Centí y Don Mariano Lagasca, con anotaciones y los estudios biobibliográficos de Cavanilles y Centí y de Lagasca (Madrid, 1917).

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CAVENDISH, HENRY (*b.* Nice, France, 10 October 1731; *d.* London, England, 24 February 1810), *natural philosophy.*

In an age when leading British scientists were largely middle-class, Henry Cavendish stood out for his high aristocratic lineage. Although without title (he was, however, often addressed by the courtesy title "Honourable"), he was descended from dukes on both sides. His father, Lord Charles Cavendish, was the fifth son of the second duke of Devonshire. His mother, formerly Lady Anne Grey, was the fourth daughter of the duke of Kent. His mother's health was poor, for which reason she went to Nice, where Henry was born. She died two years later, shortly after giving birth to her second son, Frederick.

At eleven Cavendish was sent to Dr. Newcome's Academy at Hackney, a school attended mainly by children of the upper classes. He proceeded to St. Peter's College, Cambridge, in 1749, entering as a Fellow Commoner. He remained at Cambridge until 1753, leaving without a degree, a practice frequent among Fellow Commoners. It has been suggested that Cavendish objected to the religious tests at Cambridge, but in fact nothing is known about his religious convictions or lack of them. After leaving Cambridge he lived with his father in Great Marlborough Street, London, where he fitted out a laboratory and workshop. When his father died in 1783, Cavendish transferred his main residence and laboratory to Clapham Common. He never married.

Cavendish had independent means all of his life and never had to prepare for a profession; at some point he became immensely wealthy through bequests from relatives. At no time did he show an interest in entering the nonscientific world open to one with his assets of wealth and class. He shunned conventional society, which, by all contemporary accounts, he found difficult. Instead he devoted himself almost exclusively to scientific pursuits. His father, a distinguished experimentalist and prominent figure in the counsels of the Royal Society, encouraged his scientific bent. He put his instruments at his son's disposal and, most important, introduced him into London's scientific circles. In 1758 he took Henry to meetings of the Royal Society and to dinners of the Royal Society Club. Henry was elected to membership in these organizations in 1760, and he rarely missed a meeting.

Like his father, Cavendish was heavily involved in the work of the Council and committees of the Royal Society. He was a member of the Royal Society of Arts (1760) and a fellow of the Society of Antiquaries (1773). He was a trustee of the British Museum (1773) and a manager of the Royal Institution (1800). His career in general was distinguished by a wide and usually active participation in the organized scientific and intellectual life of London. Toward the latter part of his career he was esteemed at home and abroad (he was elected foreign associate of the Institut de France) as the most distinguished British man of science.

Henry Cavendish had fitful habits of publication that did not at all reveal the universal scope of his natural philosophy. He wrote no books and fewer than twenty articles in a career of nearly fifty years. Only one major paper was theoretical, a study of electricity in 1771; the remainder of his major papers were carefully delimited experimental inquiries, the most important of which were those on pneumatic chemistry in 1766 and 1783–1788, on freezing temperatures in 1783–1788, and on the density of the earth in 1798. The voluminous manuscripts uncovered after his death show that he carried on experimental, observational, and mathematical researches in literally all of the physical sciences of his day. They correct the impression derived from his few published writings that his interests were predominantly experimental and chemical.

Many of his interests—pure mathematics, mechanics, optics, magnetism, geology, and industrial science—that are strongly represented in his private papers are barely reflected in his published works. Cavendish left unpublished whatever did not fully satisfy him, and that included the great majority of his researches. The profundity of his private studies has exercised an immense fascination on subsequent workers in the fields that Cavendish explored. Fragments of his unpublished work were gradually revealed throughout the nineteenth century, culminating in James Clerk Maxwell's great edition of Cavendish's electrical researches in 1879. Far less successful was the attempt in 1921 by a group of scientific specialists to select for publication certain of Cavendish's nonelectrical manuscripts to complement Maxwell's edition. The totality of Cavendish's researches was too vast for that design.

The unifying ideas underlying Cavendish's numerous and varied basic researches relate to the Newtonian framework in which he chose to work. While he drew immediate stimulus from his contemporaries, the ultimate source of his inspiration was Newton. In the preface to the *Principia,* after explaining how he had derived the law of gravitation from astronomical phenomena and how he had deduced from it the motions of the planets, comets, and the seas, Newton expressed his wish that the rest of nature could be derived from the attracting and repelling forces of particles and the results cast in the deductive mode of the *Principia.* It was the conception of natural philosophy as the search for the forces of particles that guided Cavendish's scientific explorations. (His one important difference with Newton was his preference for the point-particles of John Michell and Bošković over Newton's extended corpuscles.) The *Principia* was forever his model of exact science; when this fact is appreciated, his various and seemingly disconnected researches are seen to form a rational, coherent whole.

Little is known about Cavendish's scientific activities between his leaving Cambridge and his first publication in 1766. His extant manuscripts suggest that he devoted much early effort to dynamics. The most important dynamical study, "Remarks Relating to the Theory of Motion," contains a full statement of his theory of heat. He subscribed to Newton's view that heat is the vibration of particles but went beyond Newton in rendering the vibration theory precise: Heat, Cavendish said, is the "mechanical momentum," or *vis viva,* of vibrating particles. He proved that the time average of the mechanical momentum of a collection of particles remains sensibly constant, provided the forces have certain symmetry properties. He related this theorem to another conservation law. It was well known that when two bodies are placed in thermal contact, the heat lost by one equals that gained by the other. Cavendish interpreted this to mean that the mechanical momentum lost by the particles of one body equals that gained by the particles of the second. But he was not satisfied. He had observed phenomena—such as fermentation, dissolution, and combustion—that involve quantities of heat which are inexplicable, even when the "additional" mechanical momentum of elastic compression is taken into account. Cavendish turned to heat experiments, which indicated a way around the theoretical impasse.

Cavendish drafted in fair copy, but did not publish, a long manuscript entitled "Experiments on Heat," based on laboratory work done in and possibly before 1765. Although he knew something of the work of Joseph Black and his circle, he essentially rediscovered the basic facts of specific heats (a term he later privately endorsed) and latent heats (a term he also privately endorsed but only after divorcing it from its connotation of a material theory of heat). The difference in specific heats of mixtures or compounds and their component parts helped him explain the anomalous heats in the reactions violating his Newtonian heat theory. He thought that the difference in the specific heats accounted entirely for the addition or subtraction of sensible heat in reactions. Cavendish broke off his accounts of both specific and latent heats with inconclusive experiments on airs. In the one case he tried to find the specific heat of air by passing it through a worm tube encased in hot water, measuring the increase in the heat of the air. In the other he measured the cold produced by dissolving alkaline substances in acids, releasing fixed air, a phenomenon that he viewed as similar to evaporation.

In 1766 Cavendish published his first paper, for which he received the Royal Society's Copley Medal. It was on "factitious" airs, that is, airs that are contained inelastically in other bodies but are capable of being freed and made elastic. Cavendish's careful gravimetric discrimination of several factitious airs, together with the work of Black on fixed air, put forward strong evidence against the notion of a single, universal air. Cavendish produced fixed air by dissolving alkaline substances in acids, and by dissolving metals in acids he released inflammable air. He collected the airs that animal and vegetable substances yield on putrefaction and fermentation. (These agents—metals, alkalies, animal and vegetable matter—and their associated airs were the ones that Cavendish treated in the context of his last heat experiments.) He collected airs by inverting a bottle filled with water (or mercury for water-soluble fixed air) in a trough of water (or mercury); a tube led from the mouth of the inverted bottle to another, in which the reactants were placed. After collecting the airs he observed their combustibility, water solubility, and specific gravity. He found that fixed air is 1.57 times heavier than common air and that inflammable air is about eleven times lighter than common air. He showed that fermented organic substances give off a mixture of airs which includes a heavier inflammable air. From the fact that the same weight of a metal (zinc, iron, tin) produced the same volume of inflammable air regardless of the acid used (diluted sulfuric or hydrochloric acid), Cavendish concluded that the inflammable air came from the metal, not the acid. He suggested that the inflammable air of metals is pure phlogiston. In 1767 he published a related study of the composition of water from a certain pump, proving that the calcareous earth in the water is held in solution by fixed air.

In 1771, guided by his knowledge of elastic airs, Cavendish published a mathematical, single-fluid theory of electricity. In a preliminary draft he introduced the term "compression" in speaking of the state of tension of the electric fluid. Although he omitted the expression from his published theory, he retained the notion that the electric fluid within a body resembles an air compressed in a container. This was the central idea of his theory, providing an intensity measure in addition to a quantity measure of the electric fluid. There were essential differences, too, between the elastic fluids of electricity and air; and Cavendish stressed these as well as their resemblances. He proved that the particles of the electric fluid did not follow Newton's inverse first-power law of force of air particles. Just as his experimental discrimination among factitious airs helped discredit the notion that there is only one true, permanent air, so his electrical investigations indicated that, contrary to the common belief, there are elastic fluids in nature which must be represented by different laws of force. Cavendish was able to mathematize fully only one elastic fluid, that of electricity; elastic airs proved too complex.

Joseph Priestley, having stated the inverse-square law for the electric force in 1767, may have provided the occasion for Cavendish to elaborate his ideas on electricity. From the beginning Cavendish was partial to the inverse-square law, although in 1771 he had not yet performed his now famous hollow-globe experiments to settle the question of the exact numerical power. He postulated instead an elastic, electric matter of electricity, the particles of which repel one another and attract the particles of all other matter with a force varying inversely as some power of the distance less than the cube; in a symmetric manner the particles of all other matter repel each other and attract those of the electric fluid according to the same law. Cavendish's object was to exhibit the consequences of a variety of long-range electric forces and then to select the actual law from all possible laws by comparing their consequences with experience. His electrical researches are a direct expression, and partial vindication, of Newton's vision of the future of natural philosophy. From certain phenomena Cavendish deduced, but did not publish, the exact law of electric attraction and repulsion between particles; and from that law he derived a rich store of new, quantitative electrical phenomena. His greatest predictive achievement lay buried in manuscript: it was the calculation and experimental confirmation of the precise quantities of electric fluid that bodies of different geometrical form and size can contain at any electrical tension. His confirmatory experiments, together with an extended theoretical development, constituted the design of an unfinished, unpublished treatise, a work that was intended to stand as the electrical sequel to the gravitational "System of the World" of the *Principia.*

Cavendish examined minutely the facts of specific inductive capacity (not his term), an electrical corollary of chemical differences. His efforts at understanding this empirical phenomenon, which seemed at first to contradict his theory, diverted him from completing his original design. So did the fact that he came to seek a dynamics as well as a statics of the electric fluid. He attempted without success to find the relation between force, resistance, and velocity in the passage of the electric fluid through various substances. His researches trailed off into largely inconclusive experiments on conductivities. He revealed certain of his dynamical findings in a second electrical publication, a study in 1776 of the properties of a model of an electric fish, the torpedo. His electrical researches, the most sustained and organized effort of his career, came to an end in 1781.

Priestley's account in 1781 of his and John Warltire's experiments prompted Cavendish to return to the subject of elastic airs. The first of his new publications on the subject was a study of the principles of eudiometry in 1783. The most important fruit of his renewed interest was his celebrated publication in 1784 on the synthesis of water from two airs. Warltire had electrically fired mixtures of common and inflammable airs in a closed vessel, recording a weight loss that he attributed to the escape of ponderable heat. He and Priestley observed a deposit of dew inside the vessel.

Cavendish repeated the experiments and found dew but no loss in weight. He then undertook experiments to discover the cause of the diminution of common air when it is fired with inflammable air and when it is phlogisticated by any other means. He found that when inflammable and common air are exploded, all of the inflammable air and about four-fifths of the common air are converted into dew and that this dew is pure water. What Cavendish was basically interested in was the constitution of the airs; he concluded that inflammable air is phlogiston united to water and that dephlogisticated air is water deprived of phlogiston. In several papers through 1788 he pursued investigations stemming from those of 1784, concluding that phlogisticated air is nitrous acid united to phlogiston. Cavendish's publications on pneumatic chemistry in 1783–1788 involved the agency of electricity, the transition between elastic and inelastic states of matter, and the generation of heat; they drew, therefore, on the basic themes of his research for the previous quarter century.

Concurrently with his work on airs Cavendish published several papers on the freezing points of mercury, vitriolic acid, nitrous acid, and other liquids. This work was an extension of his published study of the Royal Society's meteorological instruments in 1776, and it drew heavily upon his early knowledge of latent heats. The most important of his conclusions was that the extraordinarily low readings that had been recorded on mercury thermometers were due merely to the shrinkage of solidifying mercury.

Cavendish published five papers between 1784 and 1809 relating to his astronomical interests. With one exception they were comparatively minor productions, concerned with the height of the aurora, a reconstruction of the Hindu civil year, a calculation in nautical astronomy, and a method of marking divisions on circular astronomical instruments. The exception was his determination of the density of the earth (or weighing of the world) in 1798, by means of John Michell's torsion balance. The apparatus consisted of two lead balls on either end of a suspended beam; these movable balls were attracted by a pair of stationary lead balls. Cavendish calculated the force of attraction between the balls from the observed period of oscillation of the balance and deduced the density of the earth from the force. He found it to be 5.48 times that of water. Cavendish was the first to observe gravitational motions induced by comparatively minute portions of ordinary matter. The attractions that he measured were unprecedentedly small, being only 1/500,000,000 times as great as the weight of the bodies. By weighing the world he rendered the law of gravitation complete. The law was no longer a proportionality statement but a quantitatively exact one; this was the most important addition to the science of gravitation since Newton.

Cavendish's career marked the culmination and the end of the original British tradition in mathematical physics. By the 1780's, British natural philosophy had moved away from any central concern with mathematical interparticulate forces. It had become concerned with the ethereal mode of communication of forces and with imponderable fluids and the question of their separateness or unity. These directions were antithetical to Cavendish's thought. Likewise, chemistry tended to follow Lavoisier's direction, about which Cavendish had strong reservations. Cavendish was intellectually isolated long before the end of his career. He was not a teacher; he formed or inspired no school. Rather his place in British natural philosophy is as the first after Newton to possess mathematical and experimental talents at all comparable to Newton's. In intellectual stature Cavendish was without peer in eighteenth-century British natural philosophy.

BIBLIOGRAPHY

I. Original Works. Cavendish's two electrical papers from the *Philosophical Transactions* and the bulk of his electrical MSS are published in *The Electrical Researches of the Honourable Henry Cavendish,* J. Clerk Maxwell, ed. (Cambridge, 1879), also in Cass Library of Science Classics (London, 1967). A rev. ed. of this work is *The Scientific Papers of the Honourable Henry Cavendish, F.R.S., 1: The Electrical Researches,* J. Clerk Maxwell, ed., rev. with notes by Sir Joseph Larmor (Cambridge, 1921). There is also a companion volume containing the rest of Cavendish's papers from the *Philosophical Transactions,* together with a selection of his MSS on chemistry, heat, meteorology, optics, mathematics, dynamics, geology, astronomy, and magnetism: *The Scientific Researches of the Honourable Henry Cavendish, F.R.S., 2: Chemical and Dynamical,* ed. with notes by Sir Edward Thorpe (Cambridge, 1921), with contributions by Charles Chree, Sir Frank Watson Dyson, Sir Archibald Geikie, and Sir Joseph Larmor. Some additional Cavendish MSS relevant to the water controversy are printed in the Rev. W. Vernon Harcourt's address in the *British Association Report* (1839), pp. 3-68 plus 60 pp. of lithographed facsimiles. The correspondence between Cavendish and Joseph Priestley is published in *A Scientific Autobiography of Joseph Priestley, 1733–1804,* ed. with commentary by Robert E. Schofield (Cambridge, Mass., 1966). The vast bulk of Cavendish's MS papers and correspondence has not been published; it is deposited in Chatsworth, in the possession of the duke of Devonshire.

II. Secondary Literature. On Cavendish or his work, see A. J. Berry, *Henry Cavendish: His Life and Scientific Work* (London, 1960); J. B. Biot, "Cavendish (Henri)," in *Biographie universelle,* 2nd ed., VII, 272–273; Henry Brougham, "Cavendish," in *Lives of Men of Letters and Science Who Flourished in the Time of George III* (Philadelphia, 1845), pp. 250–259; James Gerald Crowther, *Scientists of the Industrial Revolution: Joseph Black, James Watt, Joseph Priestley, Henry Cavendish* (London, 1962); Georges Cuvier, "Henry Cavendish," trans. D. S. Faber, in *Great Chemists,* E. Faber, ed. (New York, 1961), pp. 229–238; Humphry Davy's estimate of Cavendish, in John Davy, *Memoirs of the Life of Sir Humphry Davy, Bart.,* I (London, 1836), 220–222; Russell McCormmach, "The Electrical Researches of Henry Cavendish," unpub. diss. (Case Institute of Technology, 1967); "John Michell and Henry Cavendish: Weighing the Stars," in *British Journal for the History of Science,* IV (1968), 126–155; "Henry Cavendish: A Study of Rational Empiricism in Eighteenth-Century Natural Philosophy," in *Isis* (1970); J. R. Partington, "Cavendish," in *A History of Chemistry,* III (London, 1962), 302–362; Robert E. Schofield, *Mechanism and Materialism: British Natural Philosophy in an Age of Reason* (Princeton, 1970), ch. 10; Thomas Thomson's estimate of Cavendish, in his *History of Chemistry,* I (London, 1830),

336–349; George Wilson, *The Life of the Honourable Henry Cavendish* (London, 1851); and Thomas Young, "Life of Cavendish," in *Scientific Papers of the Honourable Henry Cavendish*, I, 435–447.

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CAVENTOU, JOSEPH-BIENAIMÉ (*b.* Saint-Omer, France, 30 June 1795; *d.* Paris, France, 5 May 1877), *chemistry, toxicology.*

Son of Pierre-Vincent Caventou, military pharmacist and chief pharmacist of the civil hospital of Saint-Omer, Joseph-Bienaimé Caventou decided early in life to follow his father's profession. After some preliminary training with his father he left for Paris, where he obtained an apprenticeship in a pharmacy and began course work at the School of Pharmacy and the Faculty of Sciences. In 1815 he competed successfully for an internship in hospital pharmacy, but the news of Napoleon's return from Elba aroused his patriotic feelings to such an extent that he resigned his appointment to enlist as a military pharmacist. Caventou's military service was of short duration. The small garrison where he was stationed in Holland surrendered soon after the French defeat at Waterloo, and before the end of 1815 he was back in Paris to resume his studies.

Caventou had by this time developed a keen interest in chemistry and, in order to supplement the meager allowance from his father, conceived the idea of writing a book on chemical nomenclature according to the classification adopted by Thenard. The work, *Nouvelle nomenclature chimique,* appeared in 1816 as a practical handbook designed especially for beginners in chemistry and for those who were unfamiliar with the newest chemical terminology. In the meantime Caventou again competed successfully for an internship in hospital pharmacy and in 1816 received his appointment at the Saint-Antoine Hospital, where laboratory facilities to carry on his research were available. He published a chemical analysis of the daffodil by the end of 1816, of laburnum in 1817, and a treatise on pharmacy in 1819. These were followed in 1821 by an annotated French translation, made jointly with J. B. Kapeler, physician at the Saint-Antoine Hospital, of a German work by Johann Christoph Ebermaier on drug adulteration.

In 1826 Caventou became a member of the teaching staff of the École Supérieure de Pharmacie, in 1830 associate professor of chemistry, and in 1834 full professor of toxicology, a post he held until his retirement at the end of 1859. Despite the demands of teaching and research, he found time to direct a pharmacy on the rue Gaillon. In 1821 Caventou was admitted to the Academy of Medicine. In 1827 he and Pierre-Joseph Pelletier shared the Montyon Prize of 10,000 francs, awarded by the Academy of Sciences, for their discovery of quinine.

It was in 1817 that Caventou published his first joint paper with Pelletier, a twenty-nine-year-old owner of a pharmacy on the rue Jacob, who had already attracted favorable attention by his chemical analyses of plant substances. The young men had been drawn together by their mutual scientific interests, and until Pelletier's death in 1842 their frequent collaboration resulted in a number of important discoveries in alkaloid chemistry. It is idle to speculate on Caventou's development as a scientist had he not collaborated with Pelletier; but his most impressive scientific accomplishments came from this association, particularly during the years from 1817 to 1821. By the age of twenty-six, the achievements which would bring him most fame were already behind him. During this period both scientists had embarked on the investigation of natural products: the description of a new acid formed by the action of nitric acid on the nacreous material of human biliary calculi (1817); a study of the green pigment in leaves, which they named chlorophyll (1817); the separation of crotonic acid from croton oil (1818); the examination of carmine, the coloring matter in cochineal (1818); and the isolation of ambrein from ambergris (1820).

Far more significant, however, was their extraction of alkaline nitrogenous substances (alkaloids) from plants. When Pelletier and Caventou began this phase of their work, the stage had already been set for dramatic developments in alkaloid chemistry by the pioneer work on opium by such scientists as Derosne, Armand Seguin, and especially Sertürner, who was the first to recognize the alkaline nature of morphine and whose findings, published from 1805 to 1817, established him as its discoverer. In rapid succession Pelletier and Caventou isolated strychnine in 1818, brucine and veratrine (independently of Karl Meissner) in 1819, and cinchonine and quinine in 1820. They discovered caffeine in 1821, independently of Robiquet and Runge.

The discovery of quinine was by far the most dramatic result of their collaboration, and soon there was worldwide demand for quinine as a therapeutic agent. In a letter written to the Academy of Sciences in 1827 Pelletier and Caventou pointed out that by 1826 a burgeoning French industry was annually producing approximately 90,000 ounces of quinine sulfate from cinchona bark, enough to treat more than a million individuals. The basic and salifiable nature of these new alkaloids, as well as their physical characteristics, were elucidated by Pelletier and Caventou, who demonstrated that they contained oxygen, hydrogen,