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Volta and the Quantitative Conceptualisation of Electricity: From Electrical Capacity to the Preconception of Ohm's Law[1]

The development of electric measurement technology in the eighteenth century laid the basis for establishing electricity as a new – and in a certain way quasi-technological – branch of physics. Very important in this context are the role of the frictional electrical machine from the forties onwards, the invention of the Leyden jar in 1746 and the development of lightning rod electrotechnology, from 1751, in connection with atmospheric electricity. Electricity was also useful for medical purposes. But this was not so important for the research of those scientists who were mainly interested in physics ("physique particulière", in the sense of the famous French *Encyclopédie*). The development of an independent instrumental and conceptual electrical cosmos showed that electricity required an important place within the expanding experimental physics of the eighteenth century – ranking at least with "aerometry", "thermometry" and "meteorology". At the same time electrotechnology (lightning rods) met with more response in public than any technical consequence of the other branches of science.

I will show that Volta's conceptual development itself, with his instruments and measuring methods, defined what science should be, what experimental and theoretical steps should be taken first and how one should talk about all that. I will also show how difficult it was to combine these developments with the existing complicated models of mechanics. They often stayed separated. Here action at-a-distance and fluid action were not decisive opposites. No common language was used in electricity, no broad communication – e.g. forced by a scientific society (see the isolated role of Henry Cavendish) – no constant area of phenomena existed. On the contrary, knowledge about electricity often grew so rapidly that the development

[1] See also: TEICHMANN (1974), already treating the formulation of quantitative electrical concepts and the preconception of Ohm's law; TEICHMANN (1977), discussing the influence of Volta's contact theory in Germany and its role in the understanding of galvanic circuits; HEILBRON (1979), pp. 453-7, dealing with quantitative electrostatic concepts.

of concepts seemed unripe or already outdated. "Experiments ended" before they were formulated as a scientifically acknowledged canon. In spite of this, Volta's scientific concepts of – especially – "capacity", (capacità), "tension" (tensione), "load" (quantità) became fruitful ground for new researches, e.g. for his electric battery programme, for his astonishing remarks about what was later called Ohm's law, and for Ohm's research itself in 1825-6. These concepts were very closely related to simple mechanical ones and to refined but commonly reproducible measurements. The latter were importantly different from the electrostatic experiments of Charles-Augustin Coulomb (1786) and Henry Cavendish (1771); their measurements could not be handled so transparently.

In the 1770's three scientists tried to quantify a larger number of electrical phenomena by specific concepts and measurement methods. These were the Englishman Henry Cavendish (from 1770 till 1776) and the Italians Giambatista Beccaria (especially in 1772) and Alessandro Volta (starting in 1778). Henry Cavendish was a very isolated genius between chemistry and physics, also competent in higher mathematics. Personally he was a queer fellow. Beccaria and Volta were experimental scientists in "physique particulière" without any interest in mathematical physics ("mathématiques mixtes"). Even with fractions they had some problems as we can see e.g. from their difficulty in handling the reciprocal concept of resistance instead of the commonly used conductivity.

Volta, quite clearly, followed the rough concepts of Beccaria. But he also knew the two electrical publications of Cavendish.[2] He was clearly not able to accept usefully Cavendish's important and very theoretical paper from 1771, which formed some foundation for general electrostatics.

1. The Work of Henry Cavendish and Giambatista Beccaria

Cavendish was the first researcher in electricity who clearly distinguished between two different concepts: load (quantity of charge) and degree of electricity.[3] In the course of his paper 1771 he accepted an incompressible fluid. Here the mechanical concept analogous to the degree of electricity is pressure, instead of density in the case of a compressible fluid. The concept of density (till the beginning of the nineteenth century still used as surface-density) was common for Beccaria, Volta and others. But Cavendish discussed no details of his model. He started his research (like Beccaria and Volta) from the experience of electrical shocks. The human body was used as a physiological measuring instrument mainly after 1746 (invention of the Leyden jar). To the great surprise of scientists interested in quantitative aspects,

[2] CAVENDISH (1771) and CAVENDISH (1775).
[3] We will find some steps taken in the direction of this distinction even before Cavendish: see e.g. PRIESTLEY (1767).

sometimes a shock was stronger although the electroscope showed weaker electricity. But there were only a few such scientists. This limitation to quantitative physics was not easy to accept nor very common at that time of expanding experimental knowledge in electricity. Physiological effects (and later on also chemical ones – see Volta from 1792 on) had to be restricted to only quantitative signs. Cavendish wrote in 1771:

> The shock produced by the Leyden vial seems due only to the great quantity of redundant fluid collected on its positive side, and the great deficiency on its negative side; so that if a conductor was prepared of so great a size, as to be able to receive as much additional fluid by the same degree of electrification as the positive side of a Leyden vial, and was positively electrified in the same degree as the vial, I do not doubt but what as great a shock would be produced by making a communication between this conductor and the ground, as between the two surfaces of the Leyden vial, supposing both communications to be made by canals of the same length and same kind.[4]

He also used – in unpublished manuscripts – the model concept of "reservoirs" of electricity (as Beccaria did later on) and defined the unit of capacity (without using this name) as load at some degree of electricity:

> Def[inition]. The charge of globe 1 inc[h]. diam[eter]. placed at great dist[ance] from any other body is called 1 glob[ular]. Inc[h].[5]

In 1771 Cavendish also accepted Coulomb's law (later so called) as basic to his theory. He proved it by an indirect experiment which was much simpler and more exact than Coulomb's – but also written down only in unpublished manuscripts. He also defined the concepts of electric current and – very important – electrical resistance by theoretical reflections and measuring methods. He eventually found the exact formulation of how currents divide up in parallel circuits (later called Kirchhoff laws).[6] This was partly published in 1776 – in his paper about the Torpedo fish. Even if he had not been this queer fellow, as his contemporaries described him, he would not have had much influence through this research. Physics at that time was unprepared for such mathematical electricity. Just the very slight interest of Beccaria and Volta in these publications shows this problem. Each scientist – like Volta – who did not want to suffer this fate of Cavendish, had to work hard on his explanations, if he was interested in some quantitative aspects.

To describe quantitative phenomena of the electric "current" from a Leyden jar, the model of a compressible fluid like a gas, or of an elastic body like a spring, is often to be found from 1746 onwards. In 1753 Beccaria used the word "cisterns"

[4] CAVENDISH (1771), § 128.
[5] CAVENDISH (1921a), § 654.
[6] CAVENDISH (1921b).

(serbatoi) for electricity. They had a certain "capacity" (capacità).[7] It was clear for him that "the electric vapour" or "fire" was equally distributed over the surface of electrified bodies. But we also find all this in others at this time (e.g. Le Monnier, Priestley). Not until 1772 do we find in Beccaria the clear distinction between the concepts of capacity, density and load:

> By multiplying the surplus of density, which the fire has in a given body relative to the density of the fire in the earth [...], by the capacity of the same body, the product gives the value of the surplus of electricity, that means the sum of the fire [...].[8]

That is analogous to the modern equation:

voltage x capacity = load

Instead of "sum of the fire" he also used the word quantity. We do not find this equation in Cavendish. Even if – which is quite possible – Beccaria was stimulated in his concepts of density and load by the famous first publication of Cavendish in 1771, he had changed these concepts for his empirical law. For him light, noise, shock and broadness of electric sparks were a measure for the "quantity" of charge, the length of the sparks and the signs at the electroscope measured the "density". He proved this with different electric shock experiments. These were mainly based on Franklin's research. Further on in his publication, instead of "density" he used the words "tension" (tensione) and "relaxation" (rilassamento); instead of these the words "surplus of tension" and "lack of tension" and finally only "tension" (be it positive or negative).[9] The concept of load was not precisely distinguished from the concept of velocity. With velocity (and rapidity) also Cavendish had had big problems. To be sure, the complex exponential discharge of a condenser here offered too big a challenge. Beccaria also roughly defined the concept of resistance – in its reciprocal form of "conductivity" (deferenza). It was a function of the specific characteristics (proprietà) and the thickness of the conductor and should be proportional to its length. With these concepts he also tried to clarify what happened if Leyden jars were discharged on parallel circuits of metal wires and human bodies.[10]

In this respect Cavendish's 1776 publication (and his preceding and subsequent unpublished work) was more thorough. At that time he no longer tried to develop basic electrostatics. He was mainly interested in the question of how he could prove that the shocks of the torpedo fish were really electric ones. His experimental – and at the same time theoretical – genius led him to very astonishing research. We may admire his skill and tacit knowledge e.g. in measurements where the specific conductivity, length and cross-sections of the resistances used were changed in such

[7] BECCARIA (1753), § 352.
[8] BECCARIA (1772), § 88. An English translation was published in 1776.
[9] *Ibid.*, §§ 439, 506, 509.
[10] *Ibid.*, §§ 323-9.

a way that the electric shock always stayed the same. So this unknown function shock was by-passed.[11] (Beccaria, too, tried some of those experiments).

2. Volta's Concepts: Load, Tension, Capacity and Resistance, till 1791

Cavendish and Beccaria certainly would not have had any greater historical influence without Alessandro Volta. The main reason why Volta was more effective than both those scientists is that he had a great talent for divulging his knowledge by publications, letters, lectures and personal meetings. He was just the contrary of a queer fellow. We can imagine this both from his huge correspondence, which – from 1778 on – repeatedly emphasised the distinction between "load" (quantità) and "tension" (tensione), and also from his travelling round Europe. All his colleagues praised his social skill. Georg Christoph Lichtenberg said: "Volta has plenty of knowledge and is very able to prove it, he is a raisonneur above all.".[12] His interest in developing useful and at the same time often delightful instruments and combining them with his new concepts has to be added to this skill. Already in 1763, at the age of 18, Volta exchanged letters with Jean Antoine Nollet, in France, and with Beccaria. His first publication, dated 1769, discussed Beccaria's electrical theory.[13] But not until 1775 did he use Beccaria's concept of capacity (capacità). Capacity could be measured by the "magnitude or force" of the electrical signs. He did not distinguish e.g. between the length of the sparks and the strength of electric shocks. Both seemed larger for him if the surface of his condensers was enlarged.[14] In 1775 he invented the electrophorus. One basic feature of this device was that it produced high voltages by lifting up the upper plate. Another important feature was that this operation could be repeated many times with little diminution of the efficiency. Volta embedded the electrophorus in a specific conceptual framework, claiming independence from Franz Ulrich Aepinus and Johann Carl Wilke, who had described and interpreted similar devices some time earlier. With the aid of his new apparatus and its conceptualisation Volta wanted to disprove a basic thesis of Beccaria's theory.[15]

His great publication of 1778[16] eventually brought in the distinction between load and tension. But nowhere in this paper did he cite Beccaria, despite the fact that the title (about electrical shocks from simple conductors and Leyden jars) already sketched one of the main problems of electricity that had led Cavendish and Beccaria to their important conclusions. He started with a lot of detailed experiments. From these he

[11] CAVENDISH (1921), e.g. §§ 574-8.
[12] LICHTENBERG (1784), p. 258.
[13] VOLTA (1769). Volta chose the form of a letter to Beccaria.
[14] VOLTA (1775), pp. 105-6 and VOLTA (1775-6), 2nd letter [Nov. 14, 1775], p. 118.
[15] VOLTA (1776), p. 138. See also VOLTA (1775).
[16] VOLTA (1778).

stated that – contrary to "the commonly accepted law" of proportionality between "capacity" (capacità) and surface – the capacity of a longer cylindrical conductor was larger than that of a shorter one, even if both surfaces were equal. He therefore recommended thin, long conductors as reservoirs of electricity. (This cannot be true from the point of view of modern knowledge). But they should not be too thin because, in that case, electricity would spread out into the air too quickly. A diameter of 1.4 cm for silvered wooden rods would be good enough for the highest tension. He finally accepted capacity as proportional to length. More important than this statement was his measuring technology. He found that different cylindrical conductors of the same surface contained different loads by:

- charging them till they began to discharge spontaneously and slowly into the air, and now comparing the shock by discharging them immediately against the body,
- comparing the number of rotations of a frictional electrical machine till an "electrometer" marked a certain "tension",
- comparing the "magnitude" of the spark taken by each conductor from an equally charged Leyden jar; this spark should then be a proportional measure for the "capacity" of the conductors.

That means, he measured the capacity by load at constant voltage. Quite right, Cavendish's research, of 1771, was much better but Volta was concerned with this problem continuously. In this publication Volta also tried to find out the function of the electric shock. He stated that the shock "always is the effect of a current of fire that transverses the body and is proportional to the velocity of its movement".[17] Aside from these concepts he saw only one different one: "there is no other force [energia] than that which I call tension of electricity".[18]

This "tension" is the "effort" (sforzo) with which the electricity "pushes itself out" (spingersi fuori). Further on he stressed two methods for comparing capacities:

- to measure the quantity of electricity at the same tension by the number of rotations of a machine,
- to compare the shocks by discharging a simple conductor and a Leyden jar which were both charged in contact, that means to the same tension.

Some experiments of his looked as if they had been taken directly from Beccaria. E.g. he discharged a Leyden jar against a neutral condenser of the same capacity and only got half the shock compared with when the jar was discharged against the ground. He concluded that the jar handed over so much of its "surplus of fire" to the conductor till both had the same "grade of tension". The whole quantity therefore

[17] *Ibid.*, p. 219.
[18] *Ibid.*, p. 213.

was divided up relative to the different capacities. If these were equal, he got secondary shocks from each of the now separated condensers. These shocks were equal to one another and equal to half the first one against the ground. In 1772 Beccaria used almost the same words and got the same results. If, Volta continued, the conduction was not perfect, the "current of fire" would be more or less "delayed" and the discharge would not be produced "abruptly but successively, although not in a long time". Therefore also the shock was lower. He also described this delay in the following way. No large quantity of charge would run through the "channel" in one "moment", but only a small quantity.[19] Here we have the beginnings of his later definition of current: load divided by time. In the year 1782 he wrote a letter from London about the torpedo researches of Walsh and Cavendish and mentioned the very big quantity of fluid, which was discharged in one "moment". Only the "energy, ... the tension to use my expression" was very small in respect to a battery of Leyden jars.[20] But later on in the eighties the effects of the electric current (shocks, burning effects, melting) again were ordered proportional to quantity *and* velocity. Also the model of the "circuit of the electric fire" as a "continuous run" is found in his publication of 1778.[21]

Comparing Volta's results with Beccaria's we can judge that Volta in 1778 constantly used the term "tension" and a slightly better hydrodynamic model of current. But his language was much more precise and concentrated.

We will not find further improvements before his publication of 1782,[22] where he stated the law:

tension x capacity ~ load,

analogous to the modern equation:

voltage x capacity = load.

But again Volta's terminology was used mainly with relation to a new instrument which he named "condenser" (condensatore) or "microelectroscope" (microelettroscopio). A strong analogy with the famous microscope in optics was clear. Maybe, Volta expected (or wanted to stimulate) similar importance for his own instrument in electrical research. The microelectroscope was like the electrophorus similar to a plate condenser: upon a metal plate that bore a layer of resin (ca. 0.5 mm) a further metal plate was freely movable. This metal plate now got a load of non-detectable (e.g. atmospheric) electricity. When it was then lifted up, it suddenly gave electrical signs ("attraction", "repulsion", "sparks"). The degree

[19] *Ibid*., pp. 220, 225.
[20] VOLTA (1782), pp. 10 and ff. VOLTA (1784-?), p. 457.
[21] VOLTA (1778), pp. 224-5.
[22] VOLTA (1782a). Also in VOLTA (1782b) and VOLTA (1782c).

of this "condensed electricity" could be different. In the second part of his publication Volta gave a theory for this apparatus: a metal plate in the vicinity of a second one had much larger capacity. He continued:

> It is easy to understand that there is larger capacity where a given quantity of electricity goes up to lower intensity, or, which is the same, [where] a greater quantity of electricity is required to take the action up to a given degree of intensity, and vice versa: in short the capacity and the action, or electrical tension, are in inverse proportion to one another.[23]

The English translation in the *Philosophical Transactions* avoided "action or electrical tension" and used "intensity". With further experiments he was convinced he was showing that this relation was proportional: a metal rod that was discharged against another one (one fifth of the length) showed one sixth of the tension.

His two cited cases are analogous to the modern equation:

capacity ~ load/voltage

From his words it becomes very clear that the mechanical model of springs, which mediated the electrical forces, led him to his concept of electrical tension. Volta knew that his concept of capacity was not defined very well by his measuring methods. Only the capacity of the plate condenser became exactly proportional to the area of the metal. But in general, he concluded, the capacity of a free conductor was proportional to "the surface, which is free from the action between the atmospheres of the same kind". If this conductor was placed in front of another one that was earthed, the capacity grew proportional to the surfaces and proportional to the inverse of the distance. He measured this by the tension of the charged conductor, which e.g. was diminished by bringing it closer to a second one.[24]

Now he also used the reciprocal concept of conductivity, called resistance. He described the air resistance between two metal plates as being so large that the (relatively small) tension could not overcome it. A Leyden jar would discharge an amount of load to a conductor that was proportional to the latter's capacity. This was wrong – as in 1778 – but he knew about the problem in some extreme cases: if a simple conductor instead of the Leyden jar was used, this relation did not hold true; it could not give what it did not possess.

In unpublished papers, probably read at the University of Pavia, the theoretical concepts, till now bound mainly to instruments and experiments, gained more independent life. The direct proportionality principle:

load ~ tension x capacity

[23] VOLTA (1782a), p. 286.
[24] *Ibid*., pp. 287-8. See also his ingenious use of his simple law in such condenser experiments, e.g. HEILBRON (1979), pp. 453-7.

was formulated (similar to Beccaria). Because a small but strongly electrified conductor gave long sparks but no big effect and no shock – opposite to a large but weakly electrified one – it "is very important to distinguish clearly between intensity and quantity of electricity". Electrometers would show, for example, the "existence" and "intensity" of electricity but not the "quantity".[25] All this sounded similar to Beccaria.

At that time the concept of conductivity was not an important part of Volta's research. He was mainly concerned with the specific conductivity and divided physical bodies into classes: e.g. imperfect conductors, very imperfect conductors. The imperfection of the conductors was responsible for the delay of the electric "fluid".

Atmospheric electricity was, quite rightly, very interesting for Volta. Also for this purpose he wanted to construct exactly comparable electrometers, independent of e.g. the type of electrometer – as had been previously done in thermometry and hygrometry for the respective instruments. He used the method of halving a given tension (as Cavendish did) to calibrate his quadrant electrometer (derived from Henley): a charged Leyden jar was discharged against a neutral one of equal shape. The new sign at the electrometer now marked half of the previous tension. But when he changed the initial tension of the charged Leyden jar he had the problem of marking his new, unknown, tension in relation to the first one.[26] He also used the spark distance to measure tension and tried to find out the relation between the distances and the degrees marked by the electrometer. We also find reflections about something like a calibration curve for electrometers by repeated division of a given charge. He also multiplied the charge of a conductor by repeated adding of charges with his electrophorus.[27] He also calibrated different types of electrometers against his sensitive straw electrometer. This way he got a scale from 1 degree to 2,000 degrees (of the straw electrometer). Even if these different electrometers did not become comparable in an exact manner (it would have been better for him to restrict himself to one type, as Cavendish did), this work shows that there was a vast field of development for electrical measurement technology. It would have been possible to reach the exactitude of thermometry, if Volta had concentrated more on this subject and if he had found more "supporters" or "users" for this technology. But there was no specific interest shown by any scientific society (like the Royal Society in the case of Fahrenheit) and no challenge of any electrical industry. Lightning rod technology grew very quickly – it is true – but scientists and technicians had some difficulties with quantitative measurement (tension and load from lightning were too high for electrometer measuring).

In 1787 Volta criticised the "view" (of Mahon and Coulomb) that the "effect of electricity" was proportional to the inverse of the square of the distance of the

[25] VOLTA (1784-?), pp. 417-9.
[26] VOLTA (1787-88), 1st letter, p. 37. VOLTA (*post* 1800), p. 133. VOLTA (1802), p. 183.
[27] VOLTA (1787-88), 1st letter, pp. 41-2. See also *VO*, IV, pp. 15-20.

charged bodies.[28] The "pressure" of the electric "atmosphere" would be nearer to the simple inverse proportionality. But with different plate condensers (form, surface area) he got other laws. As for other scientists, it was not clear to him that point charges were a crucial precondition for this basic law (of Coulomb/Cavendish). Indeed he remained more interested in the calibration of electrometers. E.g. he tried – being not the first one with this interest – to define a "fundamental degree" for his quadrant electrometer by the attraction of two condenser plates. He also explained again why this measurements were so important for him:

> No physicist will deny that, to develop and perfect the different branches of natural Science, it is convenient to start perfecting the corresponding instruments.[29]

This held true e.g. for barometers, thermometers, microscopes, telescopes and others. In 1790 he tried to transform his "atmospheric electrometer" into a "very sensitive hygrometer" – another new instrument.[30] Discharge time was a function of the resistance between the electrometer and the earth. And this resistance depended on the humidity in the air, to a remarkable and measurable amount, if he used for this discharge a body which had conducting characteristics "in the middle between conductor and non-conductor". He performed experiments to find out the function of the discharge time in relation to length and cross-section of the "semiconductor" employed. He defined the "discharge time" as the time that was necessary for Henley's quadrant electrometer to fall from 25 degrees to 5 degrees. His results gave a non-proportional relation (which is wrong according to modern formulas – at least for length). In respect to the influence of the cross section – quite remarkably – he concluded that, with a "very imperfect conductor", most of the fluid would flow along the surface but a certain amount would also be conducted by the inner parts. Extreme cases should be called "contained electricity" (elettricità contenuta) or "stagnant electricity" (elettricità stagnante) – here all electricity stayed at the surface. On the other hand there was the electricity "which really moves and flows from one body to another, penetrating into all the interior of the bodies". That means he distinguished between electrostatic and electrodynamic effects. For measuring the discharge time he now used his straw electrometer and summed up the results: the time needed by this electrometer to fall from a certain degree (10 degrees) to another one (2 degrees) increased with:

- worse conductors
- greater length
- smaller width and thickness
- drier conductors.

[28] VOLTA (1787-88), 2nd letter, pp. 78-9.
[29] *Ibid*., p. 84.
[30] VOLTA (1790).

His direct interest in measuring was stronger than any attempt to formulate new basic concepts (e.g. resistance), which really would have been possible, as Cavendish had shown around 1776. His remark that the electrometer fell faster from 10 degrees to 2 degrees than from 2 to 0 was also not followed by any reflection. Like Volta, no other scientist at that time – even if better at mathematics – reflected on this non-constant current.

Volta's broad interest in all the fields of electrostatics, electrodynamic phenomena, electrophysiology and meteorology was really very useful for his success in developing a comprehensive canon of electrical language (even if it was not as exact as Cavendish's). This language helped to describe a lot of electrical phenomena in a (semi-)quantitative way. There were some scientists (Tiberio Cavallo, Martinus van Marum etc.) who followed Volta in adopting similar simple concepts (e.g. tension and capacity).[31] But they did not make such full use of them as Volta did.

3. Volta's Transfer of his New Electricity "Language" to the Phenomena of Galvanism, till 1799

For the fast clarification of Galvani's discovery by Volta (from April 1792 onwards) several facts were important:

- Galvani's experiments and his theses strongly connected the discovery with known frictional electricity.
- Volta in his scientific research had been mostly concerned with electricity. He believed that all electrical phenomena belonged to an independent branch of physics. He stood out against any universal hypothesis.
- His talent was with experiments and instruments. His interest in improving measuring technology was dominant. (This he also stated in 1792).
- He used the concepts of load, tension and capacity, and separated electrostatic phenomena quite clearly from electrodynamic ones (here the problem of electric shocks played a big role). The importance of discharge time had led him to some rough conception of current and resistance.
- Even before his galvanic research, he was convinced that to produce frictional electricity no real friction was necessary but only a very good contact between the surfaces of different bodies. Friction would only multiply this effect.[32]

Volta used the side discovery of Galvani (that two different metals in the discharge circuit frog-conductor produced more effect than one) to develop a central

[31] See HEILBRON (1979), p. 457. Often Volta was cited with his distinction between "quantity" and tension, but it was not accepted as common language for research. See e.g. KÜHN (1796-97), I, pp. 149 and ff.

[32] E.g. VOLTA (*post* 1779-80), p. 175, footnote.

thesis of his theory: only the contact of two different metals with a third (non-metallic) conductor would produce a permanent electric current. The metals acted like "motors" (motori, eccitatori) and brought the electricity into "perpetual circular motion". He apparently used the model of a hydrodynamic circuit with a pump. He did not speculate what kind of "impulsion" or "secret force" was responsible for this motion, that means he did not speculate about any "perpetuum mobile". The steady current was more an opposite concept to the short discharge of a Leyden jar. Volta avoided any physiological or chemical explanation, although he must have seen some chemical effects (e.g. on the metal plates).

Even if there were no electrometric signs from the new fluid, Volta was convinced of its electric character. For example, in 1792, he described the different sensations by the tongue at the plus and minus poles – comparable with the corresponding sensations of a frictional electrical machine – and explained these phenomena by his model of electric current. His use of language showed uncertainty. So he did not use his load/tension distinction, although at the same time he operated with both concepts in handling electrostatic phenomena. He only used – sometimes – the words "quantity" or "force" of electricity: "the very copious current has such a small velocity and develops such a small force and tension that it does not give any sign at the electrometer".[33] But the concept of "velocity" was not separated clearly from "tension", although the "copious current" really meant "more quantity of electricity". In the second half of 1793 he stated (in manuscripts) that the "current" of a Leyden jar that was so "weakly charged" that it gave no electrometer signs and caused nevertheless the same sensation in the eye as the new method. The Leyden jar "current" then, with its "medium quantity of electric fluid" and its "very low tension", seemed equal to the current of the new method.[34] But we do not find such a clear distinction in publications of that time.

Still in 1792 he ordered the metals into 3 classes – relative to their physiological effects (e.g. the sensation on the tongue). Soon this was changed to one row from zinc to gold. Zinc had the largest "force and effectiveness" to give electric fluid to one metal and the least force to attract it from another metal. In 1795 he stated that this row gave a measure of the "direction and force" of the electric current.[35]

At the centre of Volta's publications of that time we see the thesis of contact electricity simply by analogy with frictional electricity. He also used the concepts of "tension" and "quantity" but the latter only incidentally, without giving any methods of measuring it and without any theoretical interpretation. He concentrated on the electrometric effects that were a sign for the "tension" or "density" or "force". When

[33] VOLTA (1792), 2nd letter [Oct. 11, 1792], p. 139. See also letter to Anton-Maria Vassalli, [April 1, 1792], in *VE*, III, 915, pp. 143-7, on p. 145.
[34] VOLTA (1793), p. 220, footnote.
[35] VOLTA (1794-95), p. 307.

he discovered (in 1796) that by the mere contact of two different metals (without any fluid conductor) he could get electricity – his experimentum crucis – he was finally bound to his analogy with frictional electricity. Shortly before he had still thought it not important if the contact metal-metal or metal-fluid was decisive. That really the unclear concepts of current prevented total analogy, also of language, with frictional electricity can be seen from his attempts to quantify the big amount of electricity in his metallic electricity. A big frictional electrical machine, too, produced "much more fluid in a given time" than a small one. But in electrostatic machines he could compare different currents with the same "tension". This was not possible with the new metallic electricity. Maybe this was a main problem for Volta's concepts before 1799.

The concept of resistance – in the reciprocal formulation of conductivity – remained quite secondary. Often he only restricted it to specific conductivity. For his new theory of metal contact, he operated with a new concept: contact resistance (coibenza, resistenza).[36]

4. The Final Proof of the Identity between Frictional and Galvanic Electricity, till 1801

In 1799 Volta invented the battery. He now had new possibilities for arrangements of elements in series. That also meant quite important opportunities for new measurements:

- The battery amplified the tension in constant steps, as electrometers proved.
- By amplifying the tension, the current could also be amplified, which led to new possibilities of measuring it (stronger physiological effects, gas electrolysis, calorific effects in conductors, brightness of sparks).
- The current could also be changed quite effectively without changing the tension by changing the inner and outer resistance (the distinction between in and out mainly became possible because of this equal ranking of both parts of the circuit).

With the battery Volta now could argue very convincingly against two important objections to his identity thesis:

- That the new electricity did not give any sparks or other "common" signs,
- That there existed non-conductors for the new electricity which, however, were conductors of the "common" electricity (e.g. the flame).

This was the main content of his big publication in 1801: the battery at once gave sparks, electrometric signs, attractions, repulsions etc.[37]

[36] VOLTA (1796-97), 2nd letter [Aug., 1796], pp. 425-6.
[37] VOLTA (1801). Volta gave this paper in Paris, at the meeting of the Institut National des Sciences et Arts, [Nov. 7, 12 and 22, 1801]. Also Bonaparte took part in these meetings.

In the letter announcing the invention of the battery, addressed to Sir Joseph Banks on 20 March 1800,[38] Volta still avoided using the clear distinction of the concepts load, tension, etc. He first had to solve some new problems. The shocks from a battery grew when the temperature of the fluid conductor between the metals was raised – or when salted water was employed – because the water now "conducted better". However:

> But all these means and all these attentions have only a limited advantage, and will never occasion your receiving very strong shocks as long as the apparatus consists but of one column, formed of only 20 pairs of plates, even though they may consist of the two metals properest for these experiments, viz. silver and zinc; for if they were silver and lead, or tin, or copper and tin, the half of the effect would not be produced, unless the weaker effect of each pair were supplied by a much greater number. What really increases the electric power (puissance) of this apparatus, and to such a degree as to make it equal or surpass that of the torpedo or electric eel, is the number of plates […].[39]

He was wondering why some effects grew only "a little" with the number of pairs of plates (e.g. the sensation on the tongue), some effects not at all (the physiological effect of light on the eye). All other experiments – especially those with the electrometer – showed that each pair of plates "adds to the electric current a degree of force".[40] Different words like "vertu", "force", "puissance", "pouvoir", "current" were used without any clear distinction. There was actually a big difference compared to the circuits with condensers in series charged with frictional electricity. The in series connection of equally charged condensers raised the tension, but not the load, which was discharged. The current at the battery also rose – sometimes – with the tension. Maybe these were some main reasons for Volta's language-problems in the letter addressed to Banks. He said nothing about chemical effects, although he had seen the changes on the surface of the plates.

In the autumn of 1800 Volta again used the concept of tension.[41] This became quite clear in the spring of 1801 – in an unpublished letter.[42] He measured the tension with the electrometer and "electric currents" by electric shocks. The "force" or "tension" especially was a function of "the quality of the coupled metals ... and of the number of these couples". To prevent a delay of the electric current, the connecting areas between the fluid conductor and the metal should be very large, especially if the fluid "'is driven by a very small force and reaches only a weak tension". He confirmed that the most important effects of his new apparatus were

[38] VOLTA (1800). For the original translation in English see VOLTA (1800a), republished in VOLTA (1800b).
[39] VOLTA (1800a), p. 294 and VOLTA (1800), p. 569.
[40] VOLTA (1800), p. 579.
[41] See Volta's letter to Prof. Brugnatelli, in *VO*, II, pp. 2-12, on p. 10.
[42] VOLTA (1801a), p. 19.

not just the electrometric ones. These he could prove only with great difficulty and they did not vary with such circumstances as temperature or salt concentration of the water used. With higher temperature and salt concentration, the water became "more conductive". This would be one of the reasons ("if not the only one") why it was better to use salt water around the hands and also between the plates of the battery for getting strong shocks. He noted that these reflections were cited from his letter to Banks "with a few words changed, omitting some remarks". But his conceptual changes were very important. He also made some additional remarks. Maybe therefore, these reflections had been included in a second letter to J. Banks, of which we only possess some manuscript parts.[43] Polvani, Volta's biographer, believed that long before 1800 Volta had looked for direct proof of the identity between the "electric" and the "metallic" fluids. And so he was led to research for raising the tension of the galvanic elements.[44] At least it is true that this development was possible for Volta – as, in 1795 and following his series of more than two metals and one wet conductor had shown.

Between March and May 1801 Volta stated several times that his letter to Banks was only the "epitome" of a more extended paper which was not ready, because "every day the number of phenomena increased in my hands".[45] Maybe he shifted the quantitative aspects (e.g. the increase of the electrometric signs in proportion to the number of pairs of plates) to his later publication of 1801, although he was clear about them. But it is more probable that the relation between physiological and electrometric effects was completely unclear to him, until eventually enough phenomena had "increased in [his] hands" and he had reflected on them.

5. Volta's Prediscovery of Ohm's Law in 1802

In 1801, in his paper about the identity of frictional and metallic electricity, Volta started discussing three objections to his own thesis. He added, to the two already well known ones (see above), a new one: the very great chemical effects of the new electricity that were caused by his battery. In spite of these important new effects, he almost totally concentrated on the first two objections replying to them by pure electrometric research. In the first part of his paper he again, for a second time, laid down his contact theory. The "tension" of one pair of plates, as he had already shown by his "condenser", would prove it. But a still better proof would be the "doubling, tripling, quadrupling, etc. of the electric tension" by correspondingly

[43] VOLTA (1800c). See also *VE*, III, 1138, pp. 472-3.
[44] POLVANI (1942), pp. 347 and ff.
[45] VOLTA (1801a), p. 15.

multiplying the number of pairs of plates in his "new shocking apparatus". He saw this as his essential progress in 1799.[46]

In the course of this paper he extensively described how electrometers were charged by his new apparatus. E.g. 60 pairs of zinc-copper produced 1 degree at his straw electrometer. The battery would also give sparks (very small ones). He concluded from experiment that the length of sparks increased proportionally to the electrometer degrees. About 2 mm length was equivalent to about 150 degrees of his straw electrometer. Quite clearly he did not possess such a big battery (with thousands of plates). Then he also refuted the second objection against his identity thesis: also the "tension" of a "big Leyden jar or electric battery" could be so low that – normally – good conductors like the flame "delayed" the discharge so effectively that no shock was felt. But why could a very "weak load" give such strong shocks? Also this would be no contradiction to the identity because it was valid for both fluids: big electrostatic batteries, even if not strongly charged, could give strong shocks. Responsible for the shocks would be the "very large quantity [of electric fluid] which runs for many subsequent moments in a continuous current".

Shortly later he really clarified the new concept for current as load/time – still without having a measuring process for it:

> in such cases isn't the electric current equal, or I would say, isn't the same quantity of electric fluid running in a given time?[47]

Only the discharge time – even if imperceptibly short – was different. And with this time the shock would increase. That means he saw the shock as a function of the *product* load x time. The values of quantity per time would be equal in each experiment if the tensions, that means the "velocities" were equal. But why did the shock not increase if the current (as really happened in his new apparatus) stayed for a long time? He answered: human reactions to a stimulus last only a certain short time and all following stimuli within this time would raise the shock. However, if they lasted longer (Volta guessed 1/10 of a second), no amplification was possible. But why would a battery give a smaller shock than a Leyden jar that was charged by the battery (even though the current lasted longer)? The reason for this was the bad fluid conductors in the battery which delayed the electric current.

Volta's physiological remarks were right – as modern textbooks in electrophysiology prove – and his concept of inner resistance was very fruitful. But he could not solve the concept of current clearly enough. First, he did not consider that the current in a condenser discharge changed from maximum to zero. Second,

[46] VOLTA (1801), p. 59. Because of this analogy Volta used in all his "chains" of elements pairs of plates also at the ends. That means he believed he had one element more in each battery than according to electrochemical theories (both historical and modern).
[47] *Ibid*., p. 75.

the distinction between "velocity" and "load/time" was not very helpful. He still preferred the model of a solid body, flowing in a fluid medium, which favoured "velocity" and suppressed the hydrodynamic concept of load/time. Maybe he could not imagine that, because of resistances in the circuit, the current itself – that means the quantity in his sense – changed. In his opinion the quantity could only be altered by metallic contact.

Now he found a measuring method for his concept load/time: the time, which was necessary to charge a given condenser. With the battery the "shortest possible touch" was sufficient. Therefore it produced "in any moment" a larger amount of electricity than the best frictional machine. But to bring the electricity "to a high point of tension", the common electrostatic machines were better. The discovery, in 1801,[48] that even along the outer resistance the tension could decrease, confirmed his opinion that resistance changed velocity. The physiological effects, he concluded, remained a very rough measure for electricity because they depended on different physical factors at the same time. We now would expect that he decided to try chemical and caloric effects to control his other results. But he did not, he only mentioned them at the end of the second part. In the third part of his identity paper he only continued to discuss the role of fluid conductors as "impediments" for the electric current.

The whole paper shows how strictly Volta was bound by his electrostatic analogies – instead of combining physiological, chemical and caloric effects. Twice he cited Cavendish with his torpedo work from 1776. If he had had the general interests and mathematical abilities of this scientist, the paper would surely have become a major landmark in nineteenth-century quantitative electrical science.

From March 1802 on, Volta also started to reflect on the importance of the outer resistance. First only the comparison of different effects of the battery was new. In burning and melting experiments (which his colleague Martinus van Marum in Harlem had performed very well) with a short, good conducting wire, connecting the poles of his battery, "the current would not be delayed so strongly" as in the "imperfect" conductor of the human body.[49] That such different effects of the same type of electricity were all explained by the one simple concept of resistance was not a problem for Volta. But a lot of his contemporaries opposed it mainly when they were chemists or working near this science. For Volta the whole circuit was only a physical object. That meant that also the concept of resistance (together with current and tension) had to be sufficient to explain all the phenomena.

In 1802 too, Volta published a paper[50] that contested different objections to his contact and identity theses. Some people did not believe that all the effects of the

[48] Report of the commission of the Institut National about Volta's paper of 1801 (VOLTA (1801)), in *VO*, pp. 106-21, also in SUE (1802), II, p. 366.
[49] VOLTA (1802a), p. 217.
[50] VOLTA (1802b).

battery were produced by electricity, because some of these effects increased if a metal was more readily oxidizable and if the touching fluid more easily oxidized the metal. But the real cause in these cases, he stated, was not the chemical properties but the varying "transparency" for the electric current. Maybe, he guessed, that any fluids reacting chemically with the metal produced a better electrical contact with it. He now discussed the differences in the effects of larger plates. Batteries with larger plates burned and melted short metallic wires better than those with smaller plates, but did not amplify shocks. The cause was the human body being a "bad conductor". According to Volta, this was proved by a simple experiment: a metal wire and the human body in series prevented any melting. Also large Leyden jars charged to weak "tension" showed smaller shocks if more human bodies were connected within the discharge circuit. The fluids themselves did not change the "electric force", they only changed the "resistance" for the electric current.

On the whole, in this paper Volta came near to explaining all the effects in a circuit by using both the concepts of inner and outer resistance.

Perhaps Volta would have been entirely content with this half solution, if a letter from van Marum in November 1801 had not again touched on this problem.[51] Together with Christian Pfaff, he had performed experiments that had been stimulated by Volta. In Paris the German physicist Pfaff had adopted Volta's theory and experimental methods and now was his most eager follower. Both scientists now compared the effects of a pile and an electrostatic battery, the latter was charged to the same "tension" as the pile. They also made experiments with batteries of different kinds and sizes.

Van Marum found that – as discharges of batteries proved – the melting of metallic wires by electric currents depended "on the velocity of the current or (which is the same) on the quantity of fluid, which the discharges cause to flow", in a given time. This was Volta's concept load/time. He also used the name "tension" for the power of the battery, which only depended on the kind and number of metallic plates. He also knew Volta's reflections about inner resistance. The larger the "velocity", the smaller the "impediments". Larger plates therefore produced a larger velocity: "very brilliant" sparks, stronger melting and more oxidation effects. He was convinced, like Volta, that:

> these large humid materials conduct the current better. [But] could it be possible, that also the big metal plates, because of their big capacity, add some amount to the velocity of the current?[52]

[51] Martinus van Marum, Letter to Volta, [Nov. 29, 1801], in *VE*, IV, 1210, pp. 97-114. Volta did not get this letter before the beginning of May 1802.
[52] *Ibid*., p. 109.

Maybe the analogy with the electrostatic law load = capacity x tension led him to this thesis. But also some chemists (like Humphry Davy) soon discussed this idea. By this analogy it seems easy for physicists who knew the concepts of tension and conductivity to find the law:

current = conductivity x tension.

But there were only very few such physicists and for them it was already difficult enough (see van Marum) to replace the concept of capacity by conductivity. What is more, they had to struggle with the complicated compound of inner and outer conductivity, which was not solved by simple addition (as it would have been in the case of the reciprocal resistance concept).

Volta was now really the first (immediately after him came the romantic German physico-chemist Johann Wilhelm Ritter) to use this analogy. He was forced to answer van Marum's question, why bigger metal plates did not amplify shocks in contrast to other effects (chemical, melting ones)? Volta answered in June 1802:

> We conclude that the velocity of the electric current, and consequently the force of the shock we feel, is in composed proportion [raison composée] to the electric tension and the liberty of ease of passing [facilité du passage] through all parts of the chain or circle […] In my view, the shock becomes stronger in so far as the passage of electric fluid through the humid discs of the pile is less hindered, until it is no more hindered than with in the human body, which also has to be passed through. When the largest obstacle is met in this body, it is this obstacle which limits the velocity of the current and then this will not be amplified further by enlarging the paths somewhere else, i.e. the paths through the humid discs. This is why, in respect to the shock, it is no use enlarging the width of the discs soaked in a good salty fluid beyond 1 or 2 inches, and why such an enlargement is very advantageous for melting metal wires when neither the human body nor any other bad conductor slows the electric current down.[53]

Volta mentioned his published paper, dated 18 March 1802, but he admitted that perhaps he had not expressed his views very clearly. He also referred to other parts of his identity paper. But there we find nothing similar to the just cited thoughts. Maybe this problem seemed not so important for him, therefore he now restricted himself to some rough interpretations. On the other hand, there really was a main problem for him: the introduction of the reciprocal resistance concept ("obstacle"), to explain circuits in series. As much as possible he preferred to use the idea of conductivity. One reason for this surely was the mechanical tradition in the way of conceiving a conductor. The existent property of conduction was more interesting than the missing one. Within the simple model of hydrodynamics, which Volta also used, conductivity seemed immediately clear because it is directly proportional to the current. Volta's poor mathematical knowledge (and interest) also prevented him

[53] VOLTA (1802c), pp. 226-8.

from shifting from conductivity to its reciprocal value. It also seemed to be unclear to him that to suppress all effects that occurred in changing the inner resistance, this resistance had to be *negligibly* small in relation to the outer one.

Nowhere in his work did Volta discuss the geometrical factors of resistance very clearly. He was mainly concerned with specific conductivity.

In any case, Volta's cited reflections would be identical with Ohm's law (in the form: current = tension x conductivity), if Volta had accepted only one of his two definitions of velocity, e.g. quantity per time (as van Marum did). But further on he stated that obstacles influenced the velocity of the current. Measuring its production by frictional machines or batteries would give the quantity of electric fluid per time. Maybe the following modern interpretation would be nearer to his mind (if we assume that the resistance of the human body is a constant): tension along the body ~ total tension x conductivity of the whole circuit.

The letter of Volta to van Marum was written in haste, as Volta admitted. We can judge as much from the style and the omission of detailed research. There is no basis for extended historical interpretation. There are also no further comments of Volta existing on any connection between current, tension and conductivity. The reason for this may be that all this research seemed not exact enough in his sense because it was necessary to use physiological effects for measuring "the velocity". Volta's later writings (published and unpublished) again concentrated more on electrostatic problems. Sometimes he also tried to improve the measurement of the shock. So he looked for the "minimum of electric tension" at a condenser at which he still was feeling a very small shock. He tried this for different capacities and found that the minimum perceptible shock was equal to a constant minimum value of the product of "tension x capacity", that meant to a minimum constant "load".[54] This was a very good result (also from the point of view of modern knowledge). Volta again remarked that for his research the electrometric measurements remained central and all other problems should be regarded only in relation to those.

We can judge overall that Volta's main conceptual result was that all such very different effects of the new electricity could be treated by only three (or four) concepts: quantity/time (or velocity), tension, resistance. This was very important (even if only the distinction between quantity and tension was more widely used by other galvanic scientists). Electrical measurement technology now in principle could be considerably extended, compared with the case of frictional electricity before 1791. On the other hand, stronger – and also different – physiological effects and the just newly discovered chemical effects complicated the situation. In the case of the latter, Volta cut through the Gordian knot: he did not treat them at all but subsumed them as far as it seemed necessary under his purely physical concepts of contact,

[54] Letter to Marco Augusto Pictet [Aug. 22, 1804], in *VE*, IV, 1418, pp. 375-81, here p. 377 and VOLTA (1803).

tension or resistance. He was therefore excluded from a rich field of phenomena and even kept to the wrong basic thesis: the direct contact of metals as single cause for the tension. A consequence of this was the unnecessary double end plates of his batteries. But he was able – with this restriction to pure physics – to describe and explain seemingly diverging phenomena in a roughly comprehensive, quantitative way, including the rough formulation of "Ohm's law".

Volta's only competitor in this respect was the romantic German physico-chemist Johann Wilhelm Ritter.[55] He started with "galvanism" in 1797 and soon became an enamoured follower of Volta, but extended his main interest to the chemical and especially biological effects of the new electricity. All this was mixed with romantic speculation – a horror for Volta. But Ritter also was a genius. He discovered e.g. the first rechargeable battery and made a lot of experiments in relation to "Ohm's law". Although Volta was reluctant, Ritter was passionate in discussing all the possible relations within the electric circuit. In 1801 he took over from Volta the distinction between load and tension, and in 1804 he finally found and published a law similar to Volta's law of 1802. But it was caked in a huge amount of words and speculations – which was typical of him. With his passionate and violent research which, in some examples, went far beyond the rules of exact science, he not only destroyed his reputation in the eyes of all physicists but also destroyed himself. He died in 1810 at the age of 34.

6. Conclusions: The Problem of Electric Language around 1800

All these very hesitating developments prove that deeper problems than only personal ones prevented the broad acknowledgement of an – even simple – conceptual system of electricity. As the ideas of Beccaria, Cavendish, Volta and Ritter show, the main reason might not have been the missing of a constant source of tension (like the thermo-element in the case of Ohm in 1826) and of an exact instrument for measuring the intensity of the current (as Ohm developed it from Coulomb's torsion balance). We also can invent experiments – similar to Cavendish's – which produce constant shocks (e.g. by varying the inner and outer resistance at the same time). These experiments would have been good enough for rough quantitative measurements.

A superficial comparison with the history of caloric research in the nineteenth century can show us (a detailed one would be worth an historical project), that the social context for quantitative electrical research (especially measurement technology) was not as good as in the case of temperature science. In temperature measurement the Royal Society was firmly engaged during the early decades of the eighteenth century. Only because of the protection of this very influential Society could the excellent

[55] TEICHMANN (1974); TEICHMANN (1977); TEICHMANN (1997).

thermometers of Fahrenheit succeed. In France, Réaumur's instruments, which were worse, remained more successful. On the other hand, the basic conceptual development of caloric theory (temperature, quantity of heat, specific heat, etc.) was similarly complicated and not quite clear to the majority of scientists. The quantitative conduction of heat was not discussed fruitfully before 1800 (before Fourier). This then had some influence on Ohm's theoretical reflections about his law.

Maybe that, starting from around 1800, first in France but then also in Germany, a new dimension of connections between mathematics and (at that time experimental) physics was born academically. But the rise of scientific interest in technology was also important (see the development of the French École Polytechnique from 1795 on, where a lot of great scientists learned and taught). The simple conceptual caloric system was of wider importance for technology (the steam engine) than the electric concepts of current, tension, resistance for any electric technology till 1820. Only meteorology had some interest in both caloric as well as in electrical concepts.

A further reason for the poor quantitative interest in electricity (and also in the basic concepts of caloric theory) is that both branches of physics belonged to "physique particulière", which was clearly separated from the acknowledged mathematical physics (mathématiques mixtes). Scientists interested in quantitative physics concentrated mainly on mechanical and optical research. Cavendish, who first and exceptionally set up detailed theoretical work in electricity combined with ingenious experiments, therefore remained – independent of his eccentric personal character – a social outsider. Even Volta, with his fantastic abilities as an "entertainer", would have had no success if he had developed or accepted such a mathematical theory as that elaborated by Cavendish in 1771 or Cavendish's electrodynamic background experiments and his conclusions in the 1776 publication.

On the other hand, Volta was no systematic teacher who could have founded an effective local school of electrical science. This would have been an equivalent factor to the – missing –influence of a famous scientific society. A development would have been possible, such as really took place in the colour center research between 1920 and 1940.[56] Here an isolated – but very fruitful – local school grew up around the ingenious experimental physicist Robert W. Pohl in Göttingen, Germany. This school made research about colour changes in salt crystals which led to a conceptual development of explaining these "colour centers" as simple atomic defects (point defects). As Volta's aim was to understand all the phenomena of electricity by means of certain basic theses (contact theory) and (mainly) electrometric research and to "improve" this science, like other branches in the eighteenth century, so the Pohl school aimed at developing basic physics for a "giant molecule" crystal, as gas and quantum physics just had done for the single hydrogen

[56] SZYMBORSKI and TEICHMANN (1992).

atom. And, as with Volta, certain methods of measurement had priority (specific electrometers for measuring very low currents instead of other devices, and absorption spectroscopy with vacuum photocells). Also Pohl was not able – and mainly did not want – to build up a systematic physical theory for real crystals. Instead, he set up a complex network of experimental results and common theses. Also his basic concept – a "colour centre" being an interstitial atom – was wrong, like Volta's contact theory. In spite of this, it was similarly fruitful. Quantum physicists put the theoretical "clothes" on this complex network, but not before the end of the period between 1938 and 1942. However, any such developments in the nineteenth century would have needed much more time.

Volta was not a Robert Boyle of electrical measurement who had had at his side the might of the Royal Society. Italy at this time – more than 100 years after the Florentine Accademia del Cimento – was not in the mainstream of European physics. But also Coulomb's electrostatic measurements in France did not stimulate thorough further theory. Electricity had become a very complex domain of phenomena, mixing up physics and early electrotechnology with meteorology, physiology and chemistry. Not before the development (from 1820 on) of electromagnetism – which restricted scientists' interest anew purely to physics and at the same time greatly enlarged the possibilities for electrotechnology – did the quantification of electricity make new progress which was also acknowledged in a broader social context. Poisson's electrostatics after 1811 also remained an isolated event. Around 1825 we can see that different scientists – stimulated by early ideas of a new electrical technology (e.g. telegraphy) or by electrical measurement – tried to quantify electrodynamic processes of the kind Cavendish, Volta and Ritter had treated years before.[57] But Ohm's law, from 1826, still needed another 15 years before it was commonly accepted. This happened eventually because it then became urgently necessary for the expansion of measurement technology and electrical telegraphy. This process went on quite independently of the development of axiomatic electrodynamics. If any such technological development had started as early as 1800, the conceptual base of simple electrodynamic processes would have become more interesting at that time – and probably Volta himself would have extended his preliminary thoughts to a more useful system. This holds true, even if no exact instruments, maybe even if no electromagnetism had been available. The language already existed but the communication which could extend and spread out this language was missing. Experiments had not "ended" for the scientific community.

But in any case the early conceptual development is astonishing. I think – apart from the genius of such figures as Cavendish, Volta and Ritter – there is one important reason for this, at least mainly concerning Volta and Ritter (to him romantic philosophy added some further aspects): the experiment as l'art pour

[57] TEICHMANN (1977a).

l'art in the "physique particulière" of the eighteenth century. Experiments could be *aperçus*, playgrounds, useful actions, significant questions to nature, far reaching analogies in natural philosophy – all at the same time. The multi-science of electricity (between physics, meteorology, physiology and medicine) fitted well the baroque philosophy of reality: emotion and rationality belonged together. It was "dolce" (sweet for our emotions) and "utile" (useful in rationalistic and technological meaning) at the same time, as the German physicist Georg Christoph Lichtenberg remarked. Volta's genius was impressive to him because he was a fantastic "raisonneur" (about all scientific aspects of electricity). At the same time, Volta knew very well how to enjoy this science – e.g. "the electricity of girls".[58] Cavendish's abstract, dry electrostatics from 1771 (not his 1776 paper!) and especially Coulomb's restricted interest only in "point" charges stood apart from this baroque philosophy. The clearing up of this playground of experiments by simple conceptual development belonged to the rationalistic part of this philosophy. It was helpful for discussion but also sufficient.

Also the experiment as an almost mythical base within empiricism seemed to be of some importance in Volta's thought: e.g. the famous telescope (macrocosm)-microscope (microcosm) analogy of the eighteenth century. We feel Volta's pathos at the invention of his "microelectroscope" (which in real research proved totally useless). Maybe with this microelectroscope he wanted to create something of similar but contrasting importance to the frictional electrical machine, which in combination with Leyden jars produced very large effects (even strong lightnings from batteries of jars). This invention of big electrical effects in the 1740s may be compared to that of the astronomical "telescope" at the beginning of the seventeenth century. In any case: the frictional machine, the Leyden jar and the lightning rod were perceived as magical power instruments in the art and literature of the eighteenth century.

Out of the electrophorus Volta unfortunately did not develop a machine for producing large quantities of electricity, which could have been more successful, as the electrostatic induction machines of the nineteenth century showed. He developed only the microelectroscope to profit from the mythical appeal of a new category of instruments which could lead to the "microworld" of electricity.

[58] LICHTENBERG (1784); VERRECCHIA (1967). See also TEICHMANN (1983).

BIBLIOGRAPHY

BECCARIA, GIAMBATISTA (1753), *Dell'elettricismo artificiale e naturale libri due di Giambatista Beccaria de' CC. RR. delle scuole pie*, Torino: Campana, Filippo Antonio, 1753.

ID. (1772), *Elettricismo artificiale di Giambatista Beccaria delle Scuole Pie all'altezza reale del signor duca di Chablais*, Torino: Stamperia reale, 1772.

CAVENDISH, HENRY (1771), "An Attempt to Explain Some of the Principal Phenomena of Electricity by Means of an Elastic Fluid" [1771], in CAVENDISH, HENRY (1921), §§ 1-139.

ID. (1775), "An Account of Some Attempts to Imitate the Effects of the Torpedo by Electricity" [1776, the paper was given on Jan.1, 1775], in CAVENDISH, HENRY (1921), §§ 395-437.

ID. (1921), *The Electrical Researches* [1st edition 1879: James Clerk Maxwell], vol. I of CAVENDISH, HENRY, *The Scientific Papers of the Honourable Henry Cavendish / edited from the Published Papers, and the Cavendish Manuscripts in the possession of His Grace the Duke of Devonshire*, LARMOR, JOSEPH et al. eds., Cambridge: The University Press, 1921, 2 vols.

ID. (1921a), "Results [of experiments on comparison of charges]" [manuscript], in CAVENDISH, HENRY (1921), §§ 647-83.

ID. (1921b), "Experiments with the Artificial Torpedo" [manuscript], in CAVENDISH, HENRY (1921), §§ 596-615.

HEILBRON, JOHN (1979), *Electricity in the 17th and 18th Centuries*, Berkeley: University of California Press, 1979.

KÜHN, KARL GOTTLOB (1796-97), *Die neuesten Entdeckungen in der physikalischen und medizinischen Elektrizität*, Leipzig, 1796-97, 2 vols.

LICHTENBERG, GEORG CHRISTOPH (1784), "Giorgio Cristoforo Lichtenberg a Samuele Tommaso Sömmerring" [Oct. 25, 1784], in *VE*, II, 614, pp. 257-8.

POLVANI, GIOVANNI (1942), *Alessandro Volta*, Pisa: Domus Galilaeana, 1942.

PRIESTLEY, JOSEPH (1767), *The History and Present State of Electricity with Original Experiments*, London, 1767 [2nd edition, London 1769].

SUE, PIERRE aîné (1802), *Histoire du Galvanisme et analyse des différens ouvrages publiés sur cette découverte depuis son origine jusqu'à ce jour*, Paris: Chez Bernard, 1802, 2 vols.

SZYMBORSKI, KRZYSZTOF and TEICHMANN, JÜRGEN (1992), "Point Defects and Ionic Crystals: Color Centers as the Key to Imperfections", in HODDESON, LILLIAN et al. eds., *Out of the Crystal Maze: Chapters from the History of Solid-State Physics*, New York-Oxford: Oxford University Press, 1992, pp. 236-69.

TEICHMANN, JÜRGEN (1974), *Zur Entwicklung von Grundbegriffen der Elektrizitätslehre, insbesondere des elektrischen Stromes bis 1820*, Hildesheim, 1974.

ID. (1977), "L'influenza di Alessandro Volta in Germania, specialmente su Georg Christoph Lichtenberg, Johann Wilhelm Ritter e Georg Simon Ohm", *Quaderni del Giornale di Fisica*, 2:2 (1977), pp. 43-60.

ID. (1977a), "Zur Entdeckungsgeschichte des Ohm'schen Gesetzes 1775-1826", *Elektrotechnische Zeitschrift*, Ausgabe A, 98 (1977), pp. 4-7.

ID. (1983), *Georg Christoph Lichtenberg: Aphoristisches zwischen Physik und Dichtung*, Braunschweig, Wiesbaden, 1983.

ID. (1997), "Johann Wilhelm Ritter: Ein romantischer Physiker", in ZIMMERLI, WALTHER CH. et al. eds., *Fessellos durch die Systeme - Frühromantisches Naturdenken im Umfeld von Arnim*, *Ritter und Schelling*, Stuttgart: Bad Cannstatt, 1997, pp. 331-9.

VERRECCHIA, ANACLETO (1967), "Lichtemberg und Volta", *Sudhoffs Archiv fur Geschichte der Medizin und der Naturwissenschaften*, 51 (1967), pp. 349-60.

VOLTA, ALESSANDRO (1769), "De vi attractiva ignis electrici, ac phaenomenis inde pendentibus Alexandri Voltae ... ad Joannem Baptistam Beccariam ... dissertatio epistolaris", in *VO*, III, pp. 22-52.

ID. (1775), "Articolo di una lettera del Signor Don Alessandro Volta al Signor Dottore Giuseppe Priestley" [June 10, 1775], in *VO*, III, pp. 93-109.

ID. (1775-6), "Quattro lettere al canonico Fromond" [Oct. 1775-Febr. 1776], in *VO*, III, pp. 115-28.

ID. (1776), "Lettera del Signor D. Alessandro Volta al Signor Giuseppe Klinkosch … " [May 1776], in *VO*, III, pp. 132-52.

ID. (1778), "Osservazioni sulla capacità de' conduttori elettrici e sulla commozione che anche un semplice conduttore è atto a dare eguale a quella di una boccia di Leyden del Signor Don Alessandro Volta in una lettera al Signor de Saussure" [Aug. 20, 1778], in *VO*, III, pp. 199-230.

ID. (*post* 1779-80) "Descrizione ed uso dell'elettroforo" [manuscript composed after the academic year 1779-80], in *VO*, III, pp. 169-84.

ID. (1782), "Lettera di A. volta a M.me le Noir de Nanteuil" [May 14, 1782], in: *VO*, I, pp. 8-12.

ID. (1782a), "Del modo di render sensibile la più debole elettricità sia naturale, sia artificiale" [March 14, 1782], in *VO*, III, pp. 270-301.

ID. (1782b), "Del modo di rendere sensibile la più debole elettricità sia naturale che artificiale", *Philosophical Transactions*, 72:1 (1782), pp. 237-83.

ID. (1782c), "Of the Method of rendering very sensible the weakest Natural or Artificial Electricity", CAVALLO, TIBERIO trans., *Philosophical Transactions*, 72:1 (1782), "Appendix", pp. VII-XXXIII.

ID. (1784-?), "Lezioni compendiose sull'elettricità" [manuscript composed no earlier than 1784], in *VO*, IV, pp. 389-467.

ID. (1787-88), "Primo gruppo di lettere di Alessandro Volta al Prof. G.C. Lichtenberg dell'Università di Gottinga sulla meteorologia elettrica" [1787-88], in *VO*, V, pp. 27-189.

ID. (1790), "Della maniera di far servire l'elettrometro atmosferico portatile all'uso di un igrometro sensibilissimo" [1790], in *VO*, V, pp. 309-34.

ID. (1792), "Due lettere a Martino Van Marum" [1792], in *VO*, I, pp. 120-43.

ID. (1793), "Account of some Discoveries made by Mr. Galvani ... in two Letters from Mr. A. Volta ... to Mr. T. Cavallo" [letters and manuscripts, Sept. 1792-Dec. 1793], *VO*, I, pp. 169-248.

ID. (1794-95), "Nuova memoria sull'elettricità animale del Sig. Don Alessandro Volta … in alcune lettere al Sig. Ab. Anton Maria Vassalli …" [5 letters, Febr. 1794 - autumn 1795], in *VO*, I, pp. 259-334.

ID. (1796-97), "Sul galvanismo ossia sull'elettricità eccitata dal contatto de' conduttori dissimili. Tre lettere al Prof. Gren di Halla e appendice" [Aug. 1796-March 1797], in *VO*, I, pp. 392-448.

ID. (1800), "On the Electricity excited by the mere Contact of conducting Substances of different Kinds in a letter from Mr. Alessandro Volta … to the Rt. Hon. Sir Joseph Banks … Read June 26, 1800" [March 20,1800], in *VO*, I, pp. 562-86.

ID. (1800a), "On the Electricity excited by the mere Contact of conducting Substances of different Kinds in a letter from Alexander Volta ... to Sir Joseph Banks. Translated from the Author's Paper published in French in the Philosophical Transactions for 1800, part 2", *Philosophical Magazine*, 7:2 (1800), pp. 289-311.

ID. (1800b), *On the Electricity excited by the mere Contact of conducting Substances of different Kinds. Bicentenary Edition in French, English, German and Italian of the Letter to Sir Joseph Banks of the 20th of March 1800*, Milano: Hoepli, 1999.

ID. (1800c), "Lettere due del Professore di Fisica sperimentale Alessandro Volta membro della Società Reale di Londra e di molte altre accademie al Cav. Giuseppe Banks Presidente di essa Società ecc." [March-April, 1800], in *VO*, II, pp. 30-35.

ID. (*post* 1800), "Memoria sperimentale sulle distanze esplosive, sull'elettrometro e sul modo di ottenere indicazioni delicate e comparabili" [manuscript composed after the invention of the battery], in *VO*, IV, pp. 133-53.

ID. (1801), "Memoria ... sull'identità del fluido elettrico col fluido galvanico" [Nov. 1801], in *VO*, II, pp. 45-105.

ID. (1801a), "Lettera ad un ignoto su l'invenzione della pila e ricerche sugli effetti chimici" [Spring 1801], in *VO*, II, pp. 13-22.

ID. (1802), "Risultati spinterometrici e calcoli numerici per la determinazione della relazione fra il grado elettrometrico e la distanza esplosiva", in *VO*, IV, pp. 164-97.

ID. (1802a), "Lettera a Martino van Marum su proposte di esperienze" [March 3, 1802], in *VO*, IV, pp. 213-20.

ID. (1802b), "Aux Rédacteurs de la bibliothèque Britannique. Alexandre Volta" [March 18, 1802], in *VO*, II, pp. 151-66.

ID. (1802c), "Lettera a Martino van Marum su discussioni di esperienze" [June 22, 1802], in *VO*, IV, pp. 221-31.

ID. (1803), "Fortgesetzte Versuche über die Electricität von Alexander Volta aus einem Briefe an den Herausgeber", in *VO*, IV, pp. 242-9.