THE BIOGRAPHICAL DICTIONARY OF SCIENTISTS

Physicists

General Editor
David Abbott PhD

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PETER BEDRICK BOOKS
New York

First American edition published in 1984 by
Peter Bedrick Books
125 East 23 Street
New York, NY 10010

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Published by agreement with Muller, Blond & White Ltd, London

Library of Congress Cataloging in Publication Data
Main entry under title:

The Biographical dictionary of scientists, physicists.

1. Physicists — Biography. I. Abbott, David, 1937-
QC15.B56 1984 530'.092'2 [B] 84-9211
ISBN 0-911745-79-3

Manufactured in the United States of America
Distributed in the USA by Harper & Row
and in Canada by Book Center, Montreal

Acknowledgements

Many people are involved in the creation of a major new series of reference books. The general editor and the publishers are grateful to all of them and wish to thank particularly the contributing authors: Neil Ardley; Gareth Ashurst; Jim Bailey; Mary Basham; Alan Bishop; William Cooksey; David Cowey; Robert Matthews; Valerie Neal; Lucia Osborne; Helen Rapson; Mary Sanders; Robert Smith and David Ward. Our thanks are also due to Mick Saunders for his artwork and to Bull Publishing Consultants Ltd whose experience in the development of reference books has made a significant contribution to the series: John Clark; Kate Duffy; Nikki Okell; Hal Robinson and Sandy Shepherd.

Contents

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Historical introduction

Physics is a branch of science in which the theoretical and the practical are firmly intertwined. It has been so since ancient times, as physicists have striven to interpret observation or experiment in order to arrive at the fundamental laws that govern the behaviour of the Universe. Physicists aim to explain the manifestations of matter and energy that characterize all things and processes, both living and inanimate, extending from the grandest of galaxies down to the most intimate recesses of the atom.

The history of physics has not been a straight and easy road to enlightenment. The exploration of new directions sometimes leads to dead ends. New ways of looking at things may result in the overthrow of a previously accepted system. Not Aristotle's system, nor Newton's, nor even Einstein's was "true"; rather statements, or "laws", in physics satisfy contemporary requirements or - in the existing state of knowledge - contemporary possibilities. The question that physicists ask is not so much "Is it true?" as "Does it work?"

Physics has many strands - such as mechanics, heat, light, sound, electricity and magnetism - and, although they are often pursued separately, they are also all ultimately interdependent. To pursue the history of physics, therefore, it is necessary to follow several separate chains of discovery and then to find the links between them. The story is of frustration and missed opportunities as well as of genius and perseverence. But however complex it may appear, all physicists seek or have sought to play a part in the evolution of an ultimate explanation of all the effects that occur throughout the Universe. That goal may be unattainable but the thrust towards it has kept physics as alive and vital today as it was when it originated in ancient times.

Force and motion

The development of an understanding of the nature of force and motion was a triumph for physics, one which marked the evolution of the scientific method. As in most other branches of physics, this development began in ancient Greece.

The earliest discovery in physics, apart from observations of effects like magnetism, was the relation between musical notes and the lengths of vibrating strings. Pythagoras (c.582–c.497 BC) found that harmonious sounds were given by strings whose lengths were in simple numerical ratios, such as 2:1, 3:2 and 4:3. From this discovery the belief grew that all explanations could be found in terms of numbers. This was developed by Plato (c.427–c.347 BC) into a conviction that the cause underlying any effect could be expressed in mathematical form. The motion of the heavenly bodies, Plato reasoned, must consist of circles, since these were the most perfect geometric forms.

Reason also led Democritus (c.470–c.380 BC) to propose that everything consisted of minute indivisible particles called atoms. The properties of matter depend on the characteristics of the atoms of which it is composed, and the atoms combine in ways that are determined by unchanging fundamental laws of nature.

A third view of the nature of matter was given by Aristotle (384–322 BC), who endeavoured to interpret the world as he observed it, without recourse to abstractions such as atoms and mathematics. Aristotle reasoned that matter consisted of four elements - earth, water, air and fire - with a fifth element, the ether, making up the heavens. Motion occurred when an object sought its rightful place in the order of elements, rocks falling through air and water to the earth, air rising through water as bubbles and fire through air as smoke.

There was value in all these approaches and physics has absorbed them all to some degree. Plato was essentially correct; only his geometry was wrong, the planets following elliptical, not circular, orbits. Atoms do exist as Democritus foretold and they do explain the properties of matter. Aristotle's emphasis on observation (though not his reasoning) was to be a feature of physics and many other sciences, notably biology, of which he may be considered the founder.

These ideas were, however, mainly deductions based solely on reason. Few of them were given the test of experiment to prove that they were right. Then came the achievements of Archimedes (c.287–212 BC), who discovered the law of the lever and the principle of flotation by measuring the effects that occur and deduced general laws from his results. He was then able to apply his laws, building pulley systems and testing the purity of the gold in King Hieron's crown by a method involving immersion.

Archimedes thus gave physics the scientific method. All subsequent principal advances made by physicists were to take the form of mathematical interpretations of observations and experiments. Archimedes developed the method in founding the science of statics - how forces interact to produce equilibrium. But an understanding of motion lay a long way off. In the centuries following the collapse of Greek civilization in around AD100, physics marked time. The Arabs kept the Greek achievements alive, but they made few advances in physics, while in Europe the scientific spirit was overshadowed by the "Dark Ages". Then in about 1200, the spirit of enquiry was rekindled in Europe by the import of Greek knowledge from the Arabs. Unfortunately, progress was hindered somewhat by the fact that Aristotle's ideas, particularly his views on motion, prevailed. Aristotle had assumed that a heavy object falls faster than a light object simply because it is heavier. He also argued that a stone continues to move when thrown because the air displaced by the stone closes behind it and pushes the stone. This explanation derived from Aristotle's conviction that nature abhors a vacuum (which is why he placed a fifth element in the heavens).

Aristotle's ideas on falling bodies were probably first disproved by Simon Stevinus (1548-1620), who is believed to have dropped unequal weights from a height and found that they reached the ground together. At about the same time Galileo (1564-1642) measured the speeds of "falling" bodies by rolling spheres down an inclined place and discovered the laws that govern the motion of bodies under gravity. This work was brought to a brilliant climax by Isaac Newton (1642-1727), who in his three laws of motion achieved an understanding of force and motion, relating them to mass and recognizing the existence of inertia and momentum. Newton thus explained why a stone continues to move when thrown; and he showed the law of falling bodies to be a special case of his more general laws. Newton went on to derive from existing knowledge of the motion and dimensions of the Earth-Moon system a universal law of gravitation, one which provided a mathematical statement for the laws of planetary motion discovered empirically by Johann Kepler (1571-1630).

Newton's laws of motion and gravitation, which were published in 1687, were fundamental laws which sought to explain all observed effects of force and motion. This triumph of the scientific method heralded the Age of Reason - not the Greek kind of reasoning, but a belief that all could be explained by the deduction of fundamental laws upheld by observation or experiment. It was to result in an explosion of scientific discovery in physics that has continued to this day. In the field of force and motion, important advances were made with the discovery of the law governing the pendulum and the principle of conservation of momentum by Christiaan Huygens (1629-1695) and the determination of the gravitational constant by Henry Cavendish (1731-1810).

The behaviour of matter

Physics is basically concerned with matter and energy, and investigation into the behaviour of matter also originated in ancient Greece with the work of Archimedes concerning flotation. As with force and motion, Simon Stevinus made the first post-Greek advance with the discovery that the pressure of a liquid depends on its depth and area. This achievement was developed by Blaise Pascal (1623-1662), who found that pressure is transmitted throughout a liquid in a closed vessel, acting perpendicularly to the surface at any point. Pascal's principle is the basis of hydraulics. Pascal also investigated the mercury barometer invented in 1643 by Evangelista Torricelli (1608-1647) and showed that air pressure supports the mercury column and that there is a vacuum above it, thus disproving Aristotle's contention that a vacuum cannot exist. The immense pressure that the atmosphere can exert was subsequently demonstrated in several sensational experiments by Otto von Guericke (1602-1686).

Solid materials were also investigated. The fundamental law of elasticity was discovered by Robert Hooke (1635-1703) in 1678 when he found that the stress (force) exerted is proportional to the strain (elongation) produced. Thomas Young (1773-1829) later showed that a given material has a constant, known as Young's modulus, that defines the strain produced by a particular stress.

The effects that occur with fluids (liquids or gases) in motion were then explored. Daniel Bernoulli (1700-1782) established hydrodynamics with his discovery that the pressure of a fluid depends on its velocity. Bernoulli's principle explains how lift occurs and led eventually to the invention of heavier-than-air flying machines. It also looked forward to ideas of the conservation of energy and the kinetic theory of gases. Other important advances in our understanding of fluid flow were later made by George Stokes (1819-1903), who discovered the law that relates motion to viscosity, and Ernst Mach (1838-1916) and Ludwig Prandtl (1875-1953), who investigated the flow of fluids over surfaces and made discoveries vital to aerodynamics.

The effects of light

The Greeks were aware that light rays travel in straight lines, but they believed that the rays originate in the eyes and travel to the object that is seen. Euclid (*c.*325–260 BC), Hero (*fl.* AD 60) and Ptolemy (*fl.* second century AD) were of this opinion although, recognizing that optics is essentially a matter of geometry, they discovered the law of reflection and investigated refraction.

Optics made an immense stride forward with the work of Alhazen (*c.* 965–1038), who was probably the greatest scientist of the Middle Ages. Alhazen recognized that light rays are emitted by a luminous source and are then reflected by objects into the eyes. He studied images formed by curved mirrors and lenses and formulated the geometrical optics involved. Alhazen's discoveries took centuries to filter into Europe, where they were not surpassed until the seventeenth century. The refracting telescope was then invented in Holland in 1608 and quickly improved by Galileo and Kepler, and in 1621 Willebrord Snell (1580–1626) discovered the laws that govern refraction.

The next major steps forward were taken by Newton, who not only invented the reflecting telescope in 1668, but a couple of years earlier found that white light is split into a spectrum of colours by a prism. Newton published his work in optics in 1704, provoking great controversy with his statement that light consists of a stream of particles. Huygens had put forward the view that light consists of a wave motion, an opinion reinforced by the discovery of diffraction by Francesco Grimaldi (1618–1663). Such was Newton's reputation, however, that the particulate theory held sway for the following century. In 1801 Young discovered the principle of interference, which could be explained only by assuming that light consisted of waves. This was confirmed in 1821, when Augustin Fresnel (1788–1827) showed from studies of polarized light, which had been discovered by Étienne Malus (1775–1812) in 1808, that light is made up of a transverse wave motion, not longitudinal as had previously been thought.

Newton's discovery of the spectrum remained little more than a curiosity until 1814, when Joseph von Fraunhofer (1787–1826) discovered that the Sun's spectrum is crossed by the dark lines now known as Fraunhofer lines. Fraunhofer was unable to explain the lines, but he did go on to invent the diffraction grating for the production of high-quality spectra and the spectroscope to study them. An explanation of the lines was provided by Gustav Kirchhoff (1824–1887), who in 1859 showed that they are caused by elements present in the Sun's atmosphere. With Robert Bunsen (1811–1899), Kirchhoff discovered that elements have unique spectra by which they can be identified, and several new elements were found in this way. In 1885, Johann Balmer (1825–1898) derived a mathematical relationship governing the frequencies of the lines in the spectrum of hydrogen. This later proved to be a crucial piece of evidence for revolutionary theories of the structure of the atom.

Meanwhile, several scientists investigated the phenomenon of colour, notably Young, Hermann von Helmholtz (1821–1894) and James Clerk Maxwell (1831–1879). Their research led to the establishment of the three-colour theory of light, which showed that the eye responds to varying amounts of red, green and blue in light and mixes mixing them to give particular colours. This led directly to colour photography and other methods of colour reproduction used today.

The velocity of light was first measured accurately in 1862 by Jean Foucault (1819–1868), who obtained a value within 1 per cent of the correct value. This led to a famous experiment performed by Albert Michelson (1852–1931) and Edward Morley (1838–1923) in which the velocity of light was measured in two directions at right angles. Their purpose was to test the theory that a medium called the ether existed to carry light waves. If it did exist, then the two values obtained would be different. The Michelson–Morley experiment, performed in 1881 and then again in 1887, yielded a negative result both times (and on every occasion since), thus proving that the ether does not exist.

More important, the Michelson–Morley experiment showed that the velocity of light is constant regardless of the motion of the observer. From this result, and from the postulate that all motion is relative, Albert Einstein (1879–1955) derived the special theory of relativity in 1905. The principal conclusion of special relativity is that in a system moving relative to the observer, length, mass and time vary with the velocity. The effects become noticeable only at velocities approaching light; at slower velocities, Newton's laws hold good. Special relativity was crucial to the formulation of new ideas of atomic structure and it also led to the idea that mass and energy are equivalent, an idea used later to explain the great power of nuclear reactions. In 1915 Einstein published his general theory of relativity, in which he showed that gravity distorts space. This explained an anomaly in the motion of Mercury, which does not quite obey Newton's laws, and it was dramatically confirmed in 1919 when a solar eclipse revealed that the Sun's gravity was bending light rays coming from stars.

Electricity and magnetism

The phenomena of electricity and magnetism are believed to have been first studied by the ancient Greek philosopher Thales (624–546 BC), who was considered by the Greeks to be the founder of their science. Thales found that a piece of amber picks up light objects when rubbed, the action of rubbing thus producing a charge of static electricity. The words "electron" and "electricity" came from this discovery, *elektron* being the Greek word for amber. Thales also studied the similar effect on each other of pieces of lodestone, a magnetic mineral found in the region of Magnesia. It is fitting that the study of electricity and magnetism originated together, for the later discovery that they are linked was one of the most important ever made in physics.

No further progress was made, however, for nearly 2,000 years. The strange behaviour of amber remained no more than a curiosity, though magnets were used to make compasses. From this, Petrus Peregrinus (*f.* 1200s) discovered the existence of north and south poles in magnets and realized that they attract or repel each other. William Gilbert (1544–1603) first explained the Earth's magnetism and also investigated electricity, finding other substances besides amber that produce attraction when rubbed.

Then Charles Du Fay (1698–1739) discovered that substances charged by rubbing may repel as well as attract in a similar way to magnetic poles and Benjamin Franklin (1706–1790) proposed that positive and negative charges are produced by the excess or deficiency of electricity. Charles Coulomb (1763–1806) measured the forces produced between magnetic poles and between electric charges and found that they both obey the same inverse square law.

A major step forward was taken in 1800, when Alessandro Volta (1745–1827) invented the battery. A source of current electricity was now available and in 1820 Hans Oersted (1777–1851) found that an electric current produces a magnetic field. This discovery of electromagnetism was immediately taken up by Michael Faraday (1791–1867), who realized that magnetic lines of force must surround a current. This concept led him to discover the principle of the electric motor in 1821 and electromagnetic induction in 1831, the phenomenon in which a changing magnetic field produces a current. This was independently discovered by Joseph Henry (1797–1878) at the same time.

Meanwhile, important theoretical developments were taking place in the study of electricity. In 1827, André Ampère (1775–1836) discovered the laws relating magnetic force to electric current and also properly distinguished current from tension, or EMF. In the same year, Georg Ohm (1789–1854) published his famous law relating current, EMF and resistance. Kirchhoff later extended Ohm's law to networks, and he also unified static and current electricity by showing that electrostatic potential is identical to EMF.

In the 1830s, Carl Gauss (1777–1855) and Wilhelm Weber (1804–1891) defined a proper system of units for magnetism; later they did the same for electricity. In 1845 Faraday found that materials are paramagnetic or diamagnetic, and Lord Kelvin (1824–1907) developed Faraday's work into a full theory of magnetism. An explanation of the cause of magnetism was finally achieved in 1905 by Paul Langevin (1872–1946), who ascribed it to electron motion.

Electricity and magnetism were finally brought together in a brilliant theoretical synthesis by James Clerk Maxwell. From 1855 to 1873 Maxwell developed the theory of electromagnetism to show that electric and magnetic fields are propagated in a wave motion and that light consists of such an electromagnetic radiation. Maxwell predicted that other similar electromagnetic radiations must exist and, as a result, Heinrich Hertz (1857–1894) produced radio waves in 1888. X-rays and gamma rays were discovered by accident soon after.

The nature of heat and energy

The first step towards measurement – and therefore an understanding – of heat was taken by Galileo, who constructed the first crude thermometer in 1593. Gradually these instruments improved and in 1714 Daniel Fahrenheit (1686–1736) invented the mercury thermometer and devised the fahrenheit scale of temperature. This was replaced in physics by the celsius or centigrade scale proposed by Anders Celsius (1701–1744) in 1742.

At this time, heat was considered to be a fluid called caloric that flowed into or out of objects as they got hotter or colder, and even after 1798 when Count Rumford (1753–1814) showed the idea to be false by his observation of the boring of cannon, it persisted. Earlier Joseph Black (1728–1799) had correctly defined the quantity of heat in a body and the latent heat and specific heat of materials, and his values had been successfully applied to the improvement of steam engines. In 1824, Sadi Carnot (1796–1832), also a believer in the caloric theory, found that the amount of work that can be produced by an engine is related only to the temperature at which it operates.

Carnot's theorem, though not invalidated by the caloric theory, suggested that, since heat gives rise to work, it was likely that heat was a form of motion, not a fluid. The idea also grew that energy may be changed from one form to another (i.e. from heat to motion) without a change in the total amount of energy involved. The interconvertibility of energy and the principle of the conservation of energy were established in the 1840s by several physicists. Julius Mayer (1814-1878) first formulated the principle in general terms and obtained a theoretical value for the amount of work that may be obtained by the conversion of heat (the mechanical equivalent of heat). Helmholtz gave the principle a firmer scientific basis and James Joule (1818-1889) made an accurate experimental determination of the mechanical equivalent. Rudolf Clausius (1822-1888) and Kelvin developed the theory governing heat and work, thus founding the science of thermodynamics. This enabled Kelvin to propose the absolute scale of temperature that now bears his name.

The equivalence of heat and motion led to the kinetic theory of gases, which was developed by John Waterston (1811-1883), Clausius, Maxwell and Ludwig Boltzmann (1844-1906) between 1845 and 1868. It gave a theoretical description of all effects of heat in terms of the motion of molecules.

During the nineteenth century it also came to be understood that heat may be transmitted by a form of radiation. Pioneering theoretical work on how bodies exchange heat had been carried out by Pierre Prévost (1751-1839) in 1791, and the Sun's heat radiation had been discovered to consist of infrared rays by William Herschel (1738-1822) in 1800. In 1862 Kirchhoff derived the concept of the perfect black body - one that absorbs and emits radiation at all frequencies. In 1879 Josef Stefan (1835-1893) discovered the law relating the amount of energy radiated by a black body to its temperature, but physicists were unable to relate the frequency distribution of the radiation to the temperature. This increases as the temperature is raised, causing an object to glow red, yellow and then white as it gets hotter. Lord Rayleigh (1842-1919) and Wilhelm Wien (1864-1928) derived incomplete theories of this effect, and then in 1900 Max Planck (1858-1947) showed that it could be explained only if radiation consisted of individsible units, called quanta, whose energy was proportional to their frequency.

Planck's quantum theory revolutionized physics. It showed that heat radiation and other electromagnetic radiations including light must consist of indivisible particles of energy and not of waves as had previously been thought. In 1905 Einstein found a ready explanation of the photoelectric effect using quantum theory, and the theory was experimentally confirmed by James Franck (1882-1964) in the early 1920s.

Another advance in the study of heat that took place in the same period was the production of low temperatures. In 1852 Joule and Kelvin found the effect named after them is used to produce refrigeration by adiabatic expansion of a gas, and James Dewar (1842-1923) developed this effect into a practical method of liquefying gases from 1877 onwards. Heike Kamerlingh-Onnes (1853-1926) first produced temperatures within a degree of absolute zero and in 1911 he discovered superconductivity.

Sound

Sound is the one branch of physics that was well established by the Greeks, especially by Pythagoras. They surmised, correctly, that sound does not travel through a vacuum, a contention proved experimentally by Guericke in 1650. Measurements of the velocity of sound in air were made by Pierre Gassendi (1592-1655) and in other materials by August Kundt (1839-1894). Ernst Chladni (1756-1827) studied how the vibration of surfaces produces sound waves, and in 1845 Christian Doppler (1803-1853) discovered the effect relating the frequency (pitch) of sound to the relative motion of the source and observer. The Doppler effect is also produced by light and other wave motions and has proved to be particularly valuable in astronomy.

The structure of the atom

The existence of atoms was proved theoretically by chemists during the nineteenth century, but the first experimental demonstration of their existence and the first estimate of their dimensions was made by Jean Perrin (1870-1942) in 1909.

The principal direction taken in physics in this century has been to determine the inner structure of the atom. It began with the discovery of the electron in 1897 by J. J. Thomson (1856-1940), who showed that cathode rays consist of streams of minute indivisible electric particles. The charge and mass of the electron were then found by John Townsend (1868-1937) and Robert Millikan (1868-1953).

Meanwhile, another important discovery had been made with the detection of radioactivity by Antoine Becquerel (1852-1908) in 1896. Three kinds of radioactivity were found; these were named alpha, beta and gamma by Ernest Rutherford (1871-1937). Becquerel recognized in 1900 that beta particles are electrons. In 1903 Rutherford explained that radioactivity is caused by the breakdown of atoms. In 1908 he identified alpha particles as helium nuclei, and in association with Hàns Geiger (1882-1945) produced the nuclear model of the atom in 1911, proposing that it consists of electrons orbiting a nucleus. Then in 1914 Rutherford identified the proton and in 1919 he produced the first artificial atomic disintegration by bombarding nitrogen with alpha particles.

Rutherford's pioneering elucidation of the basic structure of the atom was aided by developments in the use of X-rays, which had been discovered in 1895 by Wilhelm Röntgen (1845-1923). In 1912 Max von Laue (1879-1960) produced diffraction in X-rays by passing them through crystals, showing X-rays to be electromagnetic waves, and Lawrence Bragg (1890-1971) developed this method to determine the arrangement of atoms in crystals. His work influenced Henry Moseley (1887-1915), who in 1914 found by studying X-ray spectra that each element has a particular atomic number, equal to the number of protons in the nucleus and to the number of electrons orbiting it.

In 1913, Niels Bohr (1885-1962) achieved a brilliant synthesis of Rutherford's nuclear model of the atom and Planck's quantum theory. He showed that the electrons must move in orbits at particular energy levels around the nucleus. As an atom emits or absorbs radiation, it moves from one orbit to another and produces or gains a certain number of quanta of energy. In so doing, the quanta give rise to particular frequencies of radiation, producing certain lines in the spectrum of the radiation. Bohr's theory was able to explain the spectral lines of hydrogen and their relationship, found earlier by Balmer.

These discoveries, made so quickly, seemed to achieve an astonishingly complete picture of the atom, but more was to come. In 1923, Louis De Broglie (1892-) found by combining the quantum theory with Einstein's mass-energy equation that electrons could behave as if they made up waves around the nucleus. This discovery was developed into a theoretical system of wave mechanics by Erwin Schrödinger (1887-1961) in 1926 and experimentally confirmed in the following year. It showed that electrons exist both as particles and waves. Furthermore it reconciled Planck's quantum theory with classical physics by indicating that electromagnetic quanta or photons, which were named and detected experimentally in X-rays by Arthur Compton (1892-1962) in 1923, could behave as waves as well as particles. A prominent figure in the study of atomic structure was Werner Heisenberg (1901-1976), who showed in 1927 that the position and momentum of the electron in the atom cannot be known precisely, but only found with a degree of probability or uncertainty. His uncertainty principle follows from wave-particle duality and it negates cause and effect, an uncomfortable idea in a science that strives to reach laws of universal application.

The next step was to investigate the nucleus. A series of discoveries of nuclear particles accompanying the proton were made, starting in 1932 with the discovery of the positron by Carl Anderson (1905-) and the neutron by James Chadwick (1891-1974).

This work was aided by the development of particle accelerators, beginning with the voltage multiplier built by John Cockcroft (1897-1967) and Ernest Walton (1903-), which achieved the first artifical nuclear transformation in 1932. It led to the discovery of nuclear fission by Otto Hahn (1879-1968) in 1939 and the production of nuclear power by Enrico Fermi (1901-1954) in 1942.

Modern physics

Physicists have advanced along several fronts in the second half of this century. A pioneering discovery of great consequence was made in 1948 with the invention of the transistor by John Bardeen (1908-), William Shockley (1910-) and Walter Brattain (1902-), and the subsequent development of microelectronic devices has been of immense importance. Superconductivity has been another field of activity, Bardeen and others achieving an explanation of this phenomenon in 1957. The tunnelling effect in superconductivity discovered by Brian Josephson (1940-) could lead the way to superfast computers. Another important practical development has been the invention of the laser by Theodore Maiman (1927-) in 1960 and the subsequent use of lasers in holography as predicted by Dennis Gabor (1900-1979) in 1947.

In theoretical physics, the main thrust forward continues to be in atomic structure. Physicists hope to be able to relate to each other the many different nuclear particles found in experiments involving high-energy accelerators. This may involve the assembly of all particles from hitherto undetected basic particles called quarks. It may also help to provide a unified view of the four basic forces, or interactions, in nature - gravity, electromagnetic interaction and the weak and strong nuclear forces. If so, a fundamental understanding of the nature of matter and energy may be in sight.

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Abbe, Ernst (*1840-1905*), was a German physicist who, working with Carl Zeiss, greatly improved the design and quality of optical instruments, particularly the compound microscope. He indirectly had a great influence in various physical sciences, particularly in biology where the improved resolving power of his instruments permitted researchers to observe micro-organisms and internal cellular structures for the first time.

Abbe was born in Eisenach, Thuringia (now East Germany), on 23 January 1840, the son of a spinning-mill worker. On a scholarship provided by his father's employers he attended high school (graduating in 1857) and then went to study physics at the University of Jena. He gained his doctorate from Göttingen University in 1861 and three years later became a lecturer in mathematics, physics and astronomy at Jena, being appointed Professor in 1870. In 1866 he began his association with Carl Zeiss, an instrument manufacturer who supplied optical instruments to the university and repaired them. Abbe was appointed Director of the Astronomical and Meteorological Observatory at Jena in 1878. Two years earlier he had become a partner in Zeiss' firm, and in 1881 Abbe invited Otto Schott (1851-1935), who had studied the chemistry of glasses and manufactured them, to go to Jena, and the famous company of Schott and Sons was founded in 1884. On the death of Zeiss in 1888 Abbe became the sole owner of the Zeiss works. He established the Carl Zeiss Foundation in 1891, and in 1896 he formalized the association between the Zeiss works and Jena University by making the company a co-operative, with the profits shared between the workers and the university. He died in Jena on 14 January 1905.

The success of the Jena enterprise arose largely from the right combination of talents: Zeiss as the manufacturer; Abbe as the physicist/theoretician, who performed the mathematical calculations for designing new lenses; and Schott the chemist, who formulated and made the special glasses needed by Abbe's designs. Abbe worked out why, contrary to expectation, a microscope's definition decreases with a reduction in the aperture of the objective; he found that the loss in resolving power is a diffraction effect. He calculated how to overcome spherical aberration in lenses - by a combination of geometry and the correct types of glass. He also explained the phenomenon of coma (first recognized in 1830 by Joseph Jackson Lister (1786-1869), the father of the famous surgeon), in which even a corrected lens displays aberration when the object is slightly off the instrument's axis. It was overcome by applying Abbe's "sine condition", producing the so-called aplanatic lens. Finally Abbe calculated how to correct chromatic aberration, using Schott's special glasses and, later, fluorite to make microscope objective lenses, culminating in the apochromatic lens system of 1886.

In 1872 he developed the Abbe substage condenser for illuminating objects under high-power magnification. Among his other inventions were a crystal refractometer and, developed with Armand Fizeau, an optical dilatometer for measuring the thermal expansion of solids.

Alfvén, Hannes Olof Gösta (*1908-*), is a Swedish astrophysicist who has made fundamental contributions to plasma physics, particularly in the field of magnetohydrodynamics (MHD) - the study of plasmas in magnetic fields. For his pioneering work in this area he shared the 1970 Nobel Prize in Physics with the French physicist Louis Néel (1904-).

Alfvén was born in Norrköping, Sweden, on 30 May 1908 and was educated at the University of Uppsala, from which he gained his PhD in 1934. In 1940 he joined the Royal Institute of Technology, Stockholm, becoming Professor of Electronics in 1945 then Professor of Plasma Physics in 1963, this latter chair having been specially created for him. In 1967, however, after disagreements with the Swedish government, he obtained a professorship at the University of California, San Diego. Later he divided his time between the University of California and the Royal Institute.

Alfvén made his most important contributions in the late 1930s and early 1940s. Investigating the interactions of electrical and magnetic fields with plasmas (highly ionized gases containing both free positive ions and free electrons) in an attempt to explain sunspots, he formulated the frozen-in-flux theorem, according to which a plasma is - under certain conditions - bound to the magnetic lines of flux passing through it; later he used this theorem to explain the origin of cosmic rays. In 1939 he went on to propose a theory to explain aurorae and magnetic storms, a theory that greatly influenced later ideas about the Earth's magnetosphere. He also devised the guiding centre approximation, a widely used technique that enables the complex spiral movements of a charged particle in a magnetic field to be calculated relatively easily. Three years later, in 1942, he postulated that a form of electromagnetic wave would propagate through plasma; other scientists later observed this phenomenon in plasmas and in liquid metals. Also in 1942 Alfvén developed a theory of the origin of the planets in the solar system. In this theory (sometimes called the Alfvén theory) he hypothesized that planets were formed from the material captured by the sun from an interstellar cloud of gas and dust. As the atoms were drawn towards the Sun they became ionized and influenced by the Sun's magnetic field. The ions then condensed into small particles which, in turn, coalesced to form the planets, this process having occurred in the plane of the solar equator. This theory did not adequately explain the formation of the inner planets but it was important in suggesting the role of MHD in the genesis of the solar system.

Although Alfvén has studied MHD mainly in the context of astrophysics, his work has been fundamental to plasma physics and is applicable to the use of plasmas in experimental nuclear fusion reactors.

Alhazen (*c.965–1038*), was an Arabian scientist who made significant advances in the theory and practice of optics. He was probably the greatest scientist of the Middle Ages and his work remained unsurpassed for nearly 600 years until the time of Johann Kepler. His Arabic name was Abu 'Alī al-Hassan ibn al-Haytham.

Alhazen was born in Basra (Al Basra, now in Iraq) in about 965. He made many contributions to optics, one of which was to contest the Greek view of Hero and Ptolemy (who flourished in the second century AD) that vision involves rays that emerge from the eye and are reflected by objects viewed. Alhazen postulated that light rays originate in a flame or in the Sun, strike objects, and are reflected by them into the eye. He studied lenses and mirrors, working out that the curvature of a lens accounts for its ability to focus light. He measured the refraction of light by lenses and its reflection by mirrors, and formulated the geometric optics of image formation by spherical and parabolic mirrors. He used a pin-hole as a "lens" to construct a primitive camera obscura. Alhazen also tried to account for the occurrence of rainbows, appreciating that they are formed in the atmosphere, which he estimated extended for about 15 km above the ground. He wrote many scientific works, the chief of them being *Opticae thesaurus* which was published in 1572 from a thirteenth-century Latin translation of his original Arabic version.

Alhazen spent part of his life in Egypt, where he fell foul of the tyrranical (and mad) Caliph al-Hakim. In a foolhardy attempt to impress the caliph, Alhazen claimed he could devise a method of controlling the flooding of the River Nile. To escape the inevitable wrath of the caliph for non-fulfilment of the promise, Alhazen pretended to be mad himself and had to maintain the charade for many years until 1021, when al-Hakim died. Alhazen died in Cairo in 1038.

Alter, David (*1807–1881*), was an American inventor and physicist whose most important contribution to science was in the field of spectroscopy.

Alter was born in Westmoreland County, Pennsylvania, on 3 December 1807. He had little early schooling but in 1828 he entered the Reformed Medical College, New York City, to study medicine, in which he graduated in 1831. Thereafter he spent the rest of his life experimenting and making inventions, working alone and using home-made apparatus. He died in Freeport, Pennsylvania, on 18 September 1881.

Alter made his most important contribution to physics in 1854, when he put forward the idea that each element has a characteristic spectrum, and that spectroscopic analysis of a substance can therefore be used to identify the elements present. He also investigated the Fraunhofer lines in the solar spectrum. Although the significance of this work was not recognized in the United States at that time, his idea was experimentally verified a few years later (about 1860) by Robert Bunsen (1811–1899) and Gustav Kirchhoff (1824–1887) and today spectroscopic analysis is extensively used in chemistry for identifying the component elements of substances and in astronomy for determining the compositions of stars.

Alter devoted most of his life, however, to making inventions, which included a successful electric clock, a model for an electric locomotive (which was not put into production), a new process for purifying bromine, an electric telegraph that spelled out words with a pointer, and a method of extracting oil from coal (which was not put into commercial practice because of the discovery of oil in Pennsylvania).

Ampère, André-Marie (*1775–1836*), was a French physicist, mathematician, chemist and philosopher who is famous for founding the science of electromagnetics (which he named electrodynamics) and who gave his name to the unit of electric current.

Ampère was born in Polémieux, near Lyons, on

22 January 1775. The son of a wealthy merchant, he was tutored privately and was, to a great extent, self-taught. His genius was evident from an early age, particularly in mathematics, which he taught himself and had mastered to an extremely high level by the age of about 12. The later part of his youth, however, was severely disrupted by the French Revolution. In 1793 Lyons was captured by the Republican army and his father – who was both wealthy and a city official – was guillotined. Ampère taught mathematics at a school in Lyons from 1796 to 1801, during which period he married (in 1799); in the following year his wife gave birth to a son, Jean-Jacques-Antoine, who later became an eminent historian and philologist. In 1802 Ampère was appointed Professor of Physics and Chemistry at the École Centrale in Bourg then, later in the same year, Professor of Mathematics at the Lycée in Lyons. Two years later his wife died, a blow from which Ampère never really recovered – indeed, the epitaph he chose for his gravestone was *Tandem felix* ("Happy at last"). In 1805 he was appointed an assistant lecturer in mathematical analysis at the École Polytechnique in Paris where, four years later, he was promoted to Professor of Mathematics. Meanwhile his talent had been recognized by Napoleon, who in 1808 appointed him Inspector-General of the newly formed university system, a post he retained until his death. In addition to his professorship and inspector-generalship, Ampère taught philosophy at the University of Paris in 1819, became Assistant Professor of Astronomy in 1820 and was appointed to the Chair in Experimental Physics at the Collège de France in 1824 – an indication of the breadth of his talents. He died of pneumonia on 10 June 1836 while on an inspection tour of Marseille.

Ampère's first publication was an early contribution to probability theory – *Considérations sur la théorie mathématique de jeu* (1802; *Considerations on the Mathematical Theory of Games*) in which he discussed the inevitability of a player losing a gambling game of chance against an opponent with vastly greater financial resources. It was on the strength of this paper that he was appointed to the professorship at Lyons and later to a post at the École Polytechnique in Paris.

In the period between his arrival in Paris in 1805 and his famous work on electromagnetism in the 1820s, Ampère studied a wide range of subjects, including psychology, philosophy, physics and, more important, chemistry. His work in chemistry was both original and topical but in almost every case public recognition went to another scientist; for example, his studies on the elemental nature of chlorine and iodine were credited to Humphry Davy (1778–1829). Ampère also suggested a method of classifying elements based on a comprehensive assessment of their chemical properties, anticipating to some extent the development of the Periodic Table later in that century. And in 1814 he independently arrived at what is now known as Avogadro's hypothesis of the molecular constitution of gases. He also analysed Boyle's law in terms of the isothermal volume and pressure of gases.

Despite these considerable and varied achievements, Ampère's fame today rests almost entirely on his even greater work on electromagnetism, a discipline that he, more than any other single scientist, was responsible for establishing. His work in this field was stimulated by the finding of the Danish physicist Hans Christian Oersted that an electric current can deflect a compass needle – i.e. that a wire carrying a current has a magnetic field associated with it. On 11 September 1820 Ampère witnessed a demonstration of this phenomenon given by Dominique Arago at the Academy of Sciences and, like many other scientists, was prompted to hectic activity. Within a week of the demonstration he had presented the first of a series of papers in which he expounded the theory and basic laws of electromagnetism (which he called electrodynamics to differentiate it from the study of stationary electric forces, which he called electrostatics). He showed that two parallel wires carrying current in the same direction attract each other, whereas when the currents are in opposite directions, mutual repulsion results. He also predicted and demonstrated that a helical "coil" of wire (which he called a solenoid) behaves like a bar magnet while it is carrying an electric current.

In addition, Ampère reasoned that the deflection of a compass needle caused by an electric current could be used to construct a device to measure the strength of the current, an idea that eventually led to the development of the galvanometer. He also realized the difference between the rate of passage of an electric current and the driving force behind it; this has been commemorated in naming the unit of electric current the ampere or amp (a usage introduced by Lord Kelvin in 1883). Furthermore, he tried to develop a theory to explain electromagnetism, proposing that magnetism is merely electricity in motion. Prompted by Augustus Fresnel (one of the originators of the wave theory of light), Ampère suggested that molecules are surrounded by a perpetual electric current – a concept that may be regarded as a precursor of the electron shell model.

The culmination of Ampère's studies came in 1827, when he published his famous *Mémoire sur* *la théorie mathématique des phénomènes électrodynamiques uniquement déduite de l'expérience* (*Notes on the Mathematical Theory of Electrodynamic Phenomena Deduced Solely from Experiment*), in which he enunciated precise mathematical formulations of electromagnetism, notably Ampère's Law – an equation that relates the magnetic force produced by two parallel current-carrying conductors to the product of their currents and the distance between the conductors. Today Ampère's law is usually stated in the form of calculus: the line integral of the magnetic field around an arbitrarily chosen path is proportional to the net electric current enclosed by the path.

Ampère produced little worthy of note after the publication of his *Mémoire* but his work had a great impact and stimulated much further research into electromagnetism.

Anderson, Carl David (*1905–*), is an American physicist who did pioneering work in particle physics, notably discovering the positron – the first antimatter particle to be found – and the muon (or mu-meson). He received many honours for his work, including the 1936 Nobel Prize in Physics, which he shared with Victor Hess.

Anderson was born in New York City on 3 September 1905, the son of Swedish immigrants. He was educated at the California Institute of Technology, from which he gained a BSc in physics and engineering in 1927 and a PhD in 1930. Thereafter he remained at the institute for the rest of his career, as a Research Fellow from 1930 to 1933, Assistant Professor of Physics from 1933 to 1939, and Professor of Physics from 1939 until his retirement in 1976. After retiring he was made an Emeritus Professor of the California Institute of Technology.

Anderson's first research – performed for his doctoral thesis – was a study of the distribution of photoelectrons emitted from various gases as a result of irradiation with X-rays. Then, as a member of Robert Millikan's research team, he began in 1930 to study gamma rays and cosmic rays, extending the work originally published by Skobelzyn, who had photographed tracks of cosmic rays made in a cloud chamber. Anderson devised a special type of cloud chamber that was divided by a lead plate in order to slow down the particles sufficiently for their paths to be accurately determined. Using this modified chamber he measured the energies of cosmic and gamma rays (by measuring the curvature of their paths) in strong magnetic fields (up to about 24,000 gauss, or 2.4 teslas). In 1932, in the course of this investigation, Anderson reported that he had found positively charged particles that occurred as abundantly as did negatively charged particles, and that in many cases several negative and positive particles were simultaneously projected from the same centre. Anderson initially thought that the positive particle was a proton but, after determining that its mass was similar to that of an electron, concluded that it was a positive electron; he then suggested the name positron for this antimatter particle. Working with Neddermeyer, Anderson also showed that positrons can be produced by irradiation of various materials with gamma rays. In 1932 and 1933 other established scientists – notably Patrick Blackett, James Chadwick and the Joliot-Curies – independently confirmed the existence of the positron and, later, elucidated some of its properties.

In 1936 Anderson contributed to the discovery of another fundamental particle, the muon. While studying tracks in a cloud chamber, he noticed an unusual track that seemed to have been made by a particle intermediate in mass between an electron and a proton. Initially it was thought that this new particle was the one whose existence had previously been predicted by Hideki Yukawa (his hypothetical particle was postulated to hold the nucleus together and to carry the strong nuclear force). Anderson named the particle he had discovered the mesotron, which later became shortened to meson. Further studies of the meson, however, showed that it did not readily interact with the nucleus and therefore could not be the particle predicted by Yukawa. In 1947 Cecil Powell discovered another, more active type of meson that proved to be Yukawa's predicted particle. Anderson's particle – the role of which is still unclear – is now called the muon (or mu-meson) to distinguish it from Powell's particle, which is called the pion (or pi-meson).

Anderson, Philip Warren (*1923–*), is an American physicist who shared the 1977 Nobel Prize in Physics with Nevill Mott and John Van Vleck for his theoretical work on the behaviour of electrons in magnetic, non-crystalline solids.

Anderson was born in Indianapolis on 13 December 1923 and was educated at Harvard University, from which he gained his BS in 1943, MS in 1947 and PhD in 1949; he did his doctoral thesis under Van Vleck. Anderson's studies were interrupted by military service during part of World War II: from 1943 to 1945 he worked at the Harvard Naval Research Laboratories in Washington DC, becoming a Chief Petty Officer in the United States Navy. After obtaining his doctorate, in 1949, he joined the Bell Laboratories in New Jersey, becoming Consulting Director of Physics Research in 1976. In addition to this appointment he has been Joseph Henry Professor of Physics at Princeton University since 1975. Anderson has also visited several foreign universities: he was a Fulbright Lecturer at Tokyo University from 1952 to 1953; an Overseas Fellow at Churchill College, Cambridge, from 1961 to 1962; and Visiting Professor of Theoretical Physics at Cambridge from 1967 to 1975. He was a Fellow of Jesus College, Cambridge, from 1969 to 1975, and was made an Honorary Fellow in 1978.

Anderson has made many varied contributions, although most of his work has been in solid state physics. While studying under Van Vleck at Harvard, he investigated the pressure-broadening of spectral lines in spectroscopy and developed a method of deducing details of molecular interactions from the shapes of spectral peaks. In the late 1950s he devised a theory to explain superexchange - the coupling of the spins of two magnetic ions in an antiferromagnetic material through their interaction with a non-magnetic anion situated between them - and then went on to apply the Bardeen-Cooper-Schrieffer (BCS) theory to explain the effects of impurities on the properties of superconductors. In the early 1960s he investigated the interatomic effects that influence the magnetic properties of metals and alloys, devising a theoretical model (now called the Anderson model) to describe the effect of the presence of an impurity atom in a metal. He also developed a method of describing the movements of impurities within crystalline substances; this method is now known as Anderson localization.

In addition, Anderson has studied the relationship between superconductivity, superfluidity and laser action - all of which involve coherent waves of matter or energy - and predicted the existence of resistance in superconductors. Of more immediate widespread practical application, however, is his work on the semiconducting properties of inexpensive, disordered glassy solids; his studies of these materials indicate that they could be used instead of the expensive crystalline semiconductors now used in many electronic devices, such as computer memories, electronic switches and solar energy converters.

Ångström, Anders Jonas (*1814-1874*), was a Swedish physicist and astronomer, one of the early pioneers in the development of spectroscopy.

Ångström was born at Lögdö, Sweden, on 13 August 1814, the son of a chaplain. He was educated at the University of Uppsala, which awarded him his doctorate in physics in 1839; he began to lecture there in the same year. In 1843 he was appointed an observer at the Uppsala Observatory. In 1858 he was elected to the Chair of Physics at the University, a post which he held until his death, at Uppsala, on 21 June 1874.

Ångström's first important work was an investigation into the conduction of heat and his first important result was to devise a method of measuring thermal conductivity, which demonstrated it to be proportional to electrical conductivity. Then, in 1853, he published his most substantial and influential work, *Optical Investigations*, which contains his principle of spectrum analysis. Ångström had studied electric arcs and discovered that they yield two spectra, one superimposed on the other. The first was emitted from the metal of the electrode itself, the second from the gas through which the spark passed. By applying Euler's theory of resonances Ångström was then able to demonstrate that a hot gas emits light at the same frequency as it absorbs it when it is cooled.

Ångström's early work provided the foundation for the spectrum analysis to which he devoted the rest of his career. He was chiefly interested in the Sun's spectrum, although in 1867 he investigated the spectrum of the Aurora Borealis, the first person to do so. In 1862 he announced his inference (in fact, it amounted to a discovery) that hydrogen was present in the Sun. In 1868 he published *Researches on the Solar System*, a famous work in which he presented measurements of the wavelengths of more than 100 Fraunhofer. The lines were measured to six significant figures in units of 10^{-8} cm. The unit of measure for wavelength of light, called the angstrom (Å, equal to 10^{-10} m), was officially adopted by 1907.

Another of Ångström's important contributions was his map of the normal solar spectrum, published in 1869, which remained a standard reference tool for 20 years.

Appleton, Edward Victor (*1892-1965*), was a British physicist famous for his discovery of the Appleton layer of the ionosphere which reflects radio waves and is therefore important in communications. He received many honours for his work, including a knighthood in 1941 and the Nobel Prize in Physics in 1947.

Appleton was born on 6 September 1892 in Bradford, Yorkshire. He attended Barkerend Elementary School from 1899 to 1903, then won a scholarship to Hanson Secondary School. A gifted student, he also won a scholarship to St John's College, Cambridge, in 1910 and graduated with first class honours in 1913. After a short period of postgraduate research with William Henry Bragg, Appleton became a signals officer in the Royal Engineers with the outbreak of World War I in 1914. This aroused his interest in radio and he began to investigate radio propagation when he returned to Cambridge after the war. In 1919 he was elected a Fellow of St John's College, and in the following year was appointed an Assistant Demonstrator at the Cavendish Laboratory. In 1924, when only 32 years old, he was appointed Wheatstone Professor of Physics at King's College, London, a post he held until 1936, when he was made Jacksonian Professor of Natural Philosophy at Cambridge. In 1939 he became Secretary of the Department of Scientific and Industrial Research, in which position he gained a reputation as an adviser on government scientific policy. During World War II, he was involved in the development of radar and of the atomic bomb. In 1949 he was made Principal and Vice-chancellor of Edinburgh University, a position he held until his death (in Edinburgh) on 21 April 1965. While at Edinburgh, he founded the *Journal of Atmospheric Research*, which became known as "Appleton's journal"; he remained its Editor-in-Chief for the rest of his life.

Appleton began his research on radio when he returned to Cambridge after World War I. Initially he investigated (with Balthazar van der Pol Jr.) thermionic vacuum tubes – on which he wrote a monograph in 1932 – then in the early 1920s he turned his attention to studying the fading of radio signals, a phenomenon he had encountered while a signals officer during World War I.

The first transatlantic radio transmission had been made by Guglielmo Marconi in 1901, and to explain why this was possible (that is, why the radio waves "bent" around the Earth and did not merely go straight out into space) Oliver Heaviside and Arthur Kennelly postulated the existence of an atmospheric layer of charged particles (now called the Kennelly-Heaviside layer or E layer) that reflected the radio waves. Working with the New Zealand graduate student Miles Barnell – and using the recently set up BBC radio transmitters – Appleton proved the existence of the Kennelly-Heaviside layer. By periodically varying the frequency of the BBC transmitter at Bournemouth and measuring the intensity of the received transmission 100 km away, Appleton and Barnell found that there was a regular "fading in" and "fading out" of the signals at night but that this effect diminished considerably at dawn as the Kennelly-Heaviside layer broke up. They also noticed, however, that radio waves continued to be reflected by the atmosphere during the day but by a higher level ionized layer. By 1926 this layer, which Appleton measured at about 250 km above the Earth's surface (the first distance measurement made by means of radio), became generally known as the Appleton layer (it is now also known as the F layer).

Appleton continued his studies of the ionosphere (as the charged layers of the atmosphere above the stratosphere are called), showing how they are affected by the position of the sun and by changes in the sunspot cycle. He also calculated their reflection coefficients, electron densities and their diurnal and seasonal variations. Further, he showed that the Appleton layer is strongly affected by the Earth's magnetic field and that although further above the Earth, it has a greater density and temperature than does the Kennelly-Heaviside layer.

Appleton's research into the atmosphere was of fundamental importance to the development of radio communications, and his experimental methods were later used by the British physicist Robert Watson-Watt – with whom Appleton had collaborated on several projects – in his development of radar.

Arago, (Dominique) François (*1786–1853*), was a French scientist who made contributions to the development of many areas of physics and astronomy, the breadth of his work compensating for the absence of a single product of truly outstanding quality. He was closely involved with André Ampère (1775–1836) in the development of electromagnetism and with Augustin Fresnel (1788–1827) in the establishment of the wave theory of light. Arago's political commitment demanded much time during his latter years, but he maintained a continuous flow of scientific investigations until almost the end of his life.

Arago was born in Estagel, France on 26 February 1786. He studied at the École Polytechnique in Paris and was then appointed to the Bureau of Longitudes. He travelled to the south of France and Spain with Jean Biot (1774–1862) in 1806, where they intended to measure an arc of the terrestrial meridian. Biot returned to France in 1807, but Arago continued his work amidst a deteriorating political situation. His return to France in 1809 was somewhat enlivened by a shipwreck and his subsequent near-escape from being sold into slavery in Algiers!

In the same year, Arago was elected to the membership of the French Academy of Sciences and became professor of analytical geometry at the École Polytechnique, a post he held until 1830. He became a fellow of the Royal Society of London in 1818, which awarded him the Copley medal in 1825 for his work on electromagnetism.

The year 1830 was one of several changes for Arago. He resigned his post at the École Polytechnique and succeeded Jean Fourier (1768–1830) as permanent secretary to the Academy of Sciences.

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