(1795), *L'alphabet européen appliqué aux langues asiatiques* (1819), and *L'hébreu simplifié* . . . (1820), and in his bequest of 24,000 francs to establish a prize for work in this field. His studies of Greek, Jewish, and Egyptian chronology, collected in *Recherches nouvelles sur l'histoire ancienne* (1813–1814), were erudite but overambitious.

The scholar, the sociologist, the scientific traveler, and the Idéologue were united in Volney. A pioneer in several fields of inquiry, he was master of none. In all he endeavored to liberate the human mind and to rationalize human institutions by means of an *enquête des faits*.

BIBLIOGRAPHY

Incomplete collections of Volney's works are *Oeuvres complètes de Volney . . . mise en ordre et précédées de la vie de l'auteur* [by A. Bossange], 8 vols. (Paris, 1820–1822); and *Oeuvres complètes, avec notice de Bossange et buste de Volney par David d'Angers*, 4 pts. (Paris, 1837), both of which underwent subsequent eds.

The most comprehensive study of Volney, containing an extensive account of the primary sources, a chronological list of some of the eds. of his various works, and a selection of the most useful secondary literature, is Jean Gaulmier, *L'Idéologue Volney (1757–1820). Contribution à l'histoire de l'orientalisme en France* (Beirut, 1951). Gaulmier has also published Volney's *Voyage en Égypte et en Syrie* in a modern ed. with intro. and notes (Paris–The Hague, 1959). See also Gilbert Chinard, *Volney et l'Amérique d'après des documents inédits et sa correspondance avec Jefferson*, Johns Hopkins Studies in Romance Literatures and Languages, I (Baltimore, 1923). George W. White's intro. to the Hafner ed. of Charles Brockden Brown's trans. of Volney's *Tableau du climat et du sol des États-Unis d'Amérique—A View of the Soil and Climate of the United States of America by C. F. Volney Translated With Occasional Remarks by C. B. Brown . . .* (New York–London, 1968)—gives a critical evaluation of Volney's contributions to early American geology.

JOHN C. GREENE

VOLTA, ALESSANDRO GIUSEPPE ANTONIO ANASTASIO (*b*. Como, duchy of Milan, Italy, 18 February 1745; *d*. Como, 5 March 1827), *physics*.

Volta came from a Lombard family ennobled by the municipality of Como and almost extinguished, in his time, through its service to the church. One of his three paternal uncles was a Dominican, another a canon, and the third an archdeacon; his father, Filippo (1692–*ca*. 1752), after eleven years as a Jesuit, withdrew to propagate the line. Filippo Volta's marriage in 1733 with Maddelena de' conti Inzaghi (*d*. 1782) produced seven children who survived childhood; three girls, two of whom became nuns; three boys who followed precisely the careers of their paternal uncles; and Alessandro, the youngest, who narrowly escaped recruitment by his first teachers, the Jesuits.

The doctrines, social life, and observances of the church of Rome consequently made up a large part of Volta's culture. He chose clerics as his chief friends, remained close to his brothers the canon and archdeacon, and actively practiced the Catholic religion. Examples of his religiosity include a flirtation with Jansenism in the 1790's; a confession of faith in 1815 to help defend religion against scientism (*Epistolario*, V, 290–292); and an appeal in 1794 to his brothers and to the professor of theology at the University of Pavia for advice about marriage. Not that Volta was prudish or ascetic. He was a large, vigorous man, who, in the words of his friend Lichtenberg, "understood a lot about the electricity of women" (*Epistolario*, II, 269). For many years he enjoyed the favors of a singer, Marianna Paris, whom he might have married but for the weight of theological, and family, opinion.

Volta was about seven when his father died. His uncle the canon took charge of his education, which began in 1757 at the local Jesuit college, where his quickness soon attracted the attention of his teachers. In 1761 the philosophy professor, Girolamo Bonensi, tried to recruit him; his suit, sweetened by gifts of chocolates and bonbons, alarmed Volta's uncle, who took him from school. Bonensi continued his campaign in letters (*Epistolario*, I, 6–33) carried secretly by Volta's eccentric friend, the future canon Giulio Cesare Gattoni (1741–1809), until Volta's uncle the Dominican, who shared his order's opinion of Jesuits, put an end to the affair.

Volta continued his education at the Seminario Benzi, where Lucretius' *De rerum natura* made a powerful impression upon him, and at the so-called Gattoni tower, a disused redoubt rented by his richer and older friend as a laboratory and museum. This cabinet, begun about 1765, won a reputation for its collections in natural history. It also sheltered some physics: a joint study by Gattoni and Volta of the electricity brought down by its lightning rod, said to be the first erected in Como, and experiments of Volta's made possible by books, instruments, and encouragement generously supplied by Gattoni. The first fruit of these mixed studies was a Latin poem of some 500 hexameters in which Volta celebrated the discoveries of

Priestley, Nollet, Symmer, and Musschenbroek (*Aggiunte*, 123–135). Several other poems by Volta in French and Italian survive (*Aggiunte*, 136–158); according to Gattoni, he was always "an excellent judge of all kinds of literature,"[1] which, however, did not save his own style from prolixity.

Volta's uncles wished to make him an attorney, a profession well represented on his mother's side of the family. Volta preferred to obey what he called his genius, which directed him, at the age of eighteen, to the study of electricity.

Electrostatics. The chief authorities on electricity in the early 1760's were Nollet and Beccaria, to whom Volta would write whenever questions or suggestions occurred to him. His first letter to Beccaria, inspired in part by Bošković's ideas, announced that electrical phenomena arose entirely from an attractive force operating between the electrical fluid and common matter (*Epistolario*, I, 4). Beccaria, a testy man who held to the original Franklinist theory of a self-repulsive electrical fluid, took a year to reply, and did so only after Volta had apologized for his "very frivolous chatter." As a cure for frivolity Beccaria recommended reading Beccaria and doing experiments (*Epistolario*, I, 33–36; *Opere*, III, 23). Volta followed the advice, without access to the usual apparatus; forced to invent cheap substitutes, he began to develop that genius for inexpensive, effective instrumentation that determined his career.

His earliest results, communicated to Beccaria in April 1765, derived from the discovery, which Volta fancied new, that silk rubbed by hand became plus, and silk rubbed by glass, minus. He designed a machine to capitalize on the electrical properties of silk and drew up a schematic triboelectric series, doubtless independent of Wilcke's. The correspondence lasted until 1769, when Volta published a Latin dissertation, *De vi attractiva*, which boldly reinterpreted Franklin's theory and Beccaria's latest experiments in terms of the unique attractive principle (*Epistolario*, I, 36–43, 64–65; *Opere*, III, 6–7, 10–11, 19–20, 23–24).

Volta observed that Franklinist electrical matter cannot itself be the cause of electrical motions because it courses unidirectionally, from excess to defect, while in the most common of experiments, as Nollet had emphasized, the same electrified body simultaneously imposes both attractions and repulsions. Nor can the effluvia operate indirectly, by impelling the air, for electrical attraction takes place between bodies immersed in oil (an experiment Volta lifted without acknowledgment from Cigna). We must therefore admit short-range attractive forces. To the usual objection that multiplying such forces clutters matter with special nonmechanical powers, Volta countered that, since only "mixed bodies" are electric, one need imagine no special virtue of electricity, but merely a net macroscopic force compounded from the different microscopic forces possessed by the particles of pure substances, or from the universal, elemental, multipurpose force of Bošković. Nor should one falter at the great range of electrical attraction: we have, on the one hand, the patent example of magnetism and, on the other, the existence of electrical atmospheres. These, according to Volta's evenhanded compromise, consist of surplus electrical fluid, the attraction of which extends a little way beyond their physical limits. "However that might be, for present purposes it need only be granted that attractive forces really exist in bodies" (*Opere*, III, 25–29, 85).

Volta's fundamental concept is that there exists for each body a state of saturation in which the integrated attractions of its particles for electric fluid are precisely satisfied. This integrated attraction may be altered by any process, mechanical or chemical, that displaces the particles relative to one another; friction, pressure, and, perhaps, evaporation electrify bodies by destroying the existing pattern of saturated forces and redistributing the electrical fluid (*Opere*, III, 30–34). In this proposition one sees the seeds of the experiment of Volta, Lavoisier, and Laplace on electrification by evaporation, and, perhaps, of Volta's consequential concept of contact charge. As for the notion of saturation, it vaguely foreshadowed the concept of tension, Volta's qualitative equivalent of the modern potential: the condition of electrical equilibrium between two bodies being not equality of quantity of electric fluid, but of degree of departure from saturation.

For the rest, *De vi attractiva* is an exercise in reducing the standard phenomena—attraction, "repulsion" (really attraction away from the "repelling" body), the Leyden experiment, and the effects of Beccaria's vindicating electricity—to the single attractive force. Again one can see fruitful tendencies, particularly in Volta's analysis of induction in an insulated conductor *B* under the influence of a positively charged body *A*: *A*'s atmosphere supersaturates *B* without altering *B*'s integrated positive force; *B* therefore sheds fluid, which surrounds its far side in an atmosphere. Touch *B*: it loses its surplus, but shows no electrical signs because its residual fluid and *A*'s atmosphere exactly saturate it (bring it to zero potential). Now remove *A*: *B* is no longer saturated, and shows itself negative (*Opere*, III, 36–50). Here one sees seeds of the electrophore and the condensator. Although Volta soon acknowledged that the single attractive force could not account for many simple phenomena—for example, the difference between insulators and conductors, and the charging of a Leyden jar—he continued to be guided by it and to ascribe most electrical effects to it, until 1784 or even later (*Opere*, III, 56–71, 85; IV, 410–413).

The reluctance to change or discard a once-useful theory was characteristic of Volta. As he said when describing his slowness to accept Lavoisier's chemistry, he wished to be neither too open nor too resistant to novelties. He remained faithful to the Franklinist hypothesis of a single electrical fluid, "la nostra cara dottrina" (*Opere*, IV, 359, 380), while most important physicists of the Continent preferred the dualistic system of Symmer. Volta eventually was brought to agree that all known electrical effects could be explained on either system; but he preferred the singlist, partly (as he said) because of a reluctance to multiply entities unnecessarily, and mainly because of his scientific conservatism (*Opere*, IV, 269; *Epistolario*, II, 278).

To concoct the electrophore, the most intriguing electrical device since the Leyden jar, Volta had only to combine the insight that resin retained its electricity longer than glass with the fact, emphasized by Cigna and Beccaria, that a metal plate and a charged insulator properly maneuvered can produce many flashes without enervating the electric. Beccaria inspired the combination. In 1772 he published a lengthy, difficult, updated version of *Elettricismo artificiale*, which emphasized more strongly than before his odd view that the contrary electricities destroy one another in the union of a charged insulator with a momentarily grounded conductor, only to reappear, "revindicated," in subsequent separations. Beccaria also criticized the hypothesis of the unique attractive force, without deigning to mention Volta, who in return conceived that, if he could greatly increase the duration of the effects ascribed to vindicating electricity, the implausible theory of alternate destructions and incomplete recuperations would fall to the ground. After many trials Volta found that an insulator made of three parts turpentine, two parts resin, and one part wax answered perfectly; and in June 1775 he informed Priestley of the invention of an *elettroforo perpetuo*, which "electrified but once, briefly and moderately, never loses its electricity, and although repeatedly touched, obstinately preserves the strength of its signs" (*Opere*, III, 96).

The device consisted of a metal dish containing a dielectric cake, and a light wooden shield covered with tin foil rounded to remove all corners and joined to an insulating handle. The cake is first charged, say negatively, by rubbing. The shield is then set upon it, and momentarily grounded, thereby charging positively by induction. The shield may then be removed and its charge given to, say, the hook of a Leyden jar; then replaced, touched, and again brought to the hook; and so on until the condenser is moderately charged. Any number of jars and electrophores may be electrified without regenerating the original; and if it should decline, it can be reinvigorated by lightly rubbing its cake with the coating of a Leyden jar that the shield had charged through the hook. Volta set great store by this last property, which did seem to vouchsafe eternal life to the electrophore and to justify the term *elettricità vindice indeficiente*, with which he proposed to celebrate his victory over Beccaria (*Opere*, III, 98–105).

The triumph was clouded. Beccaria thundered that the "perpetuity" of the charge of the electrophore proved nothing and that he and Cigna had already described the necessary manipulations. Other claimants came or were thrust forward: Stephen Gray, Aepinus, Wilcke, and the Jesuits of Peking. With his customary good sense (*Opere*, III, 120, 137–143), Volta acknowledged the role of Cigna, but insisted, quite rightly, that he alone had made a usable instrument, and had developed the cake, the armatures, and the play with the bottle. Even Wilcke, who had fully grasped the theory, had not embodied it in the sort of apparatus—sturdy, useful, powerful, intriguing—characteristic of Volta's designs.

The electrophore killed off not only vindicating electricity but also the last vestiges of the old doctrine of literal atmospheres (*Opere*, III, 140n; *Epistolario*, I, 275–280). The only successful theories of the device, for example, those of Ingen-Housz and Wilcke, employed actions at a distance between electrical fluids confined by the surfaces of conductors. Accordingly, as contemporaries recognized,[2] the electrophore caused electricians to take seriously the neglected approach of Aepinus. Volta himself first met with a copy of Aepinus' "incomparably profound book" (*Opere*, III, 210n, 236) in the 1770's, too late to guide his invention but in time to assist his own revision of the concept of atmospheres.

The mid-1770's marked the beginning of Volta's career. In October 1774 he took his first academic job, principal or regent of the state Gymnasium in Como (*Epistolario*, I, 66–68), then recently taken over from the Jesuits. Next came the electrophore and, at Volta's request, the professorship of experimental physics at the Gymnasium, which he garnered in 1775 without the usual examination (*Epistolario*, I, 99, 100). A sally into pneumatics brought the discovery of methane (1776) and a greater reputation, which helped him in 1777 to obtain state support for a trip to the chief centers of learning in Switzerland and Alsace (*Epistolario*, I, 149–150, 178). There Volta met several savants—particularly H. B. de Saussure and Jean Senebier of Geneva—both of whom would advertise and encourage his work, and help keep him informed about transalpine physics (*Epistolario*, I, 192–193).

Volta's travel grant came from the Austrian government, which then controlled the duchy of Milan, including Como, and which, through its minister Count Carlo di Firmian, was modernizing the educational institutions of the region. Chief among these was the University of Pavia, where the Austrians had been encouraging science, particularly since 1769, when Spallanzani came to the chair of natural history.

In 1777 Pavia had two professorships of physics, both occupied by clerics: a "general" held by Francesco Luini (Jesuit) and an "experimental" held by Carlo Barletti (Scolopian). In 1778 Firmian, the "immortal Maecenas, benefactor and greatest protector of the university" (*Epistolario*, II, 285), sent Luini to Mantua, translated Barletti to general physics, and gave Volta the post he would hold for almost forty years, the professorship of experimental physics at Pavia (*Epistolario*, I, 298). Volta proved a very popular professor (*Epistolario*, II, 41, 283–284). A new lecture hall was built to house his auditors and the university's ever-increasing collection of instruments, many of which Volta bought at state expense on state-financed trips to France and England in 1781–1782 (*Epistolario*, II, 51–141) and to Germany in 1784 (*Epistolario*, II, 225–273).

As Volta's professional opportunity and acquaintance increased, his style of physics altered, at least in its public form. The change was manifest in 1778 in a published letter to his new friend Saussure on electrical capacity. While *Di vi attractiva* developed a microscopic model of electrical action, which explained but did not guide, and while the account of the electrophore was primarily a description of laboratory manipulations, the letter to Saussure applied new theoretical concepts to the design and explanation of new experiments. These powerful concepts, the macroscopic quantities capacity and tension, also appear in Cavendish's now famous memoir of 1771. There is reason to believe that Volta read this memoir, which most contemporary electricians ignored or misunderstood, and that he derived from it—and perhaps also from the works of Aepinus and even of Barletti, who first acquainted him with Aepinus[3]—the clue for the transformation of his otiose notion, "natural saturation," into a serviceable substitute for the concept of potential.

Volta's thought is that the capacity C of a conductor and the tension T of its charge Q alter with its distance from other conductors (*Opere*, III, 201–229; *Epistolario*, I, 275, 280). For example, as the charged shield is raised from the electrophore cake, electrometer threads attached to it spread, owing to an increase in the tension of its charge; since the quantity of charge does not change, the tension grows because the shield becomes less capacious, less able to hold its naturally expansive charge as it moves farther from the opposite electricity of the cake. The reverse effect occurs with a pair of similarly charged conductors: the capacity of each is enlarged, and its tension lessened, as the distance between them increases. Volta deduced that the "atmospheres" of the various surface elements of the same conductor might inhibit one another, and that, for a given surface area, the longer the conductor the greater the capacity. Perhaps, as Cavendish had suggested, the capacity of a single conductor could be increased to that of a Leyden jar. It was just this expectation that Volta confirmed in his letter to Saussure, who had earlier doubted its possibility (*Opere*, III, 213–215).

In describing the experiment Volta used the old term "electrical atmosphere," by which, however, he now no longer meant an envelope of electrical fluid but, as was becoming commonplace, merely a "sphere of activity" (*Opere*, III, 155, 160, 166–167, 182, 206, 236–240). The point is important, as many commentators, perhaps misled by Biot, have ascribed to Volta a belief in the retrograde literal atmospheres that his work helped to destroy. It is plain from Volta's manuscripts—for example, the beautiful and exact theory of the slow-motion charging of a Leyden jar (*Opere*, III, 248–258), or the *Lezioni compendiose sull'elettricità* (*Opere*, IV, 419)—that soon after, if not before, the letter to Saussure, Volta had freed himself of the ideas that "anything real" passed between bodies interacting electrically beyond sparking range, and that the surplus electrical fluid of a positively charged body resided in the air about it (*Opere*, III, 236, 273; IV, 65–68, 71–74; *Epistolario*, II, 213). Occasionally he represented this sphere of activity as a state of the space or air surrounding charged bodies (*Epistolario*, I, 296, 326–327, 376, 411); a representation not of literal atmospheres but of a crude field theory, which may be traced from Canton and Beccaria through Avogadro and on to Faraday.

Volta embodied the quantities capacity and tension, and the implicit relation that he had established between them ($Q = CT$), in a new instrument, a "condensator" for rendering sensible atmospheric electricity otherwise too weak for detection (*Opere*, III, 271–300). This famous device is nothing but an electrophore with a poor conductor like polished marble or oiled wood as its cake. One runs a wire from an apparently unelectrified atmospheric probe to the shield, waits, removes the wire and raises the shield, which can then affect an electroscope. Volta explained that owing to its great capacity the electrophore soaks up the electricity of the probe as often as it becomes charged, while the separated shield, being of small capacity, can reveal the weak collected electricity. He emphasized that the quantity of charge on a conductor increases as the product of its tension and its capacity, the former being the quantity measured by electrometers (*Opere*, IV, 71–74). Others soon incorporated this insight into ingenious multipliers of weak charges, such as the well-known "doubler" invented by William Nicholson.

Meteorology. Volta's interest in meteorology centered on atmospheric electricity, the study of which began in 1752 with the apparent confirmation of Franklin's hypothesis about the electrical character of lightning. It was quickly discovered, by Beccaria and Canton among others, that the atmosphere exhibited electricity even in fair weather, and that, contrary to Franklin's expectation, it was more often negative than positive. This information was at first deduced from the electrical state of the lower end of an insulated pointed pole or wire, which was thought to exchange electrical fluid with the surrounding air. In fact such probes charge partly by conduction but mainly by induction, and their electricity does not give an unambiguous index of the electrical state of the atmosphere. Among the few to understand and to evade this ambiguity was Saussure, whose work directly inspired Volta's.[4]

Saussure employed not a long pole but a form of the bottle electrometer invented by Cavallo, with silver wires ending in pith balls as the indicator. Saussure would touch the stem and case of the electrometer to the ground and suddenly raise the instrument above his head; the consequent spread of the wires indicated, as he said, the electrical tension of the atmosphere at the site of the electrometer. Saussure carried this device on his famous attempt at Mont Blanc in 1787, which Volta, who was then visiting Geneva, commemorated in no fewer than sixty-six *terzini* (*Aggiunte*, 146–152). When he returned to Pavia, Volta undertook to make Saussure's instrument "more obedient" (*Opere*, V, 88–90). In 1787 he began to announce his results in letters to G. L. Lichtenberg, professor of physics at the University of Göttingen, whom he had met on his trip to Germany in 1784. The nine Lichtenberg letters constitute Volta's chief writings on meteorology.

Alerted to the problematic operation of the pointed pole, Volta hit on a solution quite different from Saussure's: bathing the point in flame, which promoted the exchange of electric fluid and brought the point quickly to the potential of the atmosphere just outside it (*Opere*, V, 88–92, 152–156). Volta found that electrometers armed with flames registered four times the electricity recorded by Saussure's detector under identical circumstances (*Opere*, IV, 71–74). The device was widely used, although probably not fully understood, until William Thomson gave its theory in the 1850's and replaced it by his ingenious water-dripper.[5]

The next business was to make of Saussure's electrometer a sensitive, uniformly calibrated, international standard. Volta improved the sensitivity by replacing Saussure's wires with light straws with large effective repelling surfaces (*Opere*, V, 35–42, 68, 71); the result was an inexpensive form of the exactly contemporaneous gold-leaf electrometer (1786) invented by Abraham Bennet. Uniform calibration, which Volta deemed essential, was obtained by giving the electrometer successive sparks from a capacious Leyden jar kept at a constant potential by a small electrophore (*Opere*, V, 39–42). Taking the intercomparability of thermometers and of hygrometers as his model, Volta proposed the adoption of a fundamental unit of tension, namely that of a standard metal disk hung from one arm of a balance a distance d above a conducting surface, and counterbalanced by a certain weight W. The unit, equivalent to a spread of 350 degrees of Volta's straw electroscope, is about 13,350 volt in modern measure.[6]

In experiments with the unit, Volta found that the "force of attraction" measured by the weight W was proportional to $(T/d)^2$, T being the tension of the disk according to his straw electrometer. It is most interesting that he took this result, which is correct, as evidence against the universality of Coulomb's law, which gives the same dependence on distance, but for a different geometry (*Opere*, V, 78–79, 81–83). Moreover, other geometries yielded "diverse other laws, as curious as they are novel." Like many of his colleagues, Volta did not have mathematics enough to work from a hypothetical law of interaction of electrical elements to the observed electrical forces between macroscopic bodies.

Volta accepted the Franklinist presumption that the instruments of atmospheric electricity measured the surplus (or deficiency) of electrical fluid in the lower atmosphere; and he had suggested in *De vi attractiva* that the fluid enters (or leaves) the air during evaporation. One of the first tasks he assigned his condensator was the detection of the supposititious electrification during change of state. He was then (1782) in France, and undertook the experiments in collaboration with Lavoisier and Laplace. At first they failed, as they should have, there being no such effect; but shortly before Volta left Paris for London they succeeded, or believed they had, and made much of their success. According to Volta, everything depended on a change in electrical capacity suffered by water droplets in going from the liquid to the vapor state (*Opere*, III, 33–34, 301–305, 364; V, 173–187, 196–197; *Epistolario*, II, 104–105; *Aggiunte*, 21–24). They had probably detected electricity generated by the friction of bubbles against the evaporating pan. The subject was to remain confused for over a century.

Volta's explanation, which differed from that in *De vi attractiva*, doubtless owed something to his adherence to the doctrine of latent heat (*Opere*, VI, 313–316), which became widely known in the early 1780's. It remained the basis of his speculations about meteorological phenomena. For example, according to his much admired theory of hail, evaporation abstracts both heat and electricity from vaporizing droplets, creating charged microscopic ice seeds, which dance about under electrical forces in their parent cloud, growing at the expense of surrounding droplets until they become too heavy for the ballet, and fall to the ground (*Opere*, V, 201–206, 283–307, 421–462).

Pneumatics. Volta's work on gases shows the same genius for instrumentation and measurement, and the same failure or reluctance to establish general principles, that characterize his work on electrostatics. His first pneumatic studies concerned "inflammable air from marshes" (chiefly methane), which he discovered in November 1776 in Lago Maggiore. It was not a chance find. Inflammable air from metals (hydrogen released from acids) had been known since its isolation by Cavendish in 1766, and Franklin's description of a natural source of inflammable air had just been published by Priestley in a book quickly known in Italy.[7] In the autumn of 1776 Volta's friend P. Carlo Giuseppe Campi had found a natural source near Pavia; and Volta himself, intrigued by the "ever more remarkable and interesting subject of the different kinds of air" (*Opere*, VI, 19), had scoured the countryside for telltale bubbles. The testing of his new gas—new in source, flame color, and combustibility (*Opere*, VI, 30)—led him into the faddish field of eudiometry.

In 1772 Priestley had isolated a "nitrous air," which, when combined with common air over water, left a volume of gas less than the sum of the volumes of the ingredients. He found the reduction to be less the more the common air had been vitiated by respiration or combustion; and he proposed to take the degree of reduction as a measure of the "goodness" of the common air. Priestley's procedure was improved, and his interpretation adopted by two of Volta's friends: Marsilio Landriani, who introduced the term "eudiometry," and Felice Fontana, whose nitrous-air eudiometer won wide acceptance in northern Europe (*Epistolario*, I, 218–219; 258–260; III, 4–8). Both hoped that the instrument would help to identify malarial and other insalubrious regions; and for almost thirty years physicists visited swamps, cesspools, dung heaps, prisons, and hospitals hoping to correlate the reading of their eudiometers with the evident foulness of the air. No consistent correlations emerged. In 1805 Humboldt and Gay-Lussac put an end to the search by showing that the percentage of oxygen in unvitiated air was independent of its source. They succeeded by employing a device of Volta's, who had never believed that the eudiometer could measure the salubrity—as opposed to the respirability (oxygen content)—of the air (*Opere*, VI, 9).

Ever interested in large, reproducible effects, Volta had shifted his attention to hydrogen upon discovering that, when mixed with common air and sparked, Cavendish's inflammable air ignited more readily and burnt more fiercely than his own (*Opere*, VI, 50); whence Volta's famous "inflammable air pistol," filled with hydrogen and air or oxygen, and fired by a portable electrophore (*Opere*, VI, 134–135). To perfect this artillery (which could fire a lead ball with force enough to dent wood at fifteen feet [*Opere*, VI, 155]), he looked for the mixture that destroyed the greatest quantity of gas (*Opere*, VI, 146). He thereby came to the problem of the eudiometer, but from a new side, and with a new eudiometric fluid, hydrogen, which could be obtained purer than the standard nitric oxide (*Opere*, VI, 180–181), and acted much more vigorously (*Opere*, VI, 159–160). Volta's first eudiometric technique was to find the minimum volume of the air under test in which a standard amount of inflammable air could be ignited by a spark; the larger the volume, the poorer the air. As for the optimum explosive mixture, it turned out to be four parts inflammable to eleven parts unvitiated common air (*Opere*, VI, 179), or two parts inflammable to one part dephlogisticated air (oxygen) (*Opere*, VI, 190n). In the definitive form of his eudiometer (*Opere*, VII, 173–213), Volta mixed equal volumes of hydrogen and common air, exploded them, and determined the diminution; the maximum contraction, for the best air, fell out just under 3/5 volume, confirming that, as other of his measurements suggested, the maximum possible reduction in unit volume of common air was about 1/5 (*Opere*, VII, 197).[8] Volta's numerical results were fully confirmed by Humboldt and Gay-Lussac, who found oxygen to occupy about 21 percent of the volume of common air. This should be compared to the results obtained by Humboldt, Lavoisier, and Scheele, using the Fontana nitrous-oxide eudiometer, namely 26 to 28 percent.

Volta's eudiometer set up one of the most important discoveries of the eighteenth century, the composition of water, detected by Lavoisier, among others, by sparking oxygen and hydrogen over mercury (1783). As early as the spring of 1777 Volta had been looking for the residue of the reaction. In his version of phlogistic chemistry, inflammable air (H_2) was phlogiston (ϕ) combined with an unknown "base," which he supposed to be of an "acid" or "saline" character (*Opere*, VI, 150, 342, 400–401). He recognized that, since the base might be soluble in water, the sparking should be done over mercury, but he had not enough for the task (*Opere*, VI, 196–197, 303, 410–411; *Epistolario*, I, 267–270). While working to obtain more, he sparked inflammable and common air over water, and noticed (in 1778) that the walls of the test vessel fogged (*Opere*, VI, 382). While in Paris in 1782 he told Lavoisier about the fogging: and later in the year Lavoisier, Laplace, and Monge obtained water over mercury by Volta's method (*Opere*, VI, 410–411).

The French, following Lavoisier's ideas, thought they had synthesized water; Volta, remaining faithful to phlogiston, believed that they had analyzed the gases (*Opere*, VI, 342, 411; VII, 87–88, 101, 103):

$$\text{Inflammable air (water} + \phi) + \text{dephlogisticated air (water} + \text{caloric)} = \text{water} + \text{heat.}$$

Volta did not adopt the new chemistry for many years, perhaps not definitively until after 1800, although he began to speak of it more favorably in the 1790's (*Opere*, VII, 246, 269–270, 284; *Epistolario*, III, 61–62). He later said that the decisive proof was his own calcification of metals in closed vessels by burning mirrors. Calcification proceeded until the volume of the air fell by 1/5, precisely the amount of dephlogisticated air that, according to Volta's earlier measurements, would be available to support the combustion (*Opere*, VII, 285).

Volta's later pneumatic studies centered on the action of heat on gases and vapors. His general conception of heat followed the fluid theories of Crawford and Kirwan (*Opere*, VI, 315; VII, 45–47), with one characteristic exception: whereas his sources ascribed the phenomenon of latent heat to a chemical combination responsible for change of state, Volta made the change primary, and the latent heat the result of a consequent jump in specific heat capacity. This concept, developed in notes to the Italian edition of Macquer's *Dictionnaire de chymie* (1783–1784), derived from Volta's mature conception of electrical capacitance and from an assimilation of the properties of the two fluids: since nothing analogous to latency—the supposed inability of accumulated caloric to affect a thermometer—occurred in electricity, it was difficult for Volta to credit it in the case of heat (*Opere*, VII, 19–20). Consequently he once again opposed Lavoisier, now regarding his claim that evaporation arose from the chemical combination of heat and water (*Opere*, VII, 87–93). Volta also opposed the older theory, already under attack, that evaporation consisted of the "solution" of water in the bases of the atmosphere.

Against this last proposition Volta could adduce his own experiments on what we would now call partial pressures. Already in 1784, in a letter to Lichtenberg, Volta sketched the law usually attributed to Dalton for the case of water vapor. Volta also stated clearly in letters obscurely published in 1795 and 1796 that "the quantity of elastic vapor is the same in a space either void of air or filled with air at any density, and depends only upon the degree of heat" (*Opere*, I, 301; VII, 441). Hence he easily derived an argument fatal to the theory of evaporation by solution. Moreover, Volta anticipated and even went beyond Dalton in measuring the dependence of the density and pressure of water vapor on temperature. The laborious and difficult measurements, made in a heated Torricelli space, gave results in very rough agreement with modern determinations.[9]

Volta was more successful in measuring the dilation of air as a function of heat, or rather of temperature indicated on a mercury thermometer. The proportionality of heat and temperature so measured had been established, to Volta's satisfaction, by Deluc, "a most knowledgeable and accurate experimenter" (*Opere*, VII, 414), whose thermometric example had probably encouraged Volta's comparative electrometry. Between 1772 and 1790, when Volta took up the subject, many physicists had tried to measure α, the percentage increase in volume of a gas per degree of temperature. In his masterful memoir published in 1793 (*Opere*, VII, 347–375), Volta pointed to values of α ranging from 1/85 (Priestley) to 1/235 (Saussure) per degree Réaumur, and to uncertainty whether α varied with temperature between the freezing and boiling points. Volta cut through the uncertainty by observing that the dilation produced when heating a gas over water derives from two causes: (1) the true expansion of the gas and the water vapor it contains, and (2) the generation of additional vapor from the walls of the experimental vessel and from the water used to measure the dilation. Dry the vessel carefully, conduct the experiment over mercury or oil, and, according to Volta, you should get an α for air independent of temperature and equal to about 1/216. This value, which agreed perfectly with those obtained by Deluc and by Lambert from less systematic measurements, differs very little from that now accepted.

The journal to which Volta confided these results had little circulation outside Italy. Once again his priority was ignored, this time in favor of Gay-Lussac, who in 1802 deduced a value of α (1/213) poorer than his predecessor's and based on flimsier data, albeit for more gases. (Gay-Lussac obtained α from the total dilation between freezing and boiling points; Volta had measured it for each degree.) It is possible that Gay-Lussac did not obtain his number in total ignorance of Volta's.[10] In any case, the proposition, "the coefficient of expansion of air is constant," was restored to Volta by unanimous vote of the international congress of physicists meeting at Como in 1927 in observance of the centennial of his death (*Opere*, VII, 346).

Animal Electricity and Galvanism. In 1791 Galvani, professor of anatomy at the University of Bologna, published his now famous study of the electrical excitation of disembodied frog legs. He explained the jerking of a leg upon completing a circuit through the crural nerve and the leg muscle as the direct result of the discharge of a "nerveo-electrical fluid" previously accumulated in the muscle, which he supposed to act like a Leyden jar. The analogy between muscle and jar did not rest only on the need for a complete discharge circuit. Consider also the following phenomenon: the internal electrode of a charged grounded Leyden jar is pointed and brought near a large electrified insulated conductor; when a spark is drawn from the conductor, a "penicillum" of light flashes from the pointed electrode. According to Galvani, precisely the same sort of discharge occurred during the chance observation that had led him into his odd studies: a freshly prepared frog's leg jumped (that is, its muscle discharged, in analogy to the penicillum) if the circuit were completed at the instant that a spark was drawn from a nearby electrical machine. In Galvani's opinion the structure of the muscle, like the peculiar anatomy of the torpedo or electric eel, effected and retained the accumulation of the nerveo-electrical fluid. As for the fluid, it was similar to but distinct from frictional electricity, an "animal" electricity sui generis.

When Volta learned of Galvani's experiments he dismissed them as "unbelievable" and "miraculous." He had a low opinion of physicians, whom he found to be generally "ignorant of the known laws of electricity"; and he recognized "animal electricity" only in electrical fish, to which, however, he ascribed only the power of manipulating common electrical fluid (*Opere*, I, 10–11, 21–23, 26; *Epistolario*, III, 143–145). Moreover, even as late as 28 March 1792, just after he had first tried the experiments, "with little hope of success," under the urging of his colleagues in pathology and anatomy, his immediate research plans included only meteorology and the dilation of gases. But by 1 April the experiments had succeeded, and Volta had begun the brilliantly planned and executed experiments that step by step brought him to the invention of the pile.

Volta's first instinct was to measure the minimum tension of "artificial" or "frictional" electricity that would cause the frog to jerk: "How can causes be found if one does not determine the quantity as well as the quality of the effects?" (*Opere*, I, 27). Frog legs prepared as directed by Galvani proved to be by far the most sensitive electroscope yet discovered. When placed in a discharge train of a Leyden jar, they responded to a tension of as little as 5/100 degree of Volta's straw electrometer, an amount he could only detect after manipulation by the condensator. He also succeeded in inducing convulsions in a live frog by joining its leg and back externally by a circuit made of dissimilar metals. (Galvani had discovered by chance that prepared frog legs kicked violently and reliably when nerve and muscle were joined by a circuit composed of two kinds of metals.) Volta's discovery, probably made in April 1792, required modification of Galvani's theory. While agreeing that the electrical imbalance detected by the spasms arose from action of the animal, Volta doubted the appropriateness of the analogy to the Leyden jar; rather, it seemed to him that a weak animal electricity constantly circulated through the body of a normal frog, and that artificial circuits brought about convulsions by disturbing the natural flow (*Opere*, I, 15, 30–33).[11]

Volta's use of the whole frog—a move unnatural for an anatomist like Galvani—proved consequential. When the animal was intact it could be made to tremble only when struck by a discharge from a Leyden jar or when part of a bimetallic circuit. Volta inferred that the electricity put in action in the second case arose from the mere contact of dissimilar bodies (*Opere*, I, 55, 64–66, 73–74), a property he had already identified in "electrics" (insulators) but was surprised to meet in metals (*Opere*, I, 136). The fact, however, was plain, as well as the conclusion that animal electricity played no part in spasms inspired by bimetallic arcs. The only true galvanic effect, according to Volta, was the convulsion of a freshly prepared specimen in a circuit completed by a single metal (*Opere*, I, 116–118, 156–157, 180). And even this "beautiful and great discovery" (*Opere*, I, 175), this "truly astonishing experiment" (*Opere*, I, 178), could not occur as Galvani thought; for, as Volta showed, the muscle need not be included in the circuit. Electricity excited the nerve, and the nerve the muscle; there was no room for a Leyden jar fabricated of muscle tissue. To illustrate the office of the nerve Volta thought to excite the sense of taste by a bimetallic arc. With great satisfaction he experienced an unpleasant taste by joining a bit of tin on the tip of his tongue to a silver spoon resting further back (*Opere*, I, 56–57, 62–63, 73–74). It happened that, unknown to Volta, this experiment had been described many years earlier by J. G. Sulzer, who, however, did not associate it with electricity and doubtless—again in contrast to Volta—did not design it as a test of theory (*Opere*, I, 152–154, 196).

The tendency of Volta's results was to restrict more and more the domain of animal electricity. By November 1792, after countless trials on diverse unlucky creatures from insects ("it is very amusing to make a [headless] grasshopper sing" [*Opere*, I, 190–191]) to mammals, Volta had concluded that all galvanic excitations arose from external electrical stimulation. As for the classic case (a freshly killed and stripped frog, highly excitable, joined crural nerve to leg muscle by a single metal), Volta supposed that the electricity came not from animal power but from the contact between the metal and unobserved impurities in it (*Opere*, I, 147, 156–157). Nothing remained of the theory of animal electricity, or so Volta told Galvani's nephew and defender, Giovanni Aldini, professor of physics at the University of Bologna, in an open letter published early in 1793 (*Opere*, I, 149–159).

While the Galvanists pondered their response, Volta ranked the metals according to their electromotive power (*Opere*, I, 214, 234, 304) and tried to determine the seat of the electromotive force. He recognized that an effective circuit contained, besides a bimetallic joint, at least one "moist conductor," namely, the nerve to be excited, and he thought it more probable that the electrical imbalance occurred in the contact between the metals and the moist conductor than in the joint between the metals (*Opere*, I, 205, 212–213, 231–232). This proposition gained plausibility by his discovery in 1793 that the electromotive power of a chain of dissimilar metals depends only upon the nature of the two extreme links, precisely those touching the moist conductor, and that nothing happens if each metal is in contact only with moist conductors (*Opere*, I, 226–227).

Volta was accordingly prepared to answer the counterattack launched in 1794 by Galvani, Aldini, and a resourceful physician, Eusebio Valli, who had always thought the contact theory "ridiculous"; for "how [he said] is it possible for a single shilling to contain electricity sufficient to move the leg of a horse?"[12] Their strongest and most worrisome new evidence was Valli's excitation of spasms in freshly prepared frogs using himself as arc. It appeared that convulsions could be induced without the metallic contact which, in his reply to Galvani and Aldini, Volta had just asserted to be necessary (*Opere*, I, 274, 279, 295n, 308). Although many people conceived that Valli's stroke had saved animal electricity, Volta had no trouble turning it to his advantage. He observed that, as Valli had reported, the experiment worked best when the nerves and muscles were moistened with blood or saliva. As he explained to Sir Joseph Banks in March 1795, and then to A. M. Vassalli, professor of physics at the University of Turin, in a letter printed in 1796, a sequence of dissimilar moist conductors could generate an electrical current by contact forces without the intervention of metals (*Opere*, I, 255–256; 295–297).

Volta's next, and characteristic, step was to determine the "electromotive force" (his words) of various combinations of conductors. He tried to rank moist conductors ("conductors of the second kind") as he had the metals ("conductors of the first kind") (*Opere*, I, 371, 405–406). He confirmed that an electromotive force occurred only via the contact of dissimilar conductors (*Opere*, I, 372, 397, 411–413), and he sought the most powerful combination of "electromotors." The results, in order of decreasing power, expressed in Volta's notation (where capital and small letters signify conductors of the first and second kind, respectively [*Opere*, I, 230, 379–382]); *rABr* (where *r*, the frog, is both a conductor of the second kind and the electroscope); *raAr; rabr; rAr* and *rar*, both zero (*Opere*, 396–397, 401–402). What about *ABCA*? Volta thought that analogy favored the possibility of a weak finite current in such a circuit. But how to detect it when the only electroscope sensitive enough to register galvanic electricity was itself a conductor of the second kind (*Opere*, I, 377–378)? The difficulty instanced a much more serious one, which had long bothered Volta: that his claim of the identity of galvanic and common electricity rested on experiments in which pieces of animals played an indispensable part (*Opere*, I, 490, 540–555).

The contact of zinc and silver develops about 0.78 volt. Volta's most sensitive straw electrometer marked about 40 volt/degree.[13] By the summer of 1796 he had managed to multiply the charges developed by touching dissimilar metals together enough to stimulate his electrometer (*Opere*, I, 525; *Epistolario*, III, 349, 359). He first succeeded with a Nicholson doubler (*Opere*, I, 420–424) and then with an unaided gold-leaf electroscope (*Opere*, I, 435–436); and he later rendered contact electricity easily sensible by a "condensing electroscope," a straightforward combination of the condensator and the straw electrometer (*Epistolario*, III, 438). All these devices, including the doubler, came directly or indirectly from Volta's earlier work. Note that to obtain contact charges that he could multiply Volta had to change his mind about the principal seat of the electromotive force, which he now located in the junction of metals and not in their union with moist conductors (*Opere*, I, 419, 472). In 1797 he published a full account of his detection of galvanic electricity by electrostatic means (*Opere*, I, 393–447).

It remained to find a way to multiply galvanic electricity directly. Volta discovered soon enough that piling metal disks on one another (say *aABAB* ··· *a*) did not help, and that a circuit made only of metals gave no electromotive force. These results led to the useful rule, a precise version of his result of 1793, that the electromotive force of a pile of disks is equal to what its extreme disks would generate if put into immediate contact (*Opere*, II, 61). How or when Volta hit on the far from obvious artifice of repeating the apparently unimportant secondary conductors in his generator is not known; an anticipation appears in one of the combinations published by Gren in 1797 (*Opere*, I, 398, fig. 13, 400). The definitive pile, *AZaAZaAZa* ··· *AZ*, consisting of pairs of silver and zinc disks separated by pieces of moist cardboard, was first made public in 1800, in a letter addressed to Banks, president of the Royal Society of London, and published in its *Philosophical Transactions* (*Opere*, I, 563–582). The letter also describes an alternative arrangement, a "crown of cups" consisting of a circle of glasses filled with salty or alkaline water and connected by bimetallic arcs dipping into the liquid (*Opere*, I, 568, 571; see also *Opere*, I, 399, 403–404).

Volta represented his discovery as an "artificial electric organ," an apparatus "fundamentally the same" as the natural electrical equipment of the torpedo (*Opere*, I, 556, 582). A medium-size pile, with forty or fifty pairs, gave anyone who touched its extremities about the same sensation he could enjoy grasping an electric fish. In both cases, Volta said, a constant current running externally from top to toe of the electromotor passed through the arms and breast, and agitated the sense of touch. Were it directed at the senses of vision, taste, or hearing, the current would cause light, taste, or sound instead (*Opere*, I, 578–580). Neither the pile nor the torpedo give electrostatic signs because, as Cavendish had argued long before, they operate at too low a tension; their effects derive rather from the quantity of electrical matter they move. The analogy to the torpedo played little part in Volta's discovery; the emphasis upon it in the letter to Banks was intended to silence the Galvanists. As for the cause and continuance of the electricity generated by the contact of dissimilar conductors, Volta feigned no hypothesis: "This perpetual motion may appear paradoxical, perhaps inexplicable; but it is nonetheless true and real, and can be touched, as it were, with the hands" (*Opere*, I, 576; see also *Opere*, I, 489).

It appears that Volta possessed most of the ingredients of the pile by 1796, including even an anticipation of the outstanding key discovery, the constructive combination of the generating pairs. The delay in completing the invention may be explained by external circumstances. First, Volta's marriage, in 1794, to Teresa Peregrini, daughter of a government official in Como, quickly brought him a sizable family (three sons between 1795 and 1798) and many new demands upon his time. Second, during just these years, 1796 to 1800, Volta, like many of his colleagues, was distracted by the French invasion of Italy. In May 1796 he was chosen by the city of Como as one of a delegation to honor Napoleon, then fresh from driving the Austrians from the Milanese. Shortly thereafter he became an official of Como's new government (*Epistolario*, III, 291). But he was not comfortable in the position, which he resigned as soon as possible (*Epistolario*, III, 309–310); for although he did not, like Galvani, refuse to take an oath to the new Cisalpine Republic, he had a lingering loyalty, or rather gratitude, toward the Austrian regime, whose favor he had enjoyed. Moreover, the French authorities had not recommended themselves by allowing their soldiers to sack Pavia and to damage Volta's laboratory (*Epistolario*, III, 294). His coldness toward the French and open opposition to Jacobin colleagues, and also the accusation that he favored a proposal to move the university from Pavia to Milan, led to harassment that drove him from Pavia for some months. These opinions did him no harm when the Austrians returned in 1799 and shut up the university; for the victors only took away his job, and not—as in the case of Barletti, who had welcomed the French—his liberty. Thirteen months later the French were back. Napoleon immediately opened the university, and Volta, having recovered his professorship (*Epistolario*, IV, 8), resigned himself to citizenship in the revived Cisalpine Republic. Indeed, he proposed that he and a colleague, L. Brugnatelli, professor of chemistry, go to Paris to express the gratitude of the university directly to the First Consul (*Epistolario*, IV, 16–17).

The trip, proposed in September 1800, was put off for a year because of war (*Epistolario*, IV, 24–25). It then turned into more than a mission to "cement an alliance of talent and science for the immortality of the two republics" (*Epistolario*, IV, 52–53); for in the interim Volta's letter to Banks had been published, and the chemical power of the pile discovered. The political mission became a triumphal march. Volta showed his experiments in Geneva, at the home of his friend Senebier; in Arcueil; in Paris, in the laboratories of Fourcroy, Seguin, Laméthérie, and above all, of Charles, where a special commission on galvanism of the Paris Academy met four times to see Volta's electricity; and at the Academy itself, where he performed at three sessions, each attended by Napoleon.[14] These demonstrations brought nothing new. They emphasized the electrostatic detection of the contact tension via a condensator and straw electroscope; used the old value of 1/60 degree of the latter (0.67 volt) as the tension of a single silver-zinc pair (*Opere*, II, 39–40, 50–61); and insisted on distinguishing between high tension/low current devices, like the standard electrical machine, and low tension/high current ones, like the pile, the crown of cups, and the torpedo (*Opere*, II, 72–83). When Volta concluded, Napoleon proposed the award of a gold medal; that, providentially, was also the recommendation of the commission on galvanism, which endorsed Volta's identification of galvanic and common electricity, and showed how to compute the tensions of various arrangements of disks and condensators (*Opere*, II, 113–115).

Napoleon continued to patronize Volta, giving him a pension and raising him to count and senator of the kingdom of Italy. In this there was more than politics. Volta's discoveries captured the imagination of Napoleon, who, to ensure continuance of similar inventions, authorized the Academy of Sciences to award a medal "for the best experiment made each year on the galvanic fluid" and a prize of 60,000 francs "to whoever by his experiments and discoveries makes a contribution to electricity and galvanism comparable to Franklin's and Volta's" (*Opere*, II, 122). But there was politics too. Just before leaving Paris in November 1801, Volta received what amounted to orders (*Epistolario*, IV, 88–89) to go to Lyons, to grace, and so endorse, a meeting at which selected Italian delegates were to be inspired to elect Napoleon president of the Cisalpine Republic. The republic soon disappeared into the kingdom of Italy, of which Napoleon became king. Volta played a small part in the kingdom as president of the Consiglio del Dipartimento del Lario (from 1803) and of the Comense Collegio Elettorale (1812). He retained sufficient confidence in French administration to cast his senatorial vote in 1814 in favor of offering the crown of Italy to Napoleon's stepson, Eugène de Beauharnais.

Napoleon was quite right in predicting that the pile presaged a new era in science. Its chemical power, employed in electrolyzing alkali salts, soon revealed the existence of sodium and potassium, a discovery for which Davy won the medal established by Napoleon. Studies of the properties of the current led to the laws of Oersted, Ohm, and Faraday, and to the beginnings of electrotechnology. In all of this Volta played no part. He was not much interested in the chemical effects of the pile, which he considered to be secondary phenomena (*Opere*, II, 37, 91). What effort he devoted to galvanism after his triumph in Paris went toward refuting the old doctrine of animal electricity, still very much alive. His last memoir on the subject, a lengthy review of his reasons for identifying galvanic and common electricity, was submitted under the name of a student in a prize competition announced in 1805 by the Società Italiana delle Scienze as follows: "Explain with clarity and dignity, and without offending anyone, the question of galvanism disputed by our worthy members Giovanni Aldini and Alessandro Volta" (*Opere*, II, 206). None of the papers submitted won the prize. Volta's memoir, which indeed contained little that was new, was printed in 1814 by his student and successor Pietro Configliachi (*Opere*, II, 205–307). After this competition Volta cut down his academic work. He sought and was refused retirement by the French ("a soldier," Napoleon told him, "should die on the field of honor" [*Epistolario*, IV, 455]); the Austrians, who returned in 1814, let him go in 1819. He spent his retirement chiefly in Como, where he died in 1827.

Volta received many honors besides those bestowed by Napoleon. The Royal Society of London elected him a member in 1791 and three years later gave him its highest prize, the Copley Medal, for setting right the Galvanists. He became a correspondent of the Berlin Academy of Sciences in 1786, and a foreign member of the Paris Academy in 1803. His fame also brought tangible rewards. In 1795 his university salary, 5,000 lire, was only double what he had during his last year at the Como Gymnasium. In 1805 he received an additional annuity of 4,000 lire from Napoleon, which survived the emperor's fall; and in 1809 he began to enjoy a senatorial salary of 24,000 lire. During the last twenty years of his life he had the income of a wealthy man.

As a scientist, Volta was conservative, yet alert to novelties; a strong theoretician, a "raisonneur sans pareil" (*Epistolario*, II, 268), as Lichtenberg said, yet an exceedingly careful and painstaking experimentalist, who constantly improved and varied his apparatus to exclude adventitious special cases. His uncommon imagination for effective instrumentation extended to anticipations of important practical devices such as the electrical telegraph (*Opere*, III, 194) and the incandescent gas lamp (*Opere*, VI, 150; VII, 155). He was no mathematician. His published work contains little mathematics beyond the rule of three and no evidence (according to Biot) that its author had a "mind fit for establishing rigorous theories"; while his lectures customarily skipped the mathematical parts of physics and omitted optics altogether. For these omissions Volta was bitterly attacked by Barletti in the early 1790's, no doubt partly for political reasons, and perhaps out of jealousy as well. The episode cost Volta much time and annoyance, and ended in an elaborate letter to the ministry in defense of his practice.[15] But despite his preference for the nonmathematical branches of physics, Volta fully understood the need for measurement: "Nothing good can be done in physics [he said] unless things are reduced to degrees and numbers" (*Opere*, I, 27). His mixture of precision in experiment and of indifference to—or ineptness at—general mathematical formulations also characterized several of his close colleagues, notably Saussure and Deluc. For the rest Volta went his own way, an autodidact seldom influenced by the work of others except at the beginning of an investigation.

NOTES

1. Quoted by Volpati, *Alessandro Volta*, 119; see *Epistolario*, V, 387–389.
2. For example, F. K. Achard, *Vorlesungen über die Experimentalphysik*, III (Berlin, 1791), 60.
3. *Epistolario*, I, 121; cf. Barletti, *Dubbi e pensieri* (Milan, 1776), 61–63, 103–119.
4. H. B. de Saussure, *Voyages dans les alpes*, II (Geneva–Neuchâtel, 1786), 212–219; see *Opere*, V, 154–155.
5. W. Thomson, *Reprint of Papers on Electricity and Magnetism*, 2nd ed. (London, 1884), 206–208, 227–229.
6. *Opere*, V, 55–56, 75–79; see Polvani, *Alessandro Volta*, 145.
7. *Opere*, VII, 228; Gliozzi, ed., *Opere scelte*, 248n.

8. The 2 vols. contain about 0.2 vol. O_2 and 1 vol. H_2: the total, therefore, falls by 0.6 vols., or 30 percent.
9. Grassi, "I lavori . . .," 562–563; Polvani, *Alessandro Volta*, 221–231; *Opere*, VII, 423–425.
10. Grassi, "I lavori . . .," 528–533.
11. The spasm occurring during discharge of a neighboring electrical machine brought nothing new; as Volta observed (*Opere*, I, 46–48, 175), it arose from the discharge of electricity induced in the specimen analogous to the return stroke in the case of lightning.
12. According to T. Cavallo in a letter to J. Lind, 23 Nov. 1792, British Museum Add. MS 22898, f. 25–26.
13. One degree of Volta's most sensitive straw electrometer equaled 1/10 of a degree of the Henley quadrant electrometer (*Opere*, V, 37, 52, 81; I, 486). 35 degrees of which marked about 13.350 volt (see note 6 above). Hence, one degree of the straw electrometer indicated about 40 volt. Volta later estimated the tension between zinc and silver at 1/60 degree straw (*Opere*, II, 39), or about 0.7 volt.
14. Z. Volta, *Alessandro Volta a Parigi*, 18–19, 41–47, 53–57, 96–97.
15. L. Magrini, "Notizie biografiche e scientifiche su A. Volta dai suoi autografi recentemente rinvenuti e inediti," in *Atti dell'Istituto lombardo di scienze e lettere*, **2** (1861), 254–283, on pp. 260–262, 272; C. Volpati; "Momenti d'amarezza sul camino della gloria," in *Voltiana*, **1** (1926), 437–447.

BIBLIOGRAPHY

I. COLLECTED WORKS. The best bibliography is F. Scolari, *Alessandro Volta* (Rome, 1927), which incorporates F. Fossatti, "Bibliografia degli scritti editi di Alessandro Volta," in *Memorie dell'Istituto lombardo di scienze e lettere*, cl. sci. mat. nat., **18** (1900), 181–217. See also "Scritti del Volta o che lo riguardano stampati negli *Atti* del R. Istituto lombardo di scienze e lettere," in *Rendiconti dell'Istituto lombardo di scienze e lettere*, **60** (1927), 580–583. There are two collected works: *Collezione dell'opere*, V. Antinori, ed., 3 vols. in 5 (Florence, 1816), which is incomplete; and the magnificent national edition, *Le opere*, 7 vols. (Milan, 1918–1929), which is referred to in this article. There are also several anthologies: *Briefe über thierische Elektricität (1792)* and *Untersuchungen über den Galvanismus, 1796 bis 1800*, A. J. von Oettingen, ed., which are Ostwalds Klassiker der exakten Wissenschaften, nos. 114 and 118 (Leipzig, 1900); *L'opera di Alessandro Volta*, F. Massardi, ed. (Milan, 1927); and the excellent *Opere scelte*, M. Gliozzi, ed. (Turin, 1967).

Volta's correspondence is available in a national edition, *Epistolario*, 5 vols. (Bologna, 1949–1955), which, with the *Opere* and *Aggiunte alle opere e all'epistolario* (Bologna, 1966), supersedes all earlier editions. For the location of Volta's MSS, see *Opere*, I, x–xxi; Scolari, *Alessandro Volta*, pp. 171–462; and the unsigned "La nuova sede del Cartellario voltiano e la annessa biblioteca," in *Rendiconti dell'Istituto lombardo di scienze e lettere*, **60** (1927), 567–579. For Volta's instruments, most of which perished in a fire in 1899, see Società Storica Comense, *Raccolta voltiana* (Como, 1899) and *Il tempio voltiano in Como* (Como, 1939, 1973). Volta's library of printed books, unfortunately unannotated, is now at the Burndy Library, Norwalk, Connecticut.

II. IMPORTANT INDIVIDUAL WORKS. For electrostatics, see *De vi attractiva ignis electrici* (Como, 1769), in *Opere*, III, 21–52; Italian trans. in *Opere scelte*, M. Gliozzi, ed., 49–90; *Novus ac simplicissimus electricorum tentaminum apparatus* (Como, 1771), in *Opere*, III, 53–76; "Lettera . . . al dott. Giuseppe Priestley [sull'elettroforo perpetuo]," in *Scelta d'opuscoli interessanti*, **9** (1775), 91–107; **10** (1775), 87–113, in *Opere*, III, 93–108; "Lettera . . . a Giuseppe Klinkosch . . . sulla teoria dell'elettricità vindice e sull'elettroforo perpetuo," *ibid.*, **20** (1776), 32–67, in *Opere*, III, 131–151; "[Lettera al Saussure] Osservazioni sulla capacità de' conduttori elettrici," in *Opuscoli scelti sulle scienze e sulle arti* . . .. **1** (1778), 273–280, in *Opere*, III, 201–229; "Del modo di render sensibilissima la più debole elettricità," in *Philosophical Transactions of the Royal Society*, **72** (1782), 237–280 (English trans. in Appendix, vii–xxxiii), also in *Opere*, III, 271–300; and "Mémoire sur les grands avantages d'une espèce d'isolement très imparfait," in *Journal de physique*, **22** (1783), 325–350; **23** (1783), 3–16, 81–99, and in *Opere*, III, 313–377.

Volta's works on meteorology include "[Lettere a G. C. Lichtenberg] Sulla meteorologia elettrica," in *Biblioteca fisica d'Europa*, **1** (1788), 73–137; **2** (1788), 103–142; **3** (1788), 79–122; **5** (1788), 79–134; **6** (1788), 137–147; **7** (1789), 81–111; **9** (1789), 129–148; **10** (1789), 39–69; **11** (1789), 33–53; **14** (1790), 61–112; in *Opere*, V, 29–228, 239–307; "Sopra la grandine," in *Istituto nazionale italiano, Memorie*, Cl. fis. mat., **1**, pt. 2 (1806), 125–190, also in *Opere*, V, 421–462, and in *Journal de physique*, **69** (1809), 333–360.

On pneumatics, see *Lettere [al p. Campi] sull'aria infiammabile nativa delle paludi* (Milan, 1777), in *Opere*, VI, 17–102; "Lettere . . . al marchese Castelli sulla costruzione di un moschetto e di una pistola ad aria infiammabile," in *Scelta d'opuscoli interessanti*, **30** (1777), 86–109; **31** (1777), 3–24; and in *Opere*, VI, 123–150; "[Lettres à Priestley] Sur l'inflammation de l'air inflammable," in *Journal de physique*, **12** (1778), 365–373; **13** (1779), 278–303, and in *Opere*, VI, 173–215; "[Contributions to the Italian edition of P. G. Macquer, *Dizionario di chimica* (Pavia, 1783–1784)]," in *Opere*, VI, 349–436; VII, 3–105; "Descrizione dell'eudiometro al aria infiammabile," in *Annali di chimica e storia naturale*, **1** (1790), 171–213; **2** (1791), 161–186; **3** (1791), 36–45; and in *Opere*, VII, 173–213; and "Della uniforme dilazione dell'aria per ogni grado di calore," *ibid.*, **4** (1793), 227–294, in *Opere*, VII, 345–375.

Volta's works on animal electricity and galvanism include "[Memorie] sull'elettricità animale," in *Giornale fisico-medico*, **2** (1792), 146–187, 241–270; **3** (1792), 35–73; **4** (1793), 63–81; in *Opere*, I, 13–35, 41–74, 149–159; "Account of Some Discoveries Made by Mr. Galvani of Bologna . . . in Two Letters . . . to Mr. Ti-

berius Cavallo [in French]," in *Philosophical Transactions of the Royal Society*, **83**, pt. 1 (1793), 10–44, also in *Opere*, I, 171–197; "Nuove osservazioni sull'elettricità animale," in *Giornale fisico-medico*, **5** (1792), 192–196, and also in *Opere*, I, 143–147; "Nuova memoria sull'elettricità animale . . . in alcune lettere al sig. ab. Anton Maria Vassalli," in *Annali di chimica e storia naturale*, **5** (1794), 132–144; **6** (1794), 142–166; **11** (1796), 84–128, also in *Opere*, I, 261–281, 287–301; "[Lettere al prof. Gren] Sul galvanismo ossia sull'elettricità eccitata del contatto de' conduttori dissimili," *ibid.*, **13** (1797), 226–274; **14** (1797), 3–74, in *Opere*, I, 393–447; excerpted in German in *Neues Journal der Physik*, **3** (1797), 479–481; **4** (1797), 107–135; and in French in *Annales de chimie*, **23** (1797), 276–315; **29** (1798), 91–93; "[Lettere al cittadino Aldino] Intorno alla pretesa elettricità animale," in *Annali di chimica e storia naturale*, **16** (1798), 3–88, in *Opere*, I, 519–555; "On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds [in French]," in *Philosophical Transactions of the Royal Society*, **90**, pt. 2 (1800), 403–431, in *Opere*, I, 563–582, and *Journal de physique*, 51 (1800), 344–354; English trans. in *Philosophical Magazine*, **7** (1800), 288–311; "Sur les phénomènes galvaniques," in *Journal de physique*, **53** (1801), 309–316, and in *Opere*, II, 35–43; "Memoria sull' identità del fluido elettrico col fluido galvanico," in *Ann. chim. stor. natur.*, **19** (1802), 38–88; **21** (1802), 163–211; in *Opere*, II, 45–84 (in part in *Annales de chemie*, **40** [1802], 225–256); *L'identità del fluido elettrico col cosi detto fluido galvanico* [1805] (Pavia, 1814), in *Opere*, II, 205–307.

III. BIOGRAPHY. The best general assessment of Volta is C. Volpati, *Alessandro Volta nella storia e nell'intimità* (Milan, 1927). Giovanni Cau, *Alessandro Volta: L'uomo, la scienza, il suo tempo* (Milan, 1927), is also useful. Older influential notices are J. B. Biot, in *Biographie universelle*, XLIV, 2nd ed., 78–81; F. Arago, *Oeuvres*, J. A. Barral, ed., 2nd ed., I (Paris, 1865), 187–240; M. Monti, *Biografia degli italiani illustri*, F. de Tipalso, ed., IX (Venice, 1844), 258–288; and C. Cantù, *Italiani illustri*, 3rd ed., III (Milan, 1879), 567–602.

On Volta's family and early years, see G. Gemelli, "Geneologia ed arma gentilizia della famiglia Volta," *Raccolta voltiana*, no. 6 (Como, 1899); and Z. Volta, *Alessandro Volta. Parte prima . . . Della giovinezza* (Milan, 1875), and the review *Voltiana* (1926–1927). For Volta's travels, see A. Verrechia, "Lichtenberg und Volta," in *Sudhoffs Archiv für Geschichte der Medizin und der Naturwissenschaften*, **51** (1967), 349–360; C. Volpati, "Amici e ammiratori di Alessandro Volta in Germania," in *Nuova rivista storica*, **11** (1927), 535–570; G. Bilancioni, "Alessandro Volta e Antonio Scarpa," in *Archeion*, **8** (1927), 351–363; M. Cermenati, *Alessandro Volta alpinista* (Turin, 1899); and Z. Volta, *Alessandro Volta a Parigi* (Milan, 1879). For politics, see G. Gallavresi, "Alessandro Volta e l'epopea napoleonica," in *Nuova antologia*, **334** (1927) 201–208; and Z. Volta, "Alessandro Volta e l'università di Pavia dal 1778 al 1799," in *Archivio storico lombardo*, 24 (1899), 393–447. For Volta's honors, see S. Ambrosoli, "Le medaglie di Alessandro Volta," in *Raccolta voltiana*, no. 7 (Como, 1899); and F. Frigerio, "Saggio di iconografia voltiana," in *Como ad Alessandro Volta* (Como, [1945]), 143–156. There is additional bibliography in Scolari, *Alessandro Volta*, 30–44.

IV. WORK. By far the best general account of Volta's work is G. Polvani, *Alessandro Volta* (Pisa, 1942). On electricity, see also M. Gliozzi, *L'elettrologia fino al Volta*, 2 vols. (Naples, 1937), and "Consonanze e dissonanze tra l'elettrostatica di Cavendish e quella di Volta," in *Physis*, **11** (1969), 231–248; F. Massardi, "Sull'importanza dei concetti fondamentali . . . [in Volta's] *De vi attractiva*," in *Rendiconti dell'Istituto lombardo di scienze e lettere*, **59** (1926), 373–381, and "Concordanza di risultati e formule emergenti da manoscritti inediti del Volta con quelli ricavati della fisicomatematica," *ibid.*, **56** (1923), 293–308; and W. C. Walker, "The Detection and Estimation of Electric Charges in the Eighteenth Century," in *Annals of Science*, **1** (1936), 66–99.

On meteorology, see L. Volta, "Alessandro Volta e la meteorologia, specialmente elettrica," in *Rendiconti dell'Istituto lombardo di scienze e lettere*, **60** (1927), 471–482; and C. Volpati, "L'ultimo episodio della vita scientifica di Alessandro Volta (La questione della difesa contra la grandine)," in *Como ad Alessandro Volta* (Como, 1945), 113–142.

On pneumatics, see R. Watermann, "Eudiometrie," in *Technikgeschichte*, **35** (1968), 293–319; V. Broglia, "Alessandro Volta und die Chemie," in *Chemikerzeitung*, **90** (1966), 628–640; W. A. Osman, "Alessandro Volta and the Inflammable Air Eudiometer," in *Annals of Science*, **14** (1958), 215–242; C. Pirotti, "La pistola di Volta e il motore a scoppio," in *Nuovo cimento*, ***4:10*** (1927), cxxviii–cxxxv; and F. Grassi, "I lavori del Volta e del Gay-Lussac per l'azione del calore," in *Rendiconti dell' Istituto lombardo di scienze e lettere*, **60** (1927), 505–534, and "I lavori del Volta e del Dalton su le tensione dei vapori," *ibid.*, 535–566.

On animal electricity and galvanism, see P. Sue, *Histoire du galvanisme*, 2 vols. (Paris, 1802); G. Carradori, *Istoria del galvanismo in Italia* (Florence, 1817); A. Mauro, "The Role of the Voltaic Pile in the Galvani-Volta Controversy," in *Journal of the History of Medicine*, **24** (1969), 140–150; and T. M. Brown, "The Electrical Current in Early 19th Century French Physics," in *Historical Studies in the Physical Sciences*, **1** (1969), 61–103.

J. L. HEILBRON

VOLTAIRE, FRANÇOIS MARIE AROUET DE (*b.* Paris, France, 21 November 1694; *d.* Paris, 30 May 1778), *literature*.