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The Reception of Volta's Electrophorus Among Eighteenth-Century Electricians

A Case Study in the History of Electricity

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Abstract:
In June of 1775, Alessandro Volta announced the invention of the electrophorus, a mysterious device that could provide a seemingly endless supply of electricity through the repetition of a simple series of operations. The device compelled a reexamination of how Benjamin Franklin's theory of electricity (1747-55) could account for attraction and repulsion and resulted in a set of important changes in the scientific consensus regarding attraction, repulsion, and the location of the electric fluid for a charged body. The way the electrophorus contributed to these changes was unusual. There was no grand theory of the electrophorus, —in fact, Volta initially provided no theory of the device at all, —and the phenomena the device displayed were not novel; they were demonstrated and precisely analyzed by others, including two of the best-known electricians of the era, years before Volta's invention. The obvious, yet unanswered, question is how the scientific consensus changed and why it was the electrophorus that advanced the scientific consensus. This case study aims to answer this question by combining experimentation with the electrophorus itself and contemporaneous accounts of the device to determine the theoretically relevant phenomena the device displayed. These phenomena are then compared to step-by-step analyses of Giambatista Beccaria's double-pane experiment and Johan Carl Wilcke's dissectible condenser to determine that these prior experiments demonstrated the same phenomena. Finally, we explain the greater renown afforded the electrophorus in terms of several design features that allowed it to gain wider distribution and demonstrate its phenomena more clearly than prior experiments.

Keywords: Volta, electrophorus, history of electricity, attraction, repulsion, electrical atmospheres, electrostatic induction

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Introduction

On June 10, 1775, Alessandro Volta announced the invention of the electrophorus, a perpetual purveyor of electricity that "electrified but once, briefly and moderately, never loses its electricity, and although repeatedly touched, obstinately preserves the strength of its [charge]."[1] Through a simple series of operations, the device could provide a seemingly limitless supply of electricity, although *how* it could do this was initially quite mysterious. As a result, the device was thought to be the next Leyden jar: a simple, easy-to-build device that would revolutionize electrical theory and reinvigorate waning interest in electricity among natural philosophers. The electrophorus did indeed play an important role in shaping subsequent electrical theory. It can be easily counted among the most important electrical apparatuses in the thirty years after the Leyden jar was invented and is among the most important apparatuses of the eighteenth century.

Yet, the role of the electrophorus was not, ultimately, that of the next Leyden jar. Whereas the Leyden jar single-handedly overturned all established electrical theory and opened the door for Franklin's highly successful theory of electricity, the electrophorus instead advanced an emerging scientific consensus. It helped to overturn compelling but misleading notions about the location of the electricity of a charged body and the nature of attraction and repulsion.

The way the electrophorus accomplished this was unusual. There was no grand theory of the electrophorus—in fact, Volta initially provided no theory of the device at all—and the phenomena the device displayed were not novel; they were demonstrated and precisely analyzed by others, including two of the best-known electricians of the era, years before Volta's invention. The obvious, yet unanswered, question, and the subject of this essay, is why it was the electrophorus that advanced the scientific consensus and what this says about the nature and significance of Volta's accomplishment.

This essay will begin by focusing on the state of electrical theory after the publication of Benjamin Franklin's *Experiments* (1747–55) with a particular focus on the problems in Franklin's notion of electrical atmospheres and their use as an explanation of attraction and repulsion. Next, attention will be directed to the explanations of attraction and repulsion put forth by prominent Franklinists and how these views shaped the scientific consensus on the topic prior to 1775.

With the stage set, we will meet Alessandro Volta and his electrophorus. We will then discuss the impact of the electrophorus on electrical theory by identifying the phenomena the device displayed, how these phenomena were explained, and how these explanations changed the state of electrical theory. We will then turn our attention to why the *electrophorus* had this impact by

[1] Volta, *Le Opere*, 3:96.

discussing experiments by Wilcke and Beccaria that demonstrated the same phenomena as the electrophorus, albeit years earlier. Finally, we will conclude by discussing the implications of this analysis for understanding Volta's accomplishment.

The State of Electrical Theory prior to the Electrophorus

Attraction, Repulsion, and Franklin's Theory of the Leyden Jar

The state of electrical theory in 1775 was dominated by Franklin's theory of electricity and by the work of subsequent Franklinists to render the theory more coherent and consistent. Therefore, understanding the impact of the electrophorus on electrical theory will be eased by first reviewing some relevant background knowledge regarding Franklin's theory and, in particular, his attempt to utilize this theory to explain attraction and repulsion.

In very general terms, seventeenth- and eighteenth-century electrical theories aimed to explain two broad categories of phenomena. The first were phenomena like attraction and repulsion that occurred between bodies based on their preexisting electrical charges. The second were phenomena like the production of sparks that occurred as bodies were being charged or discharged.[2]

The introduction of the Leyden jar in 1746 not only overturned all established electrical theories, but also shifted the focus of electricians toward this second category of phenomena as they attempted to explain the alarmingly powerful sparks the device could produce. Thus, Franklin's highly successful theory of electricity was primarily a theory of the Leyden jar and, more generally, a theory of bodies' electrical behavior as they were charged and discharged. It was only after Franklin had developed his theory of the Leyden jar that he attempted to use this theory to explain attraction and repulsion.[3] This focus on charging and discharging helps to explain Franklin's failure to provide a satisfactory account of attraction and repulsion and the resultant gap in theory that subsequent electricians attempted to close.

Central to Franklin's account is the notion of an electrical atmosphere. Franklin says the following about what an electrical atmosphere is: "In common matter there is (generally) as much of the electrical as it will contain within its substance. If more is added, it lies without upon the surface, and forms what we call an electrical atmosphere; and then the body is said to be

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[2] This distinction occurs in Home, "Franklin's Electrical Atmospheres," 131–32. However, as Home notes, this is a modern distinction that not all eighteenth-century electricians would have accepted.

[3] Franklin discusses phenomena associated with attraction and repulsion as early as letter two, including the repulsion of an insulated cork ball from an electrified shot and the "counterfeit spider" experiment. Franklin, *Experiments*, 10–18, esp. 11, 16, and 17. However, these are noted as empirical facts without any real attempt to account for them. For additional discussion on this point see Home, "Franklin's Electrical Atmospheres," 131–35.

electrified."[4] Franklin also specifies that "the form of the atmosphere is that of the body it surrounds."[5] Thus, an electrical atmosphere for Franklin is a layer of electric fluid surrounding a charged body.

Franklin was not alone in proposing an essential relationship between the electrical behavior of charged bodies and changes to the electrical property of the surrounding air. Many electricians regarded this not as a theory but as a simple empirical fact that was directly apparent to the senses through what was known as the electric spider web phenomenon. Take, for example, the back of one's hand and move it toward an electrified body. There is a distinct sensation, occurring at some distance from the electrified body, that is similar to the feeling of a spider's web touching the hand. This sensation was thought to be caused by the electric fluid itself and was therefore considered direct evidence of the existence of an electrical atmosphere around the charged body.

The prevalence of this view is visible even among its critics. In his bold treatise on electricity and magnetism, *Tentamen* (1759), Franz Aepinus denied the existence of a layer of fluid surrounding a charged body. In his response to his critics, he outlines their view as follows: "[Some readers] will object that I am denying the existence of something which is directly apparent to the senses. For e.g. when the back of the hand is moved towards an electrified body or touches it, we are convinced of the existence of an electric atmosphere, it is believed, since we experience an entirely similar sensation as we do when a fine net, such as a spider's web touches the hand."[6]

For Franklin, this layer of electric fluid around a charged body was important in explaining macroscopic attraction and repulsion, although he does not provide many details. In the case of attraction, his statements suggest that this sometimes involved actual contact between the electric fluid and a body. In discussing an experiment in which a feather enclosed in a glass vessel can be affected by a nearby electrified tube, Franklin specifies that a quantity of fluid inside the sealed vessel is repulsed and "there affects the feather, returning again into its pores when the tube with the atmosphere is withdrawn."[7] In the case of repulsion, Franklin follows earlier electricians in holding that particles of electric matter, and therefore electrical atmospheres, repulse one another, but is less clear about exactly what role the atmospheres play.[8] His only statement on the matter concerns an experiment in which a charged ball, A, is brought into contact with an uncharged ball, B, resulting in the two balls repulsing one another. Here Franklin says that when

[4] Franklin, *Experiments*, 52.
[5] Franklin, *Experiments*, 55.
[6] Aepinus, *Tentamen*, 258–59. The English translation is by Peter James Connor in Home, *Aepinus's Essays*, 393.
[7] Franklin, *Experiments*, 78.
[8] Franklin, *Experiments*, 51–52. Franklin cites Ellicot's work on this point. See Ellicot, "Several Essays," 195–224.

A contacts B, "half the electric fluid is communicated, so that each now has an electrical atmosphere and therefore they repel each other."[9]

The parts of Franklin's view that *are* clear suffer from serious problems. The first is the well-known problem of minus-minus repulsion, wherein the repulsive force between two bodies can be observed to increase as they are drained of their electricity.[10] For Franklin, a single electric fluid is the cause of all electrical repulsion and a body is charged *minus* when this electric fluid is removed from the body.[11] The problem of minus-minus repulsion is that draining two bodies of their only source of electrical repulsion should cause them to lose their repulsion. Instead, they are observed to repulse each other *more* as the electric fluid is drained. This problem remained a menace to Franklinists everywhere for many years.

A second problem concerns the nature of the atmospheres themselves, specifically, the question of what holds the atmosphere in place. For Franklin, atmospheres arise once a body has been saturated with electricity, but a body saturated with electricity should repulse the electric fluid in the atmosphere and cause it to dissipate. To explain why this does not occur, Franklin provides two competing answers.

One answer is that the electric fluid is held in place by the insulating properties of air. Here, Franklin specifies the following: "*In vacuo*, the electric fire will fly freely from the inner surface . . . but air resists its motion . . . so the air never draws off an electric atmosphere from any body . . . it rather keeps such an atmosphere confin'd."[12] Thus, the electrical atmosphere would dissipate were it not for the air.

Unfortunately for Franklin, assigning to the air the role of keeping atmospheres in place is hard to reconcile with the rest of his theory. Consider, for example, the appearance of sparks over macroscopic distances. The most obvious description of what is occurring is that the electric fluid moves through the air from one body to another. Indeed, Franklin describes the electric

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[9] Franklin, *Experiments*, 55.

[10] Importantly, Franklin's use of the terms *minus* and *plus* refers to whether the body has more or less electric fluid than normal, not the modern notion of electric charge. If we assume that the electric fluid for Franklin is identical to the modern notion of electrons, then a body with a net deficiency of electrons (minus for Franklin) would have a charge of positive and a body with a net surplus of electrons (plus for Franklin) would have a charge of negative.

[11] Franklin does not allow for repulsion between particles of ordinary matter. However, in *Tentamen*, Aepinus proposed that minus-minus repulsion could be accounted for if particles of ordinary matter repulsed one another much as the electric fluid repulsed itself. He realized, of course, that this appeared to contradict the Newtonian doctrine that particles of ordinary matter were attracted to each other gravitationally. Aepinus's solution was, to use modern terms, to assign to ordinary matter both an attractive gravitational force and a repulsive electromagnetic force. This bold solution was generally not adopted by others until more than a decade after *Tentamen* was first published.

[12] Franklin, *Experiments*, 77–78.

fluid as leaping "from particle to particle thro' the air."[13] Yet, it is hard to explain how the air can both transport electric fluid in the case of sparks and be impervious to transporting electric fluid in the case of electrical atmospheres. Difficulties also arise when considering Franklin's view that electrical atmospheres do not dissipate when the body itself is moved through space. In one experiment, for example, Franklin describes electrifying a cork ball, which he then whirls like a sling over his head one hundred times without causing the ball to lose its atmosphere.[14] Franklin does not explain how the electrical atmosphere could move through the air without interruption in this case, but the air could also be responsible for stopping the movement of electrical atmospheres away from a charged body.[15]

Franklin's second explanation for what holds an electrical atmosphere in place is attraction to the surface of the body it surrounds. After explaining that the shape of the atmosphere is that of the body it surrounds, Franklin says: "And this form [the electric fluid] takes, because it is attracted by all parts of the surface of the body, tho' it cannot enter the substance already replete. Without this attraction it would not remain round the body but dissipate in the air."[16]

There is a contradiction between these two answers. If the air keeps the atmosphere in place, why would the atmosphere dissipate into the air without attraction? If attraction keeps the atmosphere in place, why posit that it is held in place by the air? Furthermore, there is an apparent contradiction between Franklin's claim elsewhere that the "air never draws off an electric atmosphere"[17] and the claim here that the atmosphere can dissipate into the air.

A further problem for Franklin concerns his claim that the electrical atmospheres do not mix. Imagine two liquified balls of ordinary matter with electrical atmospheres. If the two masses come together, it seems reasonable to assume that the ordinary matter will mix following Newtonian principles and that the atmospheres will unite into a single atmosphere via whatever force is holding them around the bodies to begin with. Yet, Franklin maintains that this is not the case, saying that atmospheres "do not readily mix and unite into one atmosphere, but remain separate, and repel each other."[18] This is particularly unusual behavior for a *fluid*, which eighteenth-century natural philosophers knew tended to mix with other fluids.

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[13] Franklin, *Experiments*, 45.
[14] Franklin to Colden, October 31, 1751.
[15] For a useful discussion of this aspect of Franklin's atmospheres, see Heilbron, *Electricity*, 336. Heilbron's assessment of Franklin's atmospheres is that the notion "suffered from outright contradictions as well as from bad physics" (Heilbron, *Electricity*, 336).
[16] Franklin, *Experiments*, 55.
[17] Franklin, *Experiments*, 78.
[18] Franklin, "Electrical Experiments," 300.

In short, Franklin's attempt to adapt his theory to account for attraction and repulsion suffered from a myriad of problems, including some apparent contradictions.

However, the core of Franklin's theory, the notion of plus and minus, did show some promise in illuminating attraction and repulsion. Franklin's theory can predict whether two bodies will attract or repulse based on whether they have more or less than their normal quantity of fluid (minus-minus repulsion excepted). Two differently electrified bodies (e.g., one plus and one minus) attract each other and two bodies electrified plus repulsed each other. As we will see, subsequent Franklinists attempted to solve problems in Franklin's account by taking a different—and more natural-seeming—approach to extending Franklin's theory to explain attraction and repulsion while preserving the core of the theory.

Franklinist Accounts of Attraction and Repulsion

We turn now to a review how Franklinists attempted to use Franklin's theory of the Leyden jar to explain attraction and repulsion. However, to grasp the differences between Franklin's theory and the theories of early Franklinists, we must make some distinctions. As already noted, the notion of an electrical atmosphere is central to Franklin's explanation of attraction and repulsion. The term is also central to the accounts of many Franklinists, but they do not always use the term as Franklin does. At least three distinct meanings for the term *electrical atmosphere* were in common usage among eighteenth-century electricians:

> **1. Excess electricity**: A layer of electrical fluid surrounding a positively charged body that occurs after the charged body is saturated with electricity.
>
> **2. Stressed air**: A modified electrical state of the air surrounding a charged body resulting from the influence of the electricity inside the body on the surrounding air.
>
> **3. Sphere of influence**: The area around a body where that body can influence other bodies' electrical behavior.

A significant source of confusion is that these different meanings are also concerned with subtly different questions. One question concerns the location of the electric fluid of a positively charged body. That is, does it reside entirely inside the body, or does it reside both inside the body and in an electrical atmosphere around the body? A second question concerns the mechanism by which the electric fluid of a charged body influences other bodies. One option is that an actual exchange of electric fluid causes attraction and repulsion. A second option is that the electric fluid in a body acts on the fluid in other bodies at a distance without a transfer of fluid.[19]

Franklin uses the term *electrical atmosphere* to refer to a layer of electric fluid surrounding a charged body, or the excess electricity meaning of the term. However, his answer to the question of what mechanism causes repulsion is that no transfer of electric fluid is involved (on attraction, Franklin is notably less clear).[20] Let us call the view that there is no transfer of fluid in attraction or repulsion the *static* view and distinguish it from *dynamic* views, in which an actual transfer of electric fluid occurs between the bodies or their atmospheres as the bodies move.[21]

Early Franklinist electricians tended to agree with Franklin that the location of the electric fluid for a changed body was both in and around the body itself, but they held dynamic views about how attraction and repulsion occurred. This would have seemed like a perfectly natural extension of Franklin's theory. At its core, Franklin's explanation of the Leyden jar rests on the notion that sparks are produced by the sudden movement of the electric fluid from the side of the glass charged plus to the side charged minus. Therefore, a natural way to account for attraction and repulsion is to similarly attribute it to a movement of electric fluid. This is precisely what dynamic accounts of attraction and repulsion offer. Indeed, dynamic accounts were so intuitively compelling that, for a time, they not only became the standard Franklinist explanation of attraction and repulsion, but in many cases they were also erroneously believed to be Franklin's explanation.[22]

For example, there is the case of John Canton, one of Franklin's most influential supporters in London, who developed a view (which he erroneously took to be compatible with Franklin's view) according to which electric matter streamed out continuously from positively charged bodies and toward negatively charged bodies and that these streams were responsible for

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[19] Notably, the stressed air definition of electrical atmospheres is not an answer to a unique question. It became a popular usage of the term as the excess electricity notion began to fall out of favor.

[20] It is clear that Franklin sees an important role for electrical atmospheres in attraction and that atmospheres do not mix. Yet, attraction could involve a transfer of fluid from the atmosphere surrounding a positive body into a negatively charged body which would make it a dynamic interaction. Franklin's discussion of the feather in a sealed glass vessel suggests a temporary movement of electricity into the feather (Franklin, *Experiments*, 78), but the example is far from definitive. Home seems to indicate that attraction is static for Franklin, (Home, Franklin's Electrical Atmospheres," 140) whereas Heilbron indicates that the mechanism is not specified by Franklin (Heilbron, *Electricity*, 339).

[21] The distinction between dynamic and static views appears in Home, "Franklin's Electrical Atmospheres," 140.

[22] For example, there is the case of William Watson, who developed a dynamic account in which bodies move in response to two streams of electric fluid. At the end of a paper on this topic read to the Royal Society, Watson comments on the remarkable similarity between his view and Franklin's, indicating that he thought Franklin shared his dynamic account (Watson, "Collection of Electrical Experiments," 98–100). See also Home, "Franklin's Electrical Atmospheres," 141–42. Notably, at the time of Watson's paper, he had only a partial account of Franklin's theory as Franklin had not yet completed the series of letters in *Experiments*.

attraction and repulsion.[23] Giambatista Beccaria, Franklin's most successful proponent on the continent, also proposed a dynamic view in his treatise *Dell'elettricismo*. Beccaria based his view on what he called the "universal theory"[24] of electricity, which reduced all signs of electricity to "the vapour expanding itself from a body in which it is in greater quantity into one in which there is less."[25] The view applied only to attraction (repulsion was explained as differential attraction) and Beccaria initially retreated to Newtonian-style agnosticism as to how to use this principle to provide a mechanical explanation of attraction.[26] When Beccaria eventually overcame his agnosticism, he outlined a series of experiments to show that the flow of electric fluid between the two attracting bodies drove out the air between them and resulted in a low-pressure region that forced the bodies toward each other.[27]

Beccaria's explication of Franklin's views was influential and was, for a time, treated as the most authoritative source on the subject.[28] Franklin himself regarded *Dell'elettricismo* as "one of the best pieces on the subject that I have seen in any languages"[29] and he thought it was sufficiently good that he abandoned his own plans for composing a formal reply to his critics, as did others.[30] He also regarded Beccaria as a "master of method" who "reduced to systematic order the scattered experiments and positions delivered in [his] papers."[31]

Dynamic views were the norm until at least 1775. Henry Cavendish, in a paper written between 1767 and 1771, reports that "it has usually been supposed that two bodies, whenever the electricity either runs into or out of both of them, repel each other; but that when it runs into one and out of the other, they attract."[32] Similarly, in the 1775 edition of Joseph Priestley's widely read *History*, Priestley discusses Franklinist attraction and repulsion in clearly dynamic terms centering on the electric fluid entering or leaving bodies (or their atmospheres) and on the

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[23] Canton's views on the topic are never clearly stated, but they can be pieced together from his publications, specifically Canton, "Electrical Experiments," 350–58; Canton, "A Letter," 780–85; and Canton, "An Attempt," 398–445. For a useful overview of Canton's views, see Home, "Franklin's Electrical Atmospheres," 141–44.
[24] Beccaria, *Dell' elettricismo*, 17.
[25] Beccaria, *Dell' elettricismo*, 17. The translation here is from Home, "Franklin's Electrical Atmospheres," 146.
[26] Beccaria, *Dell' elettricismo*, 40.
[27] Beccaria, *Dell' elettricismo*. *Lettere*, 42–43. Beccaria also outlined this view in Beccaria, "Experiments in Electricity," 514–26.
[28] Boscovich treated Beccaria as the authority on the subject in his *Theoria philosophiae naturalis* (Theory of natural philosophy). See Boscovich, *Theory of natural philosophy*, 181. Haller likewise treated Beccaria as the authority in his research into muscle physiology. See Haller, *Mémoires*, 3:207. See also Home, "Franklin's Electrical Atmospheres," 148.
[29] Franklin to Dalibard, June 29, 1775.
[30] Cohen, *Experiments*, 307; Pace, *Benjamin Franklin and Italy*, 49–53. DeLor, who translated and published some of Beccaria's work into French, also abandoned his plans to defend Franklin's views when he found that Beccaria had already done so "in a manner far superior to what I could have done." Beccaria, *Lettre sur l'electricité*, vi–vii.
[31] Franklin to Colden, August 30, 1754.
[32] Cavendish, *Electrical Researches*, 100.

restoration or disturbance of the equilibrium of fluid between two bodies.[33] Later, he discusses experiments that he says "favour the hypothesis of S. Beccaria, that there is no electrical attraction without a communication of electricity."[34]

Yet, the pathway to the eventual demise of the dynamic accounts and excess electricity was visible, if faintly, before 1775. In 1759, Aepinus published *Tentamen*, his insightful but largely overlooked treatise on electricity and magnetism in which he denied both the notion of excess electricity and dynamic accounts of attraction and repulsion, relying instead on unexplained action at a distance.[35] In 1771, Cavendish proposed a theory of electricity that also denied the existence of electrical atmospheres and relied on unexplained action at a distance, although the theory did not attract many adherents.[36]

Eventually, both Canton and Beccaria abandoned the notion of excess electricity around a charged body, opting for the stressed air conception of electrical atmospheres instead. Priestley reported that Canton had replaced the excess electricity view with the stressed air view in 1767.[37] Beccaria abandoned the notion of excess electricity in his 1772 treatise, *Elettricismo artificiale*.[38] He now claimed that the electricity in a body "does not substantially diffuse itself into the ambient air,"[39] adopting the stressed air meaning of the term. Beccaria also capitulated on his dynamical account of repulsion, indicating that repulsion occurs between two bodies when the spread of the electric fluid is *hindered* in its passage to other bodies.[40] Dynamic overtones remain, however, in his account of attraction.[41]

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[33] Priestley, *History*, 2:27–28. All references to Priestley's *History* are to the 1775 edition unless otherwise noted.
[34] Priestley, *History*, 2:374.
[35] For Aepinus's adoption of action at a distance, see Aepinus, *Tentamen*, 9. For Aepinus's denial of atmospheres, see Aepinus, *Tentamen*, 257. Aepinus does use the term *electrical atmospheres* but makes it clear that this is in the sphere of influence sense outlined above. He also indicates receptivity to the stressed air notion. Aepinus, *Tentamen*, 257–58.
[36] Cavendish, "An Attempt to Explain," 584–677.
[37] Priestley, *History* (1767), 263. It is not clear in Priestley whether Canton also abandoned his dynamic account of attraction and repulsion.
[38] The book was also translated into English under the title *A Treatise upon Artificial Electricity*. I will refer to the English translation unless otherwise indicated.
[39] Beccaria, *Artificial electricity*, 179. This quote is followed by the dubious claim that Beccaria was the first person to demonstrate this fact. Later he does cite Aepinus and Wilcke and their experiment replicating the Leyden jar effect, using air in place of glass, to support his assertion. Yet, he makes it clear that the Wilcke/Aepinus experiment is not definitive, saying, "These facts do not afford a complete demonstration of the above proposition." Beccaria, *Artificial electricity*, 181. If Beccaria changed his views under the influence of Aepinus, it appears from this passage that he is either unaware of this fact or unwilling to acknowledge it.
[40] Beccaria, *Artificial electricity*, 2.
[41] Beccaria is notably obscure on attraction. He does discuss motions as signs of the movement of the electric fluid. For example, he indicates that when the electricity diffuses from a body with greater proportions into a body with less, this "manifests itself with new signs, with particular *motions*, sparks, a wind &c." (Beccaria, *Artificial electricity*, 2; emphasis mine). However, it is unclear whether these motions refer to the motion of bodies or merely of the electric fluid itself. Notably, as of 1775, Priestley seemed to think Beccaria's view was that attraction required the communication of electricity (Priestley, *History*, 2:374).

Thus, while dynamic accounts involving excess electricity around a changed body remained common prior to 1775, one can see a small trend toward alternatives. However, it was a trend only among a handful of electrical theorists. For most, there was a robust phenomenological basis for thinking that the electric fluid formed an atmosphere around a charged body, and there was a compelling intuitive basis for believing that electric fluid was transferred between bodies in attraction and repulsion just as it was in charging and discharging. For many electricians, abandoning these views would require familiarity with suitably bewildering experimental results.

Alessandro Volta and the Electrophorus

Volta before the Electrophorus

We have just discussed the theoretical state of affairs in which Volta presented the electrophorus. To fully contextualize the reception of the electrophorus among eighteenth-century electricians, we should now meet Alessandro Volta and discuss his work before June 10, 1775, and his standing among electricians. While Volta would eventually be recognized by contemporaries and historians alike as one of the most influential electricians of his era, at the time of the electrophorus's invention, he was instead a thirty-year-old natural philosopher struggling to achieve recognition. It was the electrophorus that made Volta a well-known figure among natural philosophers, not the other way around.

Volta's earliest forays into the community of natural philosophers came at the age of eighteen, when he began trying to build correspondences with two of the leading figures in electricity: Beccaria and Jean-Antoine Nollet. By the age of twenty-one, Volta had developed a somewhat regular correspondence with both men.[42] In his letters, Volta defended an ambitious theory subsuming both electricity and magnetism and attempting to reduce all phenomena, including repulsion, to a Newtonian-style attractive force operating at a distance.[43] Neither Beccaria nor Nollet regarded this idea as particularly plausible. In fact, after one letter from Volta to Beccaria, the latter did not respond for around a year. Volta, worried that he had alienated an influential figure, sent a second letter apologizing for his frivolousness. When Beccaria's response did arrive, it included a recommendation that Volta read some of his own work and focus on experiments.[44] Nollet's response to Volta's theoretical ambitions was polite but cautious. He

[42] While the complete letters were not preserved, an excerpt of a letter to Nollet is available in Volta, *Le Opere*, 3:38n. Further details about the letters are available in Volta, *Epistolario*, 1:33–34.
[43] Many relevant letters were not preserved, but their existence can be inferred by Volta's other writings. See Volta, *Le Opere*, 3:23n for Volta's quotation of the relevant comment by Nollet and see Volta, *Epistolario,* 1:35–36 and Volta, *Le Opere*, 3:38n for a letter to Beccaria in which Volta provided a description of his own prior letters.
[44] Volta, *Epistolario*, 1:33–36; Volta, *Le Opere*, 3:23.

noted that if Volta's system were successful, it would be glorious, but that he doubted whether such a system could explain the main facts of electricity.[45]

Volta persisted and his theoretical project culminated on April 18, 1769, when he published his first treatise on electricity, entitled *De vi attractiva ignis electrici* (On the attractive force of the electric fire) and written in the form of a letter addressed to Beccaria.[46] The work developed several ideas that would prove critical in Volta's later works, including the electrophorus.[47] However, the treatise was not well received and gained Volta very little recognition. Indeed, after its publication, Volta's exchanges with Beccaria ceased abruptly. As one historian has put it, "The reception of Volta's first effort at an ambitious contribution to the theory of electricity was, to say the least, cool."[48]

Volta followed his 1769 treatise with a second treatise in 1771 entitled *Novus ac simplicissimus electricorum tentaminum apparatus*.[49] This work showed Volta's continued commitment to the model of electricity developed in 1769 and included a description of a simple, new electrical machine: an electrostatic generator utilizing wood instead of the usual glass.[50]

Volta became disenchanted with his theoretical ambitions following the reception of his treatises and began instead to focus on building useful electrical apparatuses.[51] In 1772, he invented an electrostatic generator made of baked cardboard, which he described in a letter to Joseph Priestley. Priestley responded that he found the idea interesting enough that he had one made for himself and, while it was inferior to a glass electrostatic generator, he thought the device could be improved in several respects.[52] Priestley's recognition was the first time Volta won praise from a well-known electrician in his career.

In October of 1774, just eight months before he announced the electrophorus, Volta utilized his family connections and found sufficient patronage to be appointed superintendent of secondary

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[45] Volta, *Le Opere*, 3:32.
[46] The treatise is also available in Volta, *Le Opere*, 3:21–52.
[47] See Heilbron, *Electricity*, 413–15 for a useful discussion of these ideas.
[48] Pancaldi, *Volta*, 90.
[49] Also available in Volta, *Le Opere*, 3:53–76.
[50] This device was not new, as Volta would later find out when Paolo Frisi lent him a French translation of Joseph Priestley's *History*. This work detailed experiments on wood by an electrician named Ammersinus. See Volta, *Le Opere*, 3:56n.
[51] For a useful discussion of this, see Pancaldi, *Volta*, 73–109, esp. 90–91.
[52] Volta, *Epistolario*, 1:59–60. Pancaldi translates Priestley's full remark from the original French as follows: "The idea of your machine, made of cardboard, impressed me. That is why I had it built for me, and I was much surprised to see its effects, however inferior they are compared to the ones produced by our glass globes. I can well imagine that, should the machine be built in a better manner, its force would be greater; especially by adding several sheets of cardboard or wood (what would be quite easy to do), with one friction pad acting on two sheets at a time" (Pancaldi, *Volta*, 95).

schools in Como to oversee the Austrian government's educational reforms in the area. His duties included lecturing, but only if a particular professor was unavailable. Four months after the electrophorus's announcement, Volta was appointed chair of physics in Como's secondary schools, a position that he was able to combine with that of superintendent.

Volta's Design for the Electrophorus

We are now in a position to meet the electrophorus and discuss its impact on electrical theory. Notably, most electricians who encountered the electrophorus did not experience a device built or operated according to Volta's original specifications. Instead, the design and operation of the device were simplified substantially over time. However, Volta's original design significantly shaped the device's reputation and is worth understanding in detail. Volta's diagram for the device is shown in figure 1. (Those unfamiliar with the electrophorus should first consult appendix A for a step-by-step account of the device's function and appendix B for an explanation of electrophorus in accordance with Franklin's theory of electricity.)

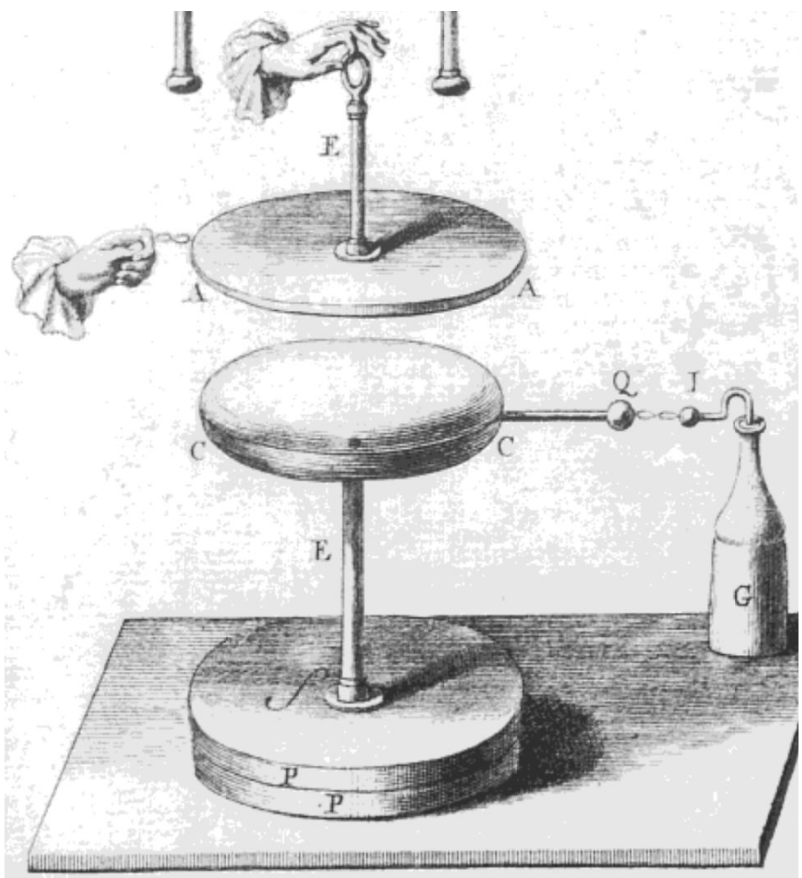

Figure 1. Volta's electrophorus with Leyden jar. From *Scelta di Opuscoli* (1775).[53]

[53] Volta, "Lettera al Signor Priestley," 91–107. Also available in Volta, *Le Opere*, 3:93–108.

The device consists of a round metal shield, *AA*, which is alternatively raised or lowered by the insulated handle, *E*, onto the resin cake that sits on the metal disc, *CC*. The metal disc is held by its own insulated handle, *E*, attached to a base, *PP*. The device can be connected to a Leyden jar, *G*, and charged through the conductors terminating at the metal balls *Q* and *I*.

Volta describes charging the device by attaching *AA* to an electrostatic generator (as indicated with the hand and chain to the left of *AA*). However, charging the device by rubbing the resin cake (later replaced with other non-conducting substances) quickly became the standard procedure. Volta would have known that the device could be charged by rubbing. He also knew that the device's ability to charge a Leyden jar without a separate electrostatic machine would be of interest to electricians. Why then, did Volta choose to describe charging the device via an electrostatic generator?

The most likely explanation is that he described charging the device this way to make the connection between the electrophorus and past experiments, particularly Beccaria's double-pane experiment, more transparent.[54] Many of the recent electrical experiments were set up as variations on the Leyden jar: some non-conducting substance (e.g., glass) is surrounded by a conductor and is charged by attaching the conductor on one side to an electrostatic generator and the conductor on the other side to ground. Volta's description of how to charge the electrophorus mimicked this setup. Additionally, it was later discovered that the lower metal disc holding the resin cake at CC was superfluous to the device's function. While it is not known whether Volta knew that it was superfluous at the time, both Beccaria's double-pane experiment and the Leyden jar utilized metal coatings on both sides of the non-conductor.[55] Volta's original design made the electrophorus's connection to those devices much clearer.

The resin cake is another aspect of Volta's device that was later replaced, typically with glass or glass coated with sealing wax. Volta went through considerable effort to perfect the design of the resin, experimenting with many different substances for the cake including sulfur, sealing wax, and mastic.[56] He finally settled on a cake made of three parts turpentine, two of rosin, and one of wax. This mixture had to be boiled for hours, and special attention had to be paid to ensure that it did not crack during the cooling process.[57] Volta would have known that glass could be used for

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[54] For a useful discussion of the connection between Volta's electrophorus and Beccaria's theory of vindicating electricity, see Pancaldi, *Volta*, 83–86, 108–9.

[55] Volta did not make a habit of taking or preserving laboratory notes until after the invention of the electrophorus. Thus, we can only infer Volta's goals and state of mind from his subsequent letters and publications. For further discussion of the resources available to Volta scholars concerning his invention of the electrophorus, see Pancaldi, *Volta*, 73–109, esp. 73–76.

[56] Volta, *Le Opere*, 3:97, 171.

[57] For additional details about Volta's process in designing the electrophorus, see Pancaldi, *Volta*, 100–4.

the non-conducting substance. He spent considerable energy perfecting a different non-conductor to find a material that would hold on to its electricity for as long as possible.

The Impact of the Electrophorus on Electrical Theory

The electrophorus had a substantial impact on the community of electricians. Many greeted it as "the most surprising device hitherto invented,"[58] "as mysterious to physicists as the Leyden [jar]" [59] and, just as the Leyden jar had thirty years earlier, it was thought that the electrophorus would "mark a new epoch"[60] of electrical theory. In France, an article in *Observations sur la physique* noted that "if [the electrophorus] is not directly contrary to [accepted theories], it presents many phenomena that can only be reconciled with difficulty."[61] A second letter in the journal went further, stating, "As for the explanation of the phenomena of the electrophorus . . . I conclude that the science of electricity still contains some principle which we do not know."[62] The French were not alone in this concern. John Ingenhousz summarized the situation nicely in *Philosophical Transactions*: "Some electricians, puzzled with the strange phenomena which [the electrophorus] affords, thought it over-turned entirely the almost universally received theory of Dr. Franklin, and that it could not be understood but by establishing new principles."[63] Of course, some were more guarded in their appraisal of the device. Franklin regarded it as "only another Form of the Leiden [jar], and explicable by the same Principles."[64] Others thought the instrument was derivative of past experiments, notably those by Cigna,[65] Gray,[66] Aepinus,[67] Wilcke,[68] and

[58] *Encyclopaedia Britannica* (1797), s.v. "Electricity," 6:424.
[59] Achard, *Vorlesungen*, 3:60.
[60] Achard, *Vorlesungen*, 3:60. Literally, the phrase in *Vorlesungen* can be translated as "the announcement of the electrophorus is therefore the epoch, since when one has become well aware of this neglected theory." The reference to the "neglected theory" is to the notion of spheres of influence or "circles of effect." This is perhaps an indirect reference to Aepinus's work in *Tentamen* although Aepinus is not specifically mentioned.
[61] Rouland and Sigaud de la Fond, "Lettre," 438.
[62] "Sur l'électrophore perpétuel de M. Volta," 505. The author is not clear in the text but is believed to be Louis Sebastien Jacquet de Malzet. See Pancaldi, *Volta*, 106–7.
[63] Ingenhousz, "How the Electrophorus May Be Accounted for," 1031–32.
[64] Franklin to Ingenhousz, Feb. 12[–March 6], 1777. Franklin had not yet seen the electrophorus in action and he hedges his response in the letter accordingly. As to the purported ability of the electrophorus to continue the sparks seemingly indefinitely, he says, "I must however own myself puzzled by one Part of your Account, viz. 'and thus the electric Force once excited may be kept alive Years together;' which perhaps is only a Mistake. . . . But though one may by repeatedly touching the Knob of a charg'd Bottle with a small insulated Plate like the upper one of the Electrophore, draw successively an incredible Number of Sparks . . . at length they will become small, and the Charge be finally exhausted." This indicates that he too may have been surprised by the degree to which the electrophorus could continue to generate sparks apparently without cessation had he seen the electrophorus in action.
[65] Ingenhousz, "How the Electrophorus May Be Accounted for," 1031; Beccaria, *Memorie*, 132. The note in *Memorie* was written by a certain Eandi as indicated on page 4.
[66] Beccaria, *Memorie*, 132; Henly, "Experiments and Observations on a New Apparatus," 515.
[67] Haüy, *Exposition*, 54; Pujoulx, *Paris*, 374.
[68] For example, Magellan, a scientific enthusiast and friend of Priestley, noted the connection between the electrophorus and experiments by Wilcke in an inscription on a book that Priestley asked him to give Volta. See Home, "Volta's English Connections," 120–21.

Beccaria,[69] and some commentators erroneously attributed the discovery of the electrophorus to those men.[70]

As it turned out, the electrophorus did not overturn established electrical theory, nor was it merely another form of the Leyden jar. The task of this section, then, will be to outline the precise role it played in changing established electrical theory by detailing the theoretically relevant phenomena it presented and how they were explained by electrical theorists.

The Phenomenon of Neutral-Neutral Electrification

The electrophorus presented at least two phenomena that were of theoretical interest to electricians. One of these was the apparent ability of a neutrally electrified experimenter to touch a neutrally electrified metal plate and obtain a spark from it (see appendix A, Step 3), an evident contradiction of Franklin's notion that sparks require a transfer of electric fluid from a body where there is more to one where there is less.[71]

One can observe that the metal disc is neutrally electrified at two stages of the operation. First, the metal disc can be touched before the experiment begins without the occurrence of a spark. Second, one can confirm that merely placing the metal disc on the non-conducting substance does not transfer electricity to the disc because it can be placed on the non-conducting substance, removed, and touched without producing a spark (see appendix A, step 2). Given that Franklin's theory would hold that the experimenter is electrified neutrally (owing to his or her connection to ground), it would appear that a neutrally electrified experimenter can touch a neutrally electrified metal disc and cause a spark to occur between them. According to Franklin's theory, this should not happen. Sparks arise when the electric fluid moves from a body where there is more to a body where there is less and thus require that at least one body is electrified either positively or negatively.

Franklinists have three basic options for how to respond to this apparent anomaly. One option is to hold that electricity is being transferred from the non-conducting substance, through the metal disc, and to the experimenter. On this view, the equilibrium is established between the non-conductor, which is not neutral, and the experimenter. This option is problematic for reasons

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[69] Ingenhousz, "How the Electrophorus May Be Accounted for," 1031.

[70] Pujoulx went so far as to claim that "all the observations and experiences of [Volta]" were first published in the memoirs of the Academy of Petersburg (presumably by Aepinus), but this was a minority view. See Pujoulx, *Paris*, 374. The most plausible disputes over Volta's priority in inventing the electrophorus tended to grant that Volta had invented a unique, useful machine that did an excellent job of demonstrating the relevant phenomenon, but argued that Volta had not been the first to discover the underlying principle behind his invention. This was the position taken by Wilcke and his supporters (Wilcke, "Electrophoro perpetuo," 54–78, 116–30, 200–16).

[71] An interesting letter that lays out the confusion around this point can be found in Serre to Franklin, May 28, 1778. See also the brief discussion in Henly, "Experiments and Observations on a New Apparatus," 516.

we will see later. The two remaining options are to either allow for the transmission of electricity between two neutrally electrified bodies, a major Franklinist heresy, or hold that the metal disc is not neutrally electrified while on the non-conducting substance. This last solution was the one suggested by Ingenhousz, and it is the solution that later became standard.[72] More specifically, Ingenhousz argued that the metal disc is not electrified neutrally *in all its parts* while on the non-conducting substance even though the total amount of electric fluid in the metal disc has not changed.[73]

The key to Ingenhousz's argument comes from the following principle:

> A conducting body insulated, being placed within the sphere of action of an excited non-conducting body, or even in contact with it, acquires at the same time two contrary electricities; *viz*. the part in contact or very near the non-conducting electrified body, acquires a contrary electricity to that of the non-conducting body, at the same time that the opposite or farthermost extremity is possessed of the same electricity with the conducting body.[74]

Thus, when the metal disc is touched while on the non-conductor, the spark results from the *separation* of charges in the metal disc brought about by the influence of the non-conductor. This occurs even though no electricity has been added or subtracted from the disc. In this principle is the core of electrostatic induction.[75]

Assume the non-conductor is electrified plus, and the metal disc possesses its natural quantity of electric fluid. When the disc is on the non-conductor, the repulsive power of the non-conductor will cause the electric fluid in the metal disc to be repulsed to the top of the disc, as far away from the electric fluid in the non-conductor as possible. Since the air is a non-conductor and the metal disc's handle is insulated, the electric fluid cannot leave. When the metal disc is touched, the repulsive force of the non-conductor now allows the electric fluid to flow out of the disc, through the experimenter, and to the common stock, producing a spark in the process. This loss of electric fluid means that the metal disc is now negatively charged. Switch the signs, and the metal disc can become positive by the same process.

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[72] A conceptually similar explanation was also given in Wilcke, "Electrophoro perpetuo," 54–78, 116–30, 200–16. The original Swedish version appeared in 1777. The more widely accessible German translation did not appear until 1782.
[73] Ingenhousz, "How the Electrophorus May Be Accounted for," 1027–48.
[74] Ingenhousz, "How the Electrophorus May Be Accounted for," 1036.
[75] The ability to separate the charge in a body was also demonstrated in 1762 in Wilcke, "Ytterligare rön," 206–29, 245–66 (translated into German in 1765 as Wilcke, "Fernere Untersuchung," 213–35, 253–74).

To complete Ingenhousz's explanation, only a few additional questions remain to be answered. For example, why can the experiment be repeated? The answer is that the electrical state of the non-conductor is unchanged by the experiment because non-conductors resist gaining or losing charge whereas conductors do not.[76] Why can the experiment be repeated over and over again with no apparent change in intensity? Because the non-conductor is a resinous body and resinous bodies hold on to their electricity tenaciously.[77] Why do all electrical signs disappear after the metal disc has been touched (as in appendix A, step 3)? Because the fluid that is added or subtracted from the metal plate is only the amount required to render the metal plate neutral while under the influence of the non-conducting substance.

Ingenhousz's explanation ended the Franklinist menace of apparent neutral-neutral electrification. Notably, the solution could be accomplished only by introducing a new principle—just as some electricians had predicted.

The Phenomenon of Repeated Sparks

The second phenomenon of interest was the production of an extensive series of sparks from the device without the need to re-rub the resin (see appendix A).[78] This is the most commented-upon feature of the device and a feature to which Volta paid considerable attention.[79] Further, in the rare event that the electrification of the resin should diminish, Volta described a procedure for reinvigorating it using a Leyden jar that had been previously charged with the device (see appendix C).[80] Thus, the device was deserving of its name, "the perpetual carrier of electricity."[81]

The importance of the electrophorus's repeated sparks to electrical theory lies in its ability to preclude explanations that require a transfer of electric fluid between the resin and the metal disc. Any such explanation must account for the fact that the resin's influence on the metal disc repeatedly results in sparks of roughly equal intensity. If the resin were to gain or lose any electricity in the process, then it should, correspondingly, increase or decrease the electrification apparent in the metal disc, but this does not occur. Thus, explaining the electrophorus requires some influence of the resin on the metal disc, but influence that does not substantially change the resin's charge. The obvious solution is that the resin exerts an attractive or repulsive force on the metal disc without electric fluid transfer. In this solution is the connection between the

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[76] Ingenhousz, "How the Electrophorus May Be Accounted for," 1035.
[77] Ingenhousz, "How the Electrophorus May Be Accounted for," 1035.
[78] Here I refer to the non-conductor as resin because the phenomenon was much more clearly demonstrated using resin than other non-conductors, like glass.
[79] For example, Volta devoted considerable attention to the exact shape and combination of ingredients to form the resin cake. See Pancaldi, *Volta*, 102. Volta also knew the importance of the name he attached to the device. See Volta, *Le Opere*, 3:137.
[80] Volta, *Le Opere*, 3:98–105.
[81] Volta, *Le Opere*, 3:99.

electrophorus and the demise of dynamic accounts of attraction and repulsion. The ability to repeatedly produce sparks of roughly equal intensity made dynamic accounts of attraction and repulsion challenging to maintain, and the widespread notoriety of the electrophorus allowed for a shift in the scientific consensus on this topic.

Notably, the argument sketched here does not straightforwardly concern the question of the location of the electric fluid of a positively charged body. It is entirely consistent to believe that charged bodies are surrounded by a layer of excess electricity and also that the excess electricity does not flow to other bodies in attraction or repulsion. As noted earlier, this appears to have been Franklin's view. It also seems to be the view taken by Ingenhousz, who makes a clear distinction between the "atmosphere of electric fluid surrounding the excited body"[82] and the repulsive "sphere of action"[83] of the body.

As dynamic accounts of attraction and repulsion declined, so too did the notion of excess electricity surrounding a charged body. There are two important reasons for this. One is that static accounts of attraction and repulsion undermine the implications of the electrical spider web phenomenon, then one of the chief sources of support for excess electricity. If attraction and repulsion can occur at a distance, without a transfer of fluid, then there need not be electric fluid in the air to cause the spider web sensation; it can be caused by the electricity in the body alone. Additionally, dynamic accounts of attraction and repulsion imply that the electric fluid passes easily and continuously into the air such that it is consistently available to attract or repulse other bodies. If the electric fluid is already in the air for attraction and repulsion, it is entirely reasonable to assume that some of the electric fluid is consistently located outside of the charged body itself. The static view, however, does not require the easy passage of electricity into the air. Given that the air was known to typically act as an insulator, it became more plausible to assume that the electric fluid remained entirely inside a charged body.

The trend toward static accounts of attraction and repulsion, and away from excess electricity around charged bodies, appears in much of the literature written after the invention of the electrophorus. A few examples will illustrate the point. In Germany, Franz Achard, the chief electrician of the Berlin Academy, makes the situation quite clear, calling the electrophorus the beginning of a new epoch in which attraction and repulsion can be understood in terms of static spheres of influence.[84] In a treatise on electrical theory given to a scientific society in Berlin, Joseph Weber notes that "we must maintain that electrical matter does not leave an [electrified] body to form an atmosphere."[85] William Enfield, a British Unitarian minister and bestselling

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[82] Ingenhousz, "How the Electrophorus May Be Accounted for," 1036.
[83] Ingenhousz, "How the Electrophorus May Be Accounted for," 1039.
[84] Achard, *Vorlesungen*, 3:60.
[85] Weber, "Die Theorie der Elektricität," 330–77. The translation is from Heilbron, *Electricity*, 425.

author on elocution, removed atmospheres entirely from his explanations of certain phenomena in attraction and repulsion.[86] In France, when Charles-Augustin de Coulomb began the series of experiments that would ultimately culminate in Coulomb's law, he started with an electrical theory consisting of static interactions between the electricity in charged bodies. Finally, Volta himself, initially agnostic as to the explanation of the electrophorus, eventually presented a sophisticated view of how a charged body can affect the electrical behavior of nearby bodies, but, as he stresses several times, no exchange of electricity occurs in this process.[87]

Conclusion

In sum, the phenomena displayed by the electrophorus engendered three specific changes to electrical theory:

> **1. Separation of charge**: The spark produced between the neutrally electrified metal disc and neutrally electrified experimenter led theorists to the view that neutrally electrified bodies can exhibit electrical behavior if the fluid inside the body is under the influence of another, non-neutral body.
>
> **2. Static accounts of attraction and repulsion**: The electrophorus's repeated sparks made accounts of attraction and repulsion that required a transfer of electric fluid implausible. As a result, electricians began to adopt the view that attraction and repulsion occurred at a distance, with no transfer of electric fluid.
>
> **3. The demise of excess electricity**: As dynamic accounts of attraction and repulsion became implausible, the idea of excess electricity around charged bodies became similarly implausible. As a result, the term *electrical atmospheres* came to refer to either a change in the electrical state of the air around a charged body or the sphere around a charged body where it can influence the electrical behavior of other bodies.

The necessity of these changes stemmed, in part, from Franklin's failure to provide a satisfactory account of attraction and repulsion in either his *Experiments* or in his subsequent work on electricity. Yet, the tendency to misunderstand the static role of Franklin's atmospheres suggests that dynamic accounts of attraction and repulsion were prevalent, in part, because they held a certain intuitive appeal. After all, if the movement of the electric fluid causes sparks, the obvious assumption is that attraction and repulsion are caused by a movement of fluid as well. Further, if the electric fluid moves between bodies in attraction and repulsion, it is quite plausible that the

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[86] Enfield, *Institutes of Natural Philosophy*, 341–53, esp. 347. Enfield also notes that electric fluid passes easily in a vacuum (page 353), a fact that makes views requiring the air as an intermediary in attraction and repulsion particularly difficult to maintain.
[87] Volta, "Osservazioni sulla capacità," 273–80, 289–312. Also in Volta, *Le Opere*, 3:199–229.

excess electricity of a charged body is located outside of the charged body, where it is easily available for transfer and for producing the electric spider web sensation.

Thus, the changes to electrical theory that the electrophorus engendered were not won easily. In fact, as we will see in the next section, the mere demonstration of apparent neutral-neutral electrification and repeated sparks was not enough to shift scientific consensus because others had already demonstrated these phenomena. It took the unique clarity with which the electrophorus demonstrated them and the device's widespread distribution to change the scientific consensus. The electrophorus did not cause these changes alone. The theoretical groundwork of others was likely required for electricians to change their views when confronted with the mysteries of the electrophorus. Additionally, some of the best Franklinist theorists had already begun to make many of the theoretical changes we have discussed before 1775, and it is entirely plausible that the electrophorus hastened a shift in views that would have occurred without Volta's invention.

Finally, it should not be supposed that this shift in electrical theory was, in any sense, *universal*. There were, in fact, several attempts at reviving dynamic accounts throughout the eighteenth century. The author of the third edition of the *Encyclopaedia Britannica*, for example, defended an unusual view stating that there is a flux of electric matter from every pore of an electrified body, which is then communicated to the surrounding atmosphere.[88] William Nicholson, the renowned English chemist, journalist, translator, publisher, and engineer, argued that "most of the electric phenomena are the consequences of the air being charged" as late as 1790.[89] There were also some still more eccentric views that failed to attract much notice.[90] Yet eventually these views too fell by the wayside as the community of electricians moved forward on the new foundation that the electrophorus helped to put in place.

Prior Experiments

As noted earlier, some electricians thought the electrophorus was derivative of several past electrical experiments. This section aims to show that, to a considerable degree, these electricians were correct. The phenomena of neutral-neutral electrification and repeated sparks were demonstrated in experiments by Beccaria and Wilcke, two of the best-known electricians of the era, years before Volta's invention.

As we will see, this fact makes the effect of the electrophorus in shaping scientific consensus all the more fascinating. The existence of these prior experiments usefully calls into question the

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[88] *Encyclopaedia Britannica* (1797), s.v. "Electricity," 6:460.
[89] Nichols, *Introduction to Natural Philosophy*, 2:301–66, esp. 2:337–38.
[90] See, for example, the effluvialist views in Lyons, *Experiments*, 85–86, 144–47; Formey, *Abrégé*, 1:276–82.

idea that the electrophorus shifted scientific consensus by demonstrating novel phenomena or that the device's renown was due to Volta himself. To explain the effect of the electrophorus on electrical theory, we will instead need to take a detailed look at the design of the electrophorus itself. In particular, we will consider how that design allowed the electrophorus to demonstrate its core phenomena more clearly and to a broader array of electricians than prior experiments demonstrating the same phenomena.

However, we will first need to discuss Beccaria's double-pane experiment and Wilcke's experiments with his dissectible condenser.

Giambatista Beccaria and the Double-Pane Experiment

At the time of Volta's invention of the electrophorus, Giambatista Beccaria was fifty-nine years old and was one of the most authoritative figures in electricity. As noted earlier, his 1753 treatise *Dell'elettricismo* was beloved by Franklin and his supporters and cemented Beccaria's reputation among electricians. Beccaria's double-pane experiment appeared in his 1769 treatise *Electricitas vindex* although he provides a repeat account in his 1772 book *Elettricismo artificiale.* The double-pane experiment is also the only experiment discussed specifically in Ingenhousz's 1778 *Philosophical Transactions* article reconciling the electrophorus with Franklin's theory.[91]

Given Beccaria's stature at the time and the discussion of his experiment in connection with the electrophorus, we can safely assume that this experiment was quite well known to electricians.

The Double-Pane Experiment

In his explanation of the double-pane experiment, Beccaria provides the diagram shown in figure 2:

[91] Ingenhousz, "How the Electrophorus May Be Accounted for," 1030–31.

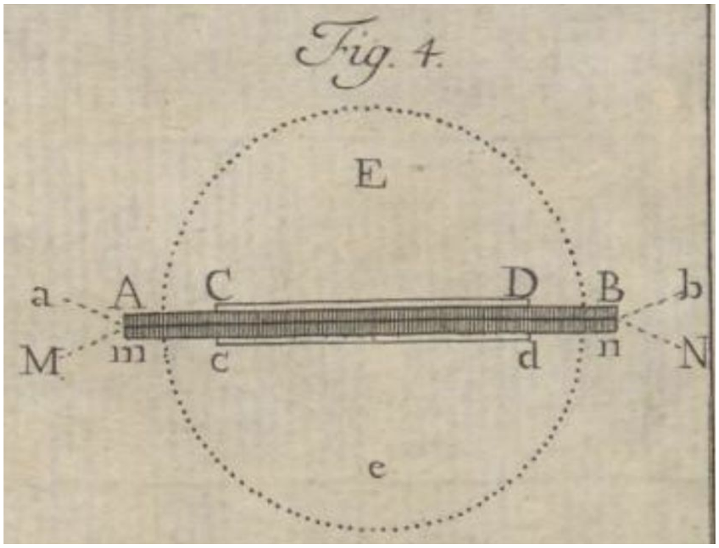

Figure 2. Beccaria's double-pane experiment. From *Artificial electricity* (1776).[92]

The experiment consists of two panes of glass pressed together with a metal coating on the outside of each pane. In the diagram, *AB* is the outside surface of a pane of glass, whereas *mn* is the outside surface of another pane of glass. The surface *AB* has a conductive metal coating *CD*, whereas *mn* has a conductive metal coating *cd*. Each glass pane also has an inside surface that is pressed against the other pane of glass. The surface *ab* is the inside surface that corresponds to *AB*, whereas the surface *MN* is the inside surface that corresponds to *mn*.

The diagram is somewhat abstract. For example, it is not clear from the diagram how the panes of glass are held in place or separated nor how the metal coatings are arranged to maintain their contact with the glass panes. Beccaria does specify, however, that one must be careful not to touch the coatings when separating the glass and that the coatings are removable (specifically, they can be taken off utilizing silk strings).

The experiment has been described in a step-by-step manner below using an annotated version of Beccaria's diagram.

Step 1: Charge the device with an electrostatic generator

[92] Beccaria, A*rtificial electricity*, pl. XI, fig. 4. The diagram can be found between pages 418 and 419 of the text.

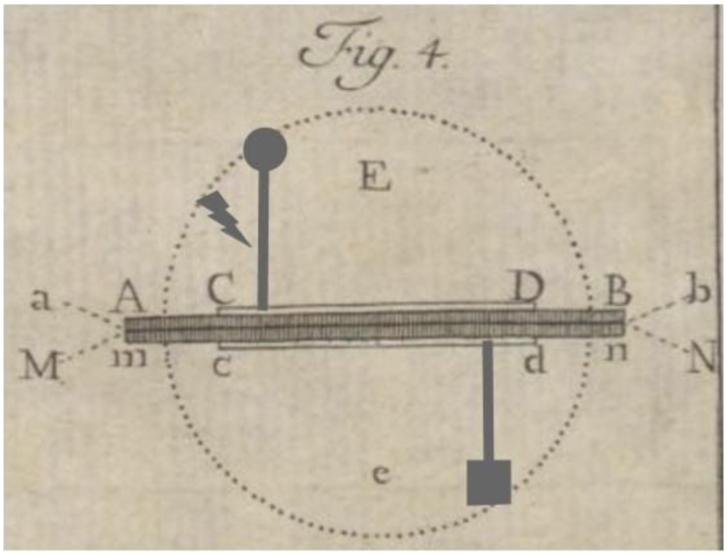

Figure 3. Pressing the sheets of glass together.

The two sheets of glass are pressed against each other by their plain surfaces. The upper coating *CD* is then attached to an electrostatic generator to be charged while the undercoating *cd* is connected to ground (see fig. 3).[93]

Step 2: Discharge the device

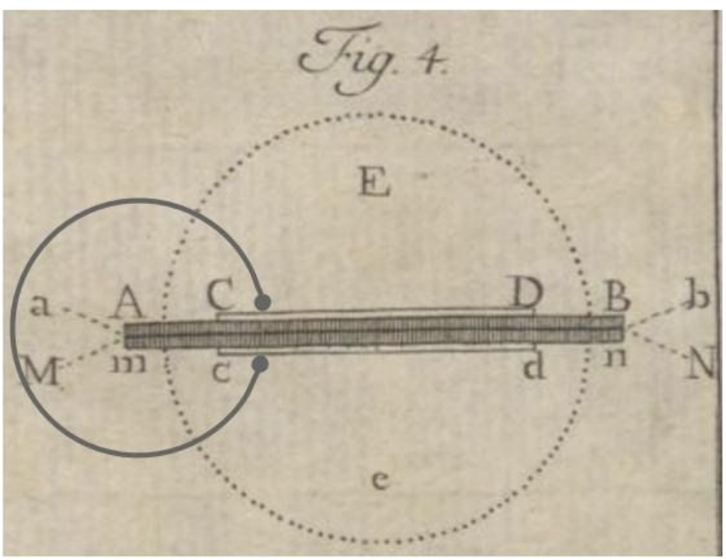

Figure 4. Discharging the device.

[93] Specifically, Beccaria says, "I join the two plates AB *ab*, MN *mn* together by their naked surfaces in contact with each other; and then introduce into the coating CD, for instance, the electricity of the Chain" (Beccaria, A*rtificial electricity*, 408–9).

CD is disconnected from the electrostatic generator, and *cd* is disconnected from ground. The device is now discharged by forming a connection between the upper and lower metal coatings, like discharging a Leyden jar (see fig. 4).[94]

Step 3: Separate the plates while touching *cd*

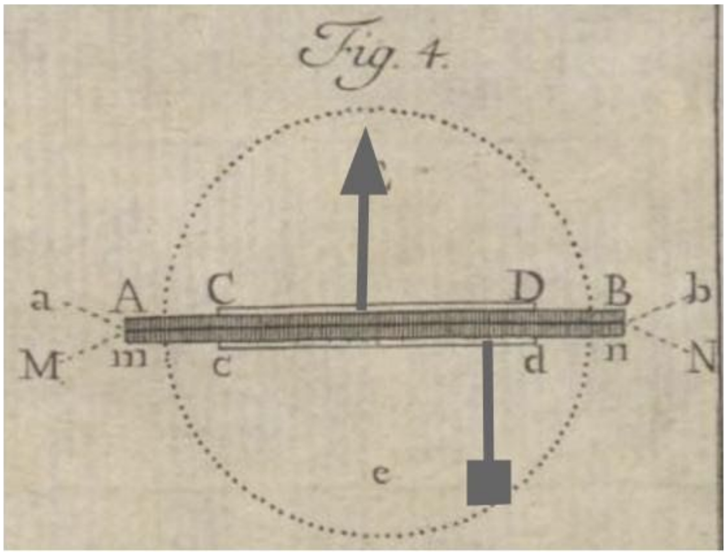

Figure 5. Separating the plates.

Now the two glass plates are separated. Beccaria specifies that in doing so, "I continually touch with one of my fingers the under coating *cd*" (see fig. 5).[95] Additionally, he says it is important to take care not to touch *CD* as the plates are being separated.[96]

Step 4: With the plates separated, touch *CD*

[94] Beccaria: "The charge being completed, I discharge them" (Beccaria, *Artificial electricity*, 409).
[95] Beccaria, *Artificial electricity*, 409.
[96] Beccaria: "I. I continually touch with one of my fingers the under coating *cd*. II. When I separate the plate AB, I take care not to touch its coating CD" (Beccaria, *Artificial electricity*, 409).

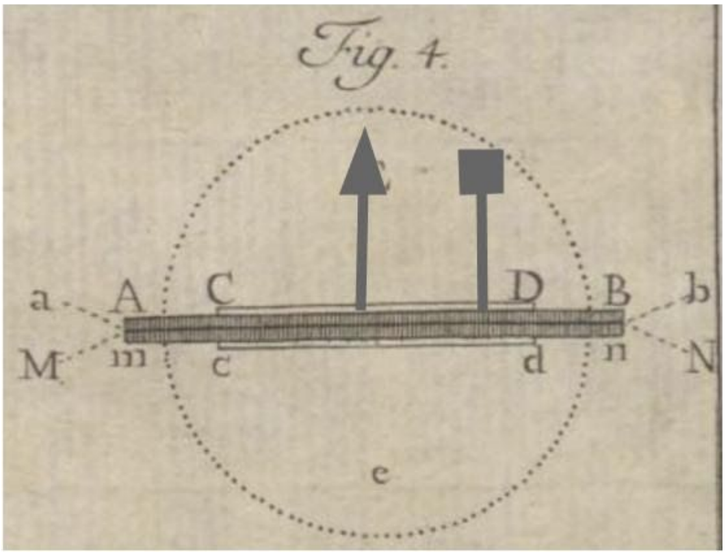

Figure 6. Touching *CD* to elicit a spark.

With the plates separated, the coating *CD* is immediately touched. This causes a small spark to occur (see fig. 6).[97]

Step 5: Rejoin the plates and then touch *CD*

[97] Beccaria specifies the following: "Having separated this plate, I immediately touch it and give a spark to it; that is to say, I give to AB an excess adequate to the deficiency contracted by *ab* at the instant of the separation" (Beccaria, *Artificial electricity*, 409). I have interpreted this to mean that one should touch the coating *CD* to give the spark and not the glass plate *AB*. This is intended to be charitable to Beccaria as he appears to suggest that one can touch *AB* alone and give a spark to it. For example, in the next sentence he says, "I cease touching AB." However, if one only touches *AB* and does not touch *CD*, no spark occurs and the rest of the operations Beccaria describes will also not occur. The claim that one can touch *AB* alone is probably a simple error, although it may instead be an artifact of the vindicating electricity account that Beccaria intends this experiment to demonstrate. According to that account, a spark can be given in step 4 because the separation of *ab* from *MN* causes a deficiency in *ab* that allows for a corresponding excess of electricity to be given to *AB* upon touching it. Because the theory explains this electrical behavior in terms of the electrical behavior of the plate, the experiment is more convincing if Beccaria discusses giving electricity to *AB* instead of giving it to *CD*.

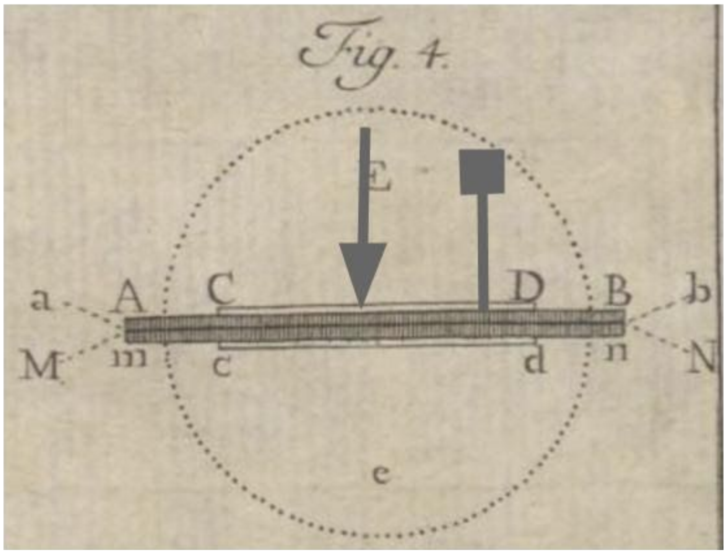

Figure 7. Touching *CD* with plates together.

Now one can rejoin the plates and then touch *CD* to receive a small shock (see fig. 7).[98]

Repeat steps 3 to 5

One can now go back to step 3 and repeat steps 3, 4, and 5 repeatedly. In each repetition, one will receive a spark in step 4 and again in step 5. An obvious question is how long this series can be repeated and with what strength the successive sparks are felt. On this point, Beccaria makes it clear that it can be continued for some time: "After jointly charging and discharging [the coatings on the plates], I continue for an hour and more to obtain sparks by touching them when separated and again touch them when rejoined; and reciprocally, the above explanations throw a complete light on that same experiment, which I never could repeat without exciting the wonder of those who were unacquainted with electrical operations and attracting the attention of the philosophers who came to see my experiments."[99]

The double-pane experiment demonstrates both of the phenomena that were important in the electrophorus. First, it shows the phenomenon of neutral-neutral electrification because the two panes are discharged in step 2, yet a spark can be drawn from *CD* in step 4 without any re-electrification. Second, it shows the phenomenon of repeated sparks through the ability to repeat steps 3 through 5 to reproduce the sparks generated in steps 4 and 5.

Yet, Beccaria's experiment wasn't the first to produce both of these phenomena. That honor goes instead to Johan Carl Wilcke.

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[98] Beccaria: "I rejoin the two plates and touch again CD, and draw sparks from it, by means of which I can draw off the excess I communicated to AB after the last separation, and which does no longer require when in a state of conjunction" (Beccaria, *Artificial electricity*, 409).

[99] Beccaria, *Artificial electricity*, 408.

Johan Carl Wilcke and the Dissectible Condenser

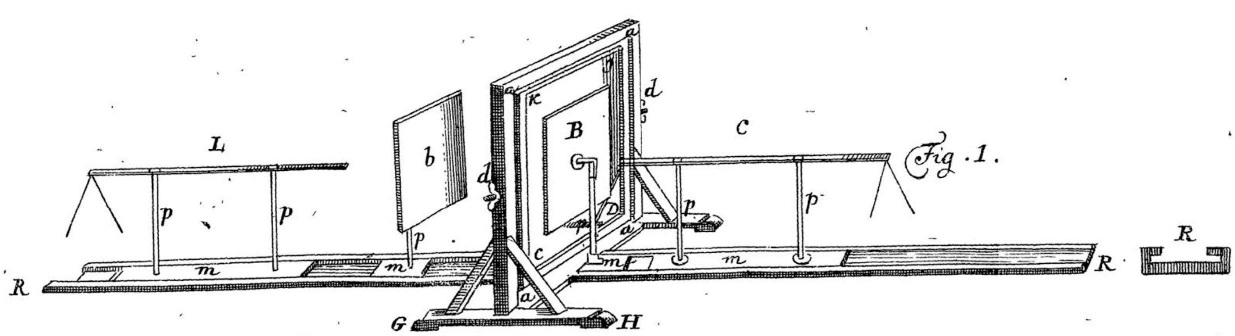
Wilcke's Background

At the time of Volta's invention of the electrophorus, Wilcke was forty-three years old. He was the first Thamisk lecturer of experimental physics for the Royal Swedish Academy of Sciences. He was especially well known among the Swedish- and German-speaking electricians owing to regular translations of the academy's *Handlingar* from Swedish to German by German polymath Abraham Gotthelf Kästner.[100] Wilcke also gained international fame. In Priestley's *History*, for example, Wilcke's work on spontaneous electricity produced by liquifying electric substances, electrical atmospheres, and electric light are all discussed extensively.[101] Regarding Wilcke and Aepinus's work on causing electrification using a "plate of air," Priestley says, "this discovery, of the method of giving the electric shock by means of a plate of air, may be reckoned one of the greatest discoveries in the science of electricity since those of Dr. Franklin."[102] Indeed, Wilcke was sufficiently famous internationally that in the 1775 edition of *Scelta di opuscoli interessanti*, where Volta published his announcement of the electrophorus, there was also a brief article by Wilcke that was translated from Swedish into Italian.[103]

Wilcke's experiments with the dissectible condenser were published in Swedish in 1762 and translated into German in 1765.[104]

The Dissectible Condenser

In his explanation of the dissectible condenser, Wilcke provides the diagram shown in figure 8:



[100] See Heilbron, *Electricity*, 125–26. See also Lindroth, *Kungl. Svenska*, 185–98, 208.
[101] Priestley, *History*, 274–76 (spontaneous electricity); 286–87 and 297–302 (electrical atmospheres); and 362–69 (electric light).
[102] Priestley, *History*, 302.
[103] Wilcke, "Sulla forma," 117–18.
[104] Wilcke, "Ytterligare rön," 206–29, 245–66. The German translation is Wilcke, "Fernere Untersuchung," 213–35, 253–74. I have relied primarily on the German translation in the ensuing discussion.

Figure 8. Wilcke's dissectible condenser. From *Der Königl. Schwedischen Akademie* (1765).[105]

The apparatus is designed to mimic a Leyden jar or Franklin square's behavior while also allowing for easy removal of the individual components. The central square, indicated by *KJCD*, is an eighteen-inch square pane of green window glass fixed to a wooden frame indicated by *aaaa*.[106] The frame has a wooden base indicated by *G* and *H*, and it can be repositioned by loosening the screws at *d* and then retightening them. On either side of the glass are conductive coatings indicated by *b* and *B*, each of which forms a fourteen-inch square. The coating is glued to cardboard sheets that can be bent so the coating can be pressed firmly against the glass.[107] Next to each coating are iron rods indicated by *L* and *C*.[108] At the end of each iron rod are detecting threads that repulse each other when charged positively or negatively. Each element of the apparatus rests on sliders indicated by *m* that slide in the wooden channel *R*. On the sliders are glass pillars *p*, which prevent the charge from dissipating.

The similarities between the phenomena displayed by the electrophorus and those displayed by the dissectible condenser can be most clearly seen in Wilcke's Experiment 20, which proceeds as follows, shown using annotated versions of Wilcke's diagram:

Step 1: Press *L*, *b*, *B*, and *C* into the glass

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[105] Wilcke, "Fernere Untersuchung," table V, located between pages 218 and 219. Wilcke indicates on page 218 that some of the experiments were actually performed on a different apparatus presented in figure 2 of table V. However, according to Wilcke, "Since both machines serve the same purpose, I will refer only to [figure 1]." I will do likewise.

[106] Wilcke specifies that the glass is indicated by *ABCD*. I've indicated it here as *KJCD* because this matches the letters that appear in the diagram. Additionally, units in the text are often specified in terms of zolls, a Prussian unit of distance that was used prior to 1872 and corresponded to approximately one inch. This has been simply translated as inches.

[107] Wilcke sometimes describes operations in which charge is transferred from the coatings to the metal rods indicated by *L* and *C,* but it is not clear from the description how the charge can pass from the coatings through the cardboard and to the metal rods. Based on the diagram, we can assume that some conductive material runs from the center of the coatings to the back of the cardboard and that this allows the coatings to transmit electricity to *L* and *C*.

[108] The text often appears to refer to *C* and *E* instead of *C* and *L* in references to the iron rods. It is assumed that this is a typo. I will refer to the rods as *C* and *L* to match the diagram.

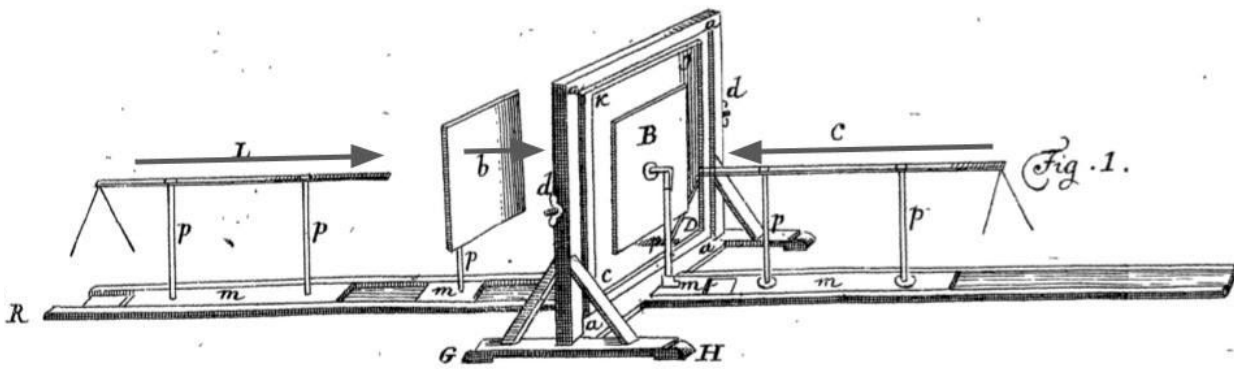

Figure 9. Pressing components into the glass.

Begin by pressing all of the condenser's components into the glass so they may be charged (see fig. 9).

Step 2: Attach *L* to ground and *C* to the prime conductor to charge the device

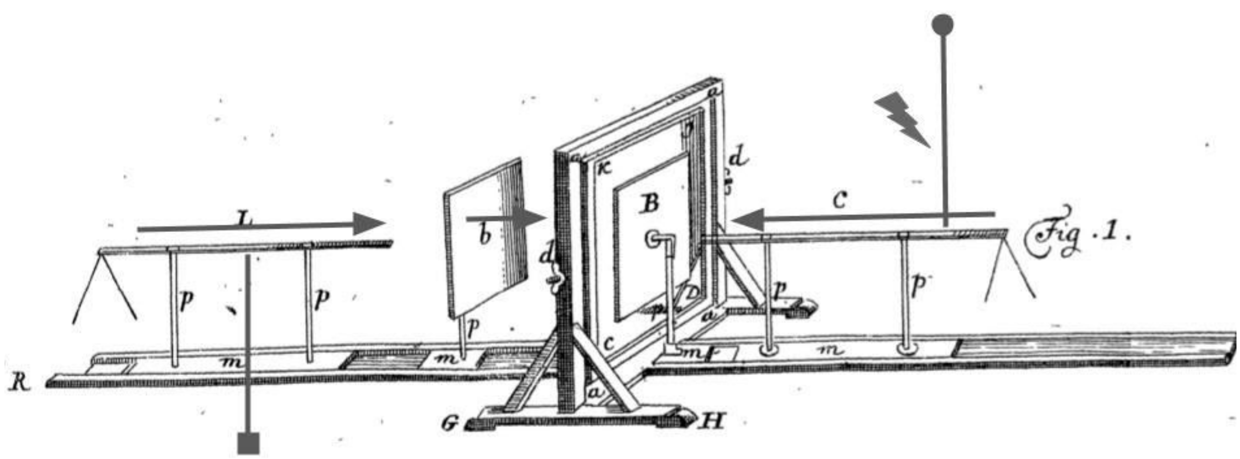

Figure 10. Charging the device.

The device charged like a Leyden jar or Franklin square by attaching one metal rod to a source of electric charge and the other rod to ground (see fig. 10).

Step 3: Disconnect L and C and move them away from the glass (fig. 11).

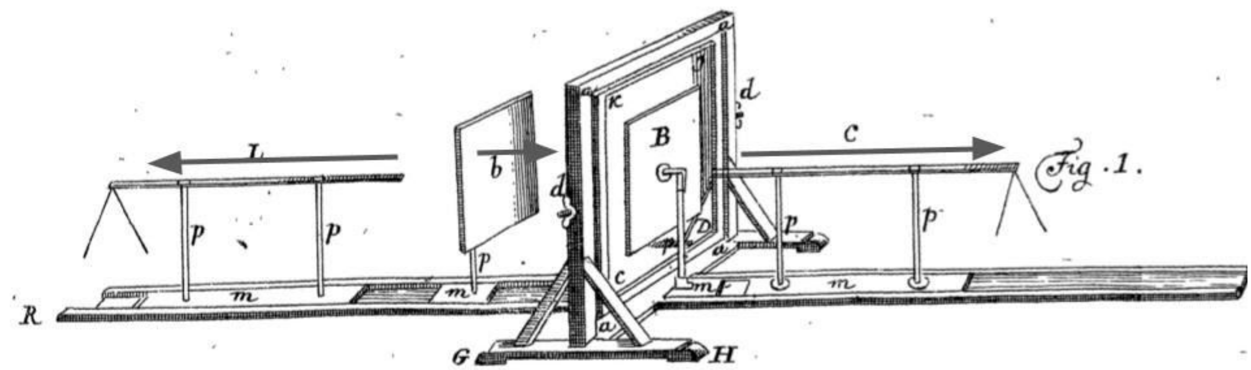

Figure 11. Moving the iron rods away from the glass.

Step 4: Neither *b* nor *B* shows any signs of electrification

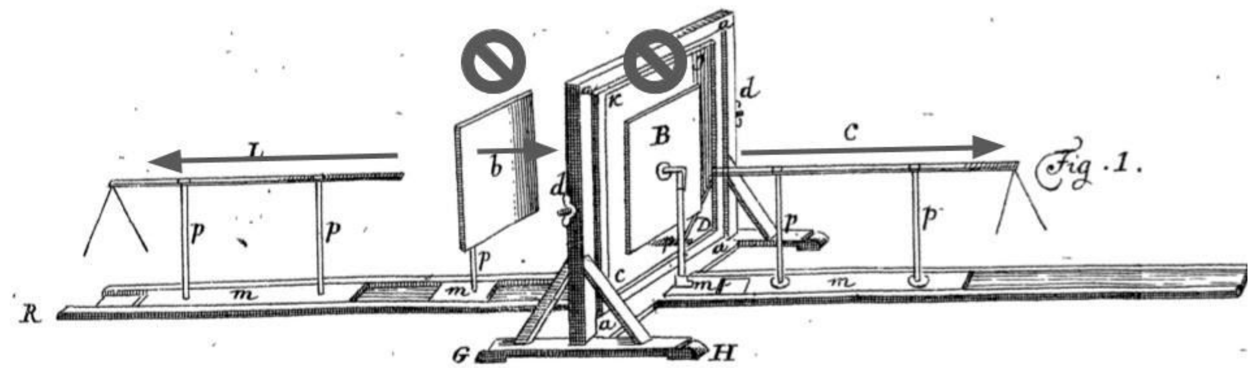

Figure 12. No signs of electrification.

At this point, Wilcke notes that neither *b* nor *B* shows any signs of electrification as long as they remain attached to the glass (see fig. 12)..

Step 5: Remove *b* and *B* from the glass

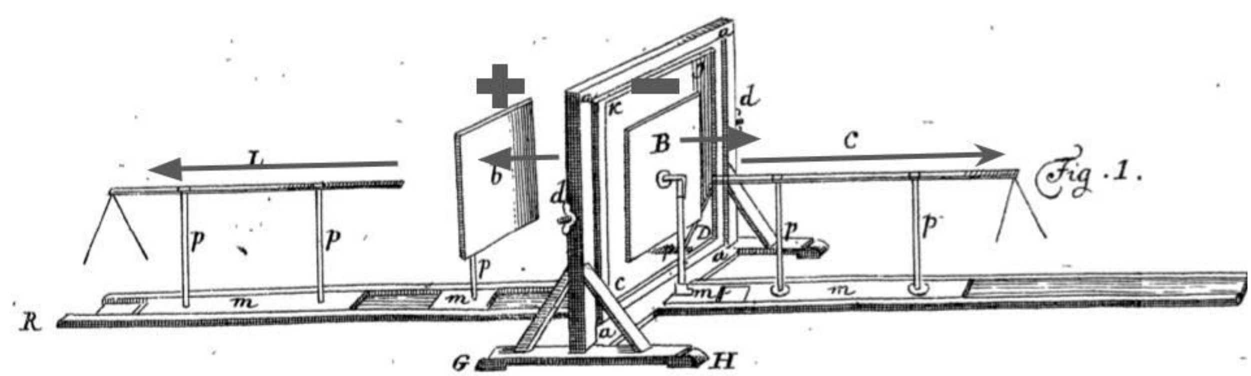

Figure 13. Removing the conductive coatings from the glass.

Both *b* and *B* are removed from the glass (see fig. 13). Wilcke describes them as having an "overly strong sparking,"[109] positive in the case of *b* and negative in the case of *B*.

Step 6: Discharge *b* and *B* and then return them to the glass

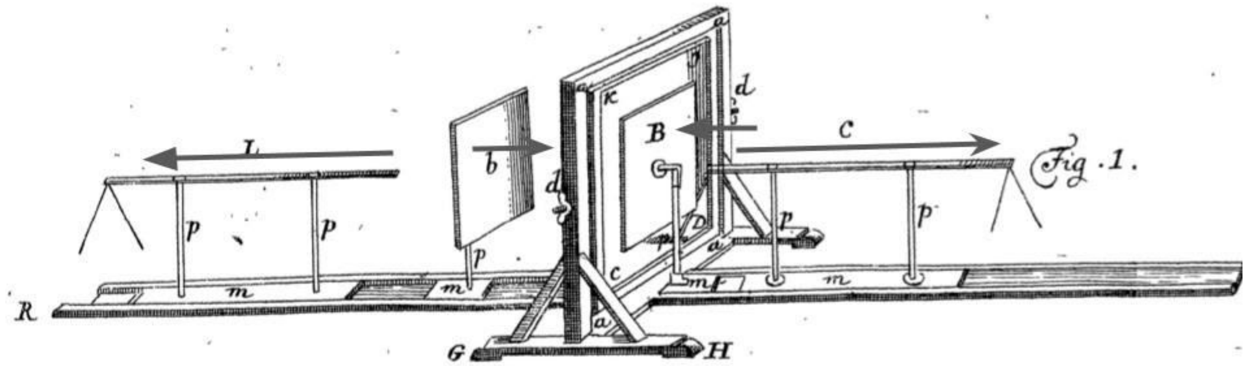

Figure 14. Discharging the conductive coatings and returning them to the glass.

While *b* and *B* are away from the glass, they are discharged and then returned to the glass (see fig. 14).[110] The reader will notice the similarity between this process and the process of discharging the electrophorus's metal disc while it is away from the plate (see appendix A, step 5).

Wilcke provides two observations that should be mentioned. First, he notes that while *b* and *B* are pressed against the glass, *b* is now *negative* and *B* is slightly *positive*.[111] Yet, "if [*b* and *B*] are removed in this way without being touched they are as before, without any electricity."[112]

Step 7: *b* and *B* are "pressed against the glass with both hands at the same time"

[109] Wilcke: "Führt man sie beide, oder jedes für sich vom Glase ab, so haben sie eine über die Maßen starke Funken gebende Elektrizität, die in B negativ und in b positiv ist" (Wilcke, "Fernere Untersuchung," 271).
[110] I have omitted Wilcke's step 4 primarily for the sake of clarity: "4) Welche sich darinnen fast stärker, als zuvor weist, wenn die eine Belegung B mit der Hand berührt wird, indem man die andere b abzieht und untersucht" (Wilcke, "Fernere Untersuchung," 271). Wilcke's meaning here is not entirely clear, but he is probably describing an operation that is similar to Beccaria's specification that one should touch *cd* while separating the plates in step 3 of the double-pane experiment (see above), namely, that if one continuously touches *B* while removing *b*, the electrical signs in *b* are strengthened.
[111] Wilcke, "Fernere Untersuchung," 271.
[112] Wilcke, "Fernere Untersuchung," 271.

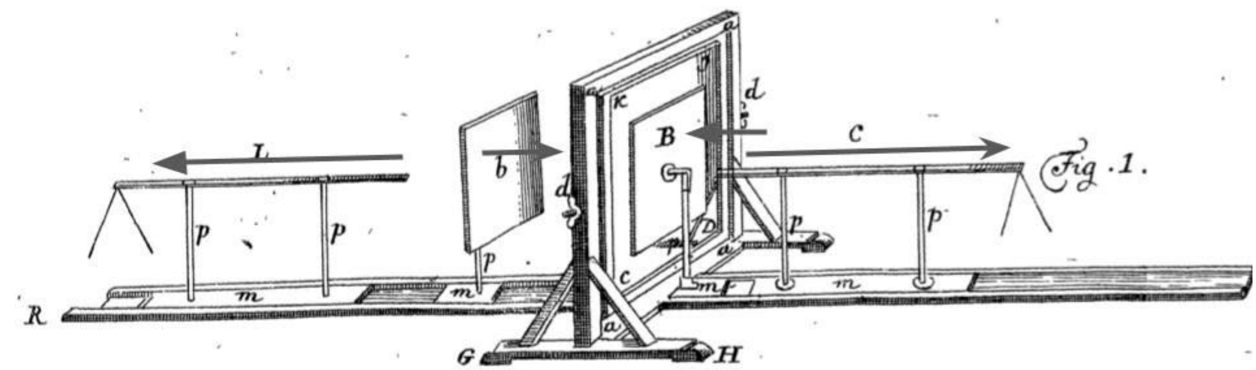

Figure 15. Pressing the coatings against the glass simultaneously.

Wilcke now specifies that "B is negative and b is positive, just as before, if they are pressed against the glass with both hands at the same time and then led away" (see fig. 15).[113] Pressing *B* and *b* against the glass this way has the effect of creating an equilibrium like the one that is created when discharging a Leyden jar. This causes *B* to become negative and *b* to become positive while away from the glass. The reader will recall that this is the same electrification in *B* and *b* that occurs in step 5 above.

Repeat steps 5 to 7

We can now repeat the experiment. As in step 5, we observe *b* is positive and *B* is negative. Then, as in step 6, we can discharge *b* and *B* and return them to the glass. Finally, we can press *b* and *B* against the glass with both hands and lead them away to return to the conditions in step 5.

Wilcke indicates that this can be repeated at some length: "In this way, the glass can noticeably electrify the coatings for many days and weeks in a row, no matter how often the experiment is repeated. This ability is gradually weakened, but it cannot be taken from the glass arbitrarily. Even in clear and dry weather, it often reappeared in the glass—which seemed to have lost it completely—of its own accord."[114]

This experiment exhibits the phenomenon of repeated sparks through the ability to repeat the experiment by repeating steps 5 to 7, which will show a spark each time *b* and *B* are discharged in step 6. It also exhibits the phenomenon of a neutrally electrified body displaying hard-to-explain electrical behavior. Wilcke notes explicitly that the signs of electrification disappear at step 4 and, similarly, the equilibrium established in step 7 would have been understood to cause *b* and *B* to be neutral.

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[113] Wilcke, "Fernere Untersuchung," 271.

[114] Wilcke: "Auf diese Art kann das Glas viele Tage und Wochen nacheinander die Belege merklich elektrifizieren, so oft auch der Versuch wiederholt wird. Dieses Vermögen wird nach und nach geschwächt, lässt sich aber nicht nach Gefallen vom Glase nehmen, es hat sich auch bei heiterem und trockenem Wetter oft von sich selbst aus wieder im Glase eingefunden, das solches gänzlich verloren zu haben schien." Wilcke, "Fernere Untersuchung," 271.

Wilcke's sophisticated experiment allows for precise observations about the movement of charge through the individual components of the apparatus and is the basis for the claim that he discovered the principle underlying electrostatic induction.[115] There is merit to this claim. In one experiment, for example, Wilcke observes that if *B* is placed one inch from the glass and connected to *C,* which is in turn connected to an electrostatic generator, the side of the glass opposite *B* is electrified positively. However, if *B* is no longer electrified, the electricity in the glass also vanishes. This indicates that even in glass, the electricity in the body can be repulsed to the extremity farthest from a source of electricity and appear to be electrified.[116]

Thus it appears that Beccaria and Wilcke each demonstrated the phenomena of electrical behavior in an apparently neutral body and repeated sparks years before the invention of the electrophorus. Additionally, Beccaria and Wilcke were among the most well-known and well-respected electricians of the era, whereas Volta was comparatively unknown. Yet, it was the electrophorus and not these prior experiments that gained widespread renown among electricians. The obvious question is why. We are now in a position to answer that question.

Why Did the Electrophorus Gain Widespread Renown?

If electricians knew about Beccaria's double-pane experiment and Wilcke's dissectible condenser, why did some electricians regard the electrophorus as "the most surprising device hitherto invented,"[117] or "as mysterious to physicists as the Leyden [jar]?"[118]

A suitable place to begin answering this question is Ingenhousz's 1778 article on the electrophorus in *Philosophical Transactions*, because Ingenhousz specifically discusses Beccaria's double-pane experiment as a precursor to the electrophorus. He explains that the electrophorus is nevertheless important because "As the inventors of these experiments did not adapt them as an electrical machine, they do not diminish at all, in my opinion the honour which Mr. Volta deserves, for having enriched the electrical apparatus with a very simple and handy machine, continually ready to excite as strong an electricity as is requisite for the most ordinary purpose."[119]

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115 The 1910 edition of the *Encyclopaedia Britannica* attributes this primarily to Canton, but indicates the importance of Wilcke's contributions (s.v. "Electricity," 9:181). Priestley suggests that Canton and Wilcke were both responsible for the discovery of the principle that "the electricity of one body repels that of another, especially if it have a flat surface, and gives it the contrary electricity" (Priestley, *History*, 338). For a more recent discussion of this topic, see Heilbron, *Electricity*, 418–19.
116 Wilcke, "Fernere Untersuchung," 227.
117 *Encyclopaedia Britannica* (1797), s.v. "Electricity," 6:424.
118 Achard, *Vorlesungen*, 3:60.
119 Ingenhousz, "How the Electrophorus May Be Accounted for," 1031.

Earlier in the piece, he comments on the practical usefulness of the device, saying:

> Once excited [the electrophorus] is for a long while ready to afford electricity enough for all experiments which do not require a very great force; it has the advantage of not being so much affected by damp weather as the common machines with glass globes, cylinders, disk, etc. It is very easily put in action by a slight friction with a dry hand, a piece of leather, a rough skin of a hare or cat, or some other animal. It is as easy to excite with this machine a negative as a positive electricity. It has the advantage of being capable at almost all times of affording at pleasure such a force of electricity as it wanted.[120]

Ingenhousz suggests that the electrophorus was notable because, unlike Beccaria before him, Volta took abstract electrical principles and turned them into a practically useful device. There is something to Ingenhousz's suggestion. The ability to use the electrophorus to charge a Leyden jar is one of its most commonly mentioned features and is undoubtedly one of the reasons electricians were interested in the device. However, this cannot be the whole picture of the electrophorus's adoption for at least two reasons.

First, Volta was not the first electrician to suggest a method of charging a Leyden jar by manipulating the distance between a charged non-conductor and a conductor. Giovanni Francesco Cigna (who, as it turns out, was Beccaria's nephew) suggested a procedure for charging a Leyden jar that involved a charged silk stocking and a lead plate before 1765.[121] This procedure is covered by Priestley, who provides a very clear description in his *History*:

> Mr. Cigna has invented a new method of charging a [Leyden] phial . . . he insulates a smooth plate of lead, and while he brings an electrified body, as a stocking, to it, he takes a spark with the wire of a phial from the opposite side; and removing the stocking, he takes another spark with his finger, or any other conductor communicating with the ground. Bringing the stocking nearer the plate a second time, he takes a second spark, with the wire of the phial, as before; and removing it again, takes another, in the same manner, with his finger. This operation he continues, till the phial is charged; which, in favorable weather, may be done with very little diminution of the electricity of the stocking.[122]

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[120] Ingenhousz, "How the Electrophorus May Be Accounted for," 1028.
[121] Cigna, "De Novibus," 31–72, esp. 50.
[122] Priestley, *History*, 338–39.

Priestley's *History* was widely read, and the procedure is easy to follow. We can safely assume that the practical usefulness of the electrophorus in charging a Leyden jar was not a novelty and thus is unlikely to explain the electrophorus's renown.

Second, the practical usefulness of the electrophorus does not straightforwardly account for why the electrophorus was thought to have "provided as much advantage to theory as to practice."[123] Improvements to electrostatic generators, for example, were practically useful but were not typically thought to change electrical theory. Indeed, the main goal of Ingenhousz's *Philosophical Transactions* paper was to rectify the electrophorus with Franklinist theory because, he notes, "some electricians puzzled with the strange phenomena which [the electrophorus] affords, thought it over-turned entirely the almost universally received theory of Dr. Franklin and that it could not be understood but by establishing new principles."[124]

To understand why the *electrophorus* shifted scientific consensus, we will need to direct attention to two important kinds of advantages the electrophorus had over the experiments of Beccaria, Wilcke, and others. The first concerns distribution, or the features of the electrophorus that caused a large number of electricians to build or acquire their own version of the device for electrical research. The second concerns clarity, or how vividly or obviously the relevant phenomena were demonstrated by the electrophorus. As we will see, Volta's design showcased the relevant phenomena more clearly and to a larger number of electricians than prior experiments and it was these improvements that led to the device's impact on electrical theory.

Distribution

One activity in which historians of science sometimes invest a good deal of time is working out the precise distribution pattern for important scientific works.[125] Knowing precisely what works a scientific figure had access to has several important implications. It can change our understanding of the context in which a work is presented, the process by which it occurred, and even the question of who deserves priority for particular discoveries. The fact that Volta knew of the works of Aepinus and Wilcke via Priestley's *History*, for example, may indicate that similarities between the electrophorus and their experiments are more than superficial.[126] This kind of research is particularly important in Volta's era as many important scientific texts were not widely available, and to the degree that they were, language barriers could sometimes preclude electricians from taking advantage of important prior works.

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[123] Achard, *Vorlesungen*, 3:60.

[124] Ingenhousz, "How the Electrophorus May Be Accounted for," 1028.

[125] Consider, for example, the detailed discussion by Pancaldi in *Volta* as to whether Volta was aware of particular devices built by Wilcke and Aepinus as these may have been influential in Volta's invention process. See Pancaldi, *Volta*, 73–109, esp. 75, 92, 95, and 104. Pancaldi notes that Volta received a copy of Priestley's *History* and was aware of Wilcke's and Aepinus's work via Priestley.

[126] Pancaldi, *Volta*, 73–109, esp. 75, 92, 95, and 104.

There is a background assumption implicit in this kind of work that should be rendered transparent:

> An intellectual work (e.g., an experiment, apparatus, or treatise) can only influence the scientific community to the degree that members of the scientific community are aware of it.

This assumption has two essential implications. First, it implies that if few scientists are aware of a work, it is unlikely to affect the scientific community. Second, it implies that if many scientists are aware of a work, it is much more likely to affect the scientific community. This is, of course, far from the only factor in explaining why some intellectual works affect a scientific community and others do not, but it is a crucial element.

The available documentation suggests that the electrophorus was ultimately quite widely distributed. It also spread quickly, particularly in European scientific circles circa 1775–76.[127]

By the summer of 1775, there were demonstrations of the electrophorus in the Brera district of Milan for audiences that included amateurs, professors, and public figures, and on August 2, the discovery was communicated to Carlo di Firmian, the Austrian representative in Milan who subsequently attended a demonstration.[128] By August 8, many similar devices were being built in Milan, and wealthy amateurs were trying to order larger versions of the electrophorus from instrument makers.[129] The local success caused Volta to try developing a larger apparatus to display more impressive effects.[130] It also led to Volta's appointment on November 1 as a professor of physics in Como, a position that he added to his existing role of superintendent.

Outside of Italy, the spread of the electrophorus is also evident. As noted earlier, in France, Rouland and Sigaud de la Fond used the journal *Observations sur la physique* to publicize a series of lectures on the electrophorus in 1776.[131] In Britain, the electrophorus's cache with instrument makers is made clear by William Henly, who indicates that he acquired the device from George Adams, philosophical instrument-maker to the king, and that Volta's role in the device was communicated to him by Edward Nairne, another celebrated instrument maker.[132] This is echoed by Priestley, who notes in a letter to Volta in April of 1776 that they had begun to make small versions of the instrument in England with success and would soon attempt to make

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[127] See the useful discussion of the device's distribution in Pancaldi, *Volta*, 105–7.
[128] Volta, *Le Opere*, 3:106n, 3:112n.
[129] Volta, *Le Opere*, 3:176n; Volta, *Epistolario*, 1:103.
[130] Volta, *Le Opere*, 3:118.
[131] Rouland and Sigaud de la Fond, "Lettre," 442.
[132] Henly, "Experiments and Observations on a New Apparatus," 513, 513n.

larger versions.[133] In Vienna, a box of electrophoruses was given to a Captain Ziegler of the Imperial Guards and circulated among the nobility and several philosophers, physicians, and amateurs.[134] The eventual recipients included John Ingenhousz, then a physician in the Austrian court, who received the device directly from Archduke Ferdinand.[135] In Berlin, Achard reported on the electrophorus in the 1776 *Mémoires* of the Berlin Academy.[136] In Prague, Joseph Klinkosh, a physician, encountered an electrophorus, which he used to discover ways of increasing the strength of the electric effect by moving the metal disc alternately between two non-conducting surfaces.[137] Thus, it appears that the electrophorus gained widespread recognition internationally around a year after Volta unveiled his invention.

Why did the electrophorus gain such quick and widespread distribution? Several potential explanations have already been called into question. The device did not gain recognition because of Volta's reputation; he was relatively unknown at the time. Volta's announcement of the device was not published in a particularly well-read journal. The device did not display any entirely novel phenomena.

The renown of the electrophorus can be explained, in part, by a combination of three advantages the device had in gaining distribution among the community of eighteenth-century electricians.

First, as Ingenhousz suggests, the device was practically useful for electricians. It could be used to charge a Leyden jar for electrical experiments and could do so under conditions unfavorable for the more conventional electrostatic generators. Volta also designed the electrophorus to be portable. The version of the electrophorus presented in *Scelta di Opuscoli* was five inches in diameter, although Volta experimented with devices as large as two feet.[138] By comparison, while electrostatic generators differed in size, they tended to be large, ranging from a few feet to

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[133] Priestley to Volta, April 25, 1776. Also in Volta, *Epistolario*, 1:123.
[134] Volta, *Epistolario*, 1:102; Volta, *Le Opere*, 3:145n. There is a discussion of this in Pancaldi, *Volta*, 105.
[135] Ingenhousz, "How the Electrophorus May Be Accounted for," 1029.
[136] Achard, "Expériences sur l'électrophore," 122–34.
[137] Ingenhousz, "How the Electrophorus May Be Accounted for," 1029.
[138] For the image of the electrophorus, see Volta, "Lettera al Signor Priestley," 91–107. It also appears in Volta, *Le Opere*, 3:93–108 and is reproduced earlier in this essay. For a discussion of the dimensions of the device, see Pancaldi, *Volta*, 102.

five feet and above.[139] Additionally, the use of a substance other than glass also contributed to the device's portability as glass tended to break when transported across long distances.[140]

Second, the distribution of the electrophorus was enhanced by the steps Volta took to ensure that the device was useful for public demonstrations. In the eighteenth century, it was fashionable for amateurs to be up to date on the latest scientific developments. A popular venue for staying updated was the public lecture, which, to be appealing to an amateur audience, typically included impressive experiments with the latest electrical apparatus. Indeed, one can see the repertoire of experiments Volta had in mind in one of his diagrams:

[139] One surviving globe-type electrostatic generator from around 1750 was just over five feet tall. See National Museum of American History, "Globe-Type Electrostatic Machine." Attempts to replicate a device of Joseph Priestley's design suggest that it was a little over three feet tall. See "Joseph Priestley's Static Electricity Machine." Images of an electrostatic generator of Hawksbee's design suggests that the apparatus was around as large as a person. See Privat-Deschanel, *Elementary Treatise*, 574, for a very clear image. Privat-Deschanel indicates that the image is from the often-reprinted *Leçons de Physique* by Nollet.

[140] This happened to Volta in 1781 when a shipment of instruments from Paris resulted in broken glass on three air pumps. As Bellodi and Brenni note, "In fact, the transportation of instruments from Paris and London to Italy was a risky business. The instruments after having been partially dismantled were packed in big wooden cases, but, in spite of these precautions, accidents were not uncommon. It is easy to imagine the vibration and the bumps experienced by these cases, as they were loaded and unloaded from horse carriages travelling for hundreds of miles, or being badly shaken on board a ship in rough seas" (Bellodi and Brenni, "Arms of the Physicist," 11).

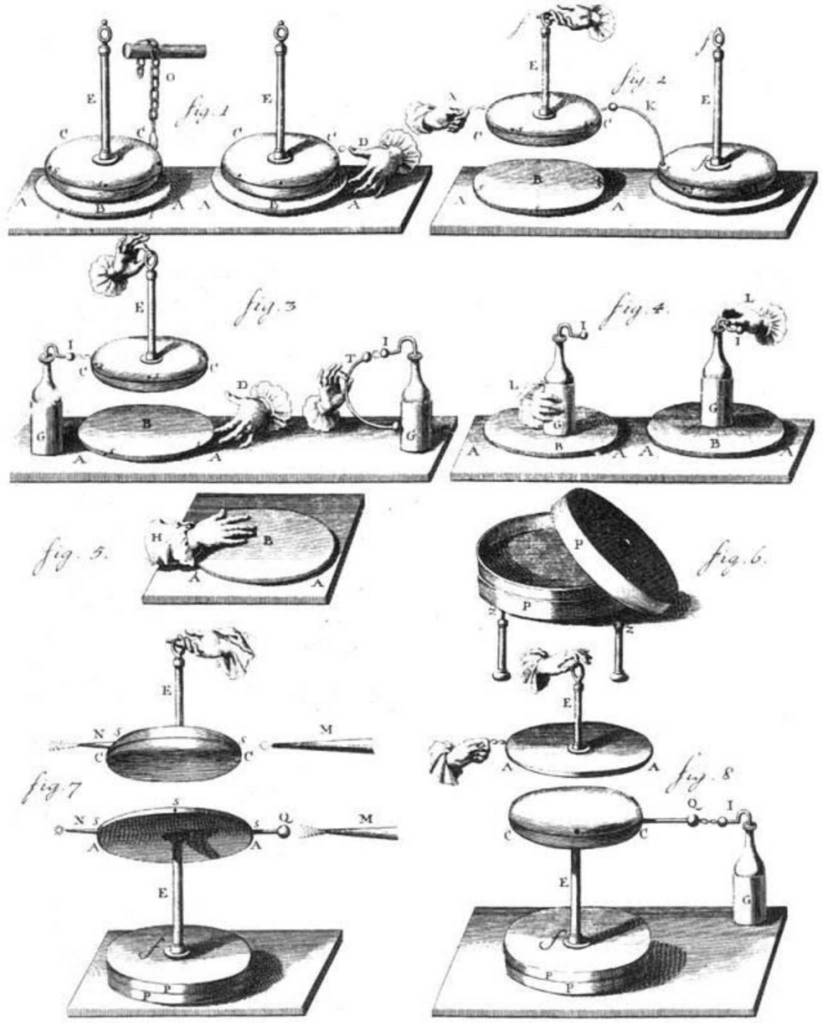

Figure 16. Experiments with the electrophorus. From *Scelta di Opuscoli* (1775).[141]

In figure 16, one can see Volta's specification that the base indicated by *PP* should be hollow. This was so that the inside of the shield could be "used to carry the paraphernalia the electrician needed for his demonstrations: silk and metal wires, a small Leyden jar, wires with cork balls fitted to them for testing the electricities."[142]

These elements of Volta's design plus the mystery of how the device worked made the electrophorus sufficiently intriguing to be the main attraction in popular courses on electricity. Indeed, in the same article of *Observations sur la physique* that claims the electrophorus could only be reconciled with the accepted theories "with difficulty,"[143] the authors also note that while the phenomena of the electrophorus are challenging and require some attention from the

[141] Volta, *Le Opere,* 3:101.
[142] Pancaldi, *Volta*, 102.
[143] Rouland and Sigaud de la Fond, "Lettre," 438.

experimenter, they would be happy to demonstrate them to amateurs who visit them at the university (presumably for a fee).[144]

Finally, the distribution of the electrophorus was aided by the device's ability to be imitated. Most electricians who encountered the electrophorus did not encounter the device as Volta specified it. Instead, they tended to experience versions that substantially simplified Volta's original design. The metal disc Volta used for holding the resin was discovered to be unnecessary and was removed. Similarly, while resin worked better than glass, glass was more widely available, so many experimenters simply used glass or used glass with a wax coating placed over it. Even the rubbing procedure that became a central component of most explanations of the device was different from the charging procedure Volta originally suggested.

Indeed, descriptions of the device itself quickly became descriptions of its imitations. One of the earliest reports of the electrophorus, by William Henly in 1776, describes it without the resin or charging procedure Volta described initially: "[A] circular plate of glass, about eight inches in diameter, covered on one side with a coating of bees-wax and rosin, about the sixteenth part of an inch thick. This coat of wax, &c. being strongly excited with a dry warm flannel, he placed upon it a circular board, of the same dimensions, coated with tin-foil and furnished with a glass handle screwed to, and standing upright upon it."[145]

Ingenhousz describes the electrophorus similarly, stating that it consists of "two different pieces; *viz*. 1. a metallic body, in the form of a plate, or any other convenient figure, furnished with an insulating handle, to be used for lifting it up; and 2. A flat non-conducting substance, such as glass, resin, or some other non-conducting matter, upon which the said metal plate is placed."[146]

This description of the electrophorus as consisting of two plates, one made of a conductor and one made of a non-conductor, occurs repeatedly in reports of the device.[147] The imitations were relatively straightforward to produce, which is why subsequent electricians chose these designs. Provided that the electrician had access to glass for the non-conducting substance, the only operation of any real difficulty would have been affixing the metal plate's insulated handle.

In summation, the electrophorus gained quick and widespread distribution in European scientific circles despite Volta's status as a relatively unknown electrician. The spread of the device was aided by three aspects of the devices's design: its practical usefulness to electricians, its ability to

[144] Rouland and Sigaud de la Fond, "Lettre," 442.
[145] Henly, "Experiments and Observations on a New Apparatus," 513.
[146] Ingenhousz, "How the Electrophorus May Be Accounted for," 1027–28.
[147] For additional examples, see "Sur l'électrophore perpétuel de M. Volta," 501–8; Cavallo, *Complete Treatise*, 2:49; *Encyclopaedia Britannica* (1797), s.v. "Electricity," 6:462–63.

be used for public demonstrations, and the ability to build much simpler imitations of the device that displayed the same core phenomena.

The widespread distribution of the device meant that many electricians were aware of it not as an abstract description in a treatise, but as a device they had either seen in operation or had experimented with personally. This made it possible, but by no means guaranteed, for the electrophorus to have a large impact on the scientific community. What remains is for the device to display its phenomena clearly enough to compel electricians to rethink electrical theory. We will now direct attention to this aspect of the electrophorus.

Clarity

While the electrophorus demonstrated the same underlying phenomena as Beccaria and Wilcke's experiments, this does not mean each experiment demonstrated the phenomena equally well. Volta designed the electrophorus to demonstrate the phenomena more vividly or obviously than past experiments, a feature we might refer to as the *clarity* of the experiment.

The reader will recall that Volta went through considerable lengths to highlight that the repeated sparking his device demonstrated was perpetual. He spent considerable time experimenting with different options for the non-conducting substance, including sulfur, sealing wax, and mastic (a kind of plant resin), ultimately settling on a mixture of three parts turpentine, two of resin, and one of wax. This concoction had to be boiled together for hours, and there was a constant danger of burning the mixture. It then had to be cooled with particular attention paid to ensure that it did not crack in the cooling process. Volta was no doubt aware that the procedure could be performed with glass alone—he was, after all, quite familiar with Beccaria's double-pane experiment that used glass, yet he found it essential to identify a substance that would demonstrate the phenomena even more clearly than glass. Volta also took care to describe a procedure for recharging the device with a Leyden jar charged by the electrophorus itself (see appendix C). Even the name of the device itself, the *electtroforo perpetuo*, or "perpetual purveyor of electricity," was designed to highlight this attribute.

Indeed, some elements of Volta's original design and description that are now understood to be unnecessary to the functioning of the device, have an important role in clearly demonstrating the underlying phenomena to eighteenth-century natural philosophers. One example is the procedure of charging the electrophorus via an electrostatic generator, which Volta described in the letter to Priestley. This was quickly replaced with the rubbing procedure, which became standard. Volta doubtlessly knew that the device could be charged by rubbing, but as charging by the electrostatic machine was more common, his suggestion of using an electrostatic machine helped to clarify the relevant phenomena and their connection to well-known devices like the Leyden jar and the work of other electricians, including Beccaria.[148]

A similar story is true of the bottom metal disc. It was later discovered that the disc was unnecessary to the device's function and it was discarded. Volta's original design allowed one to connect the top and bottom metal discs to establish an equilibrium between them. This procedure closely mimics the use of the Leyden jar, in which the spark is produced by connecting the metal coating inside the jar with the metal coating outside the jar. Unlike the Leyden jar, however, the electrophorus could continue to exhibit electrical behavior after this equilibrium was established. The inclusion of the bottom metal plate made the analogy to the Leyden jar clear. It also made the electrical behavior of the electrophorus all the more surprising.

Commentary on the electrophorus from Volta's contemporaries suggests that Volta was successful in his goal of designing an instrument that could demonstrate the phenomena of repeated sparks more clearly than past experiments. A few examples will illustrate the point. Take the case of Jean Hyacinthe de Magellan, an acquaintance of Priestley's and scientific superconnector, who noted in an inscription in a book he was asked to give to Volta that the electrophorus was similar to prior experiments by Wilcke, but that it "displayed to perfection the very remarkable phenomenon involved."[149]

The clarity of the electrophorus is also evident in Ingenhousz's *Philosophical Transaction* paper on the device. After acknowledging the similarities between the electrophorus and Beccaria's experiments, Ingenhousz takes care to identify the source of the remarkable tenacity of the electrophorus's electrical behavior, attributing it to a property of resin: "All resinous bodies, silk and many others, retain more tenaciously their state of electricity than glass, however dry. Thus a piece of glass excited is almost quite deprived of its electricity by a conducting substance being applied to it; but a resinous body, though touched, retains still a great share of its electricity."[150]

Electricians who felt similarly compelled to explain why the electrophorus's sparks could be repeated at such length settled on a similar conclusion. Achard's explanation is the same, namely that "resin plates keep their excited electricity for a long time."[151] This is echoed by Henly, who

[148] In April of 1765, Volta spent time investigating the electrical properties of different substances as they were rubbed. From these investigations he would have been aware of the electrical behavior of rubbed resin (Pancaldi, *Volta*, 80–82). For a brief discussion of the connection between the electrophorus and Beccaria's theory of vindicating electricity, see Heilbron, *Electricity*, 416–17.
[149] Home, "Volta's English Connections," 121.
[150] Ingenhousz, "How the Electrophorus May Be Accounted for," 1035–36
[151] Achard, *Vorlesungen*, 59–60, esp. §1333.

notes that “negative electrics *per se*, being once thoroughly excited are observed to retain their electrical quality very long,”[152] among others.[153]

Thus, for Volta’s contemporaries, an explanation of the electrophorus was not complete unless it included an explanation for the remarkable clarity of Volta’s invention as compared to past experiments that used only glass.

One difficulty for the view that the electrophorus gained widespread renown for its superior clarity is that most electricians did not encounter the electrophorus as Volta designed it. In particular, most electricians substituted glass coated with some other substance (frequently wax) for Volta’s carefully developed resin. Why, then, is the specific design Volta developed important to the device’s widespread notoriety?

The answer lies in the effect of Volta’s original design on the reputation the device gained among electricians. Due to both Volta’s original design and the name he attached to it, the device gained the reputation of conveying sparks for a long time. This reputation meant that electricians paid substantial attention to the sparks’ persistence in their analysis of the electrophorus. It also meant that when electricians and instrument makers attempted to make their own electrophoruses, they did so intending to produce a configuration that would increase the duration of the effects. Cavallo provides a particularly illustrative example: “The first experiments that I made relative to this machine, were with a view to discover which substances would answer best for coating the glass plate, in order to produce the greatest effect. I tried several substances either simple or mixed, and at last I observed, that the strongest in power, as well as the easiest I could construct, were those made with the second sort of sealing-wax, spread upon a thick plate of glass.”[154] Here we can see that the goal of Cavallo’s initial foray into the design of the electrophorus was to make the sparks last as long as possible. Elsewhere Cavallo notes that the instrument maker George Adams was engaged in similar research and had produced plates made of shellac and “Venice turpentine” that acted “exceedingly well.”[155] The search for which substances would “answer best” to create the repeated sparks also explains why many of the subsequent imitations of the device elected to use something more complicated than plain glass. Both Henly and the Encyclopaedia Britannica describe the non-conducting plate as

[152] Henley, “Experiments and Observations on a New Apparatus,” 515. In the quoted passage, the term “negative electrics *per se*” refers to a non-conductor (electric *per se*) that tends to lose electricity to other bodies (thus making it negative). This usage is functionally synonymous with Ingenhousz’s use of the term *resinous body*.
[153] As part of a dispute over priority in the discovery, Heilbron also attributes the following quote to Beccaria: “The perpetuity that D. Alessandro has attached to his electrophore is only a greater duration of electricity impressed on resin” (Heilbron, *Electricity*, 417).
[154] Cavallo, *Complete Treatise*, 2:52–53.
[155] Cavallo, *Complete Treatise*, 2:53n.

being glass covered with sealing wax, as do both articles on the electrophorus in *Observations sur la physique*.[156]

The electrophorus gained widespread renown for two primary reasons. First, the device was able to quickly gain wide distribution among electricians because it was practically useful, entertaining for public demonstrations, and cheap and easy to imitate. The widespread distribution allowed many electricians to become well acquainted with the device and the phenomena it demonstrated either by seeing the device in operation or by experimenting with it personally. When electricians did encounter the electrophorus, the phenomena it displayed were both clear and perplexing. This led a significant number of electricians to reevaluate their understanding of electrical theory and, ultimately, led to important changes in the scientific consensus.

Conclusion

This essay has been concerned with two primary questions: what effect did the electrophorus have on electrical theory, and why was it the electrophorus that had this impact rather than prior experiments by better-known electricians like Beccaria and Wilcke?

In answering these questions, we first focused on the state of electrical theory after the publication of Franklin's *Experiments* (1747–55). As we saw, Franklin left much to be desired in his attempt to extend his theory of the Leyden jar to account for attraction and repulsion. Despite this, the core of his theory, the notion that bodies could be electrified plus or minus, showed some promise in predicting when attraction and repulsion would occur and his notion that positively charged bodies had a layer of excess electricity surrounding them was already regarded as plausible by many electricians.

Franklin's followers tended to adopt these promising elements of Franklin's account, but unlike Franklin, they explained attraction and repulsion as arising from a transfer of electric fluid between the bodies and the excess electricity surrounding them. This view had much going for it. It elegantly explained attraction and repulsion as arising from the same mechanism that explained visible sparks, namely, the sudden transfer of the electric fluid between two bodies. It also appeared to be substantiated phenomenologically as experimenters could seemingly feel the electric atmosphere itself when moving their skin close to a positively charged body. Eventually, a handful of electrical theorists began to see that a transfer of fluid between bodies could not account for attraction and repulsion and began to revise their views accordingly. For many

[156] Henley, "Experiments and Observations on a New Apparatus," 514; *Encyclopaedia Britannica* (1797), s.v. "Electricity," 6:462–63; "Sur l'électrophore perpétuel de M. Volta," 501; Rouland and Sigaud de la Fond, "Lettre," 438.

electricians, however, abandoning these views would require familiarity with suitably bewildering experimental results like those gathered using the electrophorus.

We then directed attention to the specific effect of the electrophorus on electrical theory by analyzing both the way the device actually functioned and contemporaneous reactions to Volta's invention. Three effects on electrical theory were identified: (1) the notion that a neutrally electrified body could exhibit electrical behavior while under the influence of another body; (2) the demise of accounts of attraction and repulsion that required a transfer of electricity between bodies; (3) the demise of the notion that there is a layer of excess electric fluid surrounding charged bodies. The electrophorus did not cause these changes alone, and they may have occurred even without its invention. The electrophorus's role was in helping to hasten their adoption and thus hasten changes in the scientific consensus on these topics.

Finally, we discussed the relationship between the electrophorus and earlier experiments by Beccaria and Wilcke. A detailed examination of these earlier experiments showed that they demonstrated the same theoretically relevant phenomena as the electrophorus, albeit years earlier and under the name of much better-known electricians than Volta. To explain why the electrophorus nevertheless had an important impact on scientific consensus, we discussed aspects of Volta's design that helped the device gain widespread distribution among electricians and the clarity with which the device displayed its core phenomena.

All that now remains is to discuss what this account says about how to contextualize the nature and significance of Volta's accomplishment.

After Volta's invention of the electrophorus, he found himself in an unusual social position among natural philosophers. Some rated him among the most important electricians of the era. As one historian put it, both De Luc and Lichtenberg were prepared to grant Volta the "Newtonship of electricity" (with Franklin being the Kepler) after he visited Paris and Göttingen respectively.[157] Others were less taken with the up-and-coming Italian and wielded the similarities between the electrophorus and prior experiments to advance their cause. Pujoulx, for example, adopted the extreme view that "all of the experiments and observations" by Volta were little more than rip-offs of the work of Aepinus.[158] Most acknowledged Volta's merit in designing a useful electrical apparatus that displayed the relevant phenomena clearly, but (correctly) attributed articulation of the underlying principles involved to others. For some of Volta's contemporaries, however, the question of who first discovered the underlying principles involved was the question that really mattered. To them, Volta was an inventor of "electrical

[157] Heilbron, *Electricity*, 423 (De Luc), 424 (Lichtenberg).
[158] Pujoulx, *Paris*, 374. Volta was aware of some of Aepinus's experiments via Priestley's *History*, but did not have access to *Tentamen* until after the invention of the electrophorus.

amusements;" noble work to be sure, but not the work of a substantive natural philosopher.[159] Indeed, one sometimes sees the residue of this view today, particularly in popular discussions of the electrophorus. It probably underlies the very confusing claim that one sometimes sees that Volta did not invent the electrophorus, but instead merely popularized or improved upon Wilcke's invention.[160]

Volta cared about his standing among natural philosophers and defended himself as best he could. He ultimately decided to strengthen his reputation by going back to theory, and this culminated in 1778 with an enlightening memoir on conductors that treated the electrophorus as a special case of his overall theory.[161] Yet, what finally cemented Volta's legacy as one of the most important electricians of the late eighteenth century—the person after whom the volt is named—was his invention of another "electrical amusement," the Voltaic pile. The remarkably simple device consisted of stacks of zinc and copper on top of one another in an alternating pattern with brine-soaked cloth or cardboard in between. The device allowed electricians to produce a long-lasting, consistent charge, opening up a wide range of electrical investigations. It was also the precursor to the modern battery.

Volta was, in fact, a quite capable theorist, but this was overshadowed by the renown he acquired for his electrical instruments. Yet, his true genius was not just in designing interesting, useful, and theoretically relevant instruments. It was in designing instruments that could capture the attention—and imagination—of natural philosophers while also illustrating important theoretical concepts without the need to provide the theory himself. With these skills, Volta was able to have a profound impact, not just on electrical instruments or on electrical theory but on scientific consensus itself.

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159 This was reported to Volta by De Luc. See Volta, *Epistolario*, 2:163. See also Pancaldi, *Volta*, 111.
160 For example, as of August 2020, the Wikipedia entry for "Johan Wilcke" claims that Wilcke "invented an electrostatic generator that was a first version of the electrophorus" and the entry for "electrophorus" claims that "a first version of it was invented in 1762 by Swedish professor Johan Carl Wilcke." For a published example of this claim, see the otherwise illuminating Assis, *Experimental and Historical Foundations of Electricity*, 2:118. Many of these sources cite Heilbron, *Electricity*, 418–19, although neither Wilcke himself nor Heilbron made this claim. See Heilbron, *Electricity*, 419n.
161 Volta, "Osservazioni sulla capacità," 273–80, 289–312.

Bibliography

Achard, Franz Carl. “Expériences Sur l’électrophore Avec Une Théorie de Cet Instrument.” *Nouveaux Mémoires de l’Académie Royale Des Sciences et Belles Lettres*, 122–34. Berlin, 1776. https://books.google.com/books?id=uGYa92tkEhkC.

———. *Vorlesungen über die Experimentalphysik*. 4 vols. Berlin, 1791. https://books.google.com/books?id=KwMHAAAAcAAJ.

Aepinus, Franz Ulrich Theodor. *Tentamen theoriae electricitatis et magnetismi* [...]. St. Petersburg, 1759. https://books.google.com/books?id=70ry0vdIiM0C.

Assis, Andre Koch Torres. *The Experimental and Historical Foundations of Electricity*, Vol. 2. Montreal: C. Roy Keys, Inc., 2018. https://www.ifi.unicamp.br/~assis/Electricity-Vol-2.pdf.

Beccaria, Giambatista. *A Treatise upon Artificial Electricity, in Which Are given Solutions of a Number of Interesting Electric Phoenomena, Hitherto Unexplained. To Which Is Added, an Essay on the Mild and Slow Electricity Which Prevails in the Atmosphere during Serene Weather*. London, 1776. http://archive.org/details/b30415354.

———. *Dell’ elettricismo artificiale e naturale libri due*. Turin, 1753.

———. *Dell’elettricismo. Lettere* [...] *al Chiarissimo Sig. Giacomo Bartolomeo Beccari*. Turin, 1758.

———. *Elettricismo artificiale*. Turin, 1772.

———. *Experimenta atque observationes, quibus electricitas vindex late constituitur, atque explicatur*. Turin, 1769.

———. “Experiments in Electricity: In a Letter from Father Beccaria, Professor of Experimental Philosophy at Turin, to Benjamin Franklin.” *Philosophical Transactions of the Royal Society* 51 (1759): 514–26. https://doi.org/10.1098/rstl.1759.0052.

———. *Lettre Sur l’electricité, Par Le R. P. J. B Beccaria*. Translated by Delor. Paris, 1754.

———. *Memorie istoriche intorno gli studi del padre Giambatista Beccaria*, 1783. https://books.google.com/books?id=F-VfAAAAcAAJ.

Bellodi, Giuliano, and Paolo Brenni. "The 'Arms of the Physicist': Volta and Scientific Instruments." In *Nuova Voltiana: Studies on Volta and His Times*. Edited by Fabio Bevilacqua and Lucio Fregonese. Vol. 3, Pavia and Milan: Hoepli, 2000. [PDF]. http://ppp.unipv.it/Collana/Pages/Libri/Saggi/Nuova%20Voltiana3_PDF/cap1/cap1.pdf.

Canton, John. "A Letter to the Right Honourable the Earl of Macclesfield, President of the Royal Society, Concerning Some New Electrical Experiments." *Philosophical Transactions of the Royal Society* 48 (1753): 780–85. https://doi.org/10.1098/rstl.1753.0093.

———. "An Attempt to Account for the Regular Diurnal Variation of the Horizontal Magnetic Needle; and Also for Its Irregular Variation at the Time of an Aurora Borealis." *Philosophical Transactions of the Royal Society* 51 (1759): 398–445. https://doi.org/10.1098/rstl.1759.0040.

———. "Electrical Experiments, with an Attempt to Account for Their Several Phænomena; Together with Some Observations on Thunder-Clouds." *Philosophical Transactions of the Royal Society* 48 (1753): 350–58. https://doi.org/10.1098/rstl.1753.0053.

Cavallo, Tiberius. *A Complete Treatise on Electricity, in Theory and Practice: In Theory and Practice with Original* [...], Vol. 2. 3rd ed. London, 1786. http://archive.org/details/acompletetreati00cavagoog.

Cavendish, Henry. "An Attempt to Explain Some of the Principal Phænomena of Electricity, by Means of an Elastic Fluid." *Philosophical Transactions of the Royal Society* 61 (1771): 584–677. https://doi.org/10.1098/rstl.1771.0056.

———. *The Electrical Researches of the Honourable Henry Cavendish; Edited by J. Clerk Maxwell*. Edited by James Clerk Maxwell. Cambridge: Frank Cass & Co., 1967. http://archive.org/details/electricalresear00caveuoft.

Cigna, Giovanni Francesco. "De Novibus Quibusdam Experimentis Electricis." *Miscellanea Taurinensia* 3 (1765–1762): 31–72. https://books.google.com/books?id=V6QbAAAAMAAJ.

Encyclopaedia Britannica, 3rd ed., s.v. "electricity." Edited by Colin Macfarquhar, George Gleig, and Andrew Bell. Edinburgh: Printed for A. Bell and C. Macfarquhar, 1797. https://archive.org/details/gri_33125011197924.

Encyclopaedia Britannica, 11th ed., s.v. "electricity." Edited by Hugh Chisholm. New York: Encyclopaedia Britannica, 1910. https://books.google.com/books?id=I8LplSA1vK0C.

Ellicott, John. "Several Essays towards Discovering the Laws of Electricity." *Philosophical Transactions of the Royal Society* 45, no. 486 (1748): 195–224. https://doi.org/10.1098/rstl.1748.0019.

Enfield, William. *Institutes of Natural Philosophy, Theoretical and Experimental*. London, 1785. https://archive.org/details/b28767664.

Formey, Jean Henri Samuel. *Abrégé de Physique*. 2 vols. Berlin, 1770.

Franklin, Benjamin. Benjamin Franklin to Cadwallader Colden, October 31, 1751. In *The Papers of Benjamin Franklin*. American Philosophical Society and Yale University. published online by the Packard Humanities Institute. https://franklinpapers.org/yale?vol=4&page=202a.

———. Benjamin Franklin to Cadwallader Colden, August 30, 1754. https://franklinpapers.org/framedVolumes.jsp?vol=5&page=426a.

———. Benjamin Franklin to Jan Ingenhousz, March 12, 1777. https://franklinpapers.org/framedVolumes.jsp?vol=23&page=310a.

———. Benjamin Franklin to Thomas-François Dalibard, June 29, 1775. https://franklinpapers.org/framedVolumes.jsp?vol=6&page=097a.

———. *Benjamin Franklin's Experiments*. Edited by I. Bernard Cohen. Cambridge, MA: Harvard University Press, 1941.

———. "Electrical Experiments, Made in Pursuance of Those by Mr. Canton." *Philosophical Transactions of the Royal Society* 49 (1755): 300–305. https://doi.org/10.1098/rstl.1755.0052.

———. *Experiments and Observations on Electricity, Made at Philadelphia in America*. London, 1751. https://doi.org/10.5479/sil.211644.39088000092304.

National Museum of American History. “Globe-Type Electrostatic Machine.” Smithsonian, National Museum of American History, Behring Center. Accessed August 24, 2020. https://americanhistory.si.edu/collections/search/object/nmah_712387.

Haüy, René Just. *Exposition Raisonnée De La Théorie De L'électricité Et Du Magnétisme: D'après Les Principes De M. Æpinus*. Paris, 1787.

Heilbron, J. L. *Electricity in the 17th and 18th Centuries: A Study in Early Modern Physics*. Mineola, NY: Dover, 1999.

Henly, William. “Experiments and Observations on a New Apparatus, Called, a Machine for Exhibiting Perpetual Electricity.” *Philosophical Transactions of the Royal Society* 66 (1776). https://doi.org/10.1098/rstl.1776.0034.

Herbert, Joseph Nobilis de. *Theoriae Phaenomenorum Electricorum: Quae Seu Electricitatis Ex Redundante Corpore in Deficiens Traiectu, Seu Sola Atmosphaerae Electricae Actione Gignuntur*. Vienna, 1778. https://books.google.com/books?id=BIQ5AAAAcAAJ.

Home, Roderick Weir. *Aepinus's Essay on the Theory of Electricity and Magnetism*. Translated by Peter James Connor. Princeton University Press, 2015.

———. “Franklin's Electrical Atmospheres.” *The British Journal for the History of Science* 6, no. 2 (1972): 131–51. https://www.jstor.org/stable/4025288.

———. “Volta's English Connections.” In *Nuova Voltiana: Studies on Volta and His Times*, Vol. 1. Edited by Fabio Bevilacqua and Lucio Fregonese. Pavia and Milan: Università degli studi di Pavia, 2000, 115–32. http://ppp.unipv.it/Collana/Pages/Libri/Saggi/NuovaVoltiana_PDF/cinque.pdf

Ingenhousz, John. “Experiments, to Explain How Far the Phenomena of the Electrophorus May Be Accounted for by Dr. Franklin's Theory of Positive and Negative Electricity.” *Philosophical Transactions of the Royal Society* 68 (1778): 1027–48. https://doi.org/10.1098/rstl.1778.0049.

"Joseph Priestley's Static Electricity Machine: Replica of 1769 Apparatus." Spark Museum. Accessed August 24, 2020. http://www.sparkmuseum.com/priestley-machine.HTM.

Lindroth, Sten. *Kungl. Svenska Vetenskapsakademiens Historia 1739–1818*. Stockholm, 1967.

Lyon, John. *Experiments and Observations Made with a View to Point out the Errors of the Present Received Theory of Electricity*. London, 1780. https://books.google.com/books?id=NBc_AQAAIAAJ.

Nicholson, William. *An Introduction to Natural Philosophy*. 3rd ed. 2 vols. London: J. Johnson, 1790. https://archive.org/details/anintroductiont00nichgoog.

Nollet, Jean Antoine. *Leçons de Physique Expérimentale*. 6 vols. Paris, 1743.

Pace, Antonio. *Benjamin Franklin and Italy*. Philadelphia, 1958.

Pancaldi, Giuliano. *Volta: Science and Culture in the Age of Enlightenment*. Princeton University Press, 2018.

Priestley, Joseph. *Experiments and Observations on Different Kinds of Air*. 6 vols. London, 1774.

———. Joseph Priestley to Alessandro Volta, April 25, 1776.

———. *The History and Present State of Electricity, with Original Experiments*. 2nd ed. London, 1767.

———. *The History and Present State of Electricity, with Original Experiments*. 3rd ed. London, 1775.

Privat-Deschanel, Augustin. *Elementary Treatise on Natural Philosophy: Electricity and Magnetism*. 10th ed. 4 vols. New York, 1889. https://books.google.com/books?id=vscUAAAAYAAJ.

Pujoulx, Jean Baptiste. *Paris à La Fin Du 18e Siècle*. Paris, 1801. https://gallica.bnf.fr/ark:/12148/bpt6k64384656/f13.item.

Rouland, and Sigaud de la Fond. "Lettre." *Observations sur la physique, sur l'histoire naturelle et sur les arts*, no. 7 (1776). https://gallica.bnf.fr/ark:/12148/bpt6k9605165h.

Serre, Henri. Henri Serre to Benjamin Franklin, May 29, 1778. In *The Papers of Benjamin Franklin*. American Philosophical Society and Yale University. published online by the Packard Humanities Institute. https://franklinpapers.org/framedVolumes.jsp?vol=26&page=541a.

"Sur l'électrophore Perpétuel de M. Volta." *Observations Sur La Physique, Sur l'histoire Naturelle et Sur Les Arts*, no. 7 (1776). https://gallica.bnf.fr/ark:/12148/bpt6k9605166x/f53.item.

Volta, Alessandro. "Articolo Di Una Lettera Del Signor Don Alessandro Volta al Signor Dottore Giuseppe Priestley, Como, 10 Giugno 1775." *Scelta Di Opuscoli Interessanti,* 9 (1775): 91–107. https://books.google.com/books?id=oW58giDQsLIC.

———. *De vi attractiva ignis electrici, al phænomenis independentibus*. Como, 1769. https://books.google.com/books?id=Ha9gAAAAcAAJ.

———. *Epistolario Di Alessandro Volta*. 5 vols. Bologna, 1949.

———. *Le Opere di Alessandro Volta*. 7 vols. Milan, 1918.

———. *Novus Ac Simplicissimus Electricorum Tentaminum Apparatus: Seu de Corporibus Eteroelectricis Quae Fiunt Idioelectrica. Experimenta, Atque Observationes*. Como, 1771.

———. "Osservazioni Sulla Capacità de' Conduttori Elettrici [...] al Signor De Sauddure." *Opuscoli Scelti Sulle Scienze e Sulle Arti* 1 (1778): 273–80, 289–312. https://archive.org/details/opuscolisceltis01soavgoog.

Watson, William. "A Collection of the Electrical Experiments Communicated to the Royal Society by Wm. Watson." *Philosophical Transactions of the Royal Society* 45, no. 485 (1748): 49–120. https://doi.org/10.1098/rstl.1748.0004.

Weber, Joseph. “Die Theorie Der Elektricität.” *Schriften Der Berlinischen Gesellschaft Naturforschender Freunde*, no. 4 (1783): 330–77. https://www.biodiversitylibrary.org/item/259871.

Wilcke, Johan Carl. “Fernere Untersuchung von Den Entgegengesetzten Elecktricitäten Bei Der Ladung Und Den Dazu Gehörenden Theilen.” Translated by Abraham Gotthelf Kästner. *Der Königl. Schwedischen Akademie Der Wissenschaften Neue Abhandlungen Aus Der Naturlehre, Haushaltungskunst Und Mechanik* 24 (1765): 213–35, 253–74. http://resolver.sub.uni-goettingen.de/purl?PPN324352840_0024.

———. “Sulla Forma Della Neve Del Signor G. Carlo Wilcke.” *Scelta Di Opuscoli Interessanti* 2 (1775): 117-18. https://books.google.com/books/about/?id=cjEtAAAAMAAJ.

———. “Untersuchung Der Bey Herrn Voltas Neuen Electrophoro Perpetuo Vorkommenden Elektrischen Erscheinungen.” Translated by Abraham Gotthelf Kästner. *Der Königl. Schwedischen Akademie Der Wissenschaften Neue Abhandlungen Aus Der Naturlehre, Haushaltungskunst Und Mechanik* 39 (1782): 54–78, 116–30, 200–216. http://resolver.sub.uni-goettingen.de/purl?PPN324352840_0039.

———. “Ytterligare Rön Och Försök Contraira Electriciteterne Vid Laddningen Och Därtil Hörande Delar.” *Kungliga Svenska Vetenskaps Academiens Handlingar* 23 (1762): 206–29, 245–66.

Appendix A: An Introduction to the Electrophorus

For those unfamiliar with the electrophorus, the basic functioning of the device is explained below using a simple modern replica. This description is intended to provide an account of what is observed when using the electrophorus with as little recourse to theory as is practical. I then explain the key differences between the replica and Volta's original design. Appendix B discusses how the device can be explained in accordance with Franklin's theory of electricity.

The replica device consists of two components as pictured in figure 1:

Figure 1

On the left is a round aluminum disk, 9 cm in diameter, on which an insulated handle has been attached. The handle is affixed to the metal disc with a screw. On the right is a square plastic plate approximately .5 cm thick and 15 cm on each side. The plate has four circular feet made of rubber and affixed to each corner of the plate.

The device can be manipulated according to the following steps:

Step 1

With the metal disc removed, the plastic plate is rubbed with fur or other similar materials for a few seconds as shown in figure 2.[162]

Figure 2

Alternatively, any device known to generate electricity can be used. Figure 3 shows a small battery-operated device that generates static electricity, which I used to quickly create a charge on the plate.

[162] Finding a common household item that would easily electrify the plastic plate upon rubbing it proved somewhat difficult, which is why I opted to use a battery-operated electrostatic generator. The microfiber cloth shown in figure 2 is not very effective at electrifying the plate and is included for demonstration purposes only.

Figure 3

Step 2

The metal disc is placed on top of the plastic plate as shown in figure 4. It should be noted that prior to being placed on the plastic plate, the metal plate produces no shocks when touched.

Figure 4

If the metal disc is not touched while on the plate, one can simply lift the disc by the insulated handle, touch the disc, and observe that it produces no signs of electricity.

Step 3

The top of the metal plate is touched and a small electric shock occurs once the finger has touched the metal disc (see fig. 5).

Figure 5

Step 4

The metal disc is lifted by the insulated handle (see fig. 6).

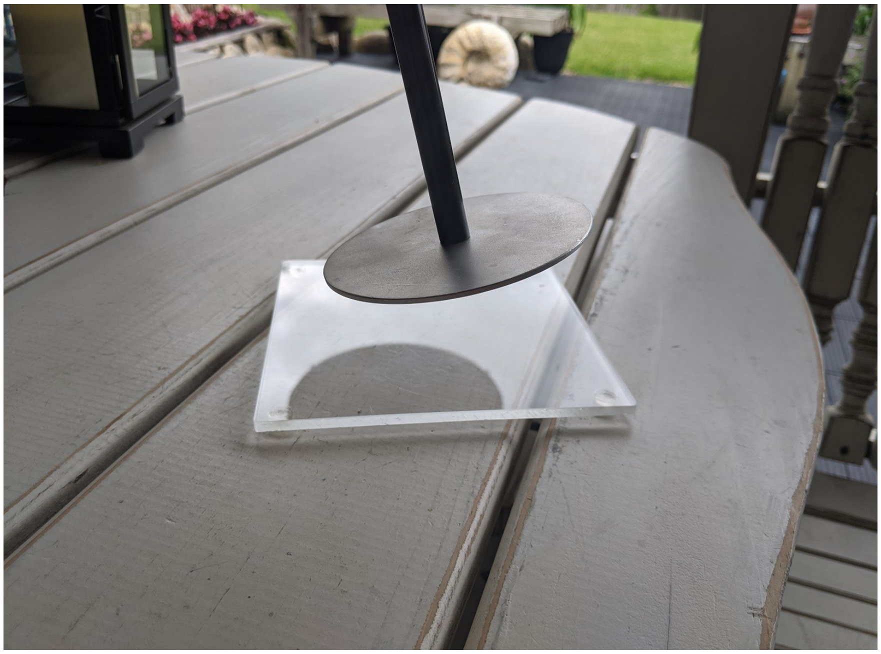

Figure 6

It should be noted that at this stage one could lift the metal disc, set the disc back on the plastic plate, and touch the metal disc without receiving a spark.

Step 5

While separated from the plastic plate, the metal disc can be touched with a finger or to some other surface and a small shock will occur. In figure 7, the metal disc is used to charge a dissectible modern replica of the Leyden jar (a device for storing electric charge).

Figure 7

After a spark has been drawn from the metal disc, the disc can be touched a second time without producing a spark or other sign of electricity.

Step 6

As in step 2, the metal disc is again placed on top of the plastic plate (see fig. 8).

Figure 8

Step 7
As in step 3, the metal disc is touched and a small shock occurs (see fig. 9). This shock is typically slightly smaller than the initial shock in step 3, but the intensity of the shock does not substantially decrease if the procedure is repeated a third or fourth time.

Figure 9

Step 8
As in step 4, the metal disc is lifted by the insulated handle (see fig. 10).

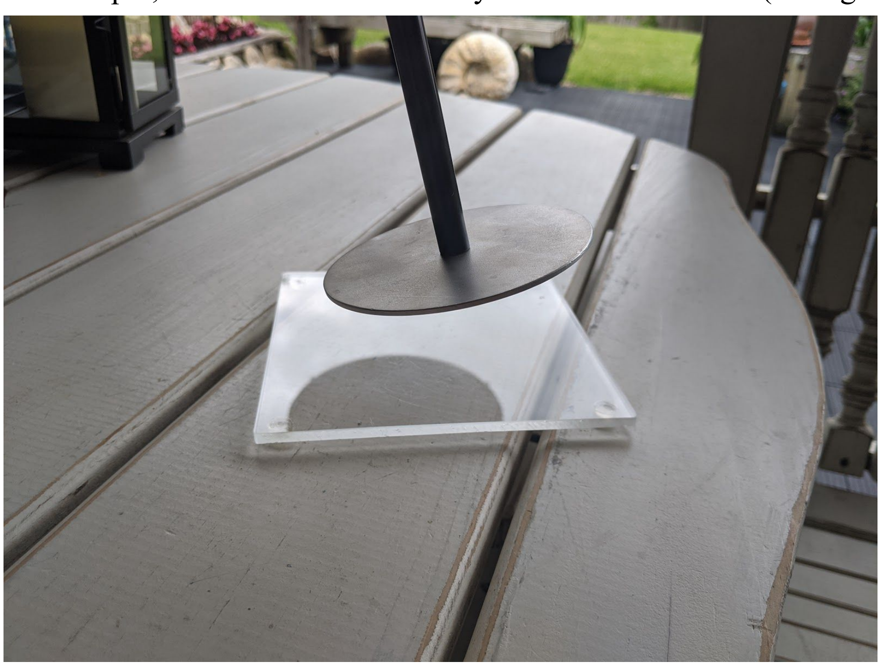

Figure 10

Step 9
As in step 5, the device can now be touched with a finger or other surface and a small shock will occur (see fig. 11).

Figure 11

Subsequent steps
The sequence of steps between step 6 and step 9 can now be repeated over and over again without re-rubbing or otherwise recharging the plastic plate. The experiment can be repeated for an hour or more and while the strength of the charge will diminish somewhat, signs of electrification are detected at step 7 and step 9 each time.

Differences between the Replica and Volta's Original Device

The electrophorus as Volta originally designed it and the simplifications of the device that became common are detailed above. However, a few key differences between the replica and the devices that would have been used by eighteenth-century electricians are worth mentioning.

The plastic plate would have been replaced with a different insulator, most commonly glass or glass coated with sealing wax. Volta's original design called for a special resin cake that he designed after considerable experimentation because it retained its electricity longer than glass. Volta's design also called for a metal plate below the insulator, although this was later known to be superfluous to the device’s functioning. Finally, his suggested procedure for charging the device was to attach the upper metal disc to an electrostatic generator and the lower metal disc to ground. The procedure for charging the device by rubbing later became the standard practice.

Appendix B: The Functioning of the Device based on Franklin's Theory of Electricity

The electrophorus was thought by some electricians to be a problem for Franklin's system, although subsequent work by Franklinist electricians helped reconcile the device with Franklin's theory. Below, I have explained how Franklin's theory can deal with the functioning of the electrophorus.

According to Franklin's theory, a body can be in one of three electrical states:

Neutral (0): The body has its normal quantity of electric fluid.
Positive (+): The body has more than its normal quantity of electric fluid.[163]
Negative (-): The body has less than its normal quantity of electric fluid.

When able, bodies will receive or transmit electricity until they reach a neutral state. Franklin's explanation of the sparks produced in the electrophorus is that electricity is being transmitted between bodies that have more or less than their normal quantity of electric fluid.

One way to understand the functioning of the device from the point of view of eighteenth-century electricians is to track the state of electrification each component of the device is in at each step and to explain, in Franklinist terms, why each body is electrified the way it is at the critical steps.

Doing so gives us the following:

Prior to the experiment
Disc: 0
Plate: 0

Neither the plate nor disc has been electrified, so both are neutral.

Step 1: After rubbing the plate
Disc: 0

[163] In modern parlance, *positive* and *negative* are flipped. That is, a body with more electrons than protons, in modern terms, is said to have a negative charge, whereas a body with less electrons than protons that is said to have a positive charge.

Plate: +[164]

Rubbing the plate electrifies it, so its electrical sign changes.

Step 2: Placing the disc on the plate
Disc: 0
Plate: +

At this stage, it is important to note that no electricity is transferred from the plate to the disc even though the disc would appear to exhibit signs of being positively electrified (e.g., the spark drawn in step 3).

This is explained in terms of the tendency of some substances to hold on to their electricity and not transfer it to other substances easily. In addition to Volta's resin or modern plastic, glass was also known to have this property and part of Franklin's theory of the Leyden jar was that the electricity was stored on the surface of the glass rather than on the metal coatings or in the water.

To account for the seemingly perpetual nature of the sparks, explanations of the electrophorus also had to posit that resin had a stronger ability to retain its electricity than the glass that electricians were most familiar with.

Step 3: After touching the disc
Disc: -
Plate: +

This is a critical step to explain from the point of view of Franklin's theory.

After the experimenter touches the disc, all signs of electricity disappear and the system appears to be neutral. One natural way to account for this is to assume that the disc and plate are now neutral because the electricity has flowed from the plate to the disc and out through the finger. Indeed, Franklin's explanation of the Leyden jar rests on the assumption that as the jar is charged, the inside of the jar is electrified positively and the outside of the jar is electrified negatively, but when a connection is made between them, electricity is transferred from the inside to the outside and an equilibrium is reached such that both sides are electrified neutrally.

Explaining the electrophorus requires a modification to this natural explanation. Instead of explaining the disappearance of the signs of electrification by saying that both the plate and disc

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[164] Depending on the materials used to rub the plate and for the plate itself, the plate could be electrified either minus or plus. I assume that the plate is electrified plus to make the explanation slightly simpler.

are neutral, we instead say that the disc is electrified negatively to the same degree that the plate is electrified positively.

To simplify, let's assume that both the plate and disc contain twenty units of electricity when in the neutral state.[165] After the experimenter rubs the plate, it gains five units of electricity for a total of twenty-five. After the disc has been placed on the plate and touched, it loses five units of electricity, bringing it to fifteen. As a result, while the plate is on the disc, both appear to be electrified neutrally even though each, individually, is not neutral.

To explain why the disc and not the plate gives up its electricity upon being touched, the Franklinists assume that the plate, like glass, tends to retain its electricity. However, it also exerts a repulsive force on the electricity in the disc, so a portion of the electricity in the disc is forced out of it when it is allowed to leave by being touched.

Step 4: Lifting the disc
Disc: -
Plate: +

Upon lifting the disc, signs of electrification can be detected on both the disc and the plate. We explain this by saying that when the disc and plate are touching, they each cancel out the signs of electrification that would be presented by the other. Once the disc is raised, it is no longer under the influence of the plate, and signs of electrification can now be detected.

Step 5: After touching the disc to another surface
Disc: 0
Plate: +

The disc is electrified negatively. When it is touched to a body electrified neutrally, electricity is transferred from that body to the disc and it becomes neutral.

Step 6: Placing the disc back on the plate
Disc: 0
Plate: +

The explanation is the same as in step 2.

Step 7: After touching the disc again

[165] Following Franklin's original presentation of the theory, I provide no units here. Units like the volt, watt, and ampere weren't in widespread usage until the 1800s at the earliest.

Disc: -
Plate: +

The explanation is the same as in step 3.

Step 8: Lifting the disc
Disc: -
Plate: +

This is the same as step 4.

Step 9: After touching the disc to another surface
Disc: 0
Plate: +

This is the same as step 5.

Steps 6 to 9 can be repeated over and over again because no electricity is ever transmitted from the plate to the disc. Instead, the charge on the plate *influences* the electrical behavior of the disc, which allows it to lose electricity in step 7 and regain electricity in step 9.

Importantly, the overall explanation requires that both of the following be true: (1) no electricity is transferred from the plate to the disc and (2) the plate exerts a repulsive force on the disc. The first condition is required to explain the seemingly perpetual nature of the electrophorus—if there was a transfer of electricity, the effect would cease after the apparent cessation of signs in step 3. The second condition is required to explain why electricity leaves the disc upon being touched. Taken together, these mean that the plate can exert repulsion on the disc without a transfer of electric fluid. Helping to move electricians toward the notion that attraction and repulsion do not require a transfer of electric fluid was one of the central contributions of the electrophorus to electrical theory.

Appendix C: Volta's Procedure for Recharging an Electrophorus with a Leyden Jar

Volta named his invention the *electtroforo perpetuo*, an "inexhaustible purveyor of electricity." An important component of Volta's justification for the notion that the electrophorus was perpetual was a procedure he described for reinvigorating the electricity in the non-conducting material by using a Leyden jar that had been charged by the electrophorus itself. Below is a brief step-by-step account of the recharging procedure.

Figure 1

The procedure requires a non-conducting substance, in this case, the plastic plate from the replica electrophorus (see appendix A) and a Leyden jar that has been charged, typically by the electrophorus itself. The Leyden jar in figure 1 is a modern dissectible Leyden jar that uses plastic instead of glass.

Step 1: Place the charged Leyden jar on the plate

Figure 2

First, place the charged Leyden jar on the plate as shown in figure 2, being careful not to accidentally discharge it by touching the knob in the process.

Step 2: Touch the knob of the Leyden jar while it sits on the plate (fig. 3)

Figure 3

Step 3: Lift the Leyden jar by the knob to remove it from the plate

Figure 4

Finally, the Leyden jar is lifted by the knob to remove it from the plate (see fig. 4). Once this step is completed, the charge in the plate will be increased.