

## CHAPTER 1

# Introduction: Important Concepts and Techniques

*Is space infinite, and in what sense? Is the material world infinite in extent, and are all places within that extent equally full of matter? Do atoms exist, or is matter infinitely divisible? The discussion of questions of this kind has been going on ever since men began to reason, and to each of us, as soon as we obtain the use of our faculties, the same old questions arise as fresh as ever.*

*James Clerk Maxwell (1831–1879)*

During college you will study many subjects—literature, history, psychology, mathematics, music, biology, art, computer science, physics, philosophy. Each of these disciplines has its own subject matter and its own approach to reality, and each will make an important contribution to your knowledge of the world. In this chapter we first define the scope and approach of one such discipline—physics. This is but an introduction, however; the nature of physics will gradually become clearer to you as you make progress through this course.

After this brief introduction, we proceed immediately to a discussion of some basic concepts used throughout the remainder of the course—units, dimensions, scalars, and vectors—and to the mathematical techniques needed to handle these quantities.

## 1.1 The Scope of Physics

Physics, the oldest and most basic of the sciences, is *the science of matter and energy and of the relations between them*. Because it is a science, physics is built on observation and experiment, and its theories and laws must stand the test of continuing comparison with the results of observation and experiment.

The domain of physics includes *matter* in all its forms—solids, liquids, gases, plasmas, molecules, atoms, and the particles out of which atoms are made. It also includes *energy* in all its forms—mechanical, electromagnetic, nuclear, thermal, and radiant energy. Physicists attempt to understand these different kinds of matter and energy that constitute the universe. Some physicists are interested in the particles inside the protons and neutrons that make up the nuclei of all atoms; others do research on the radiation produced in the “big bang” that began our universe, and have succeeded in detecting the remnants of this radiation almost 20 billion years after it was produced. Physicists firmly believe that the principles of physics are the same now as they were 20 billion years ago and that by uncovering these principles we will learn more about the early history of our universe.



Although the forms of matter and energy are many, the basic principles that govern their interactions are few. In this book we will emphasize the basic principles of physics, particularly the principle of conservation of energy. We will first apply these principles to the fields of mechanics, sound, heat, light, electricity, and magnetism. Then we will discuss the revolution produced in this century by Einstein's theory of relativity and by Planck, Bohr, and their followers in the development of the quantum mechanics of atomic systems. Finally, we will discuss briefly new developments in solid-state physics and elementary-particle physics, the fields of greatest research activity in physics today.

The concerns of physics are not remote from everyday life; all branches of engineering are based on the fundamental principles of physics, and our planes fly and our cars run because of the laws of physics. Physicists also continue to make important contributions to fields like biology and medicine by developing sensitive instruments of great utility such as the electron microscope and the CAT scanner. Some eminent biologists like Francis Crick, one of the developers of the Watson-Crick double-helix theory of DNA, and Rosalyn Yalow (Fig. 1.1), winner of the 1977 Nobel Prize for medicine, were trained as physicists and used the techniques of physics in their research.

## 1.2 The Approach of the Physicist

Physics is one of the so-called hard sciences, not because it is difficult but because it is based on hard, quantitative data and makes predictions in quantitative (i.e., numerical) form. These predictions can then be checked against measurements made in the laboratory. (In the so-called soft sciences such as psychology and sociology, human behavior plays a crucial role, and so the precision that is characteristic of physics is unattainable.) The physicist is able to extract quantitative data from nature only by focusing on the purely physical and quantitative aspects of a problem to the exclusion of other considerations. This fundamental and in some ways oversimplified approach does not take into account the interaction of physical processes with the economy, political events, or the quality of human life but concentrates on matter and energy and their interrelationships.

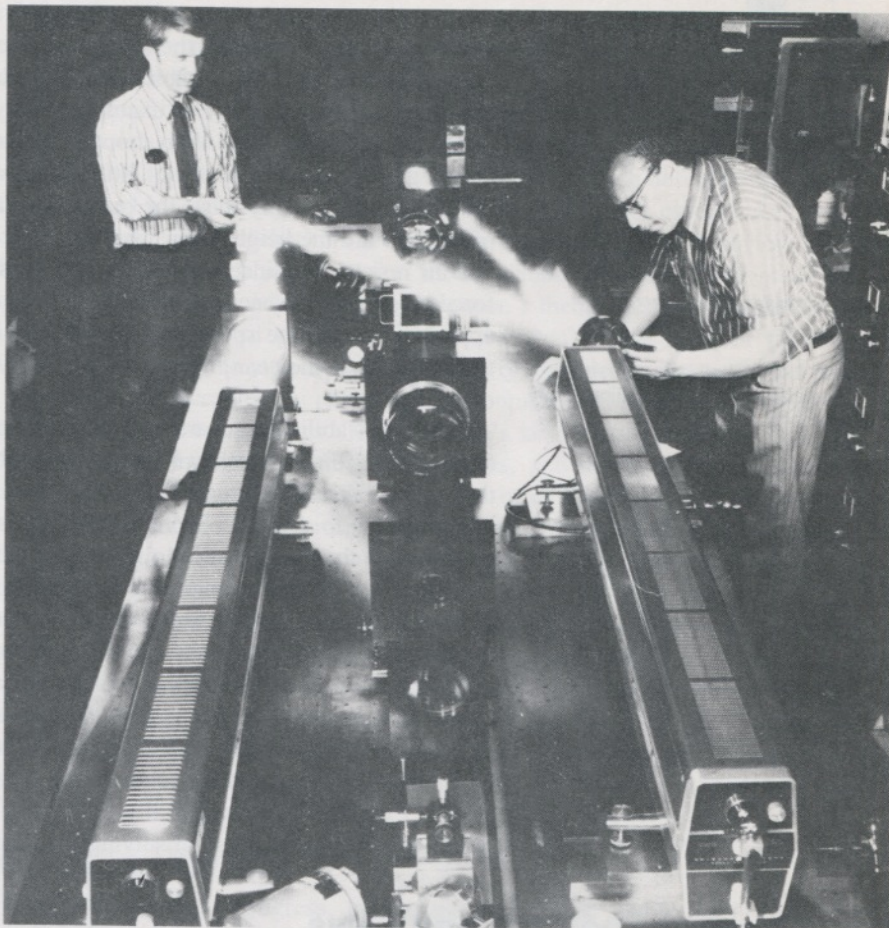
Once experimental data have been collected in a physics research laboratory of the type shown in Fig. 1.2, theoretical physicists try to develop a theory to correlate and explain these data. In so doing, they rely on the known laws of physics and their own creative imaginations. At times their explanation of the available data may involve nothing more than an application of a simple physical law such as Newton's second law of motion, which relates forces to accelerations; in other cases a break with existing physical theories may be required, as with Einstein's theory of relativity.

The test of the success of a physical theory is twofold: first, it must fit the available data that have been collected; second, it must be fruitful in making predictions about phenomena that have never been observed or measured. If these predictions are confirmed in the real world, the theory is retained; if not, it is modified or replaced by a better one that does agree with the available data. As Albert Einstein (Fig. 1.3) wrote, "The scientific theorist is not to be envied. For Nature, or more precisely experiment, is an inexorable and not very friendly judge of his work. It never says 'Yes' to a theory. In the most favorable cases it says 'Maybe,' and in the great majority of cases simply 'No.' Probably every theory will some day experience its 'No'—most theories, soon after conception."





**FIGURE 1.1** Dr. Rosalyn Yalow (born 1921), who shared the 1977 Nobel Prize for physiology and medicine for her part in creating the technique of radioimmunoassay, which uses radioactive tracers to locate antibodies present in the human body in quantities so minute that they are detectable in no other way. [American Institute of Physics (AIP) Niels Bohr Library]

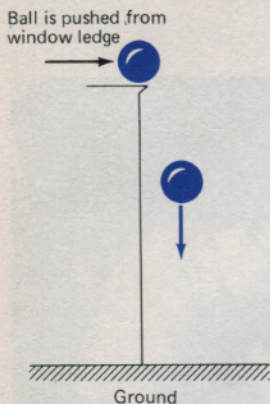


**FIGURE 1.2** Laser research. The two long rectangular boxes from which intense light is being emitted are gas lasers used for research at the Lawrence Livermore Laboratory in California. (U.S. Department of Energy.)



**FIGURE 1.3** Albert Einstein (1879–1955), with another famous theoretical physicist, J. Robert Oppenheimer (1904–1967). (International Communication Agency; courtesy of AIP Niels Bohr Library.)





**FIGURE 1.4** A ball being pushed from a window ledge and falling freely to the ground.

Physics has been extremely successful over the years in explaining matter and energy at ever-increasing levels of rigor and sophistication. In all cases, however, its secret of success has been the same—the ability to select out of a complicated situation in the real world the crucial physical quantities that determine what is going on. In this process of abstraction, much of the situation may be passed over as irrelevant for physics. For example, a physicist may see a ball falling from a window ledge (Fig. 1.4). Who dropped the ball, its color, and the material out of which it is made are usually of little importance in analyzing the physics of the falling ball. For a physicist, the only important things for the subsequent motion of the ball are the height from which it falls, the force of gravity pulling it down, and air resistance. Since the force of air resistance is often much smaller than the force of gravity, physicists initially ignore even air resistance in calculating a first approximation to the speed with which the ball is moving at any distance below the ledge. Then they can, if necessary, modify the theory later to include the effects of air resistance.

It is this ability to separate the essential points of a physical problem from the nonessentials that is the key to progress in physics. For this reason it can be said that physics has made progress more by what it has learned to ignore than by what it has chosen to take into account. We will see many examples of this important technique in the pages that follow. Solving the problems at the ends of the chapters can help you develop a similar technique—a technique, by the way, that may be of considerable assistance to you in other facets of life.

Physics is still far from complete. There are many things we do not know about the elementary particles, about the behavior of matter at very high and very low temperatures, about plasma physics and astrophysics. All over the world physicists are trying to solve very difficult problems in these and other fields. It will be their ability to penetrate to the heart of a complicated physical situation and then to express the essentials of the situation in the form of an equation that will be the key to their success in solving these problems.

### 1.3 Physical Theories and Laws

Books have been written on how physicists arrive at definitive descriptions of reality such as those found in Newton's laws of motion or Maxwell's equations for the electromagnetic field. In fact, individual physicists arrive at important conclusions in very different ways, and hence any attempt to systematize their procedures runs the risk of oversimplification. Still it is worthwhile to attempt some kind of broad outline of how physics progresses from experimental data to hypothesis to theory to physical law. The process used by physicists and all scientists for this purpose is called the *scientific method*.

The first step in developing a valid physical understanding of some aspect of reality is to collect as much good, unbiased data as possible, preferably data gathered by different physicists, perhaps in different parts of the world. Physicists then begin to suggest possible explanations of the data before them. Such tentative explanations, assumed for the sake of argument, are called *hypotheses* and usually include intellectual *models* (like the model of a gas made up of molecules flying around in random directions) constructed in an attempt to make sense of the available data. Finally one hypothesis seems to fit the data well and is advanced to the stage of a *physical theory*, i.e., a theoretical explanation, often in mathematical terms, that correlates and makes understandable the data already collected.



Once a theory has been developed, more experiments are needed to test it, perhaps by varying the circumstances of the original experiments or extending their range. Also, if the theory is a good one, it should make predictions about other aspects of reality that have not yet been measured or understood. If these predictions are verified, the theory is well on its way to acceptance by the physics community.

Theories that agree so well with experimental observations that they seem to reflect the consistent behavior of nature under a variety of conditions are called *physical laws*. Newton's law of universal gravitation, which describes the attractive force exerted by every object in the universe on every other object, is an example of such a law. The fact that this law explained not merely the behavior of apples falling from trees but also the motion of the planets around the sun provided the convincing evidence needed to convert Newton's theory into an accepted physical law. Other examples of physical laws are Newton's three laws of motion and Coulomb's law for the attraction or repulsion of electrically charged objects.

Some laws accepted by physicists for centuries have turned out to be inadequate in certain circumstances. Thus Newton's laws of motion need modification to describe the motion of high-speed particles, and in particular particles inside atoms and nuclei. For this purpose the theories of relativity and quantum mechanics have been developed.\* For ordinary objects moving at speeds small compared to the speed of light, however, Newton's laws are perfectly adequate, and we apply them to a great variety of physical situations in the following chapters.

There are also a group of "superlaws," usually called *principles*, which physicists believe are so built into the structure of nature that no exceptions are ever possible. The principles of conservation of energy, of linear momentum, and of angular momentum fall in this category and are among the greatest achievements of the human mind. We apply these principles to every branch of physics in the rest of this course.

## 1.4 Theory and Experiment in Physics

For physics to make progress, both experimental and theoretical physicists are needed. Experimental physicists make observations and perform controlled experiments to collect the physical data that any theory must explain. Theoretical physicists (Fig. 1.5) seek a theory, preferably in the form of an equation, that will fit the observed data. If successful, the theory may make additional predictions, sending the experimentalists back into their laboratories to confirm these also. If the predictions are not completely verified by experiment, the theory will have to be modified somewhat to fit the experimental data. Further predictions of the modified theory are then again checked in the laboratory. Physics thus progresses by the continual interplay of theory and experiment. Without one, the other would be of limited value.

Few physicists have been equally good at theory and experiment. Those who have include, among others, Galileo Galilei, Isaac Newton, and Enrico Fermi. Fermi (see Fig. 1.6 and accompanying biography) had an ability to turn from theory to experiment and then back again to theory in a manner almost unique among twentieth-century physicists.

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\*We delay discussion of relativistic effects until Chap. 26. Our treatment of mechanics will be totally nonrelativistic.