Gerard Turner Memorial Lecture

Instruments from Scratch? Humphry Davy, Michael Faraday and the Construction of Knowledge

Frank A.J.L. James

A few wires and some old bits of wood and iron seem to serve him [Faraday] for the greatest discoveries.[1]

So wrote the Prussian physiologist and physicist Herman Helmholtz (1821–1894) to his wife in August 1853 after being shown by Michael Faraday (1791–1867) some of the apparatus he had used during the previous few decades in the Royal Institution's basement laboratory. Although Helmholtz did not specify what Faraday had shown him, the 'bits of wood and iron' probably included the ring with which he discovered electro-magnetic induction in 1831 and the magneto-electric generator that he used a few weeks later, as well as the equipment he used in 1845 to discover the magneto-optical ('Faraday') effect and diamagnetism with his giant electro-magnet. At first sight these pieces conform to Helmholtz's description. But had he seen the electro-chemical apparatus used by Faraday in the early 1830s when formulating his electro-chemical laws, during which he introduced terms such as electrode, cathode and ion into scientific language, he would have immediately seen the difference between apparatus made in the laboratory and that made by the Royal Institution's preferred scientific instrument maker John Newman (bp.1783, d.1860).[2]

Had Faraday shown Helmholtz some of the apparatus used by Humphry Davy (1778–1829) in his own electro-chemical researches (especially his batteries) and in their joint work on the miners' safety lamp, he would have seen the same combination of laboratory-made apparatus and equipment requiring either a skilled maker or significant industrial support. Had he looked round the laboratory he would have seen equipment that could only have been constructed by a skilled scientific instrument maker and that much of the apparatus used by both Faraday and Davy in making their chemical and natural philosophical discoveries amalgamated or hybridised or modified already existing apparatus, or combinations of laboratory-made and skilfully made apparatus. Whether Helmholtz saw or thought any of this is not known, but the qualification of his comments with the word 'seem', betrays a sense of doubt about the meaning of what Faraday showed him and this scepticism will be illustrated in this essay.

I will do this by focussing on the hybrid nature of almost all the instruments and experimental arrangements used by Davy and Faraday to challenge the idea of instruments from scratch or what became known as the 'sealing wax and string' approach to experimentation implied by cursorily reading Helmholtz's description. This will be done by examining, in some detail, how designing, developing and manufacturing large batteries during the nineteenth-century's first decade involved contributions from savants, instrument makers, corporate organisations and large scale industry, not to mention finding significant financial resources to support such work. How this approach towards instruments and experimentation continued in Davy's later researches and subsequently Faraday's, will then be examined more briefly, but illustrating the same point.

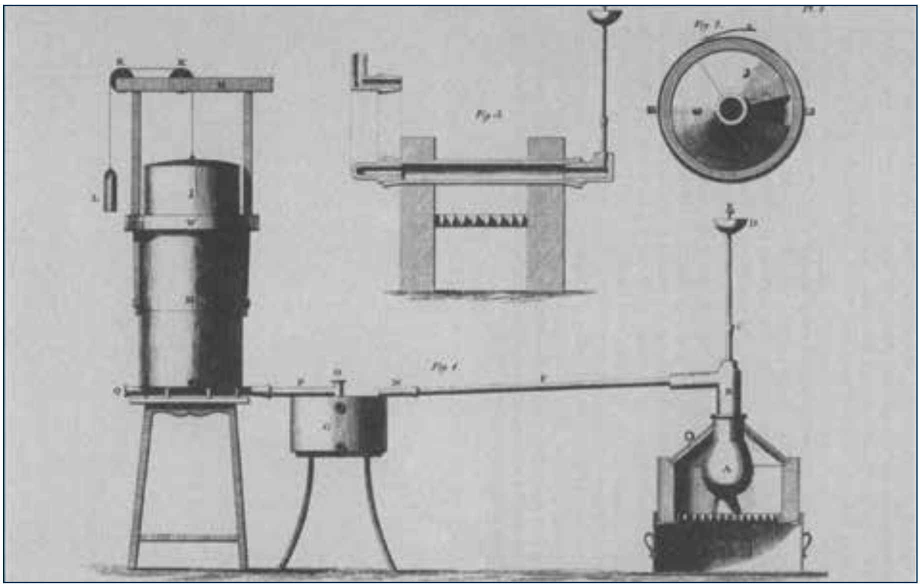

Fig. 1 *Thomas Beddoes's pneumatic apparatus designed by James Watt. From Thomas Beddoes and James Watt,* Considerations on the Medicinal Use of Factitious Airs, and on the manner of obtaining them in large quantities*, parts 1 and 2, London: Johnson and Murray, printed Bristol, by Bulgin and Rosser, [1794]. No example of this apparatus has been located, perhaps miscatalogued in some collection. A replica was on display in the Science Museum until fairly recently.*

Davy

Davy's familiarity with this hybrid approach to scientific apparatus went back to late 1790s Penzance when beginning his chemical researches whilst working as an apprentice apothecary.[3] There he used not only domestic bits and pieces such as fragments of glass tubes or tobacco paper[4], but he combined them with already skilfully constructed equipment. For instance, to obtain a vacuum he originally used a syringe[5], before being given access to an air pump.[6] From the experiments he conducted with this equipment during the first half of 1798, he wrote an essay contradicting the theories developed by the French chemists Antoine Lavoisier (1743–1794) and Antoine Fourcroy (1755–1809). Davy especially criticised their theoretical ideas surrounding caloric, central to the new French chemistry, and proposed replacing it with what he called 'phosoxygen' (a mixture of light and oxygen).[7] At the suggestion of Davies Giddy (1767–1839), a member of the West Cornish gentry, Davy sent this June 1798 essay to the medically and politically radical (Jacobin) physician Thomas Beddoes (1760–1808) whose student Giddy had been at Oxford University. Beddoes was then seeking someone to superintend the Medical Pneumatic Institution in Clifton, just west of Bristol, for which he had been raising funds for nearly five years.[8] Impressed with Davy's essay, Beddoes appointed him Superintendent, without previously meeting him; Davy moved to Clifton in October 1798, aged nineteen.

The Medical Pneumatic Institution's avowed purpose was to research into the potential therapeutic effects, especially on consumption, of the gases discovered during the eighteenth century by savants such as Joseph Black (1728-1799), Henry Cavendish (1731–1810) and Joseph Priestley (1733–1804). The Institution's central piece of apparatus was designed by the Midlands engineer and businessman James Watt sr (1736ns–1819) who had originally worked as a scientific instrument maker in Glasgow and whose daughter had died from consumption in 1794 aged fifteen years. Made and sold by Boulton and Watt, Watt's device provided a flow of gas for someone to inhale (Fig. 1). Using this and modifying it ways characteristic of his manipulative skills and practices, Davy discovered the extraordinary physiological properties of nitrous oxide, publishing the results in his first book, *Researches Chemical and Philosophical* (July 1800).[9]

Just as he was completing *Researches*, news reached him of an invention made by the Italian natural philosopher Alessandro Volta (1745–1827).[10] Volta called his invention a pile (of acidified alternate metal plates on top of each other) that produced galvanic electricity. Thomas Garnett (1766–1802) first publicly announced Volta's work during a lecture he delivered on Wednesday 28 May 1800 at the Royal Institution, founded the year before by a group of aristocratic and wealthy Proprietors.[11] He borrowed apparatus to demonstrate Volta's discovery from the practical chemist Edward Howard (1774–1816)[12], suggesting that it might have come from William Cruickshank (d.1810/11) of Woolwich with whom Howard collaborated.[13] Cruickshank had had the brilliant idea, published in September 1800[14], of simply turning the pile on its side to make it a trough, thus making the device much more stable so that larger, more powerful, examples could be made and more easily linked together.

Beddoes arranged for one, consisting of at least 110 plates (the number itself suggests a Cruickshank arrangement and that somehow news of his invention had reached Bristol), to be constructed for the Medical Pneumatic Institution.[15] Though the maker is unknown, it is clear that no one at the Institution had the necessary skills to construct it themselves. Very quickly, it began to be called a battery, the term Giddy, then staying with Beddoes at Clifton but seeing Davy frequently[16], used in his diary when he witnessed some of Davy's galvanic experiments on 7 August 1800.[17] Davy referred to it as a battery in the draft of his first paper on galvanism stemming from those August experiments, but omitted it from the text published in the September issue of *A Journal of Natural Philosophy, Chemistry and the Arts*;[18] he first used the term in print in 1801.[19]

For the remainder of 1800 Davy experimented on galvanism. He sent some of Beddoes's pupils out onto Clifton Down to collect the toads necessary for detecting the presence of electricity. Following their apparent extinction on the Down, Beddoes ordered 300 frogs. Rather sinisterly a story circulated – still current nearly forty years later – that Beddoes had ordered 10,000 frogs to feed 'French jacobins concealed in ... [his] cellar'. The actions of a 'benevolent physician', the story went, prevented Beddoes's house, and perhaps Bristol itself, from being burnt.[20] Aside from playing simultaneously both to contemporary English xenophobia and paranoia, this story surely references the Priestley riots in Birmingham nine years before and perhaps suggests the existence of a government agent provocateur in Bristol, where certainly Beddoes was unpopular with the governing classes.[21] At some point Davy realised that his political connections, and especially the 'odium'[22] that Beddoes attracted, might endanger his future prospects. Such concerns became especially acute following the publication in August 1800 of an attack on Beddoes, Davy and their work on nitrous oxide in the virulent pro-government *Anti-Jacobin Review*.[23]

Davy thus began looking for alternative employment, though his initial intentions are unclear.[24] An opportunity for him to work at the Royal Institution came about when Garnett fell foul of the committee that ran the Institution, the Managers, and in particular of Benjamin Thompson, Count Rumford (1753–1814). According to a recollection by Thomas Richard Underwood (1772–1835) a Proprietor at the time, Rumford, who oversaw much of the early Royal Institution's mundane work, then 'possessed … almost dictatorial power' in the Royal Institution.[25] By January 1801, Rumford and the Managers had decided to replace Garnett and, as a first step, appoint someone to a more junior role clearly intending that person should supplant Garnett quickly.

Davy was acquainted with various people who knew Rumford, including Underwood and the Edinburgh University chemist, Thomas Hope (1766–1844)[26] who both contributed to his appointment to the Royal Institution. In a letter to Davy's first biographer, John Ayrton Paris (1785–1856), probably written in 1830, Underwood told him about 'several conversations with Count Rumford', presumably in late 1800, 'on the subject of Davy's superior talents', adding that on 5 January 1801, following a Managers meeting, Rumford called on him with 'full powers to negotiate upon the subject'. Underwood recommended that Rumford discuss the matter with another

Fig. 2 (a) and (b) *Details from James Gillray, 'Scientific Researches! - New Discoveries in Pneumaticks! - or, an Experimental Lecture on the Powers of Air', London: Hannah Humphrey, 1802.*

of Davy's acquaintances, the calico printer James Thomson (1779–1850) on the grounds of his not being a Royal Institution Proprietor.[27] Whether Underwood or Thomson kept Davy informed about these manoeuvrings is uncertain, but around 10 January he received an invitation from Rumford about working at the Royal Institution.[28] This led to negotiations, presumably by post, lasting three weeks[29] and on 7 February he went to London for discussions with Rumford as well as with the leading Managers, Cavendish and the President of the Royal Society of London Joseph Banks (1743ns–1820).[30] Banks, on political grounds, loathed Beddoes and had tried to sabotage his efforts to raise funds for the Medical Pneumatic Institution.[31] Quite how Davy convinced him of his political soundness is not known, but he evidently succeeded for on 16 February 1801 the Managers appointed him 'Assistant Lecturer in Chemistry, Director of the Chemical Laboratory, and Assistant Editor of the Journals' which Rumford confirmed with an appointment letter.[32] He arrived to start his new positions in mid-March, now aged twenty-two.[33]

Davy took advantage of the apparatus acquired by Garnett for the Royal Institution in its early months from makers such as Robert Fidler (d.1824).[34] The remarkably extensive collection of scientific demonstration equipment so formed is indicated in a caricature by James Gillray (1756–1815) published on 23 May 1802. It shows Garnett, assisted by Davy, delivering a lecture probably towards the end of March 1801 administering nitrous oxide to the Institution's Treasurer John Hippisley (1746–1825). On the lecture bench and through the open door into the 'Professor's Ante-Room'[35] Gillray depicted part of the Royal Institution's collection (Figs 2a and b). On the bench stood various bits of chemical glassware, an air pump, but, with the possible exception of the gas bag, nothing that could have been made entirely in the Royal Institution. Similarly, the large quantity of electrostatic equipment that can be glimpsed through the door, would have all been made by a skilled instrument maker.

Davy and Batteries

Right from the beginning Davy undertook research at the Royal Institution. In his hands and later in Faraday's, scientific research became a core feature of the Institution, something not envisaged by its founders. Within a few days of arriving in London Davy resumed his galvanic experimentation begun in Clifton. Partially this was probably connected with a five-lecture course on galvanism, his first delivered in the Royal Institution, where he described some of his own experiments. Later in the year he published a summary of those lectures noting that he used four troughs (each of 50 four-inch-square plates). These were presumably made after Cruickshank's trough design, though where Davy acquired them is unknown. It is possible that, like Garnett, he had borrowed them since no galvanic batteries were listed in the inventory of apparatus made by John Sadler (bp.1779, d.1838) in August 1803 when the Royal Institution passed through its first (of many) financial crises.[36]

At the Royal Institution Davy, according to Rumford, usually sparing with praise, gave 'universal satisfaction'.[37] He quickly became the most popular scientific lecturer in London during the first decade of the nineteenth century.[38] As plotted, Garnett resigned (June 1801)[39], immediately following Davy's promotion to Lecturer, and the following year Davy was promoted again to Professor of Chemistry.[40] For two years he was joined by the polymathic Thomas Young (1773–1829) as Professor of Natural Philosophy and Astronomy and much of the apparatus on the 1803 inventory can be linked to his lectures. Not the most inspiring lecturer[41] Young was soon replaced by the pharmaceutical chemist William Allen (1770–1843). During that decade others lectured at the Royal Institution, but only the moral philosopher and wit Sydney Smith (1771–1845) came anywhere near to rivalling Davy's popularity.[42]

Davy did not resume his electrical researches until Autumn 1806.[43] This gap was due, in part, to his work related to forming the Royal Institution's mineralogical collection and also to duties connected with his appointment as Professor of Chemistry at the Board of Agriculture.[44] (For them he designed a soil analyser clearly made by an (unknown) instrument maker (Fig. 3)). The delay may also be related to Davy not knowing how to proceed with his electrical researches; their resumption stemmed from his wishing to use electricity for mineral analysis. Using 150 four-inch-square plates (4800 square inches in total, presumably in three troughs)[45] he found that an electric current could decompose most chemical compounds and theorised that all bodies possessed positive or negative electrical properties meaning they were attracted to the opposite polarities of the battery. This work formed the basis of his first Bakerian lecture read over four evenings to the Royal Society of London in November and December. In his experimentation Davy also used several other pieces of equipment belonging to the Royal Institution, including a chemical balance made by Fidler[46], a cylindrical electro-static generator made by a Proprietor, Edward Nairne (1726–1806)[47], and a condensing electrometer made by John Cuthbertson (bp.1743, d.1821).[48] All these he used to confirm his fundamental theory and also that common and galvanic electricity were essentially the same phenomenon – a crucial

Battery	Total troughs	Total plates	Number of plates per trough	Plate size (inches)	Total surface area (sq in)
Davy, early 1801	4	200	50 x 2	4 x 4	6,400
Davy, late 1806	3	150	50 x 2	4 x 4	4,800
Davy, August 1807	1 6? 3	12 300 150	12 x 2 25 x 2? 50 x 2	12 x 12 6 x 6 4 x 4	3,456 10,800 4,800 19,056
Children, early 1808	25?	1250	50 x 2?	4 x 4	40,000
Davy, spring 1808	20	500	25 x 2	6 x 6	36,000
Children, August 1808	1?	40	40 x 2?	48 x 24	92,160
Davy, 1809	200	2000	10 x 2	8 x 4?	128,000

Table 1. Summary details of the batteries that Humphry Davy and John George Children used during the opening decade of the nineteenth century. NB one square inch equals 6.45 sq cms; thus the surface area of Davy's last battery was around 82.5 sq metres.

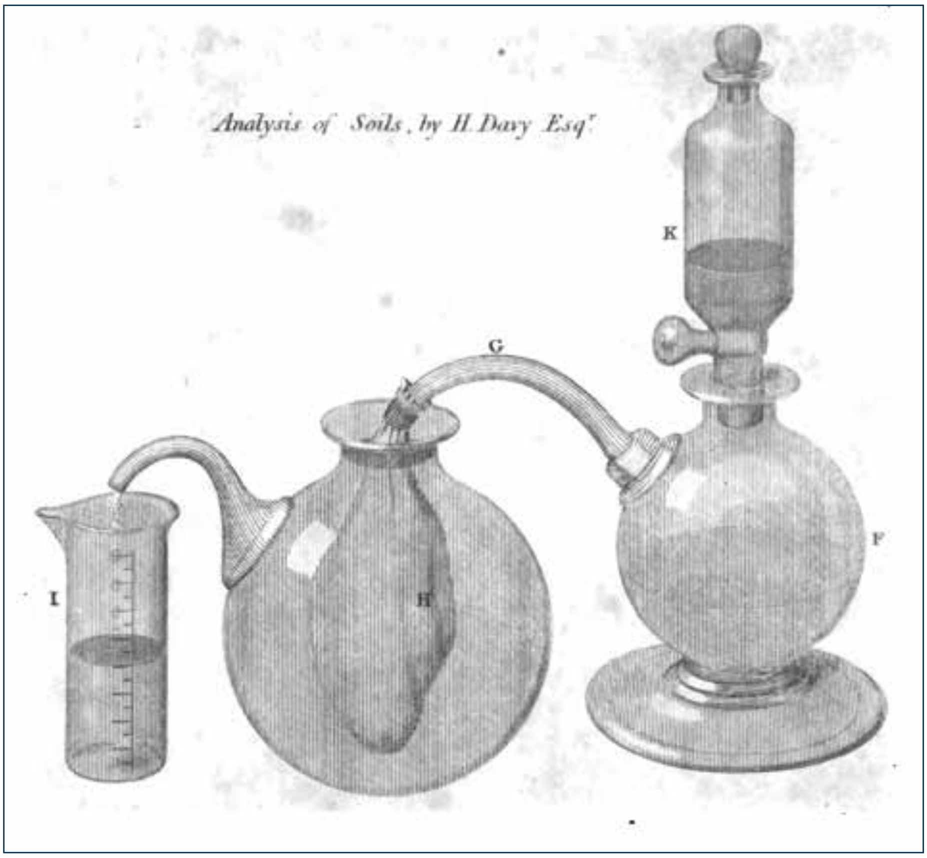

Fig. 3 *Humphry Davy's instrument for soil analysis from his 'On the Analysis of Soils, as connected with their Improvement',* Philosophical Magazine, ***23*** *(1805), pp. 26-41. There is an example of this apparatus in the Museum of the History of Science in Oxford, inventory number 45012.*

issue in the identity of electricities from different sources. In his 1807 Royal Institution lecture course on the 'Chemical Phenomena of Nature' he devoted an entire lecture (probably on 21 March) to demonstrating and discussing these experiments and results, briefly reported in *The Director*.[49] He doubtless used the Royal Institution's apparatus with which he had made his discoveries illustrating that it would have been very difficult for him to have undertaken this research anywhere else.

Davy's pattern of work in late 1807 and into 1808 was remarkably similar to the year before. Returning to the laboratory at the end of September 1807, he continued his experiments electro-chemically decomposing various compounds. These included the alkalies potash and soda from which he successfully obtained what he initially termed, imitating the practice of Lavoisierian nomenclature, 'sodagen' and 'potogen'[50], though, to emphasise their metallic properties he shortly renamed them sodium and potassium. As in the previous year, Davy was appointed, for the second time, Bakerian lecturer to tell the Royal Society of London about his work, in this case over two November evenings. He noted that he had used the Royal Institution's batteries of various plate sizes (24 12 inch square, 100 6 inch and 150 4 inch, totalling just over 19,000 square inches).[51]

Unlike the previous year, at the end of November he fell dangerously ill either from overwork or from visiting Newgate Prison to advise on its ventilation. Not fully recovered until January his courses, including a ten-lecture series devoted entirely to electrochemistry but covering other topics[52], were postponed until mid-March. Between delivering his second Bakerian lecture and his Royal Institution course, Davy obtained a completely new battery comprising twenty troughs each with twenty-five six-inch square plates, a combined area of 36,000 square inches or roughly twice the size of the miscellaneous collection of batteries 'much injured by constant use'[53], that he mentioned in his Bakerian lecture. Indeed, in his first lecture he displayed some of its component troughs claiming it was 'at least four times as powerful as any that has been hitherto constructed', though quite what he meant by powerful is not clear;[54] the entire battery was illustrated and described in *The Monthly Magazine* for August 1808 (Fig. 4).

Owing to meagre detailed financial records for the Royal Institution at this time, very little is known for certain about this battery, although later in the year Davy said that it had been 'constructed in the Laboratory the Royal Institution.'[55] In mid-July 1808 the Managers noted an invoice from William Allen for £117 10s 7d for 'Apparatus';[56] at the start of the year, using his own troughs, Allen had replicated Davy's isolation of potassium.[57] It is not known when Allen's invoice was submitted, though other invoices noted at the same time went back two years. A January 1808 report to the Managers on the Institution's (once again) poor financial situation the Visitors (essentially an audit committee) pointed out that Davy's researches (excluding salaries) had cost £166 10s.[58] This precise figure was removed from the printed Annual Report for 1808 which noted instead that the laboratory had 'added considerably to the charges on the

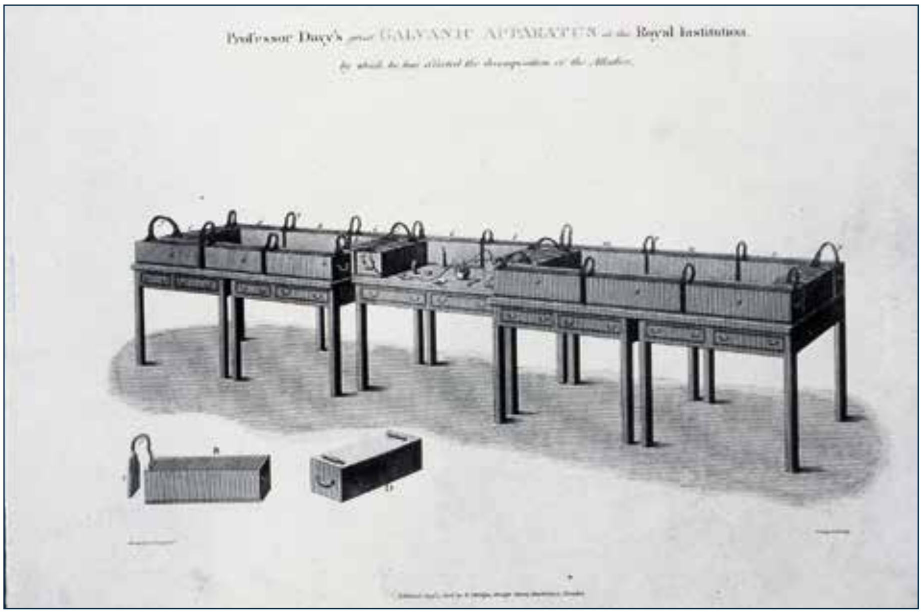

Fig. 4 *Humphry Davy's 36,000 square inch battery of Spring 1808 from 'Some Account of Professor Davy's Grand Galvanic Battery',* The Monthly Magazine, ***26*** *(1808), pp. 12-13.*

Establishment'.[59] However, the accounts for 1808 showed that £265 9s 4d had been spent on apparatus and chemicals, more than five times that expended in 1807[60], which might well be connected to acquiring this new battery.

With this powerful battery Davy in May resumed experimentation on electro-chemically decomposing various compounds.[61] Unfortunately, this work was not recorded in the Royal Institution's laboratory notebook. Although he soon decided that he needed an even more powerful battery[62], he nevertheless isolated four further new metals: barium, strontium, calcium and magnesium. He announced these results in a paper read to the Royal Society of London at the end of June and into July[63] which justified *The Monthly Magazine* claiming that with the battery depicted in its August issue Davy had decomposed the alkalies (see Fig. 4).

It must have been clear to him that the Royal Institution could not afford a second large battery. Thus, at the Managers' mid-July meeting he proposed that for urgent and patriotic reasons the necessary funds should be raised by subscription which was agreed.[64] Since obtaining funding and then constructing this new battery would take some time, Davy, impatient as ever, secured the use of the battery owned by John George Children (1777–1852).[65] The son of a wealthy banker in Tonbridge, Children, strongly interested in science, a Life Member of the Royal Institution since 1800, had been elected a Fellow of the Royal Society of London in 1807. Quite how and when Davy and Children met is not known, but by April 1808 they were going on fishing expeditions together[66], indeed, despite serious vicissitudes, they remained good friends for the rest of Davy's life.

Children had built himself a private laboratory in the grounds of his father's Tonbridge house and by the start of 1808 was repeating Davy's experiments, probably on a larger scale since he was nearly blinded by an explosion of potassium as he pseudonymously warned in a letter published in the February issue of *A Journal of Natural Philosophy, Chemistry and the Arts*.[67] The battery he may have used then was possibly that mentioned in a paper read to the Royal Society of London at the end of November where he described one of 1250 four inch plates (40,000 square inches).[68] He also considered how to improve the battery and sent the *Journal* a short letter suggesting using glass partitions instead of wood since the heat generated using wood melted the cement which, Children found, did not occur with glass.[69]

Children continued work during 1808 by having another large battery constructed. According to a later electrical writer, the goldsmith William Henry Eastwick (bp.1780, d.1854) of 102 Aldersgate Street constructed this battery.[70] Quite how Eastwick became involved in making batteries is not known. Apprenticed to his mother, he became free in the Goldsmith's Company in 1801. Working in London until around 1810, he then moved to the Midlands where his wife originated and later practiced as an engineer in Gloucestershire.[71] The battery he built for Children consisted of twenty pairs of plates each four by two feet, a total surface area of just over 92,000 square inches.[72] It is not entirely clear when Davy first saw this battery, but in July, when at Greenwich, he described Children's 'magnificent experiments & apparatus'[73] to, among others, Banks, Cavendish and the chemist William Hyde Wollaston (1766–1828). The following month Davy, Allen and the instrument maker William Haseldine Pepys (1775–1856) visited Children in Tonbridge where they experimented with his batteries. They created a carbon arc and found 'that large plates give quantity, and produce great effect in igniting; the small plates give *intensity*'[74], a result Children published in his Royal Society of London paper. At the end of the paper, Children commented on the beneficial effects of using glass partitions, adding that troughs made entirely of Wedgwood ware, an idea he ascribed to the physician William Babington (1756–1833), would be 'best of all'.[75]

Such work would have confirmed Davy in his view that ever larger batteries would allow further chemical discoveries to be made. The Royal Institution's subscription for a new battery made good progress and at the start of September Davy told Josiah Wedgwood jr (1769–1843) that £800 had been pledged. By then Davy had decided to follow Children's suggestion of using Wedgwood ware and his letter enquired about the costs of making such a battery of two to three hundred troughs.[76] Wedgwood evidently responded favourably, discussing the design details, sending a specimen trough and even pledging ten guineas himself.[77] During 1809, £520 12s 3d was spent on the battery[78] including payments of £41 17s 3d, £24 9s 6d and £11 1s to Wedgwood.[79] But Eastwick took the largest amount, £220 3s[80], illustrating the close link between Children's private battery and the Royal Institution's national battery. Other contractors involved in the project included the instrument maker John Newman then of 11 Windmill Street, Camberwell. He was paid three smallish sums (£7 4s 4d, £8 8s and £8 19s 9d) for 'sundries' during 1809 and 1810.[81]

These are the earliest records of Newman's connection with the Royal Institution, a link that lasted for the remainder of his working life and be highly significant for both. In 1810 he valued the Royal Institution's apparatus and model collections as part of the process of turning the institution from a proprietorial organisation into a public body.[82] The following year he moved to 7 Lisle Street (just north of Leicester Square) to be closer to the Royal Institution for whom, it is clear from the number of payments authorised over the years, he provided significant services. (Including, of course, his famous fight with the laboratory assistant in the lecture theatre on 19 February 1813 resulting in the latter's dismissal and Faraday's appointment in his stead[83]). In April 1823, the Managers agreed (unusually) to Newman's request that he could describe himself as 'Instrument maker to the Royal Institution' using this, for instance, on his publications.[84] Three years later, to be even nearer the Royal Institution, he moved to 122 Regent Street where he remained until retirement shortly before his death.

Davy held Newman in high regard, describing him as 'a very honest fellow' and a 'very sensible man'.[85] Indeed, doubtless owing to Eastwick's move to the Midlands, Davy only referred to Newman when he answered enquiries concerning constructing batteries from the Birmingham Philosophical Society and the Dublin Society.[86] The latter ordered the plates from Newman and the troughs from Wedgwood;[87] the batteries so constructed were doubtless those used by Davy when he lectured at the Dublin Society on electrochemistry at the end of 1810.

Some components of the Royal Institution's 200 trough battery became available during his six-lecture course on electro-chemistry that he delivered weekly from the end of April 1809; he spent the entire second lecture describing its superiority.[88] Once the battery began to be operational, Davy commenced a wide variety of experiments described in his fourth Bakerian Lecture read to the Royal Society of London over five Thursdays in November and December 1809. In the published version he did not provide a comprehensive description of the battery, though he provided an illustration of a trough (Fig. 5), noting in the caption that there were 200 of them, although 'the whole combination has not [yet] been put into action'.[89] Indeed Davy did not publish full details until his *Elements of Chemical Philosophy* (1812):

> 'It consists of two hundred instruments, connected together in regular order, each composed of ten double plates arranged in cells of porcelain, and containing in each plate thirty-two square inches; so that the whole number of double plates is 2000, and the whole surface 128000 square inches.'[90]

Or nearly 40% larger than Children's. The size of the battery, not to mention the fumes it

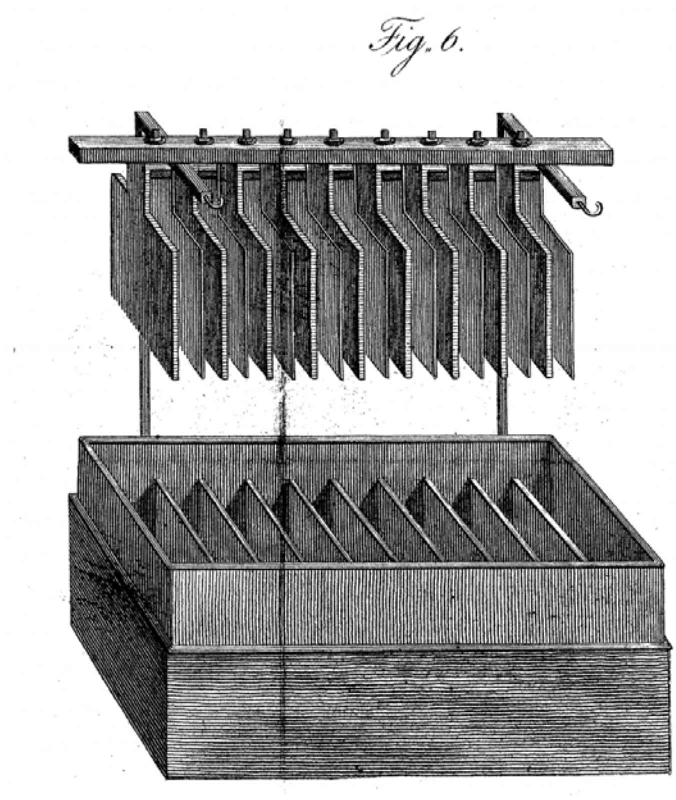

Fig. 5 *A single element of the 200 trough battery paid for by subscription. From Humphry Davy, 'The Bakerian Lecture for 1809. On some new Electrochemical Researches, on various Objects, particularly the metallic Bodies, from the Alkalies, and Earths, and on Some Combinations of Hydrogene',* Philosophical Transactions, ***100** (1810), pp. 16-74.*

would have produced, necessitated locating it in a room, 8 x 10 feet, probably built especially, on the eastern wall of the yard.[91] However, the increase in size was insufficient to enable Davy to make any further significant electro-chemical discoveries. For instance, using the battery in an extensive series of experiments he could not decompose fluoric acid, though that did not prevent him from proposing in 1813 the name fluorine for the prospective chemical element involved (though André-Marie Ampère (1775–1836) had suggested it to him).[92] Davy had enjoyed an extraordinary run of success with the batteries he used, so it is not surprising that in the opening lecture of his 1808 course on electro-chemistry he claimed the battery as the 'most wonderful & important electrical instrument ever discovered'[93] and in his *Elements of Chemical Philosophy* observed 'Nothing tends so much to the advancement of knowledge as the application of a new instrument'.[94]

Beyond Electro-chemistry

By this time Davy, newly knighted, had married a wealthy widow, Jane Apreece (*c*.1780–1855). He consequently resigned all his paid positions, to be succeeded at the Royal Institution by the chemist William Thomas Brande (1788–1866), though he retained the (now unpaid) role of Director of the Laboratory.[95] Davy claimed to his brother he would now have more time for research[96] which, on the whole, was wishful thinking. Indeed, from Autumn 1813 to Spring 1815, Davy, Lady Davy, her maid and Faraday (whom Lady Davy treated badly) toured what is now France, Italy, Switzerland and southern Germany.[97] Although, Davy undertook some experimentation, such as in Paris demonstrating the elemental nature of iodine or in Florence using the large burning lens of the Grand Dukes of Tuscany (now in the Museo Galileo) to show that diamond was composed of carbon[98], much of the urgency had gone out of his work.

Shortly after his return to Britain Davy was asked to investigate the possibility of lighting coal mines safely. This resulted in an intense period during the last three months of 1815 working with Faraday in the laboratory and supported strongly by Newman culminating in inventing the miners' gauze safety lamp in mid-December. There followed a thoroughly unpleasant row between Davy and his supporters with the Newcastle mining engineer George Stephenson (1781–1848) and his supporters over the lamp's efficacy and Davy's priority in invention.[99] Newman's role in this story has not been emphasised before[100], yet from the numerous references to him in Davy's letters throughout 1816 and into 1817, it is clear that he played a crucial role in improving the lamp, which Stephenson fully appreciated.[101] Davy acknowledged 'M^r Newman assisted me in all my enquiries from the beginning'[102] and this is evinced by a letter to Faraday written (from Yorkshire) at the start of October 1815 asking him to get Newman to make 'some strong glass cylinders' which could stand an explosion.[103] During the controversy Davy cited Newman's order book as evidence for his priority since it recorded 'all my orders for lamps and apparatus' including the earliest form of the lamp in October.[104] It seems clear, therefore, that Newman made the proto-type lamps which were then experimented on by Davy and Faraday as they evolved the gauze design. Whether they modified the successive lamps themselves, or ordered Newman to do so, is not clear. Nor is it known who paid Newman for his work as no evidence has been found of payment(s) from the Royal Institution.

Electro-magnetism

At this point the relationship between Davy and Faraday, despite the stresses of the Con-

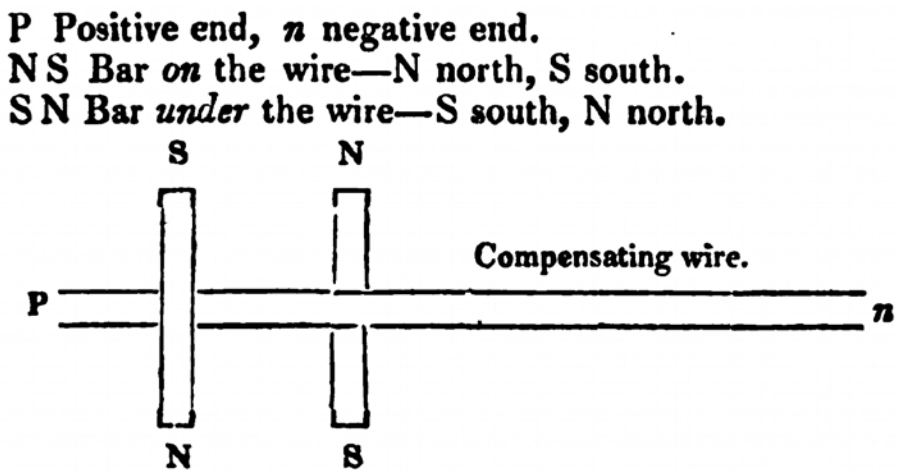

Fig. 6 *Humphry Davy's experiment on the flow of electricity in a wire near magnets. From 'Proceedings of Learned Societies. Royal Society [of London]',* Philosophical Magazine, ***56** (1820), pp. 381-2, p.382.*

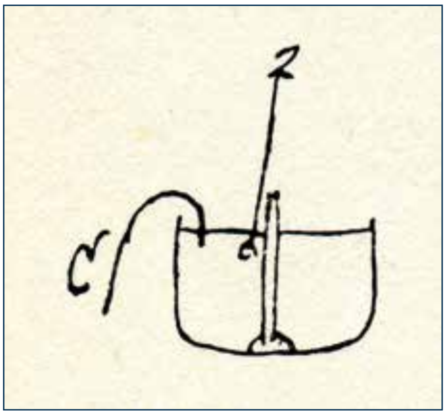

Fig. 7 *Michael Faraday's sketch of his electro-magnetic rotations apparatus of 4 September 1821. From Faraday,* Diary, ***1**, p. 50.*

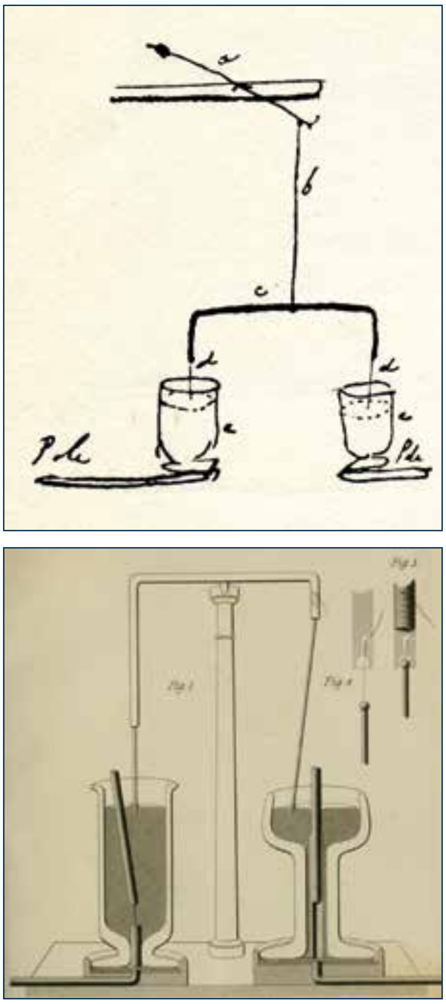

Fig. 8 (a) *Michael Faraday's sketch of the electro-magnetic rotations apparatus of 22 December 1821 (from Faraday,* Diary, ***1**, p. 62) from which followed* (b) *the basic instrument, made by Newman, to demonstrate the phenomenon (from Michael Faraday, 'Description of an Electro-magnetical Apparatus for the Exhibition of Rotary Motion',* Quarterly Journal of Science, ***12** (1821), pp. 283-5). An example exists in the collections of the Royal Institution.*

tinental tour, seems to have been fairly reasonable. That changed in the early 1820s following the discovery in 1820 of electro-magnetism by the Danish savant Hans Christian Oersted (1777–1851). Immediately men of science throughout Europe, including in London, Davy, Wollaston and Faraday, turned their attention to exploring this new phenomenon. During October and into November Davy, assisted throughout by Faraday[105] experimented on electro-magnetism; indeed, so absorbed did Davy become in this work, that he postponed visiting Cornwall to see his mother and siblings.[106] Under the guise of wishing to show Pepys his results of 'the conversion of electricity into magnetism', Davy arranged to use the giant battery at the London Institution recently opened in Finsbury Circus, with which Pepys was closely connected.[107] That Davy needed to use this battery suggests that after ten years the Royal Institution's battery had lost its power. The main finding of Davy's paper, read to the Royal Society of London on 16 November 1820, was that metal could be magnetised by passing an electric current in a wire near it and that the magnet's polarisation depended on its relative position to the wire, a result illustrated in the report published in the *Philosophical Magazine* but not in the paper itself (Fig. 6).

Two weeks later Davy became President of the Royal Society of London. With the extra duties and hectic social life entailed by the position, he did not return to electro-magnetism until the end of January 1821. At the beginning of February he demonstrated in the London Institution to the astronomer James South (1785–1867) and the mathematician Charles Babbage (1791–1871), presumably with Pepys amongst others, how electric arcs might attract each other (doubtful) and how they were affected by magnetism.[108] Davy continued these latter experiments at the London Institution in May using all 2000 plates as Faraday recorded[109], publishing his observations in a paper read to the Royal Society of London on 5 July.[110]

By this time Faraday, recently promoted Superintendent of the Royal Institution's house and laboratory in Brande's absence (which was much of the time)[111], had started taking a strong interest in electro-magnetism following a request from his old friend Richard Phillips (1778–1851), who had just taken over editing *The Annals of Philosophy*. At some point during the Summer, he asked Faraday to write a review article on the work stemming from Oersted's discovery, announced less than a year previously. Apparently written during July and August[112], the first two parts were published anonymously in September and October.[113] To understand what had been observed, Faraday adopted a strategy of repeating the experiments described in the now extensive electro-magnetic literature. As a result, in a series of experiments and theorising on 3 and 4 September 1821, that have been superbly analysed by David Gooding[114], Faraday discovered what he called electro-magnetic rotations. In this instance the apparatus, of which Faraday made a very small sketch in his notebook (Fig. 7), was almost entirely from scratch apart from the battery: a glass beaker with a permanent magnet cemented to the base, filled with mercury and a wire hanging from a hook into the mercury. When the battery was connected across the wire and mercury, the wire rotated round the magnet – the first time that continuous motion had been produced by the interaction of electricity and magnetism.[115] For the battery Faraday used a Hare's calorimeter composed of two large plates rolled in a spiral, again suggesting that the Royal Institution's ageing batteries were well past their best.[116]

Brande, who edited the *Quarterly Journal of Science*, semi-linked to the Royal Institution, was absent and so Faraday had responsibility for the journal which gave him the opportunity to rapidly publish his discovery of electro-magnetic rotations.[117] In this he only included figures relating to the geometry of the phenomenon, rather than of the apparatus with which he had discovered rotations, presumably feeling it inappropriate to publish something so basic. He soon got Newman to make a high-quality version of the apparatus, stemming from a configuration he sketched in his notebook. Faraday mentioned this briefly in the December 1821 *Quarterly Journal of Science*[118] but provided further details and an illustration in the January 1822 issue (Figs 8a and b).

Faraday's quick publication of his results began the rift between him and Davy, since the latter believed that Faraday had used some of Wollaston's (unpublished) work without acknowledgement. This was further exacerbated in 1823 when Faraday liquified a gas, chlorine, for the first time following a suggestion by Davy, but declined to give Davy any credit. The final break came the same year when Davy sought, unsuccessfully, to block Faraday's election as a Fellow of the Royal Society of London.[119] For the remainder of the 1820s Davy exploited Faraday's undoubted talents with no regard to his best interests. He got him to serve as the first (unpaid) Secretary of the Athenaeum Club and then work on a very time-consuming project to make high quality optical glass as part of a joint Board of Longitude and Royal Society of London project. The glass furnace used by Faraday displaced Davy's subscription battery in the room in the Royal Institution's yard.[120] Initially regarded as a failure[121], out of the proj-

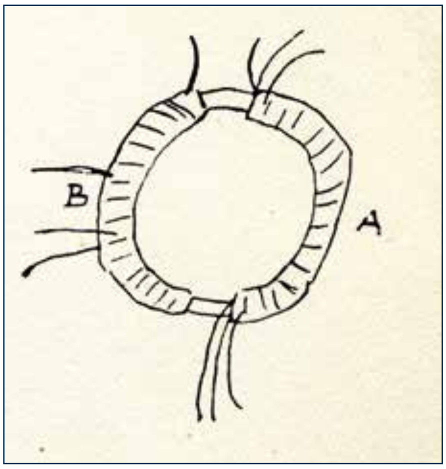

Fig. 9 *Michael Faraday's sketch of his electro-magnetic induction ring, first used on 29 August 1831. From Faraday,* Diary, ***1,*** *p. 367. The original device exists in the collections of the Royal Institution.*

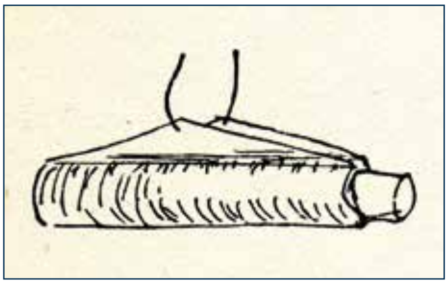

Fig. 10 *Michael Faraday's sketch of 17 October 1831 of his device to generate electricity by moving a magnet in and out of a coil. From Faraday,* Diary, ***1****, p. 376. The original device exists in the collections of the Royal Institution.*

ect Faraday acquired his long-term laboratory assistant, Charles Anderson (*c*.1791–1866).

By the early 1830s Faraday had the time to resume experimentation on electro-magnetism. He returned to seeking the long-sought phenomenon of electro-magnetic induction[122] that he discovered on 29 August 1831 using his famous ring (Fig. 9); a few weeks later found how to generate electricity by moving a permanent magnet in and out of a coil (Fig. 10).[123] These devices certainly met Helmholtz's criteria of instruments from scratch. However, one does need to remember that both devices required wire which needed to be manufactured and then insulated, which in 1831 had to be done manually by Faraday and his assistant[124] while, additionally, induction required a battery and generation required a galvanometer to detect the presence of electricity, both of which had to be made commercially.

A similar story can be told for the discoveries that Faraday made throughout the 1830s and 1840s ranging from the magneto-electric

Fig. 11 *Michael Faraday's magneto-spark apparatus in the collections of the Royal Institution was a prominent feature of the £20 Bank of England Faraday note issued in the 1990s.*

spark in 1832 through the 'Faraday cage' of 1836 to his work on the magneto-optical 'Faraday effect' and diamagnetism both in 1845. Faraday certainly by, and most likely in, May 1832[125], found that a coil of wire pulled very quickly from between the poles of powerful permanent magnet produced a spark. The coil fulfils Helmholtz's description, though it is unlikely that the magnet now associated with it (made by a Dr Schmidt[126]) was that used in 1832 (Fig. 11). Faraday clearly stated that he used a lodestone, almost certainly now in the Science Museum, that he borrowed from his friend, John Frederic Daniell (1790–1845) Professor of Chemistry at King's College London.[127] Using it he demonstrated the spark after a lecture at the Royal Institution where it 'was so bright it could be seen in broad day light in any part of the room'.[128] In mid-January 1836 Faraday had constructed (in the lecture theatre) a wooden framed twelve foot cube covered in wire and paper placed on glass feet (Fig. 12). When charged using a commercially built electrostatic generator, Faraday argued that inside the cage he became electrically isolated from the rest of the universe. From the experiments he performed in those circumstance he concluded the relative nature of electrical charge which he demonstrated in the theatre (after the cage had been removed) using ice-pails.[129] Finally, his discovery of the magneto-optical effect was entirely dependent on his access to the lead borate glass made in the apparently failed glass project of the late 1820s and some very powerful argand lamps he was testing for Trinity House, the English and Welsh lighthouse authority whom he served as Scientific Adviser from 1836. Following on from the

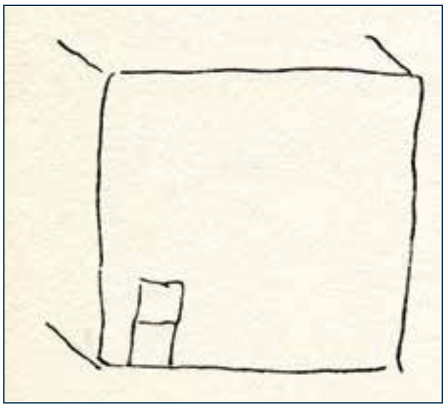

Fig. 12 *Michael Faraday's sketch of 15 January 1836 of the first Faraday cage showing the flap through which he entered the cage. Faraday,* Diary, ***2****, p. 428.*

Fig. 13 *Table turning indicator from* Illustrated London News, ***23*** *(16 July 1853), p. 26. Faraday described its operation in 'Professor Faraday on Table-Moving', The Athenaeum, 2 July 1853, pp. 801-3. Without the indicator the participants would unconsciously move the table; when the device was placed on the table, the motion ceased. No example of the indicator has been identified.*

magneto-optical effect, he had constructed a giant electro-magnet made of half an anchor ring (supplied by Enderby and Sons, whalers operating out of Greenwich) with which he discovered magnetism to be a universal property of matter.[130] That allowed him to formulate his field theory of electro-magnetism that became and remains one of the cornerstones of modern physics and which he illustrated by making iron filing diagrams, fixed in waxed paper.[131]

One unintended consequence of Faraday's discovery of the universality of magnetism was that it led to his becoming involved in the issues surrounding table-turning and spiritualism that became prominent in 1853. The proponents of such phenomena claimed that they were due to magnetism or some unknown force. Such assertions offended both Faraday's scientific and religious sensibilities which compelled him to seek to debunk the pretensions of those involved. To this end, he designed an indicator which when used at séances prevented, through what Faraday termed 'a *quasi* involuntary muscular action', tables from turning (Fig. 13**)**. Here there is no evidence of hybridity since the device was made (and sold) by Newman.[132]

Conclusion

The instruments from scratch approach that Helmholtz identified became seen as a positive virtue by Faraday's successor at the Royal Institution, John Tyndall (*c*.1822–1893). Professor of Natural Philosophy from 1853 until 1887, Tyndall's successor was the Third Lord Rayleigh (1842–1919), formerly Cavendish Professor at Cambridge University. Shortly before Rayleigh took up the appointment, Tyndall told him:

> 'our poverty as to apparatus was self-imposed. We did not buy, but we borrowed, and paid for the loan. This was Faraday's plan, and mine. It answered. Besides, we were often able to put together, through the exercise of mother-wit, apparatus which, had we resorted to the philosophical instrument maker, would have cost a ten-fold sum. We never lacked the necessary apparatus; but we declined to heap up dead stock at a time when each year's advance made the apparatus of the preceding year defective. By such methods the Royal Institution was raised from a position of poverty and difficulty now happily unknown.'[133]

This was nonsense and Tyndall, by now towards the end of his life, seems here to have mis-remembered the past into which he read current problems. For some of his later work Faraday did indeed rely on the generosity of wealthy Royal Institution Members, such as John Peter Gassiot (1797–1877) and Warren De la Rue (1815–1889), who allowed him access to their well-equipped private laboratories. But that provides evidence supporting Tyndall's comment in a postscript to his letter to Rayleigh that Faraday believed that if he wanted £1000 for experiments, the Royal Institution Members would provide it immediately. The Royal Institution, its Proprietors and Members had certainly and generously financially supported the work of its professors and had done so right from its early years. Such support ensured that for almost the entirety of his career Faraday had access to Newman's services which Tyndall had known at one point and should have recollected.[134] Furthermore, Tyndall had ordered optical instruments for the Royal Institution when visiting the 1855 Paris International Exhibition.[135] And in 1859 the Royal Institution established the Holland fund specifically for the purpose of buying apparatus which Tyndall continued to use after Faraday's death. When the fund was wound up in 1872 about £4000 had been donated, a substantial figure.[136]

Tyndall by 1887 appears to have forgotten all this or perhaps he was seeking to lay the blame, at least partly, on Faraday, for something that seems to have gone wrong towards the end of his time at the Royal Institution. That the situation was dire Rayleigh made clear in a letter to Lord Kelvin (1824–1907), soon after he arrived at the Royal Institution:

> 'I am now established in the R.I. laboratory. The apparatus has been allowed to fall behind altogether, of which I may give you an idea when I say that there is not an ohm in the place!'[137]

Evidently Rayleigh, having worked at the well-endowed Cavendish Laboratory in Cambridge and despite Tyndall's warning explanation, was shocked.

But there is an irony here, since in the interwar Cavendish the sort of approach to research implied by Tyndall's comments came to be called 'sealing wax and string'. Those, like Tyndall, who extolled the virtues of this method deceived themselves and others about the nature of their activities. As Jeff Hughes has shown, while there existed some elements of 'sealing wax and string', nuclear physics research during the 1920s and 1930s relied heavily on and was shaped by what industry could provide.[138] In this essay I have argued that the same applied in the nineteenth century. All the scientific apparatus used by Davy and by Faraday, their material culture, depended to a great extent on makers such as Newman and Eastwick, on large scale industry such as Wedgwood and corporations like the Royal Institution, Trinity House and the Royal Society of London. Yes, there were 'A few wires and some old bits of wood and iron' in the Royal Institution's laboratory when Helmholtz visited in 1853. But there was much more besides and that represented the crucial roles of commerce, industry and socety in constructing scientific knowledge.

Acknowledgements

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Note on Reference Abbreviations

The following contractions are used: Davy, *Letters* (followed by volume and letter number, unless otherwise stated), Tim Fulford, Sharon Ruston, eds, Jan Golinski, Frank A.J.L. James, David Knight, advisory eds, and Andrew Lacey, assistant ed., *The Collected Letters of Sir Humphry Davy*, 4 volumes (Oxford: Oxford University Press, 2020); Faraday, *Correspondence* (followed by volume and letter number), Frank A.J.L James, ed., *The Correspondence of Michael Faraday*, 6 volumes (London: Institution of Electrical Engineers / Engineering and Technology, 1991-2012); RI MM (followed by meeting date, volume and page number) *Archives of the Royal Institution, Minutes of the Managers' Meetings, 1799-1903,* 15 volumes, bound in 7 (London, Scolar Press, 1971-6); Faraday, *Diary* (followed by volume and page number), Thomas Martin, ed., *Faraday's Diary. Being the various philosophical notes of experimental investigation made by Michael Faraday, DCL, FRS, during the years 1820-1862 and bequeathed by him to the Royal Institution of Great Britain*, 7 vols. and index (London: Bell, 1932-6).

Notes and References

1. Herman Helmholtz to Olga Helmholtz, August 1853, quoted in Leo Koenigsberger, *Hermann von Helmholtz*, translated Frances A. Welby (Oxford: Clarendon Press, 1906), pp.110-11. ('denn einige alte Stücke Holz, Draht und Eisen schienen ihm zu den grössten Entdeckungen zu genügen', Leo Koenigsberger, *Hermann von Helmholtz*, 3 volumes (Braunschweig: Vieweg, 1902-1903), **1**: 196).

2. On Newman see H.A.L. Dawes, 'John Frederick Newman 1784-1860: 'The ingenious instrument maker, Mr Newman of Lisle Str.'', *Bulletin of the Scientific Instrument Society*, No. 50 (1996), pp.11-14; Brian Gee, 'John Newman: A Second Look', *Bulletin of the Scientific Instrument Society*, No. 51 (1996), pp. 22-5 which includes some corrections to Dawes; Brian Gee and Gloria Clifton, 'John Newman: A Further Note', *Bulletin of the Scientific Instrument Society*, No. 53 (1997), p.14 which also makes some corrections to the two previous articles.

3. On Davy generally see David Knight, *Humphry Davy: Science and Power* (Oxford: Blackwell / Cambridge: Cambridge University Press, 1992/1996) and June Z. Fullmer, *Young Humphry Davy: The Making of an Experimental Chemist* (Philadelphia: American Philosophical Society, 2000).

4. Described in [Thomas Richard Underwood], 'Appendix A: Biographical Account of Davy', *c*.1831, in Davy, *Letters*, **4**, pp. 339-43. For the prevalence of the chemical use of domestic items see Simon Werrett, *Thrifty Science: Making the Most of Materials in the History of Experiment* (Chicago: Chicago University Press, 2019), especially chapters 2 and 5.

5. Davies Giddy to Gregory Watt, 18 July 1798, Library of Birmingham MS 3219/7/5/54.

6. Frank A.J.L. James, 'Humphry Davy's Early Chemical Knowledge, Theory and Experiments: An Edition of his 1798 Manuscript, "An Essay on Heat and the Combinations of Light" from The Royal Institution of Cornwall, Courtney Library, MS DVY/2', *Ambix*, **66** (2019), pp. 303-45.

7. James, 'Humphry Davy's Early Chemical Knowledge'.

8. Frank A.J.L. James, *'the first example ... of an extensive scheme of pure scientific medical investigation': Thomas Beddoes and the Medical Pneumatic Institution in Bristol, 1794 to 1799* (London: Royal Society of Chemistry Historical Group Occasional Publication, 2016).

9. Humphry Davy, *Researches, Chemical and Philosophical; Chiefly Concerning Nitrous Oxide, or Dephlogisticated Nitrous Air, and its Respiration* (London: Johnson, printed Bristol, by Biggs and Cottle, 1800).

10. Davy, *Researches*, p.568 referenced Volta's work briefly.

11. Frank A.J.L. James , 'The Subversive Humphry Davy: Aristocracy and Establishing Chemical Research Laboratories in Late Eighteenth- and Early Nineteenth-Century England' in Lissa Roberts and Simon Werrett, eds, *Compound Histories: Materials, Governance and Production, 1760-1840* (Leiden: Brill, 2017), pp.269-88.

12. Rumford to Joseph Banks, 29 May 1800, Dartmouth College MS Rauner Rumford 800329.

13. Frederick Kurzer, 'The Life and Work of Edward Charles Howard', *Annals of Science*, **56** (1999), pp. 113-41.

14. William Cruickshank, 'Additional Remarks on Galvanic Electricity', *A Journal of Natural Philosophy, Chemistry and the Arts*, **4** (1800), pp. 254-64, esp., pp.258-9.

15. Humphry Davy, 'An Account of some Experiments made with the Galvanic Apparatus of Signor Volta', *A Journal of Natural Philosophy, Chemistry and the Arts*, **4** (1800), pp. 275-81, p. 275.

16. Humphry Davy to Grace Davy, 27 September 1800, Davy, *Letters*, **1**, 27.

17. Davies Giddy, *Diary*, 7 August 1800, Cornwall Record Office MS DG/16 (unpaginated).

18. Davy, notebook, RI MS HD/20/C, p. 10; Davy, 'An Account of some Experiments'.

19. Humphry Davy, 'An Account of Some Galvanic Combinations, Formed by the Arrangement of Single Metallic Plates and Fluids. Analogous to the New Galvanic Apparatus of Mr. Volta', *Philosophical Transactions*, **91** (1801), pp. 397-402, p.400.

20. This story was recounted by the geologist William Buckland at the 1836 meeting of the British Association held in Bristol. John King, a colleague of Beddoes's in his later years and probably the benevolent physician mentioned, immediately published a correction in *The Bristol Mercury*, 8 October 1836, 4c.

21. James, '*the first example*', pp. 32-3.

22. Humphry Davy to John Tonkin, 12 January 1801, Davy, *Letters*, **1,** 35.

23. *The Anti-Jacobin Review and Magazine*, **6** (1800), pp. 424-8. For further discussion see Frank A.J.L. James, 'The Watt Family, Thomas Beddoes, Davies Giddy, Humphry Davy, and the Medical Pneumatic Institution, Bristol' in Malcolm Dick and Caroline Archer-Parré, eds, *James Watt (1736-1819): Culture, Innovation, and Enlightenment* (Liverpool: Liverpool University Press, 2020), pp.109-35, p.131

24. Humphry Davy to Grace Davy, 27 September 1800, Davy, *Letters*, **1**, 27.

25. [Underwood], 'Appendix A', p. 441.

26. Humphry Davy to Thomas Charles Hope, 28 June 1801, Davy, *Letters*, **1**, 43.

27. Thomas Richard Underwood to John Ayrton Paris, *c*.1830, Paris, *Life of Sir Humphry Davy*, **1**, p. 115. RI MM, 5 January 1801, **2**, p. 118-21 is silent on this. 'Memoirs of Sir Benjamin Thompson, Count of Rumford', *The Gentleman's Magazine*, **64** (1814), pp. 394-8, largely a translation of Rumford's obituary published in the *Bibliothèque Britannique*, **56** (1814), pp. 398-401, but followed by 'some interesting memorials … by an intimate friend of the Count's' (pp.396-8, quotation on p. 396). This included what seems to be the first publication of Underwood's claim about his role in Davy's appointment which, in turn, suggests that the author of this piece was Underwood.

28. Mentioned in Humphry Davy to Davies Giddy, 8 March 1801, Davy, *Letters*, **1**, 39.

29. Humphry Davy to Grace Davy, 31 January 1801, Davy, *Letters*, **1**, 37.

30. Humphry Davy to Davies Giddy, 8 March 1801, Davy, *Letters*, **1**, 39.

31. James, *'the first example*', p. 22.

32. RI MM, 16 February 1801, **2**, p. 134; Rumford to Humphry Davy, 16 February 1801, Henry Bence Jones, *The Royal Institution: Its Founders, and Its First Professors* (London: Longman, 1871), pp. 317-19.

33. RI MM, 16 March 1801, **2**, pp. 150-1.

34. RI MM, 19 May 1800, **2**, p. 89 recorded a payment of £50 17s 5d to Fidler.

35. So termed on the floor plan by Thomas Webster, *c*.1800, Royal Institute of British Architects SB/58/1/13.

36. RI MS RI 5/3/4.

37. Rumford to Marc-Auguste Pictet, 10 February 1802, René Sigrist and David Bickerton, eds., *Marc-Auguste Pictet 1752-1825 Correspondance Sciences et Techniques*, 4 volumes (Geneva: Slatkine, 1996-2004), **3**: 571-3.

38. Harriet Olivia Lloyd, *Rulers of Opinion: Women at the Royal Institution of Great Britain*, University College London PhD thesis, 2018.

39. RI MM, 15 June 1801, **2**, pp. 189-90.

40. RI MM, 31 May 1802, **3**, p. 43.

41. Geoffrey Cantor, 'Thomas Young's Lectures at the Royal Institution', *Notes and Records of the Royal Society of London*, **25** (1970), pp. 87-112.

42. Lloyd, *Rulers of Opinion*, p.56.

43. Royal Institution laboratory notebook, RI MS HD/6, pp.17-46, entries September to November 1806.

44. Frank A.J.L. James, 'Negative Geology: Humphry Davy and the Forming of the Royal Institution's Mineralogical Collection, 1803-1806', *Earth Sciences History*, **37** (2018), pp. 309-32 and '"Agricultural Chymistry is at present in it's infancy": The Board of Agriculture, The Royal Institution and Humphry Davy', *Ambix*, **62** (2015), pp. 363-85.

45. Humphry Davy, 'The Bakerian Lecture, on some chemical Agencies of Electricity', *Philosophical Transactions*, 97 (1807), pp. 1-56, p.4.

46. Davy, 'on some chemical Agencies of Electricity', p.17. RI MM, 7 June 1802, **3**, p. 47 noted the authorisation of thirty-six guineas for the purchase; it is not listed explicitly on the inventory. On this instrument, which remains in the Royal Institution, see Peta Dewar Buchanan, *Quantitative Measurement and the Design of the Chemical Balance 1750-c.1900*, Imperial College PhD thesis, 1982, pp.130-1, 360.

47. Davy, 'on some chemical Agencies of Electricity', p.31. This is probably listed on the inventory, p.6, though not explicitly by name.

48. Davy, 'on some chemical Agencies of Electricity', pp.33-4. This is listed on the inventory, p.8.

49. *The Director*, 1807, **1**, p. 315.

50. Royal Institution laboratory notebook, RI MS HD/6, p.79 and 80 respectively, entry for 15 November 1807.

51. Humphry Davy, 'The Bakerian Lecture, on some new Phenomena of chemical Changes produced by Electricity, particularly the Decomposition of the fixed Alkalies, and the Exhibition of the new substances which constitute their bases; and on the general Nature of alkaline Bodies', *Philosophical Transactions*, **98** (1808), pp. 1-44, p. 3.

52. A term which he used on the front cover of the notes for his eighth lecture, RI MS HD/2/D/4.

53. Humphry Davy, 'Electro-Chemical Researches, on the Decomposition of the Earths; with Observations on the Metals Obtained from the Alkaline Earths, and on the Amalgam procured from Ammonia', *Philosophical Transactions*, **98** (1808), pp. 333-70, p. 338.

54. Davy's lecture notes, RI MS HD/2/D/1, p.15. A claim he repeated in his fourth lecture 'Literary and Miscellaneous Information', *The Athenaeum*, **3** (1808), pp. 567-71, p. 569. For a modern assessment see Allan Mills, 'Early Voltaic Batteries: An Evaluation in Modern Units and Application to the Work of Davy and Faraday', *Annals of Science*, **60** (2003), pp. 373-98.

55. Davy, 'Electro-Chemical Researches', p.339.

56. RI MM, 11 July 1808, **4**, p. 373.

57. Allen's diary entry for 8 January 1808, *Life of William Allen, with selections from his Correspondence*, 3 volumes (London: Gilpin, 1846-7), **1**, p. 90.

58. RI MM, 25 January 1808, **4**, p. 310.

59. *The Report of the Committee of Managers, upon the present state of the Institution*, 20 March 1809, p.2.

60. *The Annual Report of the Visitors on the State of the Institution, April 18, 1809*, p.1. For 1807 expenditure see *The Annual Report of the Visitors on the State of the Institution, April 18, 1808*, p. 3.

61. Davy, 'Electro-Chemical Researches', p. 338.

62. Davy, 'Electro-Chemical Researches', p. 335.

63. Davy, 'Electro-Chemical Researches', p. 346.

64. RI MM, 11 July 1808, **4**, p. 374. This project has been discussed in June Z. Fullmer, 'Humphry Davy: Fund Raiser' in Frank A.J.L. James, ed., *The Development of the Laboratory: Essays on the Place of Experiment in Industrial Civilisation* (London: Macmillan, 1989), pp. 11-21 and Patrick R. Unwin and Robert W. Unwin, ''A Devotion to the Experimental Sciences and Arts': The Subscription to the Great Battery at the Royal Institution 1808-9', *The British Journal for the History of Science*, **40** (2007), pp. 181-203. While this is not the place to further discuss the project in detail, it should be noted that the latter paper is inaccurate in many regards. For example, they confuse the battery paid for by the fund-raising with Davy's Spring 1808 battery (p. 182); they also did not study all the available, though meagre, financial records of the Royal Institution which suggests a rather different story.

65. On Children see A.E. Gunther, 'John George Children, F.R.S. (1777-1852) of the British Museum. Mineralogist and reluctant Keeper of Zoology', *Bulletin of the British Museum (Natural History) Historical Series*, **6** (1978), pp. 75-108.

66. Humphry Davy to John George Children, April 1808, Davy, *Letters*, **1**, 159.

67. Philommatos, 'Account of an Accident from the sudden Deflagration of the Base of Potash', *A Journal of Natural Philosophy, Chemistry and the Arts*, **19** (1808), pp. 146-7. That this was by Children is confirmed from it being dated 'Tunbridge, Jan. 22, 1808' and that his daughter, then aged eight, recollected the incident. [Anna Atkins], *Memoir of J.G. Children, Esq.* (Westminster: John Bowyer Nichols, 1853), p. 72.

68. John George Children, 'An Account of some Experiments, performed with a View to ascertain the most advantageous Method of constructing a Voltaic Apparatus, for the Purposes of Chemical Research', *Philosophical Transactions*, **99** (1809), pp. 32-8, p. 35.

69. J.G.C., 'An Improvement in the Galvanic Trough, to prevent the Cement from being melted, when the Action is very powerful', *A Journal of Natural Philosophy, Chemistry and the Arts*, **19** (1808), p. 148.

70. Henry Noad, *A Course of Eight Lectures; On Electricity, Galvanism, Magnetism and Electro-Magnetism* (London: Scott, Webster and Geary, 1839), p.112. See also C.H. Wilkinson, 'Description of an Improved Galvanic Trough', *Philosophical Magazine*, **29** (1807), pp. 243-4, p. 244.

71. https://www.925-1000.com/forum/viewtopic.php?t=33796, accessed 5 January 2021.

72. Children, 'An Account of some Experiments', p. 32.

73. Humphry Davy to John George Children, 29 July 1808, Davy, *Letters*, **1**, 171.

74. Allen's diary entry for 22 August 1808, *Life of William Allen*, **1**, p. 107.

75. Children, 'An Account of some Experiments', p. 38.

76. Humphry Davy to Josiah Wedgwood jr, 4 September 1808, **1**, 174.

77. Humphry Davy to Josiah Wedgwood jr, 20 October 1808 and November 1808, Davy, *Letters*, **1**, 177 and 178.

78. *The Annual Report of the Visitors on the State of the Institution, State of the Accounts for the Years 1809 and 1810*, p.1.

79. RI MM, 20 February 1809, **4**, p. 422; 22 May 1809, **4**, p. 453; 29 May 1809, **4**, p. 454.

80. RI MM, 10 July 1809, **4**, p. 471.

81. RI MM, 29 May 1809, **4**, p. 454; 9 October 1809, **4**, p. 483; 5 February 1810, **5**, p. 19.

82. RI MM, 26 February 1810 and 19 March 1810, **5**, pp. 43 and 54.

83. Frank A.J.L. James, *Michael Faraday: A Very Short Introduction* (Oxford: Oxford University Press, 2010), pp. 33-4.

84. RI MM, 7 April 1823, **6**, p. 384. An example of his using this designation occurs on the title page of *Instructions necessary to be attended to, in using Newman's Standard, or, Portable Mountain Barometer* (Earl's Court: George Nichols, 1841).

85. Humphry Davy to James Watt jr, 21 December 1810 and Humphry Davy to John Buddle, 31 December 1816, Davy, *Letters*, **2**, 249 and 566.

86. Humphry Davy to James Watt jr, 21 December 1810 and Humphry Davy to James Lynch, 26 August 1811, Davy, *Letters*, **2**, 249 and 277. For the Dublin Society see also Humphry Davy to Josiah Wedgwood jr, 5 October 1809, Davy, *Letters*, **2**, 206.

87. Payments of £117 17s 1d to Newman and £66 3s 10d to Wedgwood were authorised on 3 May 1810, *The Proceedings of the Dublin Society*, **46** (1810), p. 113. The same day the Society decided to invite Davy to lecture (p. 111).

88. James Dinwiddie notes of Davy's lecture, 6 May 1809, Dalhousie University MS Dinwiddie E6 (unpaginated). In his opening lecture (29 April 1809) Davy had said that in his second lecture he would use as much of the new battery as could be accommodated in the lecture theatre, Davy's notes, RI MS HD/3/A/1, p. 37.

89. Humphry Davy, 'The Bakerian Lecture for 1809. On some new Electrochemical Researches, on various Objects, particularly the metallic Bodies, from the Alkalies, and Earths, and on Some Combinations of Hydrogene', *Philosophical Transactions*, **100** (1810), pp. 16-74, p. 74. No component of this battery seems to have survived, possibly because unlike the earlier batteries, some of which remain in the Royal Institution's collections, no major scientific discovery was made with it.

90. Humphry Davy, *Elements of Chemical Philosophy* (London: J. Johnson, 1812), p. 152.

91. This survived until 1827 when a glass furnace was installed in that space. RI MM, 14 May 1827, **7**, p. 146; for the location and dimensions see Faraday, *Diary*, **7**, pp. 293-4. See also Michael Faraday to Robert Brown, 3 March 1846, Faraday, *Correspondence*, **3**, 1833.

92. Humphry Davy, 'Some Experiments and Observations on the Substances produced in different chemical Processes on Fluor Spar', *Philosophical Transactions*, **103** (1813), pp. 263-79, pp. 272, 278 and 'An Account of some new Experiments on the fluoric Compounds; with some Observations on other Objects of Chemical Inquiry', *Philosophical Transactions*, **104** (1814), pp. 62-73. This failure was not that surprising since owing to its very strong reactivity, fluorine was not isolated until 1886.

93. Davy's lecture notes, RI MS HD/2/D/1, p.14.

94. Davy, *Elements of Chemical Philosophy*, p. 54.

95. RI MM, 11 May 1812, **5**, p. 299.

96. Humphry Davy to John Davy, June 1812, Davy, *Letters*, **2**, 327.

97. James, *Michael Faraday*, pp. 35-7.

98. Humphry Davy, 'Some Experiments and Observations on a new Substance which becomes a violet coloured Gas by Heat', *Philosophical Transactions*, **104** (1814), pp. 74-93; 'Some Experiments on the Combustion of the Diamond and other carbonaceous Substances,' *Philosophical Transactions*, **104** (1814), pp. 557-70.

99. Frank A.J.L. James, 'How Big is a Hole?: The Problems of the Practical Application of Science in the Invention of the Miners' Safety Lamp by Humphry Davy and George Stephenson in Late Regency England', *Transactions of the Newcomen Society*, **75** (2005), pp. 175-227; Sharon Ruston, 'Humphry Davy in 1816: Letters and the Lamp', *Wordsworth Circle*, **48** (2017), pp. 6-16; Geoffrey Cantor, 'Humphry Davy: A Study in Narcissism?', *Notes and Records of the Royal Society of London*, **72** (2018), pp. 217-37.

100. Though see Robert E. Evans, 'Newman's Miners Safety Lamp', *Bulletin of the Scientific Instrument Society*, No. 51 (1996), p. 35.

101. George Stephenson to the Editor of *The Newcastle Chronicle*, in *A Collection of all the Letters which have appeared in the Newcastle Papers, with other documents, relating to the Safety Lamps* (London: Baldwin, Cradock and Joy, 1817), pp. 36-8; this letter was originally published in *The Newcastle Chronicle*, 8 February 1817.

102. Humphry Davy to John Buddle, 23 December 1816, Davy, *Letters*, **2**, 563.

103. Humphry Davy to Michael Faraday, 1 October 1815, Faraday, *Correspondence*, **1**, 60; Davy, *Letters*, **2**, 471.

104. Humphry Davy to John Buddle, 31 December 1816, Davy, *Letters*, **2**, 566. Unfortunately, Newman's business records have not been found. See also Humphry Davy to John Buddle, 10 January 1817, Davy, *Letters*, **3**, 568 for Davy's further use of Newman's work in the dispute.

105. Humphry Davy, 'On the magnetic phenomena produced by Electricity', *Philosophical Transactions*, **111** (1821), pp. 7-19, p. 18.

106. Humphry Davy to John Davy, 19 October 1820, Davy, *Letters*, **3**, 743.

107. Humphry Davy to William Hasledine Pepys, 20 October 1820, Davy, *Letters*, **3**, 744. Designed by Pepys, this battery comprised 2000 double plates, probably four inch square ('Proceedings of Learned Societies. Royal Society [of London]', *Philosophical Magazine*, **56** (1820), pp. 381-2, p. 382). By 1835 it too had lost much of its power. [E.W. Brayley], *An Historical Account of the London Institution*, London: not published, 1835, pp. 29-30.

108. Charles Babbage diary entry for 2 February 1821, Waseda University, Babbage papers, pp. 23-4. (I am grateful to Doron Swade for providing me with a copy of this diary).

109. Faraday, *Diary*, **1**, pp. 45-6.

110. Humphry Davy, 'Farther researches on the magnetic phænomena produced by electricity; with some new experiments on the properties of electrified bodies in their relations to conducting powers and temperature', *Philosophical Transactions*, **111** (1821), pp. 425-39, p. 427.

111. RI MM, 21 May 1821, **6**, p. 328.

112. Noted in RI MS F/8/12, p.393a.

113. M[ichael Faraday], 'Historical Sketch of Electro-magnetism', *The Annals of Philosophy*, **18** (1821), pp. 195-200, 274-90.

114. David Gooding, *Experiment and the Making of Meaning: Human Agency in Scientific Observation and Experiment* (Dordrecht: Kluwer, 1990).

115. Faraday, *Diary*, **1**, pp. 49-52.

116. Interestingly Pepys would soon build a large version of Hare's calorimeter (50 x 2 feet) for the London Institution. William Hasledine Pepys, 'An account of an apparatus on a peculiar construction for performing electro-magnetic experiments', *Philosophical Transactions*, **113** (1823), pp. 187-8.

117. Michael Faraday, 'On some new Electro-Magnetical Motions, and on the Theory of Magnetism', *Quarterly Journal of Science*, **12** (1821), pp. 74-96.

118. M.F., 'New Electro-Magnetic Apparatus', *Quarterly Journal of Science*, **12** (1821), pp. 186-7.

119. On this rather sad story see James, *Michael Faraday*, pp. 39-40.

120. See note 91.

121. James, *Michael Faraday*, pp. 41-5.

122. David Gooding, 'Experiment and concept formation in electromagnetic science and technology in England in the 1820s', *History and Technology*, **2**, (1985), pp. 151-176, esp. p. 156. See also Albert E. Moyer, *Joseph Henry: The Rise of an American Scientists* (Washington: Smithsonian Institution Press, 1997), pp. 78-93.

123. Faraday, *Diary*, **1**, pp. 367 and 376.

124. B.C. Blake-Coleman and R. Yorke, 'Faraday and electrical conductors: An examination of the copper wire used by Michael Faraday between 1821 and 1831', *Institution of Electrical Engineers Proceedings*, **128A** (1981), pp. 463-71. Allan Mills, 'The Early History of Insulated Copper Wire', *Annals of Science*, **61** (2004), pp. 453-67.

125. Faraday, *Diary*, **1**, p. 428. Faraday, who wrote his notes retrospectively, seems to have inadvertently mis-dated these entries in his laboratory notebook as February rather than May.

126. Faraday's annotation to William Scoresby to John Barlow, 13 May 1843, Faraday, *Correspondence*, **3**, 1493.

127. Science Museum object 1949-293 Pt1. Michael Faraday to Francis Watkins, 25 November 1833, Faraday, *Correspondence*, **2**, 692, noted the borrowing.

128. Michael Faraday to James David Forbes, 19 May 1832, Faraday, *Correspondence*, **2**, 581. 'Royal Institution', *The Literary Gazette*, 10 May 1832, p. 313 which also noted the loan from Daniell.

129. David Gooding, ''In nature's school': Faraday as an experimentalist' in David Gooding and Frank A.J.L. James, eds, *Faraday Rediscovered: Essays on the Life and Work of Michael Faraday, 1791-1867* (London: Macmillan, 1985), pp. 105-35, pp. 126-31.

130. James, *Michael Faraday*, pp. 78-82.

131. James, *Michael Faraday*, p. 86.

132. James, *Michael Faraday*, pp. 99-100.

133. John Tyndall to Lord Rayleigh, 16 December 1887, Robert John Strutt, *John William Strutt Third Baron Rayleigh* (London: Edward Arnold, 1924), p. 232.

134. For example, Henry Bence Jones to John Tyndall, 19 February 1854, Ian Hesketh and Efram Sera-Shriar, eds, *The Correspondence of John Tyndall*, vol 4 (Pittsburgh: University of Pittsburgh Press, 2018), letter 717.

135. Jules Duboscq to John Tyndall, 22 August 1855 and 19 December 1855, William H. Brock and Geoffrey Cantor, eds, *The Correspondence of John Tyndall*, vol 5 (Pittsburgh: University of Pittsburgh Press, 2018), letters 1131 and 1167.

136. Donovan Chilton and Noel G. Coley, 'The Laboratories of the Royal Institution in the Nineteenth Century', *Ambix*, **27** (1980), **27**, pp. 173-203, p. 192.

137. Lord Rayleigh to Lord Kelvin, 16 February 1888, Strutt, *John William Strutt*, p.231.

138. Jeff Hughes, 'Plasticine and Valves: Industry, Instrumentation and the Emergence of Nuclear Physics', in Jean-Paul Gaudillière and Ilana Löwy, eds, *The Invisible Industrialist: Manufactures and the production of Scientific Knowledge* (Basingstoke: Macmillan, 1998) , pp. 58-101

Author's address:
Department of Science and Technology Studies
University College London
Gower Street, London, WC1E 6BT
email: frank.james@ucl.ac.uk