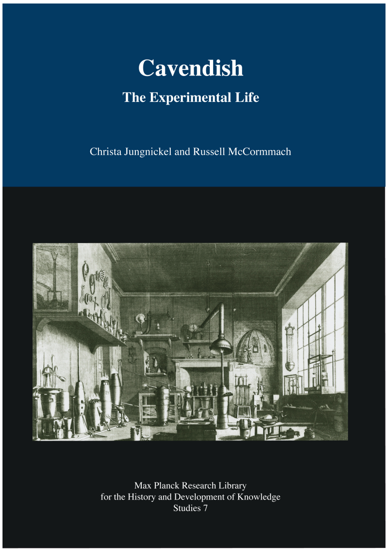
Max Planck Research Library for the History and Development of Knowledge
Studies 7

Christa Jungnickel and Russell McCormmach:
Science



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 7
Science

Henry Cavendish's family is said to have been greatly disappointed that he did not pursue a regular public career, and that his father accordingly treated him in a niggardly fashion.[1] The first half of the statement is plausible, since the Cavendishes were a political family and naturally had expectations. This was a time, we must remember, when sons of peers and even sons of sons were practically duty-bound to enter the House of Commons.[2] To appreciate how extraordinary Henry's career as an unsalaried natural philosopher might appear, consider that in the same year that he entered the Royal Society, the House of Commons had four Cavendish's, five Manners, and five Townsends, and, in general, an ample representation of aristocratic young blood. The allegation, however, that Charles Cavendish was one of the family members who disapproved of Henry's course in life runs up against certain known facts, chief among them is that he brought his son into his scientific circle from an early age. As to the charge of niggardliness, we have little to go on. Since Henry did not marry, there is no settlement in writing, and we have not found any written agreement between father and son. According to one source, until he was forty Henry received an annuity of only £120, which was modest, though by living at home he could have got along fine. The chemist Thomas Thomson said that Henry's annuity was £500, which was handsome,[3] the same as the annuity Charles received from his father at the time of his marriage; before then, he had received only the standard £300. Charles was not wealthy and he was careful with money, and he may even have been tight, but it seems unlikely that he would have punished his son for following his example. He left politics for what we take to have been for him a more fulfilling life. Bypassing politics entirely, Henry took up science, which provided him with a life that suited him. There is no reason to think that his father tried to disuade him, but on the contrary, there is every reason to think that his father instructed him in science and supported him completely.

By foregoing a career in politics, Henry Cavendish deprived his family of a reliable vote in Parliament for a number of years, but by then his vote was dispensable. What was enduring in the family tradition was a commitment to public service, and nothing in the record suggests that he deliberately defied his relatives by his choice of ends to serve. If he experienced any conflict as a result of being both a Cavendish and a servant of science, it was not obvious to people who knew him. The basic agreement between his view of British government and his family's is evident in the part he took in the politics of the Royal Society, discussed later.

With his way of life, Cavendish brought together the two main reference points of his identity, his rank and his work: in the organizations where he performed his duty of

---

[1] George Wilson (1851, 161).
[2] L.B. Namier (1929, 5).
[3] Thomas Thomson (1830–1831, 1:336). Wilson (1851, 160).

service, he was welcomed as a natural philosopher bringing useful knowledge, skill, and intelligence. The English aristocracy was in ascendancy in the social world, and during his lifetime its postion was not seriously threatened; and in the century after the Scientific Revolution, which had exhibited the power of experiment, observation, and mathematics to build solid structures of knowledge, natural philosophy was in ascendancy in the world of learning. In his time, Cavendish was enviably placed in English life.

Introduction to Scientific Society

In the summer of 1753, soon after leaving Cambridge, Henry together with his brother Frederick accompanied their father to William Heberden's house for dinner. A number of friends and colleagues of their father were invited that evening: Thomas Birch, William Watson, Daniel Wray, Nicolas Mann, and the physician and poet Mark Akenside, whom Charles Cavendish had recommended for fellowship in the Royal Society for his knowledge of natural philosophy.[4] Heberden and the first three men in this list were to sign the certificate for Henry's membership in the Royal Society. Frederick, who suffered a serious accident the following year, did not come to any more of these collegial dinners, but Henry came with his father to at least twenty-six of them. The most frequent of Henry's hosts was Heberden, though the dinners were sometimes held at Yorke's house and occasionally at Watson's, Stanhope's, Wray's, and his father's houses.[5]

Fellows of the Royal Society commonly introduced their sons to other members by bringing them as guests to the meetings.[6] Charles Cavendish first brought Henry on 15 June 1758, by which time he had already introduced him to many of the active fellows of the Royal Society at dinners at his and his friends' houses. As his father's guest, Henry came to a total of seventeen meetings of the Royal Society, and at three more meetings he came as a guest of Birch, a friend of the family, of Peter Newcome, the teacher at Henry's school at Hackney, and of Michael Lort, who had connections with the family.[7] The year before Henry began coming to the meetings, Charles had received the Copley Medal of the Society, and as vice president he presided over almost half of the meetings to which he brought Henry as his guest. Henry could feel reassured in this new public world of science.

On 31 January 1760, Henry Cavendish was proposed for fellowship in the Royal Society by Lord Willoughby, Lord Macclesfield, and James Bradley, an appropriate combination of rank and skill. Over the next three months, the certificate recommending Cavendish for fellowship, which was drafted by Heberden, was signed by six more fellows: Birch, Wray, Watson, Thomas Wilbraham, John Hadley, and Samuel Squire. All of them were members of Charles's dining circle, with whom Henry too had dined. Henry was balloted and unani-

[4] 25 Aug. 1753, Thomas Birch Diary, BL Add Mss 4478C, f. 235.

[5] Henry came with his father to dinner at Heberden's twelve times. Our knowledge of this dinner and others like them comes from Thomas Birch's Diary, and so we know only about those social occasions at which Birch was present.

[6] Examples from about this time: John Canton, Jr., was a guest of John Canton, and Jonathan Watson, Jr., was a guest of Jonathan Watson. Entries for 26 Mar. and 9 July 1767, JB, Royal Society 26.

[7] Entries in JB, Royal Society 23 (1757–60). Michael Lort was an antiquarian, who in 1759 was appointed professor of Greek at Cambridge. Since he was not yet himself a fellow of the Royal Society, he must have had the right to invite guests as a university professor. Lort was a good friend of the Cavendish in-law Philip Yorke, and he is said to have been librarian to the duke of Devonshire.

mously elected on 1 May 1760.[8] What the certificate said was that Cavendish had "a great regard for Natural Knowledge" and that he was "studious of its improvement." General though the description was, it was of a kind often given,[9] and in Henry Cavendish's case the generality was justified, as he would become known as a universal natural philosopher.

Just as at the Royal Society, at the Royal Society Club—the official name was still the Society of Royal Philosophers, changing only in 1794—prospective members were customarily brought as guests before they were elected members. This was the case with Henry Cavendish, though he was proposed for membership before he had actually attended a dinner of the Club. On 10 November 1757, Macclesfield, who as president of the Royal Society presided over the dinner, recommended Henry Cavendish for membership. This was no doubt by prearrangement, as Charles Cavendish attended that dinner. Around this time, the most active members of the Club—as indicated by their attendance at the yearly business meetings and a few special meetings and by their attendance at ordinary dinners—were members of Charles Cavendish's dining circle, which Henry Cavendish had lately joined: Watson, Knight, Squire, Wray, Birch, Colebrook, and also Burrow. Others who came frequently to the Club's dinners were also dining companions of Charles's; in particular, Willoughby, Newcome, and Akenside.[10]

Candidates for membership in the Club were not always elected. For example, at an annual anniversary meeting of the Club, there were seven candidates, two of whom were chosen unanimously, one of them the astronomer William Herschel. The others had various numbers of "black balls" against them, as reported in a letter from the president of the Club.[11] Henry would face no opposition, but he had to wait until there was a vacancy before he could be balloted. The wait, it turned out was considerable, two and a half years, though it was a formality readily circumvented. He was invited to dinners as a guest of his father's four times in 1758 and two times the following year, treated as if he were a member from the time of his proposal. As it happened, the timing was right, for he was elected member of the Club on 31 July 1760, just two months after he was elected to the Royal Society.[12] Henry was then twenty-eight; his father did not attend dinners at the Club regularly anymore, so Henry came mostly on his own.

We join Henry at his first dinner as a member, on 14 August 1760, at the Mitre Tavern on Fleet Street. He paid his admission fee of one pound one shilling together with three shillings for the dinner that day. He sat down at four o'clock before the following choices: nine dishes of meat, poultry, and fish, two fruit pies, plum pudding, butter and cheese, and wine, Porter, or lemonade.[13] A foreign guest left the one detailed description of a dinner of the Club in the eighteenth century, held on 12 August 1784, at which Cavendish was present. The members sat down to dinner at 5 PM, breaking off at 7:30 PM in time for the Royal Society meeting at 8 PM. The president of the Royal Society Joseph Banks presided over the dinner, and the astronomer royal the Reverend Nevil Maskelyne gave a short prayer. The guest noticed the quantity of alcohol that was drunk during and after the dinner, selected from a wide

---

[8] 1 May 1760, JB, Royal Society 23:845.

[9] Certificates, Royal Society 2:198 (proposed 31 Jan. 1760). Maurice Crosland (1983, 173–174).

[10] Minute Book of the Royal Society Club, Oct. 27, 1743–June 29, 1809, Royal Society, 1.

[11] Joseph Banks to Charles Blagden, 28 July 1785, Blagden Letters, Royal Society, B.35.

[12] Archibald Geikie (1917, 63, 70). At the beginning of Minute Book 4, covering the years 1760–64, it says that everyone is charged for a pint of wine, and that for those who preferred lemonade and porter, their value was reckoned as equal to that of a bottle of wine.

[13] 14 Aug. 1760, Minute Book of the Royal Society Club, Royal Society, 4.

menu: beer, port, madeira, claret, champagne, brandy, rum, and other strong liquors. It was the prince of Wales's birthday, and the Elector Palatine was admitted that day to the Royal Society, and they and each member and each guest received a toast, each calling for wine. According to the guest, by the time they left, they "were all pretty much enlivened," though their "gaiety was decorous."[14] At meetings of the Club, between eating well and drinking, members and guests talked about scientific news and sometimes performed experiments.[15]

The Club met every Thursday throughout the year. In his first year, Cavendish came to sixteen dinners, the next year twenty-eight, and eventually he came to nearly all of them. From 1770 on, he attended no fewer than forty-four dinners in a year, and usually around fifty. A dozen or so members and guests made up a typical dinner party, but there was considerable fluctuation. Cavendish's regularity is indicated by the following events. In 1767, on a day in which the meeting room of the Club was appropriated by the Society of Antiquaries, another arrangement was made, and only one member of the Club turned up for it: he was Cavendish, who brought with him as a guest Nevil Maskelyne. In 1777 the treasurer made an error in scheduling a dinner on Christmas, but Cavendish came anyway, along with two others.[16] Cavendish was the most constant attender of all the persons who had ever belonged to the Club,[17] qualifying Wilson's conclusion that Cavendish was "one of the most ungregarious of beings."

Wilson learned from his sources that Cavendish was interested only in science. That would seem to be largely borne out, though it is incomplete. Geikie in his history of the Club recognized that Cavendish had wider interests than the laboratory, as shown by his guests, who included physicians, surgeons, politicians, manufactures, engineers, explorers, seamen, and still other types.[18] Examples are John Belchier, surgeon of Guy's Hospital, Paul Joddrell, who became a physician in India, William Ogilvie, professor of humanity at the University of Aberdeen, and Henry Penruddock, former mayor of Salisbury and sheriff of Wiltshire who was interested in antiquities and topography. Some persons he brought as guests were candidates for membership in the Club, in which event he may have been performing a duty, but usually this was not the reason. He did more than attend dinners: in addition to bringing guests, he presided over an annual general meeting in the absence of the president at least once,[19] and he made gifts of fish and venison.[20]

In 1780 the meetings of the Club were moved to the Crown & Anchor Tavern on the Strand, closer to the new location of the Royal Society in Somerset House. If Cavendish had an interest in music, he might have been familiar with the Crown & Anchor: this tavern with its great ballroom had long been the site of the fortnightly concerts of the Academy of Ancient Music, as it would continue to be until 1784, combining excellent music with food and drink.[21]

---

[14] Geikie (1917, 169–171).
[15] Joseph Banks to Charles Blagden, 28 Sep. 1782, Blagden Letters, Royal Society, B10.
[16] Geikie (1917, 73–74, 80, 95, 97). Hector Charles Cameron (1952, 172).
[17] As of the time of Geikie's book, *Royal Society Club*, 73.
[18] Geikie (1917, 147, 154, 202, 234).
[19] 25 July 1782, as recorded in the Minute Book of the Royal Society Club, 7.
[20] 4 Apr. 1782, 25 Aug. 1785, Minute Book of the Royal Society Club, Royal Society, 7.
[21] Robert Elkin (1955, 51–52).

In 1760, the same year that he was elected to the Royal Society and the Royal Society Club, Cavendish was elected to the Society of Arts.[22] His father had again preceded him, having been elected three years before. The Society had been in existence for six years, and its membership was growing rapidly; at any one meeting, twenty to fifty persons might be elected. From a handful of founders, the membership stood at nearly 2000 by 1768.[23] The subscription was two guineas, or three for persons who could afford it, and five guineas were expected of peers, of whom there were many; the duke of Devonshire was elected the year after Cavendish. The membership was a cross-section of English society: mechanics, iron masters, watchmakers, opticians, glass manufacturers, wine merchants, portrait painters, writers, politicians, and a good many prominent fellows of the Royal Society, including present and future presidents of the Royal Society Sir John Pringle and Lords Macclesfield and Morton. Active in committees of the Society around the time of Cavendish's election were John Hadley, Gowin Knight, William Watson, Benjamin Franklin, Henry Baker, Matthew Maty, Lord Willoughby, and William Heberden.

Cavendish held no office in the Society of Arts, he did not publish in its journal, and it seems he did not belong to any of its committees. In 1786 he was summoned to attend the committee of polite arts to take part in an educational experiment, but he did not go.[24] It is conceivable that he attended the weekly general meetings, but there is no way of knowing this,[25] and it seems unlikely. If his membership was passive, this does not mean that he was uninterested, for he kept up his membership for fifty years, to the end of his life. We know that he was interested in many of the subjects that came up in the Society. There was probably more to his patronage of the Society than performing a duty.

The idea of the Society of Arts at its inception was that industry would be stimulated by prizes donated by interested parties. To this end, six main committees were set up, at least two of which were of interest to Cavendish, those for chemistry and mechanics. Historians of the Society find that the competitions stimulated the early stages of the industrial and agricultural revolutions, especially the latter. In industry the Society's main concern was mechanical inventions, having to do with, for example, water and steam power, measuring instruments, and standards of measurements; it was also concerned with chemicals used in industry, including the chemical processes of smelting and refining iron ore. These industrial subjects interested Cavendish, as we learn from the journeys he made, which come up later in this book. As an example, the Society awarded a gold medal to Abraham Darby III for building the first iron bridge, at Colebrookdale, which Cavendish visited on one of his journeys. In 1783, the Society began its own regular publication, *Transactions*, the first issue of which announced a gold medal for a method of burning smoke from steam engines and smelting furnaces; on a journey Cavendish took an interest in Watt's invention of a furnace for burning smoke. There is evidence that in the 1770s, leading members of the Society of Arts who were also fellows of the Royal Society agreed that the former would deal mainly

[22] On 9 January 1760, Henry Cavendish was proposed for membership by Mr. Cosheap; at the next meeting, on 16 January, he was elected. Minutes of the Society, Society of Arts, 4.

[23] *A List of the Society for the Encouragement of Arts, Manufactures, and Commerce.* 6 April 1768. Printed by order of the Society.

[24] D.G.C. Allan, personal communication, 1966, and *Journal of the Royal Society of Arts*, 1966, 1033, n. 11.

[25] After 14 Dec. 1757, the Society Minutes stopped recording names of members present at meetings.

with applications of science and the latter mainly with basic science.[26] Cavendish's original work belongs to basic science, but he was interested in applications too.

Science at the Royal Society

In Cavendish's time, scientific books were written for a variety of purposes and readers; for example, to educate students, to present the state of a field for researchers, to simplify a field for lay readers, to serve as practical manuals, to bring out new research or interpretations, to bring together previously published papers, and to make money. For example, Robert Smith wrote a textbook on optics, Colin Maclaurin wrote a book popularizing Newtonian science, and John Michell wrote a manual on making artificial magnets. Cavendish would have been expected to publish at least one book over the course of his life. He began a book on mechanics, and he nearly completed one on electricity.

As it turned out, like a few of his colleagues, notably William Herschel and John Canton, Cavendish published only papers, which appeared in only one place, a journal for all of the sciences, the century-old *Philosophical Transactions* of the Royal Society. His fields, experimental and mathematical natural philosophy, were not the journal's strengths—only ten percent of the papers it printed were experimental, and a much smaller proportion were theoretical[27]—but we have no reason to think he was dissatisfied with the journal for that reason. The journal was one of the activities of the Royal Society, to which he was committed. The era of scientific specialization with specialized journals began only toward the end of his life.

At Cambridge, Cavendish studied the mathematical methods of natural philosophy. He learned about scientific research elsewhere, presumably at home under his father's guidance, using his father's instruments and reading his father's books and journals. His primer, the *Philosophical Transactions*, came regularly into his father's house during the years he was a student. Beginning in the year he came home from Cambridge for good, his father served on the Royal Society committee of papers, passing judgment on every paper appearing in its journal. As we have with textbooks in use at Cambridge, we examine the *Philosophical Transactions* as a source of examples of how to proceed as a scientific researcher and author.

With one exception, the important papers Cavendish wrote for the *Philosophical Transactions* were experimental. In the previous century, when the journal began, the meaning of "experiment" could be as general as "any made or done thing"; the goal of experiment then was usually to discover something or to solve a debate, and the argument it supported was usually inductive. By the time Cavendish entered science, the meaning of experiment had narrowed; it was usually undertaken to solve a problem or to prove a hypothesis or a theory. Before Cavendish was through, experiment was undertaken to establish or test a general claim. On the way, experimental papers grew longer and more argumentative, corroborative, and investigative.[28]

In reporting the results of scientific work, the Royal Society's strictures against fanciful language were expected to be honored. In an exchange of letters in the *Philosophical*

[26]The competitions were extensive; for example, in 1764 there were 380 classes, and the premium list took up 91 pages. *Transactions of the Society for the Encouragement of Arts, Manufactures, and Commerce*, vol. 1, 1783. Derek Hudson and Kenneth W. Luckhurst (1954, 6, 15, 57–58, 101, 113–116, 119, 124–125).
[27]Richard Sorrenson (1996, 39–40).
[28]Charles Bazerman (1988, 66–68).

Transactions, the electrical experimenter Georg Matthias Bose conceded that by his "style and expressions" he had "embellished a little" the account of an experiment. His correspondent William Watson took him to task: "The language of philosophers should not be tainted with the license of the poets; their aim in the communicating their discoveries to the world, should be simple truth without desiring to exaggerate." Nature, the thing itself, was cause enough for "admiration."[29] Spare writing can have a force of its own, even eloquence. Cavendish's writing has that quality, and because his writing was the same whether the subject was phlogiston or farming, his adherence to the Royal Society's strictures would seem to have come naturally to him, as an extension of his personality. Few wrote as plainly as Cavendish; Bose was not unique, only chastened.

Most papers in the *Philosophical Transactions* appeared in English, the language in which they were written, though papers in Latin from abroad were not uncommon and were rarely translated, a reflection of British education and of the continuing use of Latin as a universal language of scholars. Papers in French, Spanish, and other modern European languages were translated, again reflecting British education and also British insularity.[30] Later in the century, the Council of the Society resolved to meet foreigners halfway, ordering that papers communicated in foreign languages be printed in the original language in small type at the bottom of the page containing the English translation. In a further step in this direction, English translations might be relegated to an appendix and, on occasion, omitted.[31] Fortunately, there were always fellows who were willing and able to translate, and like most readers of the journal, Cavendish was often in their debt.

Authors in the *Philosophical Transactions* were identified. At the head of his papers in the journal, Cavendishs name appeared together with his rank and affiliation, "Hon. Henry Cavendish, F.R.S." As the later president of the Society Joseph Banks explained to a contributor, by the "name" of an author the Society did not mean a "bare signature but such additions local and professional as may lead any one of us at once to a knowledge of the person intended by it."[32] The "additions" did not include terms like "botanist." Readers of a botanical paper would draw their own conclusion about the author's scientific field. In the body of their papers, authors sometimes referred to one another by specialized terms such as "botanist," "chemist," and "electrician," at other times by broad terms. A person who studied minerals might be called a "natural historian" or "naturalist," terms which also applied to a person interested in, say, stones from a rhinoceros's stomach. Someone who studied nature scientifically was a "philosopher," a term which was often qualified: Cavendish was called a "natural philosopher."[33]

Newton was the Royal Society's illustrious president forever. Over the course of Charles and Henry Cavendish's memberships, the Society elected seven presidents, none of whom remotely approached Newton in scientific stature, and in the case of several, the scientific accomplishment was negligible. As a point of honor the Royal Society was quick to defend its standard-bearer from criticisms perceived as partisan, but there was a subtle change. When Charles Cavendish entered the Royal Society, references to Newton in the

[29] William Watson (1750, 355–356).

[30] An exception was a letter sent to the instrument maker James Short, translated from the Latin: Joseph Steplin (1755).

[31] 20 May 1773, Minutes of Council, Royal Society, 6. In 1780, a paper in Swedish by Carl Peter Thunberg and one in Italian by Felice Fontana were printed in the body of the journal, their English translations in an appendix.

[32] Draft letter by Joseph Banks, 28 Dec. 1791, Banks Correspondence, Royal Botanic Gardens, Kew.

[33] Here and there; e.g., *PT* 46 (1750): 118, 362, 589.

Philosophical Transactions were generally to praise. Twenty years later, when his son Henry was at college, references to Newton were still to praise and were always respectful, but they tended to be tempered and occasionally were critical. Halley in his ode prefixed to the *Principia* wrote of Newton's "own divinity," of a thinker "nearer to the gods no mortal may approach"; to Henry Cavendish and his contemporaries Newton was definitely mortal, capable of occasional error and in need of correction. Thomas Simpson, mathematics teacher at the Royal Military Academy at Woolwich and the principal contributor of mathematics to the *Philosophical Transactions* at this time, solved a problem in inverse fluxions (integration) conscious that his solution differed from Newton's, acknowledging that it was "impossible to disagree without being under some apprehensions of a mistake."[34] Concerning the precession of the equinoxes Cavendish wrote in a letter, "As well as I remember Newton as you said really made a mistake from not considering this."[35]

If foreigners pointed out Newton's mistakes, it was in their interest to be certain. An Italian who claimed to have discovered six errors in Newton's *Principia* was answered by the home guard.[36] The French astronomer Alexis Claude Clairaut maintained that Newton's inverse-square law of gravitation was inexact. Having detected an absurdity in Clairaut's reasoning, the astronomer and fellow of the Royal Society Patrick Murdoch wrote a paper to dispel the erroneous view that Newton's propositions on the motions of the moon were "mere mathematical fictions, not applicable to nature"; on the contrary, Newton's work was "fully confirmed and verified."[37] Clairaut wrote a kind of apology for the *Philosophical Transactions*, saying that he had not intended to disparage Newton. Newton had not thought it impossible to be "opposed by experience," but in their zeal some people did not distinguish "between the different ways of opposing that great man's sentiments"; still, if the Royal Society wished, Clairaut would reword his disagreement with Newton.[38] Clairaut changed his mind about the inverse-square law and made a public retraction. His criticism of Newton was turned to praise by the Swiss mathematician Leonhard Euler, who too had once believed that Newton's theory conflicted with observations of the motion of the moon; Clairaut's retracted claim, he said, had not been damaging but on the contrary had given "quite a new lustre to the theory of the great Newton."[39]

Euler did, however, pick a quarrel with Newton on the subject of aberration in refracting telescopes. The imperfection of the image was understood to arise from two sources, the different refrangibility of different colors, and the shape of the eye-glass. The latter was a matter of craft; the former was believed to have no remedy. Newton was cited as the authority for this discouraging conclusion, and though in principle he had not ruled out the possibility of an achromatic lens, he had not succeeded in constructing one and had come to doubt its practicability.[40] Euler believed that Newton was wrong, and he corrected him in letters to the *Philosophical Transactions* containing his prescription for making achromatic refracting telescopes. The English optical instrument maker John Dolland gave the rejoinder this time, deferring to Newton, "that great man," who had proved that it was impossible

---

[34]Thomas Simpson (1748, 333).
[35]Henry Cavendish to Nevil Maskelyne, 29 Dec. 1784, draft; in Jungnickel and McCormmach (1999, 600).
[36]James Short (1753a, 14–15).
[37]Patrick Murdoch (1751, 62–63, 74).
[38]Alexis Claude Clairaut (1753, 82–83).
[39]Leonhard Euler (1753).
[40]D.T. Whiteside in Newton (1967–1969, 442–443).

to eliminate that aberration.[41] Dolland would change his mind; his polemic with Euler led him to make new experiments, the results of which differed "very remarkably" from those in Newton's *Opticks*.[42] By combining different kinds of glass, Dolland constructed achromatic lenses, for which bold heterodoxy he was awarded the Copley Medal in 1758. The problem of indistinctness of images in refracting telescopes was not completely solved, and Cavendish would investigate it. Thomas Melvil was more speculative in his disagreement with Newton. He rejected Newton's understanding that the different refrangibilities of light were owing to different sizes or densities of the particles of light of different colors, explaining that Newton had been misled by an "analogy" between the refraction of light and the gravity of bodies; the true cause of different refrangibilities was the different velocities of particles of light of different colors. As this serious challenge to Newton had observational consequences, the Royal Society ordered the instrument maker and astronomer James Short to investigate them and report back; Melvil's hypothesis was found not to hold up.[43] Henry Eeles combined his explanation of the ascent of vapors with a broad criticism of Newton. Defending his "hypothesis" of the fluid of fire against the disapproval of "our great modern philosopher" of the use of hypotheses in general, Eeles observed that Newton's objection to hypotheses appears in a place in his writings that is entirely hypothetical, the queries in his *Opticks*. Even gravitation, he said, would not have occurred to Newton without a hypothesis since a "supposition must always precede the proof"; if a hypothesis is rationally founded, it should be tested, for that is how science advances.[44] In various researches of his, Cavendish confidently spoke of his "hypothesis." Newton at midcentury was still the great Newton, but opinions could be conflicting on his authority on this or that point.

Scientific conclusions had to be supported by facts, but on the question of whether greater trust was to be placed in observation or in theory, the answer was not always observation. James Short set out to clarify the disagreement between the observed shape of the earth and Newton's theoretical prediction of it. Critics of Newton's theory such as Clairaut had erred, Short said, in regarding their observations as absolutely exact (Clairaut denied that he placed too much certainty in observations) whereas other observers such as Roger Joseph Boscovich had erred in thinking that observations were too inexact to draw any conclusions. When theory and observation were compared, theory could not be faulted until the disparity with observation was greater than the errors attributed to the instrument and its user. Newton had a just appreciation of such limits, as shown by his calculation of the ratio of the two diameters of the Earth as 229 to 230, that is, to three figures, not to four or more figures, which would have been a pretense of accuracy. It would be "absurd" for an observer to compute an angle to a second or a length to a part of an inch if the instrument could only measure to a degree or a foot. Mathematical results were rigorously true, but observations had "certain limits," and the error of the instrument was itself one of the "*data*." Short urged observers to follow the "judicious caution" of Newton and to read Cotes's treatise on errors.[45] To "di-

---

[41] Under the general heading: "Letters to a Theorem of Mr. Euler… for Correcting the Aberrations in the Object-Glasses of Refracting Telescopes," *PT* 48 (1753:287–96). One letter was by James Short; other letters were Leonhard Euler, "Letters Concerning a Theorem of His, for Correcting the Aberrations in the Object-Glasses of Refracting Telescopes," and John Dolland, "A Letter […] Concerning a Mistake in M. Euler's Theorem for Correcting the Aberrations in the Object-Glasses of Refracting Telescopes."

[42] John Dolland (1758, 736).

[43] Thomas Melvil (1753, 262).

[44] Henry Eeles (1755, 124–125).

[45] Short (1753a, 5–7).

minish the errors arising from the imperfections of instruments, and of the organs of sense," the mathematician Thomas Simpson proved that it was better to make many observations than only a few and that by taking a mean of them, the chance of making small errors was reduced and the chance of making great ones was almost eliminated. The method was used by astronomers, and Simpson urged all experimenters to adopt it.[46] In part because of his consideration of the limits of accuracy, Cavendish's experimental work was advanced for his time.

For a fact to be established by experiment, the experiment had to be repeatable. William Watson said of an experiment purporting to prove that electricity communicates odors through glass that it must succeed in Venice and Leipzig, as it did, and also in Wittemberg, Paris, Geneva, and Turin, where it did not. A friend of the original experimenter and six fellows of the Royal Society met at Watson's house to repeat the experiment, after which Watson reported that the experiment did not succeed in London either.[47] The original experimenter might himself repeat his experiment in the presence of one or more witnesses. John Canton repeated his experiment with powerful artificial magnets before the president of the Royal Society, who then informed the Society of what he had witnessed.[48] A still more objective way was for the original experimenter to have his experiment repeated by another operator as well as having it witnessed; Cavendish took this course in answering the objection of experimenters who were unable to repeat one of his experiments.

To establish a fact by observation instead of by experiment, independent observations were desirable. Peter Newcome of Hackney Academy reported that six persons in his house felt an earthquake upstairs but no one downstairs did. A similar experience was reported by another person in another house, but that report was not as valuable, since it depended "indeed upon the perception of a single person; whereas his [Newcome's] is verified by the sensations of six different ones."[49] Testimonials by witnesses were collected and weighed. The mental capacity of witnesses was considered relevant to the testimony, as were their profession, wealth, and rank.[50] The author of a paper on a bright rainbow said that he heard about similar rainbows from "intelligent persons."[51] Another author heard about earthquakes from "a very sensible Scotchman" and a woman with "superior" judgment, accuracy, veracity, and a title.[52] The president of the Royal Society was assured that certain observers of an earthquake in Plymouth were not "mean, ignorant, or fanciful" but truthful, "rational and just."[53] When a great storm struck a village, the reporter went to the spot taking with him reliable men, the local physician and clergyman.[54] The dimensions of an "extraordinary" young man, two feet seven inches tall and twelve or thirteen pounds, were confirmed by eight witnesses, all "of figure and fortune" in the neighborhood.[55] In the cases above, reliability became an issue in part because of the uniqueness of the phenomenon, which unlike an

[46] Thomas Simpson (1755).
[47] Watson (1750, 349; 1751, 237–238). Steven Shapin (1988, 399).
[48] John Canton (1751, 32–33).
[49] Peter Newcome (1750). James Burrow (1750a).
[50] Shapin (1988, 398–399).
[51] Peter Davall (1749, 195).
[52] James Burrow (1750b, 626). Lady Cornwallis told James Burrow of her experience of an earthquake: James Burrow (1750c, 703).
[53] William Barlow (1750, 693).
[54] William Henry (1753, 1).
[55] John Browning (1751, 279). This was actually an account of premature aging. The child was displayed for money in Bristol.

experiment could not be reproduced, though the young man presumably could be measured again. The character and maturity of assistants were also relevant. An experimenter who had been assisted by untrustworthy servants became "very delicate in the choice of the persons who I was desirous should be admitted to our experiment"; he would never again use "children, servants, or people of the lower class."[56] Persons Cavendish invited to witness his experiments likely were fellows of the Royal Society, whose reliability was assumed to be beyond question.

Observers sometimes came together to examine instruments jointly[57] or to collaborate in making observations.[58] No one was more active in cooperative astronomical work in the middle of the eighteenth century than James Short. At his house, he with three other persons observed the occultation of Venus by the Moon,[59] and at his and another house, he with two others observed the transit of Mercury, while at five more locations observations of this event were made by still others.[60] To observe an eclipse of the Sun, Lord Morton invited Short and a French astronomer to his castle north of Edinburgh. This excursion was part of a wider effort in Scotland to observe the eclipse, which was coordinated by cannon fired from Edinburgh Castle; bad weather obscured it at Edinburgh, but observations were made at Morton's and at nine other locations in Scotland.[61] Cavendish did extensive preparations for observing the transits of Venus, a project calling for a collaboration of observers around the world.

The *Philosophical Transactions* regularly contained papers about instruments usually submitted by the persons who made them. They were invariably illustrated by detailed, scaled drawings, without which descriptions of instruments were hard to follow; Smeaton said that the construction and use of his pyrometer were clearer from the drawing than "from many words."[62] The importance of instruments was obvious—almost; from Norwich, a keeper of records of the weather complained that many people in his neighborhood judged the weather only by their "outward senses," without resorting to the thermometer, and accordingly they made mistakes, such as putting the hottest day in June when it was in July.[63] In astronomy the importance of instruments and their quality had long since been demonstrated, though James Bradley thought that the point was still worth making in the middle of the eighteenth century. Not long ago, he said, astronomy had seemed perfected and no further progress was expected, a conclusion based on the instruments at hand, the telescope and the pendulum clock, and on the theory of "our great Newton." Bradley had shown that this confidence was misplaced. First he discovered the aberration of light by observation, and then recently he discovered another annual change in the place of the stars, nutation, caused by a nodding of the axis of the earth, which was perceptible only because "of the exactness of my instrument." The pull of the Moon on the equator of the Earth was under-

[56] Abbé Nollet (1749, 377).
[57] John Smeaton (1754a, 535, 537, 539–540).
[58] Romé de l'Isle (1954). The subject is the parallax of Mars, determined by observations at two places on earth, in France and in England.
[59] The other observers were John Bevis, John Pringle, and the duke of Queensbury. John Canton observed the event at his house too. John Bevis (1751). Also James Short (1751).
[60] The other observers at different places were John Birch, Jonathan Sisson, John Bird, John Smeaton, John Canton, and Lord Macclesfield. James Short (1753b).
[61] James Short (1748, 591).
[62] John Smeaton (1754b, 600, 605).
[63] William Arderon (1750, 574).

stood theoretically, but the nutation of the Earth had not been foreseen. This object lesson in discovery demonstrated the "great advantage of cultivating this, as well as every other branch of natural knowledge, by a regular series of observations and experiments." The "more exact the instruments are […] and the more regular the series of observations is […] the sooner we are enabled to discover the cause of any new phenomenon." Bradley advised astronomers to begin by examining the correctness of their instruments,[64] a practice he himself followed religiously. No astronomer before him had so thoroughly examined his instruments in search of error, studying them individually and comparing them one with the other.[65] In Bradley's spirit, Cavendish examined instruments in both of these ways and in every branch of physical science, and as Bradley recommended he cultivated experimental fields comprehensively. It is significant that Bradley signed the certificate proposing Henry Cavendish for membership in the Royal Society.

In the middle of the eighteenth century, observations with measuring instruments appeared in reports on a wide variety of subjects in the *Philosophical Transactions*: a measured draft given to, and blood taken from, a patient;[66] the path of a stroke of lightning;[67] the heat of a cave.[68] Henry Miles, a clergyman with a wide-ranging interest in quantities, who reported a measurement of the "bigness" of a fungus, 210th part of an inch,[69] communicated an unusual kind of paper to the *Philosophical Transactions*, a philosophical essay on quantity. In it quantity is identified with "measures," which require a "standard," so that "all men, when they talked of it, should mean the same thing."[70] As quantity applied to anything short of affections and appetites, so did measures and standards. For example, the physician John Pringle laid down "standards" in his quantitative ranking of salts by their power to resist putrefaction.[71] A quantitative experimentalist, Cavendish defined and routinely used standards.

The quantitative direction in scientific work is seen in various forms in the *Philosophical Transactions*. Chemistry suffered from the unrepeatability of its experiments, according to Cromwell Mortimer, a physician who studied the effects of chemical remedies in diseases. The reason, he said, was the failure of chemists to record the heat: the chemist's laboratory should be equipped with "various Sorts of Thermometers, proportioned to the Degree of Heat he intends to make use of," and he should keep track of the time the heat is applied, observing "his Clock with as much Exactness as the Astronomer."[72] Cavendish used thermometers extensively in his experimental work, and he improved their accuracy; and in his heat experiments he used clocks to find the rate of cooling. Richard Davies, formerly a Cambridge fellow, published an impressive quantitative study based on weighing, a table of specific gravities, justified by their "manifold applications […] for the purposes of Natural Philosophy," as shown by the "great author" Newton, who determined specific gravities with the "most scrupulous care and exactness" in his optical inquiries, and as further shown by Hauksbee, Cotes, Jurin, Musschenbroek, and other natural philosophers, mathe-

---

[64] James Bradley (1748, 1–5).
[65] Allan Chapman (1993, 209).
[66] George Bayly (1751).
[67] Henry (1753).
[68] William Arderon (1748).
[69] Henry Miles (1750b).
[70] Henry Miles (1748, 506).
[71] John Pringle (1750).
[72] Cromwell Mortimer (1747/1746, 673). This paper was first read in 1735 and printed later with revisions.

maticians, and physicians.[73] In chemistry, Cavendish distinguished different species of air by their specific gravities, an experimental measure capable of considerable accuracy. His precision chemical balance is described later in this book. Wilson could not picture Cavendish without his measuring instruments: wherever we catch sight of Cavendish, he said, "we find him with his measuring-rod and balance, his graduated jar, thermometer, barometer, and table of logrithms; if not in his grasp, at least near at hand."[74] Cavendish was doing what investigators in many subjects in the second half of the eighteenth century were doing, making measurements.

Electricity was the most active experimental field in mid century. In this "new field of researches," Stephen Hales wrote in the *Philosophical Transactions* for 1748, "there are daily new discoveries made."[75] Emanuel Mendes da Costa, future clerk of the Royal Society, wrote in 1753 that electricity was "now a days the chiefest occupation of philosophers."[76] Cavendish's father carried out experiments on electricity in collaboration with William Watson, who had improved the device that transformed the field, the Leiden jar.[77] Important in a related way was Watson's review of Benjamin Franklin's book on electricity, consisting mainly of letters to his English correspondent, all or parts of which had been read at the Royal Society.[78] There was a sense among electrical investigators that they were no longer working on the periphery of the subject but were dealing with questions of the "nature" of electricity, its "general principles," "quantities" of electricity, and the "laws of electricity."[79] Twenty years later, drawing on the work of Watson and Franklin, based on a hypothesis about the nature of electricity, Cavendish pursued experimental and theoretical researches on the quantities, principles, and laws of electricity.

Electricity had begun to be studied in the laboratory of nature. In the *Philosophical Transactions*, Franklin proposed investigating lightning and referred to the "Philadelphia experiment."[80] Watson together with several fellows of the Royal Society tried without success to draw electricity during a thunderstorm, but John Canton, Benjamin Wilson, and John Bevis succeeded.[81] Daring experiments on lightning were reported to the Royal Society from around the world. Cavendish would serve on a lightning committee of the Royal Society.

Lightning was new insofar as it was explained by electricity but otherwise it belonged to the general class of violent events, which were a staple of the *Philosophical Transactions*, as they were of life in the eighteenth century. Incidents of thunder and lightning with their attendant "melancholy accidents" were regularly reported, minutely described, and occasionally measured. Lightning struck a ship in a "violent manner, disabling most of the crew

---

[73] Richard Davies (1748, 416–435).
[74] Wilson (1851, 187).
[75] Stephen Hales (1748b, 410).
[76] Emanuel Mendes da Costa to William Stukeley, 9 Nov. 1753, in John Nichols (1817–1858, 4:503).
[77] William Watson (1747, 709 ff).
[78] In 1746, the Royal Society learned of the Leiden jar. Acting on a suggestion by John Bevis, Watson increased the effect of the Leiden jar by lining both sides of the glass with metal and also by making the glass thin. That same year he explained how his theory of electricity explained the action of the Leiden jar. In 1747, Charles Cavendish forwarded to Watson a letter from Franklin giving his explanation of the Leiden jar. In 1748, Watson told the Royal Society that his and Franklin's theories of electricity were effectively the same. Simon Schaffer, "Watson, Sir William," *DNB*, 2d ed. (http://www.oxforddnb.com/view/printable/28874).
[79] John Ellicott (1748, 196, 221–222).
[80] Benjamin Franklin (1752).
[81] William Watson (1752a); John Canton (1753). There were many papers at this time on lightning experiments.

in eye and limb."[82] The mainmast of another ship was shattered when a "large ball of blue fire" rolled over the water and exploded, "as if hundreds of cannon had been fired at one time."[83] In a valley, in the "violence of the storm," a cloudburst and flash flood threw up "monstrous stones," which were "larger than a team of ten horses could move."[84] A meteor that looked like a "black smoky cloud" split an oak, and its "whirling, breaks, roar, and smoke, frightened both man and beast."[85] Clouds and auroras were seen to turn "blood-red."[86] Plagues of locusts "hid the sun," and undeterred by "balls & shot," they "miserably wasted" the land.[87] Victims of the Black vomit" experienced delirium "so violent" that they had to be tied down so that they did "not tear themselves in pieces."[88] Bitten by a mad dog, a horse in its agony gave off breath "like smoke from a chimney-top," with "much blood scatter'd up and down the stable."[89] An experimental dog was held in a poisonous vapor on the floor of a grotto, "tortured for three minutes," then revived. After being given a South American poison, a "great number of living animals" were "seized with a sudden and almost universal palsy" before they died.[90] Many of the medical papers in the *Philosophical Transactions* described extreme pathologies and monstrocities in more or less ordinary language, unsparing of the reader. Medical procedures could be as terrible as the illness or trauma that called for them. A woman with a "violent pain" in her eye went to a surgeon, who cut out the eye, "bled her plentifully," applied a blister to her neck, and purged her repeatedly.[91] Children were carried away by contagion, in the course of which a five-year-old girl was observed to cough up a "large quantity of white rotten flesh" in her so "violent a death."[92] In Constantinople the plague was raging, becoming "most violent" when the weather was hottest, as if to make it worse.[93] Few persons escaped the "small-pox sooner or later in life," with its "very terrible consequences," and those who had escaped it lived "in continual apprehensuins and fear thereof."[94] A doctor of divinity and fellow of the Royal Society reported on an extraordinary case of a young man whose tendons and muscles were turning to bone, indicating that if the poor man lived, he would become "completely ossified."[95] When limbs were amputated, agaric was plugged into the severed arteries, eliminating the usual method of needle and ligature, the most painful part of amputations and sometimes the cause of death.[96] The fright and misery of the world eventually would be brought to an end because the world was going to end, according to astronomical calculation, by spiraling toward the Sun and on its way "necessarily be burnt."[97] Reading the journal could be a disquieting experience. Cavendish, who presumably read about violent events appearing in the *Philosophical Transactions*, was not drawn to them in his studies. He advised on the

[82] William Borlase (1753); John Waddell (1749, 111–112).
[83] Chalmers (1749, 366).
[84] John Lock (1750/1749).
[85] Thomas Barker (1749).
[86] Henry Miles (1750a, 348). William Stukeley (1750c, 743).
[87] Anonym (1749, 30–37, on 30–31).
[88] Antonio de Ullöa (1749, 46:134–39, on 135).
[89] John Starr (1750a, 474, 478).
[90] Abbé Nollet (1751, 53). F.D. Herrisant (1751, 90).
[91] Edward Spry (1755).
[92] John Starr (1750b, 439).
[93] Mordach Mackenzie (1752).
[94] Richard Brooke (1752, 470).
[95] William Henry (1751, 89).
[96] Joseph Warner (1754).
[97] Leonhard Euler (1749, 204).

way to protect against lightning strikes, but he left no first-hand observations of them or, for that matter, of most one-of-a-kind phenomena.

In the laboratory the violence of nature was simulated, and it could be dangerous; lacking apparatus with effective safety features, investigators sometimes were "intimidated" and "deterred," in "danger of being hurt."[98] In 1753 the German physicist Georg Wilhelm Richmann living in Russia was electrocuted in a room containing his apparatus while performing an experiment on the electrical nature of lightning.[99] The discharge of a Leiden jar was analogous to lightning; if the Leiden jar was mishandled, its artificial lightning could be dangerous to the operator.[100] Cavendish was aware of the potential violence of the laboratory. "To avoid being hurt" by a bottle in which he exploded gases, he manipulated his apparatus by a string at a safe distance.[101]

The most frightening event reported in the *Philosophical Transactions* was an earthquake. The year 1750 "may rather be called the year of earthquakes, than of Jubilee," a fellow of the Royal Society observed. The earthquakes of that year occurred as if on command of the Royal Society, being thought to center on London, "the place to which the finger of God was pointed."[102] Cavendish was in his second year at the University when an entire issue of the *Philosophical Transactions* was devoted to earthquakes and to the "natural philosophical understanding" of such "wonders."[103] Presented as an appendix to the regular issues, the earthquake issue consisted of fifty-seven papers submitted to the Royal Society dealing with four earthquakes felt in England and on the Continent that year, a foreshadowing of the great earthquake of 1755 that destroyed Lisbon.

About half of the observers reporting firsthand on the earthquakes of 1750 in the *Philosophical Transactions* were fellows of the Royal Society, who also collected testimony and communicated letters from other observers who were not.[104] Fellows or otherwise, observers of earthquakes rarely noted the direction, time, and duration of the shock.[105] As earthquakes went, those of 1751 were not especially severe—Gowin Knight thought it was worth reporting that in a neighbor's house a "firkin of butter" was thrown from a shelf[106]—but witnesses experienced them as "violent." People thought first of gunpowder, cannon, the explosion of a magazine or powder mill or a mine, or lightning.[107] In his house, Martin Folkes along with Macclesfield and other visitors "felt themselves strongly lifted up, and presently set down again," while the coachmen standing outside Folkes's door feared

[98] We go beyond the time when Cavendish was at the University to when he began his electrical and chemical experiments at home. CL'Epinasse (1767, 188); Peter Woulfe (1767).

[99] William Watson (1754).

[100] Henry Eeles (1752). Eeles took exception to the standard analogy between fired gunpowder and thunder, proposing in its place an up-to-date explanation based on the fire observed in electrical experiments.

[101] Henry Cavendish (1766); in *Sci. Pap.* 2:77–101, on 82.

[102] William Stukeley (1750a, 669; 1750c, 732).

[103] Issue no. 497, *Philosophical Transactions. Being an Appendix to Those for the Year 1750.* Simon Schaffer (1983, 17–18).

[104] Of the 57 papers, the first 26 were all by fellows of the Royal Society. Of the remaining 31 papers, at least 16 were by fellows of the Royal Society. They included many prominent members, but Charles and Henry Cavendish were not among them, and few of them had Cavendishes' interests: astronomy, chemistry, mathematics, and natural philosophy. The earthquakes did not provide an opportunity for those who used instruments and made measurements on a regular basis.

[105] "It is no wonder, that in a shock so sudden and alarming, that very few satisfactory observations are made." William Cowper (1750, 648).

[106] Gowin Knight (1750b, 604).

[107] Smart Lethieullier (1750).

the house coming down on their heads.[108] Gowin Knight's house "shook violently," and the duke of Newcastle's servant told him that all the way from London Bridge the people were frightened.[109] Animals too were frightened: a cat was startled, a dog was terrified, cows and sheep were alarmed, fish were disturbed, a horse refused water, and crows took flight.[110] Sensations were described variously, such as "falling into a fit."[111] Roger Pickering, a close observer of the weather and natural curiosities, gave a detailed account of his sensations while lying in bed; being a clergyman, he gave his reflections, which led him beyond the "secondary causes" of the earthquake to the grandeur and majesty of the "Lord of Nature."[112]

The "secondary causes" were the scientific question, to which two answers were published in the *Philosophical Transactions*. Stephen Hales, a clergyman, said that both the ordinary and the extraordinary events of nature were caused by God, but that they did not lie outside natural explanation for that reason. After describing his sensations while lying in bed during a tremor, he explained with reference to an experiment from his *Statical Essays* that an earthquake is caused by the explosive mixing of air with sulfurous vapors rising from the the pores of the Earth.[113] William Stukeley, another clergyman, after a perfunctory consideration of the religious view, attributed earthquakes to "electrical shock, exactly of the same nature as those, now become very familiar, in electrical experiments." With reference to Franklin, Stukeley said that the "little snap, which we hear in our electrical experiments, is the same snap, only magnified, that we hear in thunderstorms." Having gotten to know the "stupendous powers" of electricity by experiment, he called on electricity to explain the "prodigious appearance of an earthquake."[114] Hales's and Stukeley's causes of earthquakes, aerial substances and electricity, were the main experimental subjects in Britain in the second half of the eighteenth century, as they were two of Cavendish's main experimental fields.

Reports of the catastrophic Lisbon earthquake in 1755 filled the last roughly hundred pages of the volume of the *Philosophical Transactions* for that year and much of the next year's. Unlike reports of the earlier earthquakes of 1750, these recounted loss of life and physical destruction. The most important single response to the earthquake was John Michell's paper on the general cause of earthquakes, which he owed to the bounty of facts about the earthquake of 1755, many of which had been collected by the Royal Society and published in its journal. He acknowledged that observations of the earthquake were often carelessly made and reported, but the "concurrent testimonies" of so many persons established the main points. Having selected data that had the "greatest appearance of accuracy," he took a "mean" of them.[115] We move ahead a few years after Cavendish had left Cambridge to consider Michell's paper, which was printed in the *Philosophical Transactions* for 1760; Michell would be important to Cavendish, and this paper suggests why.

Michell disagreed with Hales and Stukeley, who located the cause of earthquakes near the surface of the Earth. Volcanoes were proof that fires could exist underground without contact with the air, and by analogy (and for other reasons) Michell concluded that volcanoes

[108] Abraham Trembly (1750, 611).
[109] Gowin Knight (1750b, 603).
[110] Various reports: *PT* 46 (1750): 618, 621, 641, 651, 682.
[111] Thomas Birch (1750, 616).
[112] Roger Pickering (1750, 625).
[113] Stephen Hales (1750, 676–677).
[114] William Stukeley (1750b, 642–644; 1750a, 663).
[115] John Michell (1760, 629).

and earthquakes had the same cause, the contact of underground water with underground fire, turning the water instantly and explosively into steam. The steam in turn compressed the matter of the Earth, and because the Earth was elastic, the compression was followed by dilation, generating waves that were propagated horizontally over a long distances. Michell made the scientific study of earthquakes quantitative by developing methods for determining their velocity, location, and depth, which he applied to the Lisbon earthquake, with implications for geological science. His theory of earthquakes was a beginning of an exact, dynamical science of the Earth. When Cavendish heard Michell's paper read, he would have recognized its author as a fellow natural philosopher. In the judgment of later geologists, Michell's earthquake paper contained results that were more important than his theory of earthquakes, having to do with his understanding of the Earth as consisting of uniform strata.[116] Cavendish made a prolonged study of strata, in communication with, and at least in part because of, Michell.

Like earthquakes, the weather was a force of nature to be reckoned with, and some persons (not Michell) believed that there ought to be a connection, consulting their thermometers and barometers whenever they felt a tremor.[117] Some persons read their weather instruments every day, compiling local histories both of extreme and of normal activity. In the accounts they sent to the Royal Society, they usually gave rainfall, pressure, and temperature, often including the mean and the highest and lowest. The clergyman Henry Miles submitted a paper about the thermometer, an indispensable instrument of the weather, which Newton had considered and others had tried to bring to "greater Perfection."[118] The credibility of the mercury thermometer, which was generally accepted as the best kind of thermometer, was implicitly put to the test in the extreme climate of Siberia, where temperatures below -100°F were recorded.[119] Cavendish clarified the behavior of mercury thermometers and at the same time corrected reports of extreme natural cold on Earth. He was recognized as the Royal Society's leading expert on the thermometer and other instruments of the weather.

The naturalist William Arderon, who published frequently on the weather in Norwich, kept a record of the constant temperature in a cavern under nearby hills, which he compared with the mean of the temperatures above ground, finding them almost identical, and he found the same for the temperature of a spring in the cavern.[120] Cavendish frequently measured the temperature of springs and deep wells, encouraging a worldwide effort to measure average climates that way.

Some authors appearing in the *Philosophical Transactions* worked in both the physical and the life sciences, or they brought the physical sciences to bear on the problems of the life sciences. The Royal Society's Croonian Lecture on the nature and laws of muscular motion in 1747 was given by the physician Browne Langrish, who explained muscular motion by Newton's atttracting and repelling forces, dedicating his lectures to Stephen Hales, whose "indefatigable Researches into Nature" showed that particles of air are attracted to solids. Langrish's "scheme" was based on "those Hints which Sir Isaac Newton has given us in the Queries at the End of his incomparable Book of Opticks."[121] In 1751 the physician Charles

[116]Michell (1760, 582).
[117]Henry Miles (1749).
[118]Henry Miles (1750c).
[119]John Fothergill's extracts from Gmelin (1748, 260). William Watson (1753a).
[120]William Arderon (1748).
[121]Browne Langrish (1747, i–ii, 7–8).

Morton published a paper on the same subject, muscular motion, which he, a follower of the "Newtonian, which is the philosophy of nature," organized by observations, experiments, lemmas, and scholia; in keeping with tradition, Morton regarded his subject as belonging to "natural philosophy."[122] To the physician William Watson, known for his researches alike on plants and electricity, the study of living nature had the same goal as the study of the physical world, which was to learn the "general laws" of nature, from "which however she sometimes deviates." Cavendish did research in all parts of physical science; he did not do research on plants and animals to understand *their* laws, but in several of his researches he studied physical properties of plants and animals.

Astronomy and classics came together in the *Philosophical Transactions*. The antiquarian William Stukeley said that scholars had gotten the year wrong for the solar eclipse predicted by Thales. With the help of an astronomer, he corrected them, demonstrating the "admirable use to be made of astronomy in ascertaining matters of history."[123] There was a tradition of astronomical reasoning in history, and just as in science, in chronology Newton received gentle criticism.[124] A Jesuit who had worked out a chronology of ancient China proposed to do the same for Chinese astronomy.[125] Cavendish made a study of the Hindu calendar.

Honoring Bacon's ideal of a scientific society that "labours to relieve the necessities of human life,"[126] the Royal Society accepted communications that were directed to utilitarian ends. At the time Cavendish was studying at the University, the *Philosophical Transactions* included papers on mechanical power, manufactures, gunnery, navigation, medicine and health, and the prevention of disasters. Distinguished "both as a chemist, and as a philosopher," William Brownrigg investigated salt-making. In a review, Watson hoped Brownrigg would do what the Royal Society's historians of salt-making had not, overcome Britain's disadvantage in this trade.[127] John Mitchell gave a history of potash-making, which in England was "practiced only by the vulgar, and neglected and overlooked by the learned." No nation could do without potash, an essential ingredient in soap, bleach, and glass, and England was a nation that did not know how to make it correctly.[128] John Smeaton showed the Royal Society a tackle of twenty pulleys small enough to fit into the pocket, and with another block of pulleys, he offered an Archimedean-like demonstration of a single person lifting a gun and carriage aboard a naval ship. The reason he brought his compound pulley before the Society was its promise of "much utility […] for merchants, seamen, builders, engineers, &c."[129] Like the pulley, the steam engine made possible the lifting of heavy weights, and it too could be improved, as Smeaton showed by his modification of Thomas Savery's early steam engine, which was useful in raising water from mines and supplying water.[130] In Newgate prison, infectious fevers killed convicts and officers of courts of justice who were exposed to convicts during trials; to achieve "purity of air" in the prison, it was decided to install

[122] Charles Morton (1751, 308, 314).
[123] William Stukeley (1753, 222).
[124] Ibid. George Costard (1753, 19).
[125] Gaubil (1753, 309–317).
[126] William Watson's expression, from his abstract and review of a book that fit the Royal Society's ideal: "An Account of a Treatise by Wm. Brownrigg …" (1748b, 372).
[127] Ibid., 352.
[128] John Mitchell (1748, 541).
[129] John Smeaton (1752a, 497).
[130] John Smeaton (1752c).

a ventilator designed by Hales, worked by a machine resembling a windmill.[131] On Hales and Lord Halifax's recommendation, Captain Henry Ellis installed Hales's ventilators in his ship, which caused candles to burn better, bells to ring louder, and cargo to hold up better, in addition to being "good exercise for our slaves."[132] Electrical healing was more often the product of enthusiasm than of repeatable experiments. Claims for it were received with proper caution, but some medical virtue of electricity seemed evident to nearly everyone at the time, including the careful William Watson, who acknowledged that the administration of a "large quantity" of electricity "greatly heats the flesh, and quickens the pulse," conferring "very great advantages."[133] Bills of mortality documented the relative unhealthiness of places, useful knowledge for "many excellent purposes," including the calculation of annuities on lives, on which a sizeable part of the "real estates of these kingdoms" depended.[134] Spring waters had medical uses, and seawater might be converted to freshwater.[135] Improvements were made in navigation, especially in the mariner's compass, the invention of which, Gowin Knight said, had "probably been of more general and important use to human society, than the invention of any one instrument whatsoever."[136] To celebrate the recent peace, 6000 rockets were fired in Green Park without incident, thanks to Hales's recommendation of spreading a layer of dirt or fine gravel over the wood floor to prevent fire.[137] The *Philosophical Transactions* published papers in these years on military applications such as projectile paths in gunnery and rockets. There were many papers on lightning rods; in this direct application of science, Cavendish was repeatedly called on by the Royal Society.

We see that many of the kinds of scientific problems Cavendish worked over his long life were addressed in the *Philosophical Transactions* at the time he was studying at the University. Through his manner of treating problems and not his invention of them, he left his mark on science.

[131] John Pringle (1753, 42).
[132] Henry Ellis (1751).
[133] William Watson (1752b, 406).
[134] James Dodson (1753, 333–334).
[135] John Bond (1753). William Watson (1753b).
[136] Gowin Knight (1750a, 505). John Smeaton (1750).
[137] Stephen Hales (1748a).