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An Introduction to Modern Physics

chapter one

Physics as it is usually presented seems to be subdivided in a rather strange way The freshman or sophomore general physics course gives a survey of the high points of what we shall call *classical* physics The distinction between this and the *modern* physics at first seems vague but can be explained quite simply. Physics accomplished after the turn of this century is not called *modern* arbitrarily The distinction is that between *logical* and *illogical* physics, the latter being the subject of this book The logical or classical physics deals with phenomena which take place in times which are neither unimaginably short nor very long, over lengths which are somewhere between a micron and a few million kilometers; and involve masses somewhere between a microgram and the mass of the Earth This is, very roughly, the range of parameters over which our imaginations can still have some conception of the physics involved in terms of familiar phenomena perceived in day-to day life In other words, the phenomena of classical physics involve our store of experience in a direct rather than a mathematical sense, the classical regime is where we "live Physics (and any other science worthy of the name) is a consistent scheme that allows measurement of physical phenomena to yield a predictable result The validity of a theory rests solely on its ability to predict the results of feasible experiments correctly

Classical physics reached a point shortly before the dawn of the twentieth century where all physics appeared to have been completed. A feeling of complacency was widespread in the physics community and many people thought that all the major problems had been solved and that the twentieth century would belong to the engineer. Such was not the case then nor is it ever likely to be. The experimental side of science was merely lagging behind the theoretical. There were plenty of problems just over the horizon and these problems, as we shall see, did not yield to the old methods but required radical new assumptions.

In order to appreciate the sophistication of modern physics we must go back to the beginnings of man's quest for knowledge about his physical environment and follow the development of his ability to ask nature the right questions in the right way.

The Development of Classical Physics

chapter two

2-1 The Rise of the Experimental Method

The history of science can well be considered to have begun in Greece during the Hellenistic age. Greek science was limited to speculation based largely upon esthetic considerations. There was no attempt to verify these speculations by experiment. Even so, these early Greek philosophers and mathematicians originated such ideas as matter conservation, inertia, the atomic structure of matter, and the finite speed of light.

Aristotle (384–322 B.C.) began the trend away from a purely speculative approach to science. His stature in history was such that all his scientific doctrines, both correct and incorrect, were dogmatized by the scientific and ecclesiastical establishment (which were one and the same). This sort of closed-mindedness is in direct opposition to the spirit of free inquiry that must prevail if science is to be scientific and not mystical. For example, Aristotle cherished a firm belief in a geocentered Universe wherein the Sun and fixed stars circled an unmoving Earth. The acceptance of this view as "gospel" was to prove an insurmountable barrier to progress in this area for the next two millenia.

After nearly 17 centuries of stagnation following the Greeks, science once more began to flower when Nicholas Copernicus (1473–1543) became convinced that the orthodox geocentered view of the Universe was wrong and that the Earth was a planet on the same footing with the others, all of them moving in orbits about the Sun. This same theory had been advanced by Aristarchus 2000 years earlier, but now its time had almost come. Copernicus found that the seasons and the observed retrograde motion of the planets could be *easily* explained on the basis of such a heliocentered theory. Copernicus' theory was worked out in considerable detail and, owing to the development of the telescope by Galileo soon thereafter, the theory was never again successfully rejected. Copernicus, fearing persecution for heresy, withheld publication of his theory until he was on his deathbed.

Galileo Galilei (1564–1642) might well be thought of as the father of physics as we know it. At the age of 17, he discovered the principles of the pendulum by observing the oscillations of a large chandelier in the cathedral when he was studying medicine in Pisa. By the age of 26 Galileo had drifted away from medicine and was appointed professor of mathematics at Pisa. At this time he began to dissect Aristotle's theories, illuminating errors as he found them.

Most of Galileo's colleagues refused to be convinced by his heresies against the church-sanctioned work of Aristotle and a lifelong persecution of Galileo began. Galileo refused to be prudent as his predecessor Copernicus had been. He was hounded out of Pisa in 1592 and went to Padua where he spent 18 years as professor of mathematics.

In 1608 during Galileo's tenure at Padua, a Dutch optician named Lippershey discovered, quite by accident, a way of using two spectacle lenses to make objects seem nearer but inverted. Galileo heard of this in June of 1609, immediately understood the physics involved, and threw himself into the development of the telescope. By January of 1610 Galileo had built a 30-power refracting telescope with an erect image. This instrument had an optical arrangement very much like the opera or field glass. He trained his telescope on the heavens and a flood of wonders met his eye. The Milky Way was resolved into stars; the planets were seen as discs rather than points; and the moons of Jupiter were discovered.

Galileo was now at the height of his fame. Padua was a liberal university and he was not troubled by the persecution that he had experienced at Pisa. His 18 years at Padua had apparently dimmed his memory of such things and he returned to Pisa with an impressive academic title and a substantial increase in salary, albeit at the cost of his academic freedom.

Galileo's fame protected him from persecution at Pisa for a time during which he continued to amass evidence in support of the Copernican view. In 1615 he was called before the Pope and ordered to cease his blasphemies. Galileo was imprudent when it came to sharing his marvelous discoveries; however he was far from being suicidal. He conducted his research quietly until 1623 when a friend, Barberini, became Pope Urban VIII. Galileo reasoned that this change in the ecclesiastical court should now allow him to publish his theories.

Galileo began his great book of *Dialogues on the Ptolemaic and Copernican Systems*, which was published in 1632. This book very cleverly abided by the letter of the 1615 decree but, at the same time, made a devastating argument for the Copernican cosmology. In the book, three characters carry on a discussion: Saliviati, a Copernican; Simplicio, an Aristotolian; and Sagredo, an intellegent and impartial moderator. The dialogues cover four days; no conclusions are reached but the arguments speak for themselves.

Urban's court contained much plotting and intrigue. The Pope became persuaded that Simplicio was a caricature of himself. Galileo was harassed and finally called before the Inquisition. He was 67 years old and in poor health. From that time on he was kept a prisoner in his own home. In 1636 Galileo published his *Dialogues on Two New Sciences* (cohesion and motion), which clarified all knowledge of mechanics up to that time. This work was to prove most useful to Newton, who was born in the same year that Galileo died.

A number of very important events were taking place in physics at this time. The supergiants of this era, Galileo and Newton, played out their roles on a sumptuously prepared stage.

The most significant advances were made by two men, Tycho Brahe (1546–1601) and Johann Kepler (1571–1630). Their story illustrates the nature of the interaction between theory and experiment. Tycho, the experimentalist, was born into a noble family in Sweden and, working as a hobbiest, became an exceptional astronomer. In 1575 he was hired as court astrologer by King Frederick II of Denmark. It was in this position that Tycho made his systematic observations of the planets and compiled a star catalog. This work was done with great care and an amazing degree of accuracy was achieved in measuring the planetary orbits. Incidently, all this was achieved without a telescope; Galileo was not to build the first one until 35 years later.

Apparently Tycho's astrological predictions must also have been fairly accurate since history records a peaceful relationship between Tycho and his patron. In 1599 Tycho left Denmark to establish a new observatory at Prague. He died in 1601 before his new work had progressed very far.

Kepler was one of Tycho's assistants at Prague during the last months of Tycho's life. Kepler was a theoretician and after Tycho's death he carried on with calculations based on Tycho's observations. In 1612 Kepler moved to the University of Linz and worked there until his death in 1630. Tycho had believed in a geocentered Universe and all of those painstaking measurements were made in order to provide support for this view. In Kepler's hands, Tycho's measurements became the clinching argument for the Copernican system.

The motion of Mars had been measured by Tycho. There appeared to be no combination of circular orbits of Earth and Mars that gave a reasonable fit to the data. Kepler therefore gave up the idea of uniform circular motion and assumed (1) the planets move in elliptical orbits with the Sun located at one focus of the ellipse. This was found to be consistent with the data if (2) the speed of the planet in its orbit was proportional to $1/r$, which can be shown to imply that equal area segments of the ellipse are swept out in equal times. Finally, Kepler found that (3) the square of the period of such orbital motion is proportional to the cube of the mean radius. These are the famous Kepler laws of planetary motion, which, in conjunction with Galileo's work in mechanics, provided the inspiration for Newton. Kepler spent his last years pondering the implications of his laws. He arrived at a qualitative notion of an attractive force between two bodies, but it remained for Newton to take the final step.

Sir Isaac Newton (1642–1727) discovered the binomial theorem, made significant contributions to the knowledge of infinite series, and developed the differential calculus while still a student at Cambridge. A plague closed the university for several months and while at home Newton began his work on gravitation (it was during this time that the falling apple incident is supposed to have occurred). In 1667 he returned to Cambridge as a Fellow; 2 years later at the age of 26 he was appointed Lucasian Professor of Mathematics, a Chair he held for 30 years. In 1703, he resigned his professorship and was elected president of the Royal Society for life. In 1705 he was knighted by Queen Anne. Newton died on March 20, 1727 at age 85.

Most of Newton's contribution to physics was made before the turn of the eighteenth century. From that time until his death he dabbled in metaphysics and theology. It is not possible to list all Newton's important discoveries here; there are simply too many. In the field of optics, he discovered the light spectrum (dispersion) in 1666. He is also known as the inventor of the Newtonian telescope, a form of reflecting telescope that is still most popular today for astronomy. Newton's famous book on *Opticks* was published in 1704. Newton favored (but not dogmatically) a corpuscular theory of light, unfortunately for Hooke (1635–1703) and Huygens (1629–1695) who were trying to introduce their wave theories at the same time.

Newton's contributions to mechanics are awesome. His work on gravitation culminated in the famous law that states that the gravitational force between two bodies is proportional to the product of their masses divided by the square of the distance between them. Using this law Newton could derive all three of Kepler's laws.

In 1687, the Royal Society published Newton's *Principia* in which he expounded his theory of mechanics. Newton's three famous laws of motion are presented as axioms. It is a tribute to his genius that no more suitable basis for mechanics has ever been found. Newton's calculus has been replaced by the calculus of Leibnitz (1646–1716), which is identical in content but more convenient to use. Not until we come to Einstein do we find another figure in physics with the stature of Newton.

Progress in the field of mechanics consisted mostly of the discovery of consequences of Newton's laws of motion. Lagrange (1736–1813) presented a formulation of dynamical problems in the form of a single, second-order differential equation. Euler (1707–1783), together with Bernoulli (1700–1782), derived the law of conservation of angular momentum. Euler did pioneering work in the calculus of variations, while Bernoulli is best remembered for the hydrodynamical law that bears his name and for his work in kinetic theory.

In the field of heat, Fahrenheit (1686–1736) and Celsius (1701–1744) proposed their respective temperature scales, and Joseph Black (1728–1799) measured the heats of vaporization and fusion for water, thus qualifying as the father of calorimetry. Theoretically, physics *lost* ground during this century. Newton had regarded heat as being associated with the motions of atoms; however the caloric theory of heat as a subtle fluid of some sort dominated the eighteenth century.

In the field of optics and light, Bradley (1693–1762) made the first reasonably good measurement of the velocity of light. As in the case of heat, the eighteenth century was theoretically barren as far as light was concerned. Newton's attachment to the corpuscular theory spoiled the climate for new ideas in this field. No crucial experiments were performed during this time.

Electrostatics was a busy area during this century. Du Fay (1698–1739) showed that flames conduct electricity. The electroscope and Leyden jar were invented at this time. In the last half of the eighteenth century three men dominated the work on electricity.

Benjamin Franklin (1706–1790), a versatile and rather vivid historical figure, began his scientific work around 1745. He noted that sharp points or edges of highly charged bodies "throw off electrical fire." Franklin developed a fluid theory of electricity similar in philosophy to the caloric theory of heat; a body with too much of this fluid was considered to be positively charged and a deficiency of it resulted in a negatively charged condition. The famous kite and key experiment was performed around 1755.

Henry Cavendish (1731–1810) contributed to electrostatics and chemistry; he is also known for the Cavendish experiment to measure G, the gravitational constant, first done in 1798. Cavendish was a remarkably productive scientist, but he kept most of his discoveries to himself. The extent of his achievements was not appreciated until his notes and manuscripts were finally sorted out and published by Maxwell in 1879. Cavendish found the law relating the force between two charges (independently of Coulomb), conceived the capacitor, was acquainted with the notion of electrical potential, and wrote Ohm's law 50 years before Ohm.

Charles Coulomb (1736–1806) developed the torsion balance and, using it, discovered the force law that bears his name.

2-2 The Twilight of the Classical Period

The nineteenth century was a very busy time. Classical physics reached its peak near the end of this century. So much was learned that it seemed to many people as though man must now have learned all the major physical laws of the Universe.

Mechanics plodded on, still unfolding Newton's inspiration. Hamilton (1805–1865) developed his Hamiltonian formulation that offered as an alternative to the single second-order equation of Lagrange a pair of first-order equations and established momentum as the basic variable in place of velocity. The hydrodynamics of inviscid fluids was developed during this period although many of the refinements in this field awaited the impetus provided by the invention of the airplane.

The conservation of energy is a fundamental concept in physics; however, it was not seriously proposed until around 1850. The reason for this is that energy can assume many forms and although energy conservation was known for elastic mechanics, the caloric theory had so stunted progress in heat and thermodynamics that the equivalence of heat and mechanical work was not recognized until the midnineteenth century.

The first qualitative experiments on the nature of heat were performed in 1798 by Count Rumford (1753–1814), an expatriate American who emigrated to England and thence to Bavaria where he served as a military engineer. Altogether, Rumford was a sort of nineteenth-century Dr. Strangelove. He noted that large amounts of heat were generated in the boring of cannons, too much to be explained in terms of the caloric theory. Rumford also noted that the weight of the finished cannon plus the chips from the boring equaled the weight of the cannon before boring. The specific heat of these chips and that of the original metal was the same. He therefore concluded that heat is not a material substance.

A few years later, Sir Humphery Davy (1778–1829) found that two pieces of ice rubbed together under vacuum melted even though the surrounding walls of the vacuum chamber were maintained at a temperature less than zero degrees Celsius (0°C). There was no way in which the caloric fluid could have entered the ice. For such a farfetched idea, the caloric theory died hard. Even Carnot (1796–1832), in proposing his famous ideal cycle for heat engines in 1824, based it on the caloric theory. A critical quantitative experiment was needed.

Joule (1818–1889) provided the needed key. He carried out a careful series of experiments in England wherein the mechanical energy of a falling mass was efficiently converted into a measurable amount of heat by a paddle wheel rotating in water. He found that 778 foot-pounds (ft-lb) of energy was equivalent to the amount of heat required to raise the temperature of one pound (lb) of water by one degree Fahrenheit (1°F). This result was presented as a paper at the meeting of the British Association for the Advancement of Science in 1847. Lord Kelvin alone of those assembled recognized the implications and his support was largely responsible for the rapid acceptance of Joule's work. Working independently, Helmholtz (1821–1894) read a paper at Berlin (also in 1847) before the Physical Society in which he proposed the general conservation of energy. The paper was rejected for publication by the prestigous journal, *Annalen der Physik*. Within the next few years, however, the mechanical theory of heat triumphed. Progress now became rapid. The second law of thermodynamics was discovered in 1850 by Clausius (1822–1888) and in 1851 in another form by Kelvin (1824–1907).

In the field of light and optics, a strong revival of the wave theory of light was begun by Thomas Young (1773–1829) in his work on interference. Unfortunately the scientific establishment was not yet ready for light waves. Young was attacked and ridiculed by his contemporaries. In 1818, Fresnel (1788–1827) rediscovered the phenomenon of interference. He suggested that the light vibrations in the assumed transmission medium† were transverse rather than longidinal with respect to the wave vector. This was soon verified when polarization phenomena were discovered. In 1850 Foucault (1819–1868) demonstrated experimentally that the velocity of light in water is less than the vacuum value as required by the wave theory and this pretty well clinched the argument.

Electromagnetism was an especially fruitful field of endeavor in the nineteenth century. Galvani (1737 1798) had performed his famous frog leg experiment (the excitation of muscular contraction by an electric current in the leg of a deceased frog) in 1786. He also discovered the so-called galvanic current between dissimilar metals. Volta (1745–1827) made the first wet cell in 1800 using zinc and copper plates separated by blotting paper soaked in brine. He soon found that such cells could be wired in parallel and series batteries to provide a source of considerable power. This was an invaluable contribution to research into electromagnetism since magnetic fields require a current source that was not available prior to Volta's discovery. Volta himself, no doubt following the lead of Galvani and his frog leg, constructed a battery of considerable voltage and placed a wire from it into either ear. He reported a vivid flash and a noise "... like thickly boiling soup ...."

With a current source now available, the arc and the Ohmic heating that takes place in a current-carrying resistor were soon discovered. The Ampere and Biot-Savart laws relating the current and the magnetic field were shortly found and Ampere (1775–1836) discovered the **J** × **B** force that makes electric motors possible. Michael Faraday (1791–1867), the son of a black-

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†The assumed medium in which light waves were transmitted was called the aether, and we shall discuss it more extensively in Chap. 3.

smith, built the first electric motor in the early 1820's. Faraday's best known achievements were in the area of electrical induction. Oersted (1777–1851) had shown earlier that electricity (current) can produce magnetism. Faraday believed that the converse was also true. His search for a steady current in the scheme shown in Fig. 2-1(b) failed. In 1824, Arago (1786–1853) discovered the "drag" due to eddy currents when a conducting disc is moved in to or out of a magnetic field. He found that this drag could be reduced by cutting radial slots into the disc.† Shortly thereafter Faraday discovered that when the primary coil of the apparatus shown in Fig. 2-2 was energized or switched off, the needle of a compass placed close to the secondary circuit was deflected *momentarily*, indicating that a current existed only for a brief time when the switch was opened or closed. Faraday made the association with the Arago

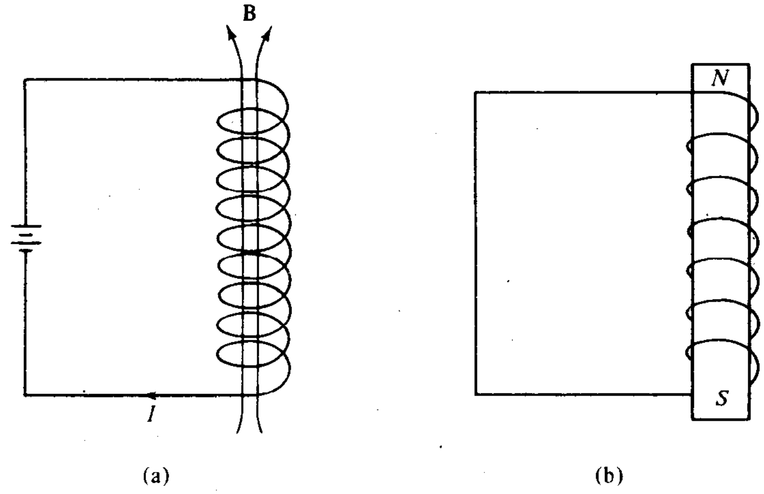

FIGURE 2-1. (a) When a current is passed through a coil, a magnetic field is established in the coil. (b) Faraday reasoned that a magnetic field established in a coil, albeit by a bar magnet, might result in the induction of a current in the circuit. Of course, it did not.

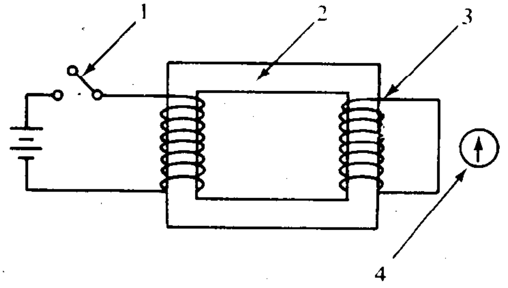

FIGURE 2-2. Faraday induction apparatus. When the switch (1) in the primary circuit is either opened or closed, the change in the magnetic flux through the iron core (2) induces a current in the secondary winding (3) that momentarily causes the compass (4) to deflect.

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†These slots serve to break up the eddy current circulation. Modern transformers use laminated cores in order to avoid the Ohmic losses due to these eddy currents.

experiment and also found that the effect could be realized by inserting or withdrawing the bar magnet from the coil of Fig. 2-1(b). In other words it is not the magnetic field that induces current, it is the *change* in the magnetic field.

Faraday's knowledge of mathematics was minimal. He operated largely on the basis of a very keen physical intuition. It was he who first conceived the concept of field lines and "tubes of Force." The idea of fields is now central to theoretical physics and it was conceived by an experimentalist with no formal education.

Joseph Henry (1799–1878), a contemporary of Faraday's, was an American who taught mathematics at the Albany Academy. His scientific work was performed largely during the one summer month each year when his teaching duties allowed. America at that time had almost no scientific activity (Europe was still the seat of learning), and thus Henry lacked the stimulation that association with other scientists would have given him. Nevertheless, he managed to construct an electric motor and to discover the laws of induction quite on his own. It was the work of Joseph Henry on electromagnets that led Samuel F.B. Morse (1791–1872) to invent the telegraph.

The final figure to be considered in our romp through 2500 years of physics is James Clerk Maxwell (1831–1879). He was born into a wealthy family in Edinburgh. Maxwell graduated summa cum laude from Trinity College at Cambridge in 1854 and had already published a number of papers by the time he was 19 years old. From 1860 to 1865, Maxwell was a professor at King's College, London. It was during this time that he published his "Dynamical Theory of the Electromagnetic Field." In 1870, he moved to Cambridge as professor of experimental physics. In this position he established the Cavendish laboratory and served as its director until his untimely death at age 48. Maxwell did pioneering work in a number of fields. He was interested in the means by which the eye perceives color. His work in kinetic theory, together with that of Clausius, resulted in the comprehensive theory we use today.

It is primarily Maxwell's contribution to the field of electromagnetism that will be of interest to us. The key piece to the puzzle was supplied with Maxwell's proposal of the displacement current. Just as Faraday had shown that changing magnetic fields give rise to electric fields, so Maxwell had been able to demonstrate that changing electric fields give rise to magnetic fields. This latter effect is smaller than the former by a factor of $1/c^2 = \epsilon_0\mu_0$. It is just this symmetry between the magnetic and electric fields that allows the feedback necessary for electromagnetic waves to exist. Maxwell found that these waves travel at the speed of light and that the phenomena of optics (reflection, refraction, etc.) could be derived from the electromagnetic equations. It was obvious that the light waves were part of the electromagnetic spectrum. Maxwell published these results in 1864. Heinrich Hertz (1857–

1894) produced the first nonoptical electromagnetic waves in 1887, using a spark gap and an induction coil. In 1895 Marconi (1874–1937) produced the first wireless telegraphy system; on December 12, 1901, he successfully transmitted the first transatlantic wireless signal.

We find at the close of the nineteenth century that physics had reached a pinnacle of success. Newton's mechanics was unchallenged and had been successfully applied in all cases from the kinetic theory of colliding molecules to the orbital motions of the planets. The wave theory of light had triumphed over the corpuscular theory and had been integrated into the electromagnetic theory. Everything seemed to have fallen nicely into place.

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