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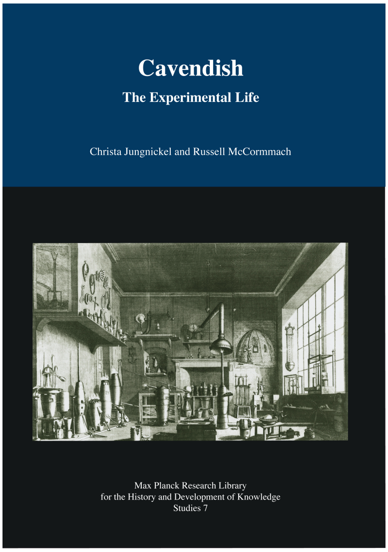
Christa Jungnickel and Russell McCormmach:

Education of Henry Cavendish



In: Christa Jungnickel and Russell McCormmach: *Cavendish : The Experimental Life (Second revised edition 2016)*
Online version at http://edition-open-access.de/studies/7/

ISBN 978-3-945561-06-5
First published 2016 by Edition Open Access, Max Planck Institute for the History of Science under

Printed and distributed by:
PRO BUSINESS digital printing Deutschland GmbH, Berlin
http://www.book-on-demand.de/shop/14971

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de

Chapter 6
Education of Henry Cavendish

A few weeks after Henry Cavendish's death, a neighbor on Bedford Square, the physician John Walker, wrote to the botanist James Edward Smith that Cavendish had been "educated and trained by his father from very early youth to scientific pursuits."[1] Of Cavendish's private education and training in science by his father we know only the outcome, but of his formal education we can say something about goals and methods.

Hackney Academy

It was from tutors, no doubt, that Henry Cavendish received his early general education. We know that the tutor to one of his first cousins was paid one hundred pounds a year,[2] and we assume that a comparable investment was made in Henry's education. With respect to his further education, his father had a choice of a "public" and a private school. Since he himself had gone to a public school, he might be expected to have sent his son to one, especially since that was increasingly the practice among the aristocracy, who regarded public schools as the proper training ground for "public life." Most of the English peerage was educated at one of two public schools, either Eton, which is where Lord Charles had gone, or Westminster, which acquired a reputation as a "nursery of statesmen." Perhaps his sons, Henry and Frederick, did not look to him like future statesmen, or perhaps he did not have good memories of his own schooling, though we note that on at least one occasion, he returned to Eton to attend the public exercises. Or, more likely, he belonged to a trend in eighteenth-century England of fathers taking greater interest in their children, one indication of which was their selection of private schools, whose masters served as surrogate fathers. Whatever his reasoning, he sent his sons to a private school.[3]

There were a good many private schools to choose from, most of them conveniently located in the suburbs of London.[4] The school selected by Charles Cavendish was one of the so-called "academies," Hackney Academy, which emphasized modern subjects (Fig. 6.1). It was the largest of the academies, with an enrollment of about one hundred. Founded

[1] John Walker to James Edward Smith, 16 Mar. 1810, ed. Smith (1832, 170–171). We assume that this John Walker was the physician who published on geography, natural history, and physiology, and was known for his promotion of vaccination. "Walker, John (1759–1830)," *DNB* 20:533.

[2] Henry Cavendish's aunt Rachel Cavendish married Sir William Morgan of Tredgar. They had two sons, William and Edward, born a few years before Henry Cavendish, and one of these "Master Morgans" had a tutor who received one hundred pounds per annum. This is according to Charles Cavendish in an account for his widowed sister, undated [1740], Devon. Coll., 167.1.

[3] Of the peers about the same age as Charles Cavendish, 46 attended Eton and 31 Westminster; of those about the age of Henry Cavendish, 53 attended Eton and 78 Westminster. From John Cannon (1984, 40, 43–44). H.C. Maxwell Lyte (1911, 287). Randolph Trumbach (1978, 292).

[4] Trumbach (1978, 265).

around 1685, it was also the oldest, and the most fashionable, academy in eighteenth-century England.[5]

Located two miles northeast of London, the village of Hackney was best known as a place where rich Londoners had their country seats. Between London and Hackney the traffic was so heavy that “hackney” became the general word for coaches of the type used there. With its magnificent playing fields and clean air, Hackney Academy enjoyed a reputation for healthy living, and like other private schools it was thought to answer the standard complaints about the public schools, their rampant sexuality.[6] The school to which Charles Cavendish sent his sons was seen as respectable, up-to-date, healthy, and safe.

Figure 6.1: Hackney. William Thornton (1784, facing 488).

There was another consideration, too; Hackney attracted students of a certain kind, not day students from the lower middle class or the crafts, as some academies did, but strictly boarding students, who came from the upper middle and upper classes, in particular, from wealthy Whig families. Ten years before Charles Cavendish entered Henry at Hackney, the hardheaded Lord Hardwicke had sent his son Philip Yorke there to get a useful education. Other Whig peers who sent their sons to Hackney included the duke of Grafton, the earl of Essex, the earl of Grey, and the duke of Devonshire, who sent his son John there at the same time that his brother Charles sent Henry. Evidently the first Cavendishes to attend Hackney, John and Henry were soon joined by Henry’s brother, Frederick. They in turn were followed

[5]Nicolas Hans (1951, 63–66, 70).
[6]William Thornton (1784, 481). Daniel Lysons (1795, 450–451). Trumbach (1978, 266).

by the sons of the next, the fourth, duke of Devonshire, Richard and George Augustus Henry, as Hackney settled in as a Cavendish tradition.[7]

Hackney Academy was run by the Newcomes, a family of teachers, Anglican clergy, and Cambridge graduates with an interest in science. Henry Newcome, the first of the Hackney Newcomes, a good classical scholar and strict disciplinarian, was still headmaster when Henry Cavendish was there. He and his son Peter, who later became headmaster, were friends of the duke of Kent's family, dining with them at St. James Square.[8] They were friends of the Cavendishes too. Just as his son Henry arrived at Hackney Academy Charles Cavendish recommended Peter Newcome for membership in the Royal Society, as one skilled in mathematics and polite literature. Cosigners of the certificate included the Hackney graduate Yorke, Thomas Birch, and Daniel Wray, suggesting that Peter Newcome was one of Cavendish's circle.[9] While Henry Cavendish was at Hackney, Newcome joined Charles Cavendish and other fellows of the Royal Society in Watson's experiment on the conduction of electricity across the River Thames, and a year after Henry left the school Newcome published his observations on an earthquake felt at Hackney in the *Philosophical Transactions*.[10] The contact between the Cavendishes and the Newcomes was ongoing: years after he had finished at Hackney, and shortly before he was elected fellow, Henry Cavendish was invited by Peter Newcome to a meeting of the Royal Society as his guest.[11] This Newcome was well regarded in the Royal Society, serving on its Council in 1763 and 1764.[12] There were connections between the scientific interests of the Cavendishes and Hackney.

Normally students were admitted to Hackney at age seven, but Henry Cavendish did not enter until he was eleven. He began with the advanced course, instructed in subjects that would apply to his later studies and work: mathematics, natural sciences, French, and Latin. At the usual leaving age, Henry, like the other Cavendishes and like most of the other students at Hackney, proceeded directly to the university, which in his case was Cambridge.

Peterhouse, Cambridge

From the fourteenth century to the time Henry Cavendish entered Cambridge, twenty Cavendishes had graduated from the University.[13] The first duke of Devonshire to get a university education was Charles Cavendish's brother William, who went to Oxford (briefly) not to Cambridge, but he sent his two sons to Cambridge. Charles's oldest son, Henry, having just turned eighteen, entered St. Peter's College, or Peterhouse, Cambridge, on 24 November 1749.[14] He was the first Cavendish to go to that college, where he remained in regular attendance for three years and three months (Fig. 6.2).

[7]Hans (1951, 72, 243–244).
[8]Thomas Birch Diary, BL Add Mss 4478C. Frequent entries beginning in 1740.
[9]25 Nov. 1742, Certificates, Royal Society 1:260. The other signers were James Jurin, Benjamin Hoadley, John Ward, and Thomas Walker. Newcome was elected on 24 Feb. 1743.
[10]William Watson (1748a, 62). Newcome reported the earthquake felt by persons at his house in Hackney. Newcome (1750); read 29 Mar. 1750.
[11]10 Jan. 1760, JB, Royal Society 23:711.
[12]Minutes of Council, Royal Society 5.
[13]John and J.A. Venn (1922, vol. 1).
[14]George Wilson (1851, 17).

The chancellor of the University was the duke of Newcastle, a minister of state, and a distant relative of our Cavendishes. When the master of Peterhouse died, Newcastle lobbied hard for Edmund Keene, a Whig and fellow of Peterhouse. A close overseer of his sons' education, Charles Cavendish was on familiar terms with Keene as he was with the Newcomes at Hackney. During the time Henry was a student at Peterhouse, Keene dined with Cavendish's friends, Birch, Heberden, Wray, Mann, and Squire, and on at least one occasion with Birch and Cavendish.[15] Although Peterhouse was not identified with the nobility, for a time in the middle of the eighteenth century it was fashionable with the upper classes.[16] Henry Cavendish, his brother Frederick, and his cousin John all went to Peterhouse.

Figure 6.2: Peterhouse, Cambridge. From David Logan, *Cantabrigia Illustrata* (Cambridge, 1688).

The attendance at the University when Henry Cavendish entered was small and declining, but the proportion of students who were, like Cavendish, aristocratic was rising.[17] Classed roughly by their station in life, in ascending order students entering Cambridge were sizars, petitioners, fellow commoners, and nobleman. Sizars, who were the poorest and were charged the lowest fees, and who were essentially a college charity, were sons of poor clergy, small farmers, petty tradesmen, and artisans. The majority of students were pensioners, who were better off, commonly sons of more prosperous clergy and professional men, but without distinction of birth. Nobleman paid the highest fees, and since they did not have substantial privileges beyond those of fellow commoners, they often settled to be fellow commoners.[18] Henry Cavendish entered Cambridge as a fellow commoner.

Fellow commoners were occasionally older men who simply liked university life, but most of them were young men of independent means, often sons of country gentleman and commercial magnates if not of nobility. Accounting for just over ten percent of the student population in the eighteenth century, they were a conspicuous minority, inclined to fine dress,

[15] 6 June 1747, 17 May 1751, 18 and 22 February 1752, Thomas Birch Diary, BL Add Mss 4478C.

[16] D.A. Winstanley (1935, 193). Winstanley says that at midcentury, Peterhouse was "much patronized" by the aristocracy, but it should be noted that of peers born in 1711–40, Henry Cavendish's period, only 3 went to Peterhouse. By contrast, 9 went to Clare College, 8 to King's College, 7 to Trinity College, and 6 to St. John's College. In attendance at Cambridge in 1740–59, while Henry Cavendish was there, out of 27 peers' sons, again only 3 were at Peterhouse. Cannon (1984, 48–51).

[17] Cannon (1984, 45).

[18] Thomas Alfred Walker (1935, 76–78). Edmund Carter (1753, 5, 29).

sometimes accompanied by their own servants, and in any case able to afford to pay poor students to wait on them. They were admitted to the fellows' table, common room, and cellar, where they could smoke clay pipes and drink Spanish and French wine, in which respects they were equivalent to fellows of the college. They were usually excused from performing the college exercises required of humbler undergraduates and of attending lectures by the college tutors.[19] From what we know of Cavendish's later habits, the extravagances of some of the other fellow commoners did not happen to be his, but his privileges were the same as theirs, including freedom to spend most of his time as he wished. The advantages of rank were significant and obvious in the University, reinforcing the generally accepted notion of hierarchy in the society of Cavendish's time.[20]

In the absence of accounts of Cavendish at Cambridge, we fall back on the usual life of Peterhouse undergraduates to give some idea of his. Their service was spare, they dined off pewter, and their diet was monotonous. If the fare remained as it had been in the previous century, they ate mutton five times a week and drank ale and beer, which was brewed at a profit by the college butler. Service was adapted to rank: for fellows and fellow commoners, the butler set four tablecloths, and for the rest, pensioners and sizers, he set two.[21] Prayers were given at six in the morning and again at six at night, supper was at eight, and the college closed at ten. During the day, students could attend college lectures, meet with their tutors, study in their rooms, or seek diversion, for which they had a range of options that included sports, games, and music. College rooms could be chilly, dark, and dreary for everyone. In the year Cavendish arrived, it was ruled that a fire was to be made in the combination room from noon to two o'clock. When students ventured outside of the college, they found themselves in a very small town, Cambridge, with shops that made money off them by selling wine, candles, menswear, books on law and medicine, and pens, pencils, and paper. Coffee houses enjoyed a brisk business, different ones frequented by fellows and by students, where for the price of a coffee they could smoke, read journals, and visit for hours. Fellow commoners usually had extra money, which helped or hindered their progress depending on how they used it.[22]

When Cavendish arrived, Peterhouse had between thirty and forty students, not all of them in residence. During the years he was there, 1749 through 1752, over fifty students were admitted; thirteen of these were fellow commoners, most of whom later went into politics; the rest were sizars and pensioners, most of whom became clerics.[23] No one but Cavendish became notable for any scientific achievement.

The fraction of eminent British scientists in Cavendish's time who had a Cambridge or Oxford education was small and steadily falling.[24] Still there were several young men of future scientific accomplishment in Cambridge while he was there. One year younger than he, Nevil Maskelyne of Trinity College would go on to a distinguished career in astronomy,

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[19] Winstanley (1935, 198). Walker (1935, 78). Cannon (1984, 58).
[20] Cannon (1984, 54–55).
[21] Walker (1935, 79–80).
[22] Ibid., 79–85.
[23] The numbers given here are based on Thomas Alfred Walker (1912). They are less precise but more accurate than those given in our *Cavendish* (1996).
[24] Hans estimates that the proportion of Oxford and Cambridge graduates among eminent British men of science dropped from sixty-seven percent in the seventeenth century to twenty percent at the end of the eighteenth century. His figures are based on rather arbitrary definitions, but the large percentage of scientific practitioners in Henry Cavendish's time who were not Oxford or Cambridge graduates is significant. Hans (1951, 34).

first as assistant to James Bradley and then in Bradley's post of astronomer royal; he was to become one of Cavendish's most valued colleagues. Of about the same age as Cavendish were the promising but short-lived chemist John Hadley, the very capable astronomer Francis Wollaston, and the "excellent mathematician" Francis Maseres.[25] Hadley, who was a guest in the Cavendish home, recommended Henry Cavendish for membership in the Royal Society, and Cavendish was first to sign the certificates recommending both Wollaston and Maseres for membership.[26] Of eventual importance to Cavendish's work was John Michell. Having graduated the year before Cavendish entered Cambridge, Michell was a fellow of Queens' College, where he gave lectures and did experimental work on his own.

Very few eminent British men of science came from the upper class. Nicholas Hans, a historian of eighteenth-century education, groups Cavendish with Robert Boyle and Edward Delaval as the three eminent scientists out of 680 British scientists who were "sons of peers." Cavendish was not, of course, the son of peer, but the point is made: in this company, aristocrats were rare.[27] Boyle the seventeenth-century chemist was a distant relative of the Cavendishes'. Delaval, a younger brother of a peer from an ancient Northumberland family, was another chemist. Because of Delaval's scientific interest, his station in society, his residence (his college, Pembroke, was across the street from Peterhouse), and his voice (which was resounding, a family trait, earning him the local name of "Delaval the loud"), Cavendish could not have failed to know him or about him; he was to receive his Copley Medal in the same year as Cavendish.[28]

The poet Thomas Gray, who resided at Peterhouse not long before Cavendish, described Cambridge fellows as sleepy and drunken and fellow commoners as their imitators, and in his letters from Cambridge he constantly referred to the stupor of the place. There was a measure of truth in his observations, but fellows also had an excuse, since they had little to occupy them officially. At an earlier time, they had given lectures, but by the middle of the eighteenth century their teaching duties had largely fallen away, while their fellowships were becoming sinecures. College lecturers still performed when Cavendish was there, but the practice was on the way out. The motivation to do any work had to come from within, and while there were fellows who had a love of learning and teaching, even a few who were great scholars, most of them contributed little or nothing of significance.[29] The exceptions were fellows who were also tutors, who did serious, regular teaching. Peterhouse had two official tutors, both formerly hard-working sizars at the college who became clerics, neither leaving a mark as a scholar.[30] Assigned to the same pair of tutors as Henry, John Cavendish brought his own private tutor, and Henry might have brought his own too. The University had a small number of professors, whose teaching was increasingly marginal, as the tutors of the colleges took over their subjects.

[25] On Maseres: William Ludlam (1785, 7).
[26] Certificates, Royal Society 3:65 (Francis Wollaston's announced candidacy, 3 Jan. 1769) and 3:104 (Francis Maseres's announced candidacy, 31 Jan. 1771).
[27] Hans (1951, 34).
[28] The name was given to Delaval by his friend Thomas Gray. Robert Ketton-Cremer (1955, 142–143). Two years older than Cavendish, Delaval became a fellow of Pembroke. "Delaval, Edward Hussey," *DNB*, 1st ed. 5:766–767.
[29] Winstanley (1935, 256–261). Thomas Gray to Horace Walpole, 31 Oct. 1734, in Walpole (1937–1983, vol. 13, pt. 1, 58–59).
[30] Charles Stuart and Chapel Cox.

If fellow commoners wanted to leave with a degree they had to fulfill the requirements, though in form only.[31] Because a degree was unlikely to make a difference in their lives, fellow commoners usually left without one, as Henry Cavendish did on 23 February 1753. The suggestion has been made that he objected to the religious tests, which were stringent,[32] but if that was his reason for not graduating, he left no record of it, then or later. The most likely reason he left without the degree was that he did not consider taking one but simply followed tradition, as did most of the thirteen fellow commoners at Peterhouse during Cavendish's stay, only five of whom took degrees, three of which were Masters of Arts only.[33]

The examination that Cavendish did not take was then on its way to becoming the renowned Cambridge mathematical tripos. Examination results were published beginning in the late 1740s, and beginning in the year Cavendish would have taken it, 1753, the list of examinees was divided into wranglers (top performers) and senior and junior optimes, reflecting the lively competition for a high rank. Because the examination was almost completely mathematical, no doubt Cavendish would have done well: John Green, bishop of Lincoln, writing in 1750 while Cavendish was a student, observed that at Cambridge, "Mathematics and natural philosophy are so generally and exactly understood, that more than twenty in every year of the Candidates for a Bachelor of Arts Degree, are able to demonstrate the principal Propositions in [Newton's] *Principia*; and most other Books of the first Character on those subjects."[34] This would surely have described Cavendish.

With the emphasis on mathematics at Cambridge, there were naturally some very able mathematics teachers, such as John Lawson of Sidney Sussex College, who was mathematical lecturer and then tutor when Cavendish was a student.[35] If Cavendish had taken a degree, his competition in the examinations of 1753 would have included William Disney and Thomas Postlethwaite, both of whom became writers on religion and stayed on in the University. Disney, who graduated first wrangler and later became regius professor of Hebrew, published against Gibbon's history of the Roman Empire and for the superiority of religious duties over worldly considerations.[36] Postlethwaite, third wrangler and later master of Trinity College, published a discourse on Isaiah, while retaining his reputation as one of the best mathematicians in the University.[37] In the previous year, the second wrangler was Henry Boult Cay, who for a time was a fellow of Clare College before becoming a barrister in the Middle Temple; Cavendish probably knew this wrangler as a student, for later he brought him as his guest to the Royal Society Club.[38] Mathematical distinction at Cambridge was not an indicator of future scientific interest; none of the three wranglers, Disney, Postlethwaite, or Cay, became a member of the Royal Society. Under Dr. Law, Keene's successor, Peterhouse produced its first senior wrangler, Robert Thorp, who became coeditor with John Jebb and George Wollaston of a selection from Newton's *Principia*, which was

[31] They had "to keep the statutory two acts and opponencies and to sit for the Senate House Examination," though in reality they were exempted from the examination and allowed to "huddle" the acts by parroting a few set sentences in Latin. Winstanley (1935, 199).

[32] Wilson (1851, 17, 181). There was no religious test at matriculation, but to graduate with a bachelor's degree, the candidates had to "sign the 36th Canon, the Articles, and the Liturgy of the Church of England."

[33] Walker (1912, 292–306).

[34] John Green, *Academic*, 1750, 23, quoted in Christopher Wordsworth (1968, 73).

[35] "Lawson, John," *DNB*, 1st ed. 11:736–737.

[36] John Nichols, ed. (1817–1858, 6:737). Gibbons attributed the decline of Rome to Christianity.

[37] "Postlethwaite, Thomas," *DNB*, 1st ed. 42:204–205.

[38] 5 Mar. 1767 and 30 June 1768, Minute Book of the Royal Society Club, Royal Society 5. Henry Boult Cay is under his father John Cay's entry in the *Dictionary of National Biography*.

used as a standard text in the University, *Excerpta quaedam e Newtoni Principiis ….*[39] In the next century a number of physicists of the first rank, William Thomson, Peter Guthrie Tait, and James Clerk Maxwell, studied at Peterhouse, known for its excellent coaches William Hopkins and E.J. Routh. There was no hint of this future in the Peterhouse Cavendish knew.

Whereas we think that Charles Cavendish learned mathematics by private lessons from mathematicians who were Newton's associates, Henry Cavendish learned his at Cambridge, if not also elsewhere. At the very least, we can say that whether or not he had a mathematically adept tutor or attended lectures on mathematics, for over three years he was exposed to the mathematical tradition of Cambridge and to the books on mathematics and natural philosophy recommended in a student guide at Cambridge.[40]

In the introduction, we discussed Charles and Henry Cavendish in relation to two revolutions, one political and one scientific. The education that Henry received at the University of Cambridge was related to both. One consequence of the political Revolution of 1688–89 was a change in the Church of England, with Cambridge becoming a stronghold of low-Church latitudinarians and Whigs, who were sympathetic to the Revolution and to Newtonian natural philosophy for the support it gave to the argument from design for the existence of a Creator.[41] Newton's main influence in Cambridge was exerted through his physical theories, the route to which was his mathematics, then the dominant study in the University.[42] Cavendish was indoctrinated in a mathematical and scientific orthodoxy originating in the Scientific Revolution in an institution that favored the poliitical settlement of the Glorious Revolution of 1688–89; for some three odd years he studied Newtonian philosophy in a Whig environment.

Cavendish was not the only major English experimentalist of the second half of the eighteenth century who was exposed to Newtonian philosophy at Cambridge—in addition to Delaval there was the chemist William Hyde Wollaston at the end of the century, for example—but there were very few of them. From his earliest researches, Cavendish demonstrated his mastery of mathematics, in which respect his work differed markedly from that of most of his fellow experimentalists. Although there were additional reasons for the direction he took in science, it bore the imprint of his Cambridge education.

We have only one record of Cavendish's thinking while he was at the University. Frederick, prince of Wales, after holding court in opposition to his father, George II, for nearly fifteen years, died while still waiting for his chance. In the meantime, he had wanted to become chancellor of Cambridge University in 1748, but his father opposed him, and the University took the safe course. As if to compensate Frederick for what it had denied him in life, the University honored his memory by publishing a deluxe edition of academic exercises in 1751 (Oxford did the same). Written in Latin, the laments met the standards of the day, which were not particularly high, inspiring Horace Walpole to make a play on words: "We have been overwhelmed with lamentable Cambridge and Oxford dirges on the Prince's death."[43] Henry Cavendish contributed a poem to the volume, "Lament on the Death of Most Eminent Frederick, Prince of Wales." The premature death of a prince was a fitting occasion to reflect on the fragility of life, and Cavendish dutifully wrote that tears are fruit-

[39] Walker (1935, 95; 1912, 73, 119).
[40] Daniel Waterland (1740), reported in Wordsworth (1968, 78–81, 248–249, 330–337).
[41] John Gascoigne (1989, 145, 147).
[42] W.W. Rouse Ball (1889, 68, 74–76).
[43] Horace Walpole to Horace Mann, 18 June 1751, in Walpole (1937–1983, vol. 20, pt. 4, 260–261).

less, the thistle and the lily alike flourish, and death plays no favorites. But the middle stanza is not conventional. Here we hear the voice of the future scientific investigator: while nature may mock us, it "does lay bare hidden causes, and the wandering paths of the stars."[44] Such were the circumstances of Cavendish's first publication and probably his last poem, for his preferred way of speaking of the hidden causes of nature would be in the unadorned language of science.

Learning Science

As the University was dominated by its colleges, so its teaching was dominated by the many tutors in the colleges. The much smaller number of university professors tend to be discounted in historical accounts of Cambridge in the eighteenth century. The criticism is often deserved, but their teaching was increasingly irrelevant to most students. Deprived of the usual incentive to lecture, some of them nevertheless took this form of teaching seriously, and almost all of the scientific professors brought out textbooks. From the standpoint of a student who would become a scientific researcher, the professors hold our interest. They alone among the teachers at Cambridge represented the specialized sciences.

William Heberden recalled that in his student days at Cambridge, around 1730, some professors made a difference. The professor of mathematics Nicholas Saunderson lectured on Newton's work when the college lecturers largely ignored the subject, and the text on optics by the professor of astronomy and experimental philosophy Robert Smith, and the text on natural philosophy by Thomas Rutherforth, future professor of divinity, drew attention to their subjects and spread the teaching of them in the university.[45] Whether or not Cavendish heard Cambridge professors lecture, he most certainly knew their texts. In this section, we look at texts written by professors for use in Cambridge, in which way we learn, as interested students in Cavendish's day learned, the approved ways of studying nature.

The education Cavendish received in Cambridge rested on major achievements of the Scientific Revolution: mathematics replaced logic in the curriculum, and natural philosophy was regarded as the most important branch of philosophy. The power of mathematics to describe Cavendish's "wandering paths of the stars" was impressively demonstrated by Newton in his *Principia*. First published in 1687, the book appeared in three editions in Newton's lifetime, the last in 1726.[46] The complementary power of experiments was demonstrated by Newton in his *Opticks*, which too appeared in three editions in his lifetime, the first in 1704 and the last in 1717/18. The treatise concluded with a series of questions and speculations, which were expanded in each edition, their object being to stimulate others to carry forward the investigation of nature, and many readers regarded them as the most important part.[47] Cavendish's library contained all editions of the *Principia* and *Opticks*.

[44] Henry Cavendish (1751).
[45] Heberden quoted in Wordsworth (1968, 66–67). Gascoigne (1989, 175).
[46] The editors of the three editions of Newton's *Principia*, were Halley in 1687, Roger Cotes in 1713, and Henry Pemberton in 1726. In 1729 an English translation was brought out by Andrew Motte, a later edition of which is *Sir Isaac Newton's Mathematical Principles of Natural Philosophy and His System of the World*, Newton (1962). I.B. Cohen (1971, vii, 7).
[47] The editions in his lifetime were: in 1704 in English; in 1706 in Latin; and in 1717/18 in English again. Isaac Newton (1952). I.B. Cohen (1974, 59).

Figure 6.3: Sir Isaac Newton. Portrait by Godfrey Kneller, 1702. Wikimedia Commons.

Newton's principal physical writings were widely accessible, but his published mathematical writings at the time of his death consisted of a few scattered tracts, which by no means revealed the extent of his researches. In the *Principia*, he introduced the mathematical ideas his readers needed to understand what followed, and in the first edition of *Opticks* he appended two Latin treatises on curves and their quadrature, which later came out in English translations. It was left to his followers to publish other mathematical writings, the existence of which was known since he lent out his manuscripts.

In the *Principia* Newton laid down the laws of matter and motion and the law of universal gravitation, from which he deduced the motions of the planets, comets, moon, and tides. The sweeping deductive power of the *Principia* was the basis of its appeal:[48] the laws of motion were presumed to contain all of the relations between matter, motion, and force in the sense that all of the theorems of geometry are contained in the axioms of that subject. Other forces besides gravitation were known to exist, but they had not yet been experimentally determined and mathematically described. The "whole burden of philosophy," Newton wrote in the *Principia*, was to observe the motions of bodies and from them to deduce the forces acting and then to deduce from these forces the other phenomena of nature.[49] Cavendish's electrical researches exemplified this objective.

Like the *Principia*, *Opticks* begins with definitions and axioms or laws, but a glance at its pages reveals that it contains an orderly progression of experiments. It argues for a new understanding of light: the white light of the Sun is compounded of heterogeneous colored

[48]C. Truesdell (1960, 6).
[49]Newton (1962, 1:xvii–xviii).

rays, which are original and immutable qualities of light, quantitatively distinguishable by their different degrees of bending, or refrangibility, upon passing through transparent substances. For the explanation of the bending and reflecting of light by bodies, Newton looked to the subject of his *Principia*, forces and motions. Between the rays of light and bodies, a force acts, and although for some results it is unnecessary to know "what kind of Force," the exact description of the force was an important question.[50] The problem of light was more difficult than the problem of gravitating bodies; the bodies of the solar system move in ellipses and parabolas, but light passing near bodies has a "motion like that of an Eel."[51] Newton did not complete a "Theory of Light," but only began one. The sixteen "queries" in the first edition of *Opticks* suggest how at the time he expected the enlarged science of optics to appear when completed. Cavendish accepted Newton's description there of light as particles that interact with the particles of ordinary bodies through forces.

Heat is the subject of nearly half of the first set of queries in *Opticks*. By the law of action and reaction, the third of Newton's laws of motion, the reflection, refraction, inflection, and emission of light by bodies induce an internal vibration in the bodies, which constitutes heat.[52] Cavendish accepted and developed the identification of heat with the internal vibrations of bodies, which he called "Newton's theory of heat."

In the second edition of *Opticks*, Newton added several queries that give the fullest statement of his expectation for the mechanics of the interaction of light and ordinary bodies. To the third edition, he added a final set of queries on the ether presumed to fill space. Backed by Newton's authority, the queries of the *Opticks* proved to be a source of new paths (and a few dead ends) for readers throughout much of the eighteenth century.

At whatever level Cavendish studied the *Principia* at Cambridge, in his later scientific work he revealed his command of the main subjects of that book, mechanics, mathematics, and mathematical astronomy. In addition, his manuscripts contain studies of dispersion, refraction, and lenses, which connect his work with Newton's other treatise, *Opticks*.

One of the first to lecture on Newtonian science in Cambridge was William Whiston, who wrote several texts still in use in the University when Cavendish was there. In his *Memoirs*, Whiston recalled returning to Cambridge after he had taken holy orders, to join what he called the "poor wretches" who were still studying Descartes' fictions. Having heard Newton lecture without understanding a word, it was only after reading a paper by the astronomer David Gregory that he realized that the *Principia* was the work of a "*Divine Genius*." With "immense pains" and "utmost zeal," he struggled with the book on his own. Later he published *A New Theory of the Earth*, which he submitted and dedicated to Newton, "on whose principles it depended, and who well approved of it." From Newton's explanation of comets, Whiston demonstrated the book of Genesis: the Earth, originally a Sun-bound comet, was struck by another comet, causing the Deluge and giving the Earth its elliptical path and diurnal rotation. These cosmic events expressed God's will, but the agency was Newton's universal gravitation.[53] When Newton left Cambridge for his post at the Mint in London, he arranged for Whiston to succeed him as Lucasian Professor of Mathematics in Cambridge.

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[50] Newton (1952, 82).
[51] Newton (1952, 339). Query 3.
[52] Ibid. Query 5.
[53] William Whiston (1749, 37, 43; 1737); *A New Theory of the Earth*…, 5th ed. (London, 1737). Jacques Roger (1976).

An ambitious man of wide interests and strong commitments, Whiston published his lectures in Cambridge on astronomy and on natural philosophy, the latter as the first extensive commentary on the *Principia*, and with the author's approval he published Newton's lectures on universal arithmetic, or algebra. He eventually fell out of favor with Newton (and Cambridge), but Newton had done much for him, placing him in Cambridge and showing him his favor for many years. Whiston reciprocated by helping implement Newtonian studies at Cambridge.[54]

While he was professor of mathematics, Whiston let the young scholar Nicholas Saunderson lecture to large audiences on the same material, Newton's universal arithmetic and his *Principia* and *Opticks*. Blind virtually from birth, Saunderson demonstrated, according to his publisher, how far the faculties of the imagination and memory could compensate for the want of a sense. His fellow mathematician Roger Cotes thought that his "want of sight" was an advantage as well as a disadvantage. He definitely was a source of local wonder, being able to distinguish a fifth part of a musical note, estimate the size of a room from sounds in it, tell the difference between genuine and false medals by touch, and, most important, gain proficiency in higher mathematics. Elected Whiston's successor as Lucasian Professor of Mathematics, Saunderson had good relations with persons associated with Newton: Cotes, Jones, De Moivre, Machin, John Keill, and others. His "reverence for Newton was extreme," as he made Newton's work the center of his teaching. Like Whiston, Saunderson's importance was not as an original mathematician—the historian of mathematics at Cambridge says that Whiston and Saunderson "barely escape mediocrity"—but as an industrious teacher of the new mathematics and natural philosophy in Cambridge. Saunderson published no books himself, but the year after his death in 1739 his lectures on algebra were brought out, *Elements of Algebra for Students*. His lectures on Newton's form of the calculus, *The Method of Fluxions Applied to a Select Number of Useful Problems [...] and an Explanation of the Principal Propositions of Sir Isaac Newton's Philosophy*,were published in 1756, four years after Cavendish had left Cambridge, but manuscripts of the lectures had long circulated there and are thought to give a good idea of how the material was taught in Cambridge at the time. The Advertisement in Saunderon's book says that it was "reckoned the best for students in the universities, of any yet published," and that any defects in the presentation could be overcome with the help of the student's tutor. *The Method of Fluxions* begins abruptly with a proposition about triangles, the sides of which are identified with Newtonian forces. Here and there in the book experiments are mentioned and empirical numbers are used in problems, but the subject is the mathematical parts of natural philosophy. Students learned the mathematical representation of nature and mathematical analysis at the same time, with fluxions, fluents, algebra, geometry, and mechanics forming a seemingly inseparable subject. In his teaching, Saunderson conveyed a way of thinking about nature, the lesson a Cambridge student in the middle of the eighteenth century would have come away with.[55]

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[54] Whiston published his astronomical lectures in 1707 in Latin; translated in 1715, they appeared as *Astronomical Lectures, Read in the Publick Schools of Cambridge*.... These lectures include "attraction" and Newton's theory of the moon; they are an astronomical preparation for Newton's philosophy, which Whiston promised to give next term. In 1710 he published his lectures on natural philosophy, which were translated in 1716, *Sir Isaac Newton's Mathematical Philosophy More Easily Demonstrated.* Maureen Farrell (1981, 200). Rouse Ball (1889, 83–85, 94–95). "Whiston, William," *DNB*, 1st ed. 21:10–14. D.T. Whiteside, in Newton (1967, 1:xvi).

[55] Rouse Ball (1889, 86, 88). "Saunderson or Sanderson, Nicholas," *DNB*, 1st ed. 17:821–822. Roger Cotes to William Jones, 25 Nov. 1711, and Nicholas Saunderson to William Jones, 4 Feb. 1714/13, in Rigaud (1965, 1:261;

Upon Saunderson's death, the ageing De Moivre, who looked to one observer as if he were "fit for his coffin," was passed over, and Whiston, who wanted to return, was not taken seriously. The new Lucasian Professor of Mathematics was John Colson,[56] a mathematical schoolmaster who had taken a modestly active part in the science of his day. As an original mathematician, he deserves no more than passing notice. His principal scientific claim to the Lucasian chair was his publication three years earlier of a tract that Newton had wanted to publish but for which there had been no market. Long circulated in Cambridge, Newton's manuscript was translated from its original Latin into English by Colson as *The Method of Fluxions and Infinite Series*, with a dedicatation to William Jones. The Cambridge diarist and antiquarian William Cole described Colson as a "plain honest man of great industry and assiduity," but who disappointed the university "in its expectations of a professor that was to give credit to it by his lectures."[57] He disappointed because of his teaching, not because of his research, of which there was none to speak of. Colson was Lucasian Professor when Cavendish was a student at Cambridge.

If Colson's accomplishments as a mathematician were minor, his enthusiasm for fluxions and its inventor cannot be faulted. His praise in the annotated edition of Newton's *Method of Fluxions* stands out among Newtonian panegyrics: Newton was the "greatest master in mathematical and philosophical knowledge, that ever appear'd in the world," and his doctrine of fluxions was the "noblest effort that ever was made by the human mind." Unlike Newton's other mathematical writings, which were "accidental and occasional," his *Method* was intended as a text for "novices and learners," a goal with which the teacher Colson could identify. Colson made clear the distinction between textbook and original work, between a teacher like himself and an inventor like Newton. The teacher and textbook had their modest place: with their aid, the beginner could comprehend the work of the greatest thinker of all time. Colson's edition was at once a textbook, an indoctrination in mathematical Newtonianism, and a polemic in defense of Newton.[58]

For the learner of fluxions and infinite series, there was Newton's own presentation, and there was Colson's. If Newton's was terse, Colson's was prolix; Newton's treatment of infinite series occupied twenty pages, Colson's "perpetual comment" ninety-eight.[59] Colson assumed little of his reader, patiently explaining what he regarded as the greatest difficulty

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265). Nicolas Saunderson (1756, ix–x, 79, 81), and Advertisement. "Saunderson or Sanderson, Nicholas," *DNB*, 1st ed. 17:821–822. Like Newton's lectures, Saunderson's consisted of a set of examples, as recalled by the Cambridge astronomer William Ludlam, who knew them firsthand. Ludlam had been one of Saunderson's pupils, who read sections of Newton's *Principia*. William Ludlam (1785, 6).

[56] Quotation about De Moivre's age and infirmity from William Cole's diary, quoted in "Colson, John," *DNB*, 1st ed. 4:801–802, on 801. From 1709 until he was named Lucasian Professor, John Colson taught at Sir Joseph Williamson's Mathematical School in Rochester. R.V. and P.J. Wallis (1986, 29).

[57] In 1738 Colson translated from the French a theoretical paper by Alexis Clairaut on the figure of the planets for the *Philosophical Transactions*. Before that, he published two mathematical papers of his own on algebra and another on spherical maps in the same journal. One of the papers on algebra was translated into Latin and appended to the 1732 Leiden edition of Newton's *Arithmetica Universalis*. "Colson, John," *DNB*, 1st ed. 4:801–802. Rouse Ball (1889, 100–101). Whiteside in Newton (1967, 1:xv; 8; 8:xxiii).

[58] Colson's comments in *The Method of Fluxions and Infinite Series…. By the Inventor Sir Isaac Newton….To Which Is Subjoined, a Perpetual Comment* ... (1736, ix–xii, xx, 335–336).

[59] Colson's commentary was considerably shorter than the commentary by John Stewart, professor of mathematics in the University of Aberdeen, to a translation of two mathematical tracks by Newton; the two tracks occupy 54 pages of Stewart's book, his commentary 497 pages plus introductory matter. *Sir Isaac Newton's Two Treatises: Of the Quadrature of Curves, and Analysis by Equations of an Infinite Number of Terms, Explained* ... (London, 1745).

for a beginner, the notion of a vanishing quantity, expanding freely on the text, giving copious examples, and writing not as a mathematician but as an eternally patient teacher. We cannot know if Cavendish read Colson's commentary, but if he did, he read two observations that might stimulate a beginning mathematical student. One is that Newton had not said the last word on the subject: improvements in the method of fluxions had been made since Newton, and the subject was capable of further perfection. The other observation has to do with Newton's method, that of analysis, which proceeds from the known to the unknown; analytics is the "art of invention," a method of discovery.[60]

The Newtonian school at Cambridge began soon after Newton left the University for London. Richard Bentley,[61] master of Trinity College, was not himself a man of science, but he was a good judge of men who were. Wanting to make his college a center of "Newtonian philosophy," he had a laboratory built for Newton's friend John Francis Vigani, who had lectured on chemistry at Queens' College. With Newton's and Whiston's help, he secured the new Plumian Professorship of Astronomy and Experimental Philosophy for Roger Cotes, who had shown mathematical talent while a student at Trinity. He raised a subscription for an astronomical observatory to be built over Trinity's entrance gate and for neighboring rooms to be assigned to Cotes ("Bentley's man") and to his assistant, his cousin Robert Smith. He arranged for Whiston, of Clare College, to have rooms in Trinity under Cotes's observatory.[62] Trinity set a precedent for other colleges. Bentley, more than any other, was responsible for the eventual dominance of the Newtonian school of science and mathematics at Cambridge.

Bentley bore the expense of a new edition of Newton's *Principia* in 1713 and was himself going to edit it, but sensibly assigned it to Cotes, whose preface to the edition became a cardinal document in the spread of Newtonian thought. Three years later, Cotes died suddenly. He had published only two papers, one of which Robert Smith included in a posthumous edition of Cotes's mathematical manuscripts, *Harmonia Mensurarum*,which contained in addition to writings on logarithms, fluxions, and mechanics the "earliest attempt to frame a theory of errors." Led to the theory by his interest in practical astronomy and its instruments, Cotes made mathematically rigorous the limits of errors arising from imperfections of the senses and of instruments.[63] With his help, observers could calculate which errors were negligible and which were not and take steps to minimize the latter. Cavendish showed a working knowledge of the theory of errors in his experimental work.

Cotes and Whiston gave experimental lectures in natural philosophy in the observatory at Trinity. When Whiston left Cambridge, Cotes continued the lectures by himself, and after Cotes's death, Robert Smith continued them, and he also published Cotes's lectures. Intended for a wide audience, Cotes's *Hydrostatical and Pneumatical Lectures*, Smith said, could be read by persons knowing little mathematics "with as much ease and pleasure, as in reading a piece of history." Unwilling to leave it at that, Smith added mathematical notes of

[60] Colson (1736, 1, 144, 335).
[61] Rouse Ball (1889, 149, 155).
[62] "Bentley, Richard," *DNB*, 1st ed. 2:306–314, on 312. A. Rupert Hall (1976, 26–27). James Henry Monk (1833, 202–204). Whiston (1749, 133). Ronald Gowing (1983, 8, 14). Rouse Ball (1889, 89). The Plumian Professorship was endowed by Thomas Plume, archdeacon of Rochester, in 1704; Cotes was elected to the chair two years later.
[63] Gowing (1983, 91–93).

his own.[64] A second edition of Cotes's lectures was published in Cambridge in 1747, two years before Cavendish entered the University.

Cotes's lectures dealt mainly with pneumatics but also with hydrostatics, both subjects relying on that most precise of instruments, the balance. Gravity, the force to which the balance responds, Cotes wrote, "is a property of so universal an extent" that even "air, which as I shall afterwards shew, may be weighed in the ballance." Cotes drew on Newton's *Principia* to explain the physical properties of air, its weight and elasticity, and its role as the medium of sound. He concluded the four-week course with a lecture on "factitious airs," taken from Robert Boyle's *New Experiments Physico-Mechanical*. These were airs, or gases, contained in bodies, which could be freed by various means: fire, explosion, dissolution, putrefaction, and fermentation. Cotes presented factitious airs not as a completed subject for textbooks but as a new subject; at the time of his lectures, Boyle's were the "best and almost only trials which have yet been made concerning factitious airs." By introducing factitious airs, Cotes extended the exact science of pneumatics to a largely unknown field of gaseous phenomena attending chemical actions. He referred to Newton's *Opticks* to point to the future direction of science: "Who ever will read those few pages [the last query] of that excellent book [*Opticks*], may find there in my opinion, more solid foundations for the advancement of natural philosophy, than in all the volumes that have hitherto been published upon that subject."[65] We know that Cavendish read Cotes's lectures, since he cited them in his first publication, which was on factitious airs. Cavendish's physical approach to "pneumatic chemistry" was foreshadowed by Cotes's and perhaps stimulated by it.

In 1716, at age twenty-seven, Robert Smith succeeded Cotes as Plumian Professor in Cambridge, the position he held for the next forty-four years. He also succeeded Bentley as master of Trinity College, and like his predecessor he vigorously promoted science in Cambridge. To encourage the student Richard Watson, later professor of chemistry at Cambridge, Smith appointed him to a scholarship, urged him to read Saunderson's *Fluxions* and other mathematical books, and gave him, Watson said, "a spur to my industry, and wings to my ambition." Israel Lyons, who lived in Cambridge, showed such promise that Smith offered to put him through school; Lyons dedicated his *Treatise of Fluxions* in 1758 to Smith. Smith completed the Trinity observatory Cotes had begun, and he gave the college a bust of Cotes and money to erect a monument to him. He left large benefactions to the College, to the University, and to science, which included funds for his own Plumian Professorship and for annual Smith Prizes to go to the two commencing bachelors of art who had done the best work in mathematics and natural philosophy. Smith presented his college with a statue of Newton by Louis-François Roubilliac.[66] As a student, Cavendish would have known that the Plumian Professor was one of the founders of Newtonian science at Cambridge.

When Cavendish was a student, the most important Newtonian work by a Cambridge professor was Robert Smith's *A Compleat System of Opticks*.[67] Newton's *Opticks* was a scientific work: his account of experiments on the analysis of white light into colored rays

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[64] "The Editor's Preface" in Roger Cotes (1747). For his joint course of experiments with Cotes, Whiston gave half of the lectures, but he did not publish them. "Cotes," *DNB*, 1st ed. 4:1029.

[65] Cotes (1747, 5, 123, 187, 201–203).

[66] "Smith, Robert," *DNB* 1st ed. 18:517–519. Winstanley (1935, 150). R.W.T. Gunther (1937, 61). Rouse Ball (1889, 91). Monk (1833, 2:168). Robert Willis and John Willis Clark (1886, 600). Richard Watson (1818, 14). In 1758 Lyons dedicated to Smith his *Treatise on Fluxions*, which was used in teaching at Cambridge alongside texts on the subject by Newton, Saunderson, and others.

[67] Robert Smith (1738).

was accessible to learners, but the rest of his book addressed difficult problems of the interaction of light and matter, raising questions and in general lacking the conclusiveness of a textbook. Smith's *Opticks* was a textbook. His treatment of Newton's optics was selective, overlooking Newton's second thoughts and hesitations, and omitting what did not fit. He cited Newton's queries where they supported his "system," treating them as assertions not questions.

Because Smith presented optics as a system, he could not ignore the question of the nature of light. In his answer, he followed Newton, only he was more decisive. Newton inclined towards a corpuscular view of light, but he speculated freely on an ether. Smith acknowledged that Newton's ether could explain the phenomena of light equally well, but he preferred Newton's corpuscles of light, in line with the thinking of the time. Smith's *Opticks* became the main authority on Newtonian optics after Newton's own *Opticks*, in some respects supplanting it.[68] Cavendish accepted the corpuscular theory, and nowhere in his writings did he use the word that characterized the alternative theory, "ether."

In discussing how we come by our ideas of things by sight, Smith considered the question the astronomer Samuel Molyneux asked of the philosopher John Locke: would a blind man who suddenly regained his sight be able to distinguish a globe from a cube by sight alone? To this question the philosophers had given a negative answer, which was apparently confirmed by the recent experience of a man reported in the *Philosophical Transactions.* Unconvinced by the philosophers, Smith had a ready subject at hand, his colleague the blind Lucasian Professor. Saunderson agreed with Smith that by "reason," the blind man upon regaining his sight could tell the globe from the cube.[69] The answer, whether correct or not, was an inference from the experimental philosophy: in knowing the world, experience is reflected upon by reason, a lesson Cavendish took to heart.

Many of the topics in Smith's *Opticks* interested Cavendish. Smith included a history of astronomy, beginning with Galileo, from whom astronomy acquired its essential, modern instrument, the telescope. The Cavendish library contained the classic works of astronomy by Copernicus, Brahe, and Kepler. Smith described Huygens's long, highly magnifying refracting telescopes, which Cavendish borrowed from the Royal Society and mounted at his house. Smith commented on the importance of London's scientific instrument makers for the progress of astronomy; George Graham, an instrument maker of "extraordinary skill," helped him in writing his book. Cavendish associated with instrument makers as much as he did with scientific investigators. Smith developed the optics of lenses and mirrors, which Cavendish took up in a number of papers. Smith treated the human eye as an optical instrument, constructing a "tolerable eye" from two hemispheres filled with water,[70] and he appended an essay on indistinct vision by his friend and colleague at Trinity, the Bentley protégé James Jurin.[71] Cavendish experimented on the eye as an optical instrument, and he corresponded with the astronomer William Herschel on indistinct vision.

Smith brought out a second scientific book, concerned with the other most discriminating sense, hearing. *Harmonics, or the Philosophy of Musical Sounds*, was well received, recommended by George Lewis Scott, one of De Moivre's pupils, to Edward Gibbon as the

[68]Henry John Steffens (1977, 48, 50, 53); G.N. Cantor (1983, 33–34).
[69]Smith (1738, 1:42–43), and "The Author's Remarks upon the Whole," at the end of the book, on 28–29.
[70]Ibid., 25, 332.
[71]James Jurin, "An Essay upon Distinct and Indistinct Vision," appended to Smith's *Opticks* (1738, 115–170).

"principal book of the kind."[72] Like natural philosophy, music had recently undergone major changes. The monodic idea had become well established, and with it so had the harmonic as opposed to the contrapuntal approach to musical composition. The emphasis had shifted to chords and the modern notion of key: by the use of a definite key and of modulation between keys, unity could be achieved in long expressive melodies. There was a problem with keys, however: modulation between closely related keys could be carried out satisfactorily but not modulation between remoter keys, as required for greater contrast.[73] Ancient musical theorists such as Ptolemy had considered only perfect consonances, and as a result their scales contained imperfect consonances, disagreeable to the ear. By distributing the largest imperfections in certain concords over the others, modern theorists tempered the ancient scales, making the imperfect concords less offensive, although there were more of them. Smith did not adopt the well-tempered scale, as promoted by Bach in the *Well-Tempered Clavichord*, but addressed the problem starting from the "first principles of the science." He redistributed the imperfections of the ancient scales in such a way as to make the imperfect consonances all equally "harmonious." For this "scientific solution" of the artistic problem, Smith constructed a theory of imperfect consonances, the first ever; it was his acoustical version of indistinct vision in optics.[74]

Smith lived in the Enlightenment, a word which referred to a felt need for clarity. Like musicians of "delicate ear," at performances Smith preferred to listen to a single string rather than to unisons, octaves, and multiple parts, in agreement with his preference for "distinctness and clearness, spirit and duration" over "beating and jarring" and "confused noise." He quoted from his other book, *System of Opticks*, from Jurin's account of what happens when a person comes out of a strong light into a closed room: at first the room appears dark, but in time the eye accommodates to the darkness and the room appears light. The discernment of clarity within a confusion of sound and the recovery of vision in darkness were analogous, symbolizing the natural philosopher's quest for order and understanding. Musicians at first disliked Smith's retuned organ despite its improved harmony, but musicians, like scientists, could be educated, Smith said, and in time they would no longer be able to stand the "course harmony" of organs tuned in the old way. Smith's aesthetics was an aesthetics supported by mathematics, experiment, and theory.[75]

The study of harmonics underscored the value of theory in the science of music. In the ancient world musicians followed their ear rather than the "theories of philosophers," Smith said; they arrived at temperament "before the reason of it was discovered, and the method and measure of it was reduced to regular theory." To the moderns, the ear was no longer sufficient. Smith, an expert performer on the violin-cello, had a musical ear but he did not need one. In harmonics, he needed only scientific theory, as he explained: a person without a musical ear could tune an organ to any temperament and to "any desired degree of exactness, far beyond what the finest ear unassisted by theory can possibly attain to." It was the same in optics as in music: Smith's colleague the blind mathematician Saunderson taught Newton's theory of colors.[76]

[72] Robert Smith (1759). First edition in 1749. "Smith," *DSB* 12:477. "Smith," *DNB* 18:519.
[73] Donald A. Ferguson (1935, 272–278).
[74] Smith (1759, v–vii).
[75] Ibid., 171–172, 210.
[76] Ibid., viii-ix, 33–35.

Because he approached music as an experimental philosopher, Smith confirmed his mathematical theory by practice. At his request, experiments were performed by the Cambridge organist and by the clockmaker John Harrison, who played the bass-viol. In the modification of musical instruments required by his theory, he was helped by "two of the most ingenious and learned gentleman in this University," John Michell, a skilled violinist, who became a colleague of Henry Cavendish's, and William Ludlam, to whom Charles Cavendish supplied astronomical calculations. Smith and his collaborators belonged to a tradition of scientists with an interest in music going back to Pythagoras and coming down to Huygens and Newton. His system was an improvement over other systems of temperament, but in the end the modification of instruments made it impractical.[77]

Modifier of instruments, experimenter, and mathematical theorist, Robert Smith was the complete natural philosopher in the fields he worked in. Of persons teaching scientific subjects at Cambridge, with the possible exception of John Michell, Smith was closest to Cavendish in his interests and skills. We would like to think that Cavendish became acquainted with Smith at Cambridge, but that seems unlikely. They were not in the same college, and Smith probably did not lecture any longer, and in any case, by then he was ill, irascible, and reclusive.[78] It is, however, virtually certain that Cavendish knew Smith through his books on optics and harmonics. We know that Charles Cavendish owned *A System of Opticks*, since he was one of its subscribers.[79] As we will see later in this chapter, Henry Cavendish was probably drawn to music, in which case he would certainly have known about Smith's *Harmonics*.

The Plumian Professorship was designated for astronomy as well as for experimental philosophy; during the time Cavendish was at Cambridge, the astronomy half was taken over by a new professorship, which combined astronomy with mathematics. In 1750 the master of Pembroke Hall Roger Long was named the first Lowndean Professor of Astronomy and Geometry, a position he would hold until his death twenty years later. Conspicuous as a Tory in predominantly Whig Cambridge and a contrarian, Long constantly feuded with the fellows of his college, especially over the right of veto, which he exercised with willful frequency. Like his Plumian colleague Smith, Long was a skilled musician, who presented the king and queen with a musical instrument of his own invention, the "lyrichord." In his field of astronomy, he was known for his models of the heavens, two of which are described in his *Astronomy*, a standard textbook in the University when Cavendish arrived. The frontispiece illustrates an early construction that Long used for demonstration, a glass celestial sphere known to a "great number of people" and imperfectly copied by several. The book describes a second construction, a narrow ring twenty feet across on which the constellations of the zodiac and the ecliptic were inscribed, treating viewers seated in the middle to

[77] Ibid., ix–xiv. Edgar W. Morse (1975, 477).
[78] "Smith," *DNB* 18:518.
[79] As the subtitle suggests—*A Popular, a Mathematical, a Mechanical, and a Philosophical Treatise*—Smith's book contains material of interest to a wide variety of readers. The 340 subscribers included members of De Moivre's mathematical circle such as Macclesfield, De Moivre, and Folkes (who subscribed for twelve copies); Cambridge mathematicians and physical scientists such as John Colson, Roger Long, Nicolas Saunderson, Charles Mason, John Rowning, and Richard Davies; Scottish professors of mathematics and physical science such as Colin Maclaurin, Robert Simpson, John Stewart, and Robert Dick; and London instrument makers such as George Graham, James Short, and Jonathan Sissons. Ten years before its publication, in 1728, Smith first advertised for subscribers, and if that was when Cavendish subscribed, it was just as he entered the Royal Society. He paid thirty shillings for each of the two volumes. Alice Nell Walters (1992, 7).

a panoramic view of this part of the heavens. Long expressed the wish to build a planetarium that would rotate around a platform of spectators. He later built and installed in a court at Pembroke Hall the revolving "great sphere" on which the zodiac and the ecliptic and planetary orbits were inscribed, measuring eighteen feet across and capable of holding thirty people. This consummate lecturer's planetarium provided the frontispiece of the second volume of *Astronomy*. Long was assisted in the construction of the revolving globe by Richard Dunthorne, formerly his footboy, who held the butlership at Pembroke; in that unlikely arrangment, Dunthorne published a number of valuable works on the motions of the moon, comets, and satellites of Jupiter, and after Long's death he assisted in completing his *Astronomy*.[80] Like his planetarium, Long's perspective was expansive. In contrast to the usual perfunctory single chapter on the fixed stars, his *Astronomy* devotes many chapters to their immense distances and other cosmic properties. Drawn to the great questions of astronomy, Long concluded after "long and careful scrutiny," incorrectly as it happened, that stars do not move. Long's main contribution to astronomy in Cambridge was his teaching, and his textbook was his main publication.[81]

Long regarded astronomy as part of natural philosophy, the study of the bodies that comprise the universe. Newton's *Principia*, he said, raised astronomy "at once, to a greater degree of perfection than could have been hoped for from the united labours of the most learned men, for many ages," the accomplishment of "the amazing genius of one man—the immortal *Newton*!"[82] Because the force of gravity was known but the forces of light, magnetism, and electricity were not, astronomy was far more advanced than the other parts of natural philosophy. Instrument makers, especially the British, supplied the observers who kept astronomy advancing after Newton. Long used mathematics sparingly, but he began his lectures with the subject of quantity, making clear what kind of science astronomy was. Because Charles Cavendish was a subscriber to Long's *Astronomy*, Henry Cavendish is certain to have seen it, and he might have attended the lectures on which it was based. After Cambridge, he would acquire telescopes and make studies of comets' orbits and other astronomical objects.

In 1748, the year before Cavendish entered Cambridge, the future regius professor of divinity Thomas Rutherforth published lectures he gave at St. John's College, *A System of Natural Philosophy*.[83] Rutherforth's combination of interests, theology and natural philosophy, made sense in a university that prepared students for clerical careers and taught Newton's mathematics. He used geometrical arguments throughout his lectures, even managing to convey a notion of infinitesimal reasoning while at the same time not assuming a

[80] Wordsworth (1968, 249). "Dunthorne, Richard," *DNB*, 1st ed. 6:235–236.

[81] The first volume of Long's *Astronomy, In Five Books* was published in Cambridge in 1742. The second volume did not appear until twenty-two years later, in 1764, for reasons of which, Long said, "it would be of no service to the public to be informed." The reasons had in part to do with his interest in music, as a letter from Cambridge noted: "Dr. Long advances, but slowly, in his astronomical work; tho' ye larger part of his 2d vol. is I believe printed. But he keeps amusing himself […] with alterations in musical instruments, of wch he is very fond." J. Green to Thomas Birch, 29 Jan. 1760, BL Add Mss 4308, ff. 192–193. Only in 1784, after Long's death, was the remaining part of the book published. Long (1742, 1764, 1784, 1:ix–x, and 2:iii, 637–638). "Long, Roger," *DNB*, 1st ed. 12:109. Rouse Ball (1889, 105). Gunther (1937, 164–167). Ketton-Cremer (1955, 83–84). "Dunthorne, Richard," *DNB*, 1st ed. 6:235–236.

[82] Long (1742, 1764, 1784, 2:717–718).

[83] Thomas Rutherforth (1748). "Rutherforth, Thomas," *DNB*, 1st ed. 17:499–500. Rutherforth used his membership in the Royal Society to promote sales of his books. Thomas Rutherforth to Thomas Birch, 30 Jan. and 6 Feb. 1743/42, BL Add Mss 4317, ff. 305–306, 308.

rudimentary knowledge of quantity.[84] His book was competent at the level of its intended audience, and popular. Its list of subscribers numbered about 1000, of whom roughly a third were identified with Cambridge.[85] Charles Cavendish did not subscribe to it. When Cavendish was a student, the Jacksonian Professorship of Natural Philosophy had not yet been established.

The Woodwardian Professor of Geology Charles Mason was a good geologist, who had charge of an important collection of fossils in Cambridge. He had scientific interests outside of geology as well, described as "a man of curious knowledge in the philosophy of mechanics and a deep mathematician."[86] It is conceivable that he contributed to Cavendish's education, but it is unlikely. Cavendish did take up geology, but it was long after he left Cambridge. The professorship of chemistry was held by John Mickleburgh, who like his predecessor Vigani was an advocate of Newtonian chemistry. Mickleburgh took his teaching seriously, excusing his delay in answering letters on the grounds that because he was "now engaged in a course of Chemistry here, I can think of nothing but calcinations, sublimations, distillations, precipitations, etc.," but by Cavendish's time he evidently no longer lectured on the subject, and to our knowledge neither did anyone else until after Cavendish.[87]

Before leaving the subject of Cambridge's potential contribution to Cavendish's scientific education, we need to look at textbooks in use there that were written by authors who were not Cambridge professors. After becoming Lucasian Professor of Mathematics, John Colson translated into English several books from several languages, one of which was Petrus van Musschenbroek's *Elements of Natural Philosophy*, subtitled *Chiefly Intended for the Use of Students in Universities*.[88] Colson explained that there was need for a complete "system" of natural philosophy in English and that Musschenbroek's was the best. For his system, Musschenbroek drew on Continental sources such as writings by Descartes and Leibniz (concerning whose use of vis viva for force Colson disagreed with), but his principal source was the "very many and great discoveries of the illustrious *Newton* (the glory of *England*, to whom no age has produced an equal)." He thought that mathematics was the right preparation for natural philosophy, in agreement with Newton and the curriculum at Cambridge. Although physics had been placed on a "firm basis" through observation and experiment, there were always problems to solve, he said, and if we are unable to solve them, we can "excite other diligent inquiries into nature, that are to come after us." That most puzzling of fields electricity would grant "eternal fame" to its genius, whose name would be struck on public monuments; as if to confirm his prophecy, in the year after the publication of Colson's translation, Musschenbroek himself made an important discovery in electricity,

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[84] Rutherforth (1748, 23).

[85] Robert E. Schofield (1970, 97).

[86] Wordsworth (1968, 345). Indicative of Mason's range of interests are "hints" about melting iron and about a burning well in a letter he sent to the president of the Royal Society at about the time Cavendish was in Cambridge: Charles Mason to Martin Folkes, 22 Jan. 1747/46, Wellcome Institute, Martin Folkes Papers, Ms. 5403. Winstanley (1935, 168–169).

[87] John Mickleburgh to Dean Moss in 1725, in John Nichols (1817–1858, 4:520). Wordsworth (1968, 188–189). L.J.M. Coleby (1952b, 167, 169–170).

[88] John Colson translated Petrus van Musschenbroek, *Elements of Natural Philosophy* from the Latin in 1744; from the French he translated Jean Antoine Nollet, *Lectures in Experimental Philosophy* in 1748; from the Italian he translated Maria Gaetana Agnesi, *Analytical Institutions* in 1801. We have already discussed his translation from the Latin of Newton's *Method of Fluxions*.

the Leiden jar. Like Colson, he gave encouragement to aspiring students, assuring them that natural philosophy "can never be exhausted."[89]

Colson would have recognized a kindred spirit in Musschenbroek, who at the time of Colson's translation was professor of mathematics and astronomy at the University of Leiden, and whose main publications were extensions of his lectures in ever larger books. His predecessor at Leiden had been Willem Jacob 'sGravesande, another systematizer and author of textbooks, whose *Mathematical Elements of Natural Philosophy, Confirmed by Experiments: or, an Introduction to Sir Isaac Newton's Philosophy* had been translated from the Latin into English by J.T. Desaguliers in 1720–21. His strength as a teacher lay in his use of experiments to support scientific truths, but like Musschenbroek he recognized the importance of mathematics for natural philosophy. The "comparing of motion" was the "continual theme of natural philosophy," and anyone who went about that subject in "any other way, than by mathematical Demonstrations, will be sure to fall into Uncertainties at least, if not into Errors." Newton had demonstrated in the *Principia* the "great use of mathematics in Physics, as no one before him ever penetrated so deeply into the Secrets of Nature." Musschenbroek and 'sGravesande had studied at the University of Leiden when its most successful teacher Herman Boerhaave was lecturing; through their teaching, which included their textbooks, the three professors made Leiden the center of Newtonianism on the Continent. The experimental philosophy had replaced stable certainty with change, they said, and they encouraged their students to discover new truths using the experimental way aided by mathematical demonstration.[90]

Leiden was probably a better place to learn natural philosophy than Cambridge, but it was not necessary to be in Leiden to learn from it. Colson's translation of Musschenbroek's textbook and translations of 'sGravesande's and Boerhaave's textbooks were recommended reading in Cambridge, and they strongly influenced texts written by British writers, just as theirs were influenced by British texts. In presenting natural philosophy, 'sGravesande followed the "Example of the *English*," by giving experiments that had "a kind of Connexion with one another"; Musschenbroek, in his presentation of optics, said that Robert Smith's *Opticks* "has gone beyond all the rest in this science."[91] At both universities the emphasis was on Newtonian philosophy, and at both universities the professors were primarily teachers not researchers. For a wide and perceptive reader like Cavendish, the experimental emphasis at Leiden would have supplemented the mathematical emphasis at Cambridge, and there would have been no contradiction.

Leiden's authors would have exposed Cavendish to points of view not found in English texts on natural philosophy. If in his time as a student in Cambridge, Cavendish read Musschenbroek's text or 'sGravesande's text he saw how vis viva could be incorporated in otherwise largely familiar presentations of natural philosophy. It was in this particular that Cavendish's use of mechanics differed from that of his British colleagues.[92]

In broad outline, we have sketched the scientific tradition at Cambridge insofar as it was represented by the texts of its early and mid-eighteenth-century professors. When Cavendish entered the ranks of scientific researchers, he was familiar with mathematical methods and

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[89] Musschenbroek (1744, 1:iii–v); Colson's advertisement, xi, 6. The Leiden jar was discovered independently by the German experimenter E.G. von Kleist.

[90] Edward G. Ruestow (1973, 7–8, 115–121, 135–139).

[91] Struik (1974). Hall (1972). 'sGravesande (1747, 1:ix, xv). Musschenbroek (1744, 2:159).

[92] Musschenbroek (1744, 1:80–82). Willem Jacob 'sGravesande (1741, 76).

concepts of science within a certain Newtonian framework, and the connections with his Cambridge education are significant and unlikely to be only coincidence.

Giardini Academy

If there was an early musical influence on Henry Cavendish, it came from his mother's side of the family. The duke and first duchess of Kent had a love of music, the duke managing to combine music with his political career when as lord chamberlain he worked to bring Italian opera to London. Later, in 1719, he was one of the original subscribers to the Royal Academy of Music, and he (but not the duke of Devonshire) became one of its twenty directors. There is a painting showing the Kent family being musically entertained (Fig. 1.3). We know that the Greys and the Yorkes attended concerts at the Rotunda.[93] Had Henry shown a musical interest, he would have been encouraged.

Evidence of Henry Cavendish's interest in music is sketchy. There is a mathematical study by him, "On Musical Intervals."[94] There is a reference to a musical event in Cavendish's laboratory notes on chemistry: in 1782 he used his eudiometer, an instrument for measuring the "goodness" of air, to compare the good air of Hampstead, to which he had just moved, to the used "Air from Oratorio."[95] He began his lament on the death of the prince of Wales with music: "Melpomene [goddess of song], pour forth a gloomy anguish on our melodies/ Let the flute breathe out faint wailings/ And sing out a grievous tune in solemn funeral procession." More significant, a grand pianoforte is listed in the auction catalog of the contents of his house at Clapham Common at the time of his death.[96] Other than for servants, Cavendish was the only person who lived in the house, and the pianoforte would have been there only because he wanted it. According to a story, which on the face of it is unlikely but which may contain a core of truth, Cavendish came together with Michell, Herschel, Priestley, and others over musical entertainment.[97] We know that Michell, Herschel, and Priestley were accomplished in music.

We suspect that Cavendish's education included education in music. Given the limited evidence, in this discussion we proceed tentatively. The professional musician Charles Burney, Cavendish's contemporary and fellow of the Royal Society, said that music and other arts are "governed by laws," and in mastering them the individual approached nearer perfection by receiving help from others than by the "mere efforts of his own labour and genius."[98] The name Henry Cavendish appears on a list of subscribers to the musical academy of Felice Giardini.[99] The name does not prove he was our subject—Sir Henry Cavendish, a

[93] Otto Erich Deutsch (1974, 91, 102). A.E. Gunther (1984, 62). Great Britain, Historical Manuscripts Commission (1920, 93, 227; 1923, 2:30).
[94] Henry Cavendish, "On Musical Intervals," Cavendish Mss VI(a), 28.
[95] This entry is unclear as to Cavendish's part. It begins with a comparison of "air caught by [the instrument maker Edward] Nairne in 2d gallery of Drury Lane playhouse Mar. 15, 1782 with air of Hampstead of Mar. 16." It follows with "Air from Oratorio about the same time." "Experiments on Air," Cavendish Mss II, 5:189.
[96] *A Catalog of an Assortment of Modern Household Furniture* […] *the Genuine Property of a Professional Gentleman; Which Will Be Sold by Auction by Mr. Squibb, at His Great Room Saville Passage, Saville Row, on Wednesday, December 5, 1810, and Two Following Days, at Twelve O'Clock.* Item 45 is a grand pianoforte, by Longman and Broderip, in a mahogany case.
[97] "Michell, John," *DNB* 1st ed. 13:333–334, on 333.
[98] Charles Burney (1799, 186, 205).
[99] Great Britain, Historical Manuscripts Commission (1913, 188–189).

distant Irish relative of the same age, was in London around this time[100]—but the evidence, sketchy as it is, points to him. Giardini arrived in London in 1751, while Cavendish was at Cambridge, and for ten years beginning in 1755 he adapted Italian operas for the King's Theatre in London. Later he composed concertos and other music for strings, several operas, and a successful English oratorio. Like Charles Cavendish, Giardini was a governor of the Foundling Hospital, where Handel gave concerts, and where Giardini proposed establishing a musical academy. He gave frequent solo performances under the auspices of his good friend J.C. Bach. By the time Cavendish was (if our supposition is right) in contact with him, Giardini was the preeminent violinist in London. Samuel Johnson sympathized with Giardini when he learned that the man did not make more than £700 a year despite his superior ability.[101] To do even this well, which to be sure made him modestly well off, Giardini had to combine activities, one being to run an academy by subscription. In 1758 or 1759, Henry Cavendish along with sixteen others agreed to continue to meet as an "academy" in the coming year as they had in the last, only under new terms, probably having to do with Giardini's finances. The members of the academy agreed to pay £8, half up front and the rest when the academy had met twenty times, the total number of meetings being sixty. It was left to the subscribers whether they would meet in the morning or the evening; if in the morning, as they had been meeting, breakfast would be provided; if in the evening, lighting. Thirteen of the seventeen, including Cavendish, had already paid their advance, and if all paid up, Giardini would have earned around £135, less out-of-pocket expenses, a good installment on his £700 for the year.

The subscribers were young and of both sexes, including husbands and wives and persons with various family connections; two of them, George Manners and Lady Granby, were related to Cavendish. Isabella Carlisle and Frances Pelham were talented singers, who arranged private concerts and may have been pupils of Giardini's. William Hamilton, a colleague of Cavendish's, who began taking lessons with Giardini in the year the Italian arrived in London, was an expert violinist, one of the rare amateur musical gentlemen who could compare in skill with amateur musical ladies.[102] Hamilton's first wife, Catherine, who performed with approval before Mozart, was also one of the subscribers to Giardini's academy.[103] Remembered as the husband of Lord Nelson's mistress Emma, Hamilton was known in his day as a solid diplomat, a learned antiquarian, and a good student of volcanoes. As envoy to the court of Naples, he leased a villa close to his favorite volcano, arranging a music room that Catherine described as "right facing Vesuvius, which now and then is kind enough to play whilst I too am playing." The other night, she said, it had sent up fiery red stones, "but we went right on playing, just as you would have done if you heard a pop-gun in the street." The president of the Royal Society Joseph Banks wrote to Hamilton in Naples to complement him on his description of a recent irruption of Vesuvius: "Cavendish in particular who you know is [given] not at all to flattery says it is a very valuable addition to the theory of volcanoes & that tho he does not on any account wish to derogate from the merit

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[100] He descended from an illegitimate branch of Henry Cavendish's family. An English and Irish politician, he is best known as a parliamentary diarist. Peter D.G. Thomas (2004).

[101] R.H. Nichols and F.A. Wray (1935, 247). Roger Fiske (1973, 284–286).

[102] Brian Fothergill (1969, 29). Horace Walpole to George Montagu, 17 May 1763, in Lewis and Brown (1941, 69–74, on 73). Horace Walpole to William Cole, 5 Feb. 1780, in Lewis and Wallace (1937, 186–189, on 187).

[103] Hamilton has helped us date the agreement between Giardini and the subscribers to his academy. By our reckoning, it was after Hamilton's marriage in 1758 and before December 1759.

of your former papers this is certainly the most valuable one we have receivd from you."[104] What exactly transpired if Hamilton and Cavendish came together in Giardini's academy is unclear, but it undoubtedly had to do with listening together, and very likely it involved performing together.

Giardini, Burney wrote in his history of music, "formed a morning *accademia*, or concert, at his house, composed chiefly of his scholars, vocal and instrumental, who bore a part in the performance." This we take to be a description of the academy to which our Cavendish may have subscribed. He may have been one of Giardini's "scholars" too, and he may have performed before an audience at the academy. It is hard to imagine the shy and taciturn Cavendish singing or performing on an instrument, but stutterers have been known to be great orators, and playing to his strength Cavendish "performed" experiments before competent audiences using scientific instruments.[105]

If Cavendish pursued an advanced education in music, there are reasons why he might have chosen to do so with Giardini. First, Giardini was a highly regarded teacher: in Thomas Mortimer's *The Universal Director* of 1763, he was listed not as a violinist but as a teacher of singing and harpsichord. Second, with Giardini's arrival in London, the "standards" of London concerts rose, coming to equal those of the best in Europe. Third, he eliminated from performances all possible extraneous ornaments, among other changes. We find parallels in Cavendish's scientific and life preferences.[106]

[104] Joseph Banks to William Hamilton, 30 Nov. 1794, BL, Edgerton 2641, 155–156.

[105] In Italy a private concert by dilettantes was called an "accademia," which may have been Giardini's meaning. This information is from a work of the time, Charles Burney (1771), quoted in Walpole (1954, 18:13, note 16a). Charles Burney (1789/1935, 1012–1014). Stanley Sadie (1988, 320).

[106] Simon McVeigh (1993, 14, 197, 220).