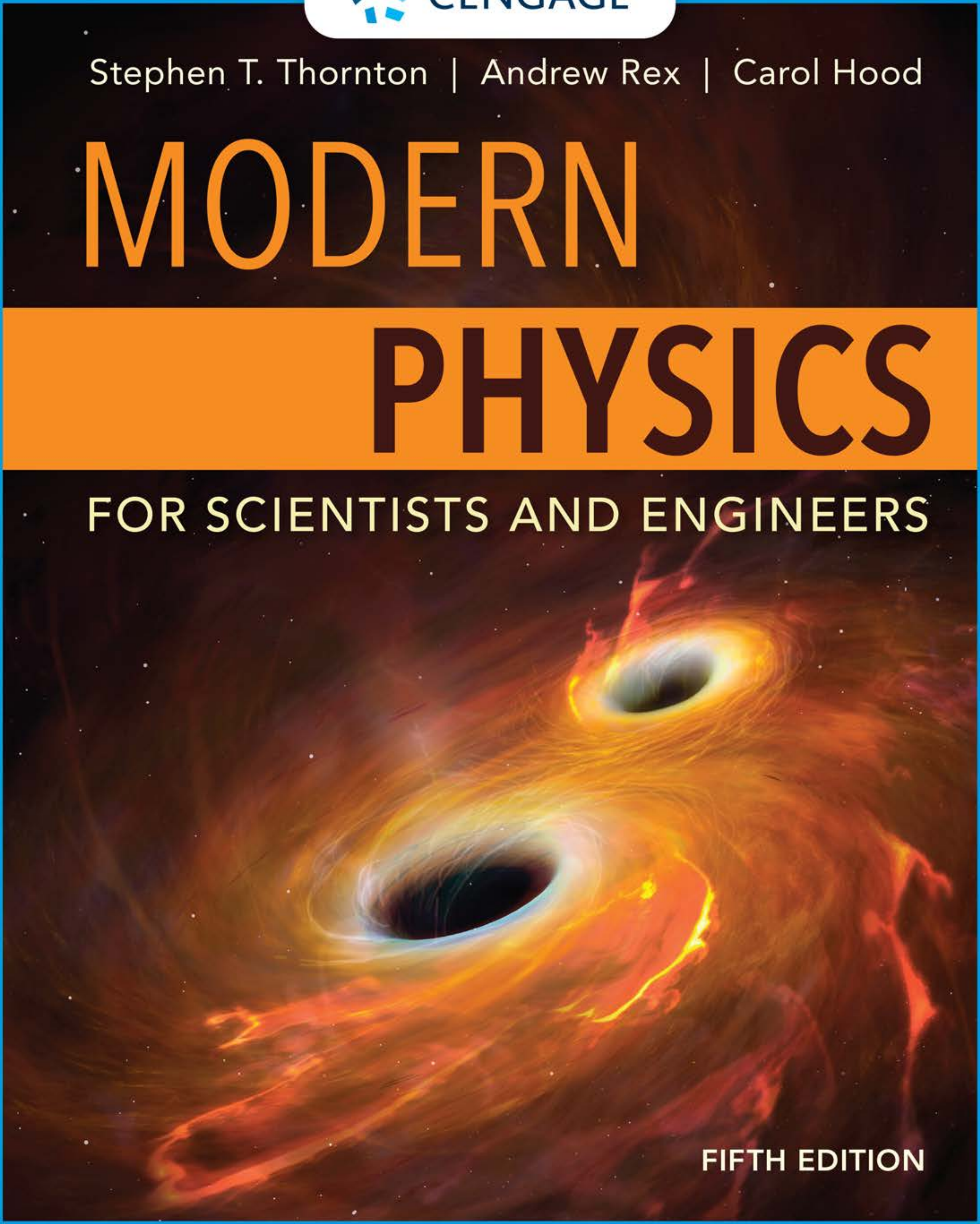
CENGAGE

Stephen T. Thornton | Andrew Rex | Carol Hood

MODERN PHYSICS

FOR SCIENTISTS AND ENGINEERS



FIFTH EDITION

Conversion Factors

$1\,\text{y} = 3.154 \times 10^{7}\,\text{s}$

$1\,\text{lightyear} = 9.461 \times 10^{15}\,\text{m}$

$1\,\text{cal} = 4.184\,\text{J}$

$1\,\text{MeV}/c = 5.344 \times 10^{-22}\,\text{kg} \cdot \text{m/s}$

$1\,\text{eV} = 1.6022 \times 10^{-19}\,\text{J}$

$1\,\text{T} = 10^{4}\,\text{G}$

$1\,\text{Ci} = 3.7 \times 10^{10}\,\text{Bq}$

$1\,\text{barn} = 10^{-28}\,\text{m}^2$

$1\,\text{u} = 1.66054 \times 10^{-27}\,\text{kg}$

Useful Combinations of Constants

$\hbar = h/2\pi = 1.0546 \times 10^{-34}\,\text{J}\cdot\text{s} = 6.5821 \times 10^{-16}\,\text{eV}\cdot\text{s}$

$hc = 1.9864 \times 10^{-25}\,\text{J}\cdot\text{m} = 1239.8\,\text{eV}\cdot\text{nm}$

$\hbar c = 3.1615 \times 10^{-26}\,\text{J}\cdot\text{m} = 197.33\,\text{eV}\cdot\text{nm}$

$$\frac{1}{4\pi\varepsilon_0} = 8.9876 \times 10^{9}\,\text{N}\cdot\text{m}^2\cdot\text{C}^{-2}$$

Compton wavelength $\lambda_C = \dfrac{h}{m_e c} = 2.4263 \times 10^{-12}\,\text{m}$

$$\frac{e^2}{4\pi\varepsilon_0} = 2.3071 \times 10^{-28}\,\text{J}\cdot\text{m} = 1.4400 \times 10^{-9}\,\text{eV}\cdot\text{m}$$

Fine structure constant $\alpha = \dfrac{e^2}{4\pi\varepsilon_0 \hbar c} = 0.0072974 \approx \dfrac{1}{137}$

Bohr magneton $\mu_B = \dfrac{e\hbar}{2m_e} = 9.2740 \times 10^{-24}\,\text{J/T} = 5.7884 \times 10^{-5}\,\text{eV/T}$

Nuclear magneton $\mu_N = \dfrac{e\hbar}{2m_p} = 5.0508 \times 10^{-27}\,\text{J/T} = 3.1525 \times 10^{-8}\,\text{eV/T}$

Bohr radius $a_0 = \dfrac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} = 5.2918 \times 10^{-11}\,\text{m}$

Hydrogen ground state $E_0 = \dfrac{e^2}{8\pi\varepsilon_0 a_0} = 13.606\,\text{eV} = 2.1799 \times 10^{-18}\,\text{J}$

Rydberg constant $R_\infty = \dfrac{\alpha^2 m_e c}{2h} = 1.09737 \times 10^{7}\,\text{m}^{-1}$

Hydrogen Rydberg $R_H = 1.09678 \times 10^{7}\,\text{m}^{-1}$

Gas constant $R = N_A k = 8.3145\,\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$

Magnetic flux quantum $\Phi_0 = \dfrac{h}{2e} = 2.0678 \times 10^{-15}\,\text{T}\cdot\text{m}^2$

Classical electron radius $r_e = \alpha^2 a_0 = 2.8179 \times 10^{-15}\,\text{m}$

$kT = 2.5249 \times 10^{-2}\,\text{eV} \approx \dfrac{1}{40}\,\text{eV at } T = 293\,\text{K}$

Note: The latest values of the fundamental constants can be found at the National Institute of Standards and Technology website at http://physics.nist.gov/cuu/Constants/index.html.

Modern Physics

For Scientists and Engineers

Fifth Edition

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CENGAGE

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CENGAGE

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Fifth Edition
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Preface

Our objective in writing this book was to produce a textbook for a modern physics course of either one or two semesters for physics and engineering students. Such a course normally follows a full-year, calculus-based introductory physics course for first-year or second-year students. Before each edition we have the publisher send a questionnaire to users of modern physics books to see what needed to be changed or added. Most users like our textbook as is, especially the complete coverage of topics such as the early quantum theory, subfields of physics, general relativity, and cosmology/astrophysics. Our book continues to be useful for either a one- or two-term modern physics course. We have reordered and expanded the topics in the final two chapters, but have not made any other major changes in the order of subjects in the fifth edition.

Coverage

The first edition of our text established a trend for a contemporary approach to the exciting, thriving, and changing field of modern science. After briefly visiting the status of physics at the turn of the last century, we cover relativity and quantum theory, the basis of any study of modern physics. Almost all areas of science depend on quantum theory and the methods of experimental physics. We have included the name Quantum Mechanics in two of our chapter titles (Chapters 5 and 6) to emphasize the quantum connection. The latter part of the book is devoted to the subfields of physics (atomic, condensed matter, nuclear, and particle) and the exciting fields of cosmology and astrophysics. Our experience is that science and engineering majors particularly enjoy the study of modern physics after the sometimes-laborious study of classical mechanics, thermodynamics, electricity, magnetism, and optics. The level of mathematics is not difficult for the most part, and students feel they are finally getting to the frontiers of physics. We have brought the study of modern physics alive by presenting many current applications and challenges in physics, for example, nanoscience, high-temperature superconductors, quantum teleportation, neutrino mass and oscillations, gravitational waves, missing dark mass and energy in the universe, gamma-ray bursts, holography, quantum dots, and nuclear fusion. Modern physics texts need to be updated periodically to include recent advances. Although we have emphasized modern applications, we also provide the sound theoretical basis for quantum theory that will be needed by physics majors in their upper division and graduate courses.

Changes for the Fifth Edition

Our book continues to be the most complete and up-to-date textbook in the modern physics market for sophomores/juniors. We have made several changes for the fifth edition to aid the student in learning modern physics.

The important contributions to physics of more female scientists, including Emmy Noether, Rosalyn Yalow, Annie Jump Cannon, and Henrietta Leavitt, have been added, as well as the contributions of the female computers at the Harvard Observatory and NASA.

Additional short biographical features highlight the achievements of physicists throughout history to illustrate the importance of individual ingenuity in advancing knowledge in the field. Similarly, throughout the text, a focus on the history of physics offers a human perspective and helps students understand the context in which scientific advancements have been made.

The discussion on gravitational waves has been greatly expanded to include the recent detections and subsequent electromagnetic detections and the discussions on dark matter and dark energy have been updated to include the most up-to-date observations and theories.

The latest information on the Higgs boson brings students up-to-date on this significant research area of physics research and theory.

The latest research and updated information about the age of the universe has been added.

Chapter 15, "Modern Astrophysics and General Relativity" and Chapter 16, "Cosmology," have been rewritten to reflect the latest research and findings and expose students to this rapidly changing body of knowledge.

Special Topic boxes are up-to-date applications of interest to physicists and engineers. These features show the relevance of modern physics to the real world and allow students a more in-depth look at particularly engaging topics like exoplanets, the "age of the Earth," neutrino detection, and scanning probe microscopes.

Finally, end-of-chapter summaries will give students a quick overview of topics covered in the chapter.

Teaching Suggestions

The text has been used extensively in its first four editions in courses at our home institutions. These include a one-semester course for physics and engineering students at the University of Virginia, a two-semester course for physics and pre-engineering students at the University of Puget Sound, and a one-quarter course at California State University, San Bernardino. These are representative of the one- and two-term modern physics courses taught elsewhere. Both one- and two-term courses should cover the material through the establishment of the periodic table in Chapter 8 with few exceptions. We have eliminated the denoting of optional sections, because we believe that depends on the wishes of the instructor, but we feel Sections 2.4, 4.2, 6.4, 6.6, 7.2, 7.6, 8.2, and 8.3 from the first nine chapters may be skipped without loss of continuity. Our suggestions for the one- and two-term courses (3 or 4 credit hours per term) are then

One-term: Chapters 1–9 and selected other material as chosen by the instructor

Two-term: Chapters 1–16 with supplementary material as desired, with possible student projects

Features

End-of-Chapter Problems

Digital versions of thought-provoking end-of-chapter questions are available to assign via WebAssign in a number of formats. The large repository of problems is now further enhanced in this edition with WebAssign-only enhanced content created by Marllin Simon and Matthew Kohlmyer. The wide variety of questions allows any instructor to make different homework assignments year after year without having to repeat problems. For those users of the earlier fourth edition a correlation guide is available via online instructor resources.

Solutions Manuals

PDF files of the *Instructor's Solutions Manual* are available to the instructor on the *Instructor's Resource Center website* (or by contacting your Cengage sales representative). This manual contains the *solutions to the printed end-of-chapter problems* and has been checked by at least two physics professors. The answers to selected odd-numbered problems are given at the end of the textbook itself.

Examples

These examples are written and presented in the manner in which students are expected to work the end-of-chapter problems: that is, to develop a conceptual understanding and strategy before attempting a numerical solution. Problem solving does not come easily for most students, especially the problems requiring several steps (that is, not simply plugging numbers into one equation). We expect that the many text examples with varying degrees of difficulty will help students.

Special Topic Boxes

Users have encouraged us to keep the Special Topic boxes. We believe both students and professors find them interesting, because they add insight and detail into the excitement of physics. We have updated the material to keep them current.

History

We include historical aspects of modern physics that many students will find interesting and that others can simply ignore. We continue to include photos and biographies of scientists who have made significant contributions to modern physics. We believe this helps to enliven and humanize the material.

Acknowledgments

We acknowledge the assistance of many persons who have helped with this text. There are too many that helped us with the first four editions to list here, but the book would not have been possible without them. We acknowledge the professional staff at Cengage who helped make this fifth edition a useful, popular, and attractive textbook. They include Product Managers Nate Thibeault and Spencer Arritt, Learning Designer Michael Jacobs, Subject Matter Expert Matthew Kohlmyer, Content Manager Michael Lepera, and Product Assistants Kyra Kruger and Tim Biddick. We acknowledge the tremendous help given to us by Lori Hazzard and her colleagues from MPS Limited for their production of this fifth edition.

Prior to and during our work on this fifth edition, we conducted a survey of instructors about the modern physics course in general and our book in particular. We received many insightful comments, and we would like to thank the following for their feedback and suggestions:

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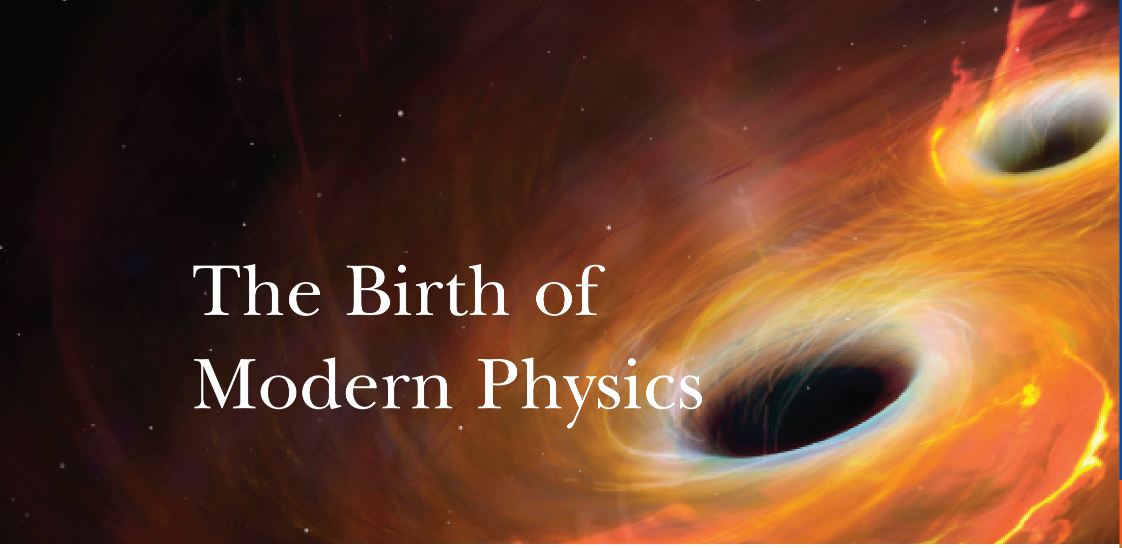
CHAPTER

1

The Birth of Modern Physics



> *The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. … Our future discoveries must be looked for in the sixth place of decimals.*
>
> ***Albert A. Michelson, 1894***

> *There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.*
>
> ***William Thomson (Lord Kelvin), 1900***

Although the Greek scholars Aristotle and Eratosthenes performed measurements and calculations that today we would call physics, the discipline of physics has its roots in the work of Galileo and Newton and others in the scientific revolution of the sixteenth and seventeenth centuries. The knowledge and practice of physics grew steadily for 200 to 300 years until another revolution in physics took place, which is the subject of this book. Physicists distinguish *classical physics*, which was mostly developed before 1895, from *modern physics*, which is based on discoveries made after 1895. The precise year is unimportant, but monumental changes occurred in physics around 1900.

In this chapter we briefly review the status of physics around 1895, including Newton's laws, Maxwell's equations, and the laws of thermodynamics. These results are just as important today as they were over a hundred years ago. Arguments by scientists concerning the interpretation of experimental data using wave and particle descriptions that seemed to have been resolved 200 years ago were reopened in the twentieth century. Today we look back on the evidence of the late nineteenth century and wonder how anyone could have doubted the validity of the atomic view of matter. The fundamental interactions of gravity, electricity, and magnetism were thought to be well understood in 1895. Physicists continued to be driven by the goal of understanding fundamental laws throughout the twentieth century. This is demonstrated by the fact that other fundamental forces (specifically the nuclear and weak interactions) have been added, and in some cases—curious as it may seem—various forces have even been combined. The search for the holy grail of fundamental interactions continues unabated today.

We finish this chapter with a status report on physics just before 1900. The few problems not then understood would be the basis for decades of fruitful investigations and discoveries continuing into the twenty-first century.

1.1 Classical Physics of the 1890s

Scientists and engineers of the late nineteenth century were indeed rather smug. They thought they had just about everything under control (see the quotes from Michelson and Kelvin at the beginning of the chapter). The best scientists of the day were highly recognized and rewarded. Public lectures were frequent. Some scientists had easy access to their political leaders, partly because science and engineering had benefited their war machines, but also because of the many useful technological advances. Basic research was recognized as important because of the commercial and military applications of scientific discoveries. Although there were only primitive automobiles and no airplanes in 1895, advances in these modes of transportation were soon to follow. A few people already had telephones, and plans for widespread distribution of electricity were under way.

Based on their success with what we now call macroscopic classical results, scientists felt that given enough time and resources, they could explain just about anything. They did recognize some difficult questions they still couldn't answer; for example, they didn't clearly understand the structure of matter—that was under intensive investigation. Nevertheless, on a macroscopic scale, they knew how to build efficient engines. Ships plied the lakes, seas, and oceans of the world. Travel between the countries of Europe was frequent and easy by train. Many scientists were born in one country, educated in one or two others, and eventually worked in still other countries. The most recent ideas traveled relatively quickly among the centers of research. Except for some isolated scientists, of whom Einstein is the most notable example, discoveries were quickly and easily shared. Scientific journals were becoming accessible.

The ideas of classical physics are just as important and useful today as they were at the end of the nineteenth century. For example, they allow us to build automobiles and produce electricity. The conservation laws of energy, linear momentum, angular momentum, and charge can be stated as follows:

Classical conservation laws

Conservation of energy: The total sum of energy (in all its forms) is conserved in all interactions.

Conservation of linear momentum: In the absence of external forces, linear momentum is conserved in all interactions (vector relation).

Conservation of angular momentum: In the absence of external torque, angular momentum is conserved in all interactions (vector relation).

Conservation of charge: Electric charge is conserved in all interactions.

A nineteenth-century scientist might have added the **conservation of mass** to this list, but we know it not to be valid today (you will find out why in Chapter 2). These conservation laws are reflected in the laws of mechanics, electromagnetism, and thermodynamics. Electricity and magnetism, separate subjects for hundreds of years, were combined by James Clerk Maxwell (1831–1879) in his four equations. Maxwell showed optics to be a special case of electromagnetism. Waves, which permeated mechanics and optics, were known to be an important component of nature. Many natural phenomena could be explained by wave motion using the laws of physics.

Mechanics

The laws of mechanics were developed over hundreds of years by many researchers. Important contributions were made by astronomers because of the great interest in the heavenly bodies. Galileo (1564–1642) may rightfully be called the first great experimenter. His experiments and observations laid the groundwork for the important discoveries to follow during the next 200 years.

Isaac Newton (1642–1727) was certainly the greatest scientist of his time and one of the best the world has ever seen. His discoveries were in the fields of mathematics, astronomy, and physics and include gravitation, optics, motion, and forces.

We owe to Newton our present understanding of motion. He understood clearly the relationships among position, displacement, velocity, and acceleration. He understood how motion was possible and that a body at rest was just a special case of a body having constant velocity. It may not be so apparent to us today, but we should not forget the tremendous unification that Newton made when he pointed out that the motions of the planets about our sun can be understood by the same laws that explain motion on Earth, like apples falling from trees or a soccer ball being kicked toward a goal. Newton was able to elucidate carefully the relationship between net force and acceleration, and his concepts were stated in three laws that bear his name today:

Newton's laws

Newton's first law: *An object in motion with a constant velocity will continue in motion unless acted upon by some net external force.* A body at rest is just a special case of Newton's first law with zero velocity. Newton's first law is often called the *law of inertia* and is also used to describe inertial reference frames.

Newton's second law: *The acceleration* $\vec{a}$ *of a body is proportional to the net external force* $\vec{F}$ *and inversely proportional to the mass* m *of the body. It is stated mathematically as*

$$\vec{F} = m\vec{a} \tag{1.1a}$$

Science History Images/Alamy Stock Photo

Galileo Galilei (1564–1642) was born, educated, and worked in Italy. Often said to be the "father of physics" because of his careful experimentation, he is shown here performing experiments by rolling balls on an inclined plane. He is perhaps best known for his experiments on motion, the development of the telescope, and his many astronomical discoveries. He came into disfavor with the Catholic Church for his belief in the Copernican theory. He was finally cleared of heresy by Pope John Paul II in 1992, 350 years after his death.

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Isaac Newton (1642–1727), the great English physicist and mathematician, did most of his work at Cambridge where he was educated and became the Lucasian Professor of Mathematics. He was known not only for his work on the laws of motion but also as a founder of optics. His useful works are too numerous to list here, but it should be mentioned that he spent a considerable amount of his time on alchemy, theology, and the spiritual universe. His writings on these subjects, which were dear to him, were quite unorthodox. This painting shows him performing experiments with light.

A more general statement* relates force to the time rate of change of the linear momentum $\vec{p}$.

$$\vec{F} = \frac{d\vec{p}}{dt} \tag{1.1b}$$

Newton's third law: *The force exerted by body 1 on body 2 is equal in magnitude and opposite in direction to the force that body 2 exerts on body 1.* If the force on body 2 by body 1 is denoted by $\vec{F}_{21}$, then Newton's third law is written as

$$\vec{F}_{21} = -\vec{F}_{12} \tag{1.2}$$

It is often called the *law of action and reaction.*

These three laws develop the concept of force. Using that concept together with the concepts of velocity $\vec{v}$, acceleration $\vec{a}$, linear momentum $\vec{p}$, rotation (angular velocity $\vec{\omega}$ and angular acceleration $\vec{\alpha}$), and angular momentum $\vec{L}$, we can describe the complex motion of bodies.

Electromagnetism

Electromagnetism developed over a long period of time. Important contributions were made by Charles Coulomb (1736–1806), Hans Christian Oersted (1777–1851), Thomas Young (1773–1829), André Ampère (1775–1836), Michael Faraday (1791–1867), Joseph Henry (1797–1878), James Clerk Maxwell (1831–1879), and Heinrich Hertz (1857–1894). Maxwell showed that electricity and magnetism were intimately connected and were related by a change in the inertial frame of reference. His work also led to the understanding of electromagnetic radiation, of which light and optics are special cases. Maxwell's four equations [Equations (1.3–1.6)], together with the Lorentz force law [Equation (1.7)], explain much of electromagnetism.

Maxwell's equations

Gauss's law for electricity
$$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\epsilon_0} \tag{1.3}$$

Gauss's law for magnetism
$$\oint \vec{B} \cdot d\vec{A} = 0 \tag{1.4}$$

Faraday's law
$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt} \tag{1.5}$$

Generalized Ampere's law
$$\oint \vec{B} \cdot d\vec{s} = \mu_0\epsilon_0 \frac{d\Phi_E}{dt} + \mu_0 I \tag{1.6}$$

Lorentz force law

Lorentz force law
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \tag{1.7}$$

Maxwell's equations indicate that charges and currents create electric and magnetic fields, and in turn, these fields can create other fields, both electric and magnetic.

---

*It is a remarkable fact that Newton wrote his second law not as $\vec{F} = m\vec{a}$, but as $\vec{F} = d(m\vec{v})/dt$, focusing on what we now call momentum. This has applications in both fluid mechanics and rocket propulsion.

Thermodynamics

Thermodynamics deals with temperature T, heat Q, work W, and the internal energy of systems U. The understanding of the concepts used in thermodynamics—such as pressure P, volume V, temperature, thermal equilibrium, heat, entropy, and especially energy—was slow in coming. We can understand the concepts of pressure and volume as mechanical properties, but the concept of temperature must be carefully considered. The internal energy of a system of noninteracting point masses depends only on the temperature.

Important contributions to thermodynamics were made by Benjamin Thompson (Count Rumford, 1753–1814), Sadi Carnot (1796–1832), James Joule (1818–1889), Rudolf Clausius (1822–1888), and William Thomson (Lord Kelvin, 1824–1907). The primary results of thermodynamics can be described in two laws:

Laws of thermodynamics

First law of thermodynamics: *The change in the internal energy ΔU of a system is equal to the heat Q added to the system plus the work W done on the system.*

$$\Delta U = Q + W \tag{1.8}$$

The first law of thermodynamics generalizes the conservation of energy by including heat.

Second law of thermodynamics: *It is not possible to convert heat completely into work without some other change taking place.* Equivalent forms of the second law may appear different, but instead describe what kinds of energy processes can or cannot take place. For example, it is not possible to build a perfect engine or a perfect refrigerator. It is not possible to build a perpetual motion machine. Heat does not spontaneously flow from a colder body to a hotter body without some other change taking place. The second law forbids all these from happening.

Two other laws of thermodynamics are sometimes expressed. One is called the zeroth law, and it is useful in understanding temperature. It states that *if two thermal systems are in thermodynamic equilibrium with a third system, they are in equilibrium with each other.* We can state it more simply by saying that *two systems at the same temperature as a third system have the same temperature as each other.* This concept was not explicitly stated until the twentieth century. The third law of thermodynamics expresses that *it is not possible to achieve an absolute zero temperature.*

1.2 The Kinetic Theory of Gases

We understand now that gases are composed of atoms and molecules in rapid motion, bouncing off each other and the container walls, but in the 1890s this had just gained acceptance. The kinetic theory of gases is related to thermodynamics and to the atomic theory of matter, which we discuss in Section 1.5. Experiments were relatively easy to perform on gases, and the Irish chemist Robert Boyle (1627–1691) showed around 1662 that the pressure times the volume of a gas was constant for a constant temperature. The relation $PV =$ constant (for constant T) is now referred to as *Boyle's law*. The French physicist Jacques Charles (1746–1823) found that $V/T =$ constant (at constant pressure), referred to as *Charles's law.* Joseph Louis Gay-Lussac (1778–1850) later produced the same result, and the law is sometimes associated with his name. If we combine these two laws, we obtain the ideal gas equation,

Ideal gas equation

$$PV = nRT \tag{1.9}$$

where n is the number of moles and R is the ideal gas constant, 8.31 J/mol·K. The ideal gas equation is also written as $PV = NkT$, where N is the number of molecules and k is Boltzmann's constant.

In 1811 the Italian physicist Amedeo Avogadro (1776–1856) proposed that equal volumes of gases at the same temperature and pressure contained equal numbers of molecules. This hypothesis was so far ahead of its time that it was not accepted for many years. The famous English chemist John Dalton opposed the idea because he apparently misunderstood the difference between atoms and molecules. Considering the rudimentary nature of the atomic theory of matter at the time, this was not surprising.

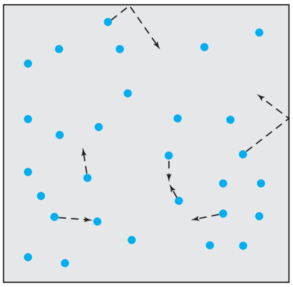


Figure 1.1 Molecules inside a closed container are shown colliding with the walls and with each other. The motions of a few molecules are indicated by the arrows.

Daniel Bernoulli (1700–1782) apparently originated the kinetic theory of gases in 1738, but his results were generally ignored. Many scientists, including Newton, Laplace, Davy, Herapath, and Waterston, had contributed to the development of kinetic theory by 1850. Theoretical calculations were being compared with experiments, and by 1895 the kinetic theory of gases was widely accepted. The statistical interpretation of thermodynamics was made in the latter half of the nineteenth century by Maxwell, the Austrian physicist Ludwig Boltzmann (1844–1906), and the American physicist J. Willard Gibbs (1839–1903).

In introductory physics classes, the kinetic theory of gases is usually taught by applying Newton's laws to the collisions that a molecule makes with other molecules and with the walls. A representation of a few molecules colliding is shown in Figure 1.1. In the simple model of an ideal gas, only elastic collisions are considered. By taking averages over the collisions of many molecules, the ideal gas law, Equation (1.9), is revealed. The average kinetic energy of the molecules is shown to be linearly proportional to the temperature, and the internal energy U is

Statistical thermodynamics

$$U = nN_A\overline{K} = \frac{3}{2}nRT \tag{1.10}$$

where n is the number of moles of gas, N_A is Avogadro's number, $\overline{K}$ is the average kinetic energy of a molecule, and R is the ideal gas constant. This relation ignores any nontranslational contributions to the molecular energy, such as rotations and vibrations.

Equipartition theorem

However, energy is not represented only by translational motion. It became clear that all *degrees of freedom*, including rotational and vibrational, were also capable of carrying energy. The *equipartition theorem* states that each degree of freedom of a molecule has an average energy of $kT/2$, where k is the Boltzmann constant ($k = R/N_A$). Translational motion has three degrees of freedom, and rotational and vibrational modes can also be excited at higher temperatures. If there are f degrees of freedom, then Equation (1.10) becomes

Internal energy

$$U = \frac{f}{2}nRT \tag{1.11}$$

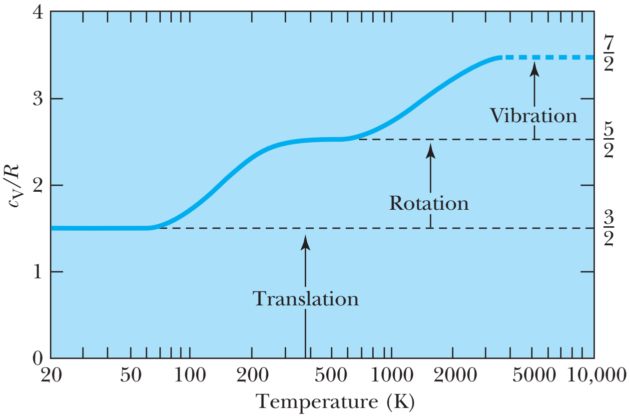


Figure 1.2 The molar heat capacity at constant volume (c_V) divided by R (c_V/R is dimensionless) is displayed as a function of temperature for molecular hydrogen gas. Note that as the temperature increases, the rotational and vibrational modes become important. This experimental result is consistent with the equipartition theorem, which adds $kT/2$ of energy per molecule ($RT/2$ per mole) for each degree of freedom.

The molar ($n = 1$) heat capacity c_V at constant volume for an ideal gas is the rate of change in internal energy with respect to change in temperature and is given by

$$c_V = \frac{fR}{2} \tag{1.12}$$

Heat capacity

The experimental quantity c_V/R is plotted versus temperature for molecular hydrogen in Figure 1.2. The ratio c_V/R is equal to 3/2 for low temperatures, where only translational kinetic energy is important, but it rises to 5/2 at 300 K, where rotations occur for H_2, and finally reaches 7/2, because of vibrations at still higher temperatures, before the H_2 molecule dissociates.

In the 1850s Maxwell derived a relation for the distribution of speeds of the molecules in gases. The distribution of speeds $f(v)$ is given as a function of the speed and the temperature by the equation

$$f(v) = 4\pi N\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 e^{-mv^2/2kT} \tag{1.13}$$

Maxwell's speed distribution

where m is the mass of a molecule and T is the temperature. This result is plotted for nitrogen in Figure 1.3 for temperatures of 300 K, 1000 K, and 4000 K. The

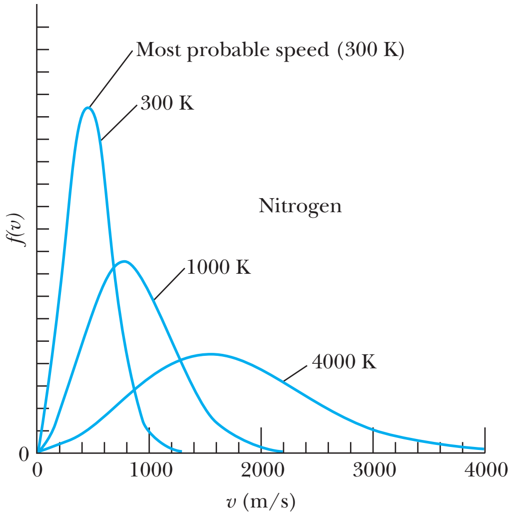


Figure 1.3 The Maxwell distribution of molecular speeds (for nitrogen), $f(v)$, is shown as a function of speed for three temperatures.

peak of each distribution is the most probable speed of a gas molecule for the given temperature. In 1895 measurement was not precise enough to confirm Maxwell's distribution, and it was not confirmed experimentally until 1921.

By 1895 Boltzmann had made Maxwell's calculation more rigorous, and the general relation is called the *Maxwell–Boltzmann distribution*. The distribution can be used to find the *root-mean-square* speed v_{rms},

$$v_{\text{rms}} = \sqrt{\overline{v^2}} = \sqrt{\frac{3kT}{m}} \tag{1.14}$$

which shows the relationship of the energy to the temperature for a monatomic ideal gas:

$$U = nN_A\overline{K} = nN_A\frac{m\overline{v^2}}{2} = nN_A\frac{3mkT}{2m} = \frac{3}{2}nRT \tag{1.15}$$

This was the result of Equation (1.10).

1.3 Waves and Particles

We first learned the concepts of velocity, acceleration, force, momentum, and energy in introductory physics by using a single particle with its mass concentrated in one small point. In order to adequately describe nature, we add two- and three-dimensional bodies and rotations and vibrations. However, many aspects of physics can still be treated as if the bodies are simple particles. In particular, the kinetic energy of a moving particle is one way that energy can be transported from one place to another.

But we have found that many natural phenomena can be explained only in terms of *waves*, which are traveling disturbances that carry energy. This description includes standing waves, which are superpositions of traveling waves. Most waves, like water waves and sound waves, need an elastic medium in which to move. Curiously enough, matter is not transported in waves—but energy is. Mass may oscillate, but it doesn't actually propagate along with the wave. Two examples are a cork and a boat on water. As a water wave passes, the cork gains energy as it moves up and down, and after the wave passes, the cork remains. The boat also reacts to the wave, but it primarily rocks back and forth, throwing around things that are not fixed on the boat. The boat obtains considerable kinetic energy from the wave.

Waves and particles were the subject of disagreement as early as the seventeenth century, when there were two competing theories of the nature of light. Newton supported the idea that light consisted of corpuscles (or particles). He performed extensive experiments on light for many years and finally published his book *Opticks* in 1704. *Geometrical optics* uses straight-line, particle-like trajectories called *rays* to explain familiar phenomena such as reflection and refraction. Geometrical optics was also able to explain the apparent observation of sharp shadows. The competing theory considered light as a wave phenomenon. Its strongest proponent was the Dutch physicist Christian Huygens (1629–1695), who presented his theory in 1678. The wave theory could also explain reflection and refraction, but it could not explain the sharp shadows observed. Experimental physics of the 1600s and 1700s was not able to discern between the two competing theories. Huygens's poor health and other duties kept him from working on optics much after 1678. Although Newton did not feel strongly about his corpuscular theory, the magnitude of his reputation caused it to be almost universally accepted for more than a hundred years and throughout most of the eighteenth century.

Finally, in 1802, the English physician Thomas Young (1773–1829) announced the results of his two-slit interference experiment, indicating that light behaved as a wave. Even after this singular event, the corpuscular theory had its supporters. During the next few years Young and, independently, Augustin Fresnel (1788–1827) performed several experiments that clearly showed that light behaved as a wave. By 1830 most physicists believed in the wave theory—some 150 years after Newton performed his first experiments on light.

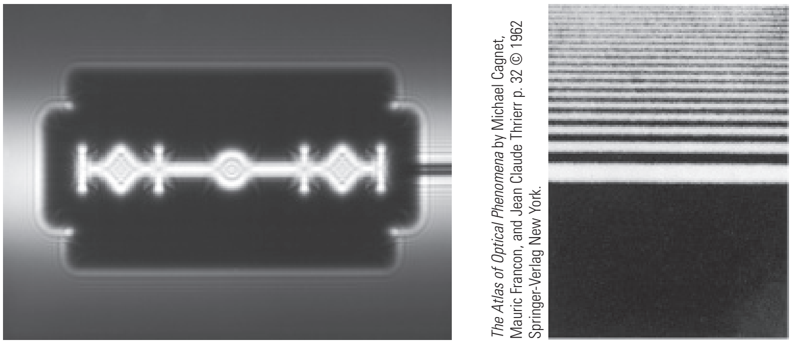
One final experiment indicated that the corpuscular theory was difficult to accept. Let c be the speed of light in vacuum and v be the speed of light in another medium. If light behaves as a particle, then to explain refraction, light must speed up when going through denser material ($v > c$). The wave theory of Huygens predicts just the opposite ($v < c$). The measurements of the speed of light in various media were slowly improving, and finally, in 1850, Léon Foucault showed that *light traveled more slowly in water than in air.* The corpuscular theory seemed incorrect. Newton would probably have been surprised that his weakly held beliefs lasted as long as they did. Now we realize that geometrical optics is correct only if the wavelength of light is much smaller than the size of the obstacles and apertures that the light encounters.

Figure 1.4 shows the "shadows" or *diffraction patterns* from light falling on sharp edges. In Figure 1.4a the alternating black and white lines can be seen all around the razor blade's edges. Figure 1.4b is a highly magnified photo of the diffraction from a sharp edge. The bright and dark regions can be understood only if light is a wave and not a particle.

In the 1860s Maxwell showed that electromagnetic waves consist of oscillating electric and magnetic fields. Visible light covers just a narrow range of the total electromagnetic spectrum, and all electromagnetic radiation travels at the speed of light c in free space, given by

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \lambda f \tag{1.16}$$

where λ is the wavelength and f is the frequency. The fundamental constants μ_0 and ϵ_0 are defined in electricity and magnetism and reveal the connection to the speed of light. In 1887 the German physicist Heinrich Hertz (1857–1894) succeeded in generating and detecting electromagnetic waves having wavelengths


(a) (b)

Courtesy Ken Kay/Fundamental Photographs New York

The Atlas of Optical Phenomena by Michael Cagnet, Mauric Francon, and Jean Claude Thrierr p. 32 © 1962 Springer-Verlag New York.

Figure 1.4 In contradiction to what scientists thought in the seventeenth century, shadows are not sharp, but show dramatic diffraction patterns—as seen here (a) for a razor blade and (b) for a highly magnified sharp edge.