throver 1992, p89 Wehnelt 1903, p150-158**

Oxide-coated heated cathodes were used in power rectifiers and shown to be usable at high frequency. Wehnelt even referred to Fleming's work as "probably stimulated" by his own. **Wehnelt 1906, pp138-156** A cathode ray oscillograph was constructed using 5-inch cathode ray tube. **Ryan 1903, pp539-552**

In March 1906, Braun's cathode ray relay was adapted as an amplifier using magnetic or electrostatic deflection of electron beam. The arrangement was similar to modern electron gun, with push-pull deflection. **Tyne 1977, p76** A cylindrical triode structure was devised to



Fleming 1924, p129

Fig. 5.10 Lieben-Reiß thermionic relay valve with Wehnelt cathode (1911)

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

measure ionisation produced by a heated filament. von Baeyer 1908, pp96-114 and, in August 1911, R. von Lieben demonstrated to leading German electrical manufacturers a three-electrode relay valve developed by himself, E. Reiß and S. Strauss. It did not have the correct characteristics to be used as a detector. Nevertheless, it could be used to boost audio output. Von Lieben, Reiß and Strauss formed a consortium to carry on development. Tyne 1977, p234 and the valves made a major contribution to the German war effort.

In America, Lee de Forest, who had been awarded his doctorate for a thesis entitled “Reflections of Herzian waves from the ends of parallel wires”, was also seeking new detectors for wireless signals. In 1900, whilst working for Western Electric with E.H. Smythe, they discovered that sound waves from a spark gap caused pressure variations in a Welsbach gas burner. Tyne 1977 De Forest then researched the rectifying properties of the gas flame. By 1905, he had set up his own company and developed a variety of detectors based on the sensitivity of gas flames to changes in electrical current. Tyne 1977, p53 On becoming aware of Fleming’s results, he turned to thermionic effects. Appendix 8 His assistant asked H.W. McCandless, a New York lamp manufacturer, to make duplicates of Fleming diodes Tyne 1977, p53 and, at the beginning of 1906 proposed the use of a two-electrode valve with battery-heated filament and separate battery in anode circuit as a detector. This was the two-electrode Audion. He was also influenced by a systematic investigation by Elster and Geitel of ionisation produced by incandescent metal in an exhausted tube with an insulated platinum plate adjacent the filament. Tyne 1977, p58 Although de Forest used only tantalum for the filaments, he postulated tungsten might be better. de Forest 1906, pp735-763 He also employed Wehnelt-type filaments coated with salts of potassium and sodium, but these had a short life. In November 1906, he ordered tubes with gridiron-shaped wire electrodes between filament and anode from McCandless. Tyne 1977, p61 The first samples were ready for testing by the end of the year. On 14 Mar 1907, he made the first public disclosure of three-electrode Audion at Brooklyn Institute of Arts and Sciences. Manufacture of triode Audions for commercial use was undertaken by McCandless, who remained responsible for all manufacture up to 1915. To address problems in the early days, some Audions were produced with a spare filament to be used when the first one burned out,

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

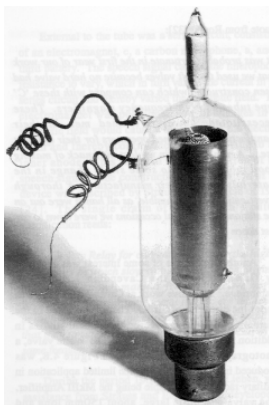
whilst others had two grids and anode plates to give higher power. Additionally, higher performance devices were selected at final test and sold at a premium price.

5.6.2 Technological evolution of the valve

Once the basic principles of the thermionic valve had been established, advances were made by developments in electrode materials and mechanical construction to enhance the emission characteristics and optimise the internal field topography. Later, changes were induced by the technological demands of new markets.

Early thermionic valves borrowed much from lighting technology. The first diodes were little more than an incandescent lamp bulb containing an extra electrode. US General Electric was the world's principal lamp manufacturer and, in 1906, they hired Irving Langmuir to investigate problems of tungsten filament incandescent lamps. He studied Edison-effect blackening of bulb ^{Tyne 1977, p135} and subsequently developed the inert-gas-filled lamp to overcome this effect. ^{Ediswan 1949, p52}

Initially, due to imperfect vacuum pumping equipment used in their manufacture, valves contained residual quantities of gas. They became known as “soft” valves and frequently glowed as a result of an electrical discharge in the ionised gases. At first, the presence of gas was thought to be advantageous, but gradually, the drawbacks were shown to be of major significance. Reiß attempted to use a soft valve containing mercury vapour as telephone repeater but it was noisy and suffered from cathode



Thrower 1994
Fig. 5.11
Round's soft valve

degradation due to ion bombardment. ^{Reiß 1913, pp1359-1383} In

July 1912, de Forest complained to his supplier McCandless that the vacuum in valves shipped to him was too low, resulting in insufficient sensitivity. ^{Tyne 1977, p113} The output

was increased by re-exhausting with a mechanical pump followed by a mercury pump whilst baking the filament and bulb to drive off occluded gases. Langmuir at GE engaged an assistant, W.C. White, who improved Audion valves primarily by removing occluded gases during manufacture ^{Tyne 1977, p137}

Finally, in 1914, E.H. Armstrong showed that the presence of gas in a valve was not essential for its proper functioning. ^{Sturmey 1958, p33} Meißner

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

produced a high-vacuum triode with metal plates on either side of filament to prevent electrons reaching the glass envelope. ^{Meißner 1922, pp3-23} Later, occluded gases were removed during valve production by heating the grid to white heat and the anode to red heat during the pumping process. ^{Dujussieu 1961, p43} Hard valves based on the structure of the Audion were developed by M. Pirani for Telefunken in Siemens' incandescent lamp factory. ^{Telefunken 1935, pp114-154}

As late as 1922, Philips were offering hard and soft versions of the same valve. ^{Tyne 1977, p416} That same year, Métal commenced using phosphorus as a getter, a technique in which a substance with a high affinity for oxygen was placed in the glass bulb and heated to cause it to combine with the oxygen in the residual gas. This principle had previously been used in the manufacture of carbon filament lamps. Other manufacturers followed. Another French manufacturer, la Radiotechnique, used induction heating to out-gas valves during evacuation. The very high vacuum required by thoriated tungsten filaments led to use of magnesium as a getter material. ^{Tyne 1977, p399} In 1924, valves produced by GE at Nela Park used a phosphorus getter, whilst those from the Harrison Works used magnesium. ^{Tyne 1977, p314} The use of phosphorus was, however, soon abandoned. ^{Tyne 1977, p315} By 1925, British manufacturers were also employing a magnesium getter. ^{Tyne 1977, p282}

Theoretical studies indicated valve life could be increased by increasing emitting area of filament and a doubled emitter area and other design changes proved to increase valve life from 400 hours (Type M) to 4500 hours (Type 101B), 50-100 times that of de Forest Audions. ^{Tyne 1977, p92} Some Audions produced by MacCandless had "Hudson" filaments (tungsten wrapped with fine tantalum wire). These were found to give enhanced emission. ^{Tyne 1977, p112} In 1918, Western Electric introduced a so-called dull emitter valve with an oxide-coated platinum alloy filament ^{Sturmey 1958, p39}

Whilst investigating the properties of tungsten, Coolidge found that it could be made more ductile by adding a small quantity of thoria. ^{Thrower 1994, p88} Langmuir discovered that filaments made from this material gave much higher thermionic emission than pure tungsten. From this, he developed a heat-treatment process for the manufacture of thoriated tungsten filaments which gave a similar emission to untreated tungsten, but at much lower operating temperatures.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Marconi-Osram introduced the dull emitter valve to the UK in 1921 ^{Sturmey 1958, p40} and, by 1925, these valves had superseded bright emitters on the French market. ^{Tyne 1977, p400} Different techniques were adopted to effect this change. Dull emitter valves, developed in the early 1920s, had thorium oxide-coated cathodes. ^{Clayton 1978, p115-116} La Radiotechnique produced a high-emission cathode by a barium

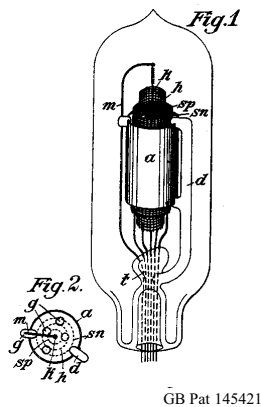


Fig. 5.12
Schottky valve with
space-charge
neutralising grid (1915)

nitride process in which an anode coating of barium nitride was heated to deposit barium on a cupric oxide cathode to form baria. ^{Tyne 1977, p400} STC produced valves which operated at lower filament currents using a process in which barium vapour was distilled into the bulb and the electrode assembly mounted at an angle. ^{Tyne 1977, p370}

In step with the improvements in efficiency effected through the use of new materials, advances were also obtained by altering the topography of the electric fields within the valve envelope. Hull showed that a triode with positive voltage, greater than the anode voltage, applied to grid exhibited a negative resistance (dynatron) effect. ^{Hull 1916, pp141-143} He subsequently constructed a four-electrode valve which performed a similar function. ^{Hull 1918, p5-35} Later valves had a space-charge-control grid comprising strips of sheet metal with their edges turned towards the cathode. ^{Tyne 1977, p253} In Germany, a triode constructed with a second grid between the filament and control grid to neutralise space charge, fell into disuse after the war when high stage gain was no longer important. ^{Schottky 1919, pp299-328} The first British screen grid valve, designed by H.J. Round of Marconi Osram, who undertook early development work on the triode valve, was introduced in 1926. Other manufacturers followed shortly after. ^{Geddes 1991, p68}

The first mass-produced valve, known as the 'R' valve, a triode developed in France in 1915, was based on light bulb manufacturing techniques. By 1918 it was being produced at rate of 1000 per day. ^{Geddes 1991, p9} These valves, which were widely used in military equipment, employed a robust, horizontally-mounted coaxial structure. ^{Girardeen 1968, p81} High performance versions were selected from general production runs. ^{Tyne 1977, p218} In 1922, it was discovered that valves made to rigid mechanical tolerances

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

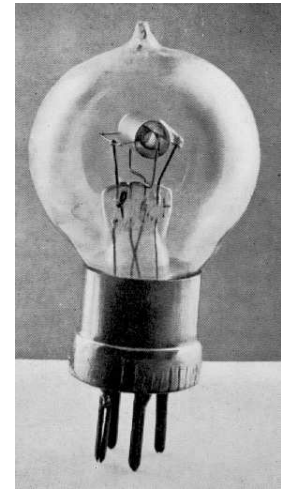
had low microphony, that is, they were less sensitive to spurious mechanical vibrations. ^{Nebel 1935, p222} Later that year, Cossor launched a successor to the ‘R’ valve in which the anode collected current more efficiently, the grid was rigidly supported to reduce microphony and the filament did not sag with age. ^{Geddes 1991, p49}

At first, valve equipment was operated using batteries. A low-tension cell provided the current for the filament and a high-voltage battery was the source of the high tension needed for the anode bias. Some circuits had a further low-voltage dry battery to supply a negative grid bias. This was clearly inconvenient and attempts were made to devise an arrangement with a single power supply. The first indirectly heated valves had the heater threaded through two holes in a ceramic cylinder inserted in a tubular cathode. ^{Geddes 1991, p68}

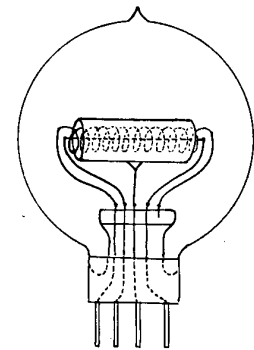
In April 1915, an experimental valve was constructed with an indirectly heated cathode consisting of a nickel sleeve coated with cathode material and having the heater inside. ^{Tyne 1977, p298}

In a French valve with an alternating current heater, produced in 1922 by Métal, operation was unsatisfactory due to excessive hum. ^{Tyne 1977, p404}

In December 1922, HW Freeman of Westinghouse developed a double-ended valve with an indirectly heated cathode. ^{Freeman 1922 p501}



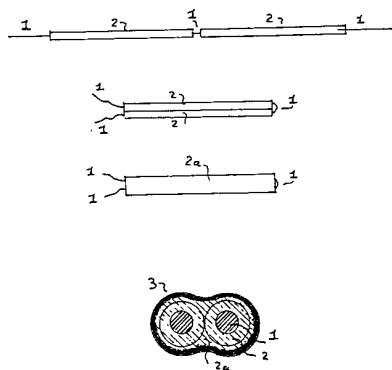
Fleming 1921



Fleming 1924, p123

Fig. 5.13

French R valve (1915)



GB Pat 2787875

Fig. 5.14

Cosmos valve slip-coated indirect-heater filament construction

ES Rogers added improved insulation to reduce mains hum in a valve which he developed from a McCullough valve. He then set up Canadian company to manufacture it. ^{Toronto 1939}

In 1926, demand for valves with ac filament heaters began to increase. ^{Tyne 1977, p319}

An improved design of E.Y. Robinson was adopted by MetroVick for their Cosmos valves. These had a thin hairpin heater insulated by baking on

5. Second case study – the birth of electronics

successive insulating coatings. The technique was adopted widely. ^{Geddes 1991, p68} In 1927, La Radiotechnique attempted to make low-heater-voltage alternating-current-heated valves employing heaters with high thermal inertia. They were an improvement but still not completely satisfactory. ^{Tyne 1977, p404} In 1929, four leading French manufacturers, la Radiotechnique, Métal, Grammont and Visseaux all produced indirectly heated valves coated with alumina by a dip-and-dry process.

Other changes were introduced to improve the gain characteristics. ^{Tyne 1977, p315} In 1924, GE engineers carried out extensive development to produce valves with a screening grid to reduce feedback capacitance between the anode and control grid.

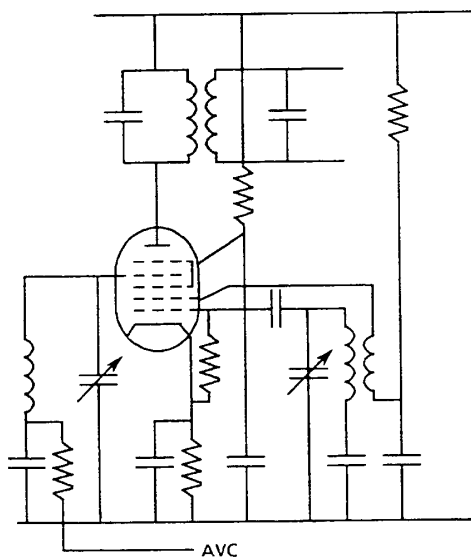
^{Tyne 1977, p318} In July 1926, the Baker-Smith Company of San Francisco sold a Quadratron valve with an auxiliary grid connected so that its polarity was opposite to that of the normal control grid.

^{Huppert 1926, pp50-51} In 1927, mesh anodes were fitted in place of sheet metal anodes in attempt to eliminate grid emission.

^{Tyne 1977, p320} In March 1929, an audio power output valve was produced by Westinghouse after nine month's development. ^{Tyne 1977, p321}

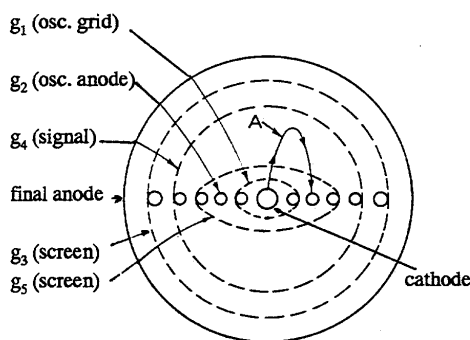
and, in 1931, Philips introduced the variable-mu (mutual conductance) tetrode and pentode. Their engineers also discovered that earthing a grid positioned adjacent the anode inhibited secondary emission of electrons. ^{[1934] RPC 333}

Due to short life, there was a large and profitable replacement market for radio valves. (Indeed, repair of burnt-out valves by replacing the filaments and re-evacuating them was economically viable until around



Thrower 1994

Fig. 5.15
Heptode frequency changer circuit



Thrower 1994

Fig. 5.16
Schematic arrangement of heptode valve

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

1926. ^{Geddes 1991, p63}) The valve manufacturers were therefore content to supply equipment makers at virtually cost price because consumers would invariably replace a worn-out valve with an identical model.

Development of new electronic circuits also created a demand for new types of valve. As early as 1905, the invention of the anode-bend detector led Fleming to construct a diode with a copper gauze shield and low filament current for the Marconi-Fleming valve receiver which was used for trans-Atlantic communication at Poldhu. ^{Fleming 1906, pp177-185} Fessenden's proposal to detect cw transmissions by heterodyning with local oscillations, conceived theoretically in 1902, became reality with the construction of multi-electrode valves such as the triode-hexode or the heptode and octode, a quarter-century later. Some amplifying valves constructed in 1916, had a protective-network grid inserted between the control grid and anode. No attempt was made to minimise grid-anode capacitance as with normal screen grids. ^{Tyne 1977, p253} Structures were modified to optimise the inter-electrode capacitance used in neutrodyne receivers invented by L.A. Hazeltine. ^{Tyne 1977, p315}

Changes were also introduced for pragmatic reasons. Increased aviation activity created a need for more rugged construction. ^{Tyne 1977, p329} Demand arose for valves capable of operation using dry batteries. ^{Tyne 1977, p330} A multiple valve comprising three triode elements with a common filament was manufactured by Cleartron Vacuum Tube Company. ^{Haynes 1927, p976-979} Westinghouse suggested the use of a five-pin base for indirectly-heated valves to eliminate double-ended construction. ^{Tyne 1977, p319} Loewe introduced multiple valves in a single envelope because patent royalties were charged according to the number of valve-holders in a receiver ^{Sturmeay 1958, p39} British manufacturers adopted a different connecting-pin spacing from that used on electrically-equivalent US valves to prevent imported valves being used for repair of British receivers – an early example of a non-tariff barrier.

5.7 The growth of radio

5.7.1 Communication with ships at sea

Although Marconi did not apply for his first patent on wireless communication until 1896, commercial operations began in 1898 with radio installations between the

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

South Foreland lighthouse and the East Goodwin lightship, and between Ballycastle and the lighthouse on Rathlin Island which were made on behalf of Lloyd's for the purpose of reporting ships passing the light. ^{Sturmev 1958, p48} Marconi's first radio transmission across the Atlantic was made on 12 December 1901 and the first complete message was sent just one year after this. ^{Sturmev 1958, p77}

Interest was widespread. In 1902, Valdemar Poulsen devised an arc transmitter which used the negative resistance of the arc, tuned by a circuit containing a coil and a condenser and in 1903, Professor Slaby and Count Arco co-operated in producing the Slaby-Arco system which was produced by the Telefunken Company. ^{Sturmev 1958, p20,23}

One of the driving forces behind the advance of radio was the need to communicate with ships at sea. In 1905, agreement was reached between the Marconi Marine Company and Trinity House for radio installations on six lightships. The arrest, in 1910, of Dr. Crippen, with its attendant publicity, provided a major boost for ship-to-shore communications. Having murdered his wife, he attempted to escape to Canada on the Canadian Pacific Liner *Montrose*. The captain became suspicious and sent a wireless message to Scotland Yard. A detective was despatched on the faster ship *Laurentic* and apprehended Crippen on his arrival.

Initially, the use of radio on ships was optional, but a number of disasters, notably the loss of the Titanic in 1915, gave wide publicity to the advantages of radio for preservation of life at sea. The 1914 Merchant Shipping (Convention) Act provided that

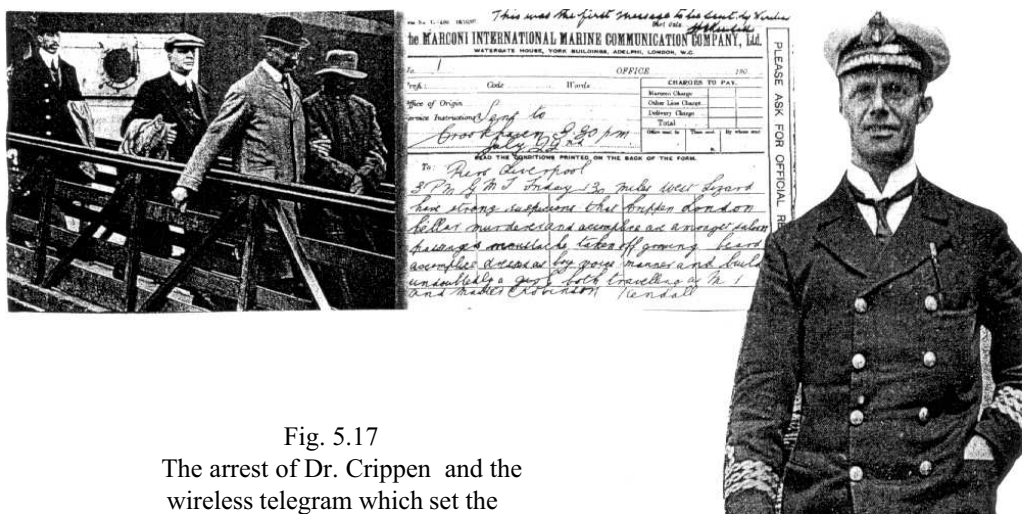


Fig. 5.17
The arrest of Dr. Crippen and the wireless telegram which set the wheels in motion (1910)

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

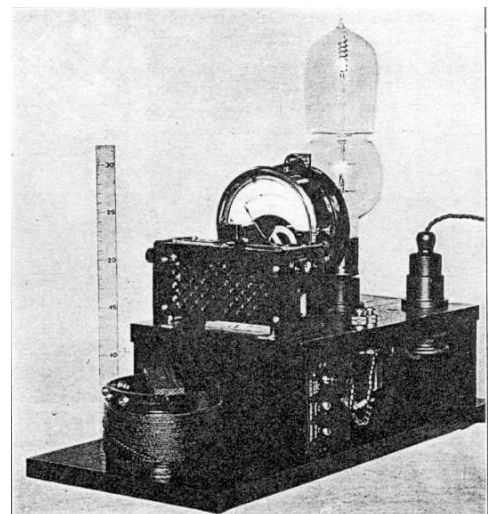
all British ships and foreign ships entering British ports, carrying fifty or more persons, must have a radio installation. Although enforcement of this act was delayed by the war, in 1916 a Defence of the Realm regulation required that all British ships of 3,000 tons and over should be fitted with radio and, in 1917, this limit was reduced to 1600 tons. *Sturmev 1958, p63*

In the early days of shipboard communications the Marconi Company attempted to defend its commercial position by refusing to communicate with installations of its competitors. Telefunken, in 1911, using a quenched spark transmitter, had entered the British marine market through its wholly-owned subsidiary Siemens Brothers, but during the war, Marconi Marine was the only company in a position to carry out the installations. It, therefore, established a dominant position and, by the end of the war, most British ships were equipped with Marconi apparatus. Subsequently, several other companies entered the field but did not take much market share from Marconi.

The development of the thermionic valve made communications much more reliable, but the use of electronic transmitters and receivers advanced only slowly. The reason for this was that spark transmitters were simple devices, both mechanically and electrically, and were relatively easy to maintain. Electronic equipment, on the other hand, demanded special skills which were not possessed by the average seaman.

Valves were rapidly adopted by the navy, but the merchant marine required the coercion of an international conference, convened at Washington in 1927, to decide to abolish the spark transmitter because of the interference which it caused. Thirteen years grace were given but, by the end of 1935, of the 14,813 merchant ships fitted with radio, 8,418 still carried spark equipment only.

Direction-finding equipment was another technology which drove wireless communication forward. Radio direction-finding in a ship is based on the reception of



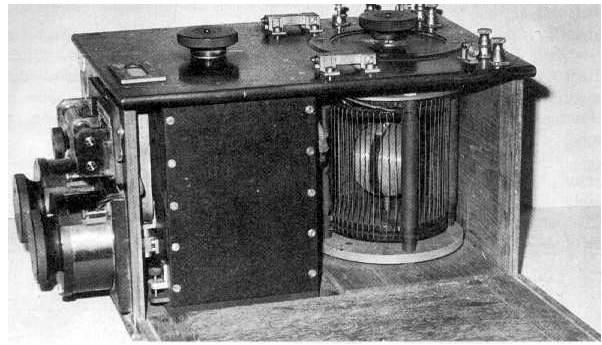
Meißner 1922

Fig. 5.18 Early Telefunken receiver using Lieben-Reiß relay valve (1913)

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

signals transmitted by beacons on the coast, the positions of which are known by their distinctive signals. Bearings can then be taken by the direction-finder and the position of the observing ship determined from the point of intersection. Results given were not always precise but were adequate for most navigational



Electronics World, Nov 1997

Fig. 5.19 Marconi-Bellini-Tosi direction finder receiver (1910)

purposes. Except in confined waters, they enabled ships to maintain their courses in conditions, such as fog, in which celestial or terrestrial observations could not be made. In 1912, the first radio direction-finder was installed on the *Mauritania*. This equipment employed the Marconi-Bellini-Tosi system, which used two large, orthogonally-mounted fixed triangular loop aerials which were suspended by their apices. *Sturme* 1958, p63 Initially, a crystal receiver was used, with the result that the direction-finder was insensitive and limited in range. However, the development of more sensitive radio receivers permitted the size of the aerials to be reduced.

The Marconi Marine Company, Siemens Brothers and RCC also produced radio direction-finder (DF) equipment but these were based on other principles which were claimed to be superior.

The installation of DF equipment was inhibited by the lack of radio beacon transmitting stations around the coast of Britain. Marconi installed the first one at Inchkeith in 1922 but Trinity House, the organisation responsible for lighthouses and lightships did not erect its first beacon until 1927.

Another major development was radio-telephony. This was a system by which voice messages were transmitted rather than the Morse code of wireless telegraphy. As well as simplifying the business of communication between ships and shore, this meant that passengers on board ships could contact telephone subscribers on shore.

The first commercial radio-telephony installation on board ship was made by the Marconi Marine Company in 1922. The company carried on experiments in radio-telephony throughout the 1920s, and in 1932 equipped a number of shore stations for

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

the Post Office. The first British installations of radio telephones date from 1930, when a service was started between the Post Office station at Rugby and trans-Atlantic liners, although similar installation had been made on a German ship as early as 1925.

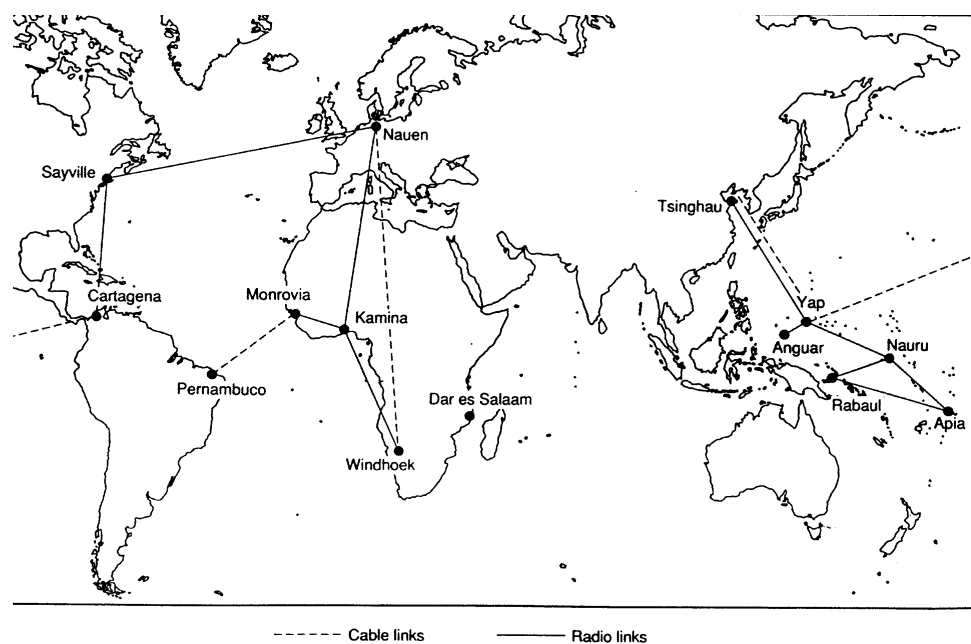
The advantage for small ships was that the equipment could be operated by any crew member. It became widely adopted in the 1920s and 1930s for communication between lightships and the shore, and between harbour craft and the shore. Shipping fleets, in particular, were fitted with RT systems.

5.7.2 The call of empire

5.7.2.1 Germany's imperial wireless system

Another force which drove electronics forward was the desire to communicate with inaccessible and distant locations. For colonial powers, this was a pressing need. Germany, for instance, had far-flung overseas territories and, at the turn of the century, was in the vanguard of the development of wireless communications.

In the early days of wireless, long distance radio communication was possible only with very long waves and was limited to a distance of a few thousand kilometres. In 1906, Germany had colonies in the Pacific, the Far East and Africa, all of which were beyond the range of the transmitters in the Fatherland. It therefore adopted a strategy of



Pickworth 1993

Fig. 5.20 German imperial communications in 1914

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

installing medium range stations throughout its possessions and linking these to Berlin via a submarine cable complex. A German-controlled station was also established at Sayville in Long Island, USA, primarily for communication with ships in the North Atlantic, and a second station, at Charlatan, Columbia, was connected to the Pacific and Atlantic submarine cable complex. ^{Pickworth 1993}

The central transmitter at Nauen and the main overseas stations employed radio frequency alternators, whilst feeder stations used Wien quenched-spark transmitters similar to those at Telefunken maritime relay stations.

When war was imminent, the range of the central transmitter at Nauen, near Berlin, was extended to reduce the dependence of the system on cables for outgoing messages. At the same time, the power of the Sayville transmitter was increased and a powerful transmitter was constructed at Kamina in Togoland to allow direct communication with Berlin. The Pacific stations were also developed to permit radio communication between all the German colonies and the German garrison at Tsinghau, China. Cables were, however, still required to link the area with Berlin.

In 1914, the range of the 24kHz Nauen transmitter was 8000km, giving good reception of signals at Sayville and Kamina, but Cartagena in Columbia, Windhoek, South West Africa, and Tsinghau remained fringe areas. The power of the Sayville station was further enhanced to maintain radio communication with Berlin and relay signals extended southwards to Cartagena which served as a staging post to smaller medium/long wave relay stations in South America.

At this time, the Kamina station could maintain direct communication with Berlin and relayed messages to and from Windhoek. If conditions were good, direct communication was also feasible between Windhoek and Nauen. This was the only radio link extending to Southern Africa. Relay stations joined Kamina to Douala in the Camerouns, Dar es Salaam in Tanganyika, and Monrovia in Liberia, which was the terminal for a German submarine cable connected with South America.

In the Pacific, the main radio station was at Yap in the Caroline Islands. This was linked by cable to Tsinghau and America. The Pacific radio network stretched north-west from Yap to Tsinghau and eastwards to Nauru Island and Apia in the Samoa Islands. There were extensions to Anguar in the Palau Islands, and Rabaul, New

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Britain, and feeder stations coupling the numerous islands with the principal stations. Overseas signals were received at Geltow, near Berlin, which like Nauen, was connected to Berlin by land lines.

Immediately on declaration of war, Britain cut all German submarine cables. The allies then proceeded systematically to destroy all of German colonial stations.

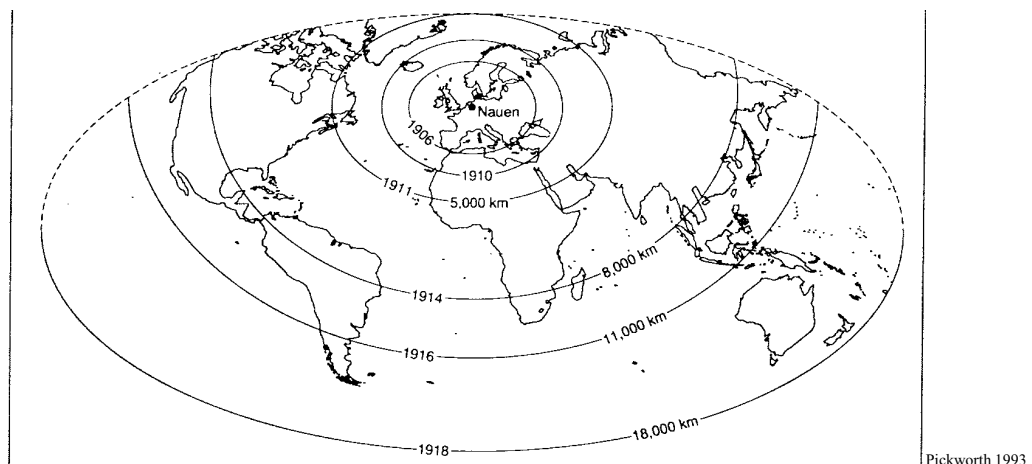


Fig. 5.21 Increase in range of Nauen transmitter between 1906 and 1918

However, radio communication was maintained between Berlin, Sayville in Long Island and Cartagena until 1916 when the US joined the allies in the war. From that year Nauen was Germany's only contact with the outside world.

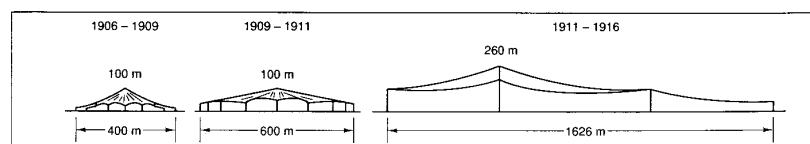
With Germany isolated, Nauen assumed a major role in broadcasting messages to German ships and agents – particularly in South America. A massive new antenna was constructed which increased the range to 12,000km. By 1918, largely as the result of the development of active receivers, signals could be received virtually world-wide without large elaborate antennas. Frequently it was possible for German agents to receive an adequate signal using only a frame antenna about 2.0m square.

Transoceanic communication with early passive receivers was possible because radio signals having a wavelength greater than about 6000m (50kHz) propagated with very little attenuation. Frequency less than about 50kHz were constrained by the earth's ionosphere. Antenna size depended on wavelength and limited the lowest frequency to about 20kHz, with the consequence that transoceanic stations, were limited to a band about 30kHz wide. This meant that a high degree of selectivity was required to prevent

5. Second case study – the birth of electronics

mutual interference. In order to achieve this continuous wave (CW) transmission had to be adopted.

It was not difficult to generate high power at frequencies less than 50kHz. Feeding these signals efficiently to the antenna, however, presented a considerable technical problem. One solution was to construct the antenna system in the form of a cone which functioned as a giant inductor/capacitor-tuned circuit. The conductors and earth formed the two plates of the capacitor, whilst the antenna coupling-coil served as the inductance. This configuration offered the advantage that only a single mast was required since the guy wires were integrated into the antenna structure. These techniques, however, would work satisfactorily only with frequencies greater than about 20kHz as, below this value, radiation efficiency fell to an unacceptable level. Telefunken medium wavelength maritime and relay station antennas were designed on these principles and the very-long-wave antennas at Nauen were developed from them. The original mast at Nauen was 100m tall with a 400m diameter cone. In 1909, the diameter was increased to 600m, and, two years later, one side of the structure was lengthened to give an overall length of 1626m. The height of the main mast increased to 260m. In 1916, the cone was replaced by a T-type antenna 1200m long, which



Pickworth 1993

Fig. 5.22 Evolution of the Nauen antennas

consisted of ten parallel wires to increase the capacitance to earth. The overall length of the antenna was 2484m and it had two main masts which were 260m high.

5.7.2.2 British imperial communications

The British, too, had a need to communicate with their overseas territories. This was discussed at Imperial conferences in 1909 and, following up a request for a licence to establish a station in Johannesburg, Marconi submitted to the UK Government a plan for a radio chain linking British territories. At the same time, Australian Wireless Limited installed two stations in Australia using Telefunken equipment. The success of this installation prompted an offer by Marconi to erect eighteen high-power radio stations on British soil in return for which he would be licensed to operate the stations

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

for twenty years, after which time the government would have the right to purchase the stations. Such a monopoly was not, however, acceptable to the government because it would have had the effect of extending Marconi's 'four-sevens' patent, which was due to expire in 1914, by a further sixteen years. **Sturmey 1958**

The Post Office, in 1910, was not prepared to take the responsibility for overseas radio services because the Treasury would not provide the finance. At this stage, Telefunken was the only serious competitor to Marconi, but its system was unacceptable because its British licensee, Siemens Brothers, was a wholly-owned subsidiary of a German company and Germany was regarded as a hostile nation. Furthermore, the Telefunken system infringed the Lodge patent which had been extended for seven years in 1911 and was then owned by the Marconi Company. A possible alternative was the Poulsen system, but in January 1912, when the holder of the British rights submitted an uninvited tender for the Imperial chain, he was unable to arrange for a demonstration of the system over the specified 2,000 miles. The Imperial Wireless Telegraphy Committee, representing the British and Dominion Governments, was appointed by the Postmaster-General to consider the Imperial chain and this committee recommended at a meeting on 9 August 1911 that the Post Office should draw up a scheme of terms to be offered to the Marconi Company.

The final settlement provided for a payment of £60,000 per station (conditional on satisfactory operation), plus a royalty of 10 per cent of the gross receipts of the service. The term of the agreement would be twenty-eight years with a break option at eighteen years. A formal contract was agreed on 19 July 1912, but was not ratified by the government, which, instead, appointed a Select Committee to inquire into suggestions of government corruption and favouritism towards the Marconi Company. **Sturmey 1958, p93** The conclusion of the Select Committee was that the Imperial chain was urgent and that the first six stations should follow the 1912 agreement.

There were five radio systems in existence which might be utilised for the Imperial chain. Both Marconi and Telefunken employed a quenched spark with undamped wave-trains to produce a quasi-continuous wave. Both the Marconi and the Telefunken companies were experimenting with continuous waves and their results were successful. The Poulsen arc system was controlled in England by the Universal

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Radio Syndicate. The arc produced continuous waves and was cheap to construct and easy to maintain. The fourth system was the Goldschmidt high-frequency alternator, supplied in England by the Anglo-French Wireless Company, under licence from Germany. Finally, there was the Galletti Company's synchronised spark system which produced a continuous wave form.

In view of the delay which had taken place and the desire of the Post Office to have a contract ratified before the House rose in mid-August, tenders were not called, and a new contract for the stations was signed on 30 July 1913. The Anglo-French Wireless Company and the Universal Radio Syndicate both complained at not being given an opportunity to tender for the first three stations, whilst the Telefunken and the Goldschmidt systems were both passed over. Telefunken had admitted at the end of 1912 that its Telefunken system infringed the 'four-sevens' patent. As a result, the two companies made an agreement determining geographical spheres of operation, under which Telefunken agreed not to enter the British home or export markets. Marconi was also able to assert patents against the Goldschmidt system. The British rights, which had been owned by the Anglo-French Wireless Company, had subsequently been taken over by the Compagnie Universelle de Télégraphie et Téléphonie sans Fil. In 1913 the Marconi Company acquired a major interest in the company, so that they controlled the important alternator patents.

After a short delay, occasioned by the need to obtain approval for technical improvements, the first station of the Imperial chain, at Leaffield, was begun early in 1914. However, when war commenced, the government decided not to proceed with the chain. In September 1914, Marconi's offered to waive their royalties and build the Imperial stations, leaving the government to pay whatever they thought fit for the stations. The Post Office turned down this proposal and, in due course, the Marconi Company took action against the Post Office to recover damages for the repudiation of the contract. The case was decided in favour of the company in 1918, and arbitrators were appointed to assess the amount of damages which should be awarded. The Post Office argued that the company was entitled to no more than £50,000 on the basis that the radio stations would not have been used between 1914 and 1919 and that, by 1919, all essential Marconi patents would have expired and so they would not have been

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

entitled to any royalties and also that Marconi would not have secured a large traffic at the expense of the cables because the Post Office would have increased the radio charges to protect the cables. These arguments ignore, for example, that during the later stages of the war the Pacific cable was ten days behind with its messages, and at least one of the Atlantic cables was eight days behind.

The Marconi Company claimed damages of £7,181,774, calculated on the basis of the Post Office cable traffic figures. They claimed that for 1916 they would have done a traffic equal to one-third of the cable traffic, and that this traffic would have increased by 10 per cent each year. The figure of 10 per cent was derived from the cable traffic figures which, it was claimed, had increased by over 10 per cent per annum for every year between 1909 and 1914, except for 1911. The Post Office denied this, saying that, except for the war years, the rate of increase was no more than 4 per cent per annum. The case was decided in favour of the company in 1918 and arbitrators assessed damages at £590,000.

At the end of the war, the Post Office returned to its plan to establish an Imperial radio chain for commercial service. In order to avoid royalties to Marconi the stations were to be equipped with Poulsen arcs, a decision which attracted considerable criticism on the ground that the Poulsen arc was obsolescent.

In November 1919, yet another committee was appointed to prepare a scheme for Imperial communications. Meanwhile, the Marconi Company had used an alternator to transmit speech from Clifden to Canada in 1919. At this stage, the Dominions decided to take matters into their own hands. In Australia, the Amalgamated Wireless (Australasia) Ltd., which had been formed by an amalgamation of the local Marconi company with the Australian Wireless Company, entered an agreement with the Australian Government to establish direct communication with the United Kingdom and Canada. In September, 1922, a similar agreement was entered between the South African Government and the Marconi Company. Finally, on 5th March 1923, Mr. Bonar Law announced in the House of Commons that the principle of maintaining a state monopoly was being abandoned and private capital would be allowed to finance Imperial communications.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

In 1924, the Marconi Company again moved the goal-posts. Since 1915, Marconi and his associates had been experimenting with directed short waves, and those experiments culminated in May 1924, in the proposals for a ‘Beam’ radio system for communication with the Empire. This circumvented the major problem with long waves, that of shortage of bandwidth and, within a few months of the successful demonstrations, the company’s suggestions for a system of Imperial radio communication using directed short waves were accepted by the government and a contract was signed on 28 July 1924 in the face of Post Office opposition. ^{Sturmev 1958, p112} The first Imperial Beam stations were opened in October, 1926, working the Canadian circuit.

5.7.3 The relationship between the wireless and cable companies

When the Marconi trans-Atlantic wireless service opened, the land-line companies were reluctant to provide a feeder service to a competitor. They would not accept a message for transmission ‘via Marconi’, thus forcing the public to take it to the Marconi office. Incoming messages were dealt with by the Marconi staff sending an inland telegram from the radio receiving station to the addressee. This caused delay and added greatly to the expense as the Marconi Company had to pay for the cost of inland telegrams. The submarine cable companies, on the other hand, enjoyed preferential tariffs for inland telegraphs and their messages could be transmitted onwards automatically. This state of affairs persisted until early in 1912 when the Marconi Company negotiated equal treatment from the Western Union and the Great Northern Telegraph Companies, using the threat of opening an inland radio chain in America for the transmission of radio messages.

At the same time, Western Union, which had recently merged with American Telephone and Telegraph, withdrew from the Atlantic Cable Pool, in which they had partnered the Anglo-American Telegraph Company and the Direct United States Cable Company. As a result, the American land-lines of Western Union then ceased to be available as feeders for the two British cable companies which were thus effectively forced to lease their cables to Western Union. ^{Sturmev 1958, p79}

In the UK, the 1904 Wireless Telegraphy Act presaged an agreement between the Post Office and the Marconi Marine Company, under which the Post Office agreed to

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

collect messages for transmission to ships by radio, charging 1d. per word to cover its services. This arrangement was extended to radio telegrams for the American continent on 1 May, 1912. The Post Office charged ½d. per word, making the total cost of a trans-Atlantic radio message 8d. per word, two-thirds of the rate charged by the cable companies.

When radio links were established, they had a drastic effect on the revenue of the cable companies. For example, the net sales of the Eastern Telegraph Company, which were £1,321,126 in 1925, had fallen to £947,926 in 1927 due to the opening of the Marconi Imperial beam services.

The cable companies had built up extensive reserves and could have survived a cost-cutting war for several years, but the low costs of beam transmission meant that radio would have been the ultimate victor. Additionally, governments within the Empire had a financial interest in two trans-Atlantic cables, and in the Pacific cable. For strategic reasons, they did not want the cable companies to be ruined, giving rise to the possibility that the world-wide network of British-owned cables would pass to foreign companies such as the International Telephone and Telegraph Corporation which was reported to be interested in acquiring them.

In 1925, an Imperial Wireless and Cable Conference was convened to consider the implications of the competition of beam wireless with cable. The Conference recommended a merger of the cable and radio interests. ^{Sturmev 1958, p117} For the cable companies, it was a case of amalgamate or die. Marconi's motives were more complex. Externally, in the United States the Mackay cable and radio companies and the Federal Telegraph Company had been absorbed into the International Telephone and Telegraph Corporation which embraced all forms of electrical communication and was a direct competitor on the Marconi foreign circuits and, internally, accounting inconsistencies had resulted in a balance sheet which greatly overstated the assets of the company.

The merger resulted in the formation of Cables and Wireless Limited with a capital of £53.7 million. A second new company was formed and called Imperial and International Communication Limited (I&IC). This company used its share capital of £30 million to purchase the communication assets of the cable companies and of the Marconi Company. ^{Sturmev 1958, p120} In addition to the cables of the telegraph companies

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

and the foreign radio circuits owned by Marconi's, I&IC took over the Pacific, West Indian and Imperial Atlantic cables. The Post Office retained the ownership of the beam stations but leased them to I. & I. C. for £250,000 per annum. However, it refused to use the beam stations for radio telephony in accordance with the recommendation of the 1928 Conference. As a result, I&IC did not receive full value for its rental of £250,000 per annum. The 1928 Conference envisaged that the stations would be used for telephony and this had played a part in determining the rent.

Ever since the inception of the Cables & Wireless merger, the attitude of the Post Office towards it has been one of unveiled hostility. Stockholders have seen, with chagrin and exasperation, the Post Office working in co-operation with American companies instead of doing all it could to encourage the British system.

In 1934 the two companies changed their names, Cables and Wireless taking the name Cable and Wireless (Holding) Ltd., while I&IC was re-christened Cable and Wireless Ltd. In 1937-38 the companies were reconstructed, arrears of preference dividends being converted into shares and over £22 million written off the capital.

5.7.4 Broadcast entertainment

“I have in mind a plan of development which would make radio a household utility in the same sense as the piano or phonograph. The idea is to bring music into the home by wireless. While this has been tried in the past by wires, it has been a failure because wires do not lend themselves to this scheme. With radio, however, it would be entirely feasible...

The receiver can be designed in the form of a simple radio music box and arranged for several wavelengths, which should be changeable with the throwing of a single switch or pressing of a single button... amplifying valves and a loudspeaking telephone. ... The manufacture of the radio music box in large quantities would make possible their sale at perhaps \$75 per outfit... if manufactured in quantities of 100,000 or so could yield a handsome profit. “

David Sarnoff, assistant manager of American Marconi
in a memorandum written to Vice President Nally in 1915

Hawker 1997

The third leg of the tripod on which electronics was built was the use of radio for entertainment. In the late 19th century, concerts had been transmitted to the home via telephone wires in many cities including London and the advent of radio telephony was immediately seen as an opportunity to develop this concept. In 1904, Nikola Tesla, wrote of a possible device, “which will be very efficient in enlightening the masses ... a cheap and simple device which might be carried in one's pocket”. Hawker 1997, p418 There are various claimants to be the pioneer in this area. The earliest was Canadian-born Professor Reginald Fessenden who made transmissions from Brant Rock in 1906. He

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

was followed by Lee de Forest, known as the father of radio, who achieved a number of firsts, regularly transmitting entertainment programmes from 1907 onwards. The advent of the cat's whisker and crystal detector – a cheap receiver technology – generated a large and eager mass audience for wireless transmissions.

In Europe, Raymond Braillard and other Belgian enthusiasts set up a transmitter OTL in the grounds of the Royal Castle at Laeken and broadcast programmes of music for public reception every Saturday at 5 pm from 28 March 1914. A report in *Le Soir* on 30 March 1914 indicated that regular programmes for the general public would be transmitted “To meet the requests from certain radio amateurs who occasionally picked up our irregular experimental transmissions, we decided to devote a special session to them every Saturday at five o'clock.” There were several hundred listeners to these broadcasts in Belgium and northern France. They continued until shortly before the German invasion.

The Dutchman, Hanso Idzerda, was the first to develop and build transmitters specifically intended for broadcasting music and speech to the public. His transmitters used a patented modulation system that produced a mixture of AM and narrow-band FM. He carried out his transmissions with the clear intention of expanding the sale of crystal sets, valve amplifiers and components made or marketed by his own firm – Nederlandse Radio-Industrie (NR-I). In 1913, he set up a Technical Wireless Bureau in The Hague, but when war broke out in August 1914, the Netherlands withdrew all experimental radio privileges.

Idzerda was permitted to resume in September 1917 and Holland became, for a time, the only country in the world where it was legal for the public to listen to radio signals. From his friends in the Dutch forces, he learned of developments in the use of thermionic valves and tried unsuccessfully to procure some from the factory in Utrecht which was engaged in military production. Later, he obtained one of the original de Forest Audion triode valves and took this to NV Philips Gloeilampenfabrieken at Eindhoven. Initially, Philips management was reluctant to enter the valve business, but eventually agreed to make near copies of the Audion provided Idzerda would purchase a minimum of 180 a year. By the end of 1918 more than 1200 had been sold at 12.50 guilders each. This revealed the potential commercial opportunity to Philips and by July

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

1919 it was marketing the Philips-Ideezet soft triodes independently of NR-I. It also produced hard valves for transmitters, although initially its Zendlampe gave only 5 to 10W rf output. From this small beginning, Philips subsequently became a global player in the world's electronics industry.

Idzerda was granted permission for regular transmissions on 14 August 1919, subject to tests with the military. NR-I was given the call-sign PCGG. On 1 September 1919, the Dutch monthly magazine *Radio News* was announcing: "Every Thursday evening there will be continuous-wave transmissions from 8 to 10pm." Further broadcasts were made on Sunday afternoons and, during these, Idzerda spoke personally to correspondents who reported reception of his transmissions. In April 1920, Idzerda launched a series of concerts, the Hague Concerts, aimed specifically at British listeners. In 1922, these were sponsored for a time by the *Daily Mail*.

Idzerda's single-valve transmitter output was initially about 75W, but this was increased to about 150W by running the valve with 1000V on the anode. By 1921 a Mullard valve was giving some 250W output and, in 1922, power was increased to about 1 to 1.5kW. The PCGG aerial, which was erected on the NR-I building at 8-10 Beukstraat, The Hague, consisted of three wires each about 40m long, raised 15m high and stretched across a road. The earth was constructed of seven and a half metres of iron pipe sunk in a well. At full load, the early transmitter gave an aerial current of about 1.3A on 1000m and about 1.6A on 800m. With The Hague Concerts established, NR-I appointed W Burnham & Co of Deptford as its British agent.

The range of the transmitter was claimed to be about 500 miles, but this was probably optimistic. However, it was clearly audible in south-east England – provided Croydon Airport radio was not causing interference.

"As regards the strength of PCGG music, the writer gets it ten miles south of London quite nicely, audible with a single valve; and, with three more magnifiers added, it is quite loud on the telephone headgear and can be heard across the room."

EW Kitchin "Notes on the reception of the Dutch concerts" *Wireless World* (14 May 1921)

A month earlier, *Wireless World* had written:

"The phonographic selections sent out by this station are also interspersed with selections by a small band, and by four mandolin performers; occasionally also some singers take part, The orchestra and singers perform under a large funnel or horn which contains the microphones connected to the transmitting apparatus, so that the voices and music modulate the radiated power in the usual way... These concerts are addressed primarily to British wireless experimenters, as is evidenced by the introductory CW messages addressed to all British amateurs with which they are prefixed."

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Idzerda was often outspoken and critical of the authorities, leading to difficulties and reprimands. Furthermore, the marketing of valves and equipment was in the hands of Philips, which was, by then, his competitor. Finance for PCGG dried up and it eventually succumbed to competition from other stations.

De Forest applied the term ‘broadcasting’ to radio transmissions directed at the public, transmitted music from the Eiffel Tower in 1908 and the first propaganda in 1909, when he transmitted an appeal on behalf of women’s suffrage by Harriot Stanton Blatch whose granddaughter he had married. He broadcast opera with Enrico Caruso in 1910 but, as was often the case with his enterprises, in 1911, the venture was curtailed by financial difficulties. He did resume in 1916, when he received the first of a number of royalty payments from AT&T but the transmissions ceased again in 1918 following the American entry into World War I, because he was alleged to be interfering with navy and commercial radio transmissions.

In Britain, too, a similar attitude prevailed. Marconi, which had broadcast a concert by Dame Nellie Melba on 15 June 1920, had its licence withdrawn by the Post Office on the ground of “interference with legitimate services”.^{Hawker 1997} There was, however, continuing pressure for broadcast programmes and, at a meeting between the Post Office and the major manufacturers on 18 May 1922, it was agreed that the British Broadcasting Company would be established. It would be financed by licence fee of ten shillings. Receivers would bear a two-part levy. One part, based on components, would go to BBC, the other (12s6d per valve-holder) would go to Marconi as royalty. The British Broadcasting Company was incorporated on 22 December 1922, with majority of shares being held by the Big Six manufacturers (Marconi, BTH, GEC, Metro-Vick, RCC and Western Electric)^{Sturmey 1958, p144} On 1 Jan 1927, the company was taken into public ownership as the British Broadcasting Corporation.^{Sturmey 1958, p160}

In 1920, R.C. Clinker, an engineer at British Thomson-Houston, constructed a two-valve radio to receive Eiffel Tower time signal transmissions. This was the first set to be commercially available in Britain^{Geddes 1991, p13} and was shown at a meeting of the Wireless Society of London (afterwards the Radio Society of Great Britain). It could be installed in the home for about £30^{Sturmey 1958, p138} In America, a Pittsburgh department store started to sell receivers to pick up transmissions from F. Conrad, a Westinghouse

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

engineer. Westinghouse then commissioned a larger transmitter. Geddes 1991, p13

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Early receivers were constructed by amateurs and there was a ready market for kits to supply those who lacked the ability to construct a receiver from scratch. Another factor in the market for kits was an announcement in the House of Commons that home-built receivers would not be subject to a royalty which was to be levied to finance the operation of the BBC. It was not until the beginning of the 1930s that the volume of sets



Geddes 1991

Fig. 5.23 Constructing a kit receiver (1930) – a series of photographs from an advertising campaign for radio dealers

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

constructed in the factory exceeded the numbers of those constructed in the home. Indeed, many of the entrepreneurs, who later were to set up as manufacturers, at first made their names as sellers of kits.

Amateur enthusiasts provided the critical mass which was necessary to make the new industry viable. Although their financial resources were limited, they had an endless supply of those other valuable resources, time and enthusiasm. As a result, they were at the vanguard of technological advance. The first advertisement for Audion detectors for sale to amateurs appeared in September 1909. In 1926, in response to demand from amateurs for HF operation, de Forest produced a valve capable of operating at 30MHz. ^{Tyne 1977, p329} RCA produced similar valve a year later and radio 'hams' played a major role in the development of short-wave communications.

1927 was the first year in which valve receivers outnumbered crystal sets. Until then, high purchase price and running costs (of high tension and low tension batteries), as well as short valve life, had biased the market against valves. ^{Geddes 1991, p16} At this time, economies of scale began to exert an influence. It was possible to buy valves more cheaply abroad and the retailer Selfridge's attempted to secure a large share of the market, selling imported Cleartron valves at about half the price of other valves. ^{Sturmey 1958, p46} British manufacturers countered this challenge by using valves with pin spacings which differed from those of the equivalent American valves so that they could not be used as a plug-in replacement.

Advances in applications and components moved in tandem. The continuous-wave spark transmitter created a need for a sensitive detector which was met by the Fleming diode. This, in turn, spawned the de Forest and von Lieben triodes which made telephony possible, but gave rise to demand for greater bandwidth, which stimulated a move to shorter wavelengths which was made possible by the screen grid valve. The propagation characteristics of medium and short waves (notably a susceptibility to fading) created a need for automatic gain control, which led to the development of the variable-mu pentode, a valve whose gain could be controlled by adjusting the control grid bias with a voltage derived from the received signal. The invention of television presaged the new glass-based valves for operation at VHF. These valves, in turn, facilitated the speedy evolution of the early radar sets.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

5.7.5 Beating ploughshares into swords and back again

“After the [first world] war a large quantity of war surplus radio equipment was placed on the market by the government. This was bought up by divers people who either resold it to amateurs, or assembled it into receiving sets. The business was highly profitable, so profitable that it was reliably reported that one of the dealers in Lisle Street, Soho, was a former madame from a bawdy house who found radio more lucrative than, her former occupation.”

SG Sturme
The economic development of radio p143

“An industry with a wartime record such as yours should turn to the tasks of peace with confidence”

President of the Board of Trade
speaking to representatives of the radio industry in August 1945
Wireless World June 1946

The 1914-18 war was a major influence on the development of the electronics industry, but the British adopted a different attitude from the remainder of the world. The UK was the world leader in cable communications. It also had an extremely strong navy and these two factors influenced its strategy. It was anticipated that the German cables would be cut by the British fleet, but the converse, that the British cables would be cut was not considered possible. (In fact, the Pacific cable was cut on 7 September 1914, at Fanning Island, and although temporary repairs were made immediately, it was not until 30 October that full working was restored.) The utility of radio for point-to-point communications was obvious. Although Britain had been unwilling to see radio services established, other countries had adopted a different attitude. This was partly stimulated by international jealousy of the British cable dominance, but also by the exposure of the inadequacies of the world cable system in an emergency.

Prior to the war, AEG, Siemens, Felten & Guillaume and Telefunken in Germany had set up a joint laboratory run by E. Reiß to develop high frequency valves which would be needed for radio communications. They used the facilities of the Reichspost for testing. ^{Tyne 1977, p235} Lieben-Reiß relay valves were later used to connect the Eastern Front with Berlin and Western Front. ^{Tyne 1977, p240}

In 1914, many countries began to establish domestic industries for the manufacture of valves. G. Ferrié (a colonel in the French Army) saw a working Audion in USA and arranged for sample to be sent to France for testing by military. ^{Tyne 1977, p192} P. Pichon, a former French Army deserter who was then employed by Telefunken,

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

returned to France with sample Audions which he handed to French military authorities. ^{Petitjean 1968, p49} In Britain, W.J. Picken of Marconi learned of hard Audion valves from R.A. Weagent and brought back samples from USA. ^{Tyne 1977, p216} Military communications requirements forced equipment makers to go to incandescent lamp manufacturers for valve supplies as they were the only ones capable of handling the requisite volume of orders. They used lamp not valve manufacturing methods. ^{Tyne 1977, p228} Initially, it was found that valves produced by incandescent lamp makers, such as Grammont, were not sufficiently robust, but improvements were made. ^{Tyne 1977, p193}

The war provided an impetus for the large-scale production of valves with uniform characteristics ^{Tyne 1977, p146} and robust, long-life valves were manufactured for military use. ^{Tyne 1977, p99} There was a need for standardisation and the R-type valve, developed by British Thomson-Houston from the French TM valve was put into production by all British manufacturers. Audion type soft valves produced by BTH at Rugby were later abandoned due to production difficulties.

In Holland, the Dutch Army requested Metaldraadlampenfabrieken Holland to analyse a captured Telefunken valve and make a device with similar characteristics. ^{Tyne 1977, p268} They produced a high vacuum triode and, shortly after, received orders to manufacture them for the Dutch Navy.

America came late into the war but, following its entry, all amateur-radio activities were banned. A moratorium on patent monopolies came into effect and de Forest commenced manufacture of valves for the US Government. Moorhead also made valves, which, latterly, were based on R-type valve, for the US and British governments. ^{Tyne 1977, p120} Still the volume was insufficient, and the US lamp manufacturers were called upon to assist.

The French 'R' valve was produced by British manufacturers at BTH, Ediswan and Osram factories. Large stocks were accumulated by end of the war and these were dumped on the government surplus market and used by radio amateurs. ^{Geddes 1991, p9} As a result of the cessation of hostilities, much idle factory space was converted to the manufacture of radio sets, and companies such as A.J. Stevens and BSA entered the field. After the Second World war there were also huge surplus stocks, but, on this

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

occasion, they were acquired by the equipment manufacturers and used to subsidise the recommencement of production of consumer goods.

The war also exerted some unusual influences. Stanley Mullard who had supplied the Royal Navy with silica valves later received covert support from the Admiralty in his defence against patent proceedings by Marconi. ^{Geddes 1991, p57} Normally, a weak individual might be expected to succumb to a large company, but he was successful in the litigation and went on to become a major force in the electronic components industry.

So far as the electronics industry was concerned, the first World War was a dry run for the second. Immediately, at the start of hostilities, consumer goods factories were mobilised for production of munitions and commercial barriers were swept away as common equipment was produced by rival manufacturers. Many of the technologies which were in use were adaptable for military equipment. Television transmission had been carried out at frequencies which were used for the early radar sets so valves had the right characteristics. Radar screens needed longer-persistence phosphors than television receiver displays, but the electron guns and vacuum equipment for their production required minimal modification.

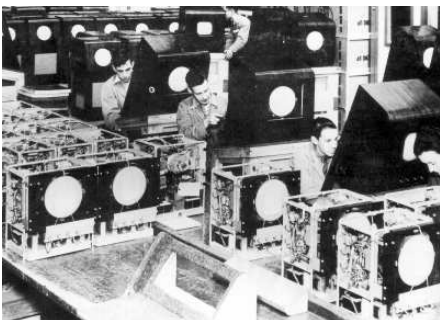


Fig. 5.24 Assembling Ekco television receivers (1939)
Geddes 1991

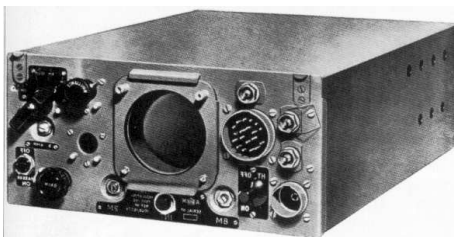


Fig. 5.25 The AI Mk VIII airborne interception radar, developed and built by Ekco
Geddes 1991

After the war, the electronics industry was demobilised and given the task of building up the economy by exporting a large proportion of its production. The factories were well equipped and setmakers were able to switch quickly back to products for which there was a large latent demand. The original export target was set at 110,000 units, but individual manufacturers estimated they could achieve sales of 500,000. It was suggested that companies were attempting to obtain large allocations of materials for export sets, which they would then unload on to the home market. In order to close the loophole, the Board of Trade licensed production of up to 400,000 sets.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics



Geddes 1991

Fig. 5.26 Wartime production in a tunnel built for an extension of the Central Line tube railway



Geddes 1991

Fig. 5.27 Post-war television receiver kit based on ex-government components

A figure very close to this was actually achieved in practice. The other concern was that huge stocks quantities of war-surplus equipment and components would be dumped on the market and would undermine full employment in the industry. However, although some amateurs constructed television receivers with green pictures on 5-inch tubes from radar equipment and others bought excellent communications receivers at bargain prices, these sales had negligible impact on overall demand.

The main potential danger was the stock of surplus components. Post-war demand for valves in 1946 was less than half of wartime demand in 1944, but the government and the industry solved this problem by an arrangement administered by the BVA. Under this scheme, valves were bought back by manufacturers at £5,000 per million, and those considered saleable were re-sold as new at their normal trading prices, most of the profits going to the Government.

The other forms of regulation used to limit demand were purchase tax, which was levied at the penal luxury-goods rate, and controls on hire purchase. The latter accounted for only 20-25% of total sales in 1948 compared with 70% before the war.

The British Radio and Electronic Equipment Manufacturers' Association (BREMA) operated a licensing scheme to protect existing manufacturers against newcomers. Raw materials were allocated in proportion to pre-war sales. All of the pre-war manufacturers participated in the post-war market. Bush and Kolster-Brandes, which were part of larger groups, continued to specialise in set-making but Murphy, Ultra, Ekco, EMI, and Pye used their wartime experience as a springboard to maintain an involvement in non-entertainment electronics, while Cossor launched a successful

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

radar company. ^{Geddes 1991, p288} Eventually, however, free market conditions were restored and economic forces began to exert their normal influence.

5.7.6 Entrepreneurial activity

After graduation, de Forest worked for Western Electric, but shortly after he made his initial discovery, he quit to set up the American De Forest Wireless Telegraph Company to exploit it. He was forced out on 28 November 1906, but given \$1000 and Audion pending patents as a severance settlement. ^{Tyne 1977, p61} In March 1907, he set up the de Forest Radio Telephone Company to manufacture and market de Forest patented wireless apparatus. In 1911, he moved to the Federal Telegraph Company and purchased Audions from McCandless.

De Forest was an entrepreneur who cut deals where he found them. He was also an opportunist who operated at the financial limits. He was obstinate, and would not compromise, even when an arrangement made sound business sense. He was indicted on at least one occasion and, although he was acquitted, associates of his were convicted of fraud and other criminal activities in connection with the business. One such person was E.B. Myers, who left Poulsen Wireless Telephone and Telegraph in 1912 to join de Forest where he worked on valve development until 1915, when he set up in valve manufacture, marketing Radiotron in competition with de Forest his former employer. ^{Tyne 1977, p331} When de Forest obtained a personal injunction against him, he ceased to make valves and, in 1918, returned to work for de Forest. Later that year, he broke into a Marconi Company station in an attempt to obtain evidence that Marconi was using triodes for commercial purposes. Marconi had Myers indicted for breaking into their plant. He was convicted, fined \$150 and put on probation for 1 year. Myers was then hired by Western Electric and improved their efficiency of valve manufacture, increasing production from 150 per day to 5700 per day. In 1922, he set up in Montreal for mail order sales to the USA. On expiry of the de Forest patents, the company moved to Cleveland, but filed for bankruptcy when RCA sued for back royalties.

In one of a series of deals, de Forest gave J. Stone an option to buy exclusive rights to use the Audion valve for wire communications. ^{Tyne 1977, p84} Stone then offered the option to AT&T for not less than \$50,000. Stone and de Forest demonstrated the

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

use of the Audion as a telephone repeater to AT&T and left a sample with them for testing. HD Arnold of Western Electric's Engineering Department, who had studied electronics at Chicago under R.A. Millikan, saw the Audion and recognised its possibilities. ^{Arnold 1928, p556} His assistant improved the performance by increasing the vacuum using a Gaede molecular pump. De Forest then licensed AT&T to use a C-bias Audion amplifier circuit. He followed this with an exclusive licence to use Audion in all fields except wireless telegraphy and telephony for a sum of \$50,000 and a non-exclusive licence to use Audion patents in the field of wireless telegraphy for a payment of \$90,000. ^{Tyne 1977, p114} He used the money from AT&T to set up a factory to make Oscillions (Audions for use as power oscillators). Eventually, de Forest transferred all remaining rights in the use of the Audion to AT&T for \$250,000, retaining only a non-transferable right to sell to direct users and the US government and to license Marconi.

In 1914, McCandless sold his business of valve manufacture to Westinghouse, ^{Tyne 1977, p116} which operated the plant for two years and then closed it down, forcing de Forest to commence manufacture of Audions for himself. ^{Tyne 1977, p116} De Forest engaged R.F. Gowen a trained scientist and amateur radio operator as chief engineer to supervise valve production, including those types formerly made by McCandless.

Marconi sued de Forest for infringement of the Fleming diode detector patent. On 20 September 1916, de Forest was held to infringe the patent and injuncted, producing stalemate since Marconi could not make triodes without infringing de Forest's patents. ^{[1916] FR 960} Three years later, Marconi and de Forest made a commercial agreement and neutralised Fleming and de Forest patents by cross-licence. ^{RAM 1919, p77}

In April 1915, O.B. Moorhead, a former employee of GE, de Forest and Cunningham, set up as an independent producer of valves, initially producing an improved Audiotron with filament life of 400 hours. ^{Tyne 1977, p167} E.T. Cunningham, a West Coast manufacturer sold these valves to amateurs without requiring them to buy auxiliary equipment. (Audions were only obtainable installed in a detector). ^{Tyne 1977, p119} The valves sold by Cunningham included a double tungsten filament, a spiral grid of copper wire and a cylindrical aluminium anode. ^{USPOG 1918, p1434} De Forest attempted to meet Moorhead's competition by offering a single filament Audion at \$5.50. Moorhead responded by offering a double-filament Audiotron at \$5.25. ^{Tyne 1977, p162} Eventually,

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

De Forest sued Moorhead and Hyde for alleged infringement of seven de Forest patents and, on 30 April 1919, an agreement was reached between Moorhead, de Forest and Marconi for Moorhead to enter employ of de Forest who would then make valves under de Forest's personal licence and sell them to Marconi. ^{Tyne 1977, p172}

In 1920, de Forest formed new company Lee de Forest Inc to manufacture radiotelephone transmitting equipment ^{Tyne 1977, p175} but, the following year, ceased active participation in radio development and emigrated to Germany where he set up laboratory to make sound film systems and equipment. ^{Tyne 1977, p300} The company was then taken over by Moorhead Laboratories Inc. ^{PRN 1921, p255}

His next company, de Forest Radio Telephone and Telegraph Company was sold in April 1923, to Detroit industrialists headed by Edward Jowett of Page Motor Car Company. ^{de Forest 1923, p1} It was reorganised with Charles C. Gilbert as president and de Forest as consultant ^{Tyne 1977, p300} and, on 24 June 1926, was placed in receivership with Arthur D. Lord as president and receiver in equity. It finally went bankrupt and was subsequently reorganised with two former Westinghouse engineers, A.B. DuMont and V.Q. Allen, experienced in valve manufacture, as engineers.

In 1916, H.V. Roome, a Los Angeles schoolboy, sold by mail order valves obtained from a San Francisco manufacturer. Roome had been advertising wireless apparatus for some time, but this was the first mention of vacuum tubes. He endeavoured to avoid the attentions of patent holders by advertising his valves as an "experimental hot cathode apparatus designed for the study of the Edison effect, thermionic currents, pure electron discharge, passage of electricity through electrons [sic], and other scientific phenomena." They also carried the following health warning:

It is distinctly understood by the purchaser that the Thermo Tron is sold for the purpose of scientific study to be used for the circuits shown in this bulletin. If the Thermo Tron is used for commercial work in wireless telegraphy as a detector, amplifier or oscillator, or if the Thermo Tron is used for commercial work in an Armstrong Circuit, or if the Thermo Tron is used in any way as an infringement of any patent, the Thermo Tron Company assumes no liability whatever.

"Thermo Tron" proved to be a new name for the Oscilaudion which Roome had sold as a wireless detector.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Roome began to advertise vacuum tubes at the time that de Forest initiated litigation against Cunningham. However, when Cunningham's Audiotron Sales Company avoided an injunction, he blatantly advertised his Supersensitive Oscilaudion valve as a detector, amplifier, and oscillator. With the Supersensitive Oscilaudion the purchaser received a leaflet of the same size and typography as that supplied with the Thermo Tron, using the same illustration, but describing the Supersensitive Oscilaudion as a wireless device. Roome's supply was eventually cut off and he disappeared from the market. ^{Tyne 1977, p166}

Another entrepreneurial figure from the early days of the valve was Stanley Mullard. He left school in 1897 and worked for an electric lamp company managed by his father. The company failed ten years later. ^{Geddes 1991, p52} In 1910, he joined Ediswan and tightened up lax production procedures. Three years later he was put in charge of lamp laboratory where he encountered thermionic valves made for Marconi. He developed the Pointolite tungsten lamp and, by demonstrating this, established contact with the Royal Naval School at Portsmouth. During the war he was offered a commission in the Royal Naval Volunteer Reserve and given responsibility for a large laboratory and valve testing station.

On his discharge after the war, he turned down an offer of £1000 per annum to return to his former job at Ediswan. He refused because he would be under same works manager whom he disliked. ^{Geddes 1991, p53} Instead, he became a director of Z Electric Lamp Company where he took a smaller salary in return for a share of the profits and the right to make valves on a small scale.

In 1920, Mullard founded the Mullard Radio Valve Company occupying space rented from Z Electric Lamp. ^{Tyne 1977, p377} producing 'R' valves, which had formed the backbone of military electronics in the war, and valves with silica envelopes, which he had previously designed whilst working at the Admiralty. ^{Geddes 1991, p53} The major share holdings were subscribed by Radio Communication Company (RCC), a competitor of Marconi, and C.F. Elwell, an American engineer. ^{Geddes 1991, p54}

As production expanded, he moved his factory to larger premises at Hammersmith, producing valves in quantity for the amateur market. ^{Tyne 1977, p377} In 1924, he moved again, to yet larger premises in Balham. ^{Tyne 1977, p377}

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

On learning of copper-to-glass sealing process from the USA which would supersede his silica valve, Mullard approached Philips for a licence on an alternative technique and proposed co-operation, with Philips taking an interest in his company. **Geddes 1991, p57** Following a brief negotiation, Philips agreed. on January 1925, to purchase a 50% interest for £65,000. Two years later, Philips agreed to purchase remaining 50% for £161,000. **Geddes 1991, p61**

In 1925, again lacking resources, Mullard commenced dull-emitter manufacture under licence from Western Electric. The design was inferior and Mullard subsequently developed its own design. **Geddes 1991, p57**

On occasion, Mullard was able to call on personal contacts, to the advantage of his company. In 1922, as a result of his wartime links with the navy, he received covert support from the Admiralty in defence against patent proceedings by Marconi. **[1923] RPC 159** In 1925, his friend, C. Wilson of Osram, who had previously supplied Mullard with liquid air, told him about the use of magnesium as getter to improve vacuum in valves.

5.8 Patents and litigation

“Fleming, [sic] who invented the Fleming [sic] valve, could not find anybody to take it up, with the result that he could not afford at that time to pay the renewal fees. That particular invention is in use in every radio set in the world.”

Lord Maugham

during the debate on the second reading of the 1949 Patents and Designs Bill
Hansard (H.L.) 29 March 1949

Marconi emigrated to England in February, 1896 and in June of that year applied for the world’s first patent in radio. **GB Pat 12039/1896** Initially, his rival, Oliver Lodge did not seek patent protection for his ideas, but the arrival of Marconi in England prompted him to file an application. He did not do this until eleven months after Marconi’s, although the application was submitted before the Marconi specification was published.

In July 1897, the Wireless Telegraph and Signal Co. Ltd. was formed with a capital of 100,000 to acquire the Marconi patent. The company paid Marconi £15,000 in cash, plus £60,000 in fully paid shares for his patent, and engaged him as radio engineer on a three-year contract at a salary of £500 per annum. The name of the company was later changed to Marconi’s Wireless Telegraph Company Ltd.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

In 1899, the company offered to the government all the Marconi patents for use for all government purposes in the United Kingdom and in British possessions for a sum of £50,000 per annum but this was turned down by the Postmaster-General.

In 1900, Marconi applied for a major patent on tuning, ^{GB Pat 7777/1900} which became generally known as the ‘four-sevens’ patent. Marconi employed separate coupled oscillating and radiating circuits at the transmitter and separate coupled absorbing and oscillating circuits at the receiver, all circuits being tuned to the same frequency or to harmonics of that frequency. The ‘four-sevens’ patent more or less controlled the use of radio until its expiry in 1914.

The Marconi Marine Company was formed 1900 with a capital of £350,000 to acquire the maritime rights to all Marconi patents in all parts of the world, with certain limited exceptions. In 1901, the Admiralty adopted the Marconi system under an agreement with the company, although they modified the Marconi equipment somewhat upon the basis of their own knowledge. ^{Sturmev 1958, p17} Two years later, the Admiralty signed a new agreement with the Marconi Marine Company under which Marconi would pass know-how to them until 1914 for an annual payment of £5000. ^{Sturmev 1958, p52}

Meanwhile, Lodge formed a syndicate with Muirhead to develop their inventions ^{Sturmev 1958, p55} and, in 1911, the term of the important Lodge wireless transmitter patent of 1897 was extended for seven years. Users of the patent, such as the Helsby Wireless Telegraph Co. Ltd. (Helsby Company), obtained licences, but the Marconi Company made no effort to do so. ^{Sturmev 1958, p20} Lodge sued for infringement and Marconi counter-claimed. Eventually, Lodge accepted an offer from Marconi to purchase his 1897 patent. As part of the settlement, Marconi engaged Lodge as adviser and gave business to Lodge-Muirhead syndicate. Shortly after the Marconi Company had secured the extended Lodge patent, Telefunken admitted infringement and a settlement was reached. In other countries the validity of the patent was generally admitted without litigation.

On 16 November 1904, Fleming applied for a patent on the use of a two-electrode valve for the rectification of high-frequency alternating currents. ^{GB Pat 24850} As a condition of his consultancy agreement with Marconi, this patent was assigned to the company.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

De Forest had copies of the Fleming valve made for his experiments on wireless propagation. He formed a company in England to acquire the patents of Neville Maskelyne and install radio stations ^{Sturmev 1958, p81} On 9 December 1905, he filed a patent application which proposed a static detector based on Fleming's incandescent lamp with a cold cathode which was known as the two-electrode Audion. ^{Tyne 1977, p55} This was followed by further applications as different variants of the Audion evolved. The first three-electrode tube was invented during 1906, but, at first, was just regarded as a sensitive detector. Its amplifying properties were not discovered until much later although an amplifier circuit based on the valve was proposed in January 1907.

De Forest was a difficult individual who operated at the limits. He was perennially short of funds and, indeed, could not afford to pay the renewal fees on his overseas patents on the Audion, an omission which would later have a major impact on the development of the electronics industry. (The effect might have been even more radical if renewal fees had been payable on US patents.) He was, however, an individual with an eye to the main chance. In 1906, when he was forced out of his first company, part of his severance agreement was that he would have the patent rights to the Audion. In due course, he was able to exploit those rights to finance new business enterprises. ^{Tyne 1977, p84, p86, p114}

The overlap of monopoly between the Fleming diode patent and the de Forest Audion patent gave rise to a battle which was to set the pattern for the subsequent conduct of the electronics industry. On the one hand, de Forest could not use his Audion as a detector for wireless transmission without infringing the Fleming patent, whilst, on the other, Fleming tried to construct a triode with an external electrode in an attempt to avoid the de Forest patent, but it was not successful. ^{Tyne 1977, p180} Marconi sued de Forest, who filed a countersuit. De Forest was intransigent and would not compromise. Stalemate prevailed until the US Government sidelined patent law when it entered World War I. ^{[1916] FR 960} Eventually, after the war, de Forest and Marconi agreed commercial terms and cross-licensed one another. ^{RAM 1919, p77} However, the litigation continued and, ironically, the Fleming patent was ultimately declared invalid – long after its expiry date – on the grounds that it contained an unduly covetous claim (to a diode *per se*) which was anticipated by Fleming's own publications. ^{Sturmev 1958, p33} By

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

this time the patterns of trade, which had been initiated by the patent, were firmly established, demonstrating that an invalid patent can have the same effect as a valid one.

Although de Forest undoubtedly made a major contribution to the development of electronics, he failed to capitalise on it and was, eventually, squeezed out by the large players. In 1916, he filed a suit against Moorhead and Hyde of the Audiotron Sales Company for infringement of Audion patents. This was settled out of court. *Pacific 1917*, pp203-206 In November of that year, Moorhead admitted infringement of the Fleming patent. He agreed to pay damages and royalties and Marconi granted him a non-exclusive licence to make and sell valves to amateurs and governments. *Tyne 1977*, p171 It was subsequently agreed that Moorhead would enter the employ of de Forest and make valves under de Forest's personal licence and sell them to Marconi.

After the war Audiotrons were again advertised for sale. They were stated to have thoriated tungsten filament with life of 2000 hours and to be licensed under de Forest patents for use as radio amplifier. *QST 1919*, p29 Moorhead Laboratories offered the Marconi VT valve and advertised that the Audiotron was not licensed under Fleming patents. *RAM 1919*, p396 When de Forest was acquired by RCA, Marconi cancelled the agreement with Moorhead. This was due, in part, to Moorhead failing to supply them with enough satisfactory valves. RCA, as successor to Marconi and de Forest, sued Audiotron for infringement of Fleming and de Forest patents. This case was settled out of court. *Tyne 1977*, p163 RCA granted Moorhead a licence to make valves under Fleming and de Forest patents subject to injunction after specified number had been made. Moorhead, on completion of the production run, formed a new company to circumvent the injunction. RCA then agreed to supply Cunningham-Audiotron valves packaged ready for sale, marked according to Cunningham's requirements, at a price 20% lower than the lowest net price to any other customer. ^[1924] *RFTC Exhbt Z* Later, Moorhead formed Universal Radio Improvement Company to make valves whilst avoiding the RCA injunction.

On 25 November 1919, Radio Lamp Corporation signed a licence agreement with de Forest for a royalty of \$1 per valve. *Tyne 1977*, p334 RCA commenced proceedings against Radio Lamp, alleging that de Forest did not have the power to grant sublicences under his personal licence. Radio Lamp was then reincorporated in Delaware as Radio

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Audion to avoid New York jurisdiction. In May 1922, AT&T was granted an injunction against Radio Audion's infringement of de Forest patents. ^{[1922] FED 200}

Following expiry of the Fleming diode patent, diodes appeared on market in USA. ^{Tyne 1977, p336} Attracted by lucrative sales, bootlegger valve manufacturers flooded the market. RCA was only partially successful in suing, licensing some, but failing to catch others.

Throughout the evolution of the radio industry there were sporadic patent litigation actions and settlements. In 1912, Siemens Brothers admitted the validity of the Marconi 'four-sevens' patent, the admission being part of a world-wide agreement between the Telefunken and the Marconi interests. ^{Sturmey 1958, p60} Marconi and Telefunken agreed to collaborate on valve development. Round and Franklin of Marconi were to work on receivers, Telefunken engineers on transmitters. ^{Tyne 1977, p207} During same year, the American Marconi Company succeeded in a patent infringement suit against United Wireless which was, by this time, bankrupt. The American Marconi Company was, therefore, able to take over all of the company's installations.

La Radiotechnique won a series of patent actions commenced in late 1920s against Philips. A proposal to settle by supply of equipment was not accepted so Philips purchased Radiotechnique. ^{Tyne 1977, p409} In December 1928, RCA, the parent company of Victor, the owner of HMV, agreed to purchase Marconiphone from Marconi for £500,000 plus £20,000 in shares for patents, the name Marconi and the M-O interest. ^{Geddes 1991, p76} The Standard Radio Manufacturing Corporation was established by E.S. Rogers to manufacture mains-operated radio sets licensed under Canadian patents of de Forest, Rogers and McCullough. ^{Tyne 1977, p249} In 1931, Sylvania Products, Hygrade Lamp Company and Nilco Lamp Works merged to form Hygrade-Sylvania Corporation to make valves under licence from RCA. ^{Tyne 1977, p356}

5.8.1 The patent pool

When broadcasting began in England, Marconi and British Thomson-Houston held the main patents necessary for construction of valve receivers. ^{Sturmey 1958, p214} Initially, Marconi administered the BTH patents under licence, but later it purchased the

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

entertainment rights. In 1928 Marconi sold its interest to EMI which formed a patent pool. Marconi continued to administer the pool, however.

Prior to the formation of the British Broadcasting Company, the terms of use of Marconi patents depended on the negotiating strength of the company concerned. Many companies did not bother to take licences, but, on the other hand, volume of manufacture was low. Marconi did, however, institute proceedings against Gamage's in 1922.

With the start of broadcasting the Marconi Company set out to obtain control of the significant patents. Agreements with Telefunken in Germany and RCA, together with a stated offer to purchase any radio patent offered to them, gave control of the British market.

Initially, the Marconi Company offered licences at a royalty of 10 per cent on the wholesale selling price of all receiving sets. The proposal was turned down by the other major manufacturers. A compromise was eventually reached at a royalty of 12s. 6d. per valve-holder. In agreeing to this rate, the Postmaster-General vetoed a suggestion that there be a sliding scale, with large manufacturers paying a lower rate. He insisted that all must be treated alike. Nevertheless, Marconi did covertly grant licences on preferential terms to the other companies in the 'Big Six' group responsible for forming the British Broadcasting Company. When this was revealed in later legal proceedings, [1929] RPC 457 Marconi argued that it was necessary in order to obtain the capital required from them. A second group of special licences was granted to large-volume manufacturers with a reduction in royalty of between 1s. 6d. and 2s. 6d. per valve-holder, depending on the amount by which the royalties exceeded £5,000.

In 1925, as a result of trade pressure, Marconi took action against unlicensed manufacturers. However, the process was slow and incomplete, so that infringement was regarded as a risk worth taking.

In the early days, a royalty of 12s. 6d. per valveholder was approximately equivalent to a 10 per cent royalty, but during the 1920s, the prices of valve sets fell considerably, so that the relative burden of the royalties increased. In 1927 the Radio Manufacturers' Association (RMA) attempted to change the royalty to 5 per cent of the net selling price. A lower proportionate charge would be applied to the more expensive

5. Second case study – the birth of electronics

receivers for which the cabinet represented a greater proportion of the price, whilst a levy of 2s. per valve-holder would be applied to very cheap sets as a percentage charge would have yielded only a small revenue to the patent pool. Marconi did not respond, so the RMA decided to support a test case in an application under the Patents Act for a compulsory licence, the terms of which would be set by the Comptroller-General.

The Brownie Wireless Company had, hitherto, been engaged mainly in making crystal sets for which no licence was required. They commenced making a two-valve amplifier which could be used with either crystal set or a valve detector set. Marconi confirmed that the amplifier did not infringe their patents and no licence was needed for its manufacture. Brownie then progressed to the construction of valve sets. They requested a licence from Marconi and were offered the general licence covering thirteen patents. Under the terms of this licence Brownie would have been liable for royalties on the previously free amplifier which, when incorporated in a valve receiver, infringed Marconi patents.

The application to the Comptroller-General was successful and it was recommended that the royalty should be reduced to 10 per cent of the wholesale selling price, subject to a minimum of 5s. on the first valveholder and 2s. 6d. on each additional valve-holder.

At the same time, the German company, Loewe, wanted to sell a set which used multiple valves.^{[1929] RPC 479} One of the valves was a triple valve with the three sets of electrodes in one envelope, while the other was a double valve. Marconi proposed to treat these as three and two valve-holders respectively in the set, making the royalty 37s. 6d. on a set incorporating the treble valve and 25s. on a set using the double valve, in addition to the usual 71 per cent of value demanded from valve manufacturers as the royalty for the use of valve patents. Loewe was willing to pay royalties of 10 per cent on the total manufactured cost, the same scale as those paid to Telefunken in Germany. This application was also granted by the Comptroller-General in August, 1928, and it was recommended that the royalty should be 10s. on each triple valve and 7s. 6d. on each double valve.

Marconi appealed from these decisions of the Comptroller-General and, as a result, the decision was overturned and Marconi remained free to continue to charge the

5. Second case study – the birth of electronics

same royalties. Nevertheless, the company offered a new licence on more favourable terms. The patents included one for a battery eliminator circuit which was previously licensed separately, whilst the royalty rate was reduced from 12s. 6d. to 5s. per valveholder. The term of the licence was, however, set at five years from 28th August, 1929 during which a royalty was payable on all sets produced, regardless of whether they used patented devices or not. If a manufacturer took this version of the licence he had to continue to pay the royalty of 5s. per valve holder until 1934, although by that time most of the important patents would have expired. As an alternative, he could continue with the previous version at 12s. 6d. per valveholder, but then he would not have access to any new circuits which became available.

The pool licence contained a clause restricting exports because the Marconi Company had cross-licence arrangements with RCA and Telefunken which contained areas of territorial exclusivity. Furthermore, in those days there was no doctrine of exhaustion of rights, so the patents which Marconi held itself in those countries blocked imports. Marconi operated these patents unevenly, preventing free export from England to an overseas territory unless a royalty had been paid in England, whereas they did not take action in that territory to prevent American sets from entering the market. The issue was not a major one. Royalties on export sales were reduced in 1927, with little effect on sales. In the 1920s most set makers were too small to be able to export in any significant quantities and, in any event, when home sales were easy, few makers worried about overseas markets.

The Marconi licensing arrangements inhibited imports. This protected the British market because both American and German manufacturers could have undercut the home producer. The shield allowed the UK industry to become established.

Before 1939, the basis of the royalties (the number of valveholders) stimulated manufacturers to devise new circuits which used as few valves as possible. This gave rise to non-optimal designs which persisted for many years. On the other hand, demand for multipurpose valves and high-gain amplifying valves led to advances in valve manufacturing. A British set used fewer valves than a comparable American set for this reason.

5. Second case study – the birth of electronics

After the initial phase, there was a number of challenges to the dominance of the Marconi patents pool. ^{Sturmev 1958, p225} The first of these was by Standard Telephones and Cables (STC) which held a number of important patents covering the moving coil loudspeaker, the double detector stage used in the superheterodyne receivers and the ‘push-pull’ amplifier. Licences were freely available at a royalty of 10s. per amplifier for the ‘push-pull’ patent and six per cent of the net selling price for the loudspeaker. The circuit patents were not widely used before the BBC’s regional broadcasting scheme was established in 1929. By the end of 1930, the two groups reached an agreement under which it was decided to include the STC patents in the pool. No change was made in the royalty of 5s. per valve-holder. The inclusive licence, however, did not cover super-heterodyne sets or radio-gramophones, which were licensed separately by STC.

The next challenge came from Hazeltine. After some initial posturing, in which it offered patents first to Marconi and then to STC, Hazeltine, in 1931, felt that its patent position was strong enough to license exports to the United Kingdom, which the patent pool would be unable to prevent. The Hazeltine Corporation advertised its willingness to license anyone in Britain, to indemnify licensees against patent actions and also the intention to prosecute infringers of their patents. In August, 1931, its licensee, the Philadelphia Dry Battery & Storage Co., (Philco) announced that it would sell a set in Britain.

In September, under pressure from the RMA, the pool announced that it would not license importers, and that licences would not be granted for sets containing more than five per cent by value of imported material. Hazeltine retaliated by issuing a writ against The Gramophone Company (owners of the entertainment rights in all Marconi patents) for infringement of a Hazeltine patent and the patent pool countered by suing Philco.

Hazeltine Corporation, Philco and the Majestic Electric Company had formed a new company to license their patents, but in September 1933, Hazelpat joined the patent pool. The inclusion of the Hazelpat patents in the pool protected the British set maker from imports from America other than those from Philco which was a member of the pool. A major influence on the decision to include the Hazeltine patents in the pool was

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

that they covered the linking of controls, trimming of capacitors and automatic volume control which were becoming increasingly important as the number of radio transmitters increased.

Philips, too, adopted a similar approach. It announced, in 1933, that licences would be available under all the patents which it owned or controlled. The licence was to be administered by its British subsidiary, Mullard, and was to run for two years from 1 June 1933, and would be granted to any well-established manufacturer. The royalty fixed was 1s. 6d. for each valve used, except in the case of multiple valves when it was 1s. 6d. for the first function and 1s. for each additional function. When royalty payments reached £1,500 in a year, the rate was to be reduced by five per cent, and a sliding scale was applied to still larger volumes. The licence included an explicit indemnity against suits for patent infringement, provided the licensee used approved circuits.

This was a challenge to the pool, and was met with strong-arm tactics. EMI sued Lissen for infringement of the patent on the use of the variable-mu valve.^{[1937] RPC 5} Philips had indemnified Lissen and was joined in the action. The High Court decided in favour of the pool, but the decision was overturned on appeal^{[1937] RPC 307} and the appeal verdict was confirmed by the House of Lords.^{[1939] RPC 23} Before the case was finished, Philips reached an agreement with the pool companies and its patents were included in subsequent licences.

New products required licences under different patents. This need was met by forming new pools. The first of these, a general licence to cover the construction of radio-gramophones, was announced in 1932. This licence was known as RG 1 and was in force for four years from 1 July, 1930. The six licensors were BTH, Columbia, The Gramophone Company, Marconi's, STC and Electrical Research Products Inc. The royalty was fixed at 10s. per valvholder, but where multiple valves were used the charge was based on the number of stages included in the valve.

When television was re-introduced after the second World War, its manufacture was covered by a further pool. By then, most of the significant patents which related to sound reception only had expired, so it was possible to make sound receivers without a licence. However, a licence was necessary to manufacture television sets. With

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

television, too, advances in technology and changes in standards took place over time scales which were less than the term of a patent, so it was possible, by constant research to maintain live cover. EMI, as successors to Marconi, derived particular advantage from this as its cross-licensing agreement with Telefunken gave it the British rights to the inventions of Dr. Walter Bruch who invented the PAL system of colour television which became the standard in most of Western Europe.

The European manufacturers of colour receivers obtained a further measure of protection from the PAL patents. From the early 1970s Japanese manufacturers were licensed to produce a quota of PAL receivers but were permitted to produce only receivers with small screens. Other Far Eastern countries were excluded completely until after 1979, when the first of the patents expired. ^{Geddes 1991, p389}

5.9 Agreements and cartels

The early days of radio were marked by a constant ebb and flow of companies, punctuated by mergers and take-overs. By and large, after an initial period of fluidity in which a number of pioneers set up their own companies and were subsequently taken over, the thermionic valve industry was controlled by the lamp manufacturers and the attitudes which prevailed in that industry carried over into the new one.

In 1913, the British lamp manufacturers, BTH, GEC, Ediswan and Siemens Bros had set up the Tungsten Lamp Association to eliminate patent conflicts and share the market ^{Stocking 1947, p319} This evolved into the Electric Lamp Manufacturers Association (ELMA) which pooled patents and controlled 95% of British lamp manufacturing industry.

In Germany in 1917, Julius Pintsch AG, Bermann Elektrizitätswerke and Wipperfürth Radio Electric Company entered into a price-fixing cartel with the Filament Trust consisting of AEG, Siemens & Halske and Auergesellschaft ^{Stocking 1947, p316} Subsequently, AEG, Siemens & Halske and Auergesellschaft consolidated their electric lamp business under common ownership of Osram GmbH KG. They also acquired all of the small German makers except Julius Pintsch ^{Stocking 1947, p317} Two years later, in 1921, they organised a price-regulating cartel, Internationale Glühlampen Preisvereinigung, with seven other continental lamp manufacturers ^{Stocking 1947, p330}

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

In France, Compagnie Française Thomson-Houston, Compagnie Générale d'Électricité and Établissements Larnaud, the major manufacturers merged their lamp-making into Compagnie des Lampes which then acquired competing companies Stocking 1947, p321

In the USA, General Electric and Westinghouse had, for many years had a cross-licensing arrangement. On 1 Jan 1927, this was extended when each agreed to grant the other a non-exclusive licence for all present and future patents on electric lamps and associated processes and manufacturing apparatus and GE authorised Westinghouse to use the Mazda trade mark Stocking 1947, p309

On Christmas Eve, 1924, the leading world lamp manufacturers signed the Convention for the Development and Progress of the International Incandescent Lamp Industry, a world-wide patent-licensing and market sharing cartel. Stocking 1947, p331

The pattern which had been set in the lamp industry carried over into the manufacture of thermionic valves. The Valve Manufacturers' Association was set up in June 1924 by British Thomson-Houston, AC Cossor, Edison Swan Electric, Metropolitan-Vickers, Marconi-Osram and Mullard as an offshoot of the Electric Lamp Manufacturers' Association (ELMA). Geddes 1991, p63 In July 1926, the British Valve Manufacturers Association (BVA) superseded the VMA with BTH, Burndept Wireless, Cleartron Radio, Cossor, Ediswan, Electron, GEC, Marconi, Mullard and STC as members. Tyne 1977, p371 Throughout its life, the BVA operated to reduce imports, regulate prices and make restrictive agreements with retailers. As the manufacturers controlled prices, competition was based mainly on performance.

A similar evolutionary pattern had been followed with wireless equipment. In response to a request from Fessenden, E.F. Alexanderson developed alternators with an output of several kilowatts at frequencies of up to 200KHz. Tyne 1977, p134 These were a viable means of producing cw radio signals for long distance communications. Marconi ordered one of these alternators, but General Electric refused to sell to the British-controlled company in a bid to return control of trans-Atlantic radio communication to the USA. On 17 October 1919, GE set up the Radio Corporation of America under laws of Delaware to exploit the Alexanderson alternator for communications. Directors were restricted to US citizens. [1924] RFTC 19 The following month, RCA merged with

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

American Marconi Company to form an operating company for ship-to-shore and transoceanic communications. ^{Tyne 1977, p308}

Many international services were started in the 1930s between mother countries and their colonies. Often these were subsidised and copied the Marconi beam system, although they were technically inferior. In an endeavour to reduce competition, Marconi, Cie Générale de Télégraphie sans Fil, Radio Corporation of America and Gesellschaft für Drahtlose Telegraphie formed a cartel, the Commercial Radio International Committee (AEFG Syndicate). These four companies were the only significant ones which were engaged in long-distance radio at the time. They allocated fields of activity and arranged the mutual use of patents with the objective of preventing overlap. One provision of their agreement was that stations of the consortium companies would not communicate with non-consortium stations. However, this stimulated the construction of extra stations because the embargo meant that potential competitors had to build duplicates. ^{Sturmev 1958, p132}

In Britain in 1922, the Postmaster-General announced that regular broadcasting was to be initiated and called a meeting of interested companies to discuss its future. ^{Sturmev 1958, p139} The manufacturers were divided into two groups – Marconi and its associates and licensees, on the one side, and those opposed to Marconi on the other. The Marconi group comprised the Marconi Company, British Thomson-Houston (BTH) and the British General Electric Company (GEC) and a number of smaller companies. Marconi and GEC were linked by joint ownership of the Marconi-Osram Valve Company, whilst BTH, which was owned by the American General Electric (GE), had a common interest with Marconi through RCA and a patent licence agreement. The other faction, which was held together mainly by its opposition to the Marconi group, consisted of Metropolitan-Vickers a former subsidiary of Westinghouse, Western Electric, which was the English operation of the Bell Telephone System and RCC, a British company competing with Marconi in the field of marine radio. Metropolitan-Vickers did, however, have a small share-holding and some commercial links with RCC.

At this time the pound sterling was overvalued and there was a fear that overseas manufacturers would flood the market for receivers. British manufacturers argued that,

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

as they would bear the costs of setting up the broadcasting infrastructure, they should also reap the rewards of domestic sales.

Following the consultation, the Postmaster-General proposed that a broadcasting company should be established and only receivers produced by members of the company should be approved for use. Any *bona fide* British manufacturer would be eligible for membership of the company.

The proposals were accepted in July, and in August the two groups, which had been unable to agree on the allocation of wavelengths, finally decided to form a single company, which was set up on 8 January 1923. The British Broadcasting Company was financed by a levy on receiver production. This was exacted according to the following tariff, which yielded an average of 15s 0d per receiver.

Description of Apparatus	Sum Payable		
	£	s.	d.
On each crystal set		7	6
On each microphonic amplifier without using valves		7	6
On each crystal set and one valve	1	7	6
On each crystal set and two valves	2	2	6
On each one valve set	1	0	0
On each two valve set	1	15	0
On each set adapted for more than two valves a further sum for each additional valve-holder of		10	0
On each telephone ear-piece			3
On each loudspeaker with or without trumpet		3	0
On each valve		2	0

As a concession, amateurs who constructed their own receiving sets would not be subject to the royalty. This led manufacturers to offer kits of parts which could be assembled by an inexperienced person with the aid of a diagram and a screw-driver thereby avoiding the levy. The policy of the British Broadcasting Company was to bring every person in the country within range of reception by a crystal set and, in order to do so, it established a long-wave transmitter at Droitwich, as well as various medium wave transmitters which were dotted around the country. This created a demand for dual-band receivers capable of receiving both long-wave and medium-wave programmes.

In 1923, the radio manufacturers formed a trade association to fight price-cutting by retailers and to protect their interests generally. ^{Geddes 1991, p62} Following the decision of the Comptroller-General in *Brownie Wireless v Marconi* ^{[1929]RPC 457} that the Marconi

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

royalty was too high, the Radio Manufacturers Association negotiated a reduction in the rate from 12s. 6d. to 5s. per valve-holder. ^{RMA Bull 1928}

5.10 Acquisitions, cross-licences and linked shareholdings

A feature of the electrical industry was the interlinked shareholdings and cross-licensing agreements. In 1912, Telefunken, which had been set up by Slaby-Arco and Siemens, became a subsidiary of AEG. ^{Tyne 1977, p235} In February 1917, Moorhead Laboratories took over Pacific Research Laboratories. ^{Tyne 1977, p170} In 1919, the Marconi-Osram Valve Company was formed as a joint venture by GEC and Marconi's Wireless Telegraph Company, each owning half the stock. GEC contributed know-how, Marconi patents. ^{Tyne 1977, p379} From before first world war, and up to the founding of Marconi-Osram Valve Company, Ediswan made valves for Marconi. ^{Tyne 1977, p372} In 1929, the Gramophone Company acquired Marconi's share of Marconi-Osram Valve Company which continued to supply Marconi. ^{Tyne 1977, p385}

In June 1921, Westinghouse Electric and its subsidiary Westinghouse Lamp Co joined the RCA consortium and contracted to make valves for RCA. ^{Tyne 1977, p310} This arrangement lasted until 1930, when RCA formed a subsidiary, RCA Radiotron, to manufacture valves. The next year Cunningham-Audiotron became a subsidiary ^{Tyne 1977, p164} and, in 1933, de Forest Radio Company was also taken over. ^{Tyne 1977, p301}

In 1921, La Radiotechnique was taken over by Compagnie Générale de Télégraphie sans Fil (CSF) ^{Tyne 1977, p398} In 1924, Radioröhrenfabriek changed its name to Valvo GmbH. It later became a subsidiary of Philips. ^{Tyne 1977, p261} In 1926, the valve manufacturer, Erich F. Huth GmbH, was taken over by Telefunken and Lorenz (later Standard Elektrik Lorenz AG, part of ITT). ^{Tyne 1977, p259} The same year, Marconi Marine Company acquired a majority, and later a full shareholding in RCC ^{Sturmey 1958, p67}

In 1923, the Electron Company commenced manufacture of valves sold initially under name Amrex but shortly after under name Six-Sixty. ^{Tyne 1977, p386} Electron entered into an agreement for the exclusive supply of valves manufactured by Mullard. Subsequently, Mullard bought all shares of Electron and changed the name to Six-Sixty Radio Company.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

NV Gloeilampenfabrieken Nijmegen changed its name in 1927 to NV Splendor and commenced to make valves. ^{Tyne 1977, p426} Two years later, the company entered into an agreement with Philips. In 1928, Standard Radio changed its name to Rogers Radio Tube Company and concentrated its operations on valve manufacture. ^{Tyne 1977, p350} After the second world war, Philips absorbed its successor, the Rogers-Majestic Corporation. ^{Tyne 1977, p350}

In 1928, MetroVick, Ediswan and BTH were merged to form Associated Electrical Industries Limited (AEI). ^{Tyne 1977, p373} BTH undertook radio set manufacture for AEI and thereafter made only specialist valves for non-domestic equipment. Ediswan manufactured Mazda valves for consumer products. ^{Tyne 1977, p391}

After an accommodation was reached by Marconi, de Forest and RCA to break the patents stalemate which was stopping the manufacture of electron tubes, GE and RCA also concluded a cross-licensing agreement ^{Tyne 1977, p308} The next year, GE and AT&T made an agreement which was subsequently extended to RCA and Western Electric. On 30 June 1921, RCA reached an agreement with Westinghouse Electric.

Philips tried to break into the US electron tube market, but, in July 1925, after being sued, they cross-licensed their valve patents with RCA and agreed to stay out of RCA's territory. ^{Tyne 1977, p429} In 1930, Philips agreed to co-operate with GE and each purchased an interest in the other's company. ^{Tyne 1977, p428} By 1935, GE owned 29% of Osram, 17% of Philips, 44% of Compagnie des Lampes, 46% of AEI, 34% of GEC and 40% of Tokyo Electric. ^{Stocking 1947, p341}

Markets were manipulated in Germany, too. Between 1920 and 1925 valves which were electrically equivalent to Siemens' type BF triode were manufactured for the German Post Office by AEG, Süddeutsche-Telefon, C Lorenz and Huth. ^{Tyne 1977, p432} whilst, from 1920 to 1930, Siemens & Halske and Telefunken, despite their separate ownership, agreed to divide development effort by application. Siemens concentrated on wire telephony and Telefunken on radio communications. ^{Tyne 1977, p431}

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

5.11 Regulation

5.11.1 Maritime communications

The Marconi Marine Company set out to establish a commercial monopoly. It adopted a policy that ships fitted with Marconi apparatus would not, other than in emergencies, communicate with ships or shore stations equipped by other companies. Marconi shore stations would only accept messages from ships with Marconi transmitters. Germany, in particular, did not like this and called an international conference on the subject of wireless telegraphy. This was attended by England, France, Russia, Italy, Austria and the United States who recommended that radio should be placed under international control with free inter-communication between all systems. *Sturmev 1958, p52*

Following this conference, public wireless telegraph services were established by the governments of Germany, France, Holland and the United States. However, these carried little traffic because the main shipping lines had signed long-term contracts with the Marconi Marine Company. In 1904, at the urging of the German government, the US closed down the Marconi station at Nantucket lightship because it would not accept non-Marconi messages. A second international convention was held in 1906 but, despite these pressures, the Marconi system was firmly established in Britain by 1907.

The British Government was intent on extending its communications monopoly to radio and, in 1904, passed the Wireless Telegraphy Act which provided for the licensing of transmitting stations. *Sturmev 1958, p54* The first Post Office radio stations, intended for internal communications in the event of failure of the land-line telegraphs, were erected in 1906. A 1908 Order in Council provided that British ships and foreign ships in British territorial waters should satisfy, in respect of their radio installations, the conditions of the 1904 Act. The next year, the Post Office took over all the coast stations, apart from that of the Amalgamated Radiotelegraphic Company (formerly de Forest Company) at Cullercoats which was not being used for public service. *Sturmev 1958, p57*

Following an international conference designed to enforce the fitting of radio to ships, the Merchant Shipping (Convention) Act was passed in 1914. This was followed, in 1916, by a Defence of the Realm regulation required that all British ships of 3,000

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

tons and over should be fitted with radio. Further legislation extended this requirement to yet smaller ships.

5.11.2 Broadcasting

During the early 1920s, there was an explosive increase in the number of broadcasting stations in Europe. In 1925, the British Broadcasting Company invited other European broadcasting authorities to a conference in London to discuss the orderly allocation of wavelengths. They agreed to form an organisation to regulate broadcasting. At a meeting of the resulting International Broadcasting Union held in Geneva in November 1926, they announced an international plan for the allocation of wave-lengths. Sturmev 1958, p158

The same year, the British government appointed a second Broadcasting Committee under the Earl of Crawford and Balcarres. As a result of its recommendation, a public corporation was established to take over when the current licence of the British Broadcasting Company expired at the end of 1926. The shareholders of the company were repaid at par.

5.11.3 Long-distance communication

An Imperial Wireless and Cable Conference was convened in 1925 to consider the effects of competition between the new beam wireless system and cable. The Conference recommended that the cable and radio interests be merged to give a unity of control and direction with subsequent economies. This would ensure the retention of the cables and leave the union free to concentrate on resisting foreign competition. This recommendation was embodied in the Plender-Garnsey scheme which was promulgated in March 1928. The cable companies, which otherwise would have been driven out of business, were content to accept this proposal.

5.12 Competition law

During the early years of the twentieth century, the only country with significant competition laws on the statute book was the USA. The electrical companies had an opportunity to flex their muscles against this when they were the subject of anti-trust action by the Justice Department in 1911. At that juncture GE and its associates and

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

licensees stood accused of restrictive practices in the manufacture and sale of incandescent filament electric lamps. The action succeeded, but they merely re-grouped and carried on much as before.

At various stages there was action by the authorities – anti-trust proceeding in the States and Monopolies Commission investigations in the UK. Viewed with hindsight, these created little more than ripples in the progress of a strong and organised industry.

5.12 Influences on the development of the electronics industry

Early communications were driven by military requirements. The semaphore held sway for many years and the advance of the electric telegraph was delayed by the cessation of hostilities between England and France. The advent of the railways provided a commercial incentive and also the wayleaves to lay cables from city centre to city centre. Once the cables had been installed, the explosion of commerce that accompanied the industrial revolution ensured their viability.

The telephone was invented in America. Edison and Bell both set up service companies in Britain which posed a threat to the General Post Office's monopoly of communications. Although the Telegraph Act was invoked in a landmark case, *Attorney-General v. Edison Telephone Co. of London*^{6 QBD 244}, to restore control to the state, the prospect of growth in the telephone system was not taken seriously because, in the words of the Chief Engineer to the Post Office, "We have a super-abundance of messenger boys."

Starting with the modest beginning of a cable under the Thames, Britain pioneered underwater communications cables. As well as the burgeoning demand of trans-Atlantic commerce, there was a need to communicate with the outposts of Empire, which provided the political incentive to undertake the massive investment required. As a maritime nation, Britain had rope-making technology available and it was readily adapted, but cable construction was a new art. Suitable materials had to be discovered by trial and error. Gutta percha, a product of the rubber industry proved to be a suitable insulator. This led to Britain, with its imperial sources of raw materials becoming a leader in cable-based communications. This eventually inhibited the progress of wireless in Britain because, by the First World War, when wireless was beginning to

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

expand, there had been a huge investment in the cable infrastructure and, it was thought, the power of the Royal Navy would prevent these cables being cut, so there was no need for an alternative form of communication – an echo of the decision a century earlier on replacement of the semaphore. Even before the laying of the first trans-Atlantic cable, the telegraph companies had formed a price-fixing cartel. This remained effective throughout the latter half of the nineteenth century.

There were many pioneers of wireless communications, including Hertz, Lodge, de Forest, Marconi and Slaby. Even Edison had tried his hand and, indeed, had made the inventions which would have laid the foundations for a successful development. He, however, was fully occupied with the exploitation of the electric light and lacked the motivation to drive the inventions through to commercial viability. With wireless, Marconi was the man of vision. Lacking support in his native Italy, he migrated to the home country of his wife, where he received the patronage which supported his early experiments.

The early detectors of wireless signals were many, various and crude, but were universally based on the creation of an audible signal which was translated by a trained operator. J.A. Fleming, scientific consultant to Marconi, suffered from progressive deafness and could not use these techniques and was forced to seek an alternative. He adapted apparatus on which he had worked two decades earlier to invent the thermionic diode detector. As a consequence of the English common law of master and servant, he assigned his rights to his employer, the Marconi Company. Lee de Forest, in the USA, extended Fleming's work and made a more sensitive detector by adding a third electrode to the diode. He did not realise that he had made an amplifier, but he later exploited the invention to the full. Wehnelt, von Lieben and Reiß in Germany mirrored the work of Fleming and de Forest to develop a thermionic relay valve.

De Forest was a difficult character, who fell out with his business associates. Shortly after his invention of the triode valve, he underwent a period of financial stringency, as a result of which he was unable to maintain his foreign patents. He became involved in litigation with Marconi and again, due his nature, was unable to reach a settlement. This led to a stand-off in the US thermionic valve industry which was not resolved until the suspension of patent monopolies during the first world war.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

The Fleming diode patent was eventually held to be invalid by the US Supreme Court, but, by then, its role in shaping the structure of the industry had been fully played out.

The upheaval caused by the war allowed the lamp manufacturers to gain control of the manufacture of thermionic valves. The industry was ruled by cartels which paralleled those of the lamp manufacturers. The demarcation of national boundaries was enforced by the adoption of non-tariff barriers such as the use of mechanically-incompatible valve bases for devices with similar electrical characteristics. In this regulated environment, the rate of technological development was slow.

The need to communicate with ships was the economic driver which stimulated the early expansion of wireless communications. Marconi adopted an aggressive commercial stance and threatened to gain a monopoly. Other nations were antipathetic and adopted countermeasures to prevent Britain gaining the degree of control of wireless which it enjoyed in cable-based telegraphy. Germany convened international conferences at which it fought for its national interests. Britain's support for Marconi was half-hearted, partly as a result of the Post Office monopoly. In the USA, commercial interests closed ranks and set up the Radio Corporation of America (RCA) to prevent Marconi gaining access to the Alexanderson alternator which would effectively have given him a monopoly of trans-Atlantic wireless.

The broadcast entertainment industry was a by-product of the wireless communications revolution, but this was completely regulated by cartels. Patents were pooled and *de facto* standards created by a need for a *lingua franca*. There was therefore little incentive to innovate other than in response to consumer demand for advances such as colour television.

5.14 Conclusion

Although Volta's battery made the electric telegraph feasible, existing technologies did not yield viable systems. The enabling step was Oersted's discovery of the magnetic effects of an electric current, but even so, the electric telegraph did not become widespread until there was a strong commercial demand initiated by railway mania.

5. Second case study – the birth of electronics

In the nineteenth century, Britain had long been a maritime nation and possessed appropriate industries to service naval activities. British manufacturers became dominant in cable manufacture because they could adapt established rope-making techniques and had exclusive access to suitable raw materials through trade with the Empire. Commercial demands attracted many new suppliers, but, almost as soon as a regular service was established, the cable operators found it necessary to set up a price-fixing cartel to maintain profits.

As with limelight in the previous case study, technological limitations at the time of the invention of the telephone inhibited its immediate acceptance. It posed a potential threat to telegraphy, but lack of a means for compensating for transmitted signal degradation blocked an early paradigm shift. In the legal environment, statute law did not keep pace with technology, but judge-made law, based on the legal fiction that the telephone was a telegraph, enabled the government to retain its monopoly of operations.

Like the luminous flame before von Welsbach, cable construction techniques did not inspire successful lateral thought. Until the invention of the fibre optic light guide towards the end of the twentieth century, there was no fundamental re-appraisal of cable communications technology.

The evolution of wireless followed the *classical* path of theoretical proposal, followed by proof of concept, development of crude practical systems with commercial utility and, ultimately, supersession by more refined systems. As with the electric lamp, although many inventors were capable of making the enabling inventions, the one who succeeded (Marconi) also possessed the necessary business acumen. The new paradigm destroyed the economic viability of its predecessor (cable communications) and Marconi used this as a threat to gain access to the cable operators' local delivery network. Like Edison and Swan, he employed a domino strategy to eliminate or marginalise competition, picking off his opponents one by one. He used patents to control the market, whilst his contemporary Lodge, who had a similar command of the technology, was timid in enforcing his rights.

Development of long-distance wireless communications was frustrated by conflicting national interests and reluctance of governments to come to terms with

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

private monopolies when they, themselves, were not prepared to commit to investment in infrastructure or write off outmoded cable systems. Political considerations over-rode technological ones.

A conflict of interest affected the British Government's stance. On the one hand, it wished to encourage national interests, but on the other it wanted to maintain the Post Office's monopoly of communications. Other nations fought their own corner vigorously.

For ship-owners, investment in wireless for safety purposes was a "distress purchase" and compliance had to be enforced by diplomatic agreement – a very slow process.

The broadcast entertainment industry was a by-product of the wireless communications revolution. Radio broadcasting excited public interest. It grew organically over many decades (and is still growing) interrupted only by the precedence accorded to the demands of military communications for limited resources, particularly during periods of war.

When broadcasting got under way, Marconi repeated the strategy he had used with maritime wireless and set out to establish a dominant patent portfolio by original invention or by acquisition of other people's. As with cable, a cartel was established to further the interests of the principal suppliers. Patents were pooled and *de facto* standards created in response to a need for an inter-working of products from different manufacturers. Pool licensing conditions created artificial constraints on receiver design and marketing. There was therefore little incentive to innovate other than to reduce manufacturing costs and to respond to consumer demand for novelties such as colour television. A radio receiver manufactured in 1955 differed little from one made in 1935, apart from the substitution of physically smaller valves with all-glass bases (albeit performing identical functions).

With the thermionic valve, there was considerable borrowing from incandescent lamp technology. Fleming's diode was a direct consequence of the unexpected (and ignored) observation by Upton and Edison two decades earlier. De Forest's discovery of the amplification by his Audion valve was also serendipitous – for a long time, he thought that he had merely made a more sensitive detector.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

In the main, technological advance in valve construction techniques went hand-in-hand with progress in communications technology. The early innovations were empirically-based. One early paradigm shift was the result of a chance contamination of materials but, once the fundamental principles of the thermionic valve had been established, subsequent advances were made by developments in electrode materials and mechanical construction to enhance the emission characteristics and optimise the internal electric field topography.

Due to their relatively short lifetimes, the replacement market for valves was profitable. This influenced the pricing structure of component supplies to original equipment manufacturers, which was designed to gain access to these lucrative later sales. Non-tariff barriers were erected to protect national markets.

War provided increased focus and direction for innovation. In the British Empire, because there was a highly developed cable communications network which was not considered vulnerable due to the strength of the Royal Navy, little effort was expended on radio. German cables, on the other hand, were constantly cut, so great strides were made there in transmitter and receiver design to improve long distance wireless communications. War also encouraged long uniform production runs and standardisation. To this end there was exchange of know-how between manufacturers and suspension of patent monopolies. Eventually it created a vast post-war surplus market which fed pioneering amateur enthusiasts and entrepreneurs. War stimulated demand, but peace switched it off again, with wireless as it had done with the electric telegraph at the start of the nineteenth century.

Paranoia about freedom-to-use created a cross-licensing culture when monopolies intersected. This was often accompanied by an overt or implicit agreement to respect exclusive territorial rights to markets – Philips exchanged licences with RCA and kept out of the US market. There were also complementary cross-holdings of shares in competing companies. Personality conflict was a significant determinant of the structure of the electronics industry because this paranoia was a direct consequence of de Forest's lack of willingness to compromise in his conflict with Marconi, which created a hiatus in the industry's progress.

Technological roulette – a multi-disciplinary study of the dynamics of innovation in electrical, electronic and communications engineering.

5. Second case study – the birth of electronics

Valves made communications much more reliable. However, the thermionic valve was a technological dinosaur. It consumed huge amounts of power to achieve a modest amplification, had a short operating life and was mechanically fragile. These drawbacks provided a strong motivation in the search for a replacement. The two world wars were periods of rapid technological advance. Probably the most important innovation during this time was the introduction of the new semiconductor materials which led to the invention of the transistor, which is the subject of the next case study.