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No actual measurement … was required: Maxwell and Cavendish's null method for the inverse square law of electrostatics

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ABSTRACT

In 1877 James Clerk Maxwell and his student Donald MacAlister refined Henry Cavendish's 1773 null experiment demonstrating the absence of electricity inside a charged conductor. This null result was a mathematical prediction of the inverse square law of electrostatics, and both Cavendish and Maxwell took the experiment as verifying the law. However, Maxwell had already expressed absolute conviction in the law, based on results of Michael Faraday's. So, what was the value to him of repeating Cavendish's experiment? After assessing whether the law was as secure as he claimed, this paper explores its central importance to the electrical programme that Maxwell was pursuing. It traces the historical and conceptual re-orderings through which Maxwell established the law by constructing a tradition of null tests and asserting the superior accuracy of the method. Maxwell drew on his developing 'doctrine of method' to identify Cavendish's experiment as a member of a wider class of null methods. By doing so, he appealed to the null practices of telegraph engineers, diverted attention from the flawed logic of the method, and sought to localise issues around the mapping of numbers onto instrumental indications, on the grounds that 'no actual measurement … was required'.

1. Introduction

In the first edition of his *Treatise on Electricity and Magnetism* James Clerk Maxwell acknowledged Charles-Augustin Coulomb's 1785 torsion balance experiments as establishing the inverse square law of electrostatics (1873, pp. 41, 43). Within a few pages he dismissed them again as demonstrating the law only to a rough approximation. Instead he cited Faraday's observation that an electrified body, touched to the inside of a conducting vessel, transfers *all* its electricity to the outside surface, as "far more conclusive than any measurements of electrical forces can be" (p. 75). He based this assertion on his mathematical contention that electricity would reside entirely on the outside of a closed conductor – with none inside - *only* if the microscopic forces between electrified bodies obeyed an exact inverse square law. This idea can be traced back to Benjamin Franklin's observation that cork balls suspended in a charged cup were not drawn to either side, and the analogy Joseph Priestley pointed to: Isaac Newton's demonstration that a massive sphere exerted no attraction on masses inside it (Heilbron, 1979, p. 463).

The next year, in 1874, Maxwell acquired the unpublished electrical researches of Henry Cavendish. He found that a hundred years earlier, in 1772-73, Cavendish had tested the prediction of no interior electricity experimentally. Cavendish had concluded that the negative exponent in the force law could not differ from two by more than about 1/50 (Maxwell, 1879, pp. 111–112). Maxwell and his student, Donald MacAlister, created their own version of Cavendish's experiment, claiming a sensitivity of 1/21600. They published their experiment shortly before Maxwell's death, in his edition of *The Electrical Researches of Henry Cavendish* (Maxwell, 1879, pp. 417–422), and in the posthumous second edition of Maxwell's *Treatise* (1881, pp. 77–82). Here Maxwell stated even more emphatically than in the first edition that a null result – this time Cavendish's – was "… a far more accurate verification of the law of force [than Coulomb's]" (p. 77).[1] He presented his own experiment as an improvement upon the accuracy of Cavendish's.

Why, given Maxwell's expressed confidence in Faraday's null demonstrations, did he bother repeating Cavendish's experiment?[2]

[1] This statement can be attributed to Maxwell as it comes from within the first nine chapters of the second edition of the *Treatise*, which were completed and in press before his death; Niven in Maxwell (1881), p. xv.

[2] Maxwell said that he was "repeating" Cavendish's experiment, and I use his term throughout. While it might be possible to consider it as a "replication" of Cavendish's, fitting Radder's (1992) classification of reproducing the result of the experiment (the inverse square law) by a (not very) contemporary scientist, this would entail expanding the domain of "replication" to an experiment that was intended to affirm, rather than verify, the inverse square law (see also fn. 9).

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Taking on board critiques of the experiments by Dorling (1974) and Laymon (1994), this paper traces the historical and conceptual re-orderings through which Maxwell aimed to secure Coulomb's law, and his motivations for doing so. It begins in §2 by examining the changing status of the inverse square law in Britain in the 1870s, concluding that it was only just becoming widely accepted. Yet, as will be discussed in §3, the law was an essential foundation for the electrical programme based on precision measurement and absolute units that Maxwell and William Thomson were attempting to establish (Smith & Wise, 1989, pp. 120–128, 237–276; Hunt, 2015). Despite the flawed logic of the mathematical tradition underpinning the null demonstration, the need to ensure acceptance of Coulomb's law drove Maxwell and Thomson's attempts to establish it by constructing an experimental tradition of null electrical measurement (§4), and arguing for the superiority of such a method (§5). By identifying Cavendish's as a null method, Maxwell mediated between the practices of telegraph engineers and the mathematical theory of electricity, through his developing 'doctrine of method' (§6).

2. The status of the inverse square law

In the years leading up to publication of Maxwell's *Treatise*, perceptions in Britain of the status of the inverse square law varied widely and were changing rapidly. Views ranged from William Thomson's that it was a mathematical truth (discussed later), to those of the prominent electrician, William Snow Harris, and the submarine cable engineer, Frederick Charles Webb, that it was not fundamental and held only in some circumstances (Webb, 1862, pp. 109–111; Harris, 1867, pp. 31–49; Thomson, 1872, pp. 24–25).[3] Since the 1840s two lines of reasoning had been evident. Harris led an inductive experimental one, based on Coulomb's and his own direct quantitative measurements. Thomson promoted a mathematical deductive argument based on potential theory and qualitative observations by numerous electricians of the absence of electricity inside conducting shells – evidence whose relevance was indirect and was not always made explicit. This was the line Maxwell took in 1873.

Harris and his followers pointed out that Coulomb had only ever published one experiment, comprising three data points, to support his conclusions (Coulomb, 1884). This left plenty of scope for measurements in different conditions to produce different laws. Between 1834 and 1839 Harris investigated high-tension static electricity (1834, 1836, 1839). He was one of the few to criticise Coulomb's experiments directly, seeking, "… by operating with large statical forces … to avoid many sources of error inseparable from the employment of very small quantities of electricity, such as those affecting the delicate balance used by Coulomb" (1839, p. 215). He concluded that Coulomb's law represented the composition of a fundamental direct inverse relation with distance, and changes to the distribution of electricity due to induction; it held only with suitable arrangements of conductors. His conclusion seems based as much on metaphysical reasoning that, "it is highly probable, if not morally certain, that every physical effect is in simple proportion to its cause" (1867, p. 209), as on his experimental measurements. Harris continued to promote this composition view until his death in 1867, and in his posthumous *Frictional Electricity* (1867). Webb followed him in suggesting that, " …. although the attractive force may … vary within certain limits, sensibly as some particular power of the distance, if increased beyond these limits, the ratio will begin to vary, and ultimately the attractive force will vary as some other power of the distance" (1862, p. 148).

However, Thomson had opposed Harris' interpretation since 1845, deeming his experiments incompetent (Smith & Wise, 1989, pp. 217, 246). Thomson assumed the inverse square law, and used his new method of electrical images to calculate the macroscopic force-distance law between Harris' conductors. By challenging the achievable accuracy of Harris' experiments, he was able to claim that his calculations agreed with Harris' observations. So, Harris' results supported rather than contradicted Coulomb's law (Thomson, 1872, pp. 24–25). In the same paper Thomson began promoting the mathematical argument for the null result as proof of the inverse square law (see §3).

Two series of textbooks provide evidence for the rising authority of the mathematical approach to electrical science among British electricians in the 1860s and 70s. They are by Edmund Atkinson, a physics teacher with a chemical background, and by Joseph D. Everett, a pupil of Thomson's who became Professor of Natural Philosophy at Queen's College, Belfast.[4] Atkinson's and Everett's books were translations of popular French textbooks by Adolphe Ganot and Augustin Privat-Deschanel respectively. The French market, mainly for medical students, provided a source of good textbooks in experimental physics at the time (Simon, 2015, p. 28).

The earlier book, by Atkinson (following Ganot), asserted the inverse square law together with a description of Coulomb's experiment, giving his three data points (Atkinson, 1866, p. 559). He included a section, that Ganot had added in 1857, on Harris who, "has found that Coulomb's first law does not obtain in cases where the two bodies are charged with unequal quantities of electricity …" (Atkinson, 1866; Ganot, 1857, p. 538, p. 561). Atkinson next described experiments by Coulomb, Jean-Gustave Bourbouze,[5] and Jean-Baptiste Biot with closed spheres, and Faraday with open cylinders and cones, showing that electricity resides entirely on the surface of a conductor with none inside. At this point Ganot had made clear that these observations might be related to the inverse square law. He presented the observation as a consequence of the law: "En effet, en soumettant au calcul l'hypothèse des deux fluids, et en admettant qu'ils s'attirent mutuellement en raison *inverse du carré* de la distance et qu'ils repoussent leurs propres molecules suivant la meme loi, Poisson est arrive à la meme consequence que Coulomb sur la distribution de l'électricité libre dans les corps," (Ganot, 1856, p. 538, my emphasis).[6] Atkinson mistranslated this passage: "Admitting the hypothesis of two fluids, and that opposite

[3] Harris (1791–1867) is best remembered for his work on lightning conductors, especially on ships, for which he was knighted in 1847; James (2004). Webb (1828–1899) was involved in many cable projects including the successful Havana to Key West, and from Marseilles to Algiers, and the less successful early Atlantic cable; Electrician (1885), Yavetz (1993).

[4] The market for such textbooks, and Atkinson's career and role are discussed by Simon (2015), especially pp. 76–86. For Everett's career, see Lees (2004).

[5] Bourbouze was *preparateur* at the Sorbonne and a teacher of experimental physics. His work is discussed by Blondel (1997).

[6] "Indeed, through calculations based on the hypothesis of two fluids, and that opposite electricities attract each other *inversely as the square* of the distance and repel like molecules according to the same law, Poisson arrived at the same conclusion as Coulomb on the distribution of free electricity on bodies" (my translation). A reviewer has pointed out that Ganot's treatment of Poisson here may be an anomaly among French textbook authors. Ganot was renowned for the exceptionally concise pedagogy with which he linked facts, theories and concepts. He had begun his career as a teacher of mathematics before moving into physics, in contrast to the majority of writers who started as chemists or medics; Simon (2015), especially pp. 68–72, 16–117. Further research would be needed to establish this point.