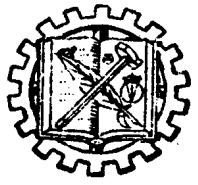
THE INTERNATIONAL DICTIONARY OF PHYSICS AND ELECTRONICS



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PREFACE TO THE SECOND EDITION

The publication of a second edition of the INTERNATIONAL DICTIONARY OF PHYSICS AND ELECTRONICS within less than five years of the publication of the first edition has been made desirable by the rapid progress in some of the fields of physics and electronics. The breakdown of parity conservation, the growth of hydromagnetics and other forms of fluid mechanics, the completion of more powerful accelerators, the rapid application of transistors and the increased quality and quantity of computers are examples of the many changes that result in the introduction of new terms and modifications in the meaning of old ones.

The differences between this edition and the first, however, are much more extensive than would be demanded by such progress alone. An attempt has been made to remove redundant entries, to make better use of cross-references, and to make entries easier to locate by the choice of initial words that are likely to be the ones that first occur to the user. Those omissions and errors which crept into the earlier volume and have been brought to our attention by published reviews or letters from readers have been corrected. We express our thanks to both reviewers and letter writers, and to the editors of other dictionaries (particularly THE INTERNATIONAL DICTIONARY OF APPLIED MATHEMATICS), who have given permission for the use of entries that are so excellent we have not wished to modify them in any way.

Another new feature of the Second Edition is the group of multilingual indices, in French, German, Spanish and Russian. They have been added to meet the ever-growing use and importance of the foreign literature.

The Second Edition, to an even greater extent than the first, avoids uniformity of the level of presentation, rather than seeking it. We have been guided by a desire to meet the needs of those users who are most likely to look up specific terms. Thus, those entries which will probably never be used by a professional physicist are generally treated in a discursive manner, while those that will be sought by such a person are based on the assumption that he will bring considerable background to bear on their interpretation. In some instances, both the discursive and the more formal treatments are combined in a single entry; in others, cross-referencing should carry the user from one level of presentation to the other. The new Introduction, we hope, will be of help to non-physicists. (The material included in the old Introduction is retained, having been transferred to appropriate entries on mechanical units, thermal units, electromagnetic units, etc.).

As in 1956, we express the hope that continued criticism will be forthcoming to aid us in future efforts.

THE EDITORS

INTRODUCTION*

During the preparation of the second edition of the *Dictionary of Physics and Electronics*, the editors have tried to increase the usefulness of the book to the varied groups that have used the first edition. These include not only professional physicists, but also chemists, mathematicians, engineers, business executives, and secondary school teachers. Many individuals in these groups are better acquainted with "classical physics"—the traditional fields of **mechanics**, **acoustics**, **heat**, **electricity** and **magnetism**, and **light**—than they are with "modern physics." It is hoped that the following pages, in which the connection between **classical** and modern developments is traced briefly, may be of help in the use of the increased number of entries dealing with atomic and nuclear physics, relativistic mechanics, quantum theory, and similar topics.

I. Physics in 1800

Although the transition from the classical to the modern period in physics is generally placed at about 1900, the groundwork for recent developments was well laid during the nineteenth century. Much of this century was characterized by a process of synthesis of the knowledge that had been accumulating since the time of Galileo (1564–1642) and Newton (1642–1727), and by a growth in the depth of understanding of this knowledge.

By 1800, the basic structure of **classical mechanics** had been erected firmly on the foundation of Newton's laws of **motion** and of his law of **universal gravitation**. The validity of the three laws of motion had been well established, not only in terrestrial surroundings, but also in the realm of **celestial mechanics**. In addition, Euler (1707–1783), D'Alembert (1717–1783), Lagrange (1736–1813), and Laplace (1749–1827) had developed increasingly elegant ways in which the laws might be applied to complex situations. In view of the high development and great success of **Newtonian mechanics** at this time, it is not strange that most nineteenth century physicists took the view that all phenomena could eventually be explained on the basis of the laws of motion.

In contrast with mechanics, the other fields of physics (or of natural philosophy, as it was then known) were in a rudimentary stage. It is true that Black (1728–1799) had established the basis for **calorimetry** and that the study of heat was thus put on a quantitative basis; yet its synthesis with the rest of physics really belongs to the nineteenth century, for Rumford (1753–1814) had proposed the connection between heat and motion only in 1798. **Geometrical optics** had progressed far, after the discovery of the law of refraction by Snell (1591–1626); lenses and mirrors of reasonably high quality had been manufactured and the **achromatic** refracting telescope had been developed. Although

* In this Introduction, as in the rest of the volume, **bold-face** words indicate cross reference to alphabetized entries. In general, primary entries are listed under the principal noun of the phrase defined, but some exceptions occur when an adjective or proper name is a very important part of the phrase. In most instances of this sort, cross references are listed under the noun as well.

diffraction and **polarization** phenomena were known, the study of them was far from complete and their theoretical explanations were founded on *ad hoc* hypotheses that had little connection with the basic theory of light.

The relationship between electricity and magnetism had not yet been established. Knowledge of each of these fields was largely qualitative and disconnected; the existing theories, such as the **fluid theory of Franklin** (1706–1790), were to need serious modification before they became powerful tools for further progress. It is true that Cavendish (1731–1810) had been able to show, even on the basis of the early qualitative experiments, that the force between static electric charges varies as the inverse square of the distance between them, just as does the gravitational force between two masses. His work was not widely known, however, and it remained for Coulomb (1736–1806) to establish experimentally the law which now bears his name. In the meantime, Volta (1745–1827), following the lead of Galvani (1737–1798), had constructed the first voltaic pile, the predecessor of the modern electric **battery**, and so had opened the way for the investigation of electricity in motion.

II. The Nineteenth Century—Age of Synthesis

First Steps

The opening years of the nineteenth century put on a sound basis three concepts that were to make physics a unified subject, rather than a collection of loosely connected studies. These were the **law of the conservation of energy**, the **wave theory of light**, and the **atomic theory** of matter.

The brilliant analyses and experiments of Rumford and of Davy (1778–1829) showed that neither the heat developed in the boring of cannon nor the melting of ice by friction was consistent with the concept of caloric (a postulated indestructible fluid involved in all thermal phenomena). Their discoveries led to the measurement of the **mechanical equivalent of heat** by Joule (1818–1889) and subsequently to the enunciation of the law of the conservation of energy. Earlier conservation laws, for **mass**, **momentum**, and **angular momentum**, had long been accepted, but this new law was broader in that it provided a connection between two different types of phenomena, each of which had been investigated in considerable detail and in each of which a separate **conservation law** had been found to be applicable under certain ideal circumstances. The gradual recognition of the extent of validity of the conservation law, coupled with the understanding that developed after the studies of Carnot (1796–1832), led to the development of thermodynamics by Kelvin (1824–1907), Helmholtz (1821–1894), Clausius (1822–1888), Gibbs (1790–1861), and others. As a result of their work it became increasingly clear that **thermodynamics**, a study based on a few basic laws and on no detailed assumptions of mechanism, was a powerful tool that applied to all phenomena. Both the **first law of thermodynamics** and the **second law of thermodynamics** may be put in the form of statements of impossibilities:

1. **Energy** can be neither created nor destroyed.
2. No process is possible if it results in a decrease in the **entropy** of an isolated system.

These two general statements define the limitations within which we believe natural phenomena to take place and hence within which scientists must work.

They therefore take a central place in science and no scientific theory that transcends their limitations can be considered to be acceptable. Thus they weld together not only mechanics and heat, but also all other branches of natural science.

The discovery of **interference** phenomena in **optics,** made by Young (1773–1829), put at least a temporary end to a controversy that had been in progress since the time of Aristotle (384–322 B.C.). Was light to be described as a stream of particles emitted by a luminous source or as a disturbance transmitted through some medium? Both hypotheses found support. During the seventeenth century, Huygens (1625–1695) and Descartes (1596–1650) had been the chief proponents of the latter; Newton of the former. Young pointed out that a crucial experiment could be performed to distinguish between the two theories. If light from the same source were to arrive simultaneously at the eye over two independent paths, it would be expected on the basis of a particle theory that the **intensity** would always be the sum of the intensities contributed by the two separate beams. On the other hand, the wave theory would suggest that the intensity could be either greater than or less than the intensity produced by a single beam, depending on the relative lengths of the two paths. In a typical **wave,** something (e.g. the surface of water) is disturbed first in one direction and later in the opposite direction. Which of the two directions is observed at a given instant depends on the distance from the source. Now, if the distances from the source to the eye are different over the two paths, it is possible that light coming over one path will be producing a disturbance opposite to that produced by light coming over the other—the resultant intensity may be less than that produced by either beam alone. At other distances the two disturbances may be in the same direction, with consequent greater intensity. Not only do experiments of this type lend strong support to the wave theory, they also allow the **wavelength** of the light to be determined. Young was able to demonstrate that a large number of known phenomena, such as the colored appearances of thin films, the occurrence of **Newton's rings,** etc., could be explained by invoking his principle of interference between two light beams. In the hands of Fresnel (1788–1827), Young's ideas led to such strong evidence for the wave theory of light that it was accepted unanimously by students of physics.

Young's work, like that of Rumford, Davy, and Joule, led to the joining of different branches of natural philosophy. Wave phenomena are very common; waves on the surfaces of liquids or in solids can be understood both qualitatively and quantitatively in terms of the laws of motion; sound was known before Young's time to be transmitted by a wave motion in air. As a result of the triumph of the wave theory of light, it became possible to argue by analogy with the behavior of these more easily observed waves and so to predict the behavior of light under circumstances that rendered the particle theories almost useless.

The third great contribution to the unity of science, the atomic theory of Dalton (1766–1844), was, like the wave theory of light, an old idea. Democritus (*circa* 460–357 B.C.) had speculated on the possibility that matter consisted of indivisible atoms and Lucretius (*circa* 96–55 B.C.) had popularized his ideas. Before the advent of quantitative experimentation, however, there was no way of demonstrating whether the properties of matter were more easily explained on the basis of such an assumption or on the hypothesis that any kind of matter could be subdivided without limit. It took the genius of Dalton to realize that

the law of constant proportions and the law of multiple proportions in chemical reactions could be most easily understood if one supposed that each chemical element or compound came in the form of large numbers of individual particles, each of which was the smallest bit of matter that had the chemical characteristics of the material. Not only did his concept lead to great simplification of chemistry —it also was to provide the basis on which one could understand the law of gas behavior that had been discovered by Boyle (1621–1679) and of the regularity in the faces of crystals that had been observed nearly two centuries before by Steno (1638–1687) and Hooke (1635–1703). The strength and power of Dalton's theory were increased greatly by the work of Avogadro (1776–1856), who developed the famous hypothesis that the numbers of molecules in equal volumes of different gases (under the same conditions) are equal, and by that of Cannizzaro (1826–1910), who combined the ideas of his two great predecessors to develop the modern concepts of atomic and molecular masses.

The Electromagnetic Field Equations

Almost simultaneously with the work that we have just been discussing, the knowledge of electrical and magnetic phenomena was moving forward at a rapid pace. At the turn of the century, the two types of phenomena seemed to be entirely independent, but in 1817 Oersted (1777–1851) discovered accidentally that an electric current produces a magnetic field. Ampere (1775–1836) seized upon this discovery as soon as he heard about it, and rapidly developed the mathematical relationship known as Ampere's law, which connects the magnitude and direction of the magnetic field with the magnitude and direction of the electric current and with the geometry of the system. The production of magnetic fields by electric currents naturally raised the question of whether the converse phenomenon took place—could magnets produce electric currents? The answer was found almost at the same time by Henry (1797–1878) and by Faraday (1791–1876), who showed that *changing* magnetic fields could produce an electric field, and so could induce currents in a conducting material. Electricity and magnetism were truly found to be closely related!

By 1867 it must have appeared to many physicists that the basic knowledge of electric and magnetic fields had progressed nearly to its ultimate state. But the most striking piece of synthesis remained to be carried through. Before commenting on it, we must mention that the application of mathematics to physical phenomena was continuing to grow from the roots established by Euler, Lagrange, and Laplace. Hamilton (1805-1865) had carried the ideas of these workers to an even more highly polished state than that in which they had left them; Fourier (1768–1830) had developed theorems that were to make possible the solution of differential equations that had previously seemed to present insurmountable difficulties. Gauss (1777–1855), by developing what is now known as Gauss' law, had simplified greatly the computation of gravitational and electric fields that surround symmetrically arranged masses or electric charges and Poisson (1781–1840) had shown that the solutions of a number of physical problems could be accomplished by the solution of the single and powerful Poisson equation. It was becoming increasingly clear that the methods of differential equations and vector analysis provided a language in which physical phenomena could be treated and understood with a minimum of difficulty.

Maxwell (1831–1879) saw in the new mathematical methods a way of combining into a short description all that was known about electricity and magnetism. There were four available principal relations: (1) The inverse square law of force between electric charges at rest; (2) A similar law for the force between magnetic poles; (3) Ampere's law connecting the magnetic field in the neighborhood of a current with the current producing it; and (4) **Faraday's law of induction,** which gave the electromotive force induced in any circuit in terms of the time rate of change of the **magnetic flux** through the circuit. Faraday had given additional meaning to these laws by the use of a quasi-mechanical model involving lines of force, which he supposed to behave very much like stretched rubber bands. These lines of force offered an alternative to the concept of action at a distance, which to most scientists and philosophers is an objectionable notion. Maxwell was able to reduce each of the four laws to a mathematical form in which two vector quantities, the **electric field strength** and the **magnetic field strength,** expressed what might be called the "state of electromagnetic strain" of the space surrounding the charges. His set of four equations shows connections between these vectors and between them and the presence of stationary or moving charges in the neighborhood of the region of space being discussed. In other words, Maxwell's equations place the emphasis on the **field,** or the changes in the nature of space, produced by charges. As we shall see later, this kind of description was to prove to be a valuable one during the next fifty years or more.

In developing his model of the **electromagnetic field,** Maxwell encountered, recognized, and overcame one difficulty that might have escaped the notice of a lesser mind. To a large extent, there seemed to be a reciprocal relationship between electricity and magnetism—we have already seen how this reciprocity led to the search for the induction of electric currents by magnetic fields. Yet the symmetry was not complete, as induction requires a *changing* magnetic field while magnetic fields are produced by *steady* electric currents. He met this apparent lack of reciprocity by imagining—and then producing sound reasoning to support the idea—that a changing electric field produces the same magnetic effect as a current flowing in a conductor, that it constitutes a **displacement current.** Here was a case, to be repeated many times later, in which symmetry considerations and the form of the mathematical expressions were to guide physical theory.

With the displacement current added to the concepts involved, Maxwell's four equations, after some routine mathematical manipulation, led to a startling prediction. Any electrical or magnetic disturbance created in free space should, if these equations were correct, be propagated through space as a disturbance, or wave motion. This should be a **transverse wave,** i.e. one in which the disturbance is at right angles to the direction in which the wave travels and therefore one that may be completely polarized. Further, the speed of the wave could be predicted from measurements that had been made on purely electrical and magnetic phenomena—it was very close to 3×10^{10} centimeters per second. The study of polarization phenomena had already shown light to be a transverse wave and measurements of its speed by Fizeau (1819–1896) and Foucault (1819–1868) agreed quite precisely with the speed predicted for **electromagnetic waves.** All of this seemed like too much of a coincidence between light on the one hand and electromagnetic phenomena on the other. From 1870 on it was accepted that light *is* an electromagnetic wave.

Atomicity and Electric Charge

Dalton's discovery of the atomicity of matter, as we have seen, followed on the development of quantitative methods in chemistry. The first evidence that electricity also occurs in very small, indivisible, and identical pieces also came about as the result of careful and quantitative measurements. Almost as soon as Volta had made the battery, and hence reasonable steady electric currents, available, various experimenters began studies of the effects produced when such currents passed through solutions of acids, bases, and salts in water. The decomposition of water into hydrogen and oxygen was brought about very early; it was not much later when it was found that metal could be removed from the **electrode** by which the current entered certain solutions (the **anode**) and an approximately equal amount of metal be deposited on the other electrode (the **cathode**). Early in his career, Faraday performed some ingenious experiments to learn about such electrochemical effects. He was able to show that the amount of any given substance that is deposited or produced in an electrochemical cell is proportional to the amount of electricity passed through the cell. This is neither surprising nor particularly revealing, but Faraday's finding about the amounts of different materials deposited or produced by **electrolysis** when the *same* amount of electricity passes was destined to be highly important.

The second **Faraday law of electrolysis** states that the amount of a substance deposited in electrolytic action by a fixed amount of electricity is proportional to the **equivalent weight** of the substance, i.e., to its atomic weight divided by a small integral number, the **valence.** Although it was not recognized at the time, this law points strongly to the atomic nature of electric charge. If individual atoms pass through the cell in a form in which they carry electricity with them and if each atom carries the same amount of electric charge, the masses transported must be proportional to the masses of the atoms. To account for the importance of equivalent weights, we need merely to suppose that different species of atoms carry different numbers of elementary charges, the number being exactly equal to the valence. No other logical explanation of Faraday's second law has ever been developed.

Although Faraday was very close to discovering the atomicity of electricity, the true significance of his work had to wait for the development of a very different line of investigation. We are all familiar with the striking effects produced when electricity is passed through a partially evacuated glass tube containing some air or other gas. These phenomena require a high voltage, or **potential difference,** as compared with that needed for electrolysis or for the conduction of electric currents through solids, hence their investigation had to wait for the invention of the **induction coil,** which came about as a direct consequence of Faraday's law of induction. When investigators began to study the gas discharge, it was noted that the glass near the cathode often exhibited a bright glow, or **fluorescence.** The cause of this fluorescence was gradually traced to particles that were either emitted from or produced near the cathode. The nature of these particles was put forward by Crookes (1832–1919), who pointed out that the known bending of their paths by a magnetic field was consistent with the idea that each of them carries a very small negative charge of electricity. After a great deal of preliminary work by many experimenters, Thomson (1856–1940) was able to measure the radius of curvature of the **cathode rays** in a

known magnetic field and the energy transported by these rays. The former depends on the speed, the mass, and the charge of the particles; the latter on the mass and the speed. By combining the two results, Thomson succeeded in estimating the **charge-to-mass ratio** of the individual particles. This ratio was found to be independent of the nature of the gas in the tube—it appeared that identical particles were produced whenever an electric discharge took place in *any* gas. Without following the rest of the work done to determine their properties, we can recognize that the cathode rays responsible for the fluorescence of the glass are made up of the particles now known as **electrons,** each of which is a very small negative electric charge, having a mass that is a little more than 1/2000 of the mass of a hydrogen atom.

Not long after the cathode rays were discovered, it was found that another type of ray could be seen if the cathode of a discharge tube had small holes, or canals, drilled through it. Through these holes there emerged streams of particles that originated in the gas discharge. By measurements of their deflections in electric and magnetic fields, it was found that the **canal rays** are streams of particles, each of which has a mass essentially equal to that of the individual atoms or molecules of the gas and carries a positive charge that is either equal in magnitude to the charge of the electron or is a small integral multiple of that charge.

The conclusions reached from the study of electrolysis and of gas discharges had, before the end of the century, gone beyond the atomicity of electricity. It was becoming increasingly clear that negatively charged electrons—with masses far smaller than the atoms—are common constituents of all atoms. As atoms in general are electrically neutral, and as the canal rays consist of positively charged particles, it seemed reasonable that the latter were the residue of an atom or molecule after one or more electrons had been removed from it in the violence of the discharge. Thus the atom, whose very name means "indivisible," was shown to possess an inner structure. The study of this structure was to become the chief activity of the physics of the twentieth century.

The Evidence of Spectra

The decomposition of white light into a spectrum of colors by **dispersion** in a **prism** had been studied extensively by Newton, who also showed that the colors could be recombined to produce white light. What distinguished the colors from each other was not clear until the wave theory of light took hold. It was then shown that the order of the spectrum colors—violet, indigo, blue, green, yellow, orange, red—is the same as the order of the wavelengths of the light producing them. Red light has a wavelength of about 7000 **Ångstrom units** (Å), violet light about 4000 Å; the other colors have wavelengths intermediate between these extremes of the visible **spectrum.**

No one seems to have noticed that the spectra obtained from various light sources were different from one another until more than fifty years after Newton's work. Even after it had been observed that the addition of salts containing sodium to a flame causes a brightening of the yellow portion of the spectrum produced by the flame, another century was required before it was clear that there are at least three distinct types of spectra. (1) **Incandescent** bodies, such as a piece of heated metal, emit all wavelengths to which the eye is sensitive (and some to which it is not). (2) Heated gases and vapors give bright **line**

spectra or **band spectra**, in which some sharply defined wavelengths are present, while many wavelengths are absent; each of the wavelengths present accounts for a spectral line. Finally, gases or vapors introduced in the light path between an incandescent source and the spectroscope result in a **dark line spectrum** or a dark band spectrum in which certain sharply defined wavelengths are missing; it was the observation of such dark lines in the spectrum of the sun by Wollaston (1766–1828) and by Fraunhofer (1787–1826) that helped greatly in the disentanglement of the puzzle of the spectrum.

It was finally recognized, as the result of the efforts of many workers, particularly of Kirchhoff (1824–1887) and Bunsen (1811–1899), that each element can emit only certain distinct wavelengths unless it is in chemical combination with other elements. (From such compounds, when their vapors are heated, spectra consisting of bands of many closely spaced lines are emitted.) Not all of the possible **spectral lines** of an element are necessarily emitted at any one time, although more and more of them are often found as the temperature of the vapor is increased. However, no lines not present in the characteristic spectrum of an element are ever emitted by that element, and each dark line produced by the element is found to have the same wave length as a bright line in its characteristic emission spectrum. To explain this, Kirchhoff and Bunsen, as well as Stokes (1819–1903), introduced the ingenious assumption that there was something in the atom that could vibrate only at particular frequencies. When the atom was disturbed, as it might be by heat, a wave was set up at the frequency of vibration and would spread out from the atom as a light wave. On the other hand, when light from an incandescent source fell on atoms of the substance, those waves having the same frequency as one of the characteristic vibrations would start the vibration—this would require energy, and light of the particular wave length characteristic of this frequency would be absorbed. Molecules, being more complex than atoms, might be expected to have many more characteristic frequencies and to give the more complex band spectra. In solids the complexities must truly be very great, since great numbers of atoms are involved, and one might well anticipate that so many wavelengths would be emitted that they would overlap, giving the **continuous spectrum** characteristic of incandescent bodies.

When Maxwell's electromagnetic theory of light had been developed and when it had become accepted that electrons were constituents of atoms, the "something" that was vibrating could almost certainly be identified. The electron meets every requirement. It is an electric charge, therefore its motion will set up an electromagnetic field in its neighborhood. It is so light that there is little difficulty in imagining that it can vibrate at the high frequencies typical of optical vibrations, which are at the rate of four to eight times 10^{14} per second.

Two models of the structure of the atom were in current use by the end of the century. In one the atom was considered to be a jelly-like ball of positive charge, in which there were imbedded a number of electrons. Each of these electrons would ordinarily be at rest at some position within the atom, but it could be disturbed by heating, by the effect of other electrons striking the atom, etc. When displaced from its equilibrium position, the electron would be subject to a force pulling it back to that position. If it is supposed that the force is proportional to the distance that the electron is displaced, the problem of finding the frequency of the resulting vibration is an easy one—the electron will undergo simple har-

monic motion analogous to the swinging of a pendulum bob. This model was very simple and was successful in many ways. The frequency of a simple harmonic motion is independent of the **amplitude** (the maximum distance that the particle departs from its equilibrium position); this fact accords with the well defined frequency (and wavelength) of spectral lines. When the atom is placed in a steady electric field, the electrons will be displaced by an amount proportional to the magnitude of the field and so the atom will acquire an electric **polarization** in the direction of, and proportional to, the field. This accounts for the constancy of the **dielectric constant** of most insulating materials. This model, in which the electrons were all in static equilibrium unless disturbed, would account for some, but not all, of the observed properties of atoms, but it encountered one very serious difficulty in principle. Earnshaw (1805–1888) had demonstrated that no system of electric charges could remain in static equilibrium under the action of their mutual electrical attractions and repulsions alone. Quite clearly, some mysterious new type of force needed to be introduced into the model to allow the atom to be stable. The origin and nature of such forces were, at the least, obscure.

A second model overcame the difficulties introduced by **Earnshaw's theorem,** but only at the cost of bringing in new ones. According to it, the atom would consist of a heavy, positively charged, **nucleus,** about which electrons move in circular or elliptic orbits, very much like planets about the sun. The mutual attraction of the nucleus and any electron then supplies the **centripetal force** needed to hold the electron in its orbit. One major problem with this model was that it would not account nicely for the sharply defined frequencies of spectral lines. The frequency of rotation of a planet or satellite depends on its distance from the attracting center, becoming greater as the distance decreases. If the radius of a circular orbit is supposed to be constant, the frequency will also be constant, but this would contradict the law of the conservation of energy; as the electron spins about, it produces an electromagnetic disturbance and so radiates energy; this energy can be supplied only by a decrease in the size of the orbit, with a consequent increase in the frequency. On the other hand, the dynamic atom model was successful in accounting for the magnetic **susceptibility** of an atom and for both **plane polarization and circular polarization** of the emitted light.

Thus as the end of the century approached, physics found itself in the not unusual position of having two models that could not be reconciled easily with each other, each having certain successes and certain failures. Much had been accomplished, but new ideas were needed if either of the existing models was to develop into a truly successful one.

One very remarkable discovery seemed to make the problem even more difficult than it would have been otherwise, but this discovery was to furnish the test of the first truly hopeful theory, some years later. It had long been recognized that the hydrogen atom, being the lightest of any, was probably also the simplest. Nature seemed to confirm this supposition, for atomic hydrogen has a simple visible spectrum, consisting of only four lines, with wavelengths of approximately 6563 Å, 4861 Å, 4340 Å, and 4102 Å. Balmer (1825–1898) was able to show that all of these wavelengths could be expressed by the same equation:

$$\lambda_N = (3645.6\ \text{A})\frac{N^2}{N^2 - n^2},$$

where $n = 2$, N takes of the values 3, 4, 5, or 6, and λ_N is the wavelength associated with the number N. Not only does the expression work for the four visible lines; when integral values of m higher than 6 are used it also gives the wavelengths of several additional lines that had been found in the ultraviolet spectrum of hydrogen.

Here is an equation that is both accurate and simple and that uses the integers in a way that would have delighted the Pythagoreans. From the moment that it was announced by Balmer, it was clear that any successful model of the hydrogen atom must be one that involves the integers 1, 2, 3, $\cdots$ in some manner. Nearly twenty years were to elapse, however, before such a model was proposed.

The Introduction of Statistical Methods

Before we consider the rest of the series of remarkable discoveries that were accomplished during the turn of the century decades of 1887–1907, we must examine one more new line of thought that was introduced into physics during the nineteenth century. With the triumph of Dalton's atomic theory, scientists had to consider the fascinating question of the connection between the atoms and molecules that make up a large scale body of material and the observed characteristics of the large scale material itself. To take the simplest illustration, **Boyle's law** had been known for a long time: the product of the pressure and the volume of a given sample of a gas is at least approximately constant at a given temperature. What properties must we suppose the molecules of the gas to have, and how must we assume that they behave, in order that their combined effects may result in this simple relation? It is clear that molecules of the same kind must, in general, attract each other when they are very close—otherwise solids and liquids would not hold together as they do. The density of a typical gas, however, is so much less than the density of a solid or liquid that we must suppose that the molecules are much farther apart in it than in the more condensed substances. It might be that the pressure of a gas results from the molecules repelling each other, but this alone should lead, as it does in the case of like electrical charges, to the molecules collecting just inside the walls of a room, instead of being distributed uniformly throughout the room. Another possibility is that the molecules are in motion, that they move about inside a container, bumping into each other and rebounding from the walls. On such a **kinetic theory**, the pressure results from the sum of the effects of individual molecules bouncing from the walls, each collision contributing a small outward push. It might be objected that the pressure on this basis should not be steady, as it seems to be, but rather that it should fluctuate as individual molecules or groups of molecules strike a wall. This difficulty was overcome as soon as the tremendous number of molecules in any large scale sample of material was estimated. A cubic centimeter of gas contains about 3×10^{19} molecules under normal conditions. With such numbers, one can well expect that collisions will be so frequent that individual ones will not be distinguishable, at least by any simple means.

The large number of molecules involved saves the day as far as fluctuations in pressure are concerned, but it contributes a discouraging factor if one attempts to tackle the computation of the pressure by the direct and obvious means. This would be to assume that the molecules are little spheres, each of which behaves like a very small steel ball and therefore moves in accordance with the laws of

mechanics. If one knew the nature of the walls of a box that contains a gas and also knew where each molecule was at some instant and how fast and in what direction it was moving, he could apply the known mechanical principles to compute the entire future history of all of the molecules. Such a procedure would involve six equations for each molecule, or some 2×10^{20} simultaneous equations for the sample of gas mentioned above—something quite beyond practicality.

Aside from the impossibility of solving the equations involved, it is inconceivable that one could even set them up, for it is clearly impossible to measure simultaneously all the positions and velocities. Any attempt to compute the behavior of the gas must therefore be based on ignorance. Fortunately, however, one branch of mathematics is specially designed to work with systems about whose details one is ignorant. This is **probability** theory. When one throws a die, it should be possible to predict, on the basis of its position and motion as it leaves the hand, the number that will be exposed when it comes to rest. In practice, one cannot obtain all the information necessary to predict how the die will fall on any given throw. If it is thrown six hundred times, however, one expects each of the six faces to be uppermost in about 100 throws. One would not be surprised if a "three" were to occur in two successive throws, but if it turned up in 150 of the 600 throws the symmetry of the die would probably be seriously questioned. Probability deals with problems of this sort—it allows the calculation of the "expectation" of what will happen "on the average."

Almost seventy years before Dalton's argument for atomicity was put forward, Bernoulli (1700–1782) had applied probability considerations to answer the question of how a gas would behave if it were made up of a large number of molecules. Following his lead, Joule, Maxwell, and Clausius brought the **kinetic theory** of gases to a high level of development. They were able to show not only that the assumption of molecules in continual random motion would lead to Boyle's law, but also that the **ideal gas law,** which relates the product of the volume and pressure to the temperature, could be obtained if one supposed that the average kinetic energy of the molecules was proportional to a quantity that came to be known as the **absolute temperature** (or the Kelvin temperature), equal to the Centigrade temperature plus about 273°. Boltzmann (1844–1906) carried their work still further. Arguing that the many collisions among the molecules would lead to a state of affairs in which their identities must be effectively lost, he and Maxwell pointed out that even the question of what speed a particular molecule could be expected to have at a given time was a question that could be answered on a probability basis. The line of reasoning is essentially based on the idea that the collisions among molecules will be so frequent and will be so random in character that every molecule in a gas must *at some time* be arbitrarily close to every possible position in the container, and that every molecule *at some time* in its history will be travelling with any speed that one cares to name. One then asks, not for the state of affairs at any instant, but rather for the most probable state of affairs. It is assumed that the effects of the many collisions will "erase" all "memory" of the past, so that any improbable state of affairs (e.g., one in which all the molecules are moving in a single direction) will soon disappear and be replaced by a state that is close to the most probable state.

Using probability methods and recognizing that both the total number of molecules and the total energy of any isolated sample of gas must remain constant, Boltzmann was able to show that the assumptions just mentioned lead to a very

interesting conclusion. Suppose that one counts the number of molecules having energies in the narrow range between E_1 and $E_1 + dE$ and then makes a similar count of those whose energies lie between E_2 and $E_2 + dE$. Suppose also that there is no *a priori* reason to expect different numbers in the two ranges. Then, according to Boltzmann's result, the ratio of the second count to the first can be expected to be

$$e^{-(E_2-E_1)/kT},$$

where e is the base of the natural logarithms, T is the absolute temperature, and k is a universal constant, now known as the **Boltzmann constant.** This exponential expression has the property that it becomes nearly unity for very high temperatures and nearly zero for very low temperatures. At very low temperatures almost all of the molecules will be nearly at rest; at very high temperatures almost equal numbers of molecules will have two widely differing energies.

The **Boltzmann factor,** as the exponential expression is known, was to play an increasingly important role in physics and in chemistry as the twentieth century came into being. More important, however, was the fact that it had been demonstrated that **statistical mechanics,** in which one calculates what will probably happen, rather than what must happen, had been made a part of scientific theory. After two centuries of work with the mechanics of Newton, in which all of the future appeared to be predictable if a sufficient number of positions and velocities were known, physicists were learning to be satisfied with a less detailed answer that was based on the assumption that the exact past history of a system of particles is unimportant, because its effects are removed by the collisions that move the system toward the most probable state.

III. The Period of Change: 1887–1907

The Michelson-Morley Experiment and Relativity Theory

The introduction of the wave theory of light had introduced one logical difficulty. When we think of a disturbance moving from point to point, the picture is hardly complete unless we suppose that there is *something* present to be disturbed. On the other hand, light passes through a vacuum. This difficulty was met by postulating the **ether hypothesis,** according to which a hypothetical material, the ether, pervades all space and is the medium in which the light wave is propagated. Between the time of Young and that of Maxwell, some strange properties had to be ascribed to the ether in order that the various observations on optical phenomena could be explained. The development of the electromagnetic theory of light might have been considered to remove the necessity for the ether, as electric and magnetic fields can exist in a vacuum; yet the idea was so firmly planted that the ether hypothesis was retained in modified form.

There seemed to be reason to believe that the ether could serve a second purpose, in addition to being a medium to transmit light waves. In experimental physics it is always necessary to make the measurements of the position of bodies relative to some **coordinate system.** The question of which of the many possible coordinate systems was best had been a perplexing one. In fact, Newton's first law of motion may be considered to be a definition of a coordinate system in which his other laws of motion, and consequently the rest of classical mechanics, will be valid. Newton and others following him had shown, for example, that the laws of mechanics had to be modified when one attached his coordinate sys-

tem to the rotating earth, rather than using a system in which the fixed stars remain at rest. The latter system had been widely accepted as the preferred, or absolute system. It was natural enough to suppose that the ether as a whole would not be moving with respect to the fixed stars, and that all natural phenomena could be best described in a coordinate system attached to the ether. This supposition made it desirable that the velocity of the earth (and therefore of the physics laboratories on it) be determined relative to the ether.

In principle, the determination of the velocity is simple. If light travels at a speed c through the ether and if the earth is moving at a speed v relative to the ether, one needs only to measure the speed of light in various directions. When the light is travelling in the same direction as the earth, its measured speed should be $c - v$; when it is travelling in the opposite direction, $c + v$. The first practical difficulty, of course, is to measure the speed of light with sufficient precision to distinguish between $c + v$ and $c - v$. The highest speed at which a laboratory can be expected to be transported through the ether is that of the earth in its orbit around the sun—approximately 18 miles per second, or 3×10^6 cm/sec. This is only one-hundredth of one percent of the speed of light, and measurements of great accuracy would need to be made to detect the motion. The difficulty is compounded when one notices that the best measurements of the speed of light have been made by using a round trip, in which the light passes from a point of observation to a distant mirror and is reflected back to the point of observation. The problem of calculating the speed from an experiment of this sort is exactly analogous to the calculation of the air speed of a plane that is flying in a wind and that makes a round trip from one point on the earth's surface to another point and back. A simple computation shows that when the plane flies directly against the wind in one direction and directly with it in the other, the time taken for the trip is $2Lv_a/(v_a^2 - v_w^2)$, where L is the distance between the two points, v_a is the speed of the plane relative to the air, and v_w is the speed of the wind relative to the earth. In terms of the light beam and the earth, the corresponding time is $2Lc/(c^2 - v^2)$. By inserting the values of $c = 3 \times 10^{10}$ cm/sec and $v = 3 \times 10^6$ cm/sec, we find that the expected time differs from that obtained with $v = 0$ by only one part in 10^8. A measurement with an accuracy better than one-millionth of a percent would be needed to detect the existence of v!

In 1887 Michelson (1852–1931) and Morley (1838–1923) reported the results of an ingenious experiment that avoided the major difficulty. Instead of trying to measure the speed of light as it travelled in different directions, they arranged to measure directly the *difference* between the times taken by two light beams, travelling at right angles to each other. Suppose that each of the two beams covers a round trip, one moving parallel to the motion of the earth through the ether and the other at right angles to this direction, and that both cover the same measured distance. Then the time taken for the first beam is $2Lc/(c^2 - v^2)$. By considering an analogy with a plane flying, with a cross wind, a round trip over the same distance, relative to the ground, it is easy to see that the distance that the light in the second beam travels, relative to the ether, is $2Lc/\sqrt{c^2 - v^2}$, or that the time taken should be $2L/\sqrt{c^2 - v^2}$. The difference between these two times is very small (about $\frac{1}{2} \times 10^{-8}$ of the round trip time) but it is possible to measure it precisely by having the two beams interfere on their return to a common starting point, and so to compare it with the time of a single oscillation of the light wave. When Michelson and Morley performed their experiment, they found that the expected difference in time, which should have been detected