Isaac Newton

Isaac Newton was born in Woolsthorpe Manor in the small village of Colsterworth, near Grantham, on Christmas day, 1642. His father, whose family had farmed a modest estate for several generations, died three months before Newton was born. At the age of twelve he was sent to the King's School at Grantham, which still exists and where his signature can be seen, carved on the library wall. There, under the influence of the perceptive schoolmaster, Henry Stokes, his intellectual interests were gradually awakened. He was fascinated with the forces of moving air and water, and more abstractly with the concept of time. He built kites, a sundial, a water-clock, and a model windmill driven by a mouse urged on by corn placed in front of it.

When he was seventeen his mother called him home, intending that he should manage the family farm. Fortunately, however, his uncle and the schoolmaster had recognised his talents, and persuaded her to allow him to go to university. In June 1661 he entered Trinity, his uncle's alma mater, equipping himself with a lock for his desk, a quart bottle with ink to fill it, a notebook, a pound of candles, and a chamber-pot.

He entered as a sub-sizar, a student who paid his way by waiting and performing menial duties for fellows and fellow commoners (wealthy students who dined on high table). He was awarded a scholarship in 1664, given a livery allowance of 13s 4d (67p) per annum, a stipend of the same amount, and commons, i.e. his meals in college. He graduated without any particular distinction in the following year.

In 1665 the Great Plague hit Cambridge. The University closed in the summer, and Newton returned briefly to Woolsthorpe. During the next eighteen months, he started the discoveries that changed the face of science. He said later, speaking of his work, 'All this was in the two plague years of 1665 and 1666, for in those days I was in the prime of my life for invention, and minded mathematics and philosophy more than at any time since'. By `philosophy' he meant natural philosophy or what we would now call science. In addition to his new discoveries in physics, he invented a new branch of mathematics, the method of fluxions, now called calculus, a powerful tool in both mathematics and science.

Newton returned to Cambridge in 1667. There were at the time several vacancies among the fellows of Trinity. Two of them had seriously injured themselves falling down stairs – let us not speculate on the reasons - and a third had been removed on the grounds of insanity. By now, Newton's talents were being recognised and he was elected to a fellowship in that year. Two years later Barrow resigned the Lucasian Professorship of Mathematics for a Court position. Newton succeeded him.

While at Woolsthorpe Newton had started experiments in optics, and he continued these in Cambridge. He showed that when a beam of white light passed through a glass prism it spread out into a range of colours, or a spectrum. He deduced that white light was a combination of colours, and proved the point by recombining the different colours and producing white light. Previously, it had been believed that white light was the pure quantity, and that colours were additional complicating effects. He realised that because different colours are refracted by different amounts in glass, the sharpness of an image in a lens telescope is limited. So he built a telescope with a spherical mirror instead of a lens--the large telescopes of today are all of this type.

But his greatest achievement was in the field of mechanics. This again began during his stay at Woolsthorpe. The starting point was what are now called Newton's laws of motion. The central idea of these is that a body continues in a straight line at the same velocity unless acted on by a force. This was contrary to the ideas of the ancient Greeks, which were still prevalent at the time, that a moving body needed a continual force to keep it moving. Newton's laws have stood the test of time; they apply in all branches of science, and although they have only been modified by Einstein, the modifications are negligible unless the bodies are moving at speeds close to the speed of light.

Next came the law of universal gravitation. The idea was said (by Newton himself in later years) to have come to him when he saw an apple fall from a tree. He realised that the same force that caused the apple to fall caused the motions of celestial bodies. The prevailing view at the time was that the causes were completely different. An important question was, how did the gravitational force between two bodies vary with their distance? Here Newton proposed the inverse square law which states that the force varies inversely as the square of the distance – for example, if the distance doubles the force drops by a factor of four. Using his laws of motion and the inverse square law, he proved that the orbits of planets are ellipses, confirming a law of Kepler that had been based on astronomical observation.

Newton published his discoveries in 1687 in the book Philosophiae Naturalis Principia Mathematica, commonly known as the Principia and regarded as the greatest work in scientific literature. It was sold for 6/- (30p), or 5/- for ready money -- a copy costs rather more today. It contained not only Newton's laws of motion and his calculations of the orbits of the planets and their satellites, but also discussions of more complicated motions such as the motion of bodies in resisting media, and the motions of fluids creating resistance. The work brought Newton great fame. It was written in Latin, but was soon translated into English and other languages.

Newton's outlook in science is contained in one of his most famous sayings, Hypotheses non fingo - I frame no hypotheses. By a 'hypothesis' he meant an axiom unsupported by observations, which was the starting point of a topic in Aristotelian science. Newton's method was to state a principle or generalisation drawn from a series of observations and to compare its predictions with the results of further observations. In his own words, his method was to 'derive two or three general Principles of Motion from Phaenomena, and afterwards to tell how the Properties and Actions of all corporeal Things follow from those manifest Principles, though the causes of those Principles are not yet discover'd'. This is the outlook of present-day scientists. They cannot tell you the cause of gravity, but they can tell you with great accuracy when the next eclipse of the sun will occur.

In 1689 Newton was elected the Member of Parliament for the University of Cambridge. He sat for less than a year and is recorded as having spoken only once, and that was to request an usher to close a window as there was a draft.

Seven years later Newton moved from Cambridge to London, following his appointment as Warden (and subsequently Master) of the Mint, which was due to the influence of Charles Montagu, a Trinity man who founded the Bank of England. Up to the time of Charles II, the coinage, represented by thin unmilled pieces of silver, was in a bad state; it was a popular fraud to clip the coins. Montagu devised a scheme of reform, and a major part of Newton's work following his appointment was to put the reform into practice. This he did very effectively: his actions included going after the fraudsters personally, often risking his own safety.

In 1703 Newton became the President of the Royal Society, a position he held until his death. Again he showed great administrative ability. Before his time the Presidents of the Society had been mainly aristocratic figureheads. But Newton made substantial improvements. He introduced the practice of scientific demonstrations at the meetings, and greatly increased the authority of the Society.

In 1704 came his second major work, *Opticks*: *or a Treatise on the Reflexions, Refractions and Colours of Light*. Written in English, it deals with all his experiments in light, greatly developed since his original work with prisms, and included topics such as colour vision and the formation of rainbows.

Queen Anne visited Cambridge in 1705 and conferred a knighthood on Newton in the dining hall of Trinity, a unique honour at the time for a scientist. Newton died on March 20, 1727. His body lay in state, like that of a sovereign, in a chamber adjoining Westminster Abbey, and he was buried in the Abbey itself. In typical fashion he had managed his own finances skilfully and he left £32,000, a very large sum in those days.

Describing only Newton's scientific and administrative work does not give a true picture of his activities. He had two other passions that occupied almost as much of his time and energy as his science and administration. These were alchemy and theology. In 1669 he bought apparatus for doing chemical experiments. He read widely in alchemy, collected many manuscripts, and copied out large numbers of others.

His deep interest in theology had more practical consequences. By 1675 he needed to be ordained to the Anglican clergy or be expelled from the college. But from his readings of the Bible he had become an Arian, a sect that rejected the orthodox Christian belief that was enshrined in the very name of the college itself ("College of the Holy and Undivided Trinity"). Newton believed that Christ was a divine mediator between God and humankind, subordinate to God who created him. Worshipping Christ as God was idolatry and a fundamental sin. He was in a serious dilemma: Cambridge was tolerant of scholarship, but not of differences of belief. He was rescued at the last minute by a royal act dispensing the Lucasian professor from taking holy orders - Newton could retain his chair and the college fellowship. He continued his theological studies and wrote a book on the chronology of ancient kingdoms, and another published after his death on the prophesies of Daniel and the Apocalypse of St John. Some idea of his interest in alchemy and theology is given by the fact that he left papers with over two million words on these subjects.

Newton believed that God had laid down mystic clues to provide a riddle of the universe, which could be solved not only by scientific endeavour but also by studying the Bible and the writings of theologians and alchemists throughout the ages. 'He was' said Maynard Keynes 'the first modern scientist and the last magician'.

As a person, Newton was not altogether admirable. He shrank from publishing his work because of an aversion to criticism and controversy. At the same time he was very sensitive on issues of priority, and involved himself in quarrels with Hooke, Leibnitz and others which were not to his credit. But he could be kind and considerate to those he thought understood his work, in particular to the young men who helped bring out successive editions of the Principia. He was greatly attached to his mother and tended her as she lay dying. His relations with other women were minimal. He dropped his acquaintance with Vigani, the first professor of Chemistry in Cambridge, when the latter 'told him a loose story about a nun'.

But whatever Newton's character traits and his view of the universe, they fade into insignificance next to his work, that of the greatest creative genius in physics. In the words of Einstein 'He stands before us strong, certain, and alone'.

Trinity Physicists

Foundations of Physical Natural Sciences

By common consent the four greatest physicists in history are Archimedes, Newton, Maxwell, and Einstein. Two of these were at Trinity. No doubt Archimedes would have come had Henry VIII lived before him, but Einstein was a late developer and would not have been admitted with the present admission standards. Trinity, and Cambridge in general, owes its list of distinguished physicists to the development of the Senate House or Tripos examination. Undergraduates were trained in mathematical problem solving, which increased in sophistication as the centuries passed. This process cultivated a competitive community of students with the same mathematical culture, technical background and language. Dissemination of research could assume this shared basis, and it was commonplace to announce new results as Tripos questions.

The mid-nineteenth century saw several Tripos reforms. The developments of applied mathematics in the theories of electricity and magnetism and of heat made it impossible for undergraduate coaches or supervisors to master the whole syllabus. This prompted a young Trinity fellow, James Stuart, to offer the first intercollegiate courses and thus initiate the eventual creation of a new class of University employee—the University lecturer. There was also concern over the practical training of scientists and engineers, resulting in the formation of the Natural Sciences Tripos in 1851. However, practical instruction had to wait until 1874 for the opening of a laboratory, which was financed by the then Chancellor and a Trinity Second Wrangler and first Smith prizeman, William Cavendish, 7th Duke of Devonshire. The first five Cavendish Professors of Experimental Physics were Trinity men. They all won Nobel prizes except Maxwell, the first Professor, who died before the prize was instituted.

Masters of Classical Physics

The end of the nineteenth century represented a watershed in physics. By that time, the phenomena that could be understood via Newton's laws were many and varied. For instance, the laws of heat or thermodynamics could be explained by the constant random motion of tiny atoms. Of everyday experience only the mystery of electricity and magnetism lay in want of explanation. Their unification was Maxwell's triumph. What remained was viewed as applied problem solving and one of the masters of this craft was Lord Rayleigh, who will be discussed later.

James Clerk Maxwell was born in Edinburgh on July 13, 1831. Unlike Newton, whose family had no scholastic tradition, he came from a family whose members were distinguished in law, science, and the fine arts. He was a bright, inquisitive child with a constant question, 'What's the go of that? What does it do?', and if he was not satisfied with the answer, 'What is the particular go of it?' He had a good memory -- at the age of eight he could recite long passages from Milton and the 176 verses of Psalm 119 by heart. Sadly, his mother, a strong influence on his early education, died in 1839. There followed an unhappy period with an unsuitable tutor who used physical punishment on the young Maxwell, treatment which may have been responsible for a later hesitation in his speech. Rescued by an aunt, he was sent to school at the prestigious Edinburgh Academy until 1847 when he went to Edinburgh University.

In 1850, he came to Cambridge and entered Peterhouse to study mathematics, but after one term he transferred to Trinity. A professor at Edinburgh University wrote a letter of recommendation to Whewell, the Master, saying 'he is not a little uncouth in manners, but withal one of the most original young men I have ever met with & with an extraordinary aptitude for physical enquiries'. Maxwell's transfer to Trinity was not because he recognised Trinity's superiority, as we might have thought, but for the opposite reason — he thought the competition for a fellowship at Trinity would be less severe than at Peterhouse. His assessment was confirmed when Peterhouse's Routh was Senior Wrangler in the 1854 Mathematics Tripos and Maxwell was second. However, they shared the Smith's Prize. Maxwell won a Fellowship the following year in Trinity, which he held for one year before taking the chair of natural philosophy in Marischal College, Aberdeen.

When Marischal College was amalgamated with King's College, Aberdeen, in 1860, only one professor in Natural Philosophy was required. Maxwell was discharged, but was finally appointed at King's College London. In the five years he spent there, he laid the foundations of his major contributions to physics, the theory of electromagnetism and the kinetic theory of gases. In 1865, he retired to work on a classical treatise in the former subject at the family home at Glenlair in Galloway.

In 1871, the Cavendish Chair in Experimental Physics was founded and Maxwell became the first holder: two others, Kelvin and Helmholtz, had turned the chair down before he was appointed. The Cavendish Laboratory was opened in 1874, and for the rest of his life Maxwell oversaw the laboratory, choosing the equipment and devising undergraduate practical classes.

Maxwell died on November 5, 1879 at the same age and of the same illness -- abdominal cancer -- as his mother. After a preliminary funeral service in Trinity Chapel, he was buried at Parton near Glenlair.

Maxwell's first major accomplishment came soon after he graduated. In 1848, St John's College established a prize to commemorate the prediction by John Couch Adams of the existence of the planet Neptune. The 1855 topic was *The Motion of Saturn's Rings*; the examiners requiring an explanation of the stability of the rings. Maxwell submitted his essay in the following year. He showed that the rings could not be solid or liquid, for such rings would not have stable motions. Rather, they must be made up of a large number of small satellites moving independently under the gravitational forces of Saturn and the other satellites. His mathematical calculations to demonstrate the stability of this model were a tour de force. The Astronomer Royal, George Airy, commented that it was one of the most remarkable applications of mathematics to physics that he had ever seen.

Maxwell was greatly interested in colour and colour vision, and he created the science of colour measurement. He showed that any colour could be matched by a combination of three primary colours, red, green, and blue, and he built instruments at Edinburgh and at Aberdeen for measuring the intensity of the three primaries to match the colour of a given sample. He tested the colour vision of several observers, and showed that colour-blind people are deficient in one of the three receptors in the eye. In 1861, he took the world's first colour photograph, shown in Figure 1.

Another field in which Maxwell made seminal contributions was the kinetic theory of gases, in which the macroscopic properties of a gas, such as its pressure, diffusion, viscosity, and thermal conductivity, may be calculated from the random motions and collisions of its molecules. When he found that a published experimental result disagreed with his calculation, he performed the experiment himself and found that the previous result was incorrect: his own calculation agreed with the theory. As the kinetic theory was in its infancy at the time, this spoke strongly in its support.

Maxwell's crowning achievement was in the theory of electromagnetism. A mass of evidence from British, French, and Danish scientists in the first half of the nineteenth century had established the basic laws of force between stationary electric charges, and between moving charges (electric currents), and also the laws governing the magnetic effects of currents. This had culminated in Faraday's discovery of the *law of induction*, which says that a moving magnet generates an electric current in a nearby circuit. Faraday introduced the idea that electric charges and currents give rise to a state in space that physicists call a *field*. The field generated by one electrical entity acts on another entity. Maxwell adopted this view, which has proved extremely fruitful, and gave it a mathematical formulation, which Faraday had been unable to do.

Maxwell put the last piece in the jigsaw of electromagnetism in 1861 with the suggestion that a changing electric field produces a magnetic field -- the counterpart of Faraday's law of induction. Thus, a changing electric field can give rise to a changing magnetic field, which, by Faraday's law, gives rise to a changing electric field, and so on, resulting in an electromagnetic wave. When he calculated the wave velocity from the theory, he found that it was the same as the measured velocity of light. He stated "*we can scarcely avoid the inference that light consists in transverse undulations … which is the cause of electric and magnetic phenomena*". (The italics are Maxwell's.) This was a revolutionary discovery. We now know that it is not only light that is propagated as an electromagnetic wave: radio waves, heat, X-rays, and gamma rays are all forms of electromagnetic waves, with the same velocity but differing wavelengths. The basic laws of electromagnetism are contained in four short equations, known as *Maxwell's equations*.

Although we have summarised Maxwell's major discoveries, mention should also be made of a paper in 1868 entitled *On governors* -- a governor here being a device for controlling the speed of a machine by using a signal fed back by the machine itself. This feedback principle is a fundamental one in the control of machines including robots, and Trinity man Norbert Wiener, inspired by Maxwell's pioneering work, called the subject *cybernetics* from the Greek for a steersman, corrupted to the Latin derivative of *governor*.

Maxwell was a deeply religious man with a profound social conscience. While at Trinity he came under the influence of F. D. Maurice, a theologian who thought that the church should be involved in social questions, and at Aberdeen and in London he taught regular evening classes for working men.

A man of considerable versatility, he painted pictures for his optical models, and he composed poetry, both serious and humorous. He had an ironic, occasionally impish, sense of humour. His inaugural lecture as the Cavendish professor was given little publicity, and few of the high University officials attended. When he gave his first undergraduate lecture, many of them came, thinking this was the inaugural lecture. They were treated to an account of the relation between the Fahrenheit and Centigrade temperature scales! It is thought that Maxwell had some part in the misunderstanding.

In contrast to Newton, Maxwell's achievements were not appreciated fully during his lifetime. As we have seen, he did not get the chair of the amalgamated colleges in Aberdeen, and he was not the first choice for the Cavendish chair. A factor that undoubtedly contributed to this was his extreme modesty. In the Presidential address to the British Association for the Advancement of Science in 1870, Maxwell discussed electromagnetism. He first gave a polite summary of the theories of others, and then continued "Another theory of electricity which I prefer …". This was how he referred to his epoch-making discoveries.

Maxwell's contributions to physics are now regarded as comparable to, and as profound as, those of Newton and Einstein. Newton said of his own work that he stood on the shoulders of giants. When Einstein was asked if he stood on the shoulders of Newton, he replied 'No, I stand on the shoulders of Maxwell'. 'From a long view of the history of mankind' said the Nobel Laureate, Richard Feynman 'seen from, say, ten thousand years from now, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics'.

John William Strutt, 3rd Baron **Rayleigh,** the second Cavendish Professor, was born in 1842. He came to Trinity in 1861 and was Senior Wrangler and 1st Smith's prize man in 1865. Though he was elected to a Fellowship in 1866, he was forced by the College statutes at the time to resign it five years later when he married Evelyn Balfour, a sister of Arthur Balfour, later to be Prime Minister. On the death of his father in 1873 he became the 3rd Baron Rayleigh.

Rayleigh was a very versatile physicist, but waves, both optical and acoustic, were his major field. One of his earliest achievements was, in 1870, to explain why the sky is blue. The light from the sky does not come directly from the sun, but is the sunlight that has been scattered by the molecules of air in the atmosphere. Rayleigh developed a theory of the scattering of light waves, from which he deduced that the shorter the wavelength of the light, the more it is scattered. Thus, blue light, whose wavelength is shorter than that of red light, is scattered more strongly, and this gives the sky its characteristic colour. The same theory accounts for the red colour of the sun that we see directly at sunrise and sunset. At those times, the light has further to travel through the atmosphere, so the blue light is scattered out completely from the rays from the sun and we see the residual red colour.

When Maxwell died in 1879, Rayleigh was offered the Cavendish chair. He would not normally have accepted, as he had his own laboratory in the family home at Terling Place in Essex and would not have wanted to be diverted from his research by the administrative duties of the head of a university laboratory. However, the family income was derived from farming (the enterprise still exists), and there was an agricultural depression in England at the time. So to supplement the family income he agreed to come for a short period. After five years, the family finances having improved, he returned to Terling Place, where he did all his subsequent work. When Balfour was Prime Minister he often stayed at Terling Place, as his own home was in Scotland. While at Terling he would help Rayleigh with his experiments -- not many scientists have had a Prime Minister as a laboratory assistant!

During his period at the Cavendish Laboratory, Rayleigh worked on the establishment of accurate standards for the basic electrical quantities: resistance, current, and voltage. The standards were necessary for theoretical purposes, and also commercially for the supply of electricity and the design of electrical equipment.

In 1892, Rayleigh measured the density of nitrogen produced from two different sources: one was from air in which all the oxygen had been removed, and one was chemically produced from ammonia. He found that the former was slightly, though significantly, denser than the latter. Two years later, the chemist, William Ramsay, joined in the work, and together they isolated a new chemically inert gas, argon, which constitutes about 1% of air. They were awarded Nobel prizes in 1904 for the discovery -- Rayleigh in physics and Ramsay in chemistry. Argon was heavier than any gas known at the time, which led some scientists to be sceptical about the discovery. Rayleigh replied that "the anomalous properties of argon seem to brought as a kind of accusation against us. But we had the very best of intentions in the matter. The facts were too much for us, and all that we can do now is apologize for ourselves and for the gas."

Rayleigh received many honours and occupied several high level positions during his life, including the Chancellorship of the University from 1908 until his death. In the course of his life he wrote no fewer than 446 papers, some of which were published posthumously. His name is attached to 17 laws, instruments, and criteria in physics. All his work was in classical physics, that is, physics before the discovery of quantum theory in 1900 and of special relativity in 1905. Although he survived nearly two decades after those discoveries, he did no work on the new theories. His reaction was that they were not his way of thinking and he would leave them to younger physicists. He was very conservative by nature and once remarked that the only change he could think of that was for the better was the exposure of the beams in Terling Church.

He died in 1919 and was buried in the family area in a quiet corner of Terling churchyard. Two years later a memorial to him was erected in Westminster Abbey. The inscription reads 'An unerring leader in the advancement of natural knowledge'.

Peering inside the atom

The next two Cavendish Professors revolutionised our thinking about atoms. The fundamental constituents of matter were called atoms from the Greek for *indivisible*. However, Thomson discovered the electron, and Rutherford the nucleus, giving us the modern picture of the atom. Their discoveries paved the way for all of nuclear physics, for the understanding of the chemical properties of the elements and their compounds, and for all electrical devices, such as the telephone, radio, television, computers…

When Rayleigh resigned the Cavendish chair in 1884 the selectors met and after a deliberation of less than a week, they offered the chair to Joseph John Thomson.

Thomson, born in 1856, came from a family of modest means that had no tradition in science. His parents had intended him to be an engineer, a fitting occupation for a bright boy in Victorian days, and, at the age of 14, he was sent to Owen's College (which became the University of Manchester) to await a vacancy in a firm of locomotive makers. Two years later his father died, and as his mother could not afford the apprenticeship premium he switched from engineering to mathematics and physics. In 1876, he entered Trinity with a minor scholarship, having failed to get one the year before. He remained there for the rest of his life. He was second Wrangler in 1880 and submitted a dissertation for a Fellowship the same year. His tutor told him that he was wasting his time and stood no chance. He was elected.

Thomson's appointment as Cavendish professor was surprising on two counts. First, he was only 28 years old, and second, the chair was a Chair of Experimental Physics. Thomson was primarily a mathematician, and up to that time had done little experimental work. However, the electors had made an inspired choice. Thomson's research, and his guidance of the work of others, made the Cavendish into the leading physics laboratory in the world.

Soon after his appointment, Thomson started to study the conduction of electricity through gases, which led to the discovery of the electron. At atmospheric pressure a gas is an insulator, but if the pressure is reduced for a gas in a sealed chamber, and a large voltage is applied between two metal terminals inside the gas, the gas becomes conducting and a current flows. A bright glow is observed between the terminals. The effect had been observed since about 1830, and many attempts were made in European laboratories to understand the phenomenon. It was observed that rays were coming from the cathode, the negative terminal, but there was controversy as to their nature; the German physicists thought that they were some kind of electromagnetic radiation, while the British and French physicists thought that they consisted of charged particles.

In 1896, Thomson succeeded in deflecting the rays with an electric field, which showed that the charged particle model was the correct one, and the direction of the deflection showed that the charge was negative. Thomson's claim to be the discoverer of the electron rests on two key observations. First, by measuring the deflections produced by electric and magnetic fields he obtained the mass of the particle, which proved to be about 2000 times less than the mass of a hydrogen atom, the lightest object known at the time. Second, he repeated the measurements using different gases and different cathode materials, and found that he got the same values for the mass. Thomson had discovered a universal particle—the electron. In his own words:

"We have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much farther than in the ordinary gaseous state; a state in which all matter is of one and the same kind; this matter being the substance from which all the chemical elements are built up."

Thomson remained the Cavendish professor until 1919, his tenure of 35 years being the longest so far. He was a popular and inspiring figure. Once a year, just before Christmas, the Cavendish research students held a dinner to which J.J. (as he was always known) and some of the senior members of the laboratory were invited. Lyrics were made up and sung to the popular tunes of the day.

Thomson was awarded the Nobel Prize in physics in 1906 for *investigations in the conduction of electricity through gases*. He was knighted in 1908, received the Order of Merit in 1908, and was President of the Royal Society from 1915 to 1920. He became the Master of Trinity in 1919 and remained so until his death. His Mastership was a great success; he maintained cordial relations with the Fellows and took a genuine interest in the academic and sporting activities of the undergraduates. Without his foresight and casting vote, Wittgenstein would not have been elected a Fellow.

The Manchester Guardian (now the Guardian) once reported the words of a dignitary on the local council. "There was a clever boy at school with me, little Joey Thomson, who took all the prizes. But what good has his book learning done him? Whoever hears of little Joey Thomson now?" The remarks were quoted by the chairman at a dinner at which Thomson was the guest of honour. Rising to reply, Thomson said "I wish you were not going to hear little Joey Thomson now".

Thomson married Rose Paget in 1890, and they had a happy private life, with two children. His son, George, another Trinity alumnus, also received the Nobel prize, for demonstrating the wave behaviour of the electron, thereby confirming one of the (many) strange predictions of quantum theory that an electron can behave as a wave or a particle. The father demonstrated the particle behaviour, and the son the wave! The elder Thomson died in 1940, and his ashes were buried in Westminster Abbey. "He, more than any other man," said Lawrence Bragg "was responsible for the change in outlook that distinguishes the physics of this century from that of the last."

Ernest Rutherford, the founder of nuclear physics and one of the greatest experimental physicists of all time, was born at Spring Grove, near Nelson, on the South Island of New Zealand on August 30, 1871. His family had no academic background. His father, who was a farmer, had emigrated from Scotland, and his mother from England. Rutherford was the 4th of 12 children. His mother was very keen on the education of her children, and Rutherford attended the local school where a single teacher taught 40 children, aged 5 to 14. Rutherford was deputed to teach two of his younger sisters; to ensure that they did not run away during the lesson, he tied their pigtails together. He later won scholarships to Nelson College and to the University of Christchurch.

After taking his degree he started experimenting with the effect of high-frequency electromagnetic waves on the magnetisation of iron. This led to the award of an 1851 Science Scholarship. Borrowing money for the passage, Rutherford came to Cambridge in 1895 to work with Thomson. Up till then research students had to be graduates of Cambridge, but in that year the university authorities changed the rules to admit students from outside, and the first one to come was Rutherford. On Thomson's advice he entered Trinity, and was later awarded a Coutts Trotter Studentship by the College, which still exists to help promising students.

He first worked on the transmission of radio waves, using his work in New Zealand to make a detector for the waves. He sent signals from the University Observatory to the Cavendish Laboratory, a distance of two miles, which was the world record in 1896. But after a time he changed to the study of radioactivity.

Radioactivity was discovered by Henri Becquerel in Paris in 1896. He found that some photographic plates near a uranium salt had become fogged. (A British physicist had made the same observation previously, but he complained to the manufacturer of the plates and received a fresh supply.) Pierre and Marie Curie entered the field and found that thorium and their newly discovered radium had the same effect on photographic plates. They deduced that the substances were giving off rays, but the nature of the rays and the underlying processes were a mystery.

In 1898, Rutherford was appointed Professor of Physics at the University of McGill in Montreal. In his first six years there he elucidated the basic features of radioactivity in a series of incisive experiments. He first showed that the emitted rays were of three types, of different penetrating powers, which, not knowing their nature, he called alpha, beta, and gamma rays, alpha rays being the least penetrating, and gamma the most. He then developed an electrical method for measuring the amount of radioactivity which was more accurate than the fogging of photographic plates.

He was joined by Frederick Soddy, a young chemist from Oxford in 1901. They showed that when a radioactive atom decays it changes to an atom of a different chemical element. This was in flat contradiction to the view held at the time that such a change, known as transmutation, was an impossible dream of the alchemists. Rutherford and Soddy called the decay a “sub-atomic chemical change”, deliberately avoiding the word “transmutation” with its alchemist associations.

Rutherford later showed that an alpha particle is a helium nucleus, a beta particle is an electron, and a gamma ray is a very short wavelength electromagnetic wave, and he showed how the change in the atom on radioactive decay was related to the particle emitted. He was awarded the Nobel Prize in chemistry in 1908 for his work. In his speech at Stockholm, he said that he had dealt with many transformations, but the quickest he had met with was his own transformation in one moment from a physicist to a chemist.

After moving to the University of Manchester in 1907, he made two further major discoveries. In 1909, he suggested that two of the workers in the laboratory should measure the scattering of alpha particles from gold foils, expecting that the particles would be deviated only by small amounts, but in fact they were scattered through large angles, some even bouncing backwards. Rutherford said this was an incredible result. “It was as if you fired a 15-inch shell at a sheet of tissue paper and it came back and hit you.” A year later he hit on the explanation: the atom must have a dense region from which the alpha particle is scattered backwards in a single collision. The model of the nuclear atom was born. Rutherford’s model, now the established one, is that an atom is like a miniature solar system, with a small heavy nucleus at its centre around which the electrons circulate like planets. His second discovery, made in 1919, was that an alpha particle that struck an atomic nucleus could cause it to disintegrate and give rise to a different nucleus. These two discoveries marked the beginning of nuclear physics.

In the same year he came back to Cambridge to succeed Thomson as Cavendish professor, a position he held until his death in 1937. While at Cambridge he continued his experiments on nuclear disintegration, finding more and more examples of the phenomenon. However, his main achievement was to direct the research of workers in the laboratory, who made important advances in nuclear physics that led to several Nobel prizes. Chadwick discovered the neutron in 1932, a particle predicted by Rutherford twelve years before, and Aston (Trinity Nobel laureate 1922), Blackett, Cockcroft and Walton and Wilson built novel instruments and machines for nuclear research.

Rutherford married Mary Newton in 1900, travelling from Montreal to New Zealand for the wedding. They had been engaged for six years and had waited until he could support a family. They had one daughter.

Rutherford was a big, burly man with a loud voice, which he was sometimes requested to moderate in the presence of sensitive equipment. A colleague, Andrade, wrote that “he was quite without affectation, self-consciousness, or pretentiousness of any kind. He was essentially kindly, but he was quite outspoken."

There are many anecdotes about him. When he was at Montreal, a colleague once asked him how it was he was always riding the crest of the wave. "Well, I made the wave, didn't I?" replied Rutherford. At Manchester, a young woman had an accident with a bottle of sulphur dioxide which left her unconscious. When Rutherford heard of the incident he summoned her to his office and said, "What's this I hear? You might have killed yourself." "Well, if I had, nobody would have cared" was the sulky reply. "I daresay not" said Rutherford "but I don't have the time to attend an inquest." On another occasion, he and a colleague, Oliphant, were conducting a PhD oral. Oliphant asked a question to which the candidate replied that he didn't know. "And neither would you Oliphant if you hadn't looked it up half an hour ago" said Rutherford.

Rutherford was ennobled in 1931, taking the title Baron Rutherford of Nelson. He died prematurely on October 19, 1937. There was a feeling of great loss, not only among scientists but throughout the world. The New York Times wrote "It is given to few men to achieve immortality, still less to achieve Olympian rank, during their lifetime. Lord Rutherford achieved both." His ashes were buried in Westminster Abbey, near the tomb of Newton.

Constructing materials

In 1912, Max von Laue at the University of Munich had the idea that by scattering X-rays from a crystal one could deduce the structure of the crystal, that is, the internal arrangement of the atoms and the distances between them, neither of which was known at the time. The phenomenon that makes this deduction possible is known as *diffraction*. Each atom in the crystal scatters the X-ray waves, and in certain directions the scattered waves are in phase, that is to say, their crests and their troughs coincide. In those directions there is a diffracted ray. In all other directions the individual beams cancel each other out. From the directions of the diffracted rays and the wavelength of the X-rays, the structure of the crystal may be deduced. The experiment was tried at Munich on a crystal of zinc sulphide (in secret because the head of the department had previously refused his consent on the grounds that it would not work) and Laue's intuition was confirmed—diffracted X-ray spots were observed on a photographic plate behind the crystal. This work provided the seed that blossomed into the new field of X-ray crystallography and gave us the structures of materials. It was now possible to start to explain the chemical and biological functions of ensembles of atoms. The pioneers of this quest to observe how atoms arranged themselves in real materials were Henry and Lawrence Bragg, who were father and son, and both Trinity men.

Lawrence Bragg shared the Nobel Prize for physics with his father in 1915 for their work on the determination of crystal structures by means of X-rays. Bragg was only 25 years old at the time. He is the youngest person to be awarded the prize, beating the next youngest by five years. He was chosen to succeed Rutherford as the Cavendish professor in 1938.

Bragg was born in Adelaide on the 31st of March 1890, his father being the professor of mathematics and physics at the university there. He attended various local schools until 1905, when he entered the university to read mathematics and physics, graduating in 1908. He came to Trinity in 1909 and read first mathematics, and then physics in the Natural Sciences Tripos, in which he obtained a first in 1911.

The paper announcing von Laue's diffraction experiments reached England in the summer of 1912. Bragg, who was in Cambridge doing some routine research in the Cavendish laboratory, joined his father at Leeds. His father was now a professor there, the family having returned from Australia in 1910. The two of them were greatly excited by the news. They examined the paper, and Bragg found that there was a mistake in Laue's analysis. The structure he had calculated for the crystal was not correct, and to account for the measurements he had made the unlikely assumption that the X-rays were of five different wavelengths. Bragg repeated the analysis for the correct structure, and the results were consistent with a single wavelength.

On his return to Cambridge he had an even greater success. While walking along the Backs one day, he realised that the diffracted X-ray beam could be regarded as the mirror reflection of the incident beam, with a plane of atoms in the crystal acting as the mirror. This result, coupled with a simple equation relating the parameters of the experiment, is known as *Bragg's law*. It has been of immense value in X-ray crystallography.

There followed two years of hectic activity in which the father and son determined the structures of many materials, including the alkali halides, and diamond. The father built an X-ray spectrometer, an accurate instrument for doing the measurements, and the son did most of the calculations. One of the simplest structures was that of common salt, in which the atoms are arranged in a three-dimensional lattice of alternate sodium and chlorine atoms. The structure was not immediately accepted by all scientists, especially chemists, the stumbling block being the absence of a molecule of a sodium atom monogamously linked to a chlorine atom. As late as 1927, a retired chemistry professor at Imperial College writing in *Nature*, said, "it is more than repugnant to common sense … it is not chemical cricket"—strong words for an Englishman.

The Nobel Prize in physics was awarded to von Laue in 1914 for the discovery of X-ray diffraction, and the two Braggs shared the prize in the following year. The latter was a unique event; there have been other cases of a father and son receiving the prize, and one of mother and daughter, but in none of those cases was the award for collaborative work.

During the first World War, Bragg was involved in sound ranging, a method of locating enemy guns by measuring the times of the arrival of the reports at different places. He was in the front line, and although he did not take part in actual fighting, the work was dangerous and he was awarded the Military Cross. Between the wars Bragg was a professor at Manchester University and determined the structures of more complicated crystals, such as silicate minerals. In 1938, he was appointed to the Cavendish chair.

His tenure of the chair, like that of Rutherford's, was marked not by original research of his own, but by the stimulus and inspiration he gave to others. The subject was the determination of the structures of biologically-important molecules. These present far greater difficulties than the structures previously solved, thanks to the very large numbers of atoms in the molecule and the complexity of their arrangement. On Bragg's initiative, the Medical Research Council set up a Research Unit in the Cavendish laboratory to promote the work, which had far-reaching consequences. Max Perutz solved the structure of haemoglobin and Trinity alumnus John Kendrew that of myoglobin. The climax of the Cavendish work came in 1953 when Crick and Watson obtained the structure of DNA, a turning point in biology. The MRC unit subsequently moved out of the Cavendish laboratory, becoming the Laboratory of Molecular Biology, and maintained its brilliant record, summarised by the title of John Finch's history *A Nobel Fellow On Every Floor*.

Bragg also had the foresight to support the beginnings of Cambridge radio astronomy which had "intriguing problems in optics". This later allowed the group of another Trinity man, Martin Ryle (Nobel Prize 1974), to discover quasars, which are cosmic objects of high luminosity and are some of the most distant known objects in the universe.

Bragg retired from the Cavendish chair in 1954 to become the Resident Professor of the Royal Institution. The Institution was in some disarray at the time, but Bragg, by his tact and enterprise, managed to put it on a sound footing. He became the Director, a newly created post, in 1966. He finally retired the following year.

Bragg married Alice Hopkinson in 1921. They had a very happy marriage with four children. Bragg was a devoted and inventive father. He built a model railway for the children, and a shadow theatre to illustrate Winnie the Pooh stories.

He was rather shy, and everyday administration was not to his taste. When he was the Cavendish professor he was ably assisted in this side of the job by a radio astronomer in the department, Jack Ratcliffe, who accompanied him at university committee meetings, opening his remarks with "We think, don't we Professor …"

Among Bragg's many awards were prestigious medals from the Royal Society. He was knighted in 1941. He died on July 1, 1971, respected and revered as the father of X-ray crystallography.

Exotic Matter

The final gallery of Trinity physicists have studied matter at the extremes. Instead of just three states of matter—solids, liquids and gases -- there are in fact myriad exotic states at high and low temperatures and pressures. These states cannot be explained by classical intuition, but instead require models consistent with the principles of quantum mechanics.

In 1921, **Pyotr Kapitsa** (1894-1984) was a member of a delegation from the Soviet Union studying European physics laboratories. When the committee came to Cambridge he jumped ship and persuaded Rutherford to allow him to stay and work in the Cavendish laboratory. His research in magnetism and low-temperature physics was so successful that a special laboratory, the Mond, was built for him in 1933.

In the following year he visited the Soviet Union as he had done many times before, despite repeated warnings that it was unsafe. This was a visit too far. He had claimed, incorrectly as it turned out, that his work would revolutionise the production of electricity. Unfortunately for him, the Soviet authorities, who were trying to modernise Russia with the emphasis on electrification, took him at his word and he was not allowed to leave. Rutherford, with characteristic generosity, sent his Cambridge equipment to him so that he could continue his work. When he was awarded the

1978 Nobel Prize for his work in low-temperature physics, he remarked that it was 30 years since he had done the experiments, which was a coded message to the Nobel committee that he should have received the prize earlier.

Kapitsa's major discovery was the superfluidity of liquid helium. When helium is cooled sufficiently it enters a state in which it can flow without resistance. It can pass through any pores in its container. Even more strangely, if a superfluid sits in an open container, it may flow up the sides and drip off the bottom!

Not only do certain liquids exhibit weird behaviour, it is possible for electrons to form a superfluid. In doing so, the host material becomes a superconductor because current can flow without resistance. Whilst still a graduate student, **Brian Josephson** (1940-) predicted the possibility for super-currents to pass between an insulator separating two superconductors. This current is extremely sensitive to external magnetic fields, which makes *Josephson junctions* perfect magnetic field detectors.

R. H. Fowler (1889-1944) studied at Winchester College before winning a scholarship to Trinity. After the First World War, he returned to Trinity as a college lecturer in mathematics in 1920. Working on thermodynamics and statistical mechanics, Fowler advanced the understanding of electron energy states in materials, and was the first person to recognise the need for the zeroth law of thermodynamics in order to make the subject logically consistent. Together with his student Dirac, Fowler discovered the type of inherently quantum mechanical electronic matter present in white dwarfs - the final phase of life for the majority of stars in our galaxy. Stars that are incapable of becoming supernovae shrink to a fraction of their former size. For instance, our Sun will contract to the size of the Earth. Gifted as a teacher, Fowler supervised fifteen Fellows of the Royal Society and three Nobel Laureates. Amongst his other collaborators was Trinity man Sir **Arthur Eddington** (1882-1944) who explained Einstein's general relativity to the English-speaking world and conducted its first experimental test during the solar eclipse of 1919.

Subramanyan Chandrasekhar was born in 1910 in Lahore, then part of British India. Initially home schooled, Chandrasekhar received his BA degree at Presidency College, Chennai, before winning a government award to pursue graduate work at Trinity in 1930, where he went on to win a Prize Fellowship. En route to Cambridge, Chandrasekhar applied quantum mechanics and relativity to stellar matter, going beyond the densities considered by his supervisor Fowler. He found that stars above a certain mass, the *Chandrasekhar limit*, would be unstable and would ultimately collapse to form a neutron star or black hole. This and his later work on the structure and evolution of stars won him the 1983 Nobel Prize.

Coming full circle, Chandrasekhar in his final years embarked on a study of Newton's *Principia*, translating Newton's geometrical language into modern notation and thereby allowing a whole new generation to uncover its secrets.

Trinity has a physics heritage indeed! But the College does not intend to rest on its laurels. Our Fellows and students are still at the forefront of discoveries in novel quantum matter, and in particle physics at the Large Hadron Collider. And once again a Trinity man heads the Cavendish. A warm and stimulating welcome awaits students who contemplate a career in a subject that has exercised some of the finest human minds.

Extra characters if space permits

G.I. Taylor on fluid dynamics.

Otto Frisch was first to realise with Meitner the possibility of neutron induced fission of uranium. He also designed the first detonator of the atomic bomb whilst at Los Alamos. He arrived in Cambridge and Trinity as the first Jacksonian professor of Natural philosophy.