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PART I

To 1874

William Cavendish (1808–1891), 7th Duke of Devonshire
Chancellor of Cambridge University (1861–1891)
Oil painting: copy after George Frederic Watts
by Katharine Maude Humphrey

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Physics in the nineteenth century 1

Where better to start than with the definition of *physics* from the *Oxford English Dictionary: The Definitive Record of the English Language*:

> **physics, n.** The branch of science concerned with the nature and properties of non-living matter and energy, in so far as they are not dealt with by chemistry or biology; the science whose subject matter includes mechanics, heat, light and other radiation, sound, electricity, magnetism, gravity, the structure of atoms, the nature of subatomic particles, and the fundamental laws of the material universe.

Most twenty-first-century physicists would find this definition sufficiently all-encompassing to describe what physics is about. Many, including the present author, would argue that the extensive nature of the subject and its emphasis upon model-building and problem-solving enables it to embrace a vastly wider range of cognate fields, including chemistry, biology, medicine and economics. But the mid-nineteenth-century scientist, and in particular one associated with Cambridge University, would have formed a very different view.

1.1 Discoveries in physics, 1687 to 1874

It is enlightening to study a time-line of major discoveries and advances in what we would now call physics, as well as selected topics from cognate disciplines such as chemistry, mathematics and particularly technology. The items in Table 1.1 span the period from the date of publication of Isaac Newton's *Philosophiæ Naturalis Principia Mathematica* (Newton, 1687) to the opening of the Cavendish Laboratory in 1874. The contents of the table are necessarily subjective but provide a broad-brush picture of the standard history of physics. The country and location where the advances were made, as well as those which originated in Cambridge, are also indicated.

There are a number of striking features of Table 1.1. There is no question about the overwhelming impact of Newton's laws of motion and of gravity of 1687. Newton and his followers promoted vigorously the corpus of Newton's great works in the sciences of mechanics, statics, dynamics, gravity and optics. Nowhere was this more assiduously practiced than in his alma mater, Cambridge University, where, well into the nineteenth century, Newton's approach to the laws of motion were taught to the exclusion of the more powerful mathematical methods of analysis which had been developed in continental Europe.

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Table 1.1 Selected advances in physics and cognate disciplines, 1687–1874

Date	Discovery	UK involvement	Cambridge involvement
1687	Newton's laws of motion and of gravity	Newton	Newton
1690	Huygens' *Treatise on Light* (Netherlands)		
1704	Newton's *Opticks*	Newton	Newton
1776	James Watt's first commercial steam engine	Watt (Birmingham)	
1782	Chemistry, conservation of mass: Lavoisier (France)		
1785	Coulomb's inverse square laws of electrostatics and magnetostatics (France)		
1788	Lagrange's equations of motions (France)		
1801	Young's wave theory of light	Young	Young
1800–10	Gas laws: Gay-Lussac (France), Charles (France), Dalton	Dalton (Manchester)	
1808	Dalton's atomic theory of matter	Dalton (Manchester)	
1811	Avogadro's hypothesis (Italy)		
1820	Electric and magnetic fields and current electricity Ørsted (Denmark), Ampère (France), Biot (France), Savart (France)		
1822	Fourier's *Théorie Analytique de la Chaleur* (France)		
1822	Babbage's design of his difference engine	Babbage (London)	
1824	The Carnot cycle and ideal gas engines (France)		
1827	Hamilton's equations	Hamilton (Ireland)	
1827	Electrical resistance: Ohm's law (Germany)		
1831	Faraday's lines of force and the law of electromagnetic induction	Faraday (RI London)[a]	
1842–43	Conservation of energy: Mayer (Germany), Kelvin[b]	Kelvin[b] (Glasgow)	
1845	Faraday on the rotation of polarised light	Faraday (RI London)[a]	
1845–50	Conservation of energy: Joule, Helmholtz (Germany)	Joule (Salford)	
1850–51	Second law of thermodynamics: Clausius (Germany), Kelvin[b]	Kelvin[b] (Glasgow)	
1854–56	Kelvin[b] and the transatlantic telegraph cable	Kelvin[a] (Glasgow)	
1857–59	Kinetic theory: Clausius (Germany), Maxwell	Maxwell (Aberdeen)	
1859	Black-body radiation and Kirchhoff's laws (Germany)		
1863	Entropy: Clausius (Germany), Maxwell (London), Kelvin[b] (Glasgow)	Maxwell (London), Kelvin[b] (Glasgow)	
1864–65	Maxwell's dynamical theory of the electromagnetic field	Maxwell (London)	
1867	Maxwell's dynamical theory of gases	Maxwell (Glenlair)	
1869	Mendeleyev (Russia) and the periodic table		

[a] 'RI London' refers to the Royal Institution of Great Britain in Albemarle Street, London.
[b] In this table, 'Kelvin' means William Thomson, who took the title 1st Baron Kelvin of Largs.

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From roughly the turn of the nineteenth century onwards, the emerging sciences of electricity, magnetism, heat and thermodynamics were added to the edifice of Newtonian physics, but these could not be readily incorporated into the Newtonian world view. Equally significantly, the new sciences were to find immediate practical application in the industrial revolution which was in full swing by the beginning of the nineteenth century – indeed, the boot was very much on the other foot, with industry driving research in the basic sciences. In parallel with the physical and mathematical elaboration of new areas of science, there was an irresistible drive by engineers, industrialists and entrepreneurs to exploit these discoveries for the benefit of industry, for military advantage and for the improvement of the well-being of society. It is revealing to review in parallel developments in the physical sciences and the corresponding needs of industry and their contributions to society at large.

1.2 Precise measurement and the determination of time

Precise measurement has always had a key role to play in astronomical observations, which were essential for keeping an accurate track of time and for navigation at sea. Pride of place must go to Tycho Brahe, who was inspired to begin his great series of astronomical observations of the stars and planets by the inaccuracies he found in the Alphonsine Tables. The predicted positions of the Sun, Moon, stars and the planets in the tables were based upon a complex Ptolemaic model of the solar system which was used to keep track of time and to establish the dates of religious festivals. With sponsorship by Frederick II to the tune of about 1% of the gross national product of Denmark for about 20 years, Tycho constructed his great observatory on the island of Hven. In fact, Tycho built two independent observatories, Uraniborg and Stjerneborg. He employed numerous clocks to ensure the precise measurement of the times of transit of the stars and planets. The instruments were the most advanced of their time and the whole enterprise resulted in an improvement in the precision with which the positions of the celestial bodies were known by a factor of 10 over previous measurements. This achievement resulted from a number of technical innovations:

- understanding of the importance of *systematic* and *random* errors
- understanding of the effects of bending of the instruments on astronomical observations
- understanding of the effects of atmospheric refraction
- maintaining the independence of the astronomical data by observers at his two observatories.

Over a period of 20 years, he measured positions to a precision of about 1–2 arcmin for the Sun, Moon, planets and 777 stars. In 1600, the year before his death, he employed Johannes Kepler to analyse his observations of the motion of Mars. From Tycho's observations, Kepler deduced his laws of planetary motion, which in turn led to Newton's laws of motion and of gravity.[1]

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The qualities of skill, craftsmanship and invention available in eighteenth-century England are well illustrated by the achievements of John Harrison in designing and building clocks which could maintain accurate timekeeping despite the rigours of life on the high seas. While the determination of latitude at sea was straightforward, by measuring the angle from the celestial pole to the horizon, the determination of longitude was much trickier. With a sufficiently stable clock, longitude could be found by comparing a clock on board ship, which kept track of Greenwich Mean Time, with the local standard of time, found when noon was observed at the location of the ship. The sea-clocks had to be able to withstand severe temperature, pressure and humidity changes, as well as the pitching and rolling motions of the ship, particularly during storms and bad weather. The importance to a maritime nation such as the United Kingdom of being able to measure longitude accurately was recognised by a prize of £20,000 offered by the British government for the construction of a chronometer which could precisely maintain time at sea. In 1761, Harrison's first marine watch achieved an accuracy of about 1 km on the transatlantic voyage to Jamaica.

1.3 Fraunhofer, Kirchhoff and the development of optical spectroscopy

In the early years of the nineteenth century, Joseph Fraunhofer opened up the new science of precision spectroscopy. The breakthrough can be traced to Thomas Young's pioneering experiments and theoretical understanding of the laws of interference and diffraction of waves. In his Bakerian Lecture of 1801 to the Royal Society of London, *On the Theory of Light and Colours*, he used the wave theory of light of Christiaan Huygens to account for the results of interference experiments such as his double-slit experiment (Young, 1802). Among the most striking achievements of this paper was the measurement of the wavelengths of light of different colours using a diffraction grating with 500 grooves per inch. From this time onwards, wavelengths were used to characterise the colours in the spectrum.

In 1802, William Wollaston, the Jacksonian Professor of Natural Philosophy at Cambridge University, made spectroscopic observations of sunlight and discovered five strong dark lines, as well as two fainter lines (Wollaston, 1802). The full significance of these observations only began to be appreciated following the remarkable experiments of Fraunhofer. He was the son of a glazier and became one of the two directors of the Benediktbeuern glassworks in Bavaria in 1814. The firm manufactured high-quality optical glass for military and surveying instruments. Fraunhofer's motivation for studying the solar spectrum was his realisation that accurate measurements of the refractive indices of glasses should be made using monochromatic light. His visual observations were made by placing a prism in front of a 25 mm aperture telescope. In his spectroscopic observations of the Sun, he discovered that the dark lines were narrow and provided precisely defined wavelength standards. He labelled the ten strongest lines in the solar spectrum A, a, B, C, D,

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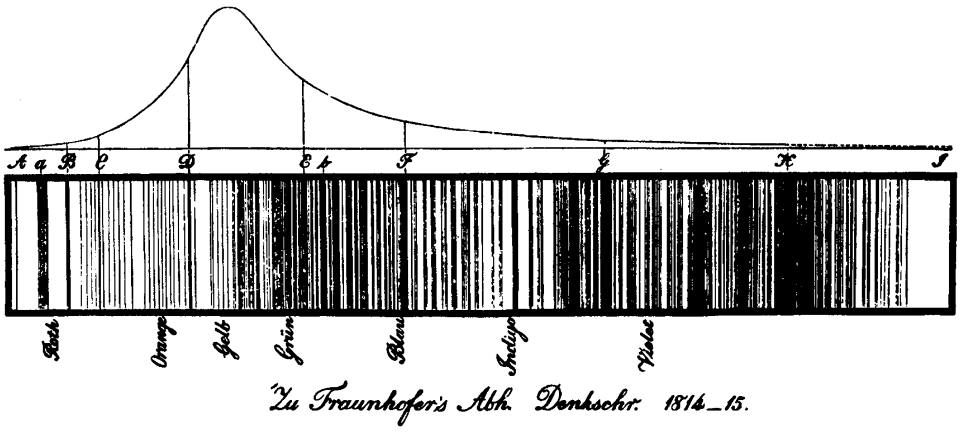

Fig. 1.1 Fraunhofer's solar spectrum of 1814, showing the vast numbers of dark absorption lines. The colours of the various regions of the spectrum are labelled, with the letters A, a, B, C, D, E, b, F, G and H indicating the most prominent absorption lines. The continuous line above the spectrum shows the approximate solar continuum intensity, as estimated by Fraunhofer (1817a,b).

E, b, F, G and H and recorded 574 fainter lines between the B and H lines (Figure 1.1) (Fraunhofer, 1817a,b). A major advance was the invention of the spectroscope, with which the deflection of light passing through the prism could be measured precisely. To achieve this, Fraunhofer placed a theodolite on its side and observed the spectrum through a telescope mounted on the rotating ring (Figure 1.2).

In a second paper, Fraunhofer measured the wavelengths of what are now referred to as the *Fraunhofer lines* in the solar spectrum using a diffraction grating, which consisted of a large number of equally spaced thin wires (Fraunhofer, 1821); he was one of the early pioneers in the production of diffraction gratings. He found that the wavelengths of these lines were stable and so provided accurate wavelength standards.

From the perspective of the glass industry, Fraunhofer was then able to characterise the chromatic properties of glasses and lenses quantitatively and precisely. These developments led to much superior glasses, as well as to much improved polishing and testing methods for glasses and lenses. These technical improvements also resulted in the best astronomical telescopes then available. Fraunhofer's masterpiece was the 24 cm Dorpat Telescope, built for Wilhelm Struve at the Dorpat (now Tartu) Observatory in Estonia. In addition, he built a heliometer for Friedrich Bessel at Königsberg, which enabled the first parallax of a star to be measured.

The understanding of the dark lines in the solar spectrum had to await developments in laboratory spectroscopy. In his papers of 1817, Fraunhofer noted that the dark D lines coincided with the bright double line seen in lamplight. In 1849, Léon Foucault in Paris performed a key experiment in which sunlight was passed through a sodium arc so that the two spectra could be compared precisely. To his surprise, the solar spectrum displayed even darker D lines when passed through the arc than without the arc present (Foucault, 1849). He followed up this observation with an experiment in which the continuum spectrum of

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Fig. 1.2 A portrait of Fraunhofer with his spectroscope (courtesy of the Deutsches Museum, Munich). This portrait is located in the museum's Hall of Fame.

light from glowing charcoal was passed through the arc and the dark D lines of sodium were found to be imprinted on the transmitted spectrum.

Ten years later, the experiment was repeated by Gustav Kirchhoff at his laboratory at the University of Heidelberg. He made the further crucial observation that, for the observation of an absorption feature, the source of the light had to be hotter than the absorbing flame. These results were immediately followed up in 1859 by his understanding of the relation between the emissive and absorptive properties of any substance, what is now known as *Kirchhoff's law of the emission and absorption of radiation* (Kirchhoff, 1859).[2] This states that, in thermal equilibrium, the radiant energy emitted by a body at any frequency is precisely equal to the radiant energy absorbed at the same wavelength. He showed that in thermodynamic equilibrium

$$\alpha_\nu B_\nu(T) = j_\nu \tag{1.1}$$

(Box 1.1). In other words, the emission and absorption coefficients, j_ν and α_ν respectively, for any physical process are related by the unknown spectrum of equilibrium radiation $B_\nu(T)$, the spectrum of black-body radiation. In 1859, very little was known about the

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Kirchhoff's law of the emission and absorption of radiation **Box 1.1**

For isotropic radiation, the *monochromatic emission coefficient* j_ν is defined such that the increment in intensity $\mathrm{d}I_\nu$ radiated into the solid angle $\mathrm{d}\Omega$ from the cylindrical volume $\mathrm{d}V$ of area $\mathrm{d}A$ and length $\mathrm{d}l$ is

$$\mathrm{d}I_\nu \, \mathrm{d}A \, \mathrm{d}\Omega = j_\nu \, \mathrm{d}V \, \mathrm{d}\Omega,$$

where j_ν has units W m^{-3} Hz^{-1} sr^{-1}. Since the emission is assumed to be isotropic, the *volume emissivity* of the medium is $\varepsilon_\nu = 4\pi j_\nu$. We can write the volume of the cylinder as $\mathrm{d}V = \mathrm{d}A \, \mathrm{d}l$ and so

$$\mathrm{d}I_\nu = j_\nu \, \mathrm{d}l.$$

The *monochromatic absorption coefficient* is defined by the relation

$$\mathrm{d}I_\nu \, \mathrm{d}A \, \mathrm{d}\Omega = -\alpha_\nu \, I_\nu \, \mathrm{d}A \, \mathrm{d}\Omega \, \mathrm{d}l.$$

In thermodynamic equilibrium, the magnitudes of the left- and right-hand sides of this equation must be equal:

$$\alpha_\nu B_\nu(T) = j_\nu,$$

where $I_\nu = B_\nu(T)$ is the unknown spectrum of equilibrium radiation $B_\nu(T)$ relating the emission and absorption coefficients for any physical process. This expression enabled Kirchhoff to understand the relation between the emission and absorption properties of flames, arcs, sparks and the solar atmosphere.

experimental or theoretical form of $B_\nu(T)$. As Kirchhoff remarked, 'It is a highly important task to find this function.' This was to remain one of the great experimental challenges for the remaining decades of the nineteenth century. Kirchhoff's profound insight was the beginning of a long and tortuous story which was to lead to Planck's discovery of the formula for black-body radiation over 40 years later.

Throughout the 1850s, there was considerable effort in Europe and in the USA aimed at identifying the emission and absorption lines produced by different substances in flame, spark and arc spectra. Different elements and compounds possess distinctive patterns of spectral lines, and attempts were made to relate these to the lines observed in the solar spectrum. In 1859, for example, Julius Plücker identified the Fraunhofer F line with the bright Hβ line of hydrogen and the C line was more or less coincident with Hα, demonstrating the presence of hydrogen in the solar atmosphere.

The most important work resulted from the studies of Robert Bunsen and Kirchhoff. In Kirchhoff's great papers of 1861 to 1863, entitled *Investigations of the Solar Spectrum and the Spectra of the Chemical Elements*, the solar spectrum was compared with the spark spectra of 30 elements using a four-prism arrangement with which it was possible to simultaneously view the spectrum of the element and the solar spectrum (Kirchhoff, 1861, 1862, 1863). Kirchhoff concluded that the cool outer regions of the solar atmosphere contained iron, calcium, magnesium, sodium, nickel and chromium and probably cobalt, barium, copper and zinc as well.

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1.4 Electricity and magnetism

The disciplines which were to drive the new physics of the second half of the nineteenth century were electricity, magnetism and heat. These advances not only opened up new fields of research in physics but were to have immediate social, industrial and commercial impact. From disciplines which had been the province of natural philosophers and learned societies, new industries were created which depended upon the understanding of the laws of physics at a fundamental level. In this section, we trace the revolutionary impact of electricity and magnetism and, in the next section, thermodynamics and the theory of heat.

1.4.1 Electrostatics and magnetostatics

By the end of the eighteenth century, many of the basic experimental features of electrostatics and magnetostatics had been established. In the 1770s and 1780s, Charles-Augustin Coulomb performed sensitive electrostatic experiments which established the inverse-square laws of electrostatics and magnetostatics. In SI notation,[3] these can be written

$$\boldsymbol{f} = \frac{q_1 q_2}{4\pi\epsilon_0 r^2}\,\boldsymbol{i}_r \quad \text{and} \quad \boldsymbol{f} = \frac{\mu_0 p_1 p_2}{4\pi r^2}\,\boldsymbol{i}_r, \tag{1.2}$$

where $\boldsymbol{i}_r$ is the unit vector directed radially *away* from either electrostatic charge q_1, q_2 or magnetostatic monopole with pole strengths p_1, p_2 in the direction of the other.

As will be discussed in Chapter 2, the late eighteenth and early nineteenth centuries was a period of extraordinary brilliance in French mathematics, and included personalities such as Siméon-Denis Poisson, who was a pupil of Pierre-Simon Laplace, and Joseph-Louis Lagrange. In 1812, Poisson published his famous *Mémoire sur la Distribution de l'Électricité à la Surface des Corps Conducteurs* (Poisson, 1812), in which he demonstrated that many of the problems of electrostatics can be simplified by the introduction of the electrostatic potential V which is the solution of Poisson's equation,

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = -\frac{\rho_e}{\epsilon_0}, \quad \boldsymbol{E} = -\text{grad}\, V, \tag{1.3}$$

where ρ_e is the electric charge density distribution and $\boldsymbol{E}$ the electric field strength. In 1826, he published the corresponding expressions for the magnetic flux density $\boldsymbol{B}$ in terms of the magnetostatic potential V_{mag}:

$$\frac{\partial^2 V_{\text{mag}}}{\partial x^2} + \frac{\partial^2 V_{\text{mag}}}{\partial y^2} + \frac{\partial^2 V_{\text{mag}}}{\partial z^2} = 0, \quad \boldsymbol{B} = -\mu_0\, \text{grad}\, V_{\text{mag}}. \tag{1.4}$$

1.4.2 Current electricity

Until 1820, electrostatics and magnetostatics appeared to be quite separate phenomena, but this changed dramatically with the development of the science of *current electricity*. In the latter years of the eighteenth century, the Italian anatomist Luigi Galvani discovered

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