8

Places of Precision

Precision measurement seems to us to be at the very heart of modern physics. Measuring their effects as accurately and precisely as possible seems a prerequisite for understanding how the laws of nature operate. This preoccupation is, however, a comparatively recent phenomenon. It was only during the nineteenth century that laboratory disciplines started to put a whole new emphasis on precision measurement. Particularly towards the end of the century, as many physicists concluded that the end of physics was nigh—that they had established the general laws by which the Universe operated—the task at hand seemed to be one of consolidation. With few fundamental discoveries left to make, measurement seemed to many the path to a scientific reputation. Finding more and more ingenious ways of determining the exact value of constants and units was the big task ahead for physics. Establishing common standards of measurement was seen as the key to progress. For physicists such as James Clerk Maxwell, this was a moral crusade as well. Maxwell argued that the absolute identity of molecules was proof positive that they were manufactured articles fresh from some celestial production line. If they were manufactured articles then they required a designer—God. On this view there was a direct line between the physicist's routines of precision measurement and Victorian Anglicanism. Maxwell's remarks provide another clue as well to account for this concern with precision. Laboratories by the second half of the century were increasingly part of an industrial culture that depended on disciplined regimes of accuracy and exactitude. Factories depended on finely measured, identical, and interchangeable components just as laboratory physics depended on reliable, robust, and universal constants.

Laboratories in the eighteenth century were few and far between. A few individuals—those who could afford to do so—maintained private laboratories in their own homes, where they carried out their own researches. Universities, however, did not maintain laboratories in anything resembling the modern sense. There might be a room or an annex behind a lecture theater where demonstrations were prepared, but these were not places of research—and neither were university professors expected as part of their duties to carry out any such research. Laboratories proliferated during the nineteenth century, however. No longer spaces of private exploration, they increasingly became centers of research and—just as importantly—teaching. Physics professors were expected to pass on their experimental skills as much as their book knowledge to the next generation. In Britain, France, Germany, and North America, institutions of higher learning jostled to acquire a physics laboratory—and preferably an eminent physicist to direct it. Laboratories became part of the trappings of a modern university. Students would learn the skills of precision measurement in a carefully disciplined and regulated atmosphere. Even as far afield as Japan, European experimental physicists were imported to establish teaching laboratories and pass on the increasingly vital skills of accurate experimentation.

In Britain by the end of the century, the preeminent leader of the pack was without doubt Cambridge's prestigious Cavendish Laboratory. By the early years of the twentieth century the majority of physicists manning university physics laboratories throughout Britain and its colonies had passed through its portals. The Cavendish manufactured experimental physicists as surely and successfully as it manufactured reliable measurements. The Cavendish's success was not achieved without encountering opposition, however. Many worried that a laboratory might not sit well with the reputation of an ancient university catering to the needs of the sons of the upper classes. Some of the dons were certainly concerned that there was more than a whiff of the factory floor about a late Victorian laboratory—hardly an appropriate adornment then for a civilized institution. James Clerk Maxwell, as the first Cavendish Professor, had to work hard to convince them otherwise. He had to find ways of integrating the laboratory into the university's established, hallowed regime.

The Cavendish's reputation by the end of the century was proof of his success. He and his successors, Lord Rayleigh and J. J. Thomson, had transformed the place from a potential thorn in Cambridge's side to a real rose in the university's crown.

For Cantabrigian physicists and other Britons, the major competition during the final decades of the nineteenth century seemed to be coming from the Germans. For much of the century German physics seemed to be in the ascendancy, having taken over from an early lead by the French under Laplace's leadership. British physicists certainly pointed to German physics as being at the root of the new German state's rising industrial (and military) clout and lobbied for increased government funding accordingly. The Germans themselves, however, were less confident. They saw their own physics institutions and laboratories as being in just as much dire need of reform. In particular, according to the electrical entrepreneur and industrialist Werner von Siemens, the new Reich needed its own physical laboratory to keep the opposition at bay, and he was prepared to put up the money for it. The result was the Physikalisch-Technische Reichsanstalt, founded in 1887 after more than a decade's planning and with the eminent Hermann von Helmholtz at its head. The aim was to create an institution devoted to the imperial, industrial, and intellectual needs of the ambitious new state. The fledgling institution would compete with and outstrip the best in Europe in the production of scientific standards, making physics a tool of German industrial progress and expansion.

The most ambitious—and consequential—of the late nineteenth century's grand standardizing projects was the scheme to found an international system of electrical units. Standards like these were deemed essential for the burgeoning international telegraph cable industry on which European and American imperial expansion increasingly depended. As well as ruling the waves, the late nineteenth century's colonial powers needed to have fast and reliable ways of communicating with their distant peripheries. This meant a network of underwater telegraph cables criss-crossing the globe. That network's reliability depended crucially on electrical standards. To maintain the highest efficiency, the cables' electrical characteristics—particularly electrical resistance—had to be known with precision. This was what underlay the British Association for the Advancement of Science's campaign to establish a reliable unit of resistance—the ohm—in the 1860s. Early efforts were spearheaded by Maxwell at King's College London and the apparatus moved with him to Cambridge in the 1870s. Under Rayleigh, standardizing the ohm became a major focus of the Cavendish's activities. It was no accident that British researchers led the field here—most of the world's undersea telegraph network was British owned. One of the Physikalisch-Technische Reichsanstalt's ambitions was to muscle in on Cambridge's preeminence in this area.

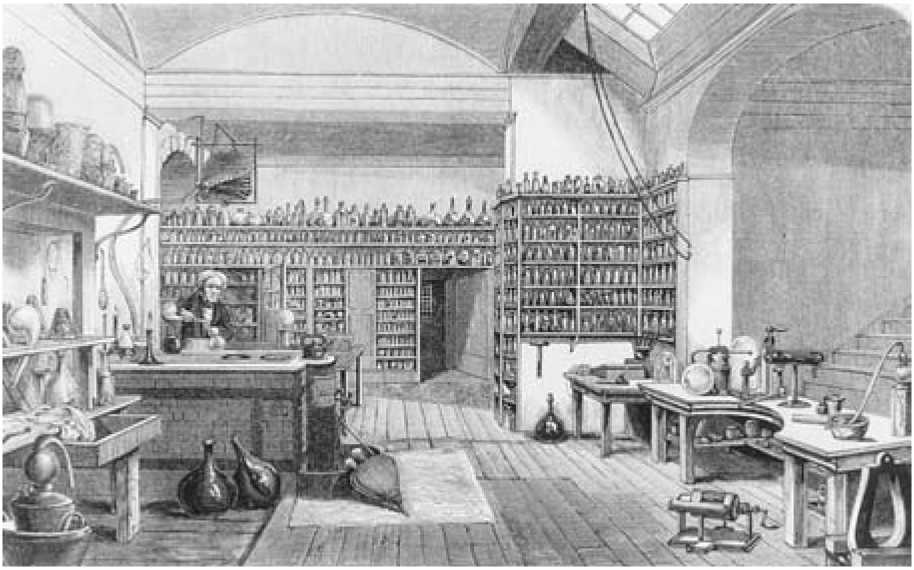
By the end of the century, large physics research and teaching laboratories were a part of the cultural landscape. Across Europe, North America, and beyond, universities without such facilities were rapidly becoming the exception rather than the rule. Such places were widely recognized as being powerhouses of industrial culture. As well as producing the hosts of experimental physicists needed to fill new university positions, these laboratories produced disciplined cadres of engineers and technicians destined for careers in industrial laboratories and workshops. These institutions were wedded to a cult of precision. Making better and ever more accurate measurements of nature's constants was the order of the day. The emphasis on precision fostered discipline. That was the key to unlocking nature's secrets. Increasingly as well, this laboratory discipline was coming to be regarded as a saleable commodity. By the end of the century physicists had a recognizable career structure stretching from undergraduate training through supervised postgraduate research to an industrial or academic position. Spokesmen for the discipline argued for ever larger allocations of public funds to expand the profession. Physics, they argued, had a crucial role to play in fin de siècle culture and in furthering social and economic progress. It was a key weapon in any industrial nation's armory.

The Rise of the Laboratory

Until well into the nineteenth century, institutional laboratories for research—and more crucially, for teaching—in physics were something of a rarity. In no European country was research, in anything resembling the modern sense of the word, taken to be part of the duties of a university professor, for example. A professor's role was regarded as pedagogical—his task was to transmit established knowledge to his students, not to produce new knowledge. University lecture theaters might have an annex—typically behind the lecturer's podium—where demonstrations were prepared, but there was no clear distinction between the backroom work of experiment and the front-of-house activity of demonstration. In some ways, the emergence of the laboratory as a distinctive research—and pedagogical—space in its own right can be thought of as the building of a wall between those two spaces. Research was coming to be regarded as an autonomous activity in its own right rather than as an adjunct to teaching. As such it was seen as requiring its own institutional spaces. Furthermore, it was coming to be regarded as something for which a specific regime of training was needed as well. By the middle of the nineteenth century, laboratories were, if not ubiquitous yet, certainly more common as institutional spaces. The structures of French academies were revamped and research started to be recognized as part of a Faculty member's remit; German physics professors insisted that their cabinets of philosophical instruments be overhauled; in Britain, natural philosophers pointed to Continental developments and insisted on the need to emulate them.

French experimental natural philosophy and its institutions enjoyed a high reputation already at the beginning of the nineteenth century. British and German natural philosophers regarded with envy the facilities and state support their French counterparts were offered. French physical sciences, like the rest of science, had been systematically reordered following the Revolution and under Napoleon's imperial rule. The result was a strictly regulated and hierarchical system of institutes and faculties, largely revolving around Paris. French universities were reorganized under Napoleon into a single University of France, with faculties in the various provincial centers, including science faculties. Experimental and mathematical physics were high on the agenda, though subservient to medicine and law. Foreign students anxious to imbibe the best possible natural philosophical education flocked to Paris to study at the École Polytechnique and the Sorbonne. The laboratories where they clamored to train with masters such as Gay-Lussac and Jean-Baptiste Dumas were not state financed, however. They were private domains. French laboratory physics had a history of concern with precision stretching back to Coulomb's and Lavoisier's pioneering experiments at the end of the eighteenth century. It was an integral part of the Laplacian approach to physics and survived the demise of the Laplacian program.

By the second half of the century, however, French physicists were increasingly agitated by what they saw as the decline of their science. French physics institutions seemed moribund compared to the innovations taking place at German universities, or even in Britain. Foreign students seemed more interested in studying in Berlin than in Paris. French politicians and industrialists worried as well about the way French industry seemed to lag behind its European competitors. The message was rammed home by France's disastrous military defeat by Prussia in 1871. French



8.1 Michael Faraday cheerfully at work in the basement laboratory of the Royal Institution.

physics advertised itself as a solution to the problem. Technical education and laboratory training could produce new cadres of proficient engineers and technicians who would revolutionize French industry. Science faculties quite deliberately sought to transform themselves into institutions with a direct industrial role. As much as preparing teachers for the nation's *lycées*, scientific directors now regarded themselves as committed to the task of producing a scientifically literate workforce. Auguste Lamy at Lille in the 1850s, for example, tailored his research and his teaching on thermodynamics to fit the needs of local Lillois industry, drawing in crowds in the process. Later in the century, science faculties across France aimed to produce engineers for the nation's burgeoning electrical industry. As in Britain and Germany, the inculcation of precision physics in the laboratory was seen as having a distinct payoff in national productivity.

In Britain, one of the first institutional (as opposed to private) laboratories with more than just a supporting role for its adjacent lecture theater was the one at the Royal Institution. Sir Humphry Davy and following him Michael Faraday used the institution's laboratories to further their own research activities (figure 8.1). Originally a chemistry laboratory, with Faraday in charge the work done in the Royal Institution's basements shifted towards physics experiments. The laboratory was used for Faraday's own private research and not to train students (he never had any) in laboratory skills and disciplines. As university professors acquired more institutional space for their experimental activities, however, it became more common for some of them to encourage favored students to join them in their laboratories. Nowhere was experimental training a formal prerequisite of academic study. Enthusiastic favorites could learn the rudiments of experiment at their masters' feet instead. James D. Forbes, professor of natural philosophy at the University of Edinburgh, for example, encouraged students to spend time with him in the laboratory. The status of these laboratories was often ambiguous. The physical space might be provided by the university, but more often than not it was the individual professor who provided the apparatus out of his own pocket, as did Charles Wheatstone at King's College London, with the experiments that led to his invention with William Fothergill Cooke of the electromagnetic telegraph.

When William Thomson arrived back in Glasgow in 1846 to take up his position as professor of natural philosophy, he was anxious to take advantage of the opportunity to embark on his own ambitious program of experimental work. He soon turned to his students to provide him with assistance in this labor-intensive business and gradually, as "other students, hearing that some of their class fellows had got experimental work to do, came to me and volunteered to assist in the investigation,"[1] the basis of an academic teaching laboratory began to form. Arrangements were formalized in the mid-1850s with the university agreeing to provide Thomson with laboratory space that could accommodate his students as well. By 1862, Thomson could boast to Helmholtz that "I have had a really convenient and sufficient laboratory for students. Out of about 90 who attend my lectures, about 30 have applied for admission to the laboratory, and of these 20 or 25 will work fairly. I hope I may have half a dozen who will do good work."[2] By then they were helping Thomson with his work on electrical measuring apparatus, with an eye to the telegraph industry and their mentor's role in the plan to lay a telegraph cable across the Atlantic. They were learning the value (in all senses of the word) of precision measurement.

Thomson's Glasgow innovations established a model that other British physicists sought to emulate. In 1866, George Carey Foster established

---

[1] Quoted in G. Gooday, "Precision Measurement and the Genesis of Physics Teaching Laboratories in Victorian Britain," 31.

[2] Quoted ibid., 35.

a physics teaching laboratory at University College London. He was followed later the same year by Robert Clifton at Oxford. In 1868 Peter Guthrie Tait formalized James Forbes's old arrangements and established a teaching laboratory at the University of Edinburgh. By 1885, speaking at the opening of the physics laboratory at University College Bangor in North Wales, William Thomson could claim that "[t]he physical laboratory system has now become quite universal. No University can now live unless it has a well-equipped laboratory."[3] Others were still a little less gung-ho on the issue. Reminiscing about his appointment at Liverpool in 1881, Oliver Lodge recalled that "it was no joke having to start a laboratory from the beginnings and collect all the apparatus. Physical laboratories were rather novelties in those days. Carey Foster's had been the first of its kind in England; I mean a place where students were trained to perform experiments for themselves."[4] At Liverpool, Lodge found himself in the unenviable position of equipping a physics department in the rooms of an old lunatic asylum. The padded room, he noted, became incorporated into his laboratory. According to Lodge, British models were still so few and far between even by the 1880s, that he felt obliged to "make a tour of the Continental laboratories and gain experience that way."[5]

For Britain's new breed of laboratory managers, the apparently inexorable rise of the laboratory was proof of their field's progress and evidence of a new, disciplined ethos of precision. Frederick Guthrie, professor of physics at the Royal School of Mines, argued in 1870 that "the exact and experimental sciences are now so much more fully developed that it is impossible to remain any longer contented with attempting to teach an experimental class by means of a blackboard and a piece of chalk; it is now necessary to have an efficient apparatus for teaching these subjects."[6] Robert Clifton at Oxford concurred. As he sought to convince the university in 1868 of the need for new facilities, he insisted that "it has now become necessary for students to achieve fuller instructions than can possibly be given in public lectures and it is as important for a student of physics to become acquainted by actual experience with accurate

---

[3] Quoted ibid., 42.

[4] O. Lodge, *Past Years* (London: Stodder & Haughton, 1931), 153.

[5] Ibid.

[6] Quoted in G. Gooday, "Precision Measurement and the Genesis of Physics Teaching Laboratories in Victorian Britain," 36.

physical processes, as it is for students of chemistry or physiology to receive practical instructions in these departments of science."[7] The point was to inculcate an ethos of precision. This was what progress in physics depended upon.

Britain was not alone in fostering the cult of precision and identifying the laboratory as the key to progress in physics. As Oliver Lodge's remarks indicate, some Britons did indeed worry that they had been rather slow in getting the message. Many looked to the German example for inspiration. Germans themselves were proud of their successes. Werner von Siemens boasted in 1883 that "[n]o nation in the world has done so much for scientific and technical education as Germany, and especially Prussia."[8] As in Britain, university teaching laboratories were very much a nineteenth-century innovation. From the early eighteenth century, German natural philosophy professors had habitually assembled physical cabinets—collections of instruments usually for demonstration purposes—which sometimes extended to lecture theaters and workshops. Again as in Britain these were usually the property and responsibility of the individual rather than the institution. In 1833, however, Wilhelm Weber established a laboratory at the University of Göttingen where he offered his students hands-on experience of performing experiments. He continued the practice and established a laboratory at Leipzig when he moved there in 1837. He was emulated by Heinrich Gustav Magnus in Berlin in 1843 and by Franz Neumann at Königsberg in 1847. Both these were private initiatives in the professors' own homes. It was not until 1862 that Magnus persuaded the university to take over the laboratory's funding.

German states for much of the first half of the century took the view that scientific discovery was not the business of the university instructor. It was not an attitude that encouraged universities to provide laboratories. By the 1860s, however, state-funded university laboratories were becoming more common. Crucially, the teaching regime increasingly included a *Praktikum*: a course of training in laboratory experimentation. By the 1870s as well, more and more German universities were establishing their own physics institutes. The expansion of experimental physics—and the cultivation as in Britain of the cult of precision—was helped by German physicists' insistence that new German industries, particularly the rising electrical industry, were "the children of physics," for whom the time

---

[7] Quoted ibid., 38.

[8] D. Cahan, "The Institutional Revolution in German Physics," 1.

had come "to reimburse their Mother for her former nursing."[9] As Emil Warburg argued in 1881, if physics were the source of Germany's newfound industrial might, then new institutes and laboratories were essential to meet "the daily increasing need of successfully communicating in a contemporary manner the theories and methods of physics to a larger audience and of winning a larger number of arms for the advancement of science."[10] Men of physics such as Rudolf Virchow argued that the impact of physics on national life would not just be "the ever-greater extension of material productivity" but to make it "the maxim of our thinking and of moral action."[11] Physics could teach the virtues of precision in everyday life as well as in the laboratory. The bible of the new German physics institutes was Friedrich Kohlrausch's *Leitfaden der praktischen Physik* (1870) with its lengthy discussions of techniques of precision measurement and exhaustive tables of constants.

Increasingly throughout the century, American natural philosophers and physicists were working to convince their institutions of the importance of laboratory work in the production of scientifically literate and proficient students. When the electrician Joseph Henry was hired from Albany by New Jersey College in Princeton, he was adamant that he should have a laboratory equipped with the best European instruments. He set out on a trip to London and Paris to stock up on the essential apparatus. The laboratory he so stocked was for his private use and for the preparation of lecture demonstrations only, however. His students' contacts with experiment were limited to Henry's own spectacular performances in the classroom. There was no hands-on experience. By the end of the century, however, American physicists had fully imbibed their European counterparts' expressions of enthusiasm for hands-on laboratory training and the importance of precision. Many had acquired their own training in experiment at the feet of European masters in Britain and Germany and brought the cult of precision back home with them. Henry Rowland at Baltimore's Johns Hopkins University was a particular enthusiast. The spectroscope diffraction gratings he developed at his Hopkins laboratory set new standards in precision that impressed even the Europeans. A colleague noted on a trip to Europe in the 1880s that the "Germans spread their palms, looked as if they wished they had ventral fins and tails to express their sentiments"[12] concerning Rowland's inventions.

---

[9] Ibid., 39. [10] Ibid., 41. [11] Ibid., 40.

[12] Quoted in G. Sweetnam, "Precision Implemented," 284.

By the 1870s the newly restored Meiji regime in Japan was looking with interest at the successes of Europe's precision laboratories. Meiji officials were anxious to transform imperial Japan into an industrial power comparable with, if not superior to, European and American economies. To this end they were keen to recruit British physicists in particular to staff new scientific institutions and pass on the tricks of the experimenter's trade. The Imperial College of Engineering in Tokyo, established in 1873, hired William Ayrton—one of Thomson's Glasgow stalwarts and a veteran of the Indian Telegraph Department—to introduce Japanese students to the delights of electrical engineering. By 1877 the students under Ayrton's command were "well practiced in the construction and use of galvanometers, electrometers, resistance coils and condensers, etc., and in the performance of all the tests employed in a land line, or submarine cable testing office: artificial lines having been arranged, as far as practicable, with resistance coils, condensers, and a hundred yards or so of the Atlantic cable that were at our disposal."[13] By the time Ayrton returned to London in 1878 to put the teaching skills he had acquired in Tokyo to work at the London City and Guilds Institute, his Japanese students had received a grounding in the business of precision measurement that was the envy of any Western laboratory. His star student, Rinzaburo Shida, graduated to work with William Thomson in his Glasgow laboratory before returning to Tokyo in 1883 as professor of telegraphy at the Imperial College of Engineering.

Precision transformed laboratories across Europe and beyond into industrial powerhouses. The "spirit of accuracy" was lauded as not only providing a much needed guarantor of present success and future progress in physics, but as underpinning the future usefulness of physics as well. Like Victorian factories, physics laboratories could be depended upon to produce a steady stream of diligently designed, mass-produced, and standardized products. It was a public expression and validation of the self-discipline that careful training inculcated into the science and its practitioners. Being precise was both difficult and easy. The culture produced carefully standardized instruments and units that were seemingly straightforwardly transferable from one place to another. On the other hand the business of precision experiment required real commitment and arduous training. Producing an accurate measurement of a physical phenomenon that would pass muster with an increasingly hard-nosed

---

[13] Quoted in Y. Takahashi, "William Ewart Ayrton at the Imperial College of Engineering in Tokyo," 200.

and competitive community of expert physicists required a great deal of hard labor. Despite (or perhaps because of) the finely balanced precision instrumentation that increasingly filled these new academic laboratories, painstakingly acquired skills were the order of the day. Just as we saw earlier that grueling preparation underlay the apparently effortless analytical performances of Cambridge mathematicians, hard work was essential to make the grade as an experimenter too.

The Making of the Cavendish

By the end of the nineteenth century, any survey of physics laboratories would certainly have identified Cambridge's Cavendish Laboratory as one of the most successful both in terms of teaching and research (figure 8.2). In the course of little more than a quarter century, Cambridge had established itself—to all appearances securely—as being among the foremost producers of experimenters and experimental physics. The first three Cavendish Professors—James Clerk Maxwell, Lord Rayleigh, and J. J. Thomson—remain stellar figures in the firmament of physics. To many eyes at the end of the century, Cambridge seemed synonymous with experimental physics. Achieving that identification was not an easy task, however. Establishing a role for laboratory physics and the cult of precision in that venerable institution was by no means straightforward. Dons used to dealing with the sons of gentlemen—and wedded to the ideal of a liberal education—needed considerable persuasion that an establishment of a sort more usually associated with grubby industry than pure intellect was really worth having. Its promoters had to persuade the doubters that laboratory physics, despite the unpromising appearance, was a fit vehicle for the promotion of liberal educational ideals—that it could train and discipline the mind appropriately. It was a dilemma of which the Cavendish's early professors were keenly aware and worked hard to overcome.

In 1869—and in the teeth of considerable opposition—a university committee reported to the senate on the vexed question of the teaching of experimental physics at Cambridge. They noted that the "importance of cultivating a knowledge of the great branches of Experimental Physics in the University was prominently urged by the Royal Commissioners appointed in 1850 to inquire into the State, Discipline, Studies and Revenues of the University and Colleges of Cambridge."[14] Topics such as

---

[14] Quoted in J. G. Crowther, *The Cavendish Laboratory, 1874—1974*, 23.

8.2 An exterior view of the Cavendish Laboratory on Free School Lane, Cambridge.

electricity, heat, and magnetism were occupying an increasingly important place in the examinations for the mathematics Tripos, and it seemed a good time to consider how those subjects might be better taught. It was no coincidence that another royal commission—presided over by the duke of Devonshire, the university's chancellor—was soon to be considering the question of scientific and technical education throughout the country. The committee concluded that it was time for the university to establish a professorship of experimental physics and that the "founding of a Professorship would be incomplete unless means were also supplied to render the Professor's teaching practical, and assistance given to him,

8.3 A group of laboratory students in the Cavendish Laboratory. Note the presence of a female student.

both in the Laboratory and Lecture-room. The need of providing instruments, Apparatus and Laboratories is obvious, and it seems not less necessary to obtain some additional assistance in giving personal instruction to students in the Laboratory"[15] (figure 8.3). While the university dithered over finding the cash, the duke of Devonshire announced his willingness to fund the proposal out of his own considerable pocket.

William Cavendish, the seventh duke of Devonshire, had himself been second wrangler and Smith's prizeman at Cambridge. He was also a successful and prominent industrial entrepreneur. His offer of largesse was well timed. It broke the colleges' resistance to the proposal, and the search was soon on for Cambridge's first professor of experimental physics. The obvious candidate was William Thomson, by then easily the most eminent British physicist. He was unwilling to leave Glasgow, however. The electors then looked to Hermann von Helmholtz in Berlin, but he too was unwilling to abandon the security of his position there

---

[15] Quoted ibid., 24.

for an uncertain future at Cambridge. The eventual choice was James Clerk Maxwell, at the time retired to live the life of a country laird on his Scottish estates at Glenlair. Maxwell was initially dubious. He had, as he said, "no experience of this kind." Furthermore, he worried that the "Class of Physical Investigations, which might be undertaken with the help of men of Cambridge education, and which would be creditable to the University, demand, in general, a considerable amount of dull labour which may or may not be attractive to the pupils."[16] He was eventually persuaded, however, and took up the chair in 1871.

Maxwell was well aware from the outset that his fragile position would require careful consolidation if he were to overcome the dons' suspicions. The new laboratory, when it opened in 1874, must not look too much like a workshop or, as Maxwell worried, "we may bring the whole university and all the parents about our ears."[17] In his inaugural lecture he was anxious to reassure his auditors that the new laboratory under his direction would be a center for far more than mere mechanical drudge work. Precision measurement mattered indeed but should not be confused with industrial production. If that were all it was, then Maxwell argued, "Our Laboratory may perhaps become celebrated as a place of conscientious labour and consummate skill, but it will be out of place in the University, and ought rather to be classed with the other great workshops of our country."[18] This was a paradox that needed careful management, since after all, precision measurement was to be at the core of the Cavendish Laboratory's activities. Maxwell presented it as something that fitted eminently well with the university's natural theological tradition. Showing the high standards of accuracy and precision with which nature had been mass-produced was, argued Maxwell, a good way of demonstrating the powers of its designer: "we may learn that those aspirations after accuracy in measurement . . . are ours because they are essential constituents of the image of Him who in the beginning created, not only the heaven and the earth, but the materials of which heaven and earth consist."[19]

Maxwell visited Thomson at Glasgow and Robert Clifton at Oxford searching for guidance on how to design and organize his new laboratory. He hired William Garnett, fourth wrangler in 1873, as demonstrator. The laboratory was stocked with apparatus (paid for by the duke of

---

[16] Quoted ibid., 34.

[17] Quoted in S. Schaffer, "Late Victorian Metrology and Its Instrumentation," 33.

[18] Quoted ibid., 25.

[19] Quoted in S. Schaffer, "Metrology, Metrication and Victorian Values," 460.

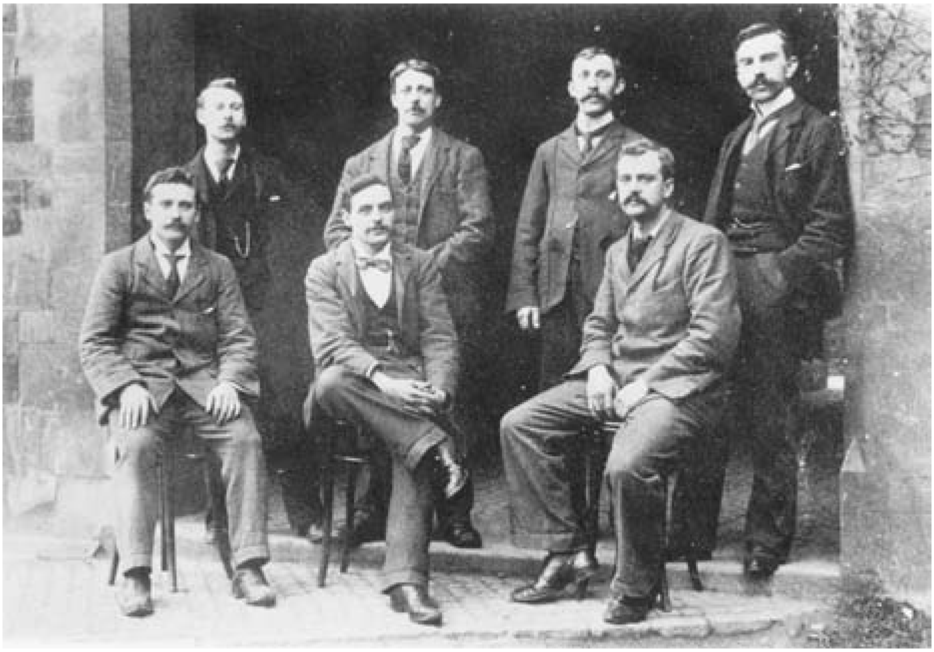
Devonshire) mostly pertaining to the physics deemed relevant to the mathematics Tripos such as heat, electricity, and magnetism. Students were few and far between. There was no requirement that undergraduates studying for the mathematics Tripos, or even the natural sciences Tripos established in 1854, should attend at the laboratory. Maxwell was keen that those students that there were, like W. M. Hicks, later professor of physics and vice-chancellor at Sheffield University, worked under their own steam. He set Hicks to work on measurements of electrical resistance and of the Earth's magnetic field. Students were encouraged to make their own apparatus, which according to Hicks was "worth any amount of routine measurement."[20] Maxwell's scheme was to give his students a thorough grounding in measurement and the use of instruments—overseen by Garnett as demonstrator—before they embarked on their own projects. The British Association's Kew magnetometer, transferred to Cambridge, was used to introduce students to the vagaries of experiment and the skills they needed to acquire. Each student entering the laboratory was, like Hicks, given the task of using the magnetometer to measure the Earth's magnetic field.

Maxwell's tragic death at an early age in 1879 left the Cavendish looking for a successor who could continue the legacy of precision experiment that he had bequeathed it. The favored candidate was Lord Rayleigh, another aristocratic former wrangler with a considerable scientific reputation. Rayleigh was initially unwilling, worrying that such a position might be beneath his dignity, despite encouragement from the duke of Devonshire. William Thomson pleaded with him that if "you could see your way to take the Chair it would I am sure be much to the benefit of the university, and of science too, as the Cavendish Laboratory would give you means of experimenting and zealous and duly instructed assistants and volunteers and would naturally lead you to more of experimental research than might be your lot, even with all your experimental zeal and capacity for investigation, if you remain independent"[21] (figure 8.4). What clinched it for Rayleigh, however, was the agricultural depression, which made it impossible for him to maintain his private laboratory at his country estate in Terling, Essex, in the style to which he had become accustomed. He deigned to take the professorship for a period of five years, by which time to hoped the depression might be over. Despite

---

[20] Quoted in J. G. Crowther, *The Cavendish Laboratory, 1874—1974*, 62.

[21] R. J. Strutt, *Life of Lord Rayleigh* (London: Edward Arnold & Co., 1924), 100.



8.4 The Cavendish Laboratory's lab assistants in 1900.

his initial reluctance, however, Rayleigh arrived in Cambridge with some very definite ideas concerning the Cavendish's future direction.

Rayleigh wanted a massive expansion of the Cavendish's teaching program; in particular he wanted to increase the number of undergraduates trained in the laboratory—most of Maxwell's students had already graduated when they studied there. The new regime was to be systematic, modeled on Helmholtz's practice in Berlin. Under the new dispensation "each experiment was set out permanently on a table to itself, and written directions were provided. The classes were at regular hours, and a demonstrator was in attendance, who assigned the experiment, and gave help in any difficulty, finally approving or disapproving the numerical result."[22] Rayleigh hired two new demonstrators, R. T. Glazebrook and W. N. Shaw, to replace Garnett. Their textbook, *Practical Physics*, based on the Cavendish course, soon became a classic of laboratory physics instruction. In April 1880, students were informed that the "Cavendish Laboratory will open daily from 12 April for the use of students, from

---

[22] Ibid., 105.

11 am until 5 pm, and the Professor or Demonstrators will attend daily to give instruction in *Practical Physics*. The fee for the use of the Laboratory will be two guineas per term."[23] Training began from the basics—Rayleigh complained that at the beginning "[a]nyone who could handle a thing without knocking it off the table was an acquisition"[24]—and aimed to give a thorough grounding in the discipline of precision measurement. As well as teaching them experimental skills, Rayleigh was inculcating his students with laboratory discipline. They were being taught the value of systematic and patient routines of inquiry.

Rayleigh also wanted to put the Cavendish's research on a systematic footing. He was emphatic in his own experimental work concerning the importance of systematization. Glazebrook remarked of his superior's researches that they were "marked by the same characteristics: perfect clearness and lucidity, a firm grasp on the essentials of the problem and a neglect of the unimportant. The apparatus throughout was rough and ready, except where nicety of workmanship or skill in construction was needed to obtain the result; but the methods of the experiments, the possible sources of error, and the conditions necessary to success were thought out in advance and every precaution taken to secure a high accuracy and a definite result."[25] These were the values to be inculcated into the Cavendish's ethos. As Sir Arthur Schuster recalled, however, Rayleigh's concern with system went beyond his individual researches: "One idea to which he attached importance and which was entirely his own, was to identify the laboratory with some research planned on an extensive scale so that a common interest might unite a number of men sharing in the work."[26] Rather than being a place for the demonstration of individual experimental virtuosity, Rayleigh planned the Cavendish as a center for collaborative enterprise. The enterprise he chose was an ambitious one. He wanted to establish the Cavendish as a center for the redetermination of electrical standards—a project with which Maxwell had been involved from the 1860s. Such a project if successful would establish the laboratory firmly at the heart of physics.

Five years after his appointment—and with the agricultural depression comfortably behind him—Rayleigh resigned the Cavendish Professorship and returned to his private laboratory at Terling. His successor

---

[23] Quoted in J. G. Crowther, *The Cavendish Laboratory, 1874–1974*, 88.

[24] R. J. Strutt, *Life of Lord Rayleigh* (London: Edward Arnold & Co., 1924), 106.

[25] Quoted in J. G. Crowther, *The Cavendish Laboratory, 1874–1974*, 98.

[26] R. J. Strutt, *Life of Lord Rayleigh* (London: Edward Arnold & Co., 1924), 109.

at the Cavendish, J. J. Thomson, was already familiar with the value system he left behind, having worked at the laboratory himself under Rayleigh's direction. From a respectable, middle-class Mancunian background, Thomson had studied at Manchester's Owens College before gaining a scholarship to Trinity College, Cambridge. He crammed with the wrangler-making coach E. J. Routh to graduate second wrangler and gain a coveted Trinity College fellowship. It was only then that he started working at the Cavendish Laboratory, a month after Maxwell's death. The aim was to acquire for himself a thorough grounding in the rudiments of precision experiment to go with the grounding in mathematical physics with which the Tripos had equipped him. This was very much in line with Maxwell's own vision of the laboratory, as J. J. Thomson put it, as "a place to which men who had taken the Mathematical Tripos could come, and, after a short training in making accurate measurements, begin a piece of original research."[27] When appointed to replace Rayleigh in 1884, Thomson was young but already a fellow of the Royal Society. His appointment surprised many—including Rayleigh—who still thought of Thomson as more of a mathematician than an experimentalist.

The work Thomson had undertaken at the Cavendish under Rayleigh's direction had been a classic piece of Maxwellian experimental physics. His challenge was to determine the ratio of the electrostatic to the electromagnetic units of electric charge. According to Maxwell's theory the ratio should be equal to the velocity of light. The project had the potential, therefore, to be a bravura demonstration of the program of systematic precision measurement that Rayleigh was putting in place at the Cavendish as well as a powerful vindication of Maxwell's theory of electromagnetism. Thomson's efforts were not, however, particularly successful, and he soon moved on to help Rayleigh with his grand collaborative project to redetermine electrical standards. He was cutting his experimental teeth on cutting-edge technology. By the mid-1880s his reputation as a diligent and productive experimenter was high. He was a good example of what the Cavendish regime under Rayleigh could produce. Moving on to find his own experimental projects as professor, he took up the study of cathode rays of the kind pioneered, as we saw earlier, by William Crookes. The research would pay dividends with his discovery of the electron a decade or so later.

J. J. Thomson's mounting reputation as an experimenter underscored the Cavendish's own rising star. He continued and consolidated

---

[27] J. J. Thomson, *Recollections and Reflections* (London, 1936), 95.

Rayleigh's program of systematic experimental instruction. As he recalled, the "number of science students in Cambridge increased rapidly after 1885."[28] A new wing to the Cavendish was opened in 1896 to relieve the pressures of massively increasing numbers. There was "a very large room used for the elementary classes in practical physics, for examinations in practical physics for the Natural Science Tripos and for entrance scholarships to the Colleges. Besides this there was a new lecture-room, cellars for experiments requiring a constant temperature, and a private room for the Professor."[29] In 1895 it became possible for graduates of universities other than Cambridge to enter the Cavendish as research students, initially for the degree of M.A. but later gaining Ph.D.s. As Thomson noted, "since the M.A. degree did not entitle a man to be called 'doctor', our students were at a disadvantage when competing for teaching posts with those who had been to a German university and had obtained the Ph.D. degree."[30] The influx (and eventual outflux) of foreign students allowed by the new regulations enabled the spread of the Cavendish's values of precision—and its reputation—across Europe, America, and the Empire.

By the end of the nineteenth-century Cambridge and the Cavendish stood at the heart of an expanding worldwide network of competing laboratories and institutes. It also represented the core values of Victorian physics. Maxwell had regarded the laboratory as an outpost through which the ethos of precision measurement could be introduced to and intertwined with the Cambridge culture of liberal education. Exact measurement could be a way of broadening and disciplining the mind as well. Care and diplomacy had been required to reassure a skittish university establishment that bringing a laboratory to Cambridge was not after all tantamount to converting the college cloisters into factory floors. Maxwell's plan had been to make the place available to graduates who had already persuaded the university of their trustworthiness by going through the Tripos ritual. Under Rayleigh and J. J. Thomson the Cavendish did indeed become more of a production line, albeit one churning out only a small number of quality items every year. Its students were systematically introduced to a carefully worked-out culture of experimental discipline through carefully graded routines. The values they imbibed and exported as they scattered across the empire and the globe were ones of discipline, diligence, and precision as the hallmarks of experiment.

[28] Ibid., 123. [29] Ibid. [30] Ibid., 137.

Berlin's Imperial Institute

As J. J. Thomson's concerns about his students' job prospects indicate, there was little doubt in British laboratory physicists' minds as to who their main rivals were. By the 1880s, Germany's new physics institutes looked like a formidable force. By the standards of envious onlookers they appeared well funded and well organized. To some German physicists, nevertheless, however enviable their institutions might seem compared with those in other European countries, things were still not good enough. Increasingly during the 1870s and 1880s they lobbied the new government in Berlin for more resources. In particular, they wanted an institution devoted to research not teaching. While British and French physicists pointed to the awesome reputation of German physics and its apparent role in boosting the new state's rapidly expanding industries, some of their German counterparts were insisting that far more needed to be done if future German industrial supremacy were to be achieved. They were anxious to persuade the Bismarckian state that physics had a key role to play in the Reich's future. The eventual result of this lobbying was the Physikalisch-Technische Reichsanstalt, set up in 1887 with Hermann von Helmholtz as its director, committed to physics research as an arm of the imperial state. The new institution was to be a powerful rival to the Cavendish in the world of precision measurement.

The resources that some German states committed to their physics institutes were already formidable. During the 1870s, Prussia committed more than 1.5 million marks to Helmholtz's Berlin Institute. The British physicist John Tyndall, Faraday's successor at the Royal Institution, remarked enviously to a colleague that "you will find in the Berlin laboratory the very things which my American and British friends and I should like to see in operation in all college and university laboratories in America and in the British Empire."[31] The powerful and influential industrialist Werner von Siemens argued, however, that this was simply not enough. His complaint was that "[s]cientific research itself, however, is not a professional activity within the state structure; it is only a tolerated private activity of scientists alongside their profession . . . The sad consequence of all this is that in most cases scientific projects that might revive and stimulate entire areas of life are not undertaken."[32] The German states encouraged and financed physics teaching, according to

---

[31] Quoted in D. Cahan, "The Institutional Revolution in German Physics," 23.

[32] Quoted ibid., 1.

Siemens, at the expense of progress in research. The institutes produced legions of teachers instead of the experimenters who could make a real contribution to the Reich. The solution in his view was a new imperial institution committed to research.

Werner von Siemens was a powerful voice in the new Germany. Siemens and his brother had made their fortunes as pioneers in the new electrical industries that emerged during the second half of the nineteenth century. While Werner took care of the German end of affairs, his brother Wilhelm emigrated to Britain, eventually taking up British nationality and turning himself into Sir William Siemens. During the 1840s, Werner von Siemens, along with his partner J. G. Halske, was at the forefront of German telegraphy. He regarded himself as a physicist as much as an industrialist. "My love always belonged to science as such," he said, "while my work and accomplishments lay mostly in the field of technology."[33] In 1884, Siemens decided to put his money where his mouth was and offered to fund the establishment of a Reich physics institute. He had made a similar offer to Prussia the previous year. It was to be an institute for research alone: "The teachers and laboratories of the universities and pedagogical schools are not appropriate for the purpose; neither are the professors employed by them. The more active these latter are and the more they have proved themselves to be pathbreaking researchers, the more they are overburdened by their teaching obligations and the extra duties bound up with them." He was convinced that "[f]rom the planned natural scientific workplace, both material and ideal advantages of great importance would accrue to the Reich."[34]

Lobbying in favor of some kind of national or imperial physics research institute had been going on since the early 1870s. Men such as the physiologist Emil du Bois Reymond, Wilhelm Foerster (director of the Berlin Observatory), and Hermann von Helmholtz argued that Prussia and the Reich needed some kind of institute devoted to precision measurement. It was an argument that found favor with Prussian military strategists such as Helmut von Moltke. Opinions were mixed as to what exactly the new institute should do. Helmholtz wanted a body that granted funds for precision instruments. Others wanted a commercial testing station. Little concrete happened until the 1880s and Siemens's offer. Siemens argued that "England, France, and America, those countries which are our most dangerous enemies in the struggle for survival,

[33] D. Cahan, *An Institute for an Empire*, 36.

[34] Ibid., 40–41.

8.5 An artist's sketch of the proposed new Physikalisch-Technische Reichsanstalt.

have recognized the great meaning of scientific superiority for material interests and have zealously striven to improve natural scientific education through pedagogical improvements and to create institutions that promote scientific progress."[35] Despite Siemens's offer, persuading the Reich's bureaucracy—particularly gaining Bismarck's indispensable support—was difficult. Some powerful interest groups, including engineers, industrialists, and physicists, worried that the proposed Reichsanstalt would encroach onto their own territory. It was not until 1887 that eventual agreement was secured.

The proposed institution needed careful planning. It would need "well-planned rooms protected from external disturbances, excellent and costly instruments" as well as "the complete devotion of the scientists." Siemens was worried that "Bismarck . . . still holds science for a type of sport without practical meaning" and that a great deal of work still needed to be done to convince him otherwise. The public and fellow physicists needed to be convinced that this would be "a place of work open to all outstanding German scientists"[36] and not just for a cabal of Berlin insiders (figure 8.5). In Siemens's plan, the institute would be divided into two

---

[35] D. Cahan, "Werner Siemens and the Origins of the Physikalisch-Technische Reichsanstalt," 204–5.

[36] Ibid., 276.

sections—physical and technical—under the control of an overall president. The technical section would be responsible for choosing scientific problems, setting the budget, and generally administering the institute. The physical section would have as its main task the development of new experimental investigations. The technical section was to be subdivided into five carefully chosen subsections, representing areas where the Reich hoped for industrial supremacy: materials testing, precision mechanics, optics, thermometry, and electrical standards testing. Siemens had already chosen the man who would be in charge of this great new enterprise. His choice was the grand old man of German physics—Hermann von Helmholtz.

Helmholtz was widely recognized in Germany and elsewhere as being head and shoulders above his contemporaries. To one fan he was the "Imperial Chancellor of German Science." An American student studying under him remarked that "the whole scientific world of Germany, nay, the whole intellectual world of Germany, stood in awe when the name of Excellenz von Helmholtz was pronounced. Next to Bismarck and the old Emperor he was at that time the most illustrious man in the German Empire."[37] It was proof of his preeminence that when he was appointed to head the new Berlin Physics Institute in 1871 he could command the staggering sum of 315,000 marks to be spent on his official residence there. He had enough clout that he virtually held the Reich to ransom before agreeing to take up the position as the Physikalisch-Technische Reichsanstalt's president. He demanded a salary of 15,000 marks along with an annual bonus of 9,000. The government in the end had little choice but to capitulate. As they recognized, the institution had to a large extent been designed with Helmholtz in mind as its eventual director. Helmholtz enjoyed a wide reputation as well as a public spokesman for science in Germany. He seemed ideally suited for the task of putting physics in its proper place at the heart of the German state.

Helmholtz proved to be an inspirational leader at the Reichsanstalt, as he had at the Berlin Physics Institute. Like his counterparts at the Cavendish Laboratory, Helmholtz was keen to get his people working as a team. Once the institute's building was complete, the scientific section had its own *Observatorium* built for the purpose, designed to be free from external disturbances. The entire building was constructed on a thick thousand-square-meter concrete slab for maximum stability and the external walls were shielded from direct sunlight to help ensure a

---

[37] D. Cahan, *An Institute for an Empire*, 65.

constant temperature. Each of the floors was devoted to a different aspect of the Reichsanstalt's research. Thermodynamics work took place on the ground floor, where it was easiest to control the temperature. Electrical and optical work was on the highest floor, with the offices and library in the middle. The experimenters also had access to a machine house and a separate entirely iron-free building for magnetic experiments. These were unrivaled facilities that underlined the Reich's hopes for what physics could deliver.

Under Helmholtz's direction, the scientific section was divided into three laboratories working on heat, electricity, and optics. The heat laboratory focused on finding better materials for thermometers, improving the accuracy of thermometric measurements at high temperatures, and improving the design of heat engines—all precision projects. The electrical laboratory was in the business of competing with the Cavendish in providing accurate and reliable electrical standards—a matter of particular concern to Werner von Siemens—as well as experimenting on the effects of magnets. They carried out experiments for the Reich navy, trying to minimize the disruptive effects of iron on ships' compasses. At the optics laboratory, the main concern was to establish reliable industrial standards in the measurement of light, following Fraunhofer's achievements earlier in the century. This was a particularly pertinent concern as Germany led the world in optical instrumentation. Under Otto Lummer, Helmholtz's former student and assistant at the Berlin Physics Institute, the laboratory's workers experimented to develop a more reliable photometer—an instrument for comparing the intensity of light from different sources. The concern throughout was to establish standards of precision measurement that could be put to industrial use. Making such standards would be a tangible demonstration of German superiority in precision physics and a warning shot across the bows of its industrial competitors in the rest of Europe and America.

Disaster struck the Reichsanstalt in the *schwarze Jahr* of 1894. Helmholtz died. Finding a replacement was not to be easy. His deputy, Ernst Hagen, worried that it was "unforeseeable how the situation here at the Reichsanstalt will develop since Helmholtz has died . . . The main problem lies in the fact that basically everything here was tailor-made for Helmholtz's *person*."[38] The eventual choice as successor was Friedrich Kohlrausch, author of the ubiquitous *Leitfaden*. Beyond his reputation

---

[38] Ibid., 123.

as the author of one of Germany's most widely used physics textbooks, Kohlrausch had much to recommend him. He was a veteran administrator, having been in charge of five physics institutes before arriving at the Reichsanstalt. His father, Rudolf, had himself been an eminent experimentalist in midcentury and had ensured a fine training and good contacts with the best in the field for his son. Friedrich had acquired his doctorate with Wilhelm Weber at Göttingen in 1863 before going on to codirect the Göttingen Physics Institute with his former mentor later in the decade. When he received the call to Berlin, Kohlrausch was director of the Strassburg Physics Institute—one of the largest (and most expensive to build) in Germany.

As well as being an old hand at administration, Kohlrausch had something else to recommend him. He had built his career as an experimenter on the activity that was in many ways the Physikalisch-Technische Reichsanstalt's raison d'être—precision measurement. Looking back over his career in 1900, he opined that "measuring nature is one of the characteristic activities of our age."[39] From that perspective, Kohlrausch's activities had certainly been preeminently characteristic. A colleague, Heinrich Rubens, remarked that "no other physicist has surpassed Kohlrausch in the skill and care with which he used instruments and methods."[40] He had been responsible for inventing and developing a whole range of revolutionary new precision instruments—dynamometers, galvanometers, magnetometers, and reflectometers. In particular, he had made his reputation in the field of electrical measurement and the establishment of electrical standards. From the beginnings of his career working with Weber he had devoted almost forty years to working at determining the values of electrical and magnetic constants and units. He had represented German interests at many of the international congresses devoted to working out acceptable international standards of electrical measurement and was widely recognized as *the* German expert in that industrially crucial field. He was regarded as eminently well-placed to steer the Reichsanstalt towards helping ensure German domination of the expanding electrical industries.

The Reichsanstalt expanded massively under Kohlrausch's direction. It had more or less doubled in size by 1903. Kohlrausch devoted the same kind of diligence to his administrative tasks as he did to his vocation of

---

[39] Ibid., 129.

[40] Ibid., 130.

precision measurement. A former colleague, Svante Arrhenius, described him as having “always lived as orderly as a chronometer and is in all social relations a strict formalist. His principal scientific endeavour is directed at improving measuring methods, so as to make the probable error smaller. Indeed he has an all-too-great predilection for finely rounded numbers.”[41] In Phileas Fogg style, Kohlrausch clearly expected those around him to conform to his orderly expectations. The informal regime inaugurated by Helmholtz as director was replaced by a far more formal and rigid administration. Kohlrausch agreed, however, with Helmholtz and the institute’s founders about the Reichsanstalt’s wider purpose. It was there to place physics at the service of the Reich. The different laboratories of the science section pursued much the same activities—albeit on a larger scale—as they had under the previous administration. Much of the institute’s expansion took place in the technical section, which by the late 1890s was fully devoted to serving the needs of German industry for scientific testing.

The Physikalisch-Technische Reichsanstalt was in many ways an entirely unprecedented institution. In no other European country had the community of physicists persuaded their national government to support their research in such lavish fashion. It was testament to the success with which physicists had maneuvered themselves into positions of real power and influence in the new German Reich. Men of science such as Hermann von Helmholtz could wield political clout that was the envy of contemporaries elsewhere in Europe. His public pronouncements on the state of science and of its relevance to German cultural life mattered. The Reichsanstalt was celebrated at home and recognized abroad as a triumphant expression of an ambitious new industrial power’s potential. The German physics community had been fashioned into a seemingly indispensable arm of the state. That fashioning had taken place around the cult of precision. As in Britain, physicists had successfully argued that their concern with precision measurement not only contributed to industrial progress, but that it also expressed important cultural values. The Physikalisch-Technische Reichsanstalt was an instantiation not only of the utility that the German Reich hoped for from the systematic application of physics to industry but of the virtues of self-discipline and application that the new state wanted to foster in its citizens.

---

[41] Ibid., 134–35.

A Real, Purchaseable Tangible Object

The importance of international standards in physics for national industry (and for national prestige) was underlined in the ongoing battles that dogged the second half of the century surrounding the measurement and use of electrical standards. The debates capture not only the ways in which precision mattered for the formation of physics as a discipline and as an important, self-defining part of the physicist's art, but the ways in which precision expressed views concerning the cultural place of physics and its potential utility. Being in a position to define international standards in an increasingly important field of research like electricity put the victorious party in a position of some advantage. It meant that everyone else had to come to them to have their apparatus validated. It also signaled the consolidation of electricity as a science. As William Thomson pointed out, turning an electrical unit into "a real, purchaseable tangible object" so that "we may perhaps buy a microfarad or a megafarad of electricity,"[42] would bring physics fairly and squarely into the Victorian marketplace. It demonstrated that physics had value in a way even the most hardheaded industrialist could understand and appreciate. This was what standardization was all about. It encompassed the progress in scientific knowledge and in industrial supremacy that disciplined physics could deliver.

The spread of commercial electric telegraph networks from the 1840s onwards encouraged the creation of a new breed of electrical experts. Putting these networks together and—just as importantly—maintaining them once they were up called for extensive electrical know-how. Telegraph engineers such as Latimer Clark soon realized that one of their biggest problems was finding the location of faults in the lines. Particularly with underground cables, unless the engineer could find a way of more or less precisely locating a fault—such as a break—valuable time was lost and valuable labor wasted digging along the line to find the problem. Latimer Clark had joined the Electric Telegraph Company as an engineer in 1850, when the company was still easily the largest in Britain, from a background in civil engineering. He rapidly became a pioneer in the new field. Along with others such as Cromwell Varley, Clark realized that the key to finding faults in underground wires was measurement. A good knowledge of the characteristics of their copper wires—particularly

---

[42] Quoted in S. Schaffer, "Late Victorian Metrology and Its Instrumentation," 32.

of their resistance to the passage of current—was a prerequisite to finding faults. One simple method, for example, was simply to see what length of wire in the workshop gave the same galvanometer reading as the faulty wire. The length of the wire then determined the position of the break in the line. This only worked, of course, if the test wire and the cable had similar resistances. Ways were needed of calibrating the components of telegraph circuits.

The problem of measurement became more urgent from the 1850s onwards with the development of underwater telegraphy. The first commercial underwater cable was laid between Dover and Calais in 1851. It soon became clear that underwater telegraphy had its own particular problems. The problem of locating faults accurately and quickly became more urgent. After all, dredging for a faulty cable underwater was a considerably more costly business even than digging for one on land. Submarine cables also suffered from a problem known as retardation—signals tended to become smeared and merged into each other over long distances. The cables seemed to leak, so that more current was needed to ensure a good signal at the other end. All of this meant that telegraph engineers needed a good understanding of the electrical characteristics of their equipment. They needed to be able to measure those characteristics and they needed to be able to compare them effectively with their workshop or laboratory apparatus. By the late 1850s, telegraph engineers were therefore increasingly working with standardized pieces of equipment like resistance coils or condensers. As William Thomson recalled, looking back at the history of precision electrical measurement, "Resistance coils and ohms, and standard condensers and microfarads, had been for ten years familiar to the electricians of the submarine-cable factories and testing-stations, before anything that could be called electric measurement had come to be regularly practised in almost any of the scientific laboratories of the world."[43]

Matters came to a head in many ways with the ambitious plans of the late 1850s and early 1860s to lay down a telegraph cable across the Atlantic, linking the Old World with the New. The Atlantic cable's promoter, Cyrus Field, had coaxed a fortune from his backers to finance the enterprise, as well as securing the cooperation of British and American governments. It was a disaster when the first cable failed in September 1858 after barely a month of operation. Since 1857, William Thomson, a director of the Atlantic Telegraph Company, had been carrying out

---

[43] W. Thomson, *Popular Lectures and Addresses* (London, 1891), 1: 82–83.

experiments at his Glasgow laboratory on the cable being used in the enterprise, finding out in the process that it was of extremely variable quality. While Thomson argued that this was a major defect—albeit one about which little could be done since much of the cable had already been manufactured and was indeed in the process of being laid—the company's electrician, Wildman Whitehouse, argued that cable resistance (or conductivity) mattered little. The key to successful signaling in his view was the use of his patent induction coil apparatus to send rapid, high-intensity bursts of electricity down the cable. The pinpointing of Whitehouse's high-intensity jolts as one of the primary causes for the cable's failure did much to concentrate minds on Thomson's suggestion that strict quality control of cable production was essential.

Following the cable's failure, the British government and the Atlantic Telegraph Company convened a committee to oversee an inquest into its early demise. Taking evidence from a raft of telegraphic experts, they also commissioned research on an unprecedented scale into the electrical characteristics of telegraph cables. Latimer Clark alone carried out experiments on hundreds of miles of copper wire and the new insulating material gutta-percha. Another key witness was Fleeming Jenkin, a young engineer from R. S. Newall's cable factory at Birkenhead near Liverpool. He carried out extensive experiments on the relative resistances of copper and gutta-percha in an effort to calculate the amount of current that would leak out through the insulation in a telegraph cable. In comparing the resistances of different substances like this Jenkin in particular came up against the problem of standards. There were no commonly agreed units of electrical measurements in which he could express his results. There were by this time a number of resistance standards in use. Telegraph engineers in Britain used coils calibrated in miles of copper wire, in France they used kilometers of iron wire, and so on. What the new tests highlighted, however, was the very unreliability of these standards themselves. Their reliability depended on the purity of their components, which was exactly what the inquest to the failed Atlantic cable cast doubt upon.

Into this breach stepped the British Association for the Advancement of Science. At its Manchester meeting in 1861 it established a committee on electrical standards to look into the whole vexed question. The committee, which included Fleeming Jenkin, William Thomson, and Charles Wheatstone (inventor of the telegraph) in its ranks, was soon joined by James Clerk Maxwell. Their aim was to act on the suggestion, put to the British Association by Sir Charles Bright and Latimer Clark, that "the science of Electricity and the art of Telegraphy have both now arrived at a stage of progress at which it is necessary that universally received standards of electrical quantities and resistances should be adopted, in order that precise language and measurement may take the place of the empirical rules and ideas now generally prevalent."[44] It was not a straightforward matter. The committee needed to set up a standard that met the needs of laboratory physicists and practical telegraph men. The British Association's ohm, as the crucial standard of electrical resistance came to be called, was the product of much hard work and negotiation. Maxwell was a critical figure; it was at his laboratory at King's College London that the crucial experiments to establish the value of the ohm were carried out. When he received the call to Cambridge and the Cavendish Laboratory, he was determined that the British Association's ohm and its instrumentation would follow him there. It was too important a piece of intellectual and commercial property to leave behind.

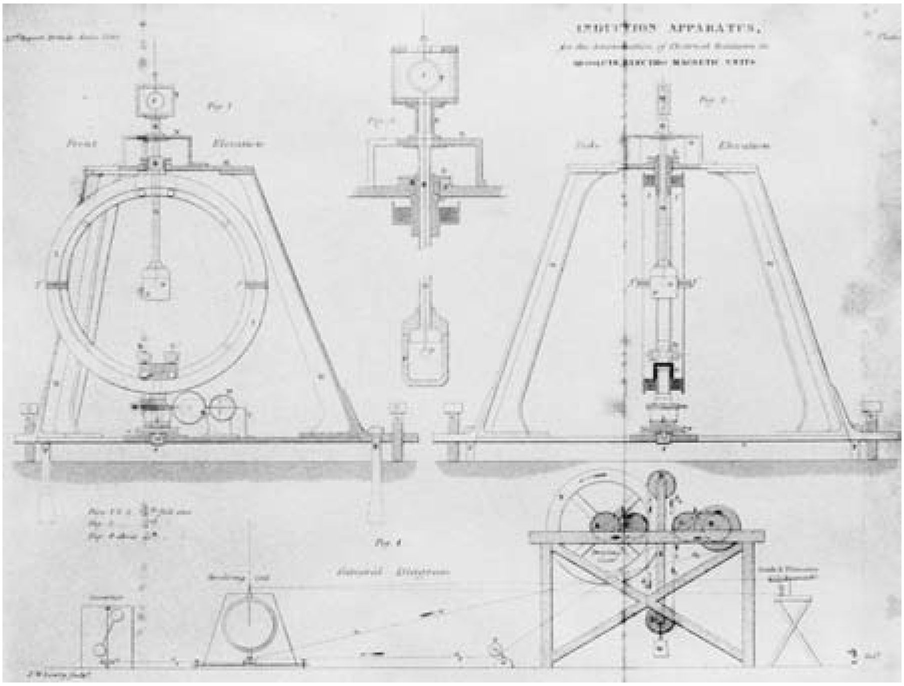
In his groundbreaking *Treatise on Electricity and Magnetism*, Maxwell argued that "the determination of electrical resistance may be considered as the cardinal operation in electricity, in the same way that the determination of weight is the cardinal operation in chemistry."[45] Carrying out this cardinal operation was to be one of the Cavendish Laboratory's chief tasks. The British Association measuring apparatus consisted of a rapidly rotating coil with a magnetized needle at the center (figure 8.6). As the coil rotated in the Earth's magnetic field, a current would be induced that caused the needle to deflect. The size of the deflection depended on the diameter of the coil, the rate at which it was spun, and the coil's resistance. Measuring the needle's deflection, the coil's diameter, and the rate at which it was spun gave a highly accurate value for the coil's resistance. This would make it possible to produce a standard resistance coil, defined as one ohm. Simple as it might appear in principle, getting the experiment right required the mobilization of major resources. Some of Britain's most skilled engineers and scientists devoted themselves to the problem. Measurements of unprecedented precision were needed to get at the right level of accuracy.

Following Maxwell's death, his successor, Lord Rayleigh, made the project his own. Measuring the ohm would provide the Cavendish with a collaborative project that would help bind its workers into a disciplined, unified corps and establish a set of laboratory values in more senses than

---

[44] Quoted in B. Hunt, "The Ohm Is Where the Art Is," 58.

[45] J. C. Maxwell, *Treatise on Electricity and Magnetism* (Cambridge, 1873), 1: 465.



8.6 The British Association for the Advancement of Science's Committee for Electrical Standards' apparatus for measuring the ohm.

one. As Rayleigh started work on the project in 1880, it was a concerted team effort: "The apparatus had been set up on the ground floor of the laboratory, in the room then known as the 'magnetic room' . . . The revolving coil was set up on a brick pillar . . . The observations were made late at night, to avoid magnetic and other disturbance. Rayleigh regulated the speed, Dr. Schuster took the main readings, and Mrs. Sidgwick recorded the readings of the auxiliary magnetometer."[46] When Schuster left to become professor of physics at Manchester, Eleanor Sidgwick—the wife of the professor of moral philosophy and university reformer Henry Sidgwick, and Lady Rayleigh's sister—took over his role, while Lady Rayleigh herself often came in to replace her on the magnetometer. Triumphantly, the revised ohm gave a value for the mechanical equivalent of heat, measured electrically, that tallied with the mechanically measured value to an unprecedented degree of precision. It was a result that closely tied the Cavendish ohm to the whole body of nineteenth-century energy

[46] R. J. Strutt, *Life of Lord Rayleigh* (London: Edward Arnold & Co., 1924), 114.

physics. James Prescott Joule hastened to congratulate Rayleigh on his success. "It is an extraordinary and gratifying result for all of us, and I congratulate your lordship and Schuster on the admirable experiments you have brought to so successful an issue,"[47] he wrote.

Rayleigh, the Cavendish, and the British Association ohm were not without their opponents, however. As early as 1851, Wilhelm Weber (Kohlrausch's old mentor) had published a highly sophisticated absolute system of standards based around units of force and motion. Following developments introduced by subsequent theorists, Weber's system had the advantage—to theoretically inclined physicists at least—of tying electrical quantities directly to the fundamental concepts of energy and work. Their definitions were highly complex, however. The resulting units were also very difficult to measure. Most seriously, Weber's units seemed of little use to jobbing electricians. Their values were too small to be of any practical use to anyone whose concern was to work with miles rather than inches of wire. The theory behind Weber's system was also increasingly suspect to British physicists weaned on Maxwell's field theories of electromagnetism.

More robust opposition came from Werner von Siemens, who advocated a standard resistance based on the use of columns of mercury. In his view, there was simply no need for any great metaphysical heart wrenching. All that was needed was to define the unit of electrical resistance in terms of the resistance of an arbitrary column of mercury. What mattered was that the unit chosen should be of a size useful for the telegraph industry: "those cases in which the expression of absolute measure is of advantage occur very seldom and only in purely scientific exercises," he argued. In Siemens's opinion, not only was the search for absolutism unnecessary, it was also suspect. It was a distraction from the task at hand. His standard (and arbitrary) mercury column resistances were handy simply because that was all they were designed to be—"every other definition would not only burden unnecessarily the calculations which occur in modern life, but also confuse our conception of the measure."[48] Part of the problem was that just as the British objected to Weber's system on the grounds that it involved adherence to Weber's theory, Siemens recognized that the British Association ohm, for

---

[47] Ibid., 117–18.

[48] W. von Siemens, "Suggestions for the Adoption of a Common Unit of Measurement of Electrical Resistance," *Reports of the British Association for the Advancement of Science*, 1862, **32**: 154.

example, increasingly embodied Maxwell's energy physics. Buying one meant buying into the other as well. Siemens's campaign to establish the Physikalisch-Technische Reichsanstalt throughout the 1870s and early 1880s was largely about trying to overcome this British imperialism in the field of electrical measurement and theory. The new institute could provide a rallying point for the opposition. At international congresses during the 1880s, the Germans fought hard against the British Association standard. It was a losing battle. In many ways, even the setting up of the Reichsanstalt was an admission of defeat. It was an acknowledgment that absolutism, not pragmatism, was the way to go after all.

The ohm demonstrated how physics furthered industrial, Victorian values. In many ways it is completely unsurprising that British electricians led the pack in the development of electrical standards and eventually dominated the field. After all, by the final quarter the century, British cable companies dominated the world's telegraph industry as well. The episode shows how the cult of precision fostered in physics laboratories across Europe fitted in with a wider set of values. Precision measurement could be seen as an answer to the question Victorian cynics often posed of physics—*Cui bono?* Whom does it benefit? What is it for? A great deal of labor was expended in the process. Establishing the ohm took mobilization on a grand scale. In Britain alone, laboratories at Cambridge, Glasgow, and London played central roles. Engineers, instrument makers, and physicists alike required and acquired new skills in the process. The biggest task of all was to make all of that labor appear invisible. All the customer purchased at the end of the day was a coil of wire. That coil stood for an absolute and universal system of measurement that was accepted as being independent of any local skills or resources. The whole point about the standard ohm was that despite the great efforts required to produce it in particular laboratories like the Cavendish, it was meant to work unproblematically anywhere in the world. In that way at least, the ohm was very much the epitome of Victorian values.

Conclusion

From being rare, exotic places at the beginning of the nineteenth century, physics laboratories by the end of the century seemed ubiquitous. Every self-respecting university anywhere in Europe, the Americas, the colonies, or beyond needed a physics laboratory. As an institutional space, it had become part of the fundamental apparatus of learning. Not only elite universities, but even high schools might well have their own teaching laboratory by the end of the period. Such laboratories as existed in the previous century had as a rule been private places, the domain of particular individuals who had the resources to indulge in the experimental investigation of nature. By the end of the century most laboratories were public institutions. They were in principle open to all—all, that is, who had the appropriate credentials and qualifications. As the discipline of physics emerged out of natural philosophy during the course of the century, laboratories came to be that new discipline's archetypal institution, as experiment appeared to be the archetypal activity. They were the training grounds where acolytes acquired the skills they needed to investigate nature and put its products to work. Laboratories forged physics' links with industry and brought large parts of the industrial ethos with them into the citadels of academe.

Precision mattered for late nineteenth-century physics as a way of inculcating new disciplinary regimes as much as anything else. It was a crucial element in the fashioning of physicists as much as of physics. In the new academic teaching laboratories, the transmission of skills from mentor to student was a highly regimented process. Laboratory teaching, as well as what was taught, was increasingly standardized. The values of precision linked the world of late Victorian energy physics and its laboratories to the world of industry as well. Not only did the standardized electrical units produced in these laboratories have an immediate role to play in electrical industry, but the work regime and the ethos that had produced those units blended easily with those of industrial culture too. When Maxwell assured his audience of Cambridge dons that he had no intention of turning the Cavendish into a "manufactory of ohms," he was addressing a real concern. He was not entirely convincing in his denials either. Late Victorian laboratories manufactured physicists as well, moreover. At the beginning of the twentieth-century, Cambridge products were to be found reproducing the Cantabrigian ethos of precision all over the globe. The same could be said of Germany's physics institutes as well. Spreading the values of precision meant multiplying and disseminating the places of precision and its duly trained adepts too.