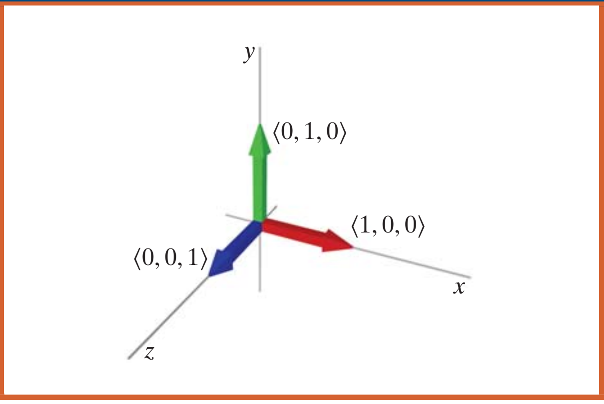
CHAPTER

1

Interactions and Motion



This textbook deals with the nature of matter and its interactions. The main goal of this textbook is to have you engage in a process central to science: constructing and applying physical models based on a small set of powerful fundamental physical principles and the atomic structure of matter. The variety of phenomena that we will be able to model, explain, and predict is very wide, including the orbit of stars around a black hole, nuclear fusion, the formation of sparks in air, and the speed of sound in a solid. This first chapter deals with the physical idea of interactions.

OBJECTIVES

After studying this chapter you should be able to

- Deduce from observations of an object's motion whether or not it has interacted with its surroundings.
- Mathematically describe position and motion in three dimensions.
- Mathematically describe momentum and change of momentum in three dimensions.
- Read and modify a simple computational model of motion at constant velocity.

1.1 KINDS OF MATTER

We will deal with material objects of many sizes, from subatomic particles to galaxies. All of these objects have certain things in common.

Atoms and Nuclei

Ordinary matter is made up of tiny atoms. An atom isn't the smallest type of matter, for it is composed of even smaller objects (electrons, protons, and neutrons), but many of the ordinary everyday properties of ordinary matter can be understood in terms of atomic properties and interactions. As you probably know from studying chemistry, atoms have a very small, very dense core, called the nucleus, around which is found a cloud of electrons. The nucleus contains protons and neutrons, collectively called nucleons. Electrons are kept close to the nucleus by electric attraction to the protons (the neutrons hardly interact with the electrons).

> **QUESTION** Recall your previous studies of chemistry. How many protons and electrons are there in a hydrogen atom? In a helium or carbon atom?

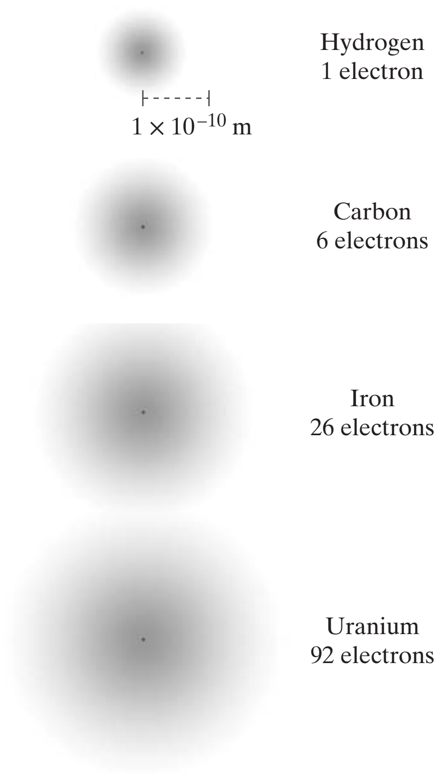


Figure 1.1 Atoms of hydrogen, carbon, iron, and uranium. The gray blur represents the electron cloud surrounding the nucleus. The black dot shows the location of the nucleus. On this scale, however, the nucleus would be much too small to see.

When you encounter a question in the text, you should think for a moment before reading on. Active reading contributes to significantly greater understanding. In the case of the questions posed above, if you don't remember the properties of these atoms, it may help to refer to the periodic table on the inside front cover of this textbook.

Hydrogen is the simplest atom, with just one proton and one electron. A helium atom has two protons and two electrons. A carbon atom has six protons and six electrons. Near the other end of the chemical periodic table, a uranium atom has 92 protons and 92 electrons. Figure 1.1 shows the relative sizes of the electron clouds in atoms of several elements but cannot show the nucleus to the same scale; the tiny dot marking the nucleus in the figure is much larger than the actual nucleus.

The radius of the electron cloud for a typical atom is about 1×10^{-10} meter. The reason for this size can be understood using the principles of quantum mechanics, a major development in physics in the early 20th century. The radius of a proton is about 1×10^{-15} meter, very much smaller than the radius of the electron cloud.

Nuclei contain neutrons as well as protons (Figure 1.2). The most common form or "isotope" of hydrogen has no neutrons in the nucleus. However, there exist isotopes of hydrogen with one or two neutrons in the nucleus (in addition to the proton). Hydrogen atoms containing one or two neutrons are called deuterium or tritium. The most common isotope of helium has two neutrons (and two protons) in its nucleus, but a rare isotope has only one neutron; this is called helium-3.

The most common isotope of carbon has six neutrons together with the six protons in the nucleus (carbon-12), whereas carbon-14 with eight neutrons is an isotope that plays an important role in dating archaeological objects.

Near the other end of the periodic table, uranium-235, which can undergo a fission chain reaction, has 92 protons and 143 neutrons, whereas uranium-238, which does not undergo a fission chain reaction, has 92 protons and 146 neutrons.

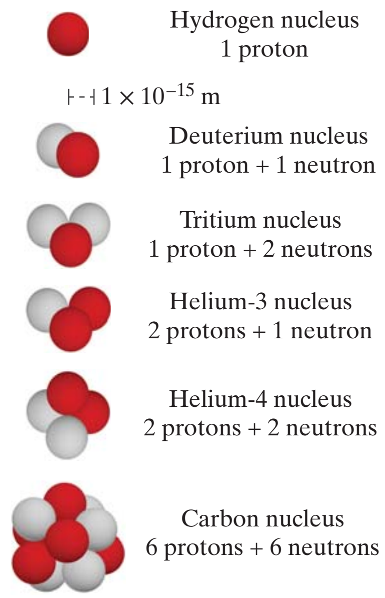


Figure 1.2 Nuclei of hydrogen, helium, and carbon. Note the *very* much smaller scale than in Figure 1.1!

Molecules and Solids

When atoms come in contact with each other, they may stick to each other ("bond" to each other). Several atoms bonded together can form a molecule—a substance whose physical and chemical properties differ from those of the constituent atoms. For example, water molecules (H_2O) have properties quite different from the properties of hydrogen atoms or oxygen atoms.

An ordinary-sized rigid object made of bound-together atoms and big enough to see and handle is called a solid, such as a bar of aluminum. A new kind of microscope, the scanning tunneling microscope (STM), is able to map the locations of atoms on the surface of a solid, which has provided new techniques for investigating matter at the atomic level. Two such images appear in Figure 1.3. You can see that atoms in a crystalline solid are arranged in a regular three-dimensional array. The arrangement of atoms on the surface depends on the direction along which the crystal is cut. The irregularities in the bottom image reflect "defects," such as missing atoms, in the crystal structure.

Liquids and Gases

When a solid is heated to a higher temperature, the atoms in the solid vibrate more vigorously about their normal positions. If the temperature is raised high enough, this thermal agitation may destroy the rigid structure of the solid. The atoms may become able to slide over each other, in which case the substance is a liquid.

At even higher temperatures the thermal motion of the atoms or molecules may be so large as to break the interatomic or intermolecular bonds completely, and the liquid turns into a gas. In a gas the atoms or molecules are quite free to move around, only occasionally colliding with each other or the walls of their container.

We will learn how to analyze many aspects of the behavior of solids and gases. We won't have much to say about liquids, because their properties are much harder to analyze. Solids are simpler to analyze than liquids because the atoms stay in one place (though with thermal vibration about their usual positions). Gases are simpler to analyze than liquids because between collisions the gas molecules are approximately unaffected by the other molecules. Liquids are the awkward intermediate state, where the atoms move around rather freely but are always in contact with other atoms. This makes the analysis of liquids very complex.

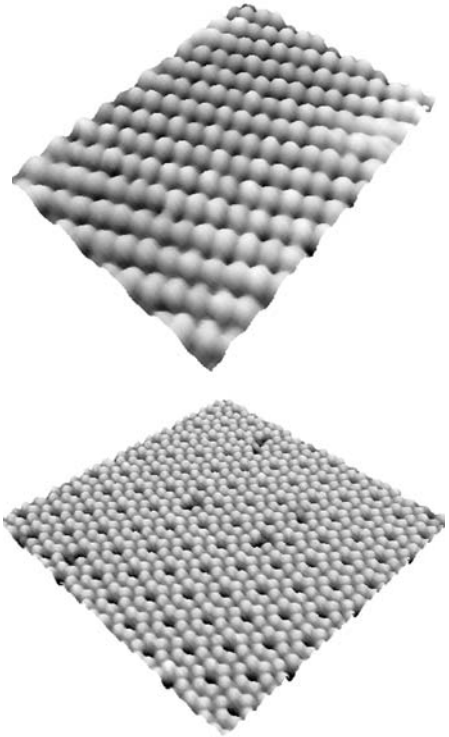


Figure 1.3 Two different surfaces of a crystal of pure silicon. The images were made with a scanning tunneling microscope. (Images courtesy of Randall Feenstra, IBM Corp.)

Planets, Stars, Solar Systems, and Galaxies

In our brief survey of the kinds of matter that we will study, we make a giant leap in scale from atoms all the way up to planets and stars, such as our Earth and Sun. We will see that many of the same principles that apply to atoms apply to planets and stars. By making this leap we bypass an important physical science, geology, whose domain of interest includes the formation of mountains and continents. We will study objects that are much bigger than mountains, and we will study objects that are much smaller than mountains, but we don't have time to apply the principles of physics to every important kind of matter.

Our Sun and its accompanying planets constitute our Solar System. It is located in the Milky Way galaxy, a giant rotating disk-shaped system of stars. On a clear dark night you can see a band of light (the Milky Way) coming from the huge number of stars lying in this disk, which you are looking at from a position in the disk, about two-thirds of the way out from the center of the disk. Our galaxy is a member of a cluster of galaxies that move around each other much as the planets of our Solar System move around the Sun (Figure 1.4). The Universe contains many such clusters of galaxies.

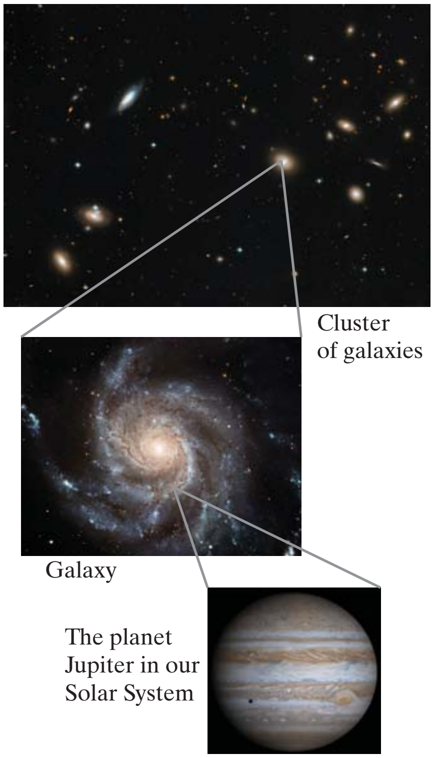


Figure 1.4 Our Solar System exists inside a galaxy, which itself is a member of a cluster of galaxies. (Photos courtesy NASA/JPL-Caltech)

Point Particles

It is common in physics to talk about the motion of a "point particle." What we mean by a particle is an object whose size, shape, and internal structure are not important to us in the current context, and which we can consider to be located at a single point in space. In modeling the motion of a real object (whether it is a galaxy or a proton), we often choose to make the simplifying assumption that it is a point particle, as if Superman or a giant space alien had come along and squeezed the object until it was compressed into a very tiny, structureless microscopic speck with the full mass of the original object.

Of course, there are many situations in which it would be absurd to use this approximation. The Earth, for example, is a large, complex object, with a core of turbulent molten rock, huge moving continents, and massive sloshing oceans. Radioactivity keeps its core hot; electromagnetic radiation from the Sun warms its surface; and thermal energy is also radiated away into space. If we are interested in energy flows or continental motion or earthquakes we need to consider the detailed structure and composition of the Earth. However, if what we want to do is model the motion of the Earth as it interacts with other objects in our Solar System, it works quite well to ignore this complexity, and to treat the Earth, the Sun, the Moon, and the other planets as if they were point particles.

Even most very tiny objects, such as atoms, protons, and neutrons, are not truly point particles—they do have finite size, and they have internal structure, which can influence their interactions with other objects. By contrast, electrons may really be point particles—they appear to have no internal structure, and attempts to measure the radius of an electron have not produced a definite number (recent experiments indicate only that the radius of an electron is less than 2×10^{-20} m, much smaller than a proton).

As we consider various aspects of matter and its interactions, it will be important for us to state explicitly whether or not we are modeling material objects as point particles, or as extended and perhaps deformable macroscopic chunks of matter. In Chapters 1–3 we will emphasize systems that can usefully be modeled as particles. In Chapter 4 we will begin to consider the detailed internal structure of material objects.

1.2 DETECTING INTERACTIONS

Objects made of different kinds of matter interact with each other in various ways: gravitationally, electrically, magnetically, and through nuclear interactions. How can we detect that an interaction has occurred? In this section we consider various kinds of observations that indicate the presence of interactions.

> **QUESTION** Before you read further, take a moment to think about your own ideas of interactions. How can you tell that two objects are interacting with each other?

Change of Direction of Motion

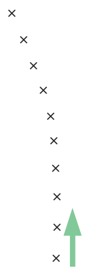


Figure 1.5 A proton moves through space, far from almost all other objects. The initial direction of the proton's motion is upward, as indicated by the arrow. The ×'s represent the position of the proton at equal time intervals.

Suppose that you observe a proton moving through a region of outer space, far from almost all other objects. The proton moves along a path like the one shown in Figure 1.5. The arrow indicates the initial direction of the proton's motion, and the ×'s in the diagram indicate the position of the proton at equal time intervals.

> **QUESTION** Do you see evidence in Figure 1.5 that the proton is interacting with another object?

Evidently a change in direction is a vivid indicator of interactions. If you observe a change in direction of the motion of a proton, you will find another object somewhere that has interacted with this proton.

> **QUESTION** Suppose that the only other object nearby was another proton. What was the approximate initial location of this second proton?

Since two protons repel each other electrically, the second proton must have been located to the right of the bend in the first proton's path.

Change of Speed

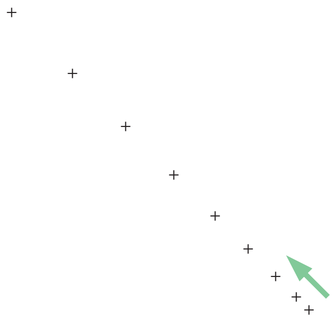


Figure 1.6 An electron moves through space, far from almost all other objects. The initial direction of the electron's motion is upward and to the left, as indicated by the arrow. The ×'s represent the position of the electron at equal time intervals.

Suppose that you observe an electron traveling in a straight line through outer space far from almost all other objects (Figure 1.6). The path of the electron is shown as though a camera had taken multiple exposures at equal time intervals.

> **QUESTION** Where is the electron's speed largest? Where is the electron's speed smallest?

The speed is largest at the upper left, where the ×'s are farther apart, which means that the electron has moved farthest during the time interval between exposures. The speed is smallest at the bottom right, where the ×'s are closer together, which means that the electron has moved the least distance during the time interval between exposures.

> **QUESTION** Suppose that the only other object nearby was another electron. What was the approximate initial location of this other electron?

The other electron must have been located directly just below and to the right of the starting location, since electrons repel each other electrically.

Evidently a change in speed is an indicator of interactions. If you observe a change in speed of an electron, you will find another object somewhere that has interacted with the electron.

Velocity Includes Both Speed and Direction

In physics, the word "velocity" has a special technical meaning that is different from its meaning in everyday speech. In physics, the quantity called "velocity" denotes a combination of speed and direction. Even if the speed or direction of motion is changing, the velocity has a precise value (speed and direction) at any instant. In contrast, in everyday speech, "speed" and "velocity" are often used as synonyms. In physics and other sciences, however, words have rather precise meanings and there are few synonyms.

For example, consider an airplane that at a particular moment is flying with a speed of 1000 kilometers/hour in a direction that is due east. We say the velocity is 1000 km/h, east, where we specify both speed and direction. An airplane flying west with a speed of 1000 km/h would have the same speed but a different velocity.

Figure 1.7 Two successive positions of a particle (indicated by a dot), with arrows indicating the velocity of the particle at each location. The shorter arrow indicates that the speed of the particle at location 2 is less than its speed at location 1.

We have seen that a change in an object's speed, or a change in the direction of its motion, indicates that the object has interacted with at least one other object. The two indicators of interaction, change of speed and change of direction, can be combined into one compact statement:

> A change of velocity (speed or direction or both) indicates the existence of an interaction.

In physics diagrams, the velocity of an object is represented by an arrow: a line with an arrowhead. The tail of the arrow is placed at the location of the object at a particular instant, and the arrow points in the direction of the motion of the object at that instant. The length of the arrow is proportional to the speed of the object. Figure 1.7 shows two successive positions of a particle at two different times, with velocity arrows indicating a change in speed of the particle (it's slowing down). Figure 1.8 shows three successive positions of a different particle at three different times, with velocity arrows indicating a change in direction but no change in speed. Note that the arrows themselves are straight; even if the path of the particle curves over time, at any instant the particle may be considered to be traveling in a specific direction.

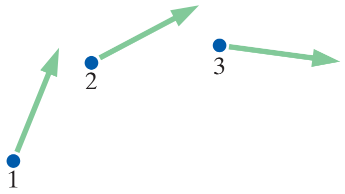


Figure 1.8 Three successive positions of a particle (indicated by a dot), with arrows indicating the velocity of the particle at each location. The arrows are the same length, indicating the same speed, but they point in different directions, indicating a change in direction and therefore a change in velocity.

We will see a little later that velocity is only one example of a physical quantity that has a "magnitude" (an amount or a size) and a direction. Other examples of such quantities are position relative to an origin in 3D space, changes in position or velocity, and force. In Section 1.4 we will see how to represent such quantities as vectors: single mathematical entities that combine information about magnitude and direction.

Uniform Motion

Suppose that you observe a rock moving along in outer space far from all other objects. We don't know what made it start moving in the first place; presumably a long time ago an interaction gave it some velocity and it has been coasting through the vacuum of space ever since.

It is an observational fact that such an isolated object moves at constant, unchanging speed, in a straight line. Its velocity does not change (neither its direction nor its speed changes). We call motion with unchanging velocity "uniform motion" (Figure 1.9). Other terms for uniform motion include "uniform velocity" and "constant velocity," since velocity refers to both speed and direction.

QUESTION Is an object at rest in uniform motion?

If an object remains at rest, then neither the speed nor direction of the object's velocity changes. This is a special case of uniform motion: the object's speed is constant (zero is a valid value of speed) and the direction of motion, while undefined, is not changing.

QUESTION If we observe an object in uniform motion, can we conclude that it has no interactions with its surroundings?

When we observe an object in uniform motion, one possibility is that it has no interactions at all with its surroundings. However, there is another possibility: the object may be experiencing multiple interactions that cancel each other out. In either case, we can correctly deduce that the "net" (total) interaction of the object with its surroundings is zero.

Figure 1.9 "Uniform motion"—no change in speed or direction.

Checkpoint 1 **(a)** Which of the following do you see moving with constant velocity? (1) A ship sailing northeast at a speed of 5 meters per second (2) The Moon orbiting the Earth (3) A tennis ball traveling across the court after having been hit by a tennis racket (4) A can of soda sitting on a table (5) A person riding on a Ferris wheel that is turning at a constant rate. **(b)** In which of the following situations is there observational evidence for significant interaction between two objects? How can you tell? (1) A ball bounces off a wall with no change in speed. (2) A baseball that was hit by a batter flies toward the outfield. (3) A communications satellite orbits the Earth. (4) A space probe travels at constant speed toward a distant star. (5) A charged particle leaves a curving track in a particle detector.