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CHAPTER I

Introduction: The Conceptual Structure of Nineteenth-Century Physics

In the nineteenth century the term 'physics' acquired new and significant connotations. Although the term was still occasionally used in the traditional sense to refer to natural science in general, by the early nineteenth century 'physics' was being used in the modern and more specialised sense to denote the study of mechanics, electricity, and optics, employing a mathematical and experimental methodology. In the article entitled 'Physical Sciences' in the ninth edition of the *Encyclopaedia Britannica* in the 1870s, James Clerk Maxwell identified the scope of physics with the programme of mechanical explanation, first enunciated in the seventeenth-century 'mechanisation of the world picture', which sought to explain physical phenomena in terms of the structure and laws of motion of a mechanical system. In a critical exposition of current physical theory, *The concepts and theories of modern physics* (1881), Johann Bernhard Stallo gave an informative and more detailed definition of the theoretical structure of physics as conceived by contemporary theorists:

> The science of physics, in addition to the general laws of dynamics and their application to the interaction of solid, liquid and gaseous bodies, embraces the theory of those agents which were formerly designated as imponderables – light, heat, electricity and magnetism, etc.; and all these are now treated as forms of motion, as different manifestations of the same fundamental energy.

In the nineteenth century the science of physics came to be defined in terms of the unifying role of the concept of energy and the programme of mechanical explanation.

The concept of energy provided the science of physics with a new and unifying framework and brought the phenomena of physics within the mechanical view of nature, embracing heat, light, and electricity, together with mechanics, in a single conceptual structure. The major theme of the development of physics in the nineteenth century is the way in which theoretical innovations – the concept of the physical field, the theory of the luminiferous and electromagnetic ether, and the concepts of the conservation and dissipation of energy – were formulated according to the mechanical view of nature, which supposed that matter in motion was the basis of all physical phenomena.

This book will focus on key themes that defined the structure of physics in the nineteenth century. I will begin with an account of the development, by around 1850, of a distinctive science of physics that took quantification and the search for mathematical laws as its universal aims and that established the law of the conservation of energy as a unifying principle and mechanical explanation as the programme of physical theory. The structure of physical theory in the nineteenth century will then be analysed by focusing on the status of the concepts of energy, force, and matter in the physics of the period. I will describe the development of the principles of the conservation and dissipation of energy, the theory of the physical 'field' (which accounted for the transmission of force by means of the mediating action of the 'field' between bodies), and the study of molecular physics. A preliminary outline of the scope of the argument will provide an introductory survey of the conceptual development of physics in the nineteenth century.

The Context of Physical Theory

In eighteenth-century physical theory mechanical phenomena were studied mathematically, and hypotheses about atoms and the nature of forces were avoided; by contrast, heat and electricity were generally explained by supposing imponderable 'fluids' of heat and electricity and forces acting between the particles of these 'fluids' and the atoms of ordinary matter. These speculative and generally qualitative theories stood apart from the exact, quantitative science of mechanics, though by the late eighteenth century attempts were made to treat heat and electricity mathematically, attempts that initiated the conceptual unification of the science of physics. The creation of a unified physics was fostered by four significant developments.

1. P. S. de Laplace and his followers formulated a mathematical theory of interparticulate forces, to be applied to mechanical as

well as to thermal and optical phenomena. Although this theory was displaced by new developments in heat and optics in the decade 1815–25, the Laplacian emphasis on mathematisation and the formulation of a unified physical world view had an important impact on the subsequent development of physical theory.

2. The publication of Joseph Fourier's mathematical theory of heat in 1822 brought the study of heat within the framework of mathematical analysis previously applied only to mechanical problems. In bridging this traditional conceptual dichotomy, and in stressing the distinction between mathematical and physical representation, Fourier's work had profound general implications for the creation of a unified physics. In the 1840s, influenced by the mathematical analogy between Fourier's theory of heat and the theory of electrostatics, William Thomson explored the mathematical and physical analogies between, on the one hand, the laws of heat and electricity and, on the other, the mechanics of particles and fluid and elastic media. Thomson's use of the method of physical analogy, in which the common mathematical form highlighted the conceptual relations between disparate phenomena, emphasised the unity of the phenomena of physics.

3. A. J. Fresnel's wave theory of light, which supposed that light was propagated by the vibrations of a mechanical ether, brought optics within the framework of the mechanical view of nature. By the 1830s the wave theory of light was generally accepted, and physicists explored a variety of physical and mathematical theories in an attempt to provide a coherent mechanical theory of optics. The mechanical theory of the optical ether established a paradigm for the programme of mechanical explanation.

4. The formulation of the law of the conservation of energy in the 1840s stressed the unity of physics, subsuming the phenomena of heat, light, electricity, and magnetism within the framework of mechanical principles. In the early nineteenth century, physicists explored the interconversion of light and heat, and of electricity and magnetism; and the experiments of H. C. Oersted in 1820 and Michael Faraday in 1831, which established the connections between electric and magnetic forces, were of especial importance in justifying the doctrine of the unity and convertibility of natural 'powers' or 'forces', an idea that was reformulated as the principle of the conservation of 'energy' in the 1840s. James Prescott Joule's experiments established the equivalence of heat and mechanical work; and in a seminal essay of 1847, Hermann von Helmholtz expressed the relation among mechanics, heat, light, electricity,

and magnetism by treating these phenomena as different manifestations of energy. Helmholtz formulated the law of the conservation of energy as a mathematical and mechanical theorem, emphasising the unifying role of the energy concept as an expression of the mechanical view of nature.

By 1850 the law of the conservation of energy had provided a new framework for physical theory based on the mechanical view of nature, which rejected the supposition of anomalous forms of matter and supposed that particles of ordinary matter in motion should be considered the basis for physical theory. The physical problems of light, heat, and electricity were conceptualised in a way that made them amenable to mathematical analysis and thereby fostered the unification of physics.

Energy Physics and Mechanical Explanation

The study of the relationships between heat and mechanical work was of central importance in nineteenth-century physics. The formulation of the laws of 'thermodynamics' bridged the disjunction between mechanics and heat and helped to establish the dominance of the mechanical view of nature. Whereas eighteenth-century physicists had considered mechanical and nonmechanical processes as separate physical systems, Joule's demonstration of the equivalence of heat and mechanical work in the 1840s, and the formulation of the law of the conservation of energy, established the unification of mechanical and thermal processes.

The science of thermodynamics was concerned with the direction of heat flow in the production of work, as well as the establishment of the principle of the equivalence of heat and work. In formulating the conceptual basis of thermodynamics in 1850, Rudolf Clausius resolved a problem that had been raised by Thomson, an apparent conflict between Joule's claim that heat was consumed in the generation of mechanical work and the theory of heat engines that had been proposed by Sadi Carnot in 1824. Carnot had argued that the crucial factor in the generation of work by a heat engine was the temperature difference in the engine: Work was generated by the passage of heat from a warm to a colder body, heat being conserved in the process. Clausius established that Carnot's theory that heat passes from a warm body to a colder one whenever work is done by a heat engine was consistent with Joule's assertion that whenever work is produced by heat, a quantity of heat proportional to the work generated is consumed, if Carnot's assumption that heat was conserved in the generation of

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mechanical work by heat engines was abandoned. Joule's principle and Clausius's modified form of Carnot's theory provided the basis for the two laws of thermodynamics.

Thomson and Clausius formulated the science of thermodynamics in terms of the mechanical view of nature, and they maintained that the principle of the equivalence of heat and work was consistent with the mechanical theory of heat: that heat consists of the motions of the particles of bodies. While affirming his support for the mechanical view of nature, Thomson specifically avoided suggesting any mechanical model of thermal processes. Clausius, by contrast, ultimately sought to render the laws of thermodynamics intelligible by appealing to a theory of molecular motions.

The postulation of a model of molecular arrangement became fundamental to Clausius's interpretation of the second law of thermodynamics. In proposing his own account of thermodynamics in 1851, Thomson argued that the key issue was the explanation of irreversible thermal processes. In Thomson's view the second law of thermodynamics asserted the dissipation of energy in irreversible processes. The two laws of thermodynamics were consistent, for although energy was dissipated in irreversible processes, it was not destroyed but was merely transformed into other forms of energy. In the 1850s and 1860s Clausius sought to formulate concepts that would provide a measure of the direction of thermodynamic processes and clarify the nature of irreversible processes. His concept of 'entropy' denoted the directional character of physical processes: The law of the increase in entropy became the familiar form in which the second law of thermodynamics was expressed. Clausius sought to explain entropy by grounding it on a mechanical model of molecular arrangement and motion, a model that for him had a more fundamental status than the entropy concept itself.

Although the relationship between entropy and models of molecular arrangement became the subject of debate, physicists were agreed that the laws of thermodynamics provided an expression of the mechanical view of nature. Thomson maintained that all forms of energy were forms of mechanical energy, and he strove to establish the energy principle as the kernel of the mechanical view of nature. In the 1850s and 1860s Thomson and W. J. Macquorn Rankine elaborated a framework of physical theory based on the primacy of the energy concept, attempting to clarify the mathematical and physical basis of the principle of the conservation of energy as a reformulation and generalisation of the doctrine of the convertibility of natural 'forces'. Thomson and Peter Guthrie Tait's

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Treatise on natural philosophy (1867), based on energy and mechanical explanation, became the text of the new framework of physics, establishing energy within the conceptual structure of the theory of mechanics.

Ether and Field Theories

The concept of the physical 'field', which supposed that electric and magnetic forces were distributed in space and mediated by the agency of a physical field, had become established in British physics by around 1850; its further development was bound up with the elaboration of mechanical theories of the ether to explain the physical constitution of the field. In the 1830s and 1840s Faraday had argued that electric forces were transmitted between particles in an ambient medium, and used the concept of 'lines of force' to represent the disposition of electric and magnetic forces in space. These theories provided the conceptual basis for the notion of the mediating agency of the field existing in the intervening spaces between electrified and magnetic bodies. In formulating theories of electricity and magnetism in the 1850s, Thomson and Maxwell appealed to the field concept rather than to the supposition of 'distance' forces acting directly between electrified and magnetic bodies across finite distances of space.

To explain the physical structure of the field, Thomson proposed that its action could be represented by molecular vortices in the ether; later, however, he conceived the ether as a plenum, representing the field of force by an ethereal continuum. In the 1850s and 1860s Maxwell formulated a series of physical and mathematical theories of the field, drawing on Faraday's physical concepts as well as Thomson's notion of molecular vortices in elaborating a mechanical model that represented the action of the field in transmitting forces by the action of particles in the ether. Maxwell's physical ether theory of 1861–2 provided a systematic theory of the propagation of electric and magnetic forces, employing a mechanical ether that was intended as an illustrative model rather than an ultimate physical explanation. He refined his theory of the field in a paper published in 1865, and though he continued to uphold his mechanical interpretation, emphasising that electromagnetic phenomena were produced by the motions of particles of matter in the ether, he abandoned any attempt to formulate a specific mechanical model of the field, employing instead the methods of Lagrangian analytical dynamics, a generalised formalism not linked to any specific mechanical model.

Maxwell's theory of the electromagnetic field had an unexpected implication: that the velocity of electromagnetic waves propagated in the ether was identical to the velocity of light. This led Maxwell to the identification of the electromagnetic and luminiferous ethers and to his 'electromagnetic theory of light', the concept of light as an electromagnetic vibration in the ether, a unification of optics and electromagnetism that was grounded on a mechanical theory of the ether. The experimental detection of electromagnetic waves by Heinrich Hertz, announced in 1888, was immediately viewed as a striking confirmation of the electromagnetic field. To Continental physicists, especially, it served to establish Maxwell's field theory of electromagnetism in place of the various versions of the action-at-a-distance theory that had been developed by German physicists in the nineteenth century.

By the 1890s the concept of the physical field was subject to a variety of interpretations. Some British physicists tried to integrate Maxwell's theory of the electromagnetic field and Thomson's concept of the ethereal continuum; several physicists developed formulations of the electromagnetic field equations that were not based on a mechanical ether model. The most radical approach was adopted by H. A. Lorentz, who proposed a universal physics grounded on purely electromagnetic concepts. Lorentz's theory also provided an explanation of the experiments performed by A. A. Michelson and E. W. Morley in the 1880s, which had raised serious difficulties in the explanation of the relationship between ether and matter. In Lorentz's 'electron' theory, matter was conceived in terms of charged particles (electrons), and the relationship between ether and matter was explained as the connection between electrons and the electromagnetic field. Lorentz envisaged an electromagnetic rather than a mechanical view of nature, denuding the ether of mechanical properties. By 1900 developments in ether and field theory challenged the hegemony of the mechanical view of nature.

Problems of Molecular Physics

The mechanical view of nature received additional support in the 1850s and 1860s, with the development by Clausius and Maxwell of the kinetic theory of gases, which supposed that gases consisted of particles of matter in motion. Physicists began to stress the molecular theory of matter. Throughout the latter part of the nineteenth century they based speculations about the properties of matter on the kinetic theory of gases, but it became apparent that this theory could not satisfactorily explain molecular structure. Moreover, the evidence of spectroscopy seemed to conflict with conclusions about molecular structure derived from the theory of gases. These problems led to much debate about the nature of molecular models, and doubts concerning the status of the kinetic theory challenged the coherence of the mechanical view of nature.

The problems of the molecular theory of matter also bore on the interpretation of thermodynamics. Maxwell's theory of gases was based on his introduction of a statistical theory of molecular motions, and he invoked this theory in discussing the second law of thermodynamics. Maxwell introduced his 'demon' paradox to show that any molecular interpretation of the second law must be based on a statistical analysis of the motions of an immense number of molecules. There were continual spontaneous fluctuations of individual molecules, he noted, in which heat was transferred from a cold body to a hotter one by the random motions of molecules, but these fluctuations did not constitute a violation of the second law of thermodynamics. This law, an essentially statistical one, applied to an immense number of molecules, not to the behaviour of individual molecules; and hence any interpretation of it that was based on a theory of the motions of individual molecules (as suggested by Clausius) was misconceived.

In a seminal paper of 1877, Ludwig Boltzmann established the relationship between entropy and the statistical analysis of molecular motions, characterising the irreversible increase of entropy in natural processes as a statistical law. Boltzmann sought to defend the mechanical view that nature consisted of particles of matter in motion by explaining the second law of thermodynamics in terms of a statistical theory of molecular motions. In the 1890s this interpretation of thermodynamics came under attack. Max Planck emphasised the absolute validity of the entropy concept, and criticised Boltzmann's interpretation of entropy as a statistical concept. Planck questioned the intelligibility of an explanation of entropy drawn from the kinetic theory of gases. This denial of the idea that entropy should be explained in terms of mechanical principles of matter in motion challenged the whole programme of mechanical explanation.

The Status of Mechanical Explanation

Though the programme of mechanical explanation came under attack in the 1890s, the mechanical or, as it was often termed, the 'dynamical' world view, which supposed an ontology of particles of matter in motion as the substratum underlying physical reality, dominated physical theorising in the nineteenth century. I will use the term 'ontology' to denote assumptions about the basic constituents of physical reality, as distinct from specific hypotheses or models about reality. The ontology of the 'dynamical' theory of particles of matter in motion was fundamental to the dominant programme of physics in the nineteenth century, the explanation of physical phenomena by the structure and laws of motion of a mechanical system. Nevertheless, physicists recognised the gap between the presupposition of the ontology of the mechanical world view and the invention of hypothetical mechanical models to represent physical phenomena; and the relationship between physical reality and the symbolic representations employed for its depiction was a theme of fundamental importance. Many physicists stressed the gap between the structure of physical reality and the encompassing net of theory, and discussions about the conceptual status of the mechanical models employed to represent phenomena were interwoven with debates on the nature of physical reality, and shaped the interpretation of mechanical explanation as a coherent programme.

Physicists used mechanical explanation in three ways. The first appealed to theories of the configuration and motion of particles of matter, aiming to explain natural phenomena by the arrangement of particles of matter and the forces acting between particles. The second sense of mechanical explanation involved the postulation of mechanical models, either the depiction of hypothetical models involving wheels and springs or the construction of working mechanical devices as representations of phenomena. These mechanical models were not necessarily envisaged as representations of reality, but were seen as demonstrating that phenomena could in principle be represented by mechanisms; mechanical construction rendered phenomena intelligible. The third sense in which mechanical explanations were formulated involved an attempt to avoid speculation about the physical structure of the mechanical system supposed to represent the phenomena. Theorists using this approach held that it was impossible to elaborate a unique mechanical model of any phenomenon, and appealed to the abstract formalism of Lagrangian analytical dynamics. The equations of motion obtained in this way were independent of the structure of the connections of the mechanical system, but phenomena were nevertheless subsumed under the principles of mechanical explanation, though not represented by a specific, visualisable mechanical model.

The tension between physical and mathematical models of mechanical systems, and the relationship between mechanical representations and physical reality, played an important role in shaping nineteenth-century theories of physical reality. Maxwell in particular discussed these problems in a sophisticated and influential manner, and debates about the appropriate assumptions to guide the formulation of physical theories underlay the elaboration of new theories in the period. Aware of the gap between theory and reality, many nineteenth-century physicists noted the limitations as well as the objectives of the programme of mechanical explanation.

The Historiography of Physics

The profound conceptual changes in physics in the twentieth century, the abandonment of the doctrines of absolute space and time in Einstein's theory of relativity and of causality and determinism in quantum mechanics, have customarily led to a depiction of the development of physics by means of a disjunction between 'classical' or 'Newtonian' and 'modern' physics. The interpretation of eighteenth- and nineteenth-century physics as monolithic and possessing a unified conceptual structure, its domination being curtailed only by the advent of 'modern' physics, is deeply embedded in the historiography of science. This traditional interpretation is sustained by an account of the 'Scientific Revolution' of the seventeenth century that misrepresents the implications of this intellectual revolution for later scientific developments. The Scientific Revolution has been traditionally characterised as a philosophical revolution in which explanations of natural phenomena came to be couched in mechanical laws. The 'mechanisation of the world picture' is depicted as culminating in the Newtonian synthesis of mechanics and astronomy, and the establishment of Newtonian mechanics and of the programme of mechanical explanation is seen as providing the framework for 'classical' physics in the following two centuries.

Although the shifts in attitude in seventeenth-century conceptions of nature were profound, it is misleading to label this transition the Scientific Revolution if this label is meant to carry the implication that later developments can be comprehended in terms of the scientific categories propounded in this period. The term 'Newtonian' as applied to eighteenth- and nineteenth-century physics implicitly conflates Newton's natural philosophy and the physics of this later period, and is hence a misleading designation. The developments in theoretical mechanics in the eighteenth