6 From Braun to Hertz

Ferdinand Braun (1850–1918)

Germany enjoyed a period of exceptional prosperity in the last quarter of the nineteenth century. The country overtook France in many ways, and engineering was one of these. Electrical engineering was a German speciality. Ferdinand Braun was born on 6 June 1850 at Fulda, a Catholic enclave in a Protestant region not far from Frankfurt. His father was a minor civil servant, who married the daughter of his superior. Ferdinand, their youngest son, had, altogether, four brothers and two sisters. After leaving the local gymnasium, Braun began studying physics at the minor University of Marburg but he soon moved to Berlin, where he received his doctorate in 1872. Like Heinrich Hertz later on, he became a protégé of Helmholtz. Two years later, as a young gymnasium instructor in Leipzig, he wrote his first book *Der Junger Mathematiker und Naturforscher*. He then progressed up the academic ladder, being außerordentliche professor first in Marburg and then in Strasbourg, then ordentliche professor first in Tübingen and then back to Strasbourg, where he remained for almost the whole of the rest of his career, during which time the city was in German hands.

Braun was the first to investigate the rectifier effect in semiconductor crystals, the phenomenon behind most solid-state electronics. In 1897, he invented, but refused to patent, the cathode ray oscilloscope, which became the basis for the television tube, computer terminals and many other electronic devices. At the time, however, it was considered that his most important work was in the field of wireless telegraphy. Puzzled by the limited range of Marconi's transmitter, Braun experimented in 1898 with a resonant antenna circuit that provided a more efficient transfer of energy. This powerful and practical design was soon competing successfully with those of Marconi and others. Braun was the most formidable rival of Marconi, whom he regarded as an amateur who took a long time to solve a problem that a professional scientist would find quite easy.

In 1901, under pressure from the Kaiser, competing German interests in the new technology were merged into the Telefunken company, which soon became internationally important. Braun played an important

part in its formation. He later supplemented his wireless transmitter with the development of a crystal detector, multiple tuning and a directional antenna. Not satisfied with mere laboratory devices, Braun actively promoted their development and commercial exploitation. He negotiated for capital, secured patents and supervised lengthy commercial trials.

Meanwhile Braun remained at Strasbourg despite calls from Leipzig and Berlin. In 1909, he shared the Nobel Prize for Physics with Marconi, in recognition of their contributions to wireless telegraphy. Telefunken had established a wireless station on Long Island. As soon as the First World War began, Britain cut the German transatlantic cable and attempted to shut down this American outpost by requiring Marconi's company to sue Telefunken for patent infringement. Although his health was failing, Braun went to the United States to help defend the action but felt that he could not risk crossing the Atlantic again to return home. He lived quietly in Brooklyn and died there on 20 April 1918. His wife Amalie, whom he married in 1885, had died in Germany the previous year. They had two children, Siegfried, in 1886, and Hildegard, two years later. Not only a researcher and academic

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entrepreneur, Braun was also a personality of diverse interests who wrote satirical verse in his youth and painted watercolours in his later years. One of his last publications was a successful book, *Physics for Women*, which he wrote while he was in Brooklyn.

Hertha Ayrton (1854–1923)

We now return to England, and the first of our two women engineers. Phoebe Sarah Marks, afterwards to become famous as Hertha Ayrton, was born on 28 April 1854 in Portsea. Her parents, Alice Theresa and Levi Marks, were then living in the old Sussex town of Petworth, but it seems that her mother returned to the home of her own parents to give birth to Hertha, her third out of eight children. Her father, the son of a Polish innkeeper, had fled to England to escape the Jewish persecutions under the tsarist régime. His health, probably undermined by these youthful experiences, was never good. He traded as a clockmaker and jeweller from a shop in Petworth, until his last year when he took out a license to hawk his wares as a pedlar. An unworldly man, he was unsuccessful in business and when he died in 1861 his family was left in poverty.

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Thus, Sarah, as she was known as a child, was mainly brought up by her mother Alice, whose parents were also Polish refugees. Alice was a remarkable woman, who brought with her the strict and narrow Judaism of her Polish forebears. Sarah's education began at a dame school in Portsea, to which her widowed mother had moved. When her exceptional ability began to show itself, she was sent to continue her education at a private school in north-west London kept by her maternal aunt Miriam and her husband Alphonse Hartog, through whom she got to know some remarkably gifted cousins.

At school, Sarah learnt fluent French from her uncle Alphonse, amongst other subjects. After school hours she gave private tuition to earn some money to send home to help her impoverished mother, who was struggling to raise her other children. Sarah, who was short in stature, had penetrating grey-green eyes and raven-black hair. Like her father, she was good-looking, but took no trouble over her personal appearance. Fiercely independent, free-thinking and stubborn, on one occasion when she felt unjustly accused of some misdemeanour, Sarah went on hunger strike for several days. At the age of 16, she told everyone that in future she wished to be known as Hertha, the earth goddess in one of Swinburne's poems.

In London, Hertha's social circle began to widen. The most important of her friends was Barbara Leigh Smith (1827–91), a first cousin of Florence Nightingale, who was an outspoken feminist and a prominent figure in the movement for women's emancipation, a cause dear to Hertha's own heart, as we shall see later. After Barbara married a French-born physician named Eugene Bodichon, she was generally known as Madame.

Madame was one of the founders of Girton College, Cambridge. She encouraged Hertha to try for a college scholarship. Although Hertha was not awarded this, she was nevertheless admitted to the college in 1876, supported by a loan from Madame Bodichon and her friends. At Girton, Hertha was prominent in the Choral Society and helped to form the famous Girton Fire Brigade, which is still going strong. After her first term, she was taken ill and left Cambridge for the rest of the year to convalesce. At this time, women were only permitted by the university to sit the Tripos examination in college, rather than in the Senate House with the other candidates, and however well they did they could not proceed to take their degree. When the time came, Hertha did not do at all well; she was only fifteenth in the third class. The university never granted her a degree, but she remained attached to the college until the end of her life. Cambridge did not grant degrees to women until 1948, when it was the last British university to do so.

After leaving Cambridge, Hertha and one of her classmates rented a flat in London where they gave private tuition. She invented a device designed to divide a line into any number of equal parts. Based on an idea of one of her cousins, this was accorded a favourable reception by architects, artists and engineers. After two years of preparing candidates for university entrance, she decided that she wanted to study applied physics and took a course at the Finsbury Technical College under William Ayrton, a pioneer in physics education and electrical engineering. The son of a barrister, he had studied mathematics at University College, London and electricity at Glasgow under William Thomson. For some years he had worked abroad, in India and Japan. After he returned to London, he was appointed lecturer at several of the technical colleges, of which Finsbury was one.

Ayrton had recently lost his first wife. He married Hertha in 1885; they raised two children, one daughter from each of his two marriages. Thanks to a legacy from Madame, Hertha was able to employ a housekeeper, which enabled her to start assisting her husband with his experiments on the electric arc. The arc, which is produced when an electric current flows between two electrodes, had been discovered in 1820 by Humphry Davy, and by this time it was in regular use when a very bright source of light or very high temperature was required. Soon she was conducting her own experiments at home while her husband looked after their daughters, and these led her to make some important discoveries.

Hertha began to lecture on her research, at home and abroad, and wrote her only book *The Electric Arc*, published in 1902 (and still in print, see Ayrton, 2007). This was a practical treatment as well as theoretical; later it was partly superseded by technical developments in the practice of welding but for arcs between carbon electrodes it remained the standard work, containing the only complete history of the subject. She worked on the design of electric searchlights for the Royal Navy between 1904 and 1908, although her improvements were attributed to her husband. He had been elected a fellow of the Royal Society in 1881 and was awarded a Royal Medal 20 years later. Efforts were made to get Hertha elected to the Royal Society as well but, although she had strong support, the statutes in force at that time blocked the nomination of women, and the attempt was not repeated even after the statutes had been changed. The argument was that a woman's person was, in common law, covered by that of her father or husband; no woman was elected until 1945. However, her work was recognized in 1906 by the award of the Society's Hughes Medal for 'an original discovery in the physical sciences, especially in the field of electricity and magnetism or their applications'. The previous year, she had been admitted a full member of the Institution of Electrical Engineers.

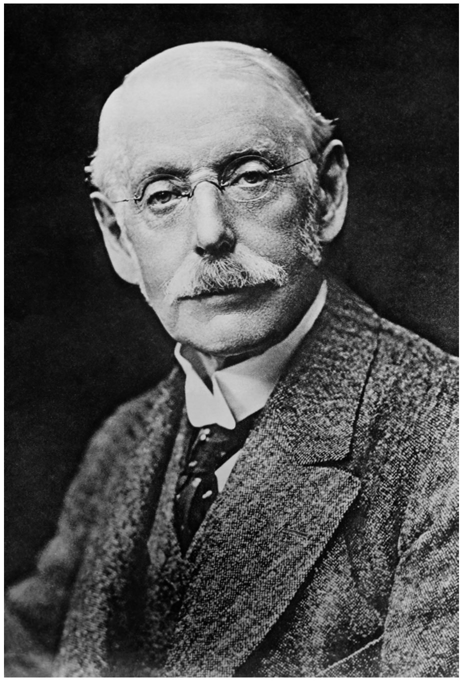
Hertha gave an invited address in French on her research into the electric arc at the International Electric Congress of 1900, held in Paris. She returned to Paris in 1911 to lecture, also in French, to the Société de Physique on her theory concerning the formation of ripples in sand under standing waves in water. When the Curies came to London to report on their isolation of the element radium, Hertha found a kindred spirit in Marie Curie. Whenever she was in Paris, she would visit Mme Curie who, on her own in 1912 and with her daughters the following year, came to stay with her in England.

When poison gas was used in the First World War, Hertha succeeded, not without difficulty, in persuading the War Office to make use of a simple invention of hers, which could disperse clouds of gas when used in a certain way, based on her understanding of the reasons for the formation of sand-ripples. Over a hundred thousand of these Ayrton fans, which also had other applications, were used on the Western Front.

Being left-wing in her political views, Hertha joined the new Labour Party when it was formed. She had always been a staunch supporter of women's rights, as was her husband. In 1899, she presided over the science section of the second meeting of the International Congress of Women. She played a leading part in the suffragette movement, especially after the war, and was proud that her daughter became an even more militant suffragette than herself. In 1898, her mother died; her husband died ten years later. She herself died on 26 August 1923, at the age of 69.

Sir Charles Parsons (1854–1931)

Like Scotland, Ireland has produced a number of fine engineers, of whom Charles Parsons was the most remarkable. He was the youngest of the six sons of William, third Earl of Rosse, a distinguished astronomer who was president of the Royal Society 1848–54 and died in 1867. His mother Mary, née Field, daughter of a Yorkshire squire, excelled in every form of handicraft, including modelling and photography. Two of their sons died in early boyhood. The remaining four spent their boyhoods at the Irish family seat, Birr castle, Parsonstown, where they were brought up by their mother. Three of the four were fascinated by mechanics and engineering. They never went to school, but spent much of their time in their late



father's excellent workshop. Amongst other machines, they made a steam wagon with which they used to give rides to visitors. They were also keen on sailing, and eventually bought the late Robert Stephenson's capacious yacht *Titania*, which took them to other parts of the British Isles and to the Low Countries.

At 17, Charles followed family tradition by spending a year at Trinity College, Dublin, and then went up to St John's College, Cambridge, where he was prominent in the college boat club. At Cambridge, Parsons was described as a 'spare athletic young man, with bright blue eyes and fair reddish hair'. He had an eager and enthusiastic disposition, although he was constitutionally shy, self-contained and inexpressive. He was able to pursue the same problem almost endlessly. Perhaps he had some degree of autism. The people with whom he was most at ease socially were eccentric Irish aristocrats like himself.

Parsons graduated from Cambridge as 11th wrangler in 1877. Since there was no engineering department at the University, he went to the Armstrong Whitworth engineering works near Newcastle as a pupil-apprentice, where he impressed Sir William Armstrong with his industry and ability.

He was particularly interested in the development of the underwater propulsion of torpedoes by means of rockets. After completing his apprenticeship, he worked in the firm of Kitson and Company at Leeds, which allowed him to try out some of his ideas. He then became a junior partner in the firm of Clarke Chapman of Gateshead, who were making vacuum pumps for exhausting the new electric light bulbs produced by Swan's firm in Newcastle. Shortly before, he had become engaged to Katherine Bethel, of Rise Park in the East Riding of Yorkshire, and they were married in 1883. They honeymooned in America, exploring the continent from coast to coast with horse and buggy. In Pittsburgh, they went over the engineering works. On their return, their first child, Rachel Mary, was born. Their second child, Algernon George, was born less than two years later; he was killed in action towards the end of the First Word War, causing Parsons long-lasting grief.

Parsons realized the urgent need for a high-speed engine capable of driving dynamos directly. For this, a reciprocating engine is inherently unsuitable, and he was led to develop the steam turbine, the first patents for which he took out in 1884. The principle was not new, but unlike earlier inventors he realized that the drop in pressure must take place in stages. His first engine, built in 1884, developed 10 horsepower at 18,000 revolutions per minute. Later he introduced a condenser to utilize low-pressure steam formerly wasted, and the use of high pressure superheated steam. He used it to drive dynamos of a novel but reliable type which, although he was not an electrical engineer, he designed and constructed himself.

Parsons had assigned his patents to Clarke Chapman, as part of the partnership agreement, but regretted this when he found that although his fellow-partners were interested in developing turbines they did not agree with the need for haste. He therefore dissolved the partnership and, after a lawsuit, they agreed to sell the patents back to him. Parsons then established a successful business of his own, and this concentrated on developing the turbine further for use at sea; his knowledge of seamanship stood him in good stead. In 1897, his *Turbinia*, which was capable of 34 knots, created a sensation at the great naval review in the Solent marking Queen Victoria's diamond jubilee. He developed reduction gearing, which made it possible to use turbines in slow powerful vessels as well as light fast ones. In 1906, the British Admiralty installed them in the famous Dreadnought series of battleships; the great Cunarders *Lusitania* and *Mauretania* followed. By 1915, they had become the predominant form of propulsion on the high seas.

Parsons was a capable and successful businessman, but not good at management. Many very able and loyal senior employees found it impossible to work with him. Yet the British physicist J. J. Thompson wrote of working with him on the wartime Inventions Board:

> He was a very agreeable as well as a most efficient colleague. I have rarely been on a Board where there was less friction and where proceedings were more harmonious. He had the engineering instinct more fully developed than anyone I had ever met, beside being by far the greatest and most original engineer this country has had since the time of Watt, he was one of the kindest and most steadfast of friends.

Parsons did not believe in monopolizing the applications of his ideas but granted licenses to avoid ruinous legal disputes. He sold the American rights to his turbines to Westinghouse, who after making some improvements used them in the Niagara Falls power station. The profits from his manufacturing business went mainly into further development; he became rich from licensing fees and royalties. However, he was very reluctant to license the innovations of others, preferring to find another way of achieving the same end.

Invention and engineering were his recreation as well as his vocation; like Edison Parsons enjoyed his work. Altogether, he took out 300 patents. Turbines were his speciality but by no means his sole interest. For example, he was an early supporter of aeronautical engineering. He purchased an Irish optical factory and started to improve the methods of making optical glass, initially for use in searchlights but later for the large telescopes used in astronomy. He invented a novel form of sound amplifier but was too busy to develop it. His most costly failure was an attempt to make artificial diamonds by submitting carbon to high pressures and temperatures.

The importance of Parsons' work was widely recognized in his lifetime. He was made Knight Commander of the Order of the Bath in 1911, and admitted to the Order of Merit in the same year. He was elected to the Royal Society in 1898, and became a vice-president ten years later. He was awarded the Rumford medal and the Copley, as well as numerous honours from other bodies. It is recorded that although an excellent mathematician, formal calculations interested Parsons very little. He generally reached his results almost instinctively, by obscure mental processes, which he himself did not properly understand. He died at the age of 76 while on a cruise with his wife in the West Indies on 13 February 1931.

Granville Woods (1856–1910)

Charles Parsons was born rich and became richer. The subject of my next profile was born poor and remained poor. The son of Tailer and Martha Woods, Granville was born in Australia on 25 April 1856. Apparently, his mother's father was a Malay Indian and his other grandparents were full-blooded Australian aborigines, born in the wilds back of Melbourne. Although his complexion was coffee-coloured rather than black, he was regarded as a Negro throughout his life, but not by himself. A newspaper declared him to be the greatest coloured inventor in the history of the race, and the equal, if not superior, to any inventor in the country.

Woods' early years were spent in Columbus, Ohio (according to some accounts of his life he was born there). When he was 10 he left school and went to work in a machine shop. At 16, he moved from Ohio to Missouri and took a job as a fireman and engineer (driver) on a railroad. An avid reader, during his leisure time he borrowed books on electricity from the local library and from friends. Moving to Springfield, Illinois and then to New York City, Woods found work wherever he could, first in a steel mill and then in another machine shop, but he was determined to become a proper engineer. Where he did so is uncertain, but he attended courses at an electrical and mechanical engineering school. With his new knowledge, he secured a job as engineer on *Ironsides*, a British steamship. After working on this ship for two years, he took a more senior engineering job on another railroad, the Danville and Southeastern. Unfortunately, the company, being in financial trouble, paid its employees in scrip of little value, and so Woods had barely enough to live on.

Woods' first invention was an elevator (lift) signalling system using electromagnetic induction. He showed his plans to a patent attorney, who pointed out that elevators could be signalled by the ordinary method very cheaply. However, Woods knew that there was a pressing need for a means of communication between trains and railway stations, and so he adapted his inductive communication device for this purpose. Unfortunately, he did not have the funds to develop this idea. Moreover, he came down with a severe case of smallpox. This not only kept him bedridden for several months but also left him extremely weak for the next few years. After he regained his health, he began to work on other inventions, which he hoped would finance the development of his system of inductive communication. He tried to interest the Westinghouse Air Brake company in an idea he had for an electromagnetic braking system for trains.

In 1883, Woods filed a patent application for a steam-boiler furnace. He also filed applications for two telephonic devices. One, he called the synchronous multiplex railway telegraph, whereby the dispatcher could discover the position of any train at a glance. The system also provided for telegraphing to and from the train when it was in motion. The same lines could also be used for local messages without interference with regular train signals. In using the device, there was no possibility of collisions between trains as each train would always be informed of the position of any other while in motion. Woods sued the Thomas Edison Company for infringement and won his case. He often had to defend his patents against others.

The other was a device that combined the telegraph with the telephone. Woods called it telegraphony and patented it in 1885. Instead of reading or writing the Morse code signals, an operator could speak near the telegraph key. This made it possible to receive both oral and signal messages clearly over the same line without making changes in the instrument and without understanding the Morse code. Woods' patented telegraphony was purchased by the Bell Telephone Company for a hundred dollars, but they did not develop it.

In 1886, Woods and two Cincinnati businessmen formed the Woods Electric Company in Kentucky. Woods signed a working agreement with the company, expecting that he would then be able to develop some of his inventions, but unfortunately his partners preferred to make money by selling the patent rights to the inventions, not by developing them. Moreover, the company only paid Woods' salary occasionally and so to

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make ends meet he opened a small machinery repair shop in Cincinnati. At the same time he hunted for a way to extricate himself from the contract he had signed, and in 1890 he succeeded by forming a different Woods Electrical Company, incorporated in Ohio rather than Kentucky.

Woods was now free to apply for patents for inventions that the original company would not develop. In 1890, Woods moved to New York City and joined his brother, Lyates Woods, who was also an inventor, but the best he could do for himself was a poorly paid job as porter on the Manhattan Elevated Railway. There was also an ailing sister in Ohio whom he supported, although he could hardly afford to do so. In 1891, Woods was still looking for investors, and an advertisement by the American Patent Agency attracted his attention. 'Inventions promoted and companies formed for inventors' were declared to be its specialities. The manager, James Zerbe, showed interest in Woods' inventions, particularly his design for a simple electric railway. A partnership was formed, called the American Engineering Company, to which Woods was contracted as a consultant. He expected that Zerbe and his associates would help him develop his invention but it soon became clear that their real intention was to deprive him of it. This was not the only time Woods was cheated of his intellectual property.

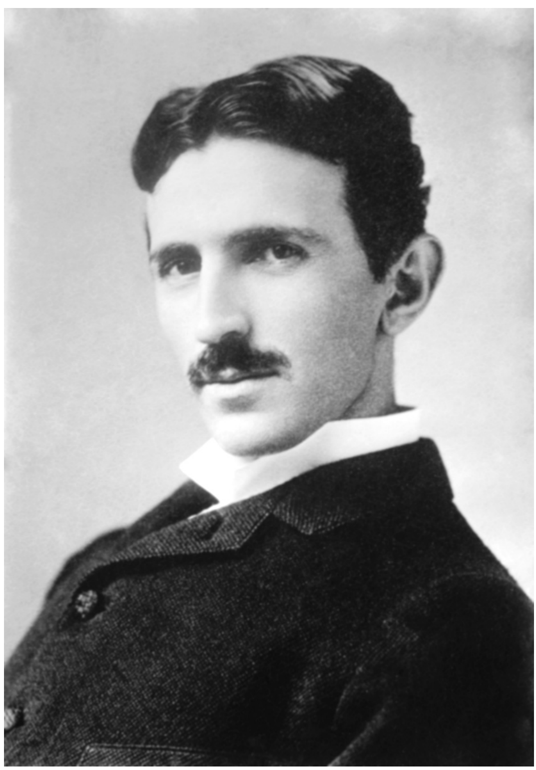
Whereas his partners, especially Zerbe, deceived him, Woods was not entirely innocent. In 1891, he began secretly filing a patent application for his latest version of the electric railway system, based on work he had done before he became an employee of the company. The following year, he began to realize that he had been cheated and put out a warning in a newspaper to the effect that the company was offering for sale an electric street railway system covered by Woods' patents, using plans purloined from the inventor and without his consent. Zerbe promptly sued Woods for libel and had him held in jail for several days. When the libel action came to trial, Zerbe lost his case and his unsavoury history came to light.

By the end of 1893, Woods had been awarded 20 patents; afterwards he was to be awarded 25 more. He had learned from bitter experience how to use his inventive skills for financial gain, modest as it was; he was involved in almost constant litigation, and what he earned mainly went to pay lawyers. Woods faced as many defeats as victories. Legal fees he could barely afford and powerful enemies in business and politics made his life a struggle right to the end. He died after a stroke in 1910.

Some people considered the third rail to be his greatest invention. Used in subway systems throughout the world, the third rail put electrical conductors along the path of the train so that it would receive the current directly. Woods received a patent for this in 1901 and sold the invention to General Electric shortly after. Others believed that Woods' air brake technology was equally important. Starting in 1902, he had developed several devices that led to the automatic air brake, which he sold to the Westinghouse Company He was determined to make a living as an independent inventor, not as an employee, but he was always lacking in the necessary capital and connections.

Nikola Tesla (1856–1943)

Nikola Tesla was one of the most brilliant inventors of his age: the word genius does not seem inappropriate in his case. The inventor's forebears were Serbs living in Croatia, who (if they were men) entered the Church or the Army. His father, Milutin, was politically active, wrote poetry and entered the Orthodox priesthood. In 1847, Milutin married Djouka Mandić, daughter of one of the more prominent Serbian families. Although illiterate, she was cultured, intelligent and hardworking; also gifted with an unusually



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retentive memory. Nikola recalled that his father spoke many languages fluently and also understood mathematics well. He was an omnivorous reader and possessed a large library, which his son made good use of. However Tesla ascribed his inventive powers more to his mother.

In his childhood, the Tesla family moved from the rural hamlet of Smiljan, where he was born at midnight 9–10 July 1856, to the town of Gospić, where Milutin was pastor and taught at the Real Gymnasium, which his son attended. After his brilliant elder brother, Dane, died from injuries sustained when he was thrown from his horse, Nikola moved to the city of Karlovac (Carlstadt), where there was a Higher Real Gymnasium with good teachers. Here, he apparently contracted malaria, which persisted through most of his later life, and this was followed by cholera, which was nearly fatal.

He persuaded his father that he wanted to become an engineer, not to make his career in the church. To prepare for this, he went to the polytechnic school in Graz, the capital of Austrian Styria, which had a high reputation for science. Although he studied so hard that his teachers worried about his health he also sowed some wild oats, gambling and womanizing. Without graduating from the polytechnic, he transferred for one semester to the University of Prague, where he studied informally under some of the leading thinkers of that time. After that he set out to earn his living.

His first job was as a draughtsman in the engineering department of the Central Telegraph Office of the government in Budapest. When a telephone exchange opened in the Hungarian capital, he moved to the more interesting job of checking the lines and repairing the equipment. He took the various instruments apart and designed ways of improving them. However, his main goal during this period was to design an electric motor that would harness alternating current without the cumbersome intermediaries that direct current required. Eventually, he saw that the solution was to use an out-of-phase pair of currents. Others were working on the same lines but when Tesla applied for a patent his priority was confirmed. Direct current electricity at normal voltage could only be transmitted for short distances, even when just required for lighting, but alternating current could be economically transmitted for hundreds of miles and, after Tesla, used to power industrial machinery.

In 1882, Tesla left Budapest for Paris, where the Edison Continental Company was manufacturing dynamos, motors and lighting systems under the Edison patents. He was employed as a junior engineer in the company's factory at Ivry-sur-Seine. When Edison lighting systems were installed, the generators supplied often broke down until Tesla invented automatic regulators. The firm sent him to Strasbourg where the system was being installed, and his job was to investigate any problems that arose. He discovered that the wiring was defective but while he was putting this right he was, on the side, constructing his first electric motor. When he demonstrated his motor to some of the leading citizens of Strasbourg, they were impressed but were unwilling to invest money to enable its commercial possibilities to be realized.

So, in the spring of 1884, Tesla went to New York, where he hoped to find investors who would help him manufacture his motors. He met Thomas Edison, the wizard of Menlo Park, who was impressed by the young man and employed him as a consultant, without agreeing the financial terms. After a while, when Tesla asked for payment for his services, Edison prevaricated, whereupon Tesla walked out, understandably feeling that he had been cheated. Working independently, Tesla began to take out American patents for his inventions and formed the Tesla Electric Light and Manufacturing Company to exploit them. Before long, his backers forced him out of the company and so Tesla founded another company, the Tesla Electric Company, to exploit his inventions for alternating current technology. Westinghouse, as we know, was also developing alternating current systems, based on different principles, and building power stations, which produced high-tension alternating current, stepped down at the point of use for safety's sake. However, Tesla's system was far better and Westinghouse decided to purchase the American rights to it. He offered the equivalent of $75,000 in instalments, plus royalties amounting to $180,000 and 200 shares in the Westinghouse Company. Tesla accepted and as part of the deal agreed to spend a year working at the Westinghouse facility in Pittsburgh.

It was a frustrating year, in many ways, and Tesla was glad to leave Pittsburgh at the end of it and return first to New York and then to Europe. There he heard about the discoveries of Hertz, on the propagation of electromagnetic waves. In Europe, he met some of the leading scientists of his day, and also found time to visit his family in Croatia. When he returned to Manhattan, he established a laboratory with equipment loaned by Westinghouse. He contacted Michael Pupin, a fellow Serbian, who had emigrated to the United States in 1874. They had much in common, and together made several profitable inventions, based on Tesla's principles.

In 1891, Tesla visited London, where he lectured to a distinguished audience at the Institution of Electrical Engineers, at which he demonstrated some of his more spectacular inventions with remarkable

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showmanship. He repeated this at the Royal Institution, and then went on to Paris, where he was equally successful. Hearing that his mother was dying, he went to Gospić to see her for the last time, after which he met a delegation of Serbian scientists, lectured at the University of Zagreb, and at an audience with the king was awarded the title of Grand Officer of the order of St Michael. He also went to Berlin, to pay his respects to Helmholtz, and to Bonn, to meet Hertz, whose experiments he had replicated. They did not get on well, but Hertz was already suffering from the disease that led to his untimely death.

Before returning to New York, Tesla had been elected a fellow of the Royal Society. The lectures he gave in various places drew large audiences and he was lionized in the popular press. He gave demonstrations at the Chicago World's Fair of 1893. In these demonstrations he passed high frequency electricity through his body without, apparently, feeling anything or suffering any ill-effects. The same year when contracts were awarded for harnessing Niagara Falls technology based on Tesla's polyphase system was adopted.

In 1895, there was a fire in Tesla's laboratory, originating in the dry-cleaning establishment on the floor below, which not only destroyed much of his equipment but also all his notes and papers. Fortunately, his photographic memory helped him recover some of the written material, which would otherwise have been lost. Since he was not insured, he suffered financially when Westinghouse started charging him for machinery he had borrowed from his company. Edison gave Tesla temporary use of facilities at Menlo Park while he was arranging a new laboratory for himself in Greenwich Village.

Meanwhile, the Niagara scheme was successfully completed and Tesla received much of the credit for this. At this stage, he was interested in lighting and he invented both gaseous tube lighting and fluorescent lighting, although these were not commercially exploited until much later. He also found Roentgen rays, which had just been discovered, and radio waves. In the case of the latter, he was in a race with Marconi, with whom Edison was about to join forces.

In 1897, the luxurious Waldorf Astoria, the tallest hotel in the world, opened its doors and Tesla moved in and made it his base for the next 20 years. In 1899, he went out to Colorado where he constructed an experimental wireless station, using the El Paso electrical station as its source of power. Tesla was fascinated by a stupendous electrical storm he observed over the nearby Rocky Mountains. Tesla's imagination ran away with him when he found that he was receiving radio signals from a mysterious source, which he thought must be one of the planets. It seems likely that he was picking up signals from Marconi's trials.

The next year, Tesla returned to New York, without paying the outstanding account with the local power company. With the backing of J Pierpont Morgan, he purchased a 200-acre tract at Wardencliffe on Long Island sound, some 65 miles from Manhattan. There he planned to construct a wireless transmission station from which he could communicate with almost anywhere in the world. Marconi, at the same time, had been secretly transmitting messages between England and Newfoundland, using long waves that followed the curvature of the earth. The plan included a tower, originally to be 600 feet in height, had been scaled down to 200 feet when it was erected in 1892. At Wardencliffe, there was also extensive tunnelling underground, for some mysterious reason. However, creditors were now hounding Tesla and began to remove some of the heavier equipment, which belonged to the Westinghouse Company. The tower was broken into by vandals, who wrecked valuable equipment, and there were rumours that it was going to be destroyed by dynamite. In fact, it was demolished by a salvage company for the materials it contained.

By 1906, Tesla was in serious financial trouble on all sides. He continued to throw off ideas for inventions, such as a speedometer for motor cars, but they were not followed up. If he had put aside his more grandiose visions for a time in order to bring some of these into profitable enterprises, he might have been able to continue. Often he did not take out patents or defend them when he did; as a result, he was frequently the victim of piracy. He suffered a nervous collapse. His commercial sponsors began to desert him, since he habitually used money they provided for development to fund further research.

Tesla had become a United States citizen in 1891. A rumour that Edison and Tesla were to share the Nobel Prize in Physics for 1915 turned out to be unfounded, but Tesla was awarded the Edison Medal of the American Institute of Electrical Engineers in 1917. Twenty years later his 81st birthday was celebrated with the award of the Order of the White Lion from Czechoslovakia, and the Grand Cordon of the White Eagle from Yugoslavia. More helpfully, Belgrade also awarded him a pension of $600 a month. In his declining years, Tesla lived alone and became more and more eccentric. He adored pigeons and devoted much of his time to feeding and caring for them. He was 86 years old when he died in New York City on 7 January 1943.

Tesla had the ability to visualize in great detail. He claimed that he could see in his mind the structure of a machine, put it in motion, detect problems, make adjustments and thus design a perfect invention without ever having placed pen to paper or having performed an experiment. These mental characteristics brought him extraordinary insights. He experienced vivid unsolicited images, sometimes accompanied by strong flashes of light. To protect his secrets, he did not commit his major inventions to paper but depended on an almost infallible memory for their preservation.

Tesla had many characteristics of Asperger's syndrome. He was a visual thinker who had an eidetic memory. He hated touching another person's body and had a particular aversion to pearls. Except for one long-standing platonic relationship with a married woman he did not enjoy female company. He was always well dressed, in a formal, old-fashioned style. He preferred to buy new handkerchiefs or gloves rather than have the old ones washed or cleaned. He insisted that his table in the dining room of his hotel was never used by anyone else. He was punctual to a fault, usually working through the night. He was a generous but demanding employer. After his death, his reputation declined at first but recovered as some of his more speculative ideas were successfully developed. On the centenary of his birth in 1956 an international electric unit – the magnetic flux density – was named the Tesla.

Heinrich Hertz (1857–1894)

The name of Heinrich Hertz, the discoverer of radio waves, has already been mentioned several times. He was born in the free Hanseatic city of Hamburg on 22 February 1857, and grew up in a prosperous and cultured family. His father Gustav was a barrister and later a judge of appeal, with a seat in the Senate, his mother was Anna Elizabeth (née Pfefferkorn). He had three younger brothers and one younger sister. Hertz was a Lutheran, although his father's family were Jewish. At age six, Hertz entered a strict private school where his 'benign and understanding' mother watched over his progress: he was always first in his class. He had an uncommon gift for languages both modern and ancient. He left the private school at 15 to enter the Johanneum Gymnasium, where he was first of his class in Greek; at the same time he took private lessons in Arabic. Very early on, Hertz showed a practical bent; at the age of 12, he had a workbench and woodworking tools. Later, he acquired a lathe and with it made spectral and other physical apparatus. On Sundays, he attended trade school for lessons

in mechanical drawing. His skill in sketching and painting marked the limit of his artistic talent; he was totally unmusical.

After taking his Abitur in 1875, Hertz went to Frankfurt to prepare for a career in structural engineering. He gained some work experience with a civil engineering firm in Frankfurt. After a brief spell, in 1876, in the Dresden Polytechnic, he put in his year of military service, serving with the railway regiment in Berlin. He then moved to Munich in 1877, with the intention of studying further at the technical university there. Since his schooldays, Hertz had been undecided between natural science and engineering. While preparing for engineering, he had regularly studied mathematics and natural science on the side. With his father's approval and promise of continued financial support, he chose to enrol at the University of Munich rather than the Technical University. The latter institution had a more vocational emphasis but its facilities included a good physics laboratory. The university by contrast promised a life of study and research, one that suited Hertz's scholarly, idealistic tastes. He was relieved at having decided on an academic and scientific career after long vacillation and was confident that he had decided rightly.

Hertz spent his first semester at the University of Munich studying mathematics. Following the advice of the experimental physicist Philipp von Jolly he read the works of the French masters, learning mathematics and mechanics in their historical development and deepening his identification with investigators of the past. Elliptic functions and the other parts of the newer mathematics he found too abstract, unlikely to be any practical use. Although Hertz thought that, when properly grasped, everything in nature is mathematical; throughout his career he was interested primarily in physical and only indirectly in mathematical problems. It was expected at this time that an intending physicist should have a grounding in experimental practice as well as in mathematics. Accordingly, Hertz spent his second semester at Munich in Jolly's laboratory in the university and his third at the Technical University. He found this practical experience immensely satisfying, especially after intensive mathematical studies.

After a year in Munich, Hertz was eager to make the customary student migration. After consultation, he decided in favour of Berlin, where he was attracted by the fame of Helmholtz and Kirchhoff. He attended Kirchhoff's lectures on theoretical physics but found little new in them. Helmholtz was a poor lecturer, who simply read out verbatim passages from the books he had written in a halting and ponderous voice. However, the great man took a special interest in the new arrival. The research environment in Berlin was highly competitive, especially in physics. Hertz found that a prize was being offered by the Berlin philosophical faculty for the solution of an experimental problem concerning electrical inertia. Although only in his second year of university study, he was anxious to begin original research and try for the prize. Helmholtz, who had proposed the problem in question and had great interest in its solution, provided Hertz with a room in his new Physics Institute, directed him to the relevant literature, and paid daily attention to his progress.

Helmholtz saw the two sides of physics as complementary, so that an experimentalist needed to have a good grasp of theory, and vice versa. Hertz showed himself to be an extremely persistent and self-disciplined researcher. Outside the laboratory Hertz wrote home that his greatest satisfaction lay in seeking and communicating new truths about nature. His belief in the conformity of the laws of nature to the laws of human logic was so strong that to discover a case of non-conformity would make him highly uncomfortable; he would spend hours closed off from the world pursuing the disagreement until he found the error. He won the prize in 1879, earning a medal, a first publication in *Annalen der Physik* in 1880, and the deepening respect of Helmholtz.

Helmholtz encouraged Hertz to compete for another, much more prestigious and valuable, prize, which was being offered by the Berlin Academy. The subject was to test experimentally the critical assumptions of Maxwell's theory of electromagnetism. Hertz decided against doing so, feeling that the project might take him three years to complete and that the outcome was uncertain. Instead, he wrote a doctoral dissertation on electromagnetic induction in rotating conductors, a purely theoretical work that took him only three months. It was a thorough study of a problem that had been partially treated by many others, from Arago and Faraday to Emil Jochmann and Maxwell. He submitted his dissertation in January 1880 and took his doctoral examination the following month, earning a magna cum laude, a distinction rarely awarded in Berlin. The same year Hertz began as a salaried assistant to Helmholtz in the practical work of the Berlin Physics Institute, a position he held for three years. He got to know Helmholtz and his second wife Anna well; they entertained in great style, bringing together intellectuals, scientists, artists and leaders of both government and industry. His duties left him time to write 15 research papers and with them to begin establishing a reputation. This work in his Berlin period is difficult to summarize because of its diversity, but it was mainly concerned with electricity.

Hertz was very happy to be working under Germany's greatest physicist and enjoying the use of the country's finest research facilities. When the Berlin Physical Society began meeting in the Physics Institute, he attended regularly, enjoying the sense of being at the centre of German physics. However, it was time for him to advance to a regular faculty appointment, and for this the first step was to serve as a privatdozent. It was at this time that mathematical physics began to be recognized as a separate subdiscipline in Germany, and Hertz's opportunity came when the University of Kiel requested a privatdozent in that field and Kirchhoff recommended Hertz for the post. So, in 1883, Hertz moved to Kiel, where he proved to be a success as a lecturer; by the second semester he drew an audience of 50 students, an impressive number for a small university. The drawback was that Kiel lacked a physics laboratory, so that he could not carry out much experimental work. Instead he returned to theoretical physics and wrote a penetrating study of Maxwell's theory of electromagnetism. When Kiel offered to promote him to the rank of extraordinarius he declined because he did not want to be a purely theoretical physicist. When this became known, the Technical University of Karlsruhe offered him the position of ordinarius in physics and once he had inspected the physical laboratory there he accepted.

Hertz spent four fruitful years at Karlsruhe, from 1885 to 1889. His stay began inauspiciously: for a time, he was lonely and uncertain about what research to undertake next. In July 1886, after a three-month courtship, he married Elizabeth Doll, the daughter of a colleague. A few months later he began the experimental studies that were to make him world-famous. He settled the problem proposed for the Berlin Academy prize by confirming the existence of the electromagnetic radiation predicted by Maxwell, which extended the visible spectrum of light into what we now call the radio spectrum. He not only showed that electromagnetic waves exist but that they can be propagated in free space. The nine papers Hertz published on these researches at Karlsruhe won him immediate international recognition. With his experiments, Hertz had gone far towards his goal of testing Maxwell's theory decisively.

Helmholtz informed the Berlin Physical Society of Hertz's demonstration of the existence of these 'electric waves' in these words: 'Gentlemen, I have to communicate to you today the most important discovery of the century.' In summing up the significance of Hertz's experiments, Helmholtz said that they showed that light and electricity are very closely connected. Hertz was asked to lecture and repeat his experiments in Berlin and elsewhere. He took no interest in the commercial applications made possible by his revolutionary discovery, which had to wait for the development of wireless telegraphy by Braun, Marconi and others after his death.

In September 1888, the University of Giessen tried to recruit Hertz, while the Ministry of Culture pressed him to consider Berlin instead. At 31 he considered that he was too young for a major position in German physics, which would draw him away from research. In any case Berlin wanted a mathematical physicist. In America, Clark University tried to recruit him to join Albert Michelson at its new physical institute, planned to be as splendid as Berlin's, and then Graz tried to secure him as Ludwig Boltzmann's successor; without success. Finally, when he was offered the physics chair at the Rheinish University of Bonn he accepted, more because of Bonn's attractive location than its scientific reputation.

So Hertz moved to Bonn in the spring of 1889, succeeding the great thermodynamicist Rudolf Clausius. He and his wife moved into the house that Clausius had lived in for 15 years; the historical connection mattered a lot to him. He found the Bonn Physical Institute cramped and the apparatus a jumble, which he had to put in order. Hermann Minkowski, then a privatdozent in mathematics, joined him in research into electromagnetism. He also had his one and only assistant in Philipp Lenard, later to win a Nobel Prize for Physics but notorious in Hitler's Germany as a fervent Nazi. According to Max Born, Lenard, at a conference in 1920, maintained that it was the theoretical works of Heinrich Hertz that were the product of his Jewish inheritance, not his more important experimental work. Hertz's research on electromagnetism not only facilitated the acceptance of Maxwell's theory among German physicists, it taught them the value of a good theoretical basis for experimental work. Hertz himself, once he had finished arranging his laboratory at Bonn, returned to experimental research, but became discouraged by repeated failures. He published two more classic papers on Maxwell's theory in the *Annalen*; and then turned to something quite different.

The principle of least action has a long history in mechanics and physics. Helmholtz had been studying it afresh and Hertz decided to follow his example by writing a purely theoretical study of the principles of mechanics. While Helmholtz and others looked on his work in this field with respect they suspended judgement, and Hertz' theories have never been generally accepted, although Ludwig Wittgenstein believed in them. Meanwhile Hertz was starting to suffer from ill health. The decline began at Karlsruhe with toothaches; all his teeth were extracted. Then his nose and throat became so painful that he had to stop work. The cause was diagnosed as a malignant bone condition that his physicians could not deal with. He had several surgical operations but to no avail and he died from blood poisoning on New Year's Day 1894 at the age of 36, almost the same lifespan as Mozart. His wife and two daughters emigrated to England from Nazi Germany in 1937 and settled in Cambridge.

After his early death, his mother wrote a most interesting account of his childhood. Hertz himself kept a diary, in which he recorded the events of his everyday life. With other material, including a short biography by Max von Laue, these memoirs have been published in English (Hertz, 1977). Appleyard (1930) concludes his admirable outline of Hertz' life and work by saying:

> Among those who knew him best, the remembrance that remains of him is of a man of amiable disposition, social, genial, a good lecturer, possessed of singular modesty, who gave himself no airs as of a great professor, and who, when speaking of his own discoveries, never

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mentioned himself. When the Royal Society presented him with the Rumford medal, he silently disappeared for a few days – none knew why – and he returned as silently. The habit he formed early in his life of solving difficulties for himself continued with him; he preferred on occasion to puzzle things out in loneliness in the laboratory. His decision to follow pure science instead of a technical career was faithfully kept, and yet the importance of the part he played in the ultimate technical advance in electrical science is important beyond measure.