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Changing a Theory: The Case of Volta's Contact Electricity

1. Introduction

Volta's theory of contact electricity was introduced in 1792 and had been in use for about a century. Its early development – 1792-1800 – has been extensively discussed in the framework of the Galvani-Volta debate.[1] The subsequent period, however, only recently became a subject of studies, primarily from the perspective of the debate on the nature of voltaic electricity.[2] Certain difficulties were encountered in these studies, in particular, a disagreement on how the contact electricity eliminated animal electricity and how it itself yielded to chemical electricity. The longevity of contact electricity hints at a possible association with a paradigm. This suggest to apply to this case Kuhn's theory of scientific change to see whether the changes in question can be treated as a paradigm change.

According to Kuhn, paradigm is a certain tradition in doing research in a particular branch of science developed on the basis of a new theory. It includes new theoretical concepts, new instruments, specific experimental techniques, a particular approach to solving problems, and new applications. A new theory should be preceded by some remarkable discoveries unexplained within an old paradigm, or by pre-paradigmatic theories.[3] A failure to solve these puzzles leads to a theoretical crisis, which is felt until a swift change (a revolution) brings in a new theory. After a new paradigm is established and until anomalies are accumulated, there must be a crisis-free period.[4]

While applying Kuhn's concepts to all three theories – contact electricity, animal electricity, and chemical electricity – I will also examine the role of factors that were not addressed in Kuhn's theory. One is an influence of a theory's status (challenger or incumbent) on choosing the means in a scientific discourse. Another is an effect of the time lag between the appearance of competing theories on their interaction.

[1] KIPNIS (1987), PERA (1992).
[2] KIPNIS (2001), KRAGH (2000).
[3] KUHN (1970).
[4] KUHN (1970a), p. 12.

According to Kuhn, it is easier to dislodge a theory before it becomes well entrenched.

2. "Animal" Electricity versus "Contact" Electricity

In 1791, Luigi Galvani (1737-1798), Professor of Anatomy and Obstetrics in Bologna, described a new phenomenon: when he connected the sciatic nerve and the leg of a prepared frog by a metal arc, preferably made of two different metals, the leg twitched.[5] He concluded from his investigations that the agent responsible for this effect must be electricity, and, having excluded one by one all known kinds of electricity, Galvani suggested that it was the "animal" electricity long sought for by physiologists.[6] In his view, "vital forces" produce and store opposite electricities in the nerve and the corresponding muscle as in a Leyden jar, and connecting the two with a good conductor makes an instant current of electricity which stimulates the nerve.

Galvani was aware of several inconsistencies in his theory. Since it had been long known that all animal tissues conduct electricity, a nerve and a corresponding muscle were electrically connected and therefore there could not be an electrical imbalance between them as in a Leyden jar. To fix this flaw, Galvani supposed that the nerve's cover is oily and thus works as an insulator, while the moisture on the cover play the role of an external conductor of the "Leyden jar". However, the assumption that an electrical imbalance exists only between a nerve and a muscle, contradicted Galvani's observations of contractions excited by a bi-metal touching two parts of a nerve or two parts of a muscle, one of which was wrapped with a metal. Eusebio Valli (1755-1816), a physician from Pavia, saved the muscle-muscle stimulation by saying that each muscle is permeated by nerves, and electricity reaches them through muscle fibers.[7] Yet, the nerve-nerve phenomenon remained unexplained. Nor could Galvani explain why convulsions were stronger when the connecting arc consisted of two different metals rather than of a single one. These difficulties averted some from Galvani's theory, and this trend increased after Volta offered an alternative theory.

Alessandro Volta (1745-1827), Professor of Physics at the University of Pavia, repeated Galvani's experiments and at first agreed with his interpretation. A few months later, however, he supposed that the electricity originated outside the frog, in the metals, the frog being merely a wet conductor.[8] According to the then generally accepted view, electricity permeated all bodies, and Volta assumed that each metal attracted electricity from the animal tissues according to its affinity to electricity. In such a case, a pair of different metals could have created an imbalance of electricity.

[5] GALVANI (1953).
[6] BERNARDI (2000).
[7] VALLI (1793), p. 154.
[8] Lettera prima al Sig. Vassalli, 10 February 1794, in *VO*, I, pp. 263-8 (p. 268).

Soon, however, he observed that convulsions took place even when identical metals touched the animal, provided that the connecting circuit included different metals. Volta concluded, therefore, that an imbalance of electricity was created between different metals.

Eusebio Valli called Volta's electricity of metals "imaginary".[9] In fact, the idea was not new, Galvani himself toyed with it in 1786.[10] He abandoned it because it could not explain how two identical metals – he initially succeeded with an iron-iron connector – could destroy electric equilibrium. Thus, when Volta offered his theory of bi-metal electricity he had known that a single-metal connector could have also produced contractions. For this reason, Volta kept for a while animal electricity in addition to his metal electricity. Then he discovered in 1794 that a difference in temperature or polish at the ends of a wire was sufficient to excite contractions.[11] Thus, he concluded, the contact electricity was sufficient to explain *all* phenomena, since a single wire with heterogeneous ends could be considered as two different metals.

Giovanni Aldini (1762-1834), Professor of Physics at the University of Bologna and Galvani's nephew, countered this argument with a new experiment.[12] He showed that mercury free of the heterogeneity described by Volta still produced contractions, and so did charcoal. Another strong blow to Volta's theory came from Galvani's experiment with the "all-animal" circuit, in which contractions occurred when a nerve directly touched the corresponding muscle without any intermediaries.[13]

To account for these new phenomena Volta further modifies his theory using the idea of heterogeneity. A single metal, he says, becomes heterogeneous at its ends, for instance, when it touches two different liquids, such as animal fluids moistening a nerve and the muscle. In 1795, he makes an additional step to account for the effect of the all-animal circuit: it produces contractions, because the two animal fluids that wet a nerve and a muscle are heterogeneous substances.[14] In other words, Volta contends that *any* contact that creates some heterogeneity can be an *electromotor*, that is able to move electricity. However, the force with which the contact moves electricity depends on the substances involved: two metals or other solid bodies create the strongest electromotive force; a metal with two different liquids, a weaker one, and two liquids or wet substances, the weakest of all.

By 1795, Volta realized that he could not fully establish the existence of the contact electricity without eliminating the potential source of animal electricity. Thus he replaced the frog's preparation with another sensitive detector of electricity,

[9] VALLI (1793), p. 152.
[10] GALVANI (1937), pp. 36-7, 397-403.
[11] Lettera prima al Sig. Vassalli, 10 February 1794, in *VO*, I, pp. 263-8.
[12] ALDINI (1794), pp. 5-9.
[13] GALVANI (1794), pp. 4-6.
[14] Lettera al cav. Banks, 30 March 1795, in *VO*, I, pp. 251-7 (p. 255).

Nicholson's doubler.[15] He claimed to prove by this means that two different metals, separated after being in contact with one another, showed opposite polarities. However, the doubler had been known for creating electricity of its own, and Volta's experiment convinced only a few.

A number of scientists felt that Volta's theory was no more convincing than Galvani's theory, because neither could explain, for instance, contractions produced by means of an open circuit. They supposed that galvanic phenomena were not electrical, and some of them assumed that their cause was chemical. The chemical theory originated in 1792 with G. Fabbroni who immersed two different metals in water and observed that one of them oxidized, but only if the metals touched one another on the outside. Thus, Fabbroni supposed that galvanic phenomena were due to oxidation.

It is important to note that although during the debate Volta was eager to modify his theory so as to fit all *new* experiments directed against it, this was not so when he first offered his theory. Then, he ignored such phenomena as contractions produced by a single metal or by an open circuit. In other words, the contact theory was born defective, and Volta knew it.

These facts question Volta's intent in offering his contact theory: did he try to provide a better account of galvanic phenomena or did he want to eliminate Galvani's theory? There are facts pointing to the latter. For instance, Volta's theory could not prove the existence of the electromotive force in metal-liquid or liquid-liquid contacts. This did not bother him, however, because if these hypotheses could not have been demonstrated, they could not have been refuted either. Apparently, Volta's rejection of Galvani's theory was prompted by metaphysical rather than physical arguments. Being a reductionist, he wanted to eliminate "vital forces" in an animal body as a possible source of animal electricity. This was easy in the case of a frog, where he believed to have proven that electricity involved was produced outside the animal body. The task was more difficult with the electric torpedo, and we will see further how Volta dealt with it.

Another proof that Volta was not really interested in investigating galvanic phenomena can be seen in the fact that as soon as he rebuffed attacks by Galvani and Aldini, he devoted all his experiments to studying circuits that did not include animal tissues. He tried to modify these circuits so as to make their electricity detectable by an electrometer. At the end of 1799, he finally succeeded, inventing an apparatus he called an "electric pile".

3. The Pile

Volta described the pile in his paper *On the electricity excited by the mere contact of conducting substances of different kinds* read at the Royal Society of London in June

[15] Lettera seconda al Prof. Gren [August 1796], in *VO*, I, pp. 417-31 (p. 418).

1800.[16] The pile consisted of many pairs of different metals, such as silver and zinc, separated from one another with cardboard moistened with water or another liquid, or placed in a cup filled with the liquid. The metals were arranged so that the zinc plate of one pair was electrically connected to the silver plate of another pair, and so on. The pile affected an electrometer and produced sensations of shock, taste, light, and sound.

By offering a theory of the pile up-front (in the title) Volta implied that its theory has been already proven. Actually, only one of his theories might have been considered proven (by means of a condenser electrometer), namely, that a contact of two different metals produces electricity. When he suggested that the electric organ of the torpedo resembles a pile consisting of many pairs of different muscular tissues, the contact of which makes electricity, it was a sheer speculation. Volta needed it to complete his research program of proving that animal electricity, wherever it exists, is produced by physical rather than "vital" forces.

Volta's theory of the pile led many scientists to the following (erroneous) refutation of animal electricity: 1) since the action of a pile is electrical and its effect is nothing else as a multiplied effect of a single couple, a single contact of two different metals creates electricity too; 2) electricity created by a bimetal must be the same whether it is detected by an electrometer or by a frog; 3) thus, Galvani's phenomenon was due to contact electricity rather than animal electricity. In fact, the last conclusion was not logical at all, since a circuit with a frog could have had both sources of electricity, but this detail went unnoticed.[17] Although Galvani's research program – to prove that all animals have electricity produced in their organs – was undermined, a small group of researchers never stopped working on it until the concept was eventually accepted.[18]

4. Chemical Theory versus Contact Theory: Phase I

While helping Volta to refute the theory of animal electricity, the pile stimulated another rival, the chemical theory. This happened after several English scientists found that a pile can produce various chemical phenomena not mentioned in Volta's paper. William Hyde Wollaston (1766-1828) and Humphry Davy (1778-1829) suggested that, contrary to Volta's opinion, liquids must play an active role in galvanic phenomena, and Wollaston went so far as to state that chemical reactions may be the cause of electricity rather than its consequence.[19] Thus, the chemical theory changed its meaning: before 1800 chemical reactions were supposed to cause galvanic non-electric phenomena, while after 1800 they were held responsible for producing voltaic electricity.

[16] VOLTA (1800).
[17] KIPNIS (1987), p. 135.
[18] KIPNIS (1985).
[19] WOLLASTON (1801).

In his first responses to this criticism, Volta insisted that he had already proven the role of a contact of different metals as an "electromotor" in his experiments with a condenser electrometer.[20] In particular, when he held a zinc and a silver plates by insulating handles, touched them to one another, separated, and brought them in contact with the plates of a condenser electrometer, its leaves diverged by 2 degrees, the multiplication rate of the condenser being 120. Applying the same condenser to a pile he found its tension to be proportional to the number of couples and such that the tension of one couple in a pile was the same as that for a contact of zinc and silver plates. Volta also mentioned that the closer two metals were in his electromotive series: (silver, copper, iron, tin, lead, zinc, etc.), the smaller was the electromotive force for this pair.

The role of the liquid was a mystery to Volta, and he defined it only in a negative sense: it had almost no action on production of electricity by preventing each couple from acting on the neighboring couples. He had already found experimentally that electromotive force of two metals cannot be changed by connecting them by means of other metals. He reasoned as follows. The electromotive force (*emf*) of the chain Zn(1)-Cu(1)-Zn(2)-Cu(2) was equal to that of a single Zn-Cu pair, because Zn(2) moved electricity back towards Cu(1) with the same force as Zn(1) moved it forwards to Cu(1). An addition of a liquid separator L(Zn-Cu-L-Zn-Cu) prevented this backward movement and thus increased the *emf* by the factor of two. Metal-liquid contacts did not affect the total *emf*, Volta said, because many alternations of metal and wet substances produced the same total *emf* as that of a single bimetal multiplied by the number of couples. He acknowledged, however, that some concentrated acids and alkalis produced a very sensible *emf* when coming in contact with metals.

Volta himself only implied that the electromotive force of each pair of metals is constant. This hypothesis of his was spelled out by the *commissaires* of the Paris Academy of Sciences evaluating his paper for the Great Prize on galvanism established by Napoleon:

> It remains to determine in a rigorous manner whether it [*emf*] is constant for the same metals or varies with the quantity of electricity [...] It is necessary to evaluate with the same precision the action that liquids exercise on one another and on metals. But these delicate researches require using the most precise instruments invented to measure the force of the electric fluid.[21]

Having reconsidered the fact that a chain of substances of the first class (metals and solids) does not increase the *emf* compared to a single pair, Volta began to suspect that the same may be true when applied to the second class (liquids). Thus he modified his theory once more, by separating a sub-group from the second class, he called the "third class", consisting of animal tissues. In the new theory, a current-

[20] VOLTA (1801).
[21] ACADEMIE DES SCIENCES (1802), p. 20.

producing couple in an all-animal circuit consisted of two different substances of the third class and one substance of the second class.

As to the chemical effects observed in England, Volta called them the "secondary effects", or an effect of electricity rather than its cause. In his view, a shock became stronger after adding salt or acid to water because of an improvement in conductivity of the circuit, rather than an increase in tension.[22]

W. Nicholson, who translated and published Volta's paper, was not satisfied with his explanations and brought forth Davy's experiments as refuting Volta's theory.[23] Davy argued that a liquid in a voltaic cell played an active role, because iron was charged positively in an iron-copper pile filled with water, but it became negative when water was replaced with sulfate of potassium.[24] He also invented a pile that consisted of pairs of cells with the same metal but different liquids (one acid and one alkaline), connected by paper strips moistened with water.

Volta answered that he had been aware of the electromotive force created by a metal-liquid contact well before 1798 and found it to be too weak, compared to the one produced by bimetals.[25] He noticed, however, an exception: with alkaline solutions or concentrated acids the effect was quite sensible. Volta also claimed to have executed Davy's experiment with one metal and two different liquids, only in another form (galvanic experiments with a single-metal stimulation). Finally, Volta agreed to give chemical reactions a role, but only in improving the conductivity of the pile rather than in producing electricity: when an acid, for instance, attacked a metal surface, it adhered closer to it than water and thus diminished the resistance of this liquid-metal contact.[26]

Volta's theory had a number of difficulties. It was unclear what was the "proper" way to measure the "power" of the pile: by a shock (a function of current) or by tension shown by an electrometer, which he believed to measure electromotive force. The two methods provided different clues as to the role of the liquid, for the strength of a shock heavily depended on it, but not tension. Volta could have dispensed with shocks altogether, because he considered tension to be a more precise and reliable parameter. However, since he thought of a pile as a model of the torpedo fish, he had to retain shocks. Having been preoccupied solely with the role of metals, Volta discussed liquids only when challenged by someone. For such occasions, he explained the advantage of an acid over water by a change in conductivity, as described above.

Another difficulty was in deciding whether to attribute an active role to contacts other than that of bimetals. Drawing on his experience with galvanic circuits, Volta decided to ignore them as insignificant. Naturally, he had no direct way of proving this hypothesis for voltaic cells. A small variation of *emf* of a pile with a change of

[22] VOLTA (1802a), pp. 138-9.
[23] NICHOLSON (1802).
[24] DAVY (1800).
[25] VOLTA (1802a), p. 280.
[26] VOLTA (1802b), p. 344.

the liquid in it could have been an indirect proof, but there were other ways to explain it. While Volta neglected the *emf* of metal-liquid and liquid-liquid contacts in his own research, he never failed to point out his priority in studying it when facing a challenge on this point. Thus, in using his contact theory he made no difference between galvanic and voltaic experiments. This presumed unity of his theory was a mixed blessing: it helped him to refute animal electricity by appealing to those who wanted to reduce life phenomena to physical-chemical processes, but it created unnecessary difficulties in the controversy with the chemical theory. For instance, to study his favorite bimetal piles, Volta did not have to consider liquid-liquid contacts; however, he needed to retain them to explain both all-animal circuits and the pile in the same theory. Due to its internal inconsistencies, Volta's theory became so flexible that it could counter any attack with ease. While this allowed Volta to win any argument, subsequently, it created a confusion about his true views even among his followers.

After Volta's clarifications of 1801-2, no important arguments were advanced against him. The "chemists" tried to connect the cause of voltaic electricity with oxidation of the plates. It was shown, indeed, that the activity of the pile decreased when oxygen was no longer available. However, since the pile still functioned, it was clear that oxidation could not be the primary cause of its activity. J. Berzelius and some other chemists believed that Volta's attempt to reduce the role of chemical reactions to improving conductivity was inadequate.[27] Davy chose another way: he tried to show by means of an electrometer that chemical reactions released electricity. Yet, except for dry solid alkalis and acids, he failed. As a result, he acknowledged that the cause of electricity was a contact phenomenon. At the same time, he insisted that this cause would not support a current for more than a moment, if the electricity would not have been constantly restored by oxygen and acids moving to zinc plate and alkali and hydrogen to copper. Thus, he tried to "reconcile" Volta's theory with the chemical theory.[28] Some scientists based their support of a "compound" theory on Volta's precise experiments with a condenser electrometer.[29]

For the next twenty years, Volta's theory appeared to be so fully accepted that all textbooks classified voltaic electricity as "electricity by contact".[30] While such a domination points to a paradigm, the everyday research in voltaic electricity and electrochemistry focused on practical problems rather than on "puzzle solving". During that time, the theory did not undergo any improvement: apparently, its adherents found no "puzzles" that would have required it.

[27] GILBERT (1808).
[28] DAVY (1807).
[29] BOSTOCK (1802).
[30] BEUDANT (1824), BAUMGARTNER (1824).

5. Chemical Theory versus Contact Theory: Phase II

The new controversy between chemical electricity and contact electricity began in the middle of the 1820s, and this time it was long and extensive. Its beginning had nothing to do with resolving difficulties in the contact theory. There was a steady interest among scientists in finding connections between electricity and chemical affinity, and Antoine-César Becquerel (1788-1878) decided to try for this purpose a recently invented electromagnetic galvanometer. He wanted to see if electricity is developed during a chemical recombination. For instance, he filled a platinum cup with an acid and held potash in platinum pincers, both were connected to a galvanometer by means of platinum wires. When potash touched the acid, the needle deviated showing that the acid was positive relative to the alkali. Using a sensitive condenser electrometer he also proved that sometimes a metal-liquid contact also creates a charge, with metals being negative relative to an alkaline solution and positive relative to an acid.

Having started as a follower of Volta, Becquerel gradually began to suspect that the *emf* of a metal-liquid contact may be a result of their chemical interaction. In a few cases, he was able to prove this, but in others he could not, because a current appeared when there was no visible chemical reaction.[31] Thus, Becquerel assumed that electromotive force and chemical action were two independent causes of electricity.

Becquerel did not argue then that electricity associated with chemical reactions refuted the contact theory, this claim was brought forth by August Arthur de la Rive (1801-1873), a physics professor in Geneva.[32] He began with a study of currents produced inside a voltaic pile and their role in chemical decompositions. The intensity and direction of these currents appeared to contradict Volta's theory. For instance, current produced by a tin-copper couple changed its direction when the couple was moved from ammonia to an acid, which appeared impossible, because in Volta's theory the liquid did not play any active role and the *emf* for a given pair of metals was constant. De la Rive began to apply the chemical theory to his experiments and came up with such empirical laws as: 1) the metal most strongly attacked is charged positively about the other, 2) the greater the difference in chemical action of the liquid on two metals, the stronger the current, 3) a contact itself does not produce current electricity if there is no chemical reaction; and others. He also offered a chemical explanation of Volta's condenser experiment by suggesting an involvement of humidity. Here is an example of his reasoning applied to the tin-copper couple mentioned above: since the acid attacks copper less vigorously than tin, copper charges negatively, while ammonia reacts stronger with copper than with tin making copper positive.

[31] BECQUEREL (1823).
[32] DE LA RIVE (1828).

Stefano Giovanni Marianini (1790-1866), a physics professor in Venice, took upon himself to defend the contact theory against de la Rive's onslaught.[33] As a part of defense, he offered a new explanation of polarity change produced by different liquids. In the example cited above, when the couple is moved from an acid to ammonia the electromotive force of tin increases and that of copper decreases. In a similar way, two identical zinc plates affect a galvanometer if one of them is immersed in an acid earlier than the other. The first plate undergoes a change before the second plate is submerged, which makes the plates heterogeneous, and, according to Volta's theory, creates an electromotive force. He did not offer, however, any rules about expected changes.

While on the offensive, Marianini criticized the chemical theory for not explaining an increase of tension of a pile with the number of couples, or its independence of the liquid. He also cited examples of violation of the law of proportionality between the intensity of a chemical reaction and the current produced by it. In his view, the chemical theory did not provide "plausible explanation" to many phenomena explained by the contact theory.

In his response to Marianini, de la Rive addressed the issue of tension, but unsuccessfully. He acknowledged exceptions to the law of proportionality. Having observed that some chemical changes, such as tarnishing (oxidizing) of metals, which are not readily noticeable, still released some electricity, he realized the ambiguity of the term "intensity of a chemical reaction". Consequently, de la Rive suggested a reverse reasoning: to assume that a current was a sign of a chemical reaction and to use a galvanometer to search for "invisible" chemical processes.[34]

Marianini did not accept the modification of the proportionality law: to him this constituted a proof of an insufficiency of the chemical theory. His position was shared by Ch.H. Pfaff (1773-1852), G.S. Ohm (1789-1854), E. Péclet (1793-1857), J.Ch. Poggendorff (1796-1877), G.T. Fechner (1801-1887), and others. On the other side, Michael Faraday and Ch.F. Schönbein (1799-1868), Professor of Chemistry at the University of Basel, and others came to support the chemical theory. The debate, sometimes quite bitter, raged for 20 years, stimulated a great number of new experiments, yet, it produced no consensus: the "chemists" continued to prefer their theory and the "contactists", theirs.

The changes in both theories reflected a certain mutual rapprochement. For instance, shifting the emphasis from a "bimetal" contact to merely a "contact" was a step towards a greater role to chemical reactions, for the latter included metal-liquid and liquid-liquid contact, which were much more suggestive of a chemical interaction than Volta's "contact of two metals". The same was with admitting that a liquid could change the electromotive force of a metal, for the change was obviously chemical.

[33] MARIANINI (1830).
[34] DE LA RIVE (1836).

In their turn, the "chemists" had no choice but to bring in "invisible" chemical reactions. Having realized that no one knows how a chemical reaction begins, Schönbein redefined it so as to make it independent of its visibility. To him, the important part was that forces of attraction created a "*tendency* to decomposition", even if the decomposition did not realize.[35]

In the 1840s, some people began to see the differences between the two theories as only semantic. Indeed, what is the difference between the two forces setting electricity into motion, one called "electromotive force" and the other "chemical affinity"? A "contactist" would say that he does not know the nature of the "electromotive force" and does not care. A "chemist" would start saying that the nature of his force is chemical, and then he would stop incapable to explain its meaning.

In the 1820s, the contact theory had an important advantage over the chemical theory: simplicity. The "chemists" promised more than they could deliver, for their knowledge of chemical reactions involved was insufficient for arriving at correct laws connecting the reactions with the release of electricity. The "contactists" were content with asserting the existence of the contact force and finding empirical laws for it, such as the electromotive series. By the 1840s, the understanding of chemical reactions improved and with it the possibility of predicting the character of the current produced; thus the agnostic position of the "contactists" was no longer justified by lack of knowledge. Thus, a movement began (Becquerel, Matteucci, and others) to assume that the contact (electromotive) force and chemical force are the same. Some scientists came to the conclusion that the only acceptable way out of the controversy was to abandon the original problem as unsolvable and reach a compromise.

6. Can Kuhn's Theory Be a Framework in This Case?

As shown above, both contact electricity and chemical electricity have been in use for a long time, each developing its peculiar set of ideas and experimental techniques, and acquiring a separate following. Thus, either satisfies Kuhn's definition of a paradigm.

How about animal electricity? Before Galvani, it was one of pre-paradigmatic hypotheses of the "nervous fluid". Galvani transformed this hypothesis into a theory. By 1800, animal electricity had a number of proponents who introduced new experiments to support it, as well as new applications for this theory. Contrary to what is commonly believed, Volta's criticism did not eliminated animal electricity as a research subject. A number of scientists continued to work in this field by repeating and modifying experiments of Galvani and Aldini, until new ideas and experimental techniques introduced by Leopoldo Nobili, Carlo Matteucci, and Emil Du Bois-Reymond gave a new boost to this field, transforming it into what became

[35] SCHÖNBEIN (1838).

known as “electro-physiology”. Thus, one may argue that animal electricity has been a paradigm for a group of researchers, mostly physiologists and physicians, since at least 1800.

If we assume – as commonly done – that animal electricity and contact electricity were competing paradigms, this assumption disagrees with Kuhn’s theory on several points. First, these paradigms coexisted side-by-side for a long time without contact electricity replacing animal electricity. Secondly, anomalies of animal electricity were discovered not within this paradigm but by outsiders. Finally, these anomalies were discovered too early: instead of waiting for Galvani’s theory to fail in explaining *new* experiments, Volta addressed its inborn defects. These facts do not conform to such concepts as “puzzle-solving”, “crisis” and “revolution”.

To explain the long coexistence of animal electricity and contact electricity, one needs to separate the initial period from 1792 to 1800, characterized by a vigorous debate between the theories, from the post-1800 period, marked by very little controversy. The difference was due to a change in the application of the contact theory and a corresponding change in the group supporting this paradigm. In the first period, Volta offered his theory for the sole purpose of explaining a physiological phenomenon of muscular contractions. His goal was to eliminate animal electricity as a universal factor in all animals, because such a hypothesis implied that animal electricity might have been produced by “vital forces”. He argued that a new sort of electricity, produced outside an animal, could explain all experiments by Galvani and Aldini. Where he could not achieve this, as in the torpedo fish, he suggested a physical cause for animal electricity, namely, a contact of different tissues. At that time, the community behind the contact paradigm was not of physicists who had no vital interest in a physiological issue, but that of reductionists. This group included both physicists and physiologists who were concerned with eliminating the concept of “vital forces” from science.[36]

After 1800, the contact theory became a physical theory that aimed at explaining the nature of the voltaic pile and processes in voltaic circuits. The new paradigm was supported by the “voltaic” group, which consisted of physicists and chemists. While some members of this group also belonged to the reductionist group, their interest in fighting vital forces considerably decreased, because they have their hands full of physical-chemical problems. They limited their role to refuting explanations of physiological experiments that were based on animal electricity without providing an alternative physical theory. Naturally, this had little hindering effect on the activity of electro-physiologists who continued to improve their experimental techniques until, finally, late in the nineteenth century, the concept of animal electricity acquired a certain legitimacy as one of mainstream science.

As to the other two difficulties, their only unusual aspect in the first period was a passion with which Volta attacked Galvani’s theory. It points to an ideological

[36] Since scientists of that period were “universalists”, the terms “physicist” or “physiologist” mean here those who did research on physical or physiological topics related to the debate.

motivation rather than a professional one of a physicist who teaches a physiologist how to do experiments. A noteworthy fact for the second period was that some electro-physiologists adopted Volta's hypothesis of electricity in the torpedo fish as produced by a contact of different tissues. Unlike Volta, however, they extended this hypothesis to *all* animals.[37] In a way, this was a merger of animal electricity and contact electricity.

While the early challenge coming from outside of an incumbent paradigm prior to any crisis felt within it and a non-revolutionary resolution of the conflict may appear to be very unusual and peculiar only to the controversy between animal electricity and contact electricity, this impression subsides when we pass to the debate between contact electricity and chemical electricity.

The pile gave the contact theory a second life by providing it with a positive purpose: to show the nature of voltaic electricity. Thus, in respect of their purposes and experimental means, there were in fact two contact theories. Volta had two reasons to connect them. First, he wanted to prove that the same electricity acted in animal bodies as in the pile. Second, to preserve his general theory he had to rely on Galvani's experiments as his only proof that solid-liquid and liquid-liquid contacts moved electricity. His followers, however, were not interested in physiology, thus they ignored the first theory together with supporting experiments. This means they had to develop physical-chemical means to prove the existence of *emf* in solid-liquid and liquid-liquid contacts.

The first theoretical challenge to the second contact theory came immediately after its publication. Its authors believed that the contact theory could not explain the connection between the power of a pile and the chemical composition of its cells. Thus, like the theory of animal electricity, the contact theory was challenged for its original flaws rather than for its inability to account for new phenomena.

A peculiar aspect of the contact electricity paradigm was an absence of the "puzzle-solving" activity as understood by Kuhn. An improvement of voltaic cells – the major preoccupation of electro-chemists – did not require them to engage into a discussion of the nature of voltaic electricity. Although the "contactists" did modify the theory to explain some new experiments, they did so only in response to a challenge from the "chemists", never on their own free will. In other words, the "anomalies", which are supposed to eventually lead to a crisis, were not uncovered from within the paradigm, but were provided by the rival theory. This fact suggest a fresh look at how and when the chemical paradigm was actually introduced.

According to Kuhn, an arrival of a new paradigm is reflected in textbooks. The chemical theory first appeared in a textbook – as an alternative to the contact theory – in 1845, and it became common in teaching in the 1860s-1870s. On the other hand, the chemical theory reached an intellectual parity with the contact theory no later than 1845, when it already possessed specific theoretical and experimental means, a way for identifying problems for solution, a group of devoted followers,

[37] KIPNIS (1985).

and when it began to attract converts from the other camp. These are features of a new paradigm. It appears, therefore, that there was a period that lasted for at least 20 years when the two paradigms coexisted, and this coexistence ended with a merger.[38]

We do not see any activities within the older paradigm that prepared the way for the newer one. There was no specific weakness in the post-1800 contact theory that inspired the early works on the chemical theory. It was their publication and the subsequent debate that attracted more followers to the chemical theory. Quickly, the two theories became to be seen as equal alternatives. Thus, the new paradigm was established without any prior crisis in the old one. If some "contactists" had ever become disillusioned with their theory, they revealed this only after defecting to the other side. There was no event (a particular paper or an experiment) that could be called "revolutionary" in the transition between the paradigms, and the very word "transition" is hardly proper in this case, "coexistence" being a more precise one.

Another disagreement with Kuhn's theory concerns emergence of simultaneous theories.

According to Kuhn, if there is a paradigm, a new theory is born within it, and this does not happen until the old theory shows an inability to cope with phenomena. Thus, simultaneous theories may emerge only at a pre-paradigmatic stage. In a such a case, an alternative theory does not meet a strong resistance a paradigm would have offered. However, the fact that Volta offered his theory before the galvanic paradigm was established was incidental: if Galvani's discovery had drawn his attention ten years later, he would have offered the same theory, because the motivation for his objections – an apparent presence of "vital forces" in Galvani's theory – would have remained in force.

Thus, we may say that the debate between animal electricity and contact electricity developed while both paradigms grew up and strengthened. This means that simultaneous theories are possible when they belong to different paradigms. If this is so, simultaneous theories ought to be of about the same strength, while a challenger, introduced into a well-entrenched paradigm, must experience a much stronger resistance. This suggests that we should expect a difference in the rhetoric of a scientific debate in the two cases.

However, we have seen that the competing theories in our cases used the same means in their debate whether they emerged at the same time or one much later than the other. Modifying a theory was the main tool in defense, which was facilitated by an essentially qualitative character of the theories. For instance, to deal with different galvanic circuits Volta conceived several independent contact theories. Since voltaic circuits did not allow this, to retain a single theory the "voltaists" proclaimed one sort of a contact, such as metal-metal, to be more important in some experiments and another sort of a contact, such as liquid-liquid, in other experiments. While introducing these changes in the contact theory, they did not

[38] KIPNIS (2001), pp. 139-45.

hesitate to correct (or "clarify") Volta himself. In particular, while Volta emphasized bi-metals and the permanency of electromotive force, his followers extolled metal-liquid and liquid-liquid contacts and considered electromotive force to be changeable by chemical reactions.

In their turn, the "chemists" invoked the law of proportionality only when it agreed with their experiments, otherwise they supplemented it with the hypothesis of secondary reactions. Actually, the "contactists" adopted the secondary reactions too, but used them to explain changes in electromotive force. Characteristically, neither group introduced any changes on its own, without a challenge from the opponents.

The primary offensive means was *experimentum crucis*. As a proof, it turned out ineffective, being easily reinterpreted by the opponents, but it stimulated new experiments. Another strategy to advance a theory was to increase the *number of facts* that favored it or contradicted its rival.[39] The conversion of Becquerel and Matteucci to the chemical theory shows that positive evidence was more effective than the negative one. Here is, for instance, how Becquerel changed his perception of the relative role of chemical force in a pile compared to electromotive force: in 1824, he believed contact electricity to be of chemical origin only in a few cases; in 1834 they became "almost all cases;" and in 1842 he already spoke about "electricity of the pile *totally* originating from the chemical action".[40]

Each theory was known to possess flaws from its very birth, and there was no objective way to decide which flaws were serious and which negligible. Thus, logic was not the main factor in formulating alternative theories or judging their comparative values. As shown above, different versions of Volta's theory contradicted one another, and some of his proofs were illogical. These deficiencies were left unchallenged, however. When most scientists decided after 1800 that the contact theory finally replaced animal electricity, this conclusion was logically unfounded. Likewise, de la Rive's claim that electricity by any contact was in fact produced by a chemical reaction was not the only possible logical conclusion from observations.

Apparently, when facing a difficult choice between two theories, scientists relied on their *expectations* of the future proofs more than on logical conclusions from contemporary experiments. These expectations were based on a variety of factors, of which I will mention only two. One was metaphysical concepts, such as "vital forces" or the "Occam's razor". In the Galvani-Volta debate, many treated this factor as working against the theory of animal electricity. Another factor was a belief in the importance of quantification in science. While the chemical theory was purely qualitative, the contact theory had a quantitative aspect (*emf*) in it. Thus, those who considered a quantitative capacity to be an essential attribute of a theory, had no choice but to support the contact theory.[41]

[39] FARADAY (1839).
[40] BECQUEREL (1842), I, p. 69.
[41] KIPNIS (2001), pp. 142-3.

7. Conclusions

An interaction of animal electricity, contact electricity, and chemical electricity shows that:

- A new theory may be challenged immediately after its birth, without waiting for its failure to explain new experiments.
- Anomalies in a theory may be pointed out by outsiders rather than produced by a "puzzle-solving" activity within a paradigm.
- A new theory may be offered without a crisis being perceived within a paradigm.
- A conflict between two theories may be resolved without one replacing the other, in particular, by a sort of a merger.
- Two paradigms may emerge at the same time and coexist, even for a long time. Simultaneous theories may emerge when they belong to different paradigms.
- An interaction between alternative theories may be similar, whether they are simultaneous or consecutive.

Thus, Kuhn's theory of scientific change is not applicable to this case. Either the theory of contact electricity is an exception, the reason for which remains to be explained, or Kuhn's theory is in need of modifications.

BIBLIOGRAPHY

ACADEMIE DES SCIENCES [First Class] (1802), "Rapport [...] sur les expériences du cit. Volta", *Annales de Chimie*, 41(1802), pp. 3-23.

ALDINI, G. (1794), *De Animali Electricitate. Dissertationes Due*, Bologna, 1794, I.

BAUMGARTNER, A. (1824), *Die Naturlehre*, Vienna: Heubner, 1824, II, pp. 221-42, 2 parts.

BECQUEREL, A.-C. (1823), "Des actions électro-motrice produites par le contact des metaux et des liquides", *Annales de Chimie et Physique*, 25 (1823), pp. 405-15.

ID. (1842), *Traité de physique*, Paris, 1842, 2 vols.

BOSTOCK, J. (1802), "On the Theory of Galvanism", *Journal of Natural Philosophy, Chemistry and the Arts*, 3 (1802), pp. 69-79.

BERNARDI, W. (2000), "The Controversy on Animal Electricity in the Eighteenth-Century Italy: Galvani, Volta and Others", in BEVILACQUA and FREGONESE eds. (2000), pp. 101-14.

BEVILACQUA, F. and FREGONESE, L. eds. (2000), *Nuova Voltianas*, Milan: Hoepli, I, 2000.

ID. eds. (2001), *Nuova Voltian*, Milan: Hoepli, III, 2001.

DAVY, H. (1800), "Notice of some Observations on the Causes of the Galvanic Phenomena", *Journal of Natural Philosophy, Chemistry and the Arts*, 4 (1800), pp. 337-42.

ID. (1807), "On some chemical agencies of electricity" [1807], in DAVY. (1839-40); [facsimile: New York, Johnson Reprint, 1972, 9 vols., V, pp. 1-56].

DAVY, H. (1839-40), *Collected Works of Sir Humphry Davy*, London, 1839-40.

DE LA RIVE, A. (1828), "Sur des circumstances qui déterminent le sens et l'intensité du courant électrique dans un élément voltaïque, *Annales de Chimie et Physique*, 37 (1828), pp. 225-86.

ID. (1836), "Troisième mémoire sur l'électricité voltaïque", *Annales de Chimie et Physique*, 62 (1836), pp. 147-207.

DESPRETZ, C. (1825), *Traité élémentaire de physique*, Paris, 1825.

FARADAY, M. (1839), "On the source of power in the voltaic pile", 16th and 17th series, in *Experimental Researchers in Electricit*y, in series "Everyman's Library", edited by Tyndall, London-NY, [n.d.], pp. 232-316.

GALVANI, L. (1953), *Commentary on the Effects of Electricity in Muscular Motion* [1791], Foley, M.F., trans., Norwalk, CT: Burndy Library, 1953.

ID. (1937), *Memorie ed esperimenti inediti di Luigi Galvani* [1786], Bologna, 1937.

ID. (1794), "Supplemento al trattato dell'uso e dell'attività dell'arco conduttore", in *Dell'uso e dell'attivita dell'arco conduttore nelle contrazione dei muscoli*, Bologna, 1794, pp. 3-23.

GILBERT, L.W. (1808), "Noch einiges über die Electricität, welche in Berührung entsteht", *Annalen der Physik*, 28 (1808), pp. 203-22.

KIPNIS, N. (1985) " "Animal" Electricity in the First Half of the Nineteenth Century", presented at Midwest Junto, Minneapolis, 1985, unpublished.

ID. (1987), "Luigi Galvani and the Debate on Animal Electricity, 1791-1800", *Annals of Science*, 44 (1987), pp. 107-42.

ID. (2001), "Debating the nature of voltaic electricity, 1800-1850", in BEVILACQUA and FREGONESE eds. (2001), pp. 121-51.

KRAGH, H. (2001), "Confusion and Controversy: Nineteenth-Century Theories of the Voltaic Pile", BEVILACQUA, F. and FREGONESE, L. eds. (2001), pp. 133-57.

KUHN, T.S. (1970), *The Structure of Scientific Revolutions*, Chicago: University of Chicago Press, 1970^2.

ID. (1970a), "Logic of Discovery or Psychology of Research", in LACATOS. and MUSGRAVE eds. (1970), pp. 1-23.

LACATOS, I. and MUSGRAVE, A. eds. (1970), *Criticism and the Growth of Knowledge*, Cambridge: Cambridge University Press, 1970.

MARIANINI, S. (1830), "Mémoire du docteur Etienne Marianini [...], sur la théorie chimique des électromoteurs voltaïques simples et composés", *Annales de Chimie et Physique*, 45 (1830), pp. 28-55, 113-57.

NICHOLSON, W. (1802), "Observations on the preceding memoir", *Journal of Natural Philosophy, Chemistry and the Arts*, 1 (1802), pp. 142-4.

OSTWALD, W. (1980), *Electrochemistry: History and Theory*[1896], transl. from German, New Delhi: Amerind Publishing Co.; Sprinfield, Va, 1980, 2 vols.

PERA, M. (1992), *The Ambiguous Frog*, Mandelbaum, J., trans., Princeton: Princeton University Press, 1992.

SCHÖNBEIN, CH.F. (1838), "Observations sur le role électromoteur de quelques peroxides métalliques, du platine et du fer passif", *Bibliothèque Britannique*, 14 (1838), pp. 150-61.

VALLI, E. (1793), *Experiments on Animal Electricity with Their Application to Physiology, and some Pathological and Medical Observation,* London, 1793.

VOLTA, A. (1793), "Account of some discoveries made by Mr. Galvani [...] in Two Letters from Mr. A. Volta [...] to Mr. Tiberius Cavallo", *Philosophical Transactions of the Royal Society of London* , 83 (1793), pp. 10-44; [also in *VO*, I, pp. 169-208].

ID. (1800), "Mémoire sur l'électricité excitée par le contact mutuel des conducteurs même les plus parfaits", *Philosophical Tranactions of the Royal Society of London*, 90, pt. 2 (1800), pp. 403-31, [also in *VO*, I, pp. 563-82].

ID. (1801), "De l'électricité dite galvanique", *Annales de Chimie*, 40 (1801), pp. 225-56.

ID. (1802), "Letter to J.C. Delametherie, on the galvanic phenomena", *Journal of Natural Philosophy, Chemistry and the Arts*, 1 (1802), pp. 135-42.

ID. (1802a), "Aux redacteurs de la *Bibliothèque Britannique*", *Bibliothèque Britannique,* 19 (1802), pp. 274-89.

ID. (1802b), "Fin de la réponse d'Alexandre Volta à quelques objections à sa théorie insérées dans les journeaux anglais", *Bibliothèque Britannique,* 19 (1802), pp. 339-50.

WOLLASTON, W.H. (1801), "Experiments on the Chemical Production and Agency of Electricity", *Philosophical Transactions*, 91:2 (1801), pp. 427-34.