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A Revolutionary Science

When the Parisian crowds stormed the Bastille fortress and prison on 14 July 1789, they set in motion a train of events that revolutionized European political culture. To many contemporary commentators and observers of the French Revolution, it seemed that the growing disenchantment with the absolutist regime of Louis XVI had been fostered in part by a particular kind of philosophy. French *philosophes* condemning the iniquities of the *ancien régime* drew parallels between the organization of society and the organization of nature. Like many other Enlightenment thinkers, they took it for granted that science, or natural philosophy, could be used as a tool to understand society as well as nature. They argued that the laws of nature showed how unjust and unnatural the government of France really was. It also seemed, to some at least, that the French Revolution provided an opportunity to galvanize science as well as society. The new French Republic was a tabula rasa on which the reformers could write what they liked. They could refound society on philosophical principles, making sure this time around that the organization of society really did mirror the organization of nature. Refounding the social and intellectual structures of science itself was to be part of this process. In many ways, therefore, the storming of the Bastille led to a revolution in science as well.

To many in this new generation of radical French natural philosophers, mathematics seemed to provide the key to understanding nature. This was nothing new in itself, of course. Greek philosophers such as Pythagoras had argued that nature could be comprehended mathematically. Far more recently, Galileo, Kepler, and Descartes, among others, had shown just what could be achieved by approaching nature through the language of mathematics. The hero of the mathematical worldview—in France as much as in his native England—was, however, Sir Isaac Newton. To French philosophers such as Condillac, Diderot, and Voltaire, Newton's *Principia* set the standard for the mathematical understanding of nature. Many late eighteenth-century natural philosophers—seeing themselves as following in Newton's footsteps—placed increasing emphasis on accurate measurement, on numbers, and on the development of powerful new mathematical analytical tools with which to manipulate their findings about nature. In revolutionary France, in particular, this new emphasis on the mathematical and the quantitative in natural philosophy was held up as a prerequisite for finishing Newton's task and producing a complete and final picture of an ordered and rational clockwork universe. Newton's French followers set aside Newton's vision of a universe in which God was continually present and refashioned his work as the epitome of Enlightenment rationalism.

Following the revolution, French scientific institutions were overturned, as ancient institutions as well as heads toppled to the ground. The royalist Académie Royale des Sciences was abolished and replaced with an Institut Nationale in 1795. At about the same time, new educational establishments such as the École Polytechnique and the École Normale were set up to train new cadres of revolutionary savants. Particularly following Napoleon Bonaparte's coup d'état of 1799, senior natural philosophers at the institute held positions of increasing political power. Napoleon was a keen advocate of, and enthusiast for, the physical sciences. The physicist Pierre-Simon Laplace, along with his close ally the chemist Claude-Louis Berthollet, held a firm grip on the reins of scientific power in France. Laplace, seeing himself as a committed Newtonian, wanted to complete what he regarded as Newton's grand project of reducing the universe to clockwork. French mathematicians such as Joseph-Louis Lagrange were producing powerful new mathematical techniques and applying them to understanding nature. Major strides forward across the board of rational mechanics were being made by the likes of Jean-Charles Borda, Réné-Just Hauy, and Laplace himself. Laplace promoted his allies and his protégés to positions of influence. His *Mécanique Celeste* was a manifesto of Newtonian science and an exemplar of how scientific progress should take place.

Radical young mathematicians in England such as Charles Babbage and John Herschel looked enviously on at the great strides achieved in revolutionary and Napoleonic France. Undergraduates at the University of Cambridge, they regarded their alma mater as a reactionary backwater—in both political and scientific terms. Cambridge's mathematicians were not only fervent Newtonians, but still wedded to Newton's way of doing mathematics as well. They had no time for the revolutionary gibberish being produced across the Channel. It was atheistic, materialistic, and (of course) French. Babbage, Herschel, and their cohorts vowed, however, to change all that and introduce analysis to Cambridge and to England. Cambridge professors and fellows devoted themselves to educating the sons of the gentry, preparing them to govern the burgeoning empire. They were taught mathematics because its rigors were held to be good training for the mind. Babbage and Herschel concurred with that at least. They wanted to make mathematical analysis into the foundation of a whole new understanding of the way the mind worked and how science could progress. They looked for links with business and commerce, moreover. The new science of analysis would lead to a proper understanding and organization of political economy as well.

By midcentury, Cambridge's mathematical reputation had been transformed. The university was probably the premier European institution in terms of mathematical training. Undergraduates underwent rigorous preparation in the latest mathematical techniques and their applications to physics before undergoing a grueling examination at the end of their student careers. Mathematics was still held to be a study calculated to breed gentlemen fit to govern an empire—a high ranking in Cambridge's mathematical league table could guarantee a successful career. Increasingly, however, ambitious young natural philosophers looked to the Cambridge mathematical Tripos (as it was called) as well, to provide them with a thorough grounding in the latest mathematics and its applications. Competition for the highest honor—the senior wranglership—was fierce. The university developed a unique culture of mathematics training designed to carry students through the rigors of the Tripos. Sporting prowess was encouraged as a means of relaxing the mind while turning the body into a fit receptacle. Two giants of nineteenth-century British physics—Maxwell and Kelvin—were products of the Cambridge system, as were a host of others. By the end of the century, Cambridge mathematical physics in many ways epitomized British science.

The German lands were developing their own culture of mathematical physics during the nineteenth century as well. The mid-nineteenth-century generation of German natural philosophers reacted strongly against what they perceived to be the metaphysical excesses of early nineteenth-century Romantic *Naturphilosophie*—as we shall see in more detail in subsequent chapters. Natural philosophy played an increasingly central role in German education as the century progressed. New research institutions were established with the express aim of placing German scientists at the forefront of natural philosophy. In many ways, theoretical physics as now recognized had its origins in these nineteenth-century German institutions. Physicists such as Rudolf Clausius in Zurich, Ludwig Boltzmann in Vienna, Bernhard Riemann in Göttingen, and Carl Neumann in Leipzig prided themselves on the abstractedness of their theoretical practice. Theory was a valid exercise in its own right. Where British natural philosophers worried about the material foundations of the terms and concepts deployed in their theories, German theoretical physicists by and large had no such concerns. What mattered was the integrity of the theory and its capacity to explain and predict the phenomena.

Physics in the nineteenth century was developing into strong and robust forms of practice, each with its own styles and traditions of research and institutional bases. As the century went on, success in physics increasingly came to be recognized as a marker of national status as well. Great men of science started to be recognized as national heroes as much as statesmen and soldiers. Laplace in France, Kelvin in Britain, and Helmholtz in Germany were national figures. Physics was becoming a way of fashioning oneself upon the national (and international) stage. In many ways the story of nineteenth-century physics is the story of the struggles of its practitioners to carve out a distinctive cultural niche for themselves and their way of doing things. For much of the nineteenth century there was no clear-cut, straightforwardly defined way of "doing" physics. There was no career pattern that the budding physicist might follow from school to university to research institution. Nineteenth-century physicists had to fashion themselves. They had to make up their careers as they went along.

The French Revolution

French scientific institutions in the late eighteenth century were unmistakably part of the *ancien régime*. The country's premier scientific institution, the Académie Royale des Sciences in Paris, was the creature of royal patronage. There was nothing surprising therefore in the revolutionary

Committee of Public Safety's decision to suppress the Académie, along with other royalist institutions, including the universities. It was perceived as privileged, aristocratic, and elitist and opposed therefore to the ideals of the Revolution. When it was replaced a few years later in 1795 by the first class of the Institut Nationale, that new establishment was regarded as having a crucial role to play in furthering the Revolution and France's interests. Men of science were being mobilized for the war effort and came to play increasingly important roles in the Republic's affairs. This trend continued after Napoleon's takeover of the state. This forging of a new relationship between scientific institutions and the state provided the opportunity for some influential natural philosophers to implement their own particular visions of physical science. Pierre-Simon Laplace in particular took advantage of this chance to implement his grand Newtonian vision of a comprehensive physical theory that would lay bare the clockwork mechanism of the universe.

Physical astronomy, for Laplace, was the exemplar science. It was implicit in his view of science that all natural phenomena could be accounted for in just the same way that Newton had accounted for the movement of heavenly bodies. Just as the force of gravity dictated the movements of the stars and planets and of bodies on the Earth's surface, so could similar forces acting in the same way explain other kinds of movement. "By means of these assumptions," he asserted, "the phenomena of expansion, heat, and vibrational motion in gases are explained in terms of attractive and repulsive forces which act only over insensible distances . . . All terrestrial phenomena depend on forces of these kinds, just as celestial phenomena depend on universal gravitation. It seems to me that the study of these forces should now be the chief goal of mathematical philosophy."[1] Laplace's monumental *Traité de Mécanique Céleste*, in which these words appeared, was published in five volumes between 1799 and 1825. It contained a comprehensive manifesto of Laplace's vision of the end of natural philosophy in a unified Newtonian theory of everything. All of physical science could be reduced to the study of the force interactions between particles. The active powers of electricity, magnetism, heat, light, and so forth were to be understood as imponderable fluids made up of discrete particles interacting with each other in just the same way as the planets interacted with the Sun.

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[1] P.-S. Laplace, *Traité de Mécanique Céleste* (Paris, 1799–1825), 5: 99, trans. in R. Fox, "The Rise and Fall of Laplacian Physics," 89.

Entrenched in a situation of ever increasing power and prestige within the Napoleonic French state, Laplace was in an ideal position to put his project into practice. He gathered a constellation of committed disciples around himself, all of them convinced like him that the holy grail of physics was to reduce everything to the interaction of particles in space. Laplace and his friend and fellow Bonapartist Claude-Louis Berthollet both owned country properties at Arcueil, a few miles south of Paris. There from 1801 onwards they organized the Société d'Arcueil, an informal society of their friends and protégés similarly committed to the project. They met there weekly to discuss their mutual interests in science and to plot their activities within the first class of the institute. The society provided Laplace and Berthollet with a secure base and a support structure from which they could engineer the elevation of their protégés into key positions within the powerful first class of the Institut Nationale and into influential teaching positions within the École Polytechnique and elsewhere.

French scientific institutions as reorganized under Napoleon were structured in a strict and centralized hierarchy. At the top of the pyramid were the prestigious members of the first class of the Institut Nationale. Membership in the institute was by election, and holders were salaried servants of the state. Members wielded a considerable power of patronage as well. Their say-so could be instrumental in determining the appointment of a budding young scientist to a salaried position teaching at one of the Parisian écoles or at a provincial university. Through his powers of patronage, Laplace was in a position to further the careers of his protégés; Jean Baptiste Biot and Étienne Louis Malus, students at the École Polytechnique, were promoted to positions of power and influence by Laplace. One function of the institute was the organization of prestigious prize competitions for significant new work in physics. Laplace was in a position to help ensure that prizes were awarded in areas of research in which his disciples were active. Thus, in 1807, for example, the first class of the institute proposed as a subject for the prize in mathematics a study of the phenomena of double refraction. Malus duly won the prize of 3,000 francs in 1808 with a theoretical extension of Laplace's own work on refraction in the *Mécanique Céleste*.

One of the exemplars of how to do Laplacian science was Laplace's own theory of capillary action. Trying to explain the tendency of a liquid in contact with a solid surface (such as the inside of a tube) to creep up that surface to some extent was a standard problem for eighteenth-century natural philosophers. It was axiomatic in Laplace's approach that such capillary action was the result of short range forces acting between the particles of liquid and the particles of solid. The issue was what form the law governing those forces should take. Some argued that it must be an inverse square law such as Newton had identified for gravitational force. Others argued that the inverse square law could be modified for intermolecular distances. Laplace succeeded in sidestepping the dispute with an elegant mathematical demonstration showing that the precise form of the law was unimportant for its solution. Compared with previous efforts to solve the problem, Laplace's offering was lengthy and comprehensive. Along with his treatment of refraction, again based on the assumption that the phenomena were to be understood as the result of short-range interactions between particles—of light and solid matter in this case—this work not only supplied his allies and protégés with concrete examples of what a comprehensive theory should look like and how it ought to be constructed, but also provided them with a wealth of experimental work to confirm and expand Laplace's own hypotheses.

Étienne Malus's work during the 1800s on the reflection and refraction of light beams fitted neatly into this picture. As a good Laplacian and faithful disciple it was axiomatic to Malus that light was made up of particles rather than waves. This was a moot point for eighteenth-century natural philosophers. The illustrious Newton was ambivalent on the matter, while the eminent Dutchman Christiaan Huygens had produced solid results with a wave theory. According to the particle theory, or corpuscular theory, light consisted of a stream of particles emanating from the illuminated body and striking the eye of the observer. The theory was highly successful. By applying the laws of Newtonian mechanics to the light particles it was possible to explain a range of optical phenomena like reflection and refraction. Proponents of the wave theory, on the other hand, argued that light was the result of undulations in a universal, cosmos-filling immaterial medium. Vibrations in the illuminated body were transmitted like waves through this universal medium—or ether—to impinge on the observer's vision. Huygens applied the wave theory to provide rival explanations to those of the corpuscularians. He also succeeded in explaining the curious phenomenon whereby objects viewed through crystals of Iceland spar appeared double—a phenomenon known as double refraction.

Malus succeeded, however, in reproducing Huygens's results and his explanation of double refraction using a corpuscular theory of light. He also made a major discovery. He found that light was polarized by reflection. In other words, light reflected from a surface appeared to be asymmetric—it acted differently along different directions. Polarization could be demonstrated by looking at light through particular kinds of crystals. If the crystal was held one way, the light source was visible. If the crystal was rotated by a right angle, the light source disappeared. This was a major triumph for the corpuscular theory of light. It seemed incompatible with the wave theory but easily explicable by assuming that the individual particles of light rotated around axes that were at an angle to their direction of motion. Malus's triumph was to reduce the various phenomena of reflection, refraction, and polarization to a single mathematical law, built around the assumption of asymmetric particles of light: "If we consider in the translation of the light molecules their motion around their three principal axes, a, b, c, the quantity of molecules whose b or c axes become perpendicular to the direction of the repulsive forces will always be proportional to the square of the sine of the angle these lines will have to describe about the a-axis in order to take up this new direction."[2] It was a classic piece of Laplacian science.

Laplace's success and that of his vision of a complete Newtonian philosophy of nature were closely tied to the fortunes of the Napoleonic state. While the empire flourished, so did Laplace. When the empire collapsed, however, so did the Laplacian empire of natural philosophy. Following Napoleon's fall at the Battle of Waterloo in 1815, Laplace lost a great deal of the political power he had wielded so effectively for the past fifteen years. Laplace's position under the restored Bourbon monarchy was by no means as secure as it had been before. His powers of patronage were increasingly curtailed along with his power to prevent political and scientific opponents from having their voices heard. In the years following the Restoration, therefore, an increasing number of Young Turks from a new generation set themselves up in explicit opposition to the Laplacian camp. Some of these rebels, such as Pierre Dulong and François Arago, were defectors from the Laplacian camp—both had been members of the Société d'Arcueil and had benefited from its patronage. Others, such as Joseph Fourier and Augustin Fresnel, were provincials who had had little previous contact with Laplace and Parisian scientific circles. Fourier, the oldest member of the burgeoning anti-Laplacian alliance, was a former army officer who had served under Napoleon in the disastrous Egyptian campaign. Fresnel was a known royalist sympathizer, a graduate of the

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[2] E. L. Malus, "Théorie de la Double Refraction," *Mémoires Savants Étrangers*, 1811, **2**: 496, trans. in E. Frankel, "Corpuscular Optics and the Wave Theory of Light," 147.

École Polytechnique and the École des Ponts et Chausses who had spent most of his career in the provinces as a civil engineer.

Fourier had first come to Parisian scientific attention with a mammoth treatise on the distribution of heat in solid bodies, read out before the first class of the Institut Nationale in December 1807. Completely bypassing the standard Laplacian route of deriving his equations by treating the phenomena as the result of force interactions between particles of heat (the caloric theory of heat), Fourier developed his own way of approaching the problem, cultivating a whole new mathematical technology along the way. In his presentation, Fourier was determinedly agnostic concerning the physical nature of heat, preferring to focus on a more abstractly mathematical formulation of the problem. A few years later he successfully submitted a revised version of his treatise for one of the first class's prize competitions, judged by a panel including Laplace himself as well as Lagrange, Legendre, Malus, and Hauy—all good Laplacians. Despite that achievement, publication of his work was blocked and his prize-winning contribution did not appear in full until 1823, long after Laplace's fall from grace and when Fourier himself was already permanent secretary of a revived Académie Royale des Sciences. In the meantime, an extended abstract of his work was published by the sympathetic anti-Laplacian, Arago, in the *Annales de Chimie et Physique* of 1816.

More trouble came to the Laplacians from the field of optical theory, so recently hailed as the site of some of their greatest triumphs in the form of Laplace's work on refraction and Malus's discovery of polarization. This work had been extended by both Jean Baptiste Biot and François Arago in classic Laplacian fashion. Before long, however, the two experimenters fell out in a public and acrimonious priority dispute in which Arago accused Biot of appropriating his discoveries for himself. Disenchanted with the Laplacians, Arago was more than happy to place his considerable influence at the disposal of Augustin Fresnel when the young outsider tried to interest Parisian savants in his own rival wave theory of the phenomena of diffraction—the breaking up of a beam of light into a series of light and dark bands when it passes through a narrow slit or past the edge of a body. Fresnel explained diffraction by supposing that dark bands were caused by the coincidence of peaks and troughs in waves of light canceling each other out at particular points along the wave front while light bands were the result of two peaks reinforcing each other. Having arrived in Paris in the summer of 1815, Fresnel was soon in contact with Arago, who took him under his wing and pointed him in the direction of the Englishman Thomas Young's studies on the wave theory of light. Arago undertook, moreover, to act as reporter for Fresnel's first presentation before the first class of the institute later that year. As well as submitting a highly complimentary report, Arago also had Fresnel's memoir published in his *Annales de Chimie et Physique* and succeeded in finding him a permanent position in Paris so that he could continue his researches. The turncoat Arago was turning the Laplacian patronage network against itself.

The Laplacians threw down the gauntlet. In 1817 a commission of the academy, packed with Laplacians, called for a prize competition on the subject of diffraction. Their hope was to repeat the triumph of 1808, when Malus had carried off the laurels with his corpuscularian study of refraction. There was even a staunch Laplacian, Claude Pouillet, one of Biot's students, working on the problem. The terms in which the competition was posed made it clear that the commission expected a corpuscularian victor. The commission, however, underestimated Fresnel, who responded with a revised treatise, ironing out problems in his original presentation and producing new mathematical laws for deriving the phenomena of diffraction. The commission, despite its corpuscularian bent, had little choice but to award him the accolade. A few years later, even Biot, a committed proponent of the corpuscularian theory, was admitting that "the principle of interference is, up to now, the only one with which one can explain the particularities of diffraction, and in that this phenomenon is favourable to the undulatory system." He still maintained though that there was something unsatisfactory about the solution: "one feels that it offers rather a representation of the phenomena than a rigorous mechanical theory."[3] In due course he hoped that it would be replaced by a suitably materialist, that is to say corpuscularian, theory.

Biot was to be disappointed. One by one the citadels of Laplacian physics fell before the interlopers. By the 1820s, both the caloric theory of heat and the Laplacian two-fluid theories of electricity and magnetism were under fierce attack as well. In mechanics, orthodox Laplacian "physical mechanics" was being replaced by the "analytical mechanics" practiced by Fourier and his protégés such as Claude Navier and Sophie Germain. Laplace's ally Simeon-Dénis Poisson deplored the new style and hankered for the days when mathematicians would "re-examine the leading problems of mechanics from this point of view, which is at once

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[3] J. B. Biot, *Précis de Physique*, 3rd ed. (Paris, 1824), 2: 472–73, trans. in E. Frankel, "Corpuscular Optics and the Wave Theory of Light," 162.

physical and consonant with nature."[4] Abstract analysis was all very well, but what was really needed was a mathematics that stayed in touch with material reality. As the Laplacian generation either grew older or fell out of political favor under the restored monarchy, their positions in the seats of power were usurped by their political and scientific opponents. Arago, Ampère (another anti-Laplacian), and Fourier were already members of the reconstituted Académie Royale des Sciences. Fresnel was elected in 1823. A year earlier, in 1822, Fourier had scored a decisive victory by trouncing Biot in the election for one of the permanent secretaryships. The loss of political power and the loss of scientific credibility appeared to go hand in hand.

Laplace had presided over a remarkably productive two decades of science in France. His brand of revolutionary science had brought about a transformation in the eighteenth-century Newtonian synthesis. As far as his adherents were concerned, his magisterial *Mécanique Céleste* provided the blueprint for a thoroughgoing Newtonian overhaul of physics. It showed as well how successful mathematics could be as a tool with which to comprehensively interrogate nature. This new, sweeping, and powerful science went hand in hand with the revolutionary reform of France. Its uncompromising materialism fitted in well with the guiding philosophy of the newly dominant elite. The Revolution and its Bonapartist aftermath gave Laplace the political clout to put his vision into practice as well. Laplace had the power to hire and fire. He could put into positions of influence those who shared his commitment to a materialist reading of Newtonianism. The shake-up of French scientific institutions after the Revolution and under Napoleon's dispensation allowed for scientific careers for the talented in a way that few had previously been able to aspire to. To envious eyes beyond the boundaries of the Empire, French science could easily appear as an ideal to be fondly emulated.

The Analytics

English science at the turn of the century—at least in its upper echelons—was very much an aristocratic affair. A smattering of natural philosophy was part of the cultural repertoire of leisured gentility. Practicing natural philosophers were often either gentlemen themselves, with the time and

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[4] S. D. Poisson, "Mémoire sur l'Équilibre et le Mouvement des Corps Élastique," *Mémoires de l'Académie des Sciences*, 1829, **8**: 361, trans. in R. Fox, "The Rise and Fall of Laplacian Physics," 118.

resources to devote themselves to science, or men beholden to such gentlemen for patronage. English men of science and fellows of the Royal Society prided themselves on their scientific heritage. They were after all the inheritors of the great Sir Isaac Newton's mantle. The president of the Royal Society in 1800—Sir Joseph Banks, who had made his name as a botanist on Captain Cook's voyages of exploration in the South Seas—had already been at the helm for more than twenty years and was to remain there for another twenty. As his reign lengthened, more and more of the younger generation of natural philosophers became restive—particularly those interested in the mathematical sciences of which Banks (reputedly at least) disapproved. They regarded English science as becoming ever more backward and reactionary, losing touch with the developments taking place in Continental Europe. They abhorred Banks and his patronage networks and wanted science to be a meritocracy instead. They wanted to forge links between science and commerce rather than kowtow to lords and ladies of leisure.

Early nineteenth-century Cambridge remained a bastion of academic and aristocratic privilege. Its students were largely drawn from the ranks of the landed gentry and the university's purpose was to provide the finishing touches to their education, to prepare them for service to church or state. Mathematics was perceived as having a central role to play in achieving this end. It provided an unparalleled means of training the mind. A student who could follow the complexities of Euclid's geometry or Newton's fluxions (as Newton's style of calculus was called) was judged to be capable of following a course of reasoning in other walks of life as well, be it the law, politics, or theology. Cambridge's mathematical professors and scholars had little time for new developments. The university was a citadel of learning, not of research. They preferred to follow tried and tested methods rather than dabbling with dubious (and foreign) innovations. As befitted its status as nurturer of the nation's future elite, the university, particularly during the Revolutionary and Napoleonic wars, was politically and theologically conservative as well. Students had to swear their allegiance to the thirty-nine articles of the Church of England before graduation; heresy both in politics and in theology was firmly stamped down.

For a new breed of student in early nineteenth-century Cambridge, however, this state of affairs was deeply unsatisfactory. Men such as Charles Babbage and John Herschel admired French science and politics and were deeply contemptuous of what they regarded as the culpable ignorance and reactionariness of the Cambridge dons. Babbage was the son of a wealthy banker. Herschel, of course, was the son of the celebrated Hanoverian emigré, the musician and astronomer William Herschel, discoverer of Uranus. Both had republican sympathies. Babbage was acquainted with Napoleon's exiled younger brother, Lucien. Herschel had visited Paris with his father and been introduced to Napoleon himself. In letters to Babbage he addressed him as "citizen" in the French fashion and after Waterloo expressed disquiet to his friends as to his future as a "poor snivelling democratic dog"[5] in a world dominated by triumphalist aristocrats. Along with others such as George Peacock, Alexander d'Arblay, and Edward Ffrench Bromhead, they mixed their enthusiasm for revolutionary politics with a taste for revolutionary mathematics. Disdaining the Newtonian bias so prevalent in Cambridge, they immersed themselves instead in the latest products of French analysis. In their politics and their intellectual allegiances they stood for everything that stalwarts of the Cambridge regime such as Isaac Milner, the redoubtable president of Queens' College, found abhorrent.

The outcome of their backroom conspiracies was the foundation of the Analytical Society in 1811, committed to introduce French mathematics into the University of Cambridge. The society was started almost as a joke—a joke at the expense of the university's conservative politico-theological wranglings. A dispute was raging over the foundation of a Bible Society. While some argued that the Bible should be circulated along with the Book of Common Prayer to guard against heretical misinterpretations of the word of God, others were adamant that the Bible should be distributed alone. It was a dispute as to the extent the poor could be trusted to read God's word unsupervised. In the midst of this furor, Babbage in his rooms at Trinity College drew up plans for an alternative society. It was to be established to support the publication of the French mathematician Silvestre François Lacroix's *Differential and Integral Calculus* in English, a work, according to Babbage's broadside, already "so perfect that any commentary was unnecessary."[6] The lampoon did have a serious intent, however. Babbage and his cohorts—all high-flying mathematicians aiming at high honors in the mathematical Tripos—were disgusted by the state of affairs at Cambridge. They wanted to revolutionize the Tripos and bring it, as they saw it, up to date.

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[5] J. Herschel to J. Whittaker, 7 July 1815, quoted in H. Becher, "Radicals, Whigs, and Conservatives," 411.

[6] C. Babbage, *Passages from the Life of a Philosopher* (1884; reprint, London: Pickering & Chatto, 1991), 20.

The society's aim was to support "the Principles of pure D'ism in opposition to the Dot-age of the University."[7] The slogan was a barbed in-joke and a pun. The new French analytical calculus employed the now conventional notation *dx/dy*. The university's favored approach was that of Newtonian fluxions, which would express the same concept as $\dot{x}$. At the same time, the radical theological principles of deism (denying Revelation and the Trinity) were being opposed to the university's muddleheaded dotage. Babbage and Herschel were the new society's leading lights, both committed to the new system. They consumed French mathematics voraciously and produced their own contributions prodigiously, published in their own in-house journal, the *Memoirs of the Analytical Society*. Both, along with Peacock, had eyes on a Cambridge fellowship. Babbage flunked, however. Having moved to Peterhouse from Trinity so that he might have a chance of a fellowship without taking holy orders, he fell afoul of the university's religious ordinances and thus was unable to aim for honors. He got an ordinary degree without examination and lost his chance of a college career. Herschel graduated senior wrangler at St. Johns in 1813, gaining a college fellowship. Peacock came second and gained a fellowship at Trinity, accepting ordination along the way.

Within a few years, George Peacock was appointed one of the university's examiners and took advantage of his position to start introducing the new, infidel "d-istic" notation into the Cambridge examination papers. The analytics' logic was simple—if the new mathematics were in the examination papers, then Cambridge's private tutors, who undertook the bulk of teaching, pragmatists to a man, would start teaching it to their students. Its introduction in 1817 was highly controversial to say the least. Looking back, Peacock suggested that only the success of students from St. John's at the examination (the master of St. John's was vice-chancellor of the university that year) prevented him from being hauled in front of the university courts for his temerity. The opposition had some real intellectual concerns about the new mathematics. As George Peacock's opponent Daniel Peacock (no relation) put it, "Academical education should be strictly confined to subjects of real utility, and so far as the lucubrations of the French analysts have no immediate bearing on philosophy, they are as unfit subjects of academical examination, as the Aristotelian jargon of the old schools."[8] The complaint was that French

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[7] Ibid., 21.

[8] D. Peacock, *A Comparative View of the Principles of the Fluxional and Differential Calculus* (Cambridge, 1819), 85.

analysis lost its grip on reality. Powerful it might be, but its symbols did not refer to anything in the real world. Its techniques simply provided a shortcut through a problem without providing the kind of intuitive, if plodding, understanding that an undergraduate needed if he were to have his mind trained for empire.

For Herschel and Babbage, however, there was more to analysis than a debate about the appropriate mathematical symbols, or the proper education of Cambridge undergraduates, or even mathematics itself. Analysis was part and parcel of a grand project of intellectual, economic, and cultural reform that they hoped would turn British society on its head. They agreed with the Cambridge dons that mathematics was preeminently a way of training and organizing the mind. They differed, however, in their methods and in what they wanted the mind trained for. These were representatives of the new urban industrial middle class. They saw Britain's future in industrial expansion and the thoroughgoing application of political economy. The key to the success of analytical algebra as they saw it was its efficiency. It was a problem-solving technology that could produce answers quickly and without wasting resources. That was why it was good mental training. It exemplified efficiency. More than that—it mirrored the workings of an ideal mind as well. It was a way of economizing mental labor. As such it could be used to recognize what the most efficient way of proceeding in other enterprises might be too. It could provide the key, for example, to the most profitable way of deploying resources in order to maximize factory production.

Following his enforced departure from Cambridge, Babbage switched his field of operations to the metropolis. There, his enthusiasm for finding ways of maximizing the efficiency of mental labor in the same way that the division of labor was increasingly being deployed to maximize the efficiency of manual labor earned him a receptive audience. London's bankers and industrialists were as keen as he was to find ways to improve their balance sheets. Babbage's circle in London included men such as the stockbroker Francis Baily and the actuary Benjamin Gompertz. Both were enthusiastic mathematicians and astronomers, convinced, like Babbage, that their science could and should be prosecuted like their business—and vice versa. Efficiency was the name of the game in both cases, and efficiency was best achieved by due attention to, and proper application of, the laws of nature and the operations of the mind. Babbage, Baily, and Gompertz, as well as Herschel, were instrumental in establishing the Astronomical Society in 1820 as an alternative power center to Sir Joseph Banks's corrupt (as they saw it) domination of the Royal Society.

Following Banks's death in office in 1820 and throughout Sir Humphry Davy's precarious presidency of the Royal Society during the 1820s, radicals, spearheaded by Babbage and his Astronomical Society cohorts, battled with the conservatives for control of the Royal Society and its near monopoly of governmental patronage for science. The battle culminated in John Herschel's unsuccessful stand against the duke of Sussex (the king's younger brother) for the Royal Society's presidency in 1830.

This was a battle about efficiency and the proper division of labor in science. The problem with the Banksian regime and its successor, in Babbage's and his friends' minds at least, was that it interfered with the proper and transparent workings of the scientific community. It depended on backroom backhanders instead of meritocracy. The superiority of algebraic analysis over geometrical reasoning lay in its efficiency and transparency as well. Babbage argued that "[t]he power which we possess by the aid of symbols of compressing into a small compass the several steps of a chain of reasoning, whilst it contributes greatly to abridge the time which our enquiries would otherwise occupy, in difficult cases influences the accuracy of our conclusions: for from the distance which is sometimes interposed [in geometrical reasoning] between the beginning and the end of a chain of reasoning, although the separate parts are sufficiently clear, the whole is often obscure. This observation furnishes another ground for the preference of algebraic over geometrical reasoning."[9] Not only was analysis more efficient, it was less prone to error than geometry—it was easier to scrutinize. That kind of oversight, according to Babbage, was the key to good science and the key to good management in both industry and science.

Babbage's ultimate solution to the problem of how to guarantee efficiency, transparency, and accuracy in reasoning was the same as his solution to the same problem in political economy: replace humans with machinery. Babbage was a firm exponent of the division of labor in factory management and equally enthusiastic for mechanization as the ultimate realization of the principle. His primary concern throughout the 1820s and beyond was to work on his projected calculating and analytical engines and to persuade a sometimes reluctant government to finance the project. The calculating engine would replace the human drudge work of calculating mathematical tables to be used (for example) in actuarial work and in astronomy. The analytical engine would go further—it

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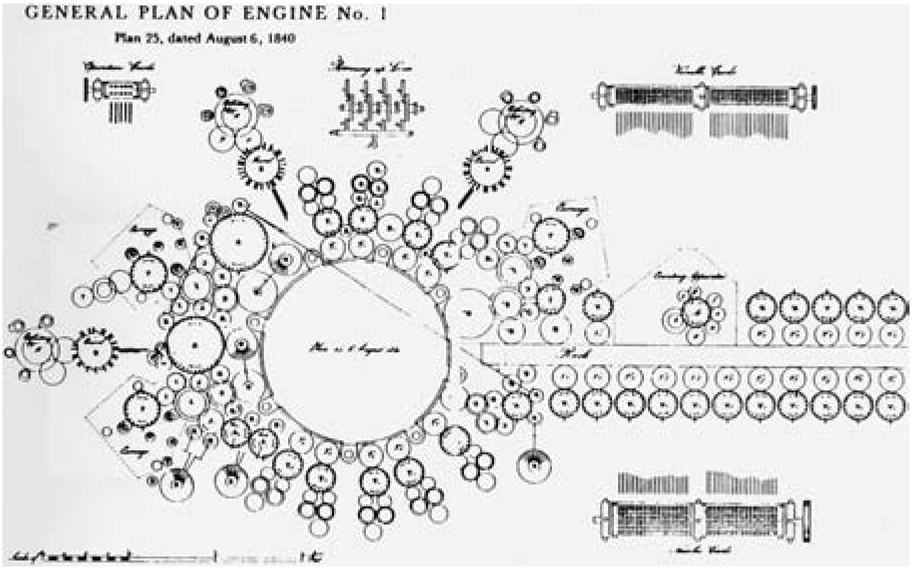
[9] C. Babbage, "On the Influence of Signs in Mathematical Reasoning," M. Campbell-Kelly (ed.), *The Works of Charles Babbage* (London: Pickering & Chatto, 1989), 1: 376.



2.1 Plans for Charles Babbage's ambitious Analytical Engine, showing details of its inner mechanism. Babbage argued that by finding a way of mechanically reproducing the mental attributes of memory and foresight he could build an intelligent machine that could be used to replace monotonous mathematical labor.

would replace the human capacity to reason as well (figure 2.1). "Memory and foresight," according to Babbage, were the foundations of human intelligence, and he had found a way of embodying them in a machine. Memory was achieved by the "principle of successive carriages." Foresight was more difficult. Babbage recalled triumphantly that "[i]t cost me much thought, but the principle was arrived at in a short time. As soon as that was attained, the next step was to teach the mechanism which could foresee to act upon that foresight. This was not so difficult: certain mechanical means were soon devised which, although very far from simple, were yet sufficient to demonstrate the possibility of constructing such machinery."[10] His analytical engine was to be the final realization of the analytics' dream of industrializing the operations of the human mind and the scientific community along the same lines as the industrialization of the economy.

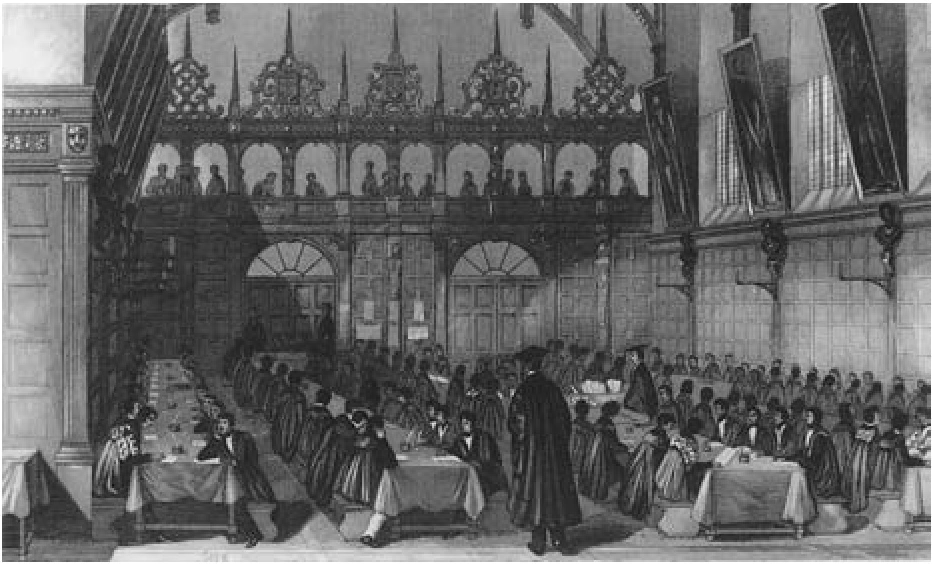
[10] C. Babbage, *Passages from the Life of a Philosopher* (1884; reprint, London: Pickering & Chatto, 1991), 46.

Herschel's failure to defeat the duke of Sussex in the 1830 election for the presidency of the Royal Society, along with his own continuing difficulties in acquiring government financial support for his calculating engines, lay behind Babbage's publication in 1830 of his controversial *Reflections on the Decline of Science in England*. The book was a passionate broadside against the corruption, mismanagement, and nepotism of English science in general and of the Royal Society in particular. The Royal Society needed a complete overhaul so that it could be recognized as the legitimate overseer of the division of scientific labor between the growing number of specialist scientific societies (like the Astronomical Society) and the proper allocation of government resources. Babbage's model for future reform was unambiguous. He had his eye on the power and prestige of the Académie des Sciences across the Channel. Its officers were salaried servants of the state and had the financial and political clout to push science forward. Babbage saw this centralized, Bonapartist monolith as an antidote to corruption and the epitome of efficient management. Others, even among his fellow reformers, disagreed of course, pointing out that the academy was even more prone than the Royal Society to corruption and backroom power broking. It seemed obvious to Babbage, however, that the importation of French science and French scientific structures should go hand in hand.

Babbage's, Herschel's, and the rest of the analytics' apparently local battle to introduce French analysis into Cambridge's moribund mathematical culture and the fierce opposition their efforts encountered were symptomatic of broader battles within the world of English science. Young Turks such as Babbage and his cronies wanted to turn English science upside down and remake it in their own image. New methods of mathematical analysis, bizarre as it may seem to modern readers, were a way of trying to achieve this. These men saw analysis as encapsulating a new and more efficient way of thinking that could be applied outside the narrow confines of the university and its hidebound curriculum, just as it could be used to drag that curriculum and its guardians screaming and kicking into the new century. Cambridge was not a bad place to start the battle, since its professors presided over the education of a large portion of the country's future ruling elite. Efficiency and meritocracy were the buzzwords of an increasingly confident new industrial class that was just embarking on its own campaign for political power to match its growing economic clout. The analytics and their analysis were in the vanguard of that campaign.

Cambridge Culture

By the end of the nineteenth century, the University of Cambridge was internationally recognized as a powerhouse of mathematical physics. Its former students could be found staffing new universities in Britain, throughout the Empire, and beyond. The place had become a veritable factory production line of mathematical physicists. This clearly was a huge change from the state of affairs that so depressed the Analytical Society in the 1810s. Indeed, their drive to reform the Cambridge Tripos was partially responsible for the transformation of the university's international reputation. There was more to it than that, however. The examination regime and the regime of mathematical training developed in Cambridge during the first half of the nineteenth century were quite explicitly designed to churn out mathematically adept individuals in large numbers (figure 2.2). The aim was not to produce mathematicians or mathematical physicists as such. Mathematics was taken to be a means of inculcating a rigorous education of the mind just as it had been earlier in the century. Cambridge products were meant to be fit to govern an expanding Empire that required their services in ever increasing numbers.



2.2 A Cambridge examination taking place in the Great Hall of Trinity College around 1840. Regimented and closely invigilated examinations like these are common nowadays but were a relative innovation at the time.

A candidate who was successful in the Tripos was taken to have demonstrated precisely those virtues of self-discipline, mental rigor, and iron determination that were assumed necessary to be capable of such service.

By midcentury, the Cambridge system of examination that Babbage, Herschel, and friends had considered so inadequate had undergone a major overhaul. In fact, the process had been under way for some time when they were undergraduates. From the late eighteenth century onwards, the emphasis in assessing students' ability gradually shifted from oral to written examination. Mathematics—the only subject to be examined formally and through which a student could attain honors—became increasingly important as a topic of study. Honors students were divided into three classes: wranglers, senior optime, and junior optime. Within these divisions, the examiners developed ever finer means of discrimination aimed at individually ranking each candidate for honors in the Tripos. Graduating as senior wrangler (first in the list of wranglers) or indeed as second or third wrangler was considered a major achievement. The analytics' efforts to introduce new mathematical styles and techniques into the syllabus had a major effect on the system. Increasingly, examiners developed finer means of grading questions so as to discriminate between different levels of ability. William Whewell, the polymathic master of Trinity College, played a major role during the 1830s and 1840s in reforming and rationalizing the Tripos system. As the examination system became ever more rigorous and taxing, submitting oneself as a candidate for honors meant being prepared to undergo a grueling and arduous regime of training.

The key to success in this punishing process was the acquisition of a well-established and successful personal tutor—or "coach," as they were popularly known. As the examination process became more demanding and punishing, the role of the university's own professors in the pedagogical process became less significant. After all, every student had easy access to their lectures. What was needed to gain an edge was a personal tutor with a proven track record of producing high wranglers. Coaches worked with their own chosen "teams" of students, inculcating tried and tested ways of approaching problems speedily and reliably. The teams worked their way through example after example of problems, internalizing the best ways of getting through the examination successfully, answering as many questions correctly in as short a time as possible. The best students aiming at the top few places in the lists needed to demonstrate considerable flair, ingenuity, and originality to attain the high honors they hoped for. This could be achieved only if they had the mathematical techniques required to solve the examination questions at their fingertips. Coaches attracted considerable personal reputations. The best of them could pick and choose the best potential candidates as they arrived at Cambridge, having been tipped off by grammar and public school headmasters of the likely prospects.

The king of these wrangler makers was William Hopkins, a graduate of Peterhouse with a string of outstanding high wranglers to his name, including William Thomson, Peter Guthrie Tait, and James Clerk Maxwell. As one of his former students, Francis Galton, Charles Darwin's cousin and an enthusiast for eugenics, recalled, Hopkins worked hard not only to drill his team in the finer points of examination technique but to imbue them with an enthusiastic and competitive team spirit as well. "Hopkins, to use a Cantab expression," enthused Galton to his father, "is a regular brick; tells funny stories connected with different problems and is in no way Donnish; he rattles on at a splendid pace and makes mathematics anything but a dry subject by entering thoroughly into its metaphysics. I never enjoyed anything so much before."[11] Hopkins's impressive track record was testimony to the efficacy of his methods. It also helped guarantee him a steady source of talented pupils that would sustain his reputation and his income. Hopkins charged his students £100 or more per annum for his services and reckoned to pocket between £700 and £800 a year in fees—more than enough to ensure a comfortable living.

There was far more to the coaching process than the avuncular bonhomie that Galton enjoyed, however. An American student, Charles Bristed, studying at Cambridge in the 1840s, emphasized that "a man must be healthy as well as strong—'in condition' altogether to stand the work. For in the eight hours a-day which form the ordinary amount of a reading man's study, he gets through as much work as a German does in twelve; and nothing that [American] students go through can compare with the fatigue of a Cambridge examination."[12] Success required constant practice and application. "You can never know too much about the solutions to $\mathrm{del}^2 V = 0$"[13] enthused one coach to his pupils. This was the kind of knowledge and skill that a good coach could instill in his students that could not be acquired elsewhere. The coaches knew the shortcuts and the tricks of the trade that could give candidates a crucial edge. Their

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[11] K. Pearson, *Life, Letters and Labours of Galton* (Cambridge: Cambridge University Press, 1914), 163, quoted in A. Warwick, "Exercising the Student Body," 296.

[12] C. Bristed, *Five Years in an English University* (New York, 1852), 1: 331, quoted in Warwick, "Exercising the Student Body," 295.

[13] Quoted in A. Warwick, *Masters of Theory*, chapter 5.

aim was to drum such techniques into their disciples' heads by constant repetition and exercise. A good candidate was expected to be able to read a question, recognize the techniques required for its solution, and apply them successfully while barely thinking about the matter.

Unsurprisingly perhaps, such an arduous and in many ways unprecedented regime of mental training had its failures. The road to Tripos stardom was littered with casualties. Even candidates who excelled at the Tripos recorded their dismay at the mental and physical strain they had been subjected to. Leslie Ellis, senior wrangler in 1840, recorded in his journal his "bitter dislike of Cambridge and my own repugnance to the wrangler making process."[14] Cambridge had developed its own solution to the problem of mental breakdown during the course of Tripos preparation, however. As they exercised their minds, Tripos candidates were encouraged to exercise their bodies as well. From the 1810s onwards, as the analytical revolution gathered pace and grinding application became more and more a prerequisite of Tripos success, hard physical exercise as an adjunct and antidote to rigorous study became commonplace. Cambridge was developing a culture of "work hard, play hard"; solitary activities were discouraged to prevent undue introspection. Students entered into sporting activity with as much self-discipline and rigor as they applied to their mathematical studies. Sport at Cambridge was not just the preserve of the idle aristocratics who had no interest in submitting themselves to the rigors of the Tripos examination. It was part and parcel of the university's mathematical culture.

Much of the university's culture by the late nineteenth century was built around the mathematics Tripos. The most successful candidates, who filled the highest positions in the rankings, were lionized not only within Cambridge but nationally as well. Their images and their histories would appear in the popular press. Their future careers would be assured. The awarding of degrees was hedged in by ritual. The results of the Tripos examination each year were publicly read out at the university's Senate House in strict order of ranking. Colleges vied with each other for the honor of the highest number of wranglerships. The senior wrangler each year would be carried from the Senate House on the shoulders of his peers and paraded around the city streets. Failure was accorded its ritual as well. The candidate achieving the lowest result each year was awarded the wooden spoon. The "spoon," fashioned, ironically enough, from a boating oar, would be lowered from the Senate House's galleries down to

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[14] Quoted in A. Warwick, "Exercising the Student Body," 298.

the unfortunate recipient below. Success in the Tripos was a guarantee of entry into the country's cultural elite. Comparatively few high wranglers became professional mathematicians or men of science—that, after all, was not really what the Tripos was about. Those that did however, were sure of a head start.

Relatively few eminent British men of physical science during the second half of the nineteenth century had not passed through the Cambridge Tripos. William Thomson and James Clerk Maxwell are only the most eminent examples. They were joined by Peter Guthrie Tait, George Gabriel Stokes, George Bidell Airy, Lord Rayleigh, Joseph Larmor, and J. J. Thomson among others. These men and others like them contributed to constructing a distinctive style of mathematical physics in the second half of the century. It was a style that owed a great deal to their original training in the mathematics Tripos. Despite the analytics' revolution during the 1810s and 1820s and the consequent introduction of French and Continental methods of analysis, the Cambridge system still maintained a strong commitment to the traditional concern with "mixed mathematics." Examiners (and coaches) encouraged students to work on mathematical problems with a strong physical component. Mathematics was expected to describe and solve problems in the real world. Challenging questions in the Tripos examination often formed the basis for ambitious students' future research. The late nineteenth-century articulation of mathematical theories of the electromagnetic ether, for example, was very much a product of this Cantabrigian approach. Even much of the early twentieth-century British response to Einstein's newfangled theories of relativity was firmly grounded in this tradition of mathematical research.

Cambridge's mathematical culture during this halcyon period was, like the university's culture more generally, avowedly masculine. Mathematics was unambiguously men's business. As women were grudgingly admitted into the university's lecture theaters during the second half of the century, they were even more grudgingly admitted into the coaches' teams without participation in which they had no hope of achieving honors. Even when women were allowed to participate in the Tripos from the 1870s onwards, they were excluded from the public ranking system for several years. It caused a major scandal in 1890 when Phillipa Fawcett from Newnham College actually beat that year's senior wrangler. Not only did women's success bruise male egos and undermine the cultural kudos attached to mathematical preeminence, it also severely challenged views of the relationship between mathematicians' bodies and their minds. Athleticism mattered to Cambridge wranglers because it was held that a balance was needed between energies devoted to mental and those devoted to physical exertion. Such a balance was impossible in women's bodies since their physical energies were meant to be overwhelmingly directed towards maintaining their reproductive organs. They were thus judged incapable in principle of the rigorous mental work required for Tripos success. Cambridge mathematical physics itself, in the form of the doctrine of the conservation of energy, underpinned this model of bodily economic management.

By the end of the century, the Cambridge mathematics Tripos was under attack from reformers once again. Women were showing themselves quite capable of playing the game; this did nothing to help those who defended the Tripos as the preeminent means of sorting out the men from the boys. New centers of excellence in research and training were emerging as well, challenging Cambridge's claim to provide the best. Even within the university, the mathematics Tripos's position as the route to success in the physical sciences was being challenged by the natural sciences Tripos and the increasingly important role of the Cavendish Laboratory as a center of research. The popularity of German models of theoretical physics could be seen as a potent threat and a challenge to the hegemony of Cantabrigian mathematical physics in the "mixed mathematics" tradition. For much of the century however, Cambridge was acknowledged as one of Europe's most prolific producers of physical scientists. Shared experiences as fodder for Cambridge's wrangler mills and common ground in shared techniques and practices produced a highly cohesive and productive scientific elite that dominated physics for a large part of the second half of the century.

The Reign of Theory

German natural philosophy and its institutions underwent their own reformation during the nineteenth century. The German lands at the beginning of the century were a patchwork of states, each with its own local university. By the end of the century, a unified Germany was one of the most powerful countries in Europe, its economy threatening to overtake that of Great Britain. Germany had universities to match its political and economic clout as well. In the sciences particularly, German universities increasingly looked world-beating. The new state placed great emphasis on scientific and technical education for its citizens, not only seeing science and technology as the foundations of its burgeoning economic power, but seeing scientific prestige as reflecting glory on the country that had produced it. Internationally recognized German men of science such as Hermann von Helmholtz and Emil du Bois Reymond were people to be reckoned with on the cultural and political scene as well. Their views mattered. Just as radical young natural philosophers in England at the beginning of the century cast envious eyes over the Channel at French scientific institutions, those calling for a new dispensation for British science and its institutions at the end of the century pointed to Germany as their model. Germany was a country that recognized the increasingly important role of science in its struggle for economic supremacy. British failure to emulate its institutions would be a recipe for British industrial decline.

As in England (and in France for that matter), universities in the early nineteenth-century German states had as their aim the education of the country's professional and ruling elite. German states usually had at least one university for this purpose—those that could afford them had more. As institutions they were designed to provide their privileged students with the kind of education that would mold them into future leaders of society. They would produce lawyers, medical men, teachers, and clerics. Typically, each university was divided into four faculties—law, medicine, theology, and philosophy. The first three of these provided particular professional training. Philosophy included the humanities, mathematics, and natural philosophy. Philosophy in particular was seen as providing for students at university level the opportunity to develop *Bildung* that was a major purpose of education. *Bildung* was in many ways the German equivalent of the English ideal of a liberal education—a training of the mind that was meant to produce depth and discrimination. At many German universities, this was achieved through immersion in a classical education (as it was at Oxford). Reformers argued, however, that another route to *Bildung* existed that did not involve the recapitulation of ancient knowledge. It could be achieved through science and mathematics.

Natural philosophy's status within philosophy faculties at the beginning of the century—and hence within German universities as a whole—was low. It was not considered as essential training for a profession such as medicine, theology, or the law. Neither was it regarded as an important component in the development of *Bildung*. Natural philosophy teaching took place as part of a general education curriculum that was not dissimilar to what students at schools and *Gymnasien* might experience. In no sense was a capacity for research considered a prerequisite for a university professorship in natural philosophy. The function of universities in general was pedagogy rather than the production of new knowledge.

When Carl Friedrich Gauss was asked by the University of Göttingen about his opinions concerning the filling of their vacant professorship of physics in 1831, he emphasized that the successful candidate's main obligation would be to deliver accessible lectures to a mixed audience who would only want to acquire a general knowledge of the subject. The candidate would also be a member of the Göttingen Society of Sciences and would therefore be expected to be proficient in mathematics and capable of producing work that could be published in the society's *Transactions*. Even for an eminent man of science such as Gauss, however, this was a secondary consideration. If anything, Gauss argued that a first-class mathematician would be unsuitable as he would be incapable of appealing to a broader audience through his lectures.

By the later 1830s and 1840s, however, the pedagogical status of natural philosophy teaching was changing. As early as 1824, for example, the curator of the University of Heidelberg proposed to the state of Baden's interior ministry that a "mathematical seminarium" should be established at the university. It was to be modeled on the increasingly popular and successful seminars in philology that were being credited with improving German classical education. Other universities followed suit. By the late 1820s, the University of Halle had a "physical seminar" in place, and when Wilhelm Weber, a student at Halle, was appointed to the professorship at Göttingen, he brought the model with him. The seminar model provided more intensive training, primarily aimed at improving the quality of schoolteachers. As Moritz Stern, extraordinary professor of mathematics at Göttingen argued in 1849, "The philological seminars came into being in an intellectual epoch . . . in which the knowledge of antiquity was seen as the almost exclusive foundation of all scientific knowledge. But the louder the so-called realistic direction demands its right, the greater the need becomes for all educated people to understand the foundations on which rest the mechanical and physical discoveries and inventions that affect our conditions so mightily, and the more it also becomes necessary that future teachers of mathematics and physics be offered an academic institute that has their further training as its special purpose."[15] Gradually, it came to be understood that some grounding in physical research might form a part of that "further training." The foundation of the Berlin Physical Society in 1845 was an augury of things to come.

Research increasingly came to be regarded by German natural philosophers as a potential route to prestige and career. The *Annalen der Physik*

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[15] Quoted in C. Jungnickel and R. McCormmach, *Intellectual Mastery of Nature*, 1: 79.

devoted more and more of its pages to the productions of native men of science rather than to translations of works from foreign journals. Founded in 1790, the *Annalen* was by the 1840s the premier German journal of physical science. Its editor since 1824, Johann Christian Poggendorff, had the power to make or break a scientific career. Increasingly, research publication, and publication in the *Annalen* in particular, came to be regarded as a prerequisite for any hopeful candidate for a university professorship. Research was coming to be regarded as a value in its own right. Such a cultural sea change had a clear impact on the status of physics research in Germany. Researchers were no longer enthusiastic individuals or wealthy dilettantes with the leisure to indulge in experimental or mathematical tinkering. They were hardheaded professionals with all the prestige of state-salaried university professors. Research was turning into a career and increasingly prestigious German physics professors could demand ever more from their academies in terms of resources and facilities as rival institutions battled for their services.

Carl Friedrich Gauss was one of the towering figures in this transformation of German physics. As professor of higher mathematics and of astronomy at the University of Göttingen he had been instrumental in securing an institutional niche for research there during the 1830s. His increasing reputation as a mathematician and astronomer—particularly his international collaborations in astronomy and geomagnetic observations—raised the profile of research throughout the German lands. Gauss also established his own style of mathematical investigation in physics, particularly electromagnetism, that served as a crucial resource for the next generation. Bernhard Riemann had studied mathematics under Gauss during the 1840s, attracting his patronage along with that of Weber. Gauss encouraged his mathematical researches and his efforts to establish mathematical connections between previously disparate areas of physical inquiry. Riemann's work on electrodynamics in turn inspired another young German mathematician, Carl Neumann. Neumann's work in electrodynamics, along with that of Gauss, Riemann, and Weber, had a profound impact in establishing a crucial German theoretical presence in discussions of electromagnetism during the second half of the century. Electromagnetism—the science of the telegraph cables so crucial to imperial expansion—was, as we shall see, in many ways at the core of nineteenth-century physics.

Poggendorff continued editing the *Annalen* until his death in 1877. By this time his name had become synonymous with the flagship journal of German physics. Following his departure from the scene, the Berlin

Physical Society took the journal under its auspices, with Gustav Wiedemann as editor, advised by Hermann von Helmholtz on theoretical matters. A clear division of labor was emerging between the experimenter and the theoretician. The discipline of theoretical physics—a distinctively German institution in its origins—was taking off. German theoretical contributions to the *Annalen* were increasingly autonomous, contributors referred more and more to the theoretical contributions of fellow Germans as opposed to work from France or Britain. This is not to suggest that such work was ignored. Work by Faraday and Maxwell in particular was heavily drawn upon. It does show, however, the development of a distinctively German culture of theoretical physics with its own concerns and direction. The institutional structure of German science increasingly encouraged research. Directors of new physics institutes in particular had the time and resources to devote themselves to new theoretical investigations. Rather than being an adjunct to teaching, research by the 1860s or 1870s was regarded as being an end in itself. Institutes, their directors, and their students were state supported since their research contributed to the cultural prestige of the state itself.

From the 1870s in particular, extraordinary professorships of theoretical physics were established at a number of German universities. They were typically set up as junior positions in conjunction with the already established ordinary professorship of physics. The aim as a rule was to provide an additional source of teaching that would free the holder of the senior appointment to carry out research. The additional result, however, was to institutionalize the notion that theoretical physics was a separate discipline. Most of these new extraordinary professorships were founded in Prussia. A good example of the way they worked is provided, however, by the circumstances at the University of Strassburg, newly under German administration in the early 1870s, following German victory in the Franco-Prussian War. The first ordinary professor of physics and director of the physics institute there was August Kundt. He soon hired his former student and collaborator Emil Warburg as extraordinary professor of theoretical physics in 1872. While there, Warburg taught theoretical physics as well as collaborating with Kundt on an investigation of the kinetic theory of gases based on Kundt's development of a new method of measuring the velocity of sound. Warburg's responsibility was to conduct the theoretical part of the investigation. Increasingly, the theoretical physicist was the specialist, aiming his teaching at those planning a career in physics, while the experimental physicist lectured to more general audiences.

German models for the organization of teaching and research within universities increasingly prevailed in German-speaking regions outside the reunifying state. In Austria, for example, the appointment of Ludwig Boltzmann as ordinary professor of mathematical physics at Graz in 1869 was a signal of a move towards a German system. Boltzmann was rapidly making a reputation for himself as a theoretical physicist doing groundbreaking work in the kinetic theory of gases—as a "passionate molecular physicist."[16] He did not stay long in Graz on his first appointment. By 1873 he was in Vienna as ordinary professor of mathematics. During his absence, however, Graz founded an institute of physics and in 1876 Boltzmann returned as director of the new institute with a brief to develop his "far reaching theoretical ideas through the circle of his students."[17] The Graz Institute was to be as much a research as a teaching school. Boltzmann took his proselytizing duties there seriously, diligently supervising student research dissertations as well as continuing with his own work. He was in the process of founding a research school in theoretical physics. Students took Boltzmann's investigations as the starting point for their own efforts, keeping themselves abreast of the latest breakthroughs in theoretical work.

Theoretical physics was increasingly regarded as an autonomous activity. It was an independent way of looking at the world rather than an adjunct to experimentation. Woldemar Voigt's appointment as director of the Göttingen Mathematical Physics Institute was a recognition that such appointments needed to be given to a proper theoretical physicist who could direct theoretically inclined research students in their endeavors rather than simply provide a supplement to experimental teaching. Voigt had been a student of the aging Franz Neumann at the University of Königsberg and had inherited his old master's lectures there before moving on to Göttingen in 1883. He regarded himself as a theoretical physicist by training and inclination and aimed to make the Göttingen institute into a center of theoretical excellence. Extracting the necessary finances from the Prussian government for his purposes was not, however, an easy task. They had to be reminded that even minor German universities like Bonn and Kiel outspent the Göttingen physics budget before they relaxed the purse strings. Voigt made a name for himself as a writer of textbooks as well, trying to forge a wider audience for the

[16] Quoted ibid., 2: 61.

[17] Quoted ibid., 2: 67.

2.3 The Berlin Physics Institute in about 1877. Prestigious new physics institutes such as this were increasingly important institutional features of German academic science.

new discipline of theoretical physics. His *Kompendium der Theoretischen Physik*, published in two volumes in 1895 and 1896, was a concerted and unprecedented effort to provide a unified view of the new field.

By the final decade of the nineteenth century, the new discipline of theoretical physics was well established in German universities. Gustav Kirchhoff, at Berlin since 1875 as a member of the Prussian Academy, focused his attention more and more on theoretical physics. Hermann von Helmholtz in Berlin both as a director of the Berlin Physics Institute and later as the president of the Physikalisch-Technische Reichsanstalt from 1888 directed his teaching and his research increasingly towards theoretical matters (figure 2.3). After Kirchhoff's death in 1887, Boltzmann was headhunted from Graz to replace him, but declined at the last minute, going instead to a professorship in theoretical physics in Munich, fearing apparently that the Prussians would prove too dour for his taste. Even in the 1890s the position offered to Boltzmann there as an ordinary professor in the new subject was nearly unprecedented. He had the independence of being the director of a state-funded institute with freedom to organize things as he wished. His power was increased when the Austrian government tried to entice him back to Vienna in 1893. The Bavarians responded with an improved salary and the appointment of an assistant. Boltzmann abandoned Munich, however, in 1894 for the professorship in theoretical physics at Vienna and a salary that at 6,000 florins was the highest then paid to an Austrian university professor. It had become a question of national honor that Austria should retain the services of this peripatetic but preeminent theoretical physicist.

This international wrangling over Boltzmann is a good indication of the way that theoretical physics had established itself in German-speaking countries by the end of the nineteenth century. It was a startling achievement considering that the discipline had barely existed less than half a century previously. Half a century later, philosophers of science such as Karl Popper would take it for granted that grand speculation and theorizing was the be-all and end-all of physics, with the experimenter relegated to bottle-washing duties. Theoretically concerned physicists had engineered a spectacular cultural coup by carving out institutional niches for themselves where none had existed before. From being ill-regarded placemen in turn-of-the-century philosophy faculties, physicists—and the new breed of theoretical physicists in particular—had been successful in establishing their discipline at the core of German academic life. The key figures in German theoretical physics—men such as Boltzmann and Helmholtz—were internationally recognized celebrities, not just within their specialist communities but on the broader cultural stage as well. They were recognized as making crucial contributions not just to physics, but to the newly confident and increasingly powerful Germany as well. They helped forged Germany's reputation as a scientific, industrial, and therefore modern state.

Conclusion

Natural philosophy at the beginning of the nineteenth century looked to many like a potentially revolutionary science. To others it merely looked dangerous. Early nineteenth-century men of science had inherited from the Enlightenment a sense of the ways in which natural philosophy could be used to change the world, to overturn the social order and establish new institutions in its place. For the radicals among them, this sounded like a wonderful idea. To their opponents it was a prospect to be regarded with horror. Depending on one's perspective, natural philosophy could either subvert the proper order of society or reveal in nature what that proper order should be. For those who wanted to put this science to good use, however, the clear conclusion was that scientific institutions needed revolutionizing as well. To make their science matter, they had to find ways of changing these institutions. They had to find ways of changing what it meant to be a man of science. As this chapter shows, different natural philosophers in different countries and locations had a variety of views as to how their practices and their institutions might be transformed. This is not a narrative of continuous and progressive development to a self-evident end.

The state of physics by the end of the nineteenth century was profoundly changed from what it had been at its beginning. At the beginning of the century, natural philosophy was the vocation of a dedicated but tiny band. By the end of the century, new institutions across Europe and America were producing professional physicists in ever increasing numbers. There was no such word as “physicist” in the English vocabulary at the beginning of the century. It was coined by William Whewell to describe what appeared to him to be a new kind of natural philosopher—just as he coined the word “scientist” at about the same time to describe a new breed of practitioner. Its gradual acceptance by the end of the century as the term to describe a particular kind of professional man of science studying nature in a particular fashion was a sign that this new way of doing things had found a secure cultural place for itself. Physicists—and mathematical or theoretical physicists in particular—had managed to secure a vital cultural role for themselves as the ultimate arbiters of what the natural world was like.