Animal electricity at the end of the 18th century: the many facets of a great scientific controversy

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INTRODUCTION

The "De viribus electricitatis in motu musculari" ("Commentary on the forces of electricity in muscular motion"), the Memoir where Galvani first described his electrophysiological experiments and presented his theory of animal electricity, appeared at the beginning of 1792 in the seventh volume of the official journal of the Institute of Sciences of Bologna (one of the most important scientific institutions of the time), of which Galvani was an important member (see Dibner, 1971; Heilbron, 1991; Bresadola, 1998). According to Galvani, an intrinsic form of electricity exists between the interior and the exterior of a single muscle fibre in a condition of disequilibrium and a nerve fibre would penetrate inside the muscle fibre allowing in physiological (or experimental) conditions for an electric flow leading eventually to muscle contraction. This conclusion was mainly based on the results of experiments in which contractions were obtained in a frog preparation by connecting, through a metallic conductor, the nerve and muscle of the leg.

Very soon the news of Galvani's research reached various centres in Italy and across the Alps through the numerous channels, which ensured intellectual exchanges in the 18th century: the circulation of printing, reviews in scientific and literary journals, the correspondence between scholars, the journeys on which artists, men and women of letters and science went more and more frequently in the Europe of the Enlightenment. Within two months from the publication of the "De Viribus", physicians and naturalists in Pavia, Padua, Modena, Milan started to repeat the main experiments described in the Memoir, using frogs and other animals. After eight months, at the end of the summer of 1792, animal electricity had become one of the scientific novelties actively discussed in places like Geneva, Paris, London, Edinburgh and in the German states.

Volta, at the time a forty-five-year-old professor of 'experimental physics' at the University of Pavia (he was born in Como in 1745), was one of the first scientists to read the "De Viribus" and to repeat, in March 1792, some of Galvani's experiments, in collaboration with the physician Bassiano Carminati, professor in the same University (see Fig. 1). Volta was then an authority in the field of electricity, thanks to the invention of new instruments like the 'electrophorus' (an atypical generator of electricity) and the 'condensatore' (an instrument useful to detect very small quantities of electricity). He was also a fellow of the Royal Society of London, as well as an important official of the Austrian administration in Lombardy (see Pancaldi, 2003). Volta became interested in Galvani's text because of its topic and its content. Besides presenting new experiments on electricity, the "De Viribus" provided a new tool for the study the so-called 'weak electricity' – i.e., electricity difficult to detect, because of its low intensity, in the atmosphere of a calm day or in phenomena like water evaporation – an issue on which Volta and other electricians had focused their attention in the previous years (see Heilbron, 1999). According to Volta, the contractions of the frog's legs which Galvani had obtained by connecting nerves and muscles through a metal conductor made the animal a particularly sensitive detector of electricity. The frog could thus be considered an "*animal electrometer*, by far more sensitive than any other highly sensitive electrometer" (Volta, 1918, p. 28).

This feature of the animal preparation had been underlined by Galvani himself, who believed, however, that the frog was far more than a sensitive electrical detector. From the experiments he had been doing for over ten years of tireless activity, Galvani came to the conclusion that the muscles were like ‘machines’ resembling small Leyden jars (the first electrical capacitors, made up of a glass container usually coated both internally and externally by metal sheets indicated as “armatures”). The Leyden jar could be discharged by connecting the two surfaces through the metal hook coming out of its mouth, thus producing shocks, sparks and other electrical effects. In an analogous way, according to Galvani, the discharge of the ‘animal Leyden jar’ obtained by connecting the two muscular surfaces through the nerve produced the contractions of the muscle (see Fig. 2). Although Galvani did not specify how the flow of electricity produced muscle contraction, he clearly stated that the contraction depended on this intrinsic ‘animal electricity’, which, in his view, did not differ in its essential features from ‘artificial electricity’, i.e. the electricity produced by the instruments available at the time, and from ‘natural electricity’, i.e. the electricity involved in lightning and in other kinds of natural phenomena (Galvani, 1791/1953).

In the “De viribus” animal electricity was presented as a novelty both for medicine and science. Galvani’s discovery was indeed considered an important achievement by many of his contemporaries, including Volta. In his “Memoria prima sull’elettricità animale” (“First Memoir on animal electricity”), dated 5th May 1792 and appeared in the “Giornale fisico-medico”, an important scientific journal published in Pavia by the physician and chemist Luigi Valentino Brugnatelli, Volta gave his first account of Galvani’s work. According to him “the dissertation published a few months ago by Dr. Galvani of the Institute of Bologna, and Professor in that University, renown for other anatomical and physiological discoveries, on the action of electricity on muscular motion, contains one of those great and luminous discoveries which deserve to be a landmark in the annals of physical and medical sciences” (Volta, 1918, p. 15). For Volta, who showed a remarkable knowledge of the physiological studies made in the 18th century, the innovative character of Galvani's research came out of the comparison with previous experiences and theories. Among these were the phenomena observed by manipulating various substances—cats' hair, parrots' feathers, people's hair and clothes, rats and even human urine— in which appeared some features typical of electricity, such as the attraction of light bodies and the shock felt by the experimenter. According to Volta, however, those experiences did not prove the existence of an electricity typical of living organisms, because in most cases the electricity involved was of the common physical type, and the involvement of a living body was not essential to its production. As for the previous physiological theories of muscle contraction involving a fluid analogous or identical to electricity, produced by the brain and flowing through the nerves, they were, according to Volta, "vague and uncertain" hypotheses, hardly supported by the experiments. The only true animal electricity discovered up to then was that of some fish like the torpedo and some kinds of ray or eel, which were able to produce an electric shock thanks to the structure of some organs in their body. For Volta, Galvani had the merit to extend this discovery from a few singular fish to the whole animal reign and for this reason the Bologna physician could be compared to nothing less than Benjamin Franklin, who had laid the foundations of the science of electricity and had proved the electric nature of lightning:

> Thus then also our Galvani, having verified with unequivocal experiments animal electricity, assumed by some but proved by none (except for the torpedo, the electric eel, etc), has for this the merit of an original discovery, not differently from the American philosopher [i.e. Franklin] with regard to electricity in clouds (Volta, 1918, p. 24).

After summarizing Galvani's experiments and underlining their innovative character, in his Memoir Volta reported some considerations deriving from the experimental activity he had carried out in the previous weeks. Such considerations reveal some differences between the two scientists' interpretation of the phenomena of muscular motion. First, Volta maintained that, in contrast to Galvani's claim that the electricity internal to muscle fibre was positive and the external one negative, just the opposite occurred. Secondly, the physicist from Como suggested an explanation of voluntary motions which partially differed from the one expounded in the "De Viribus". Galvani had supposed that the contraction depended on a peripheral mechanism, placed in the muscle and contrived in such a way as to make electricity flow from the internal to the external surface of the muscle through the nerve, whenever "the mind, with its extraordinary power" transmitted a given impulse to the brain or to the nerve. Volta, on the other hand, believed that electricity was constantly circulating through the organism and produced contractions only when, for various reasons, there occurred "a disturbance and disconcertment in the harmonious circulation, rolling or motion - whatever it may be - of the electric fluid within the organs of the animal" (Galvani, 1791/1953, p. 82; Volta, 1918, p. 33).

In his "Memoria prima" Volta still referred to an electrical imbalance present in the animal as due to its "organization" and to "life forces", and therefore to an intrinsic electricity. His attitude was, however, to change in the course of a few weeks, when "after examining the question more carefully, varying the experiments and trying new ones, finally I had to realize that the role played by the electric fluid in animal organs is far more limited than Galvani believed, and I with him" (Volta 1918, p. 58). This is how the long controversy between the two scientists began: it would last until Galvani's death in 1798 and would leave a fundamental mark on the culture of the end of the 18th century and on all science in the years to come. It was a pressing debate, not devoid of strongly polemic tones, rhetorical arguments and personal criticisms. Its characteristic feature was the ability of both protagonists to take into account the objections raised by their opponent, and to incorporate them in their experimental and theoretical activity. For these reasons it came to be a genuine and important scientific controversy, which influenced Galvani and Volta's research and played a decisive role in fostering extraordinary innovations such as Galvani's experiment on the contact between nerve and nerve (a capital experiment in the history of physiology) and Volta's invention of the battery (see Piccolino-Bresadola, 2003, chapts. 7-8; Pancaldi, 2003, pp. 178-210).

THE MAIN STEPS OF THE CONTROVERSY

One of the most significant grounds on which the controversy between Galvani and Volta developed was the experimental one. Besides repeating the experiments described in the "De Viribus", from the very beginning Volta started to vary the experimental arrangements in new and original ways, using mostly live and whole animals (instead of dead animals prepared by carefully isolating their muscles and nerves, as Galvani suggested) and applying the electric stimulus with different modalities from those proposed by the Bologna physician. In these new conditions Volta found that contractions occurred in a constant and effective way only by applying different metals to the parts of the animal, either as "coatings" or "armatures" (under the form of small metal sheets) to the nerve and to the muscle, or by using a connecting "arc" made by two different metals in order to transfer electricity from one part to the other of the animal. This and other observations, already made partly also by Galvani, led Volta to the conclusion that metals were not simple electrical conductors, as the Bologna scientist believed (and as the laws of electricity of the time indicated), but they were proper 'motors' of electricity. Thus, Volta concluded, contractions were produced by an extrinsic electricity set in motion by the metals, and they did not result from the flow of an intrinsic electricity according to the neuro-muscular mechanism envisioned by Galvani. In his "Memoria terza sull'elettricità animale" ("Third Memoir on animal electricity"), written in the form of a letter addressed to Giovanni Aldini, Galvani's nephew and an active supporter of his uncle in the controversy, and dated 24 November 1792, Volta proposed his theory of the electromotive power of metals and launched an all-round attack on animal electricity:

> In all these experiments it is quite clear that only the nerves are affected, or actually that just a few points of the same nerves are affected in the very short course done by the electric fluid from the place where the nerve is in contact with tin to the very close one in contact with silver; and that this electric current - whatever it may be - is caused by the metals themselves, because they are different one from the other: in other words they are in a proper sense excitors and motors, while the animal organ, and nerves themselves, are nothing but passive.
>
> [....]
>
> If things are like that, as the observations reported in my above-mentioned Memoir, and many others concur to prove, Galvani's theory and explanations, which you [i.e. Aldini] are striving to support, are very difficult to sustain and the whole building threatens to ruin (Volta, 1918, pp. 152-53).

In Volta's view, physics was thus acquiring a novel principle, well beyond the traditional classification of substances into insulators and conductors, and leading to a new vista on electrical phenomena. The notion of discharge, central to the study of electricity in the previous decades, was integrated by that of "transflux", "torrent" or "current" put into action by the contact of different metals (to mention some of the terms used by Volta).

From the point of view of the history of physics, Volta's theory of metallic electricity is an important step towards the birth of electrodynamics. As to the controversy on animal electricity, it was extremely important as it led Galvani to a further development of his theoretical views, elaborated in the treatise "Dell'uso e dell'attività dell'arco conduttore nelle contrazioni dei muscoli" ("On the use and activity of conducting arc in muscular contractions”), published anonymously in Bologna in April 1794. In this work the Bologna scholar kept the model of the muscle as an animal Leyden jar but reassessed it in light of the experimental novelties emerged in the previous two years, mainly thanks to Volta’s research. In particular, the notion of discharge between the muscle and the nerve was replaced by that of an electric current, constantly circulating among the animal parts and producing contractions whenever the circuit or ‘arc’ between the muscle and the nerve was established or interrupted (or modified in some way). By developing this new version of the theory of animal electricity, Galvani was able to account for a larger number of observations, and in particular for the greater effectiveness of different metals in producing contractions, a crucial issue in the controversy with Volta. Moreover, against the role of metals in the phenomenon of contractions Galvani launched a powerful attack based on a new experiment (the so-called Galvani’s ‘third experiment’), in which he could excite contractions in a frog’s leg by directly connecting the muscle and its corresponding nerve, without the interposition of any metal whatsoever. Taking Volta’s triumphant statement in his “Memoria Terza” quite literally and reversing it in his own favour, Galvani could then declare:

> But if things are like that, if such electricity is completely peculiar to the animal and not common and extrinsic, what will happen to Volta’s opinion, who with his experiments pretended to rule out animal electricity in toto, and to limit Galvani’s discoveries to the sole invention of the most exquisite animal electrometer? (Galvani, 1794a, p. 123)

Galvani’s strategy in his treatise “Dell’arco conduttore” (and, we shall see, in a “Supplemento” that he also published anonymously in the autumn of the same year) was thus based on both experimental and theoretical grounds. As a matter of fact, the controversy on animal electricity not only drove the two opponents to create new experiments in order to face the problems emerged in the course of the debate, but it acted as a powerful stimulus for the theoretical approach and the research program of both scientists. Volta was soon aware of the relevance of the experiments and arguments described in Galvani's treatise, and of the danger they might represent for his own interpretation of the phenomena at stake. Indeed, in various scientific circles Galvani's work had apparently convinced many scholars to take sides with the theory of animal electricity. As Volta himself wrote in 1795, the experiments published by Galvani and by some of his followers in the previous year "convinced many, and drew them again under Galvani's standards after they had already endorsed, or were about to endorse, my quite different views" (Volta, 1918, p. 289).

Both Volta and Galvani were highly sensitive to the opinions of colleagues and members of the 'Republic of letters', and strove for their approval, especially in the case of the most authoritative among them. This social aspect of scientific research, though always present, is particularly evident during controversies and debates, when scientists are more exposed to criticisms and attacks to their ideas and results. Under these conditions, the need for consensus and support is necessary not only in order to affirm and support one's contribution, but also as an important stimulus to carry on further his/her investigative activity.

Volta reacted to the publication of Galvani's "Dell'arco conduttore" by modifying both his interpretation of phenomena and the direction of his research. On one hand, he enlarged the extent of his theory of 'metallic electricity' to include the new experimental arrangements developed by Galvani. According to the new version of Volta's theory, an electromotive effect is produced not only by the contact of two different metals, but also by connecting two different non-metallic conductors and in particular humid bodies (indicated as second-class conductors, in Volta's terminology). This was the case of the nerve and muscle tissues connected directly to produce contractions in Galvani's 'third experiment'. On the other hand, it became decisive for Volta to eliminate the animal from the experimental setting, in a symmetrical way to what Galvani had done by producing contractions in the absence of metals. Volta realized that, as long as he was obliged to use the animal as an electrical detector, his contention on the physical origin of the electricity responsible for muscle contraction was precarious.

The adoption of his new theory of 'contact electricity' induced Volta to widen the scope of his research and to investigate all the possible combinations of different conductors capable of producing an electric current. The decision to exclude the animal preparation from his experiments led him to concentrate his attention on measuring instruments that could reveal the weak electricity involved in the experiments. These two moves, dictated by the need to respond to Galvani's experiments and arguments, represented a major turning point in Volta's research activity and played a fundamental role in the path which led him to the invention of the battery, as he himself would later acknowledge.

The first successful outcomes of the new experimental course were made public by Volta in 1797. The measurement of the electricity produced by metallic contacts obtained by means of physical instruments, without recurring to the animal, was greeted by many of his contemporaries as a great victory on his part and as a strong argument against the existence of animal electricity. Moreover, the contact theory seemed to be capable of accounting for all the experiments carried out to date in a simpler and more comprehensive way than Galvani's conception could do.

In an unpublished letter dating as early as December 1795, after presenting his addressee the new version of his theory of contact electricity, Volta wrote that "in order to maintain the pretended animal electricity, which I declare does not exist, and through many experiments I believe I have completely demolished, replacing it with my other principle of solely artificial electricity, that is to say produced by an extrinsic cause, my adversaries should show me the contractions in frogs, etc., being excited by using conductors all of the same kind, in no way dissimilar one from the other, which they will never be able to do" (Volta, 1918, p. 395). To face Volta's challenge seemed even more difficult after his purely physical measurement of contact electricity. Nevertheless, in a crescendo of creative experimental designs Galvani came soon to be in the position to counteract his adversary's challenge, and to obtain what Volta had believed impossible to be attained. In fact, in 1797, the Bologna scientist published an experiment in which the contractions of the frog's legs were brought about by forming an arc made up exclusively of nervous matter (and thus homogeneous), i.e. by establishing a circuit made exactly by "conductors all of the same kind, in no way dissimilar one from the other" (as Volta had requested in his provocative - but somewhat apparently unconsidered - statement). Galvani was thus able to retort to his opponent with these words:

> Now then, which heterogeneity can be summoned to explain the occurring contractions, as only the nerves come into contact with each other?
>
> […]
>
> Therefore it seems to me that it is possible to state that there is a series of contractions, which are obtained without a stimulus, without a metal, and without the least suspicion of heterogeneity; [contractions] produced indeed by a circuit of electricity intrinsic to the animal, and naturally unbalanced in it (Galvani, 1797, p. 17).

Galvani's experiment of the contractions by the contact between nerve and nerve is described in his five "Memorie sulla elettricità animale" ("Memoirs on animal electricity"), published in Bologna in September 1797 and addressed to Lazzaro Spallanzani, one of the most famous naturalists of the time. The work, which was considered by Spallanzani "one of the finest and most remarkable works that the physics of the 18th century can boast", was Galvani's last contribution to the controversy on animal electricity.

For the importance of the experiments and the arguments included, as well as for the clarity in the exposition of his interpretation of the phenomena of muscular motion, the "Memorie" also represented a sort of scientific testament of Galvani. Moreover, the last Memoir was entirely devoted to one of the most significant issues of the naturalistic investigation of the end of the 18th century, largely present to Galvani's reflection but until then never confronted by him through experimental work. It dealt with the research carried out by Galvani two years before on the torpedo, that is one of those fish which was almost unanimously recognized as possessing an intrinsic electricity, i.e. an electricity properly animal. Galvani had decided to carry out experiments on the torpedo not only because he wished "to be able to examine and deal with this same animal electricity in one of those animals in which its presence and circuit are beyond doubt", but also to meet an objection which Volta had raised from the very beginning. In fact, according to Volta, animal electricity, being a property related to life, should be proved in living animals, and not in the frogs killed and beheaded which the Bologna physician usually used (Galvani, 1797, p. 64; see Piccolino, 2003).

Among the experiments Galvani carried out on live torpedoes caught in the Adriatic Sea near Rimini, the most significant regarded the mechanism of the shock produced by the fish and the comparison between the electricity of the torpedo and that responsible for muscular contraction in more ordinary animals. As for the first point, Galvani found out that no shock occurred if there was an interruption in the nerves connecting the brain to the organs of the fish where electricity was known to accumulate (or "electric organs" as they were named twenty years before by John Walsh, the English naturalist who first proved the electrical nature of the fish shock). It was possible on the other hand to produce the shock for some time after taking out the heart from the animal. Moreover, it was possible to stimulate the contractions of the muscles of the torpedo using the same experimental arrangements adopted for the frog. In Galvani's view these experiments confirmed his idea of the brain as the seat of animal electricity, of the nerves as conductors through which animal electricity flowed, and of muscular motion as a function depending on a fluid of an electrical nature. They proved, moreover, that the torpedo's shock occurred independently of the presence of the heart, the organ par excellence to which life was linked, thus suggesting that animal electricity could persist for some time after the death of the animal. For these reasons, in Galvani's view, these experiments allowed him to rebut Volta's criticism to the use of dead animals in his experiments – an issue we shall deal with later on.

As had been the case with the "Trattato dell'arco conduttore", Volta was much impressed with Galvani's "Memorie". However, in this occasion he did not feel the need to change his interpretation of phenomena nor did he attribute much importance to the experiment of the direct nerve-to-nerve contact. Being confident in his theory of contact electricity (and in the possibility of carrying out his experiments without making recourse to a biological detector of electricity), he continued his intense research activity aimed at studying the electromotive power of various substances. What did particularly impress Volta were Galvani's observations on the torpedo presented in his fifth Memoir; this caused Volta to further elaborate his ideas on the physiology of the brain and of nerves, and especially to devote his attention to the studies on electric fish. In 1797, in an English scientific journal there appeared an article by William Nicholson, a famous English naturalist and electrician, entitled "Observations on the electrophorus, tending to explain the means by which the torpedo and other fish communicate the electric shock". Volta read the article towards the end of 1799 and this proved a fundamental turn in his investigative pathway, which ended in a few months with the invention of the battery (see Pancaldi, 2003, pp. 196-207).

A COMMON GROUND

The reconstruction of the main steps of the controversy between Galvani and Volta in the 1790s shows the great influence that the two scientists had on each other's experimental activity, theories and research programs. Contrary to the opinion of those historians who consider the controversy as a clash between two irreconcilable views of phenomena – Galvani's electrobiological viewpoint against Volta's electrophysical viewpoint (see e.g. Pera, 1992) – the two scientists could engage in a genuine scientific controversy just because they shared the same basic conception of the investigation of natural phenomena, emerged between the 16th and 18th century, with the rise of modern science in Europe. Three were the main fundaments of the new "experimental philosophy" to which both Galvani and Volta fully adhered: experiments are the key to disclose nature's secrets, the sharing of results and their public control are the basis on which the scientific quality of a thesis could be assessed, and the improvement of the human condition is the aim of natural philosophy. Even if Galvani and Volta had a different background and were involved in different professional activities, they were in total agreement with all these aspects of the science of their time. Without this common ground the two scientists would have probably ignored each other and, likely, no controversy would emerge.

It is not by accident that Galvani started his "De viribus" with an explicit statement of his belief in the experimental method and in the cooperative character and the utilitarian aim of scientific research:

> Since I wish to bring to a degree of usefulness those facts which came to be revealed about nerves and muscles through many experiments involving considerable endeavor, whereby their hidden properties may possibly be revealed and we may be able to treat their ailments with more safety, there seem no better way for fulfilling this desire than by publishing these discoveries at length (such as they are). For after reading of our experiments, learned and distinguished scholars will not only be able to develop them through their own studies and investigations, but even to carry out other experiments which we may have attempted but perhaps could not bring to conclusion (Galvani, 1791/1953, p. 45).

In his “Memoria prima sull’elettricità animale” Volta countered the “conjectures and merely ideal hypotheses” and the “ill-conceived or at least equivocal observations”, which had characterized the previous works on animal electricity, with the “many well-conducted and accurately described experiments by Galvani”, who should be considered, for this very reason, the sole and true discoverer of the existence of an electric force in the living organism.

As a matter of fact, Galvani and Volta showed always great respect for each other even when their interpretations of phenomena began to differ in the course of the debate on animal electricity. In the letter to Volta accompanying the second edition of the “De Viribus”, Aldini paid the physicist from Como “the best regards” of his uncle, who “greatly admired his [Volta’s] industry and the felicity of his experiences” (Volta, 1949-55, III, pp. 181-82). On his side, Galvani referred to Volta as a “most learned physicist and experimenter”, “one of the most celebrated physicists and experimenters of our century”. In 1797, when the differences between their theories appeared irreconcilable, Galvani pointed out Volta’s “learning and lively intelligence”, referred to his “many wonderful, and fine experiments”, and stated:

Now then I do not wish to support my reasons by the sole argument of analogy; and as Mr. Volta uses experiments to prove the truth of his theory and the falsity of mine, thus it is right for me to follow a similar path (Galvani, 1797, p. 5).

This experimental ‘path’, on the other hand, was not devoid of obstacles and difficulties: in order to be worthy of other scientists’ consideration one should describe his experiments in a careful way so that they could be replicated, at least in principle, by anyone wanting to control their outcomes. This need for a public control, which has become a basic feature of modern science, implied very detailed descriptions of the instruments, the experimental arrangements and the procedures being used. Such descriptions were often supported by illustrations which had the aim of making the experimental situation clearer and of facilitating the replication of the experiments (see fig. 3). But even if the 18th century experimenters took great care in making the reproduction of their experiments possible, criticisms and attacks based on the impossibility of obtaining the same results were frequent. This was due to several reasons: scientific research was not yet organized in a wide network of institutions endowed with well-equipped laboratories and professional staff, where the work of scientists could be checked and developed in an effective way and in a relatively short time. Moreover, there were no standard units of measurement, and there was a lack of instruments with the same building and working characteristics, as well as methods for an objective permanent recording of experimental data. All these elements, together with the predominance of prevalently qualitative type of research in many fields, often prevented other scientists (and sometimes the experiments’ author himself) from obtaining analogous results starting from the same experimental arrangement and from conditions and circumstances which could be considered similar.

Both Galvani and Volta were well aware of the decisive importance of experimental replicability. In his “De viribus” the Bologna physician endeavoured to provide all necessary directions to “those who intend to take up this kind of research”. On the basis of his own laboratory activity, he was aware, however, of the “utmost irregularity and inconstancy and anomaly” of the experimental results, especially in a field dealing with living organisms, as it was the case of the investigation of animal electricity. Also in his “Supplemento al Trattato dell’arco conduttore” Galvani amply discussed the cares and precautions to be taken in the experiments, as “unfortunately it is some very small circumstances which sometimes deceive and lead into error even the most learned seekers of truth”. To use Volta’s words “it is not enough to read or hear the descriptions from others, it is necessary to see the experiments, to carry them out, to repeat them again and again, changing shape and method, as I myself have done, in order to achieve a complete persuasion” (Volta, 1918, p. 294). Thus, Galvani and Volta (and other great experimenters of the 18th century) added a new virtue – perseverance – to the two values which had characterized the scholar of nature from the 17th century, i.e. curiosity and search for usefulness. Indeed, it was perseverance which also distinguished the true scholar from the simple amateur of science. Obviously the need to repeat and vary the experiments in order to include all circumstances and factors responsible for a given phenomenon called for researchers with much time at their disposal. Such need was possibly one of the elements which concurred to the shaping of the professional scientist, which was to dominate the scientific scene in the next centuries.

In various occasions during the controversy both Galvani and Volta criticized their opponent for presenting dubious experiments and inconstant results. This, however, never prevented them from taking the other’s observations very seriously, as we have seen in previous pages. The two scientists considered each other reliable and worthy of attention and this attitude was based both on the common belief in the value of experiment as the basic tool of scientific investigation, and on a similar notion of how nature works. According to this last notion, which had also emerged in the course of the scientific revolution, in spite of the great difference and variability of observable phenomena, nature had a simple structure and a uniform course. Its phenomena could thus be understood through a limited number of constant laws of a quantitative character. In his “Supplemento al Trattato dell’arco conduttore” Galvani resumed the idea of the simplicity and uniformity of nature in order to explain how the “cautious philosopher”—that is the one who based his work on the experimental method—should act:

> How many natural phenomena perhaps depend on known laws and causes, even if we ascribe them to altogether different laws and causes, only because we still ignore the way they are connected? I believe, in agreement with the common opinion of scholars, that when the cautious philosopher has discovered a long series of phenomena all depending on the same cause and then comes across one of the same kind which does not seem to adapt to the same cause, he should make all efforts to find such connection rather than create new laws and causes (Galvani, 1794b, p. 16).

This passage referred to Galvani’s criticism to Volta’s theory of metallic electricity. According to the Bologna physician, the theory implied the existence of a new property of metals and thus involved a new law for phenomena which, instead, could be well explained within the framework of widely accepted conceptions. Volta, too, accused Galvani of multiplying causes without need, thus breaking the rules of right ‘philosophizing’, when he invoked an animal electricity in the presence of phenomena that could be referred to common electricity. The fact that both antagonists used the same methodological arguments clearly indicates that they had fundamentally similar approaches to nature and to scientific investigation. In the great importance attributed to the simplicity and uniformity of the natural world and in the necessity not to multiply natural causes without need they were referring to the constitutive ‘regulae philosophandi’ of modern science, elaborated by Newton and added to the second and third editions of his “Philosophiae naturalis principia mathematica” (1713 and 1726).

The notion of nature conceived as simple and ruled by universal laws, fostered the interchange between different fields of study. In the 18^{th} century the disciplinary boundaries which characterize today’s science had just started to emerge and those involved in physical, chemical, meteorological or biological studies felt themselves as part of the same intellectual enterprise—natural philosophy—even when they came from very different cultural backgrounds and professional careers (see Rousseau-Porter, 1980; Clark-Golinski-Schaffer, 1999). In spite of their different professional status (Galvani a physician who taught anatomy and also obstetrics, Volta a professor of physics), the two antagonists were, in the first place, natural philosophers whose research activity spanned a wide range of phenomena. Galvani applied to the investigation of the living world approaches derived from the study of electricity and chemistry. On his hand, Volta, besides dealing with electricity, worked also in the field of meteorology and chemistry. Moreover, in the controversy with Galvani he was deeply concerned with physiological topics or ‘animal physics’ (as the investigation of animal functions was also called in the 18^{th} century, after the Aristotelian notion of *physis*), and he also expressed his interest for the possible medical implications of his research. In the course of his experiments on the phenomena of Galvanism, for example, Volta devoted much study to the effects of the electric stimulus on various sense organs, in particular on taste, sight and touch. He observed the specific physiological response of different senses to the same stimulus and discovered that sensations depended on the type of nerve being stimulated, and not on the stimulating agent. Moreover, the physicist from Como sometimes suggested the use of electricity to treat some pathologies like deafness, thus embracing the great interest of the time for 'medical electricity', a field of fruitful exchange between physics and medicine (see Piccolino-Bresadola, 2003, chapt. 9; Bertucci-Pancaldi, 2001).

The most tangible sign of the deep interest of Volta 'the physicist' for the living world is to be found in his repeated reflections on the role of electricity in animal functions, and in the importance of the physiology of electric fish in the path which led him to the invention of the battery. Between 1797 and 1799, the crucial years of this research path, the torpedo and other electric fish represented for Volta a fundamental reference in his attempt to multiply the electromotive effect of metals by assembling one above the other many couples of two different metals. In fact the electric organs of the torpedo and electric eel, made up of columns of humid disks or 'prisms' piled one on top of the other, became for Volta a mental image of great importance for the invention of his electric battery: through a multitude of trials carried out in those decisive years, it directed him to place between the metallic couples piled up in column, the famous 'bullettini', circular pieces of pasteboard impregnated with water or some other salty liquid (see fig. 4). In the letter dated 20 March 1800, and addressed to Joseph Banks, President of the Royal Society of London, where he announced the invention of the battery, Volta underlined the close connection--both physical and functional-- between his apparatus and the electric organ of the torpedo with the following words:

To what electricity then, or to what instrument ought the organ of the torpedo or electric eel, etc. to be compared? To that which I have constructed according to the new principle of electricity, discovered by me some years ago, and which my successive experiments, particularly those with which I am at present engaged, have so well confirmed, *viz*. that conductors are also, in certain cases, exciters of electricity in the case of the mutual contact of those of different kinds, etc. in that apparatus which I have named the *artificial electric organ*, and which being at bottom the same as the natural organ of the torpedo, resembles it also in its form, as I have advanced (Volta, 1800, pp. 430-31).

Mental images have a great value in science, both because they act as 'catalysts' in the mental processes at play in the crucial phases of a discovery, and because they allow a scientist to present in a metaphorical and symbolic form the processes leading to the discovery itself, processes which very often are too complex and elusive to be recorded in an analytical report devoid of ambiguities. In some ways the electric organ of the torpedo (and of other similar fish) played in Volta's research the same role which the Leyden jar did in Galvani's (see Piccolino, 2006). Ironically, a 'physicist' like Volta was at least partly guided in his discovery by an image drawn by the animal world, while a 'physiologist' like Galvani was inspired by one of the most representative objects of the physical science of the 18th century. The explanation of this apparent paradox lies in the unitary character of 18th century scientific enterprise, which makes it impossible to explain the controversy between Galvani and Volta by recurring to clear-cut disciplinary boundaries and, even less, to irreconcilable views of natural phenomena.

Besides representing a great scientific event for the results achieved by its protagonists, the Galvani-Volta controversy also helps to reveal some fundamental aspects of science and of the view of natural phenomena in the 18th century. Indeed it is in moments of particular ferment, as are controversies, that such aspects—normally given for granted and implicit in scientific research—come to light and can thus be perceived in all their extent and depth by contemporaries and posterity. However, for their own nature, controversies highlight also contrasts: different interests and interpretations, and different approaches to phenomena. This is what distinguishes a controversy from a collaborative activity or from a simple debate (see Dascal-Freudenthal, 1998; Machamer-Pera-Baltas, 2000). In the following pages, the main aspects which divided Galvani's and Volta's positions will be examined and the reasons why the two Italian scholars were unable to reach an agreement on the interpretation of experiments and on the phenomenon of muscular motion will be discussed.

SCIENTIFIC PROBLEMS AND EXPERIMENTAL PRACTICES

Among the aspects attesting the nature of genuine scientific controversy of the discussion between Galvani and Volta is the impossibility of each of the two antagonists to abandon his own interpretation and to adhere to his opponent's views, and, moreover, the failure to reach a compromise in spite of repeated efforts on both parts. A first proposal of agreement was put forward by Volta in 1795, after Galvani and other supporters of animal electricity had made public the experiments on the stimulation of contractions by means of homogeneous metals or in the absence of any metal whatsoever. These experiments, as we have seen, put Volta's theory of metallic electricity in a difficult position and urged Volta to imagine the existence of two different causes for the phenomena of Galvanism, i.e. metallic electricity when metals were present, and animal electricity when there were no metals. However, immediately after suggesting such a possible compromise, Volta himself discarded it in the name of his 'contact theory', suggesting the heterogeneity of substances apparently homogeneous like the mono-metallic arc used by Galvani and his followers in their experiments. A similar move was made by Galvani two years later, when he assumed that in the experiments with armatures or arcs made of different metals there could be an extrinsic electricity moved by the metals, as Volta maintained, while in those experiments without metals or with homogeneous arcs the cause of contractions was to be found in animal electricity. As the physicist from Como had done before him, however, Galvani soon rejected this possible compromise and refused the opponent's theory, in the name of the laws of scientific method, which ruled out any unnecessary multiplication of causes.

More than real attempts at reconciliation, the compromise proposals of the two scientists appear to us as rhetorical strategies devised to show their open-mindedness, and to highlight the limitations and pointlessness of the interpretation of phenomena advanced by their opponent. The polemic tones used by both Galvani and Volta in putting forward their agreement proposals, and in rejecting them immediately afterwards, clearly appear in a passage, where the physicist from Como admitted that, in the experiments of stimulation of voluntary movements in living animals, the contraction could be due to the electricity present in the nerves (although not in an unbalanced state as Galvani had argued):

> If the Galvanians are satisfied with limiting animal electricity to these terms, I shall be very happy to be in agreement with them; if they still refuse this means of reconciliation, which I am happy to offer them, if they pretend that electricity is excited by pure organic force, that is to say that the electric fluid gets prepared and works in the brain and in the nerves, accumulates in them or in the interior side of the muscles, gets unbalanced in some way, and due to this unbalance stimulates immediately, by its discharging, those same muscles; if, I am saying, they continue to claim the existence of such electricity produced, as they will, by a purely organic mechanism, even in severed limbs or muscles [...]; if, in short, they do not yield to such reconciliation proposal, perhaps I shall withdraw also this, that is to say I will no longer accept the other type of animal electricity depending and moved by will in the whole and intact living being (Volta, 1918, p. 561).

Many reasons could explain Galvani's and Volta's refusal to reach a compromise on the interpretation of the phenomena they were discovering in their laboratories. A first important reason is to be found in the nature of the scientific problem they were investigating and which has found a solution only in light of researches carried out in the following two centuries. Today we know that nervous conduction and muscular contraction are the expression of a complex organization of the cellular membrane. It is based on the presence of molecular structures (named ionic pumps) which are capable of separating ions, thus creating concentration gradients between the interior and the exterior of the cell by exploiting its metabolic energy. Moreover, it depends on the presence of other molecular structures – ionic channels – which transform the energy of ionic gradients into different electrical potential differences. Electricity is accumulated in the organism in an unbalanced state, but in normal conditions it cannot flow through excitable fibres, because it is blocked by the impermeability of cellular membranes to the passage of ions. Membranes change their characteristics and allow the ions to pass (thus producing nervous impulse) when a stimulus, itself of electrical nature, determines a variation in the electrical potential existing between the interior and exterior of the cell (see Piccolino-Bresadola, 2003, esp. chapts. 10-11).

In Galvani's and Volta's experiments with bimetallic conductors, it is the extrinsic electricity produced by the contact of different metals, invoked by Volta, that acts as a stimulus to change the characteristics of the cellular membrane; the resulting movement of electrical charges accumulated in an unbalanced state between the interior and the exterior of the fibre, as supposed by Galvani, produces the electric signal which eventually results in muscular contraction. In short, in the dilemma faced by Galvani and Volta about the cause of muscular contraction produced by metallic arcs, *tertium datur*. There was a third possibility which the two opponents did not consider – and could not do so, as this would have implied knowledge impossible to reach within the framework of the 18th century science. In fact, any statement or question on how 'right' and 'wrong' could be split up between Galvani and Volta is meaningless, even though it reflects the human tendency to separate truth from error in a definite way.

The state of knowledge of the time did not make it possible either for Galvani or for Volta to provide a comprehensive explanation of the mechanism of nerve conduction and muscular motion. We might thus wonder why the two scholars developed and defended so strenuously different, and in some ways antithetical, theories in order to solve one of the fundamental problems of science since antiquity. Even if Galvani and Volta shared a similar view of nature and agreed on the method of scientific investigation, they belonged to partly different disciplinary traditions and their scientific interests did not always correspond. The Bologna scholar was a physician and an anatomist, trained in the 'rational' school of medicine of which Marcello Malpighi had been an outstanding exponent. For Malpighi the knowledge of diseases and their treatment were to be based on the understanding of the structure and functions of the healthy organism. Among those functions, muscular motion played a very important role, both because it was, together with sensation, one of the distinctive traits of animals and man, and because many diseases (palsy, strokes, muscular and articulations disorders) were believed to depend on some block or alteration of nerves and muscles. The medical explanation of muscular motion, elaborated in the 17th century on concepts derived from Galenic medicine, ascribed this function to an invisible weightless material fluid – 'animal spirits' or nervous fluid – flowing from the brain to the muscles through the nerves and producing contractions according to a quite unclear mechanism. Around 1750, however, the Swiss physician Albrecht von Haller attacked this theory, which he considered hypothetical and devoid of observational evidence. On the basis of a large number of experiments performed on animals of different species and age, Haller concluded that contractions were due to an intrinsic property of the muscular fibre, named irritability, which did not depend on the action of the nerves (see Hoff, 1936; Home, 1970; Duchesneau, 1982; Clarke-Jacyna, 1987; Monti, 1990; Steinke, 2005).

When in the early 1770s Galvani decided to concentrate his efforts on the study of muscular motion, he was well aware of both the traditional explanation and that proposed by Haller. On developing the preparation of the animal and setting up the experimental methodology to investigate the phenomenon Galvani was certainly influenced by the research that had taken place in Bologna during the debate on Hallerism (see Cavazza, 1997). Thus he chose the frog as the experimental animal because of anatomical and physiological characteristics particularly suitable for the type of study he wanted to undertake. Moreover, he used electricity as a stimulus because, in previous investigation, it had proved much more effective than other mechanical or chemical agent in exciting muscular contractions.

A major problem to be faced in the choice of the animal preparation was due to the fact that the action of voluntary muscles depended, by their own nature, on a voluntary act on the part of the subject. To Galvani it appeared hardly possible to identify the mechanism underlying the contractions because a necessary condition for their production resided in will, that is on a subjective domain which was, for him, out of the control and understanding of the experimenter. The choice of the Bologna scientist, not new by the way, was to perform his experiments on animals which had been freshly killed, in which will was no longer at play, thus making it possible, at least in principle, to investigate muscular motion under controllable conditions. This choice was rooted, on the one hand, in the idea developed by 17th century Mechanism (and shared by many 18th century scientists like Haller), that animal functions could be studied independently from the question of the origin and ultimate cause of life; as Malpighi had underlined, “in the operations of vegetation, sensation and motion, the soul must act in conformity with the machine to which it is applied” (Malpighi, 1698, pp. 213-14). On the other hand, the experiments performed during the debate on Hallerism had proved that it was possible to excite muscular contractions using electricity as a stimulus, even after the cessation of typical life signs like heart beat and respiration, especially in the case of cold-blooded animals like the frog. Galvani himself had found that it was possible to excite the contractions of the frog's limbs even after the animal had been dead for forty-four hours. Thus the use of the frog and of electricity by Galvani can be explained also in terms of a solution to a problem – that of the use of dead animals – which derived from fundamental methodological issues.

On his side, Volta differed from Galvani in the lack of anatomical training and he was less content than Galvani with the idea that one could study physiological functions on dead animals or on parts of them. In fact, the physicist from Como devoted the last part of his "Memoria prima sull'elettricità animale" to the description of experiments performed on "whole and intact" frogs – i.e. in animals alive and not prepared in Galvani's manner – and in these experiments contractions occurred only under particular circumstances. While Galvani (who had also experimented on live animals) did not believe that these two ways of treating the animal made any difference for the understanding of the mechanism of muscular motion, Volta had a different opinion. According to him, the experiments on whole frogs were "easier" to perform, as they did not require any dissecting skill to isolate and separate nerves and muscles; therefore they could be carried out also by scholars who had no anatomical or surgical training. Besides, Volta thought such experiments were more "instructive", as they were performed on animals in which all the typical signs of life were still present:

These new experiments on whole and intact animals, perhaps more striking than others performed up to now by cutting limbs, isolating nerves, etc., [are] certainly more instructive, at least under certain respects, as they allow us to penetrate in some ways the natural state of animal electricity in a whole and healthy living body (Volta, 1918, p. 33).

Volta's lack of a specific anatomical training and his little familiarity with the methods developed in the investigation of the living organism induced him to concentrate on animal preparations which differed from those on which Galvani had built his interpretation of the mechanism of muscular motion. The physicist from Como was much impressed by the fact that muscular contractions could be excited in living and whole animals only when different metals were used to connect the nerves and the muscles, and this circumstance became central in his scientific investigation. Volta was thus led to investigate the relative effectiveness of different metals in the phenomenon of contractions, or, to use his own words, "what difference between metals is more favourable to the success of the experiments, i.e. excites stronger motions in the animal, and in an easier way". The result of this investigation was the construction of a scale of metals ordered according to their power in stimulating contractions (a scale which is still of reference in modern physics textbooks as a basis of Volta's effect). His choice of bimetallic couples would remain a constant feature in his further research and would play a fundamental role in the invention of the battery. The difference in the metals became for Volta the central element in the explanation of the phenomenon of contractions, bringing him to formulate the theory of metallic electricity, a real alternative, as we have seen, to Galvani's theory of animal electricity.

Besides concentrating on experimental conditions, not considered by Galvani significant for the understanding of the phenomena of muscular contraction, from the outset Volta devised experiments which were new with respect to those reported by Galvani in the "De viribus". One of the most significant of them was described in his "Memoria seconda sull'elettricità animale" ("Second Memoir on animal electricity"), dated 14 May 1792 and published, like his "Memoria prima", in Brugnatelli's "Giornale fisico-medico". In this experiment Volta applied "a tin or lead foil, polished and clean" to the tip of his tongue and placed “a gold or silver coin, a silver spatula or spoon” in the middle of the tongue; when he put the two metals in contact, he could taste a “slightly acid taste”, i.e. a gustative sensation similar to the one that could be induced by applying to the tongue the electricity of an electric machine or of a Leyden jar. No contraction of the tongue muscles resulted in this experiment. Contractions of the tongue could be produced, however, in an experiment carried out in an animal preparation with a different arrangement, in particular by placing one of the two metallic armatures on “one of the main nerves of the root” of a lamb’s tongue: the tongue moved when the two metals came into contact through a conducting arc. From this experiment Volta drew an important conclusion:

> It then becomes evident that depending on which nerve is being stimulated and on which is its natural function there will ensue a corresponding effect, that is to say, of sensation and of motion, whenever that nervous virtue is activated by the electric fluid which affects it; and that, therefore, the play of muscles, the contractions, etc. are an immediate effect of this nervous action, not of the electric fluid (Volta, 1918, pp. 62-63).

Here Volta was making a distinction between “motor nerves” and “sensory nerves”, thus catching a fundamental aspect of the physiological principle which would be later clarified by Johannes Müller’s theory of specific nervous energies. He also ascribed the effects of electricity on sensations or on muscular motion to the action exerted by the nerve, and not to an electrical mechanism present in muscles, as Galvani maintained in his model of the neuromuscular complex as an animal Leyden jar. For Volta it was thus the type of nerve being stimulated to influence the physiological response. The experiment based on the application of the bimetallic arc exclusively to the nerve had shown that it was not necessary to include the muscles in the discharge circuit in order to obtain contractions. For Volta this represented a serious blow to Galvani’s model of the muscle as a Leyden jar because in the 'physical' Leyden jar no discharge could be obtained by connecting two points of the metal rod (in contact with the internal armature), which acted as 'conductor' of the jar (and was by Galvani assimilated to the nerve). Moreover, the rod had only a passive function of conducting the electricity, and did not influence in any way the type of effects which could be obtained through the instrument. In light of these experiments, Volta concluded, Galvani's explanation of muscular motion and the analogy between the muscle and the Leyden jar could no longer be considered valid.

Galvani devoted only a couple of pages of his "Trattato dell'arco conduttore" to Volta's tongue experiment. He considered it "uncertain and very doubtful" and argued that it did not have "that strength and truth of conjecture and even less of reasoning which is expected from philosophers". For Galvani, it was not possible to put forward hypotheses, and even less demonstrative arguments, on the basis of sensations, in particular gustative sensations, because these were "foundations which were not strong and sound enough". In fact, the type of taste – acid or alkaline – could depend on subjective circumstances such as imperceptible alterations in the tongue, the previous consumption of different foods or the different response of different palates to the same stimulus (Galvani, 1794a, pp. 120-21). Galvani's refusal to take into account experiments based on sensations derived from the same attitude that had led him to exclude will from the study of muscular motion and to choose dead animals for his experiments. In order to obtain reliable results from the study of animal organism, for Galvani it was necessary the eliminate from the investigation the subjective aspects of the phenomena, introduced by the experimenter, as it was necessary to abolish, with the use of a proper experimental preparation, the indeterminacy introduced by the will of the animal.

Volta, on the contrary, believed the indications coming from the senses to be quite acceptable; indeed he devoted much effort to the investigation of the effects of electricity on taste, hearing and touch, obtaining outstanding results. Engaged in the study of electrical phenomena well before he started to deal with animal electricity, the physicist from Como shared with his colleagues 'electricians' the idea that the living body, and particularly that of the experimenter, could be, under certain circumstances, a quite reliable instrument to understand natural phenomena. The invention of the Leyden jar around 1745 had been accompanied by the observation of the violent shock it produced on the limbs of the person holding it, an effect "new but terrible […], which I advise you never to try yourself nor would I do it again for all the kingdom of France, having suffered its violence and having survived by the grace of God" (as one of the inventors of the instrument wrote to a French colleague). Among the distinguishing properties of electricity there were also various effects on the human body, such as an increase in the heartbeat, in perspiration and temperature. Even among non experts the new field was becoming more and more fascinating, and people from different social status were increasingly keen to prove on their own body the 'wonders' of electricity (see esp. Shaffer, 1983, 1994).

The different attitude of Galvani and Volta towards the experimentation on the living body depended, at least to a certain extent, on the fact that the two scientists had a different training and belonged to different areas of study – medicine and anatomy in Galvani's case, the investigation of electrical phenomena (and, in general, 'experimental physics') in Volta's. Such difference did not affect, as we have seen, their basic notion of nature and scientific method, but did influence their scientific practice and the choice of research problems to be investigated. From the very beginning Volta was attracted by Galvani's investigation mostly because it suggested a new method of dealing with so-called weak electricity, a field considered by many electricians very important in order to define the domain and the laws of electrical phenomena. The fact that the use of different metals was a necessary condition to produce muscular contractions in some circumstances led the physicist from Como to attribute to metals a crucial role in the manifestation of an electricity otherwise undetectable. Besides, Volta was greatly interested in the quantitative aspect of electrical phenomena; he had in fact devoted much effort to the construction of instruments for the detection and measurement of electricity – as he himself explicitly stated in his "Memoria prima sull'elettricità animale":

What results can be achieved, if things are not reduced to degree and measure, especially in physics? How will causes be assessed, if we do not determine not only the quality but also the quantity and the intensity of effects? (Volta, 1918, p. 27)

This statement summarizes the 'quantitative spirit' – meant as an interest for order, systematization, measure and calculus – which characterizes science at the end of the 18th century and which represents a breakthrough in natural philosophy (see Frängsmyr-Heilbron-Rider, 1990; Heilbron, 1993). Galvani, too, was sensitive to quantification: he repeatedly tried to measure, even if unsuccessfully, the electricity involved in the phenomenon of contractions, and performed many experiments aimed at explaining the difference in the number and intensity of contractions in various experimental arrangements. His familiarity with animal experimentation, however, induced him to ascribe great importance to the variability proper to the living organism, besides that depending on the way in which it was stimulated. Besides, the Bologna scholar had discovered the electrical nature of muscular motion through a series of stimulus-response experiments, in which the occurrence (or not) of the contractions appeared to be a more reliable indication of the nature of the phenomena than their intensity. Both in his laboratory notes and in his published writings Galvani noted time and again the diversity of the results obtained by applying the same procedure in different animals and also in the same animal after a certain length of time. And in his "Memorie sulla elettricità animale", in response to Volta's observation on the greater excitability of contractions obtained through the use of metals, there is a statement which, if compared to Volta's quotation above, sheds light on the different approach to phenomena developed by Galvani:

> It is the presence of the effect which decides the presence of the cause; on its quantity depends the strength and force of the same cause: and, in fact, if we would allow ourselves to be led to establish the cause by the sole quantity of the effect, how often would we be mistaken? (Galvani, 1797, pp. 6-7)

Galvani and Volta differed not so much on the interpretation of the same experiments, but on the importance to ascribe to different experiments, i.e. on the ways in which the animal should be prepared and its parts should be connected. To the dead and dissected frog of Galvani, Volta opposed the whole and live animal. Both Galvani and Volta considered a great victory their success in eliminating what constituted a fundamental feature of the phenomena being investigated by their opponent: the nerve-muscle system in Galvani's case (through Volta's tongue experiment and the measurement of the electricity produced by sole metals); metals in Volta's case (through Galvani's experiment of contractions obtained through the direct contact between nerve and muscle and nerve and nerve). The controversy between the two scientists could not possibly find a solution, both because the object of their investigation was particularly complex and difficult to understand with the body of knowledge available at the time, and because Galvani and Volta were guided by interests and approaches which were partly different and influenced their laboratory activity and experimental practice. Even if they shared the same notion of nature and of experimental science, their ideas on how to proceed in their investigation differed in some basic aspects. In fact, Galvani and Volta lived at a time when the disciplinary boundaries which would characterize modern science were still on the make; they lived in an age of great ferment, an epoch of great transition from modern to contemporary times. The controversy between Galvani and Volta represents a significant episode of such process, and can be taken as a sort of magnifying lens to reconstruct both the elements of continuity and the elements of change that characterised the age of Enlightenment.

AN UNSOLVED CONTROVERSY

The ‘Republic of Letters’ of the end of the 18th century – that supra-national community of intellectuals who shared the same Enlightenment ideals of cosmopolitism and of the useful and collaborative character of knowledge beyond all political or religious divisions – was very sensitive to Galvani’s discovery of animal electricity and to the controversy between Galvani and Volta. This topic, together with Lavoisier’s new chemistry, was indeed among the main subjects to be studied and discussed in the last decade of the 18th century (see Kipnis, 1987; Bernardi, 1992; Trumpler, 1992; Bresadola-Pancaldi, 1999; Poggi, 2000).

The news of the investigations of the two Italian naturalists reached the various places in different ways, and, together with the specific interest which were being cultivated by scholars scattered in various European scientific centres, this contributed to direct the research on animal electricity into different directions. The “De viribus”, for example, was read by relatively few outside Bologna (and some other nearby places like Pavia), and an even worse destiny befell Galvani’s subsequent works which were written in Italian, a language scarcely known beyond the Alps. Things worked out better for Volta, who was much more aware than Galvani of the communicative strategies needed to find consensus: in fact he chose to make his ideas known both by writing memoirs in French—the official language of the scientific communication of the time (together with Latin)—and by keeping up correspondence and contacts with many Italian and foreign colleagues. For Galvani and Volta's contemporaries it was much more difficult to follow the various ups and downs of the controversy than it is for us nowadays, and this certainly influenced the judgment on the contribution of the two protagonists.

Let us consider the case of the circle around the Royal Society of London, under many respects the most prestigious scientific institution of the time (see Jacyna, 1999; Cavazza, 2002; Bresadola, 2005). The first news of Galvani's research reached the English capital through a letter sent in June 1792 by the Milanese physician Pietro Moscati to Tiberio Cavallo, a fellow of the Royal Society of Neapolitan origin who had been living in London for several years and was well known as an instrument-maker and as the author of successful works on electricity and on its applications to medicine. Cavallo was immediately intrigued by a topic which might reveal promising both for the medical and scientific implications it suggested and, moreover, for his activity as a writer and popularizer of natural philosophy. He first informed James Lind, also a fellow of the Royal Society and physician of King George III, trying to convince him to carry out experiments on the new subject. He tried afterwards to obtain a copy of the "De viribus", which was evidently unknown in London; finally he presented a Memoir on animal electricity to the Royal Society in November 1792 (see Bertucci, 1999). In his Memoir Cavallo mentioned the name of Galvani as the author of the first discoveries on the role of electricity in muscular motion, but highlighted only some aspects of the research of the Bologna physician. In particular, he mentioned the ability of the animal's legs to react, by contracting, when they were stimulated by a quantity of electricity which could not be detected by the most sensitive electrometers, and the observation that muscular contractions occurred, in the absence of an artificial electrical stimulus, only when the connection between the nerve and the muscle of the animal was made through different metals (J.B., 1790-1793, 15-22 Nov. 1792).

As seen above, the interpretation of the frog as an electrometer and the role of metals in the production of contractions were the elements on which also Volta had concentrated his attention in the first stage of his electrophysiological research. In fact, Cavallo's main source of information on Galvani's research were two letters sent him by the physicist from Como in September and October 1792, where Volta's theory of metallic electricity was already mentioned (Volta, 1918, pp. 169-197). Like Volta, Cavallo was interested in the investigation of weak electricity and attributed great importance to the quantitative aspects of natural investigation: this is why he extolled the contribution of the physicist from Como to his colleagues of the Royal Society. However, he was extremely cautious as regards the interpretation of the experiments, avoiding to commit himself in favour either of animal electricity or of metallic electricity; and he even cast doubt on the electrical nature of muscular contractions, which both Galvani and Volta had claimed with vigour:

> The experiments hitherto made, however numerous and ingeniously contrived and executed, do not however as yet decide anything concerning the origin of this power and the manner in which it is generated; nor indeed are we fairly warranted to call it electricity, since it has hitherto exhibited no property in common with electricity except the preference it gives to conductors before non-conductors. Whether the want for the other characteristick properties of electricity be owing to the very small quantity of that agent in the animal body, remains to be ascertained by future investigation (J.B., 1790-1793, 22 Nov. 1792).

Afterwards Cavallo changed his mind, taking sides with Volta. Cavallo, however, was not the only intermediary between Italy and England in the circulation of the news about animal electricity. At the meeting of the Royal Society of 22 November 1792, where he concluded reading his Memoir, there was, among the 'strangers' – those who did not belong to the Society – a 'dottor' Valli. This was Eusebio Valli, a Tuscan physician who had moved to Pavia to complete his studies. In Pavia Valli had participated in March 1792 to the repetition of Galvani's experiments with Volta and other members of the local scientific community. Valli was especially interested in the medical implication of Galvani's work, and he immediately devoted all his energies to the new field, in the conviction that by investigating it he could achieve his admission to the Republic of Letters. In the spring of 1792, after publishing a first Letter on animal electricity, Valli left Pavia for a long trip to the scientific capitals of the time: he went to Paris, where he spent the summer, and then to London, where he arrived in the autumn and stayed until the spring of 1793. Besides attending several meetings of the Royal Society and performing various electrophysiological experiments with scholars like the president of the Society Joseph Banks and William Nicholson, in London Valli published a three-hundred page book in English, entirely devoted to animal electricity and to its implications in physiology and medicine ("Experiments on Animal Electricity, with their Application to Physiology"; see Bernardi, 1992, pp. 151-54).

The position taken by Valli towards Galvani's and Volta's theories was strongly in favour of the former. Referring to the physicist from Como, Valli declared: "It is with no small pain that I observe that an Italian author, for whom I entertain sentiments of regard, […] has even gone so far as to declare himself an adversary of this brilliant doctrine ", i.e. animal electricity (Valli, 1793, p. 152). However, quite similarly to what Cavallo had done before him, in his work the Tuscan physician reported only a couple of the experiments described in the "De viribus", devoting to Galvani's research only a few pages of his long treatise and describing in the remaining part the results of his own investigations. Moreover, while claiming the existence of an electricity intrinsic to the animal organism, he presented an interpretation of the experiments which partially differed from that of Galvani:

In the explanation of the mechanism of the muscular motions which arise from the action of the mind, I have by no means followed the theory of M. Galvani.

Electricity (in my opinion) does not act as a stimulus, nor does it ever equilibrate. The contractions and relaxations of muscles derive only by a change in the state of this fluid (Valli, 1793, pp. xiii-xiv).

According to Galvani, muscle contraction was due to an electric discharge between the internal and external part of the muscular fibre, which temporarily eliminated the normal electrical unbalance existing in the muscle. Valli believed instead that an electricity contained in the nerves acted on the muscles, by varying their electrical state and thus producing the contractions. In Valli's views the real cause of muscular motion resided in the nerves and, more precisely, in the fluid of electric nature contained in them. In that same fluid he even identified the fundamental principle which characterized life. Valli thus proposed to the English scientific community a third notion of animal electricity besides those of Galvani and Volta, a notion which considered animal electricity the vital principle of animal (and human) life.

Valli's work was not appreciated by Cavallo, it was criticized by several English-speaking authors who wrote about animal electricity between 1793 and 1794, and was basically ignored by the Royal Society, which never discussed the "Experiments", nor gave the physician from Pisa the opportunity to illustrate his ideas in an official meeting. On the other hand, it was not customary for the London institution, as well as for the other scientific academies of the time, to pass explicit judgment (in favour or against) on the research which was communicated, a choice which aimed at avoiding controversies and personal confrontations among the members of the institution. However, the position of the Royal Society in the debate on animal electricity can be inferred from its decision to award the

Copley Medal – one of the most prestigious scientific prizes of the time – to Volta for his letters to Cavallo, published in the "Philosophical Transactions", the official journal of the Society, of 1793. In the official speech for the prize award, addressed to the Fellows on 1 December 1794, the Society President Joseph Banks mentioned Galvani as the author of the discovery of muscular contractions in animals "apparently deprived of life" through the communication between nerves and muscles; he related the theory of the Bologna physician, according to which these motions were due to a "fluid inherent in the structure of animals" named "animal electricity"; he reported the opinion of other scholars – referring to Valli without mentioning his name – that this fluid was "that vital principle" on which "the manifold functions of life" depended. After that, Banks went on to stress Volta's merits:

> To Professor Volta was reserved the merit of bringing his countrymans [*sic*] experiment to this test of sound reasoning and accurate investigation; he has explained them to Dr. Galvani himself and to the whole of Europe with infinite acuteness of judgement and solidity of argument […] (J.B., 1793-1796, 1 Dec. 1794).

According to Banks Galvani's merit had been to devise a new experimental method for exciting muscular contractions, but Volta had the much greater merit to submit the discovery of his fellow-countryman – which may possibly have occurred "casually" or "accidentally" – to precise reasoning and accurate investigation. Thus, the physicist from Como had proved that the principle on which muscular contractions depended resided in metals, and not in animal electricity, as Galvani and his "followers" claimed. For the President of the Royal Society, in sum, "it requires greater powers in the human mind, to reason with precision on the result of an experiment, and to explain with certainty the various consequences deducible from it, than to invent the experiment itself".

The decision of the Royal Society to award the Copley Medal to Volta derived from a series of reasons of different nature. In favour of the physicist from Como was certainly the fact that he was already a well-known and highly-regarded member of the London institution (since 1791), a "valuable brother", as Banks addressed him; besides, there was his choice to send his English colleagues the results of his first research on animal electricity. Galvani's situation was quite different from Volta's both regarding his relationships with English scholars – in fact he had none – and the circulation of his works. A copy of his "De viribus" was given to the Royal Society by Aldini only in 1796, and in the library of the London institution there are all the volumes of the "Commentarii" of the Institute of Sciences of Bologna except the one where Galvani's work appeared for the first time. As for the "Trattato dell'arco conduttore", it was probably unknown in England and, in any case, there is no trace of it in Banks' speech. But another very important reason behind the judgement of the Royal Society may have been the confusion created in the English circles between Galvani's and Valli's theories: the critical attitude of many scholars towards the idea of electricity as a vital principle, claimed by the Tuscan physician, may have conditioned negatively the opinion of the members of the Society on the interpretation of the phenomena of muscular motion expressed by Galvani, even if it was different in some important respects from Valli's views. In London, at least in the years just after the discovery of animal electricity, Galvanism was perceived as a novelty coming from Italy, but not from Bologna, where his discoverer lived.

For Banks, as we have seen, Galvani's discovery consisted mainly in having devised a new 'method' to excite muscular contractions; but it had been Volta who had faced the harder – and for this reason more remarkable – task to submit the phenomena to careful investigation and accurate reasoning, that is to say to that quantitative approach which, according to many scholars of the time, was the trademark of the true experimental philosopher. The separation made by the President of the Royal Society between the planning and the execution of experiments on the one hand, and the interpretation of the results on the other hand, became a common feature of the debate on Galvanism which took place in the last decade of the 18th century. The term 'Galvanism', used in various European languages starting from about 1795 ('galvanismo' in Italian, 'galvanisme' in French, 'Galvanismus' in German), referred to the experimental arrangement derived from Galvani's research rather than to his theory of animal electricity. The German naturalist Alexander von Humbold, one of the protagonists of the debate on Galvanism in the second half of the 1790s, defined the new investigative field in the French edition of his work "Versuche über die gereizte Muskel- und Nervenfase" as follows:

> The property observed in the nerves of animals to be irritated by metallic or coal matters, or even by the simple contact with other living organs, offers a multitude of phenomena which are known as *galvanic phenomena* […] The knowledge [of galvanic phenomena], increased day after day, has led to reject these erroneous or false terms [i.e. *metallic irritation* and *animal electricity*], and all physiologists keen to avoid error, nowadays do not use other terms than that of *galvanism*, which does not refer in any way to the cause of phenomena (Humboldt, 1799, pp. v, x).

Humboldt's appeal to avoid investigating the causes of the phenomena involved in the experiments on Galvanism – shared by many other scientists of the time – implied that it was possible to separate the physiological or physical research from controversies on the nature of the fluid involved in the experiments. Of course naturalists, physicians, chemists who increasingly dealt with these phenomena kept on in the attempt to provide their interpretation of the experiments. However, they were all aware that their common ground should be based on the instruments and experimental procedures being used, and not on their interpretations. Some of these procedures derived directly from Galvani's early researches, others were developed in the following years, both by Galvani himself and by Volta and other scholars involved in this field of investigation. After Volta, in March 1800, announced the invention of the battery, the new instrument became one of the main devices (in fact also an emblem) of Galvanism, and it was also given the name of 'galvanic battery' or 'galvanic apparatus' (see Bresadola, 2001).

It may be useful to deal briefly with the events of the reception of Volta's battery, as there are several features in common with the ones which characterized the debate on Galvani's discovery of animal electricity. In his famous letter of 1800 to the Royal Society announcing the invention of his new device, the physicist from Como concentrated mainly on the way the apparatus was built (in its two versions, as pile and chain of cups), on how it worked and on the description of a series of experiments performed with it. Only the last part of his Memoir was devoted to demonstrating that the battery was a consequence and an application of the theory of contact electricity. As had been the case with Galvani's research, the many scientists who took an immediate interest in Volta's invention did not find any difficulty in replicating the instrument and in repeating the experiments described by the physicist from Como. However, from the very beginning, the interpretations of the phenomena produced by the battery started to differ one from the other and from Volta's own interpretation. Nicholson, for example, focused on the chemical effects of the battery – among which the main one was the decomposition of water – and considered the instrument invented by Volta as a powerful chemical apparatus, not an electrical one, as its inventor claimed. Étienne Gaspard Robertson, a Parisian 'amateur' and public lecturer of science, who possibly was the first one to acknowledge Volta's invention in France, concentrated instead on the effects of the battery on the human body, including the new instrument in the area of medical galvanism. As Giuliano Pancaldi has brilliantly showed, the prompt circulation of the battery not only among experts but also among laymen interested in science went together with the recognition of the Italian scientist as the author of this great invention. On the other hand, the instrument was soon associated with different, and sometimes contradictory, interpretations; this was favoured by Volta's decision not to link the construction and the working of the battery too closely to a specific theoretical framework. As had been the case with Galvani's experiments on animal electricity, in the case of the battery as well the fact that it could be easily replicated did not imply uniformity in interpretations, and this fact may have contributed to determine its great success (see Pancaldi, 2003, esp. pp. 211-256).

Great writers have always said that once it has left their hands and reached the public a literary work acquires a life of its own, generating reactions that sometimes its author could never have even imagined. The products of science – be they experiments, instruments or theories – share this feature with literary activity (while differing in many others), as they are themselves the results of highly creative processes. Galvani's discovery of the electricity of living bodies and Volta's invention of the battery not only were fundamental steps in the scientific understanding of nature, but they also opened new paths to the investigation of phenomena which neither the Bologna physician nor the physicist from Como could have envisaged. From this point of view it is difficult to find an end of the controversy on animal electricity: if the direct confrontation between the two Italian scholars found its conclusion with Galvani's death in 1798, and the invention of the battery decreed Volta's success in many scientific circles (even if not in all of them), one of the most important outcomes of the controversy was the emerging of new problems and new approaches to the study of nature which are still matter of study and discussion.

Figures

1. Alessandro Volta (left) and Luigi Galvani (right) face to face.
2. Galvani's structural analogy between the Leyden jar and the nerve-muscle apparatus (sketch by Nicholas Wade and Marco Piccolino)
3. Plate 3 of Galvani's De viribus, showing various experimental arrangements developed by the Bologna scholar in his electrophysioloogical investigation
4. The structural analogy between the "electric organ" of the torpedo and Volta's battery (courtesy of Marco Piccolino)

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