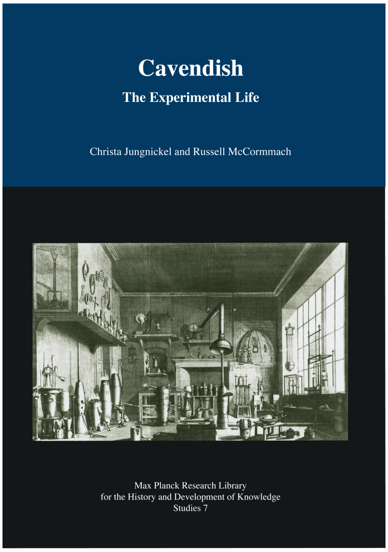
Christa Jungnickel and Russell McCormmach:

Earth



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Chapter 16
Earth

Philosophical Tours in Britain

Active in planning voyages of discovery, Cavendish never went on one himself. He did, however, make a number of journeys by carriage within Britain to expand his knowledge. On the first journey we know anything about, he passed through Oxford to Birmingham and back by way of Towcester, making trials of Edward Nairne's Earth-magnetic dipping needle at each stop, usually in a garden. Those trials may have been the whole point, for it was 1778, soon after Cavendish's report on the meteorological and magnetic instruments of the Royal Society, and he was still very much involved.[1] Beginning in 1785 Cavendish became a regular and more rounded scientific tourist. This fiftyish man of fixed, secluded habits had recently taken on an associate, Charles Blagden, who encouraged his adventurous turn. For three successive summers, Cavendish and Blagden made journeys to several parts of Britain, always in the summer when roads were at their best. A person who helped with arrangements for one of their journeys called it their "philosophical tour,"[2] which it was, though Cavendish called it simply a "journey."

An inveterate traveler, Blagden recorded his journeys in notes and letters, beginning with a journey he took to Scotland to study at age seventeen.[3] We have his report of a visit to Wales when he was twenty-three, an impressionable if unfocused tourist. An admirer of Rousseau, the "most eloquent & feeling of men,"[4] he was drawn to abbeys and vistas but he was also interested in mines, ironworks, and "philosophical curiosities." Having a strong desire to know the larger world, he was struck by the "extreme stupidity" of people who were entirely satisfied with their "little world." Wherever he traveled he was frustrated because people could not answer his simple questions about what lay a mile around them—places, routes, departures.[5] When after serving several years as a surgeon to the British Army in North America he returned to England, he toured Devonshire where he found the coves and rocks "beautiful" and "romantic," and where he also observed mileages, weather, slate, and

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[1] Henry Cavendish, "Trials of Nairne's Needle in Different Parts of England," Cavendish Mss IX, 11:45–54. Dates in the second half of August 1778 are scattered through this record of observations.

[2] George Hunt to Mr. Hext, 23 Jan. 1787, Blagden Papers, Yale, box 1, folder 4.

[3] Charles Blagden to Sarah Nelmes, 1 Nov. 1765, Blagden Letters, Royal Society, B. 159. In other letters from 1767 Blagden gave Nelmes accounts of shorter journeys in Scotland. Nelmes, who lived in Bristol, was related to Blagden. "Accounts, Bills, Insurance, and Copy of Will of S. Nelmes," Blagden Mss, Royal Society.

[4] Blagden recommended reading Rousseau to Thomas Curtis, 26 July 1771, Blagden Letters, Royal Society, B. 162.

[5] Charles Blagden, "Memorandum of a Tour Taken for Four Days Beginning August 18 1771," Blagden Papers, Yale, box 1, folder 3.

clay.[6] His most consequential journey was from Plymouth to London in 1781, where he made a life for himself in science.

It was Blagden who suggested the journey that he and Cavendish made in 1785. Early that year he proposed that they visit John Michell in Yorkshire to see the progress he had made with his "great telescope." Blagden was unsuccessful at first, and by the time Michell extended a formal invitation, he and Cavendish had set out in a different direction.[7] The journey they did make that year was Blagden's idea too, as he explained: he "proposed the scheme one day" of visiting the ironworks near Cardiff, and when he described them, Cavendish became "very curious" and agreed to make the trip. Blagden wrote about their plans to his brother-in-law William Lewis, who was ironmaster at Pentyrch near Cardiff. Lewis offered them his house, but if the "Hammers should be too noisy" he would put them up at another house at a remove from the pounding.[8]

There was nothing odd about Cavendish's curiosity about ironworks. The English aristocracy was generally forward-looking, ready to promote and invest in industry and sometimes to participate directly. They often took a lively interest in engineering and industrial development. When they got together, they might inspect a new canal lock or the draining of a fen, and on journeys they might visit industries on the way. From early on, they had a correct appreciation of the importance of transportation, especially if they were fortunate enough to own land containing minerals. The duke of Bridgewater built a canal running from coal mines on his estate to Manchester, the beginning of a network of water connections. Other peers followed the example.[9]

Cavendish and Blagden kept an account of their tours, written in part by Blagden, and in part by Cavendish.[10] Their first stop in 1785 was Alderley in Gloucestershire, where they stayed with Blagden's older brother John Blagden Hale, and from where they made a side trip to a dye works, the first of their many industrial visits. From Alderley they went to Pentyrch in Wales, where they stayed with William Lewis, who showed them the ironworks. They explored the nearby hills and coal pits, observing strata and testing stones with acid. The dominant feature of the land there is Garth Mountain, which they climbed carrying a barometer (Figs. 16.1–16.2). One of the objectives of Cavendish and Blagden's journeys was to measure heights by the barometer, a method used by surveyors and improved by scientists, in which there was considerable interest at the time.

Ever since Pascal sent his brother-in-law up a mountain with a barometer in 1648, the prospect of measuring the heights of scalable mountains with a barometer was seen as an alternative to the trigonometric method. The barometer measures the difference in height of a mercury column in air and in a vacuum. To translate that difference into the pressure of the atmosphere corrections need to be made for capillarity and temperature (and later for gravity and errors of the scale and the zero of the scale). In his report on the Royal Society's instruments, Cavendish gave corrections for capillarity, using a table prepared by his father

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[6] Charles Blagden, "Tour of the South Hams of Devonshire," 1780, Charles Blagden Diary, Yale, Osborn Shelves f c 16.

[7] Charles Blagden to John Michell, 25 Apr. 1785 and 13 Sep. 1785, drafts; in Russell McCormmach (2012, 399).

[8] Charles Blagden to William Lewis, 20 June 1785, draft, Blagden Letterbook, Yale. William Lewis to Charles Blagden, 25 June 1785, Blagden Letters, Royal Society, L.46.

[9] Montagu of Beaulieu (1970, 150).

[10] The journal is in a wrapper labeled in Cavendish's hand, "Computations & Observations in Journey 1785," Cavendish Mss X(a) 4:8. The journal was written by Blagden, but the copy at Chatsworth is in a copyist's hand. The original is in Blagden's papers at Yale.

of depressions in inches of mercury for bores varying from 0.1 to 0.6 inch diameters.[11] His colleagues Roy, Deluc, and George Shuckburgh, an expert on instruments, gave rules for temperature corrections, Roy's being the best.

Writing in 1777 Shuckburgh said that the method of measuring heights with a barometer had been "capable of but little precision till within these few years." He and Deluc published observations of elevations they had taken on Mont Blanc, Europe's highest peak. Although Shuckburgh used Deluc's rules for correcting the barometer for temperature, his measurements on the mountain differed from Deluc's. Using Deluc's and Shuckburgh's readings, Cavendish calculated the height of Mont Blanc, obtaining a result that was lower than Shuckburgh's by 700 feet. Cavendish also compared rules for taking heights by the barometer by Deluc, Maskelyne, and Pierre Bouguer, referring to his father's experiments on the specific gravity of air at different temperatures and pressures, and he assisted Roy in experiments on the expansion of mercury, again drawing on his father's work. Cavendish did a good deal of work on the barometric method of finding heights before applying it on his journeys in the 1780s.[12]

For carrying up mountains, Cavendish had a portable barometer made by Ramsden. Because it had to be vertical, the barometer came with a tripod, which folded up as a carrying case, with legs hollowed out at the bottom to accommodate the cistern. This barometer was very accurate: the height of the mercury column was read to one-five hundredths part of an inch by means of a nonius moved by rack work. Roy had two instruments identical to Cavendish's, finding them to agree within a few thousandths of an inch.[13]

Heights of Mountains

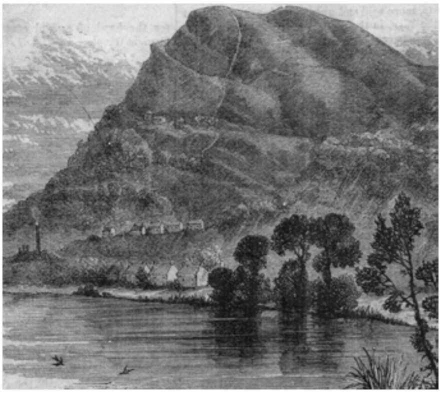

Figure 16.1: Garth Mountain. Near Cardiff. On the lower left, we see a furnace. Courtesy of Cardiff Central Library.

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[11] Middleton (1964, 172, 179, 189).

[12] Gavin de Beer (1956, 3–4). George Shuckburgh (1777, 1–2, 12–13). William Roy (1777, 673). Henry Cavendish, "Rule for Taking Heights of Barometers," Cavendish Mss VIII, 12; "Observations of Thermom. on Mont Blanc," Cavendish Mss, Misc. Charles Blagden to Joseph Banks, 5 Oct. 1786, BL Add Mss 33272, pp. 19–20.

[13] Middleton (1964, 132–133, 161).

Figure 16.2: Portable Barometer. Photograph by the authors at Chatsworth. This is probably the barometer that Cavendish carried to the top of Garth Mountain to measure its height. When folded into its mahogany case, the barometer measures 43½ inches. The instrument is suspended in gimbals. At the bottom, near the wooden cistern, there is a thermometer with a corrections scale. William Roy, with whom Cavendish collaborated on experiments with barometers, used a portable barometer almost identical to this one for taking heights of mountains. Although the Chatsworth barometer is unsigned, we know from Roy that this kind of barometer was made by Jesse Ramsden. Roy (1777, facing p. 658). The photograph is reproduced by permission of the Chatsworth Settlement Trustees.

Lewis showed Cavendish and Blagden the ironworks at Merthyr, where he was a part owner. Between 1759 and 1784, four independent ironworks were built near one another on the outskirts of Wales's first industrial town, Merthyr (Fig. 16.3). The works were still modest in size when Cavendish and Blagden saw them, but in the nineteenth century they would be the center of the British iron trade, and for a time two of the ironworks were the largest in the world.

The operations that Cavendish and Blagden witnessed centered on iron smelting, the first stage of which was carried out in blast furnaces. Built into hills, blast furnaces were usually made of stone blocks, narrowing toward the top and reaching to considerable heights. The furnace at Pentyrch was not especially tall, measuring twenty-six feet with a funnel that rose a bit higher, but the furnace at Merthyr was sixty feet tall. At the ground level of a blast furnace, there was a hearth with access in the front for tapping molten iron and slag. Ore, fuel, and limestone, a flux, were alternately introduced from the top.[14] Once going the red-hot charge might continue burning for weeks or months. A blast of air entered the furnace through one or two side openings near the bottom, increasing the flow of oxygen and raising the temperature of the furnace high enough to melt the materials. Traditionally the blast was produced by leather bellows operated by cams from a waterwheel, but by the time of Cavendish's visit most of the bellows had been replaced by cast-iron cylinders and pistons six feet in diameter, which had greater force. These too were operated by waterwheels, sometimes augmented by steam engines, usually the older Newcomen type, which returned water from the downstream to the upstream side of the wheel.[15] The iron produced by blast furnaces, called pig iron, could be used for making cast iron, but the most common kind of iron in the eighteenth century was wrought iron, which had to be refined. This was done by reheating the pig iron in smaller furnaces, or hearths, called forges.

Ironworks

Figure 16.3: Working Iron at Merthyr Tydfil. Watercolor by J.C. Ibbetson in 1792. A mass of hot iron is being struck by a trip hammer to remove slag. Courtesy of Cyfarthfa Castle Museum.

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[14] Laurence Ince (1993, 9).

[15] Ibid., 9–11.

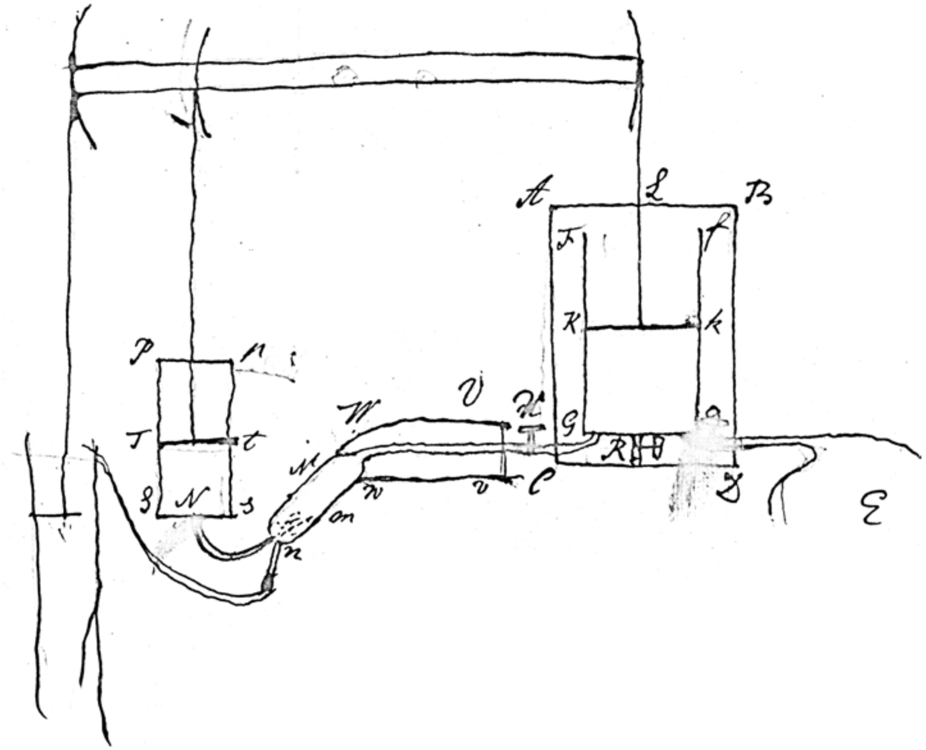

Figure 16.4: Cavendish's Drawing of a Steam Engine. In this diagram, Mm is the condensation chamber, Pp is the air pump, and is Ff is the working cylinder. Cavendish gives the dimensions and the strokes per minute of the engine, and he notes its advantage: "In common [Newcomen] engine as much steam condensed on sides as is used to fill the cylinder." Cavendish Mss, Misc. Reproduced by permission of the Chatsworth Settlement Trustees.

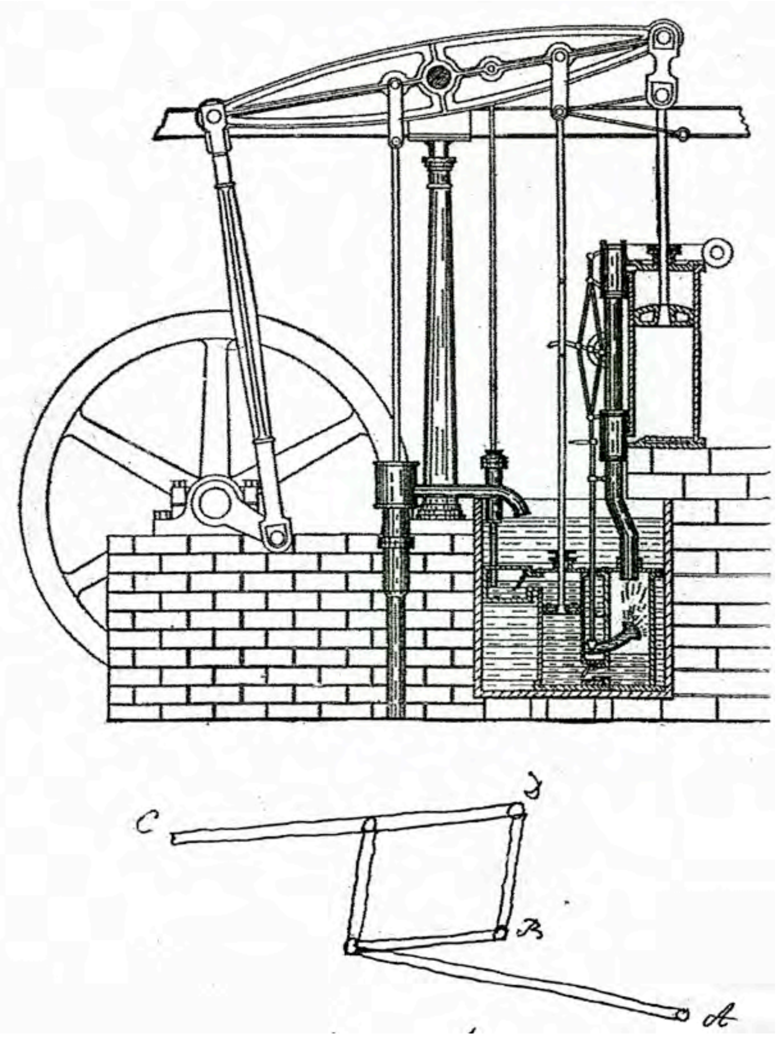

Figure 16.5: Parallel Motion. In the early Watt engines, the piston was connected to the beam by a chain. By replacing the chain with a rod, it was possible to develop power on the upward as well as the downward stroke, to push as well as pull, doubling the action of the engine. There was a problem, however. The piston rod moved vertically, while the beam moved circularly. Watt solved the problem with a four bar linkage between the rod and the beam in the form of a familiar pantograph, which produces parallel lines; in this case, parallel motion. A piston moving vertically up and down transmitted force in both directions to a circularly moving beam. Watt took out a patent on his "parallel motion" in 1784. Cavendish drew a picture of the linkage in his 1785 journal; it is shown at the bottom of this illustration.

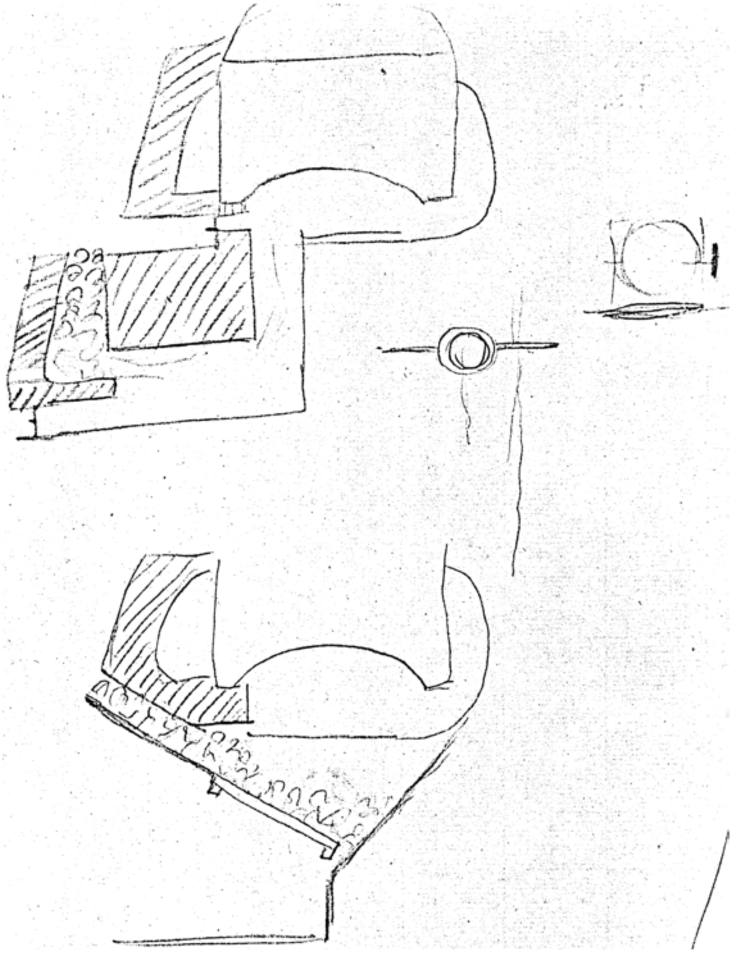

Figure 16.6: Cavendish's Drawing of Watts Furnace for Burning Smoke. In 1785, Watt patented a smoke-consuming furnace. It had two sources of heat. On a grate, there was a regular fire, the first source. Where the fire was drawn into a flue or chimney, there was a second grate containing red-hot coals that had ceased to smoke, the second source; there the smoke of the first fire was consumed. Cavendish Mss, Misc. Reproduced by permission of the Chatsworth Settlement Trustees.

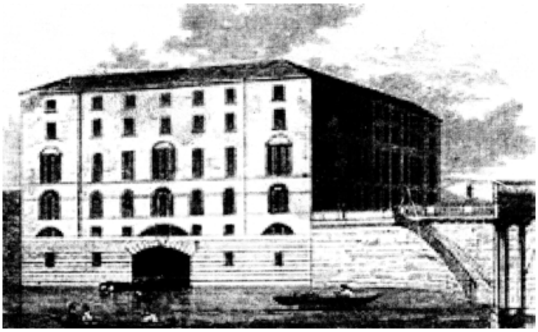

Figure 16.7: Albion Mills. Cavendish may have observed Watt's smoke-consuming furnace in Birmingham on his journey in the summer of 1785, or he may have observed it at Albion Mills, located on the Surrey side of Blackfriars Bridge. Built-in 1783–86, Albion Mills was the largest and technologically most up-to-date flour mill of the time. In the fall of 1785, Watt came to Albion Mills where his steam engine was to be installed. It was his advanced double-acting, rotative engine, proper for turning mills, and it was to be worked by his newly invented smoke-consuming furnace. In 1789, a second engine was installed. In 1791, Albion Mills burned down. It bears on Cavendish's interest that later that year, he together with Blagden, Banks, and the engineer John Smeaton were invited to inspect drawings of a steam engine and a waterwheel at Falcon Stairs, near Blackfriar's Bridge and the former Albion Mills. Charles Blagden to Joseph Banks, 23 Oct. 1785, Banks Correspondence, Kew, 1:212. John Maitland to Joseph Banks, 19 Dec. 1791, Manuscript Department, British Museum, Add Mss 33979, p. 118. Wikimedia.

Iron production was attended by intense heat, fiery chemical reactions, copious emission of gases, and heavy mechanical violence. Cavendish and Blagden's journals recount the scenes they witnessed. Under the hammer, fiery balls of iron "strike off sparks, some of which fly to a great distance, and a few have the brilliant appearance of steel dust in fireworks. There comes besides a white flame from different parts of the mass, and at times a different flame from certain spots, of a light bluish colour, like that from burning Sulphur."[16] Coalfields in the vicinity of the ironworks added to the effect. They passed a pit that had been burning many years, which they described: "from some places close by the road, a strong flame was now issuing, and the earth seen through the crevices and apertures in many places was red, or even white hot. All about the places actually burning, lay the cinders of old conflagrations."[17] Yet but for a difference of scale, there was a resemblance between ironworks and Cavendish's laboratory at home. In extracting pure metal from raw earth, workers used the same chemicals he did; they similarly combined their materials by proportionate weights and contended with impurities; and they had similarly used hearths and bellows.

Midway through their journey Blagden sent Banks an encouraging report. They had seen cloth and iron manufactures in "great perfection," and they had been "perfectly successful" in measuring the highest mountains in four counties and had plans to measure the Malvern Hills on the way to Birmingham.[18] In Birmingham they visited James Watt and

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[16] Blagden, Journal of 1785, p. 53.

[17] Ibid., p. 57.

[18] Charles Blagden to Joseph Banks, 31 July 1785, Banks Correspondence, Royal Botanic Gardens, Kew 1.199.

his partner Matthew Boulton at the latter's Soho Manufactory. Cavendish's papers contain a drawing he made of a steam engine of Watt's construction. In the 1780s Watt patented three major improvements of his steam engine, which itself was an improvement over the Newcomen engine. The first translated the reciprocal motion of the steam engine into a rotary motion, useful in manufacturing. The second doubled the amount of power the engine could deliver. The third was an application of the pantograph principle giving the piston the motion it needed for a double-acting engine, the invention Watt considered his masterwork (16.4). Watt told Cavendish about a scientific experiment he had performed with the steam engine on the condensation of steam, and Cavendish no doubt told him about his own experiments on the subject. Cavendish learned that Watt had invented a furnace to burn smoke, which he intended to apply to the steam engine. Later that year, Watt came to Albion Mills, near Blackfriar's Bridge in London, where his advanced double-acting, rotative steam engines worked by his new smoke-consuming furnaces were installed. Cavendish's papers contain a sketch he drew of Watt's furnace, probably on a visit to Albion Mills (Figs. 16.6–16.7).[19]

New Willey Ironworks near Broseley in Shropshire was their next stop. Its ironmaster was John Wilkinson, whose innovative boring mill for making cannon was exactly what Watt needed to make accurate cylinders for his engines, improving their efficiency by correcting for leakage of steam. They visited a second, new ironworks of Wilkinson's at Bradley, near Birmingham. This ironworks differed from others they had seen in the use of reverberatory furnaces instead of the traditional hearth forges, in which iron lies directly on the fuel, which contains impurities. The advantage of reverberatory furnaces is that the iron is separated from the fuel, heated by hot gases flowing over it and by radiant heat reflected from the roof of the furnace.

They visited the ironworks at Colebrookdale, a large plant a quarter mile in length, near the historic Ironbridge. Abraham Darby III, the third-generation head of the company, had made castings for the bridge, the first major structural use of cast iron. The still-standing 100-foot, semi-circular bridge spanning the River Severn linked ironworks at Coalbrookdale with sites across the river.[20] The blast for the two furnaces at Coalbrookdale was delivered by two cylinders powered by water raised by a steam engine of Watt's design. The year of Cavendish and Blagden's visit another steam engine was installed to blow air at two forges located outside the building.[21]

Steam engines came with the setting of their journeys, which was the Industrial Revolution. A new landscape was taking shape, into which Cavendish ventured with the same curiosity he brought to his studies in mechanics, chemistry, and heat. On their first journey, in addition to iron-making, he and Blagden saw a range of industrial operations: quarrying, coal-mining, coke-making, brass-drawing, tin-plating, and more. They saw slitting mills, flattening mills, cannon mills, trip-hammers, cranes and other equipment for moving hot heavy masses. They saw the finished products, iron and steel made into buttons, needles, nails, and ship bolts.

Wherever they went, they talked to owners, engineers, and workman, who gave them information no one else could. In their journals they also recorded observations of strata, rocks, and pebbles surfacing the roads, and on separate sheets they kept a record of barometer

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[19] Initially there were problems with the piston rod and the sun-and-planet gear of Watt's engine, but by early 1786 the repairs had been made. In 1789, a second engine was installed.

[20] S.B. Hamilton (1958, 455–456).

[21] Richard Hayman (2003, 71).

and thermometer readings, from which Cavendish calculated elevations. Blagden wrote to Banks that Cavendish "bears the journey remarkably well."[22] The journey lasted about three weeks.

The following year, 1786, Cavendish and Blagden set out again on a three-week journey, this one longer than the first, to the north of England.[23] They traveled directly to John Michell's parsonage at Thornhill, near Wakefield in Yorkshire; after a short visit, they left Michell and then returned to stay several more days.[24] By then Michell had worked for many years on a telescope, which when Cavendish and Blagden saw it had the biggest mirror of any telescope in the world. Blagden wrote in his diary the only account of what it was like to look through it. "At Mr Michell's took some altitudes & looked over his fossils [. . .] At night looked thro' his telescope: tho' much false light & confused images yet observed ♄ with it well: could see the belt plainly; & observed an emersion of the 3 sat. much better than it appeared thro' the 2 feet reflector."[25] On Saturday, Blagden went to Michell's sermon, which he had heard or read before; he said nothing about Cavendish attending the sermon. Cavendish discussed geology with Michell, and he came away with a copy of Michell's table of strata going down 221 feet, measured to the inch.[26]

Cavendish took advantage of the journey to follow up his chemical interests. He accepted Lord Mulgrave's invitation to visit his alum works, "having formerly made experiments himself on the crystalization of alum."[27] After the journey, alum liquor and related substances from the alum works were sent to Cavendish in London.[28] The connection of the journey with Cavendish's scientific work can be seen in the interest he took in plumbago, a graphite substance formed in furnaces during the extraction of iron from its ore. He and Blagden made a special trip to Rotheram to enquire about plumbago, and in Chesterfield Cavendish succeeded in acquiring a specimen of kish iron "for examination," kish being the workmen's name for plumbago. Plumbago had come up in connection with Kirwan's criticism of Cavendish's 1783 paper "Experiments on Air" for failing to take into account the production of fixed air. In his answer, Cavendish said that Kirwan's belief that a mixture of iron filings and red precipitate produced fixed air would be a strong argument if it were not that iron contains plumbago, and plumbago was known to consist mainly of fixed air. Cavendish performed an experiment to show that Kirwan's fixed air had come from the plumbago in his iron filings rather than from the iron itself, as Kirwan believed.[29] Before Cavendish and Blagden began their first journey, no doubt at Cavendish's request, Blagden wrote to the chemist Peter Woulfe in Paris asking him to apply to a French chemist there for

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[22] Charles Blagden to Joseph Banks, 31 July 1785, Banks Correspondence, Royal Botanic Gardens, Kew, 1.199.

[23] "Computations & Observations in Journey 1786," Cavendish Mss X(a), 5. The wrapper is labeled in Cavendish's hand; the narrative is written in the copyist's.

[24] Charles Blagden to C.J. Phipps, Lord Mulgrave, 2 Aug., 1786, draft, Blagden Letters, Royal Society 7:17. Charles Blagden to John Blagden Hale, 14 Sep. 1786, draft, ibid. 7:33. Charles Blagden to John Michell, 5 Aug. 1786, draft; in McCormmach (2012, 407–408).

[25] 2 Sep. 1786, Charles Blagden Diary, Yale, Osborn Shelves f c 16

[26] Henry Cavendish, "Strata Which Michell Dug Through for Coal," in Cavendish's journal of the 1786 trip, Cavendish Mss X(a), 3:13–14.

[27] Charles Blagden to C.J. Phipps, Lord Mulgrave, 2 Aug. 1786, draft, Royal Society 7:17.

[28] "Examination of Substances Sent from Lord Mulgrave's," in "White Book," Cavendish Mss Misc., pp. 7–13.

[29] Kirwan thought that the phlogistication of air generates fixed air. Cavendish knew that it does not. Henry Cavendish (1784b, 184). In 1779 Scheele performed experiments on plumbago, a substance which had been used in pencils, showing that it consists mainly of carbon with some iron. Thomson (1830–1831, 2:71).

an abstract of his memoir on plumbago.[30] Cavendish brought his interest in plumbago with him on his journey to the ironworks.

In Sheffield they observed file-making and other manufactures "pretty much in detail." They stayed at a place recommended by Michell, the Fortune Inn, which proved to be "the vilest house," Blagden complained to Michell, at which he "ever had the misfortune to put up."[31] Michell said that he knew it only by reputation and would not recommend it again. In Chesterfield they went down a mine, which Blagden found "fatiguing," his legs too short for the turns in the ladder; he said nothing of Cavendish's discomfort, if he experienced any.[32] "Tempestuous" wind and rain frustrated their plans to climb mountains in the Lake District, forcing them to leave sooner than they had planned, but not before Blagden had caught a glimpse of the "magnificent & beautiful" scene.[33] What Cavendish thought of the natural beauty of the lakes he did not say, but it would seem that he was indifferent to it. The closest Blagden came to criticizing Cavendish in writing was in a letter fifteen years later, where he wrote, "When I went to the lakes it was in company with Mr. Cavendish, who had no curiosity for several things which it would have given me great pleasure to have seen. Winander More struck me as the *prettiest* piece of water I had ever beheld."[34] What Cavendish took away from the scene is suggested in a letter Blagden wrote to Banks a month after their return: Cavendish was "making experiments upon the stones we brought home," and on specimens from the industrial works, "which will find him some employment if he critically examines them all."[35]

For the third straight year, in 1787 Cavendish and Blagden set off on a journey, this time to the southwestern corner of England, Cornwall. They brought with them letters of introduction written by Watt and Boulton among others.[36] Cavendish and Blagden went down a tin mine 800 fathoms deep, Blagden again finding the descent troublesome and little of interest at the bottom except for the manner of working, which had to be seen to be understood. On the rest of the trip he and Cavendish contented themselves with seeing what was above ground.[37] They visited Josiah Wedgwood's clay pits for porcelain manufacture; the previous winter Wedgwood had sent Blagden specimens of feldspar, with the request that he show them to Cavendish.[38] They visited smelters with their strong smell of arsenic and their workman covered with red dust. They saw big stampers driven by waterwheels, crushing ore, and steam engines emptying mine shafts of water and hauling up ore.[39] They saw pumping machinery improved by Watt, to whom, Blagden thought, the Cornish were

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[30] Peter Woulfe to Charles Blagden, 26 June [?] 1785, Blagden Letters, Royal Society W30.

[31] Charles Blagden to John Michell, 19 Sep. 1786, draft; in McCormmach (2012, 409–412).

[32] Charles Blagden to Joseph Banks, 17 Sep. 1786, BL Add Mss 33272, pp. 9–10.

[33] Charles Blagden to Joseph Banks, 4 Sep. 1786, ibid., pp. 7–8.

[34] Charles Blagden to Henry Temple, Lord Palmerston, 25 Nov. 1800, Blagden Papers, Yale, box 63/43.

[35] Charles Blagden to Joseph Banks, 8[?] Oct. 1786, BL Add Mss, 33272, pp. 15–16.

[36] Charles Blagden to James Watt, 23 Aug. 1787, draft, Blagden Letters, Royal Society 7:349. Two letters of introduction from George Hunt, 23 Jan. 1787, who was asked to write them by his nephew R. Wilbraham, "The bearers of this are Mr.Cavendish …." Blagden Papers, Yale, box 1, folder 4. Along the way Blagden solicited letters: James Reynolds to Rev. Burlington, 18 Aug. 1787, "The bearer, Dr Blagden, is my particular friend …." Blagden Letters, Royal Society, R.5.

[37] Charles Blagden to Mrs. Grey, 14 June 1787, draft, Blagden Letters, Royal Society 7:324. Charles Blagden to William Watson, 22 Aug. 1787, draft, ibid. 7:347.

[38] Josiah Wedgwood to Charles Blagden, 30 Dec. 1786, Gloucestershire Record Office, D 1086, F 158.

[39] Thirty-page journal of the 1787 journey, by Blagden, in a copyist's hand, and with many insertions in Cavendish's hand. Cavendish Mss X(a), 6.

indebted to be able to "work their copper mines at all."[40] Cavendish collected specimens to subject to "chemical analysis" which Blagden expected would "shew some more light" on how they were formed.[41]

On their route to Cornwall, they followed the seacoast "on account of particular experiments to be done there."[42] On Dartmoor in southwest Devonshire, they carried out an elaborate series of observations with barometers, thermometers, and rain gauges having to do with a problem in the barometric measurements of heights. Blagden, who had lived in nearby Plymouth, made the local arrangements, which involved the assistance of three other men and the construction of a small meteorological observatory on the boulder-strewn hills of Dartmoor, rising to 2000 feet.[43] The scientific expedition into the wet and windy moors was planned and funded by Cavendish.

On their journey, between industrial sites they observed strata as usual,[44] and this time fair weather permitted them to climb mountains with their barometer.[45] On their return through north Devon, Blagden, who had been there before, took "great pleasure in shewing to Mr.Cavendish" the "grand beauties of that remarkable coast." Blagden reported to Banks that Cavendish looked "the better for his journey."[46]

Cavendish and Blagden made no more journeys together. In the summer of 1788, Blagden went to France, sending back scientific news to Cavendish.[47] So familiar had they become as a traveling pair that the following year Blagden had to correct Deluc, explaining that he was planning a tour of Italy not with Cavendish but with Lord Palmerston.[48] Cavendish made one more journey we know of, in 1793. Blagden was then living in Europe,[49] and this time it was Banks who planned it. He wanted Cavendish to witness trials of a new steam engine working the Gregory lead mine in Derbyshire, in which Banks had an interest. Banks urged Watt and Boulton to meet with Cavendish at the mine,[50] and in the notes Cavendish kept of the journey, he mentioned an experiment of Watt's to determine the specific gravity of steam.

Such were Cavendish's journeys in his middle years. Setting out from London in different directions, he explored different corners of the kingdom. Wherever he went, he examined industrial processes, materials, and products, determined the heights of mountains, observed the "order of the strata," and collected stones, noting their physical characteristics and investigating them chemically. From his observations and other sources, he wrote a paper on the strata of the island.[51] He was a tourist with an active curiosity and definite tastes: what interested him he pursued tirelessly, and what did not he silently ignored.

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[40] Charles Blagden to Mrs. Grey, 28 Aug. 1787, draft, Blagden Letters, Royal Society 7:351.

[41] Charles Blagden to John Michell, 1 Sep. 1787, draft; in McCormmach (2012, 434–436).

[42] Charles Blagden to William Lewis, 11 July 1787, draft, Blagden Letters, Royal Society 7:338.

[43] Brian Le Messurier, ed. (1967, 15). Charles Blagden to William Farr, 12 June 1787, draft, Blagden Letters, Royal Society 7:67; and other correspondence with Farr around this time.

[44] Henry Cavendish's journal of the 1787 trip, Cavendish Mss X(a), 7.

[45] There are several large sheets of observations taken with the barometer on the 1787 trip, in Cavendish Mss Misc.

[46] Charles Blagden to Joseph Banks, 14 Aug. 1787, Add Mss 33272.

[47] Charles Blagden to Joseph Banks, 13 July 1788, ibid.

[48] Charles Blagden to Jean André Deluc, 5 Sep. 1789, draft, Blagden Letters, Royal Society 7:301.

[49] Charles Blagden to Joseph Banks, 11 May 1793, BL Add Mss 33272, pp. 119–20. Henry Cavendish to Joseph Banks, 23 Sep. 1793; in Jungnickel and McCormmach (1999, 696).

[50] Joseph Banks to Matthew Boulton, 6 and 18 July, 10 Aug. 1793, Birmingham Assay Office.

[51] This twenty-one page paper on strata in Cavendish's hand does not have a group number, but it is kept with the travel journals in the Cavendish Mss.

A great reader of travel books, as we know from his library, Cavendish was prepared to be enticed out of his study by Blagden and to become himself, for a time, a traveler. His journals differ from the usual types of travel journals by their exclusive focus, though they have much in common with the geological and industrial observations of William Lewis's and Charles Hatchett's, and with the geological observations of Deluc's and Saussure's.[52]

The journeys marked a change in the direction of Cavendish's work. His course of experiments in pneumatic chemistry came to an end with his paper on phlogisticated air in 1785, the year he made his first journey with Blagden. In 1786 he began keeping a new record of chemical experiments, an indexed, bound book, which he labeled "White Book No. 1." It contains transcriptions from his laboratory notes, some of which are inserted loosely, not yet transcribed, bearing telltale chemical stains.[53] The experiments it records span twenty years, to 1806; their subject could be called geological and industrial chemistry, but the simpler description of mineralogical chemistry would not be misleading, given the eighteenth century practice of using of "mineralogy" to stand for both ores and stones.[54] The *Philosophical Transactions* at the turn of the century contained substantial papers in this field, the challenge of which one of the authors Richard Chenevix described: to establish qualitatively the presence of different substances in the specimens required "delicate research," and to determine quantitatively their proportions was the "most difficult operation of analytic chemistry."[55]

The "White Book" came to light relatively recently. The variety of substances Cavendish examined can be suggested by a few entries: whitish sparkling ore from Hudson's Bay, native iron from Mexico, earth from Isle of Man, lava from Mount Vesuvius, limestone, chalk, clay, and mica. Making no distinction between the natural and the manmade, the book also records experiments on specimens from mines and wastes from industrial processes such as kish from iron furnaces, slag from the purification of copper, finery cinder, and dust from lead smelting furnaces. The engineer James Cockshutt supplied Cavendish with specimens of coal and iron, and Cavendish wrote a paper on the making of iron with recommendations for the engineer,[56] an exchange we might view as an early meeting of two revolutions, the scientific and the industrial.

Cavendish's journals are the first indication of his active interest in geology. In Britain in the late eighteenth century, the main spur to geology came from what he was doing, crossing large tracts of country making observations of strata.[57] When Blagden toured the Continent, he reported to Cavendish on the soils there, extending his observations on the other side of the Channel.[58] Cavendish acquired considerable knowledge of geology, but

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[52] Horace Bénédict de Saussure (1786). Jean André Deluc (1810). Charles Hatchett (1967). F.W. Gibbs (1952, 211).

[53] This book has 138 numbered pages; 90 loose sheets are laid between the bound ones. Large blank spaces are left in the book for cross referencing and later additions. It is a copy book for preserving results of experiments. "White Book No. 1," Cavendish Mss, Misc. On p. 59 Cavendish refers to "2d book," which suggests that there was once a "White Book No. 2."

[54] V.A. Eyles (1969, 175).

[55] Richard Chenevix (1801, 209).

[56] Henry Cavendish, "Paper Given to Cockshutt," inserted loosely in "White Book No. 1," Cavendish Mss Misc.

[57] Roy Porter (1977, 119).

[58] The guiding thought appeared in John Michell's paper on earthquakes, where he noted that level countries show great expanses of the same strata: "we have an instance of this in the chalky and flinty counties of England and France, which (excepting the interruption of the Channel, and the clays, sands, of a few counties) compose a tract of about 300 miles each way." John Michell (1760, 587).

nothing suggests that he had any thought of publication. In one place he acknowledged that he was scratching the surface of the Earth, and that only superficial knowledge could come of it.[59] He mentioned an experiment of Watt's to determine the specific gravity of steam. The last candidate Cavendish recommended for fellowship in the Royal Society was a geologist, James Hall, in 1806.[60] Known as the "father" of experimental geology, Hall is remembered especially for his experiments in answer to criticisms of James Hutton's *Theory of the Earth*. A principal criticism came from an early result of pneumatic chemistry. Against Hutton's explanation of the formation of limestone by subterranean heat, his critics argued that heat would have calcined the limestone, driving off its fixed air (carbon dioxide) and converting it to quicklime, as Black had shown. Using Wedgwood pyrometers to measure temperatures upwards of 1000°, and using Benjamin Thompson's method of measuring the force of gunpowder to determine very high pressures, Hall proved that Hutton was right. In other experiments, to which he was led in part by observations in a glass factory, Hall proved that fused basalt becomes stony masses when it cools, not just glass as Hutton's critics maintained.[61] We do not know what Cavendish thought of Hutton's theory, but we suspect that he liked it better than he did the theories of Hutton's critics such as Deluc and Kirwan, who upheld the account in Genesis of the origin of the world.[62] John Playfair, the foremost exponent of Hutton's theory, said that geology used to explain everything by the "first origins of things," the reason it was so long in becoming a science; geology as a science was properly concerned to "discover the laws" of the great "revolutions" of the Earth.[63] Hall, he said, agreed that geology as a science properly sought "laws." That Cavendish would have approved of Hall's direction in the science is supported by his experiment of weighing the world, discussed next.

Weighing the World

The first indication of Cavendish's interest in the experiment appears in a letter to John Michell in 1783. Michell was having difficulty completing his large telescope, and Cavendish wrote to him with a suggestion: "if your health does not allow you to go on with that I hope it may at least permit the easier and less laborious employment of weighing the world." Tactfully, Cavendish expressed his preference: "for my own part I do not know whether I had not rather hear that you had given the exper. of weighing the world a fair trial than that you had finished the great telescope."[64] Michell died ten years later, in 1793, without having tried the experiment (or finished the telescope). Most of his instruments and apparatus were left to his former college in Cambridge, Queens'.[65] What happened next is explained at the beginning of Cavendish's paper in the *Philosophical Transactions* for 1798, "Experiments to Determine the Density of the Earth." "Many years ago, the late Rev. John Michell, of this Society, contrived a method of determining the density of the Earth, by ren-

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[59] Archibald Geikie, "Note on Cavendish as a Geologist," in Cavendish, *Sci. Pap.* 2:432.

[60] 20 Feb. 1806, Certificates, Royal Society, 6.

[61] V.A. Eyles (1972, 54).

[62] Jean André Deluc (1809, vi, 24, 63–64). Deluc argued against Hall's experimental conclusions, pp. 359–361. Kirwan said that geological facts are historical, relying on testimony, and that recourse cannot be made to experiment. Richard Kirwan (1799, 4–6, 482).

[63] Playfair quoted in Deluc (1809, 11–14).

[64] Henry Cavendish to John Michell, 27 May 1783, draft; in Jungnickel and McCormmach (1999, 567–569).

[65] "Michell, John," *DNB*, 1st ed. 13:333–334, on 334.

dering sensible the attraction of small quantities of matter; but, as he was engaged in other pursuits, he did not complete the apparatus till a short time before his death, and did not live to make any experiments with it. After his death the apparatus came to the Rev. Francis John Hyde Wollaston, Jacksonian Professor at Cambridge, who, not having conveniences for making experiments with it, in the manner he could wish, was so good as to give it to me."[66] Wollaston belonged to a family of men of science and the Church, all of whom had studied at Cambridge; Cavendish knew them all.[67]

Michell's apparatus came to be known as a "torsion balance." In a footnote to his paper in 1798, Cavendish referred to Coulomb's use of an apparatus of the same kind for measuring small electric and magnetic attractions in the mid 1780s: "Mr. Michell informed me of his intention of making this experiment, and of the method he intended to use, before the publication of any of Mr. Coulomb's experiments." As to when Michell came to his idea of measuring the density of the Earth with a torsion balance, and when Cavendish learned about it, we are not told. We know that it was no later than 1783, for Cavendish referred to it that year. We can set a lower limit on the time by a paper that Cavendish gave to Maskelyne in or around 1773 in which he said that he knew of only two practical ways of finding the average density of the Earth, by a pendulum beating seconds and by the attraction of a mountain;[68] he said nothing about Michell's third way, by a torsion balance.

Cavendish was nearly sixty-seven when he "weighed the world," the name he and Michell used for the experiment. He began the experiment, which was in reality seventeen "experiments," each consisting of many trials, on 5 August 1797, completing the first eight of these by the last week in September. The remaining nine he carried out in April and May of the following year. The paper reporting them was read to the Royal Society on 21 June 1798, just three weeks after the last experiment.

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[66] Henry Cavendish (1798, 249)

[67] Wollaston's father, Francis, born the same year as Cavendish and a classmate of Cavendish's at Cambridge, took his degree in law but entered the Church instead. Skilled in astronomy, he had his own observatory and first-class instruments. With at least that much in common, on 8 Dec. 1768 Cavendish brought Francis Wollaston as a guest to a meeting of the Royal Society. The certificate proposing Wollaston's membership is signed by Cavendish along with Maskelyne and several other prominent members. 3 Jan. 1769, Certificates, Royal Society 3:65. "Wollaston, Francis," *DNB*, 1st ed. 21:778–779. One of Francis Wollaston's sons, William Hyde Wollaston, was an eminent chemist, whom Cavendish proposed as he had his father for membership in the Royal Society. 9 May 1793, Certificates, Royal Society 5; "Wollaston, William Hyde," *DNB*, 1st ed. 21:782–787, on 782. Another of Francis's sons George Hyde Wollaston was one of Cavendish's neighbors on Clapham Common, where Cavendish performed his experiments on the density of the Earth. George Hyde Wollaston's house along with Cavendish's are on the map of Clapham Common (Fig. 11.12). Another of Francis's sons was Francis John Hyde Wollaston, Jacksonian Professor of Chemistry, from whom Cavendish received Michell's apparatus. "Wollaston, Francis John Hyde," *DNB*, 1st ed. 21:779–780. Michell's association with the Wollastons went back as far as Cavendish's. As a recently elected fellow of the Royal Society, Michell's first recommendation for a new member, in 1762, was for Francis's youngest brother, George Wollaston, then fellow and mathematical lecturer in Sidney-Sussex College, Cambridge. "Wollaston, Francis," 779.

[68] Henry Cavendish, "Paper Given to Maskelyne Relating to Attraction & Form of Earth," VI(b), 1:19.

Apparatus for Weighing the World

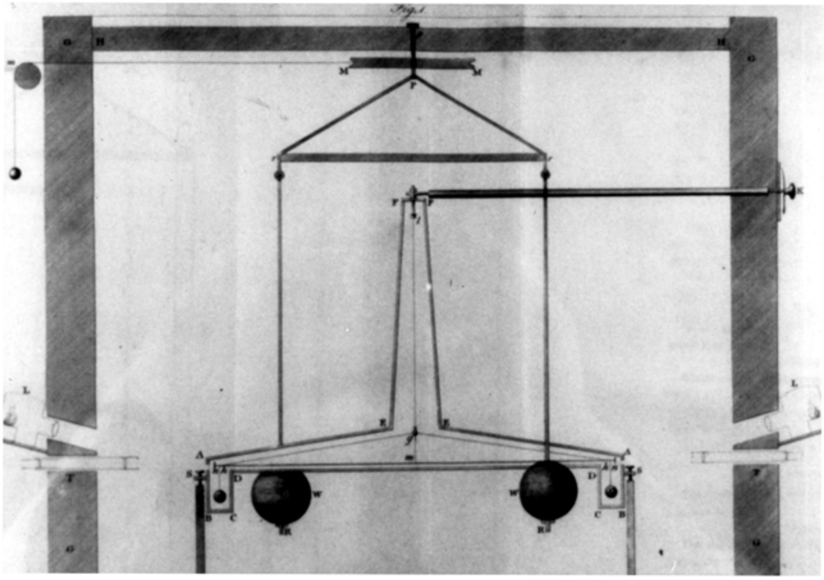

Figure 16.8: Apparatus for Weighing the World. Cavendish's modified and rebuilt version of John Michell's apparatus. The large metal spheres R are weights that attract small metal spheres suspended from the ends of the arm, which in turn is suspended by the fine wire gl. The room in which the apparatus is housed and protected is also shown as are the arrangements for viewing it from outside the room. "Experiments to Determine the Density of the Earth," *PT* 88 (1798):526.

Cavendish began his account with words that should encourage readers, "The apparatus is very simple" (Fig. 16.8). Its principal moving part was a six-foot wooden rod suspended horizontally by a slender wire attached to its center, and suspended from each end of the rod was a lead ball two inches across. The whole was enclosed in a narrow wooden case to protect it from air currents. Toward the ends of the case and on opposite sides of it, were suspended two massive lead balls, or "weights," each weighing about 350 pounds. Cavendish rebuilt Michell's apparatus.

The force that turns the rod aside is the gravitational attraction between the weights and the balls. From the angle of twist of the rod and the period of vibration of the rod moving freely as a horizontal pendulum, the density of the Earth is deduced. It is not obvious how the Earth enters the experiment, becoming "obvious" only when the formulas for the forces acting in the experiment are written out and the resulting equations are combined. Cavendish did not use equations but worked with proportions, and as a result his reasoning is unfamiliar to a modern reader. The experiment essentially compares the gravitational attraction of the lead weights on the balls with the gravitational attraction of the Earth on the same, the source of the Earth in the experiment.[69]

Earlier in the century it had been an open question whether or not a mass the size of the mountain is sufficient to cause a measurable effect. Twenty-five years before Cavendish's experiment, the Royal Society had carried out a successful experiment on a mountain, and as we have seen, Cavendish had helped prepare for it. In the experiment Michell invented, Cavendish achieved a measurable effect with masses small enough to fit into an apparatus. Newton had been discouraging, having calculated that if two one-foot spheres of Earth-matter were placed only one-quarter inch apart, they would not "come together by the force of their mutual attraction in less than a month's time." Newton was right about the minuteness of the force: in Cavendish's experiment the gravitational attraction of the weights on the balls was of the order of one part in 10^8 (one hundred million) of the gravitational attraction of the Earth on them, that is, of their weight.[70]

Because the smallest disturbance could destroy the accuracy of the "weighing," Cavendish placed the apparatus in a small, closed "room" about ten feet high and as many feet across. From outside the room, Cavendish worked pulleys to swing the weights close to the case to set the rod in motion, the deflection and vibration of which he observed by means of telescopes installed at each end of the room. Veniers at the end of the rod enabled him to read its position to within one hundredth of an inch. The only light admitted into the room was provided by a lamp near each telescope. Once an experiment was underway, it was not interrupted until the end; depending on the stiffness of the suspension wire, it might take as long as two and one-half hours.

Given that the apparatus was simple and the procedure straightforward, it might seem that Cavendish's report of the experiment would be brief. It was not, taking up fifty-seven pages in the *Philosophical Transactions*, in length second only to his paper on the theory of electricity. The reason it was long was Cavendish's concern with accuracy. Near the beginning of his paper, where he estimated the minuteness of the gravitational force, he began a discussion of errors and corrections, which he continued to the end. The following account gives an idea of Cavendish's meticulous way of experimening.

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[69] In more detail, his reasoning is as follows. He deduces the density of the Earth in two steps. The first step assumes the laws of pendulum motion. The second step assumes the inverse square law of gravitation. Step 1. Cavendish draws on two relations: the period of vibration of a pendulum is proportional to the square root of the length of the pendulum and inversely proportional to the square root of the restoring force on the pendulum. With the aid of an analogy between the horizontal torsion pendulum and an imagined vertical simple pendulum beating seconds, the length of which is known, Cavendish expresses the force required to move the small balls at the ends of the torsion arm, with its observed period of vibration, through any observed angle of deflection of the arm in terms of the weight of a ball. Step 2. Cavendish invokes Newton's law of gravitation twice, once to express the attraction between a small ball and the nearby larger ball, or "weight," and once to express the attraction between the small ball and the Earth. The latter attraction is written so as to include the to-be-determined average density of the Earth. Forming a ratio of the two attractions, he expresses the attraction of the "weight" on the ball in terms of the attraction of the Earth on the same ball. Finally, he combines Steps 1 and 2. The force of the twisted wire from Step 1 is equal to the force of attraction between the small balls and the "weights" from Step 2. By dividing one force by the other, Cavendish arrives at the desired result: the density of the Earth, expressed in terms of the density of water, is equal to a numerical factor times the square of the period of vibration of the torsion arm divided by the deflection of the arm. By means of this reasoning, Cavendish brings the world into his laboratory.

[70] Isaac Newton (1962, 2:569–570). Cavendish stated the proportion as one part in fifty million, which applied to the 8-inch weights Michell intended to use. For the 12-inch weights Cavendish used, the proportion is roughly 3 times larger, but the order of magnitude of the minuteness remains the same.

Looking ahead to the conclusion, that unequal heating of the air was the disturbing force that was hardest to avoid, Cavendish explained how he located and designed the apparatus to minimize this main "source of error." Other sources of error he considered first. He found "some inaccuracy" in the vibration of the arm caused by the resistance of the air, but the "error" caused by the motion of the point of rest he found to be inconsiderable. He determined the time of vibration of the apparatus for each experiment separately to minimize the effect of "accidental attraction, such as electricity," arising from the plates of glass through which he observed the moving arm, causing an "error in the result." To determine the incidental attraction on the arm by the iron rods from which the heavy lead weights were suspended, he removed the weights. When he did, he found a disparity between his observations and his theoretical calculations of the attraction of the rods, which he first attributed to magnetism, but then upon replacing the iron rods by copper ones and still finding the same excess attraction, he concluded that it was due to an "accidental cause." Being unable to "correct" the "error," he calculated that its effect on the final result was no more than one thirtieth of the whole. With this measure of reassurance he continued with the main experiment. Next, observing that the attraction of the weights on the balls seemed slowly to increase with time, he suspected a "want of elasticity" in the wire or in something the wire was attached to, but by drawing on his knowledge of the limits of elasticity, and doing experiments on the wire he was using, he decided that this was an unlikely cause; he replaced the wire with a stiffer one nonetheless. His description of elastic after-working in the wire, it has been noted, was original, its discovery usually being assigned to the late nineteenth century. Finding that the attraction of the weights continued to vary, he suspected magnetism again; to check it out, he performed experiments to see if the weights and balls acquired the polarity of the Earth, arranging the weights so that they could turn on a vertical axis and rotating them daily, and then replacing the two-inch lead balls with ten-inch magnets and reversing them. The latter replacement is an example of what has been called one of the "grand principles of experimental physics": if a disturbing effect is suspected, it is made bigger to see how serious it is; Cavendish used this principle in his chemical work too, pointed out earlier. He decided once again that magnetism was not the source of the error. He next supposed that the cause of the variable attraction was "a difference in temperature between the weights and the case," producing a current of air. Even though he thought that this cause was "improbable," he took the apparatus apart and did new experiments, this time placing lamps beneath the weights and a thermometer next to the case. The effect was large after all, and so he did more experiments, burying thermometers in the weights and viewing them through the telescope by light reflected from a convex mirror, convincing himself that he had found a major source of this error: overnight the weights did not cool as much as the case, giving rise to convection currents, which pushed the balls toward the sides of the case. He then carried out the remaining experiments to determine the density of the Earth.[71]

Cavendish was not finished with errors. In calculating the density of the Earth from his data, he made several idealizations: the arm and the copper rods holding the weights have no weight, the weights attract only the nearest ball, and the attraction of the case is ignorable. In light of these, he made *six* "corrections," five of which were not of "much signification," but were "not entirely to be neglected" either. The important correction was the effect of the position of the arm on the attraction between the weights and the balls, which

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[71] Cavendish (1798, 250, 252, 254–255, 259, 263–267). C.W.F. Everett (1977, 548).

influenced the time of vibration. One of the corrections, that of the effect of the mahogany case on the arm inside it, required an extensive analysis, which Cavendish included in the paper as a mathematical appendix, even though the "whole force is so small as not to be worth regarding." In the conclusion of the paper, Cavendish gave a table of results of the seventeen experiments. They agreed closely with one another, but still the differences were too large to be explained fully by the "error of observation" or by air currents owing to temperature differences. He expressed the final outcome of the experiments as a mean of the results for each of the two wires, finding the two means to be the same. Noting that the extreme results differed from the mean by no more than one fourteenth of the whole, he concluded that the mean density of the Earth was determined "to great exactness" as 5.48 that of the density of water.[72]

Cavendish thought that his readers might object that because the outcome was influenced by currents of heated air, it could be influenced by yet another source, "some other cause, the laws of which we are not well acquainted with," leading to "a considerable error in the result." To put to rest this objection, he reminded his readers that he had made the experiments in various weathers and temperatures. He anticipated another objection; "namely, that it is uncertain whether, in these small distances, the force of gravity follows exactly the same law as in greater distances." His reply was that there was no evidence that the law differs "until bodies come within the actions of what is called the attraction of cohesion, and which seems to extend only to very minute distances." Nevertheless he carried out a number of experiments with the balls placed as close to the case as possible, finding no difference. In these ways, Cavendish concluded his paper with second and third thoughts about possible factors affecting the accuracy of the outcome.[73]

The experiment of weighing the world consisted of observations of matter moving in response to two of the best-known forces, gravity and the restoring force of twisted wire, but as we have seen, to achieve accuracy, Cavendish had to consider nearly all of the forces known to natural philosophy: in addition to gravity and elasticity, they were forces associated with magnetism, electricity, deformation, heat, and cohesion. Cavendish's mastery of the art of experiment rested on his mastery of natural philosophy.

Despite and in part because of his last experiment Cavendish had not freed himself from the claims of the earlier method of determining the density of the Earth, the attraction of mountains. His paper brought a prompt response from Charles Hutton, who had received copies of Cavendish's manuscript from both Maskelyne and the Royal Society. From the Royal Military Academy in Woolwich where he worked, he wrote to Cavendish about his "ingenious" paper, which made the density of the Earth 5.48 that of water. What led him to write the letter was the last paragraph of the paper, which called attention to the earlier, lower value of $4\frac{1}{2}$, in the "calculation of which" he, Hutton, had borne "so great a share." Anyone who has looked at Hutton's laborious calculations can sympathize. Hutton thought that Cavendish's wording hinted at inaccuracies in his calculations and seemed to disparage the Royal Society's experiment on the mountain in Scotland. That experiment, Hutton reminded Cavendish, had determined not the density of the Earth but only the ratio of that density to the density of the mountain, 9 to 5. Hutton had supposed that the density of the mountain is the density of ordinary stone, $2\frac{1}{2}$ times that of water, but the actual density of the mountain was unknown, as Hutton had pointed out at the time. All that was known was that Schehallien

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[72] Cavendish (1798, 277, 280, 283–284).

[73] Ibid., 284.

was a "massive stone," and Hutton now believed that its density was higher, 3 or even $3\frac{1}{2}$, which would make the density of the Earth "between 5 and 6," where Cavendish had put it, and "probably nearer the latter number." The Royal Society had not finished its experiment because it had not determined the density of stone, Hutton said. Even now, he hoped that the Society would do it, so that "an accurate conclusion, as to the density of the earth, may be thence obtained."[74]

Cavendish, as we have seen, repeated his experiment many times, in different seasons, and with attention to a range of possible errors and corrections, and he had taken mean values, considered the spread of the extreme values, and in general estimated the confidence that could be placed in 5.48. At the bottom of Hutton's letter to him, Cavendish drafted a brief response, which is identical to the last paragraph of his published paper.[75] In that paragraph, Cavendish did not commit himself as to which density, his or the Royal Society's, was more to be "depended on," since the Society's was "affected by irregularities whose quantity I cannot measure."[76]

In 1811, the year after Cavendish's death, John Playfair investigated the structure of the rocks of Schehallien, finding three kinds, with densities 2.4, 2.7 to 2.8, and 2.75 to 3. On the basis of these figures, Hutton calculated a new mean density of the mountain, about 2.75, which gave a value for the mean density of the Earth of "almost 5." As for the Royal Society's experiment on the attraction of mountains, Hutton said, "we may rest satisfied" with this result.[77] Playfair's values for the density of the mountain raised the density of the Earth, though it was still under Cavendish's 5.48, which was closer to, within 1 percent of, the accepted value today. After Cavendish's death, it was noticed that in averaging over the results of his experiments, he had made an arithmetic error; the corrected mean density of the Earth is 5.45, which is not as close, but still it is within 1.3 percent of today's value.

In the next century, the astronomer Francis Baily thought that Cavendish wrote his paper "more for the purpose of exhibiting a specimen of what he considered to be an excellent method, than of deducing a result which should lay claim to the full confidence of the scientific world."[78] In light of what Cavendish said at the end of his paper, we are inclined to think that he had both ends in view, but Baily was right to call attention to the method. It is that, not Cavendish's measurement, which has secured the experiment a lasting place among the methods of experimental physics.

Weighing the world had a precedent in William Gilbert's experiments on magnetism 200 years before. In his *De Magnete*, a classic work in early experimental physics, he wrote that he had formed "a little lodestone into the shape of the earth," and that he had "found the properties of the whole earth, in that little body," on which he could experiment at will.[79] Gilbert called his little Earth-shaped magnet a "terrella," a little Earth. We wonder if there was an association of ideas; at Chatsworth there is a terrella in a silver mount said to have belonged to Henry Cavendish.[80]

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[74] Charles Hutton to Henry Cavendish, 17 Nov. 1798; in Jungnickel and McCormmach (1999, 710–711).

[75] Cavendish's manuscript in the Royal Society does not show an interpolation on the last page. Perhaps Cavendish rewrote the last page, or perhaps he made no change in his wording in response to Hutton's letter. Henry Cavendish to Charles Hutton, draft, n.d. [after 17 Nov. 1798]; ibid., 712.

[76] Cavendish (1798, 284).

[77] Charles Hutton (1814, 2:64).

[78] Baily quoted in P.F. Titchmarsh (1966, 330).

[79] Kenelm Digby, 1645, quoted in "Biographical Memoir," in William Gilbert (1958, xviii).

[80] Mary Holbrook (1992, 113).

Cavendish had assisted the Royal Society in preparing the experiment on the mountain, but he did not take part in the experiment. His own experiment with metal spheres, his gravitational terrellas, corresponded to his normal way of life. To weigh the world, he did not need to go out into it; he could do it, and do it more precisely, in his laboratory, using an apparatus and reasoning from universal principles. He stayed at home and looked inside of the room and through a slit in a case, inside of which was the world on his terms.

At his home on Clapham Common, he worked largely in seclusion, though he used assistance when he needed it; in the last two parts of his experiment on the density of the Earth, he had George Gilpin, the clerk of the Royal Society, replace him at the telescope. Just as he was a private man and yet a constant companion of men of science, the work he carried out in seclusion entered the public world of established scientific problems, instrumental possibilities and qualified parties. If his experiment on the density of the Earth is looked at for what it tells us about Cavendish, as if it were a diary, which he did not keep, or a formal portrait, which he did not allow, it is a revealing experiment.

Weighing the world has been called a beautiful physics experiment, but it would be incorrect to call Cavendish a physicist, as we understand the word. He was a natural philosopher of the eighteenth century. One of the differences between the two is the conditions of work. In 1878 John Henry Poynting gave an account of experiments he undertook "to test the possibility of using the Common Balance in place of the Torsion Balance in the Cavendish Experiment," and in 1891 he reported on his continuing experiments with the common balance. For his repetition of the Cavendish experiment, he received a grant from the Royal Society, and he was given a place to work in the laboratory at Cambridge named after the Cavendish family. James Clark Maxwell, the first director of the Cavendish Laboratory, gave Poynting permission to do the experiment.[81] His experiment belongs to the time of physics, with its principal home in places of higher learning, with laboratories, directors, and grants. By contrast, Cavendish did his experiment by himself at his expense on Clapham Common.

When physics emerged in the nineteenth century, the worldview of physical science had changed from from Cavendish's day. An example is the role of time. Herschel, Kant, Buffon, and others from the middle of the eighteenth century envisioned the Earth and the heavens as evolving over eons in accordance with mechanical principles, but it would be scientists who came later who would work intensively within a worldview strongly imprinted by history.[82] Not eons but short durations, capable of exact measure, were the frame of reference of Cavendish's work; his instruments at the time of their auction contained "a very curious machine for measuring small portions of time."[83] Time for him was a measure of events, not a generator of events. He kept a number of clocks going, comparing them, timing the cooling of mixtures with them, and by the standard portrait of him, subjecting himself to their rule; they marked the regularity and sameness of nature and of his life. His interest in time is suggested by his study of the Hindu civil year, which is based on astronomical periodicities, portending nothing new in the world. In his work on heat, he arrived at the first law of thermodynamics, but he did not foresee a second law of thermodynamics, which implies

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[81] John Henry Poynting (1892, 565–566).

[82] Stephen Toulmin and June Goodfield (1965, 125, 266).

[83] Item 20 in *A Catalogue of Sundry Very Curious and Valuable Mathematical, Philosophical, and Optical Instruments [...] Of a Gentleman Deceased. ... On Saturday the Fifteenth of June 1816, at Twelve O'clock,* (London, 1816), Devon. Coll.

the physical directionality of time. His geological observations in the field led him to the chemistry of minerals not to ideas about the Earth evolving in time. His last important published experiment, the subject of this chapter, replaced the chemical balance, an instrument of precision, with a torsion balance, also an instrument of precision, both balances being instruments of equilibrium. The secular changes in his readings of the torsion balance were an error in the experiment. In the vanguard of the emerging physical science of precision, the Cavendish experiment was a complement in the laboratory of the periodic motions of the solar system, and as such it belonged to the classical Newtonian worldview.

The Cavendish Experiment

John Playfair wrote that skeptics would have predicted that after the systems of Aristotle and Descartes, Newton's too would pass: "This is, however, a conclusion that hardly anyone will now be bold enough to maintain, after a hundred years of the most scrupulous examination have done nothing but add to the evidence of the *Newtonian system*."[84] In his lectures on natural philosophy, Thomas Young said that Cavendish's result for the mean density of the Earth lay halfway between the limits guessed by Newton, between 5 and 6, a "new proof" of the "accuracy and penetration of that illustrious philosopher."[85] Conceived as a continuation of Newton's work, Cavendish's weighing of the world bestowed new honor on Newton, discoverer of imperishable truth.

Writing to Banks in 1802, Blagden reported a conversation with Laplace, which he thought Banks might want to pass along to Cavendish. Laplace said that many people suspected that the attraction Cavendish measured may involve electricity as well as gravity. For his part, Laplace wished that "Mr. Cav. would repeat it [the experiment] with another body of greater specific gravity than lead," such as a glass globe filled with mercury or a gold ingot.[86] In his paper Cavendish wrote that he planned to correct a defect in his method "in some future experiments," but so far as we know he did no more experiments, nor did he need to, for others would do them. In the following century, the density of the Earth was measured at least six times using Cavendish's method, twice using the Royal Society's method of the attraction of mountains, and several more times using a different method of the attraction of mountains; it was also done using the seconds pendulum and, as mentioned, the common balance.[87]

In time the Cavendish experiment ceased to be regarded as a way to determine the density of the Earth, even as it continued to be performed. It became instead the experiment to determine "big G," the gravitational constant appearing in the law of gravitational force, defined as the strength of attraction between two one-kilogram masses one meter apart. As C.V. Boys put it in 1892, "Owing to the universal character of the constant G, it seems to me to be descending from the sublime to the ridiculous to describe the object of this [Cavendish's and now Boys's] experiment as finding the mass of the earth or the mean density of the earth, or less accurately the weight of the earth."[88]

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[84] Playfair, quoted in Deluc (1809, 14–16).

[85] Thomas Young (1807, 2:575).

[86] Charles Blagden to Joseph Banks, 1 Apr. 1802, BL Add Mss 33272, pp. 172–173.

[87] B.E. Clotfelter (1987, 211). Notable repetitions include F. Reich (1838); Francis Baily (1843); C.V. Boys (1895).

[88] Boys is quoted by Clotfelter (1987, 211). Boys recommended using a room with a more uniform temperature then Oxford's; his accuracy was great, despite his room.

The Cavendish experiment today is often called the experiment to determine *G*, which is correct given that the experiment is the common possession of physics. It is often said that Cavendish's object was to determine *G*, which as a historical statement is incorrect but understandable given that the constant is more significant than the density of the Earth. In Cavendish's time, there was no independent unit of force, such as our dyne and Newton. The strength of any force was expressed in terms of an equivalent gravitational attraction, and weight was the measure of mass. The universal gravitational constant did not come up, though we can easily calculate it from Cavendish's data.[89] We find implicit in his work two of the three principal universal constants, the velocity of light *c* and *G* (Planck's constant *h* is the third), but Cavendish did not think of *c* as necessarily having a constant value, and it was the better part of a century after Cavendish's experiment before *G* entered physics.

Today, 300 years after Newton and 200 years after Cavendish, gravity is still at the center of physical research. To quote from a publication by researchers in the field: the "most important advance in experiments on gravitation and other delicate measurements was the introduction of the torsion balance by Michell and its use by Cavendish …. It has been the basis of all the most significant experiments on gravitation ever since."[90]

By its method and example, Cavendish's experiment has had a far-reaching influence on physics. In "Cavendish's skillful hands," the torsion balance has "revolutionized the science of precision measurement"; not only have nearly all of the determinations of *G* been done with that instrument, but it has been used in "countless other applications, such as seismological measurements and electrical calibration—wherever precise control over very small forces is called for."[91] A contributor to a symposium on general relativity traces the "noble tradition of precise measurement to which we are heirs" to Cavendish's experiment, which he calls the "first modern physics experiment."[92]

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[89] Cavendish did not write an equation for the force of universal gravitation, as we do: $F = \frac{GMm}{R^2}$. He could have calculated *G* without having a unit of force, but he had no need for it, and it would not have occurred to him. Clotfelter (1987, 213).

[90] A.H. Cook (1987, 52). Appropriately, Cook talks of the Cavendish experiment only in connection with *G* and not with the density of the Earth. Only recently, he says, has the accuracy of *G* been improved upon over what can be obtained from Cavendish's own experiment, and although in the study of materials we can achieve an accuracy of one part in 10^{12}, we still know *G* only to about 1 part in 10^3.

[91] Christian von Baeyer (1996, 98–99).

[92] Everett (1977, 546).