Laws and Their Limits: The Organization of Scientific Knowledge

How do we know? Reality and interpretation

Theory and model
"Laws"
Constructs: what is real?
From push and pull to operational definition

The Newtonian model and its limitations

Classical physics and the Newtonian world view
Is the universe programmed?

Mechanics and beyond

From elementary particles to composite materials and the edge of the known

The word *science* comes from the Latin *to know*, and if we follow that origin it should include every kind of knowledge. Instead it is usually used as synonymous with *natural science*, the study of the natural world, and that is the way we will use the word here: a statement of science has to have some relation to the world around us, as we observe it and as we experiment to explore it.

No matter how many symbols we use, no matter how many equations we write down, what we are trying to do is to describe the world. The symbols, units, and the mathematical operations are just parts of the language, as we try to describe, predict, and understand the phenomena that we observe.

There is no science without that contact with the world, without observation and experiment. That's why we won't call mathematics a science. It is wonderful, it can be beautiful, and it is enormously useful. It is the language without which modern science is unthinkable.

Sometimes it seems as if the language is the main part. The technique tends to take over. Which equation should I use? Is this the right unit? How do I get the right answer? But the technique is never the main part of doing or learning science. It may take up most of our time, but it is only the means to the end of greater knowledge.

We need to make time to ask: what does it *mean*? What are we trying to achieve and what have we learned? What do we know and how can we know more?

The essential part is to be able to have a conversation with nature—to let the world speak to us, so as to allow us to see its patterns, to see the relationships between the parts of which it is composed, and to understand its inner workings, its *mechanisms.*

5.1 How do we know? Reality and interpretation

In this chapter we want to look more carefully at how we gain scientific knowledge, how we organize it, and what methods we use. People sometimes talk about a *scientific method*, a regular sequence of steps that leads to scientific knowledge. Although there are common features in the way new science is learned, different questions require different kinds of answers, and different ways of finding answers.

Our knowledge of stars begins with observation, first of their positions, and then of the radiation that they emit. Today we know much more than can be observed directly. We know what stars consist of, how the different chemical elements are created in them, how the stars themselves are created, how they radiate, and how the radiation changes with time, until eventually they cease to be the stars that we know. To gain this knowledge required putting together pieces of knowledge that seemed at first to have nothing to do with stars, such as the interaction between atomic nuclei, which we now know to be responsible for the energy that the stars release.

Our knowledge of atoms began quite differently. It wasn't until long after people were convinced of the existence of atoms that ways were found to observe them directly.

In each case we use the methods that seem to be most appropriate. The most straightforward way to find out is observation. We can create special situations that we can then observe, study, and analyze. That's what we do when we conduct an experiment.

Sometimes the experiment comes first. That was the case for Galileo, when he dropped different objects and found that they all took the same time to reach the ground. At other times it is the analysis that comes first. That's what happened when Einstein thought about the nature of time and space and developed the theories of relativity. In both cases the object was to describe what is observed, and the essential test and requirement for what Einstein and other theoretical physicists achieve is that it must be in accord with what is or can be observed.

We conclude that there is no single method that leads to new knowledge. Rather, we do our best using any method we can.

A list of observations represents only rough and limited knowledge. We look for order in what we observe, and we try to make it quantitative. For example, we see the earth and the sun in motions that repeat, some every day, some every year. We make measurements and we attempt to detect patterns and relationships in the observed quantities. We can then test the scope and validity of the relationships by seeing whether they allow us to predict what will happen in other related situations.

If we describe what happens when we drop a stone, we can look for relationships that we can express in mathematical language, such as those that connect the height from which the stone is dropped to the time it takes to reach the ground and to the speed it has at various points along its path. We can test the relations that we develop by using different heights and different stones. They will be "good" and useful if they also allow us to describe, and so to predict, what will happen in these different circumstances.

Theory and model
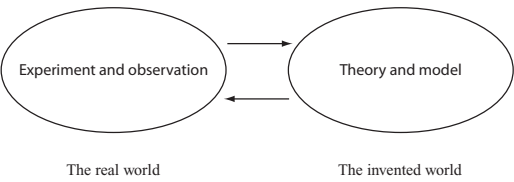
In ordinary language the word "theory" is often used to talk about a speculation or a guess. In science its meaning is different. It usually refers to a set of relationships between observations. In physics a theory is most often expressed in the language of mathematics, and describes relationships between quantities that are observed or are related to observed quantities. Let's look at an example that you are familiar with.

Newton's second law of motion ($\Sigma F = Ma$) tells us what force is: it is what leads to or can lead to acceleration. Newton's law of gravitation ($F = G\frac{M_1 M_2}{r^2}$) describes a particular kind of force, namely the gravitational force of attraction between two objects. Together these two relations can be used to describe the motion of the planets around the sun in great detail. They represent a theory of planetary motion.

If we look closely at what we are doing, we see that we are making some crucial assumptions. We are imagining a place where the sun and the planets have no internal structure; they

behave like particles, each with its actual mass. Newton's law of gravitation describes the force between them exactly.

We have created an imagined universe. We call it a *model* of the sun and the planets. In it we leave out many of the sun's and the planets' properties, such as their sizes and shapes, their complex structure, their atmospheres, and their temperature distributions. The model is also different in that it is exact. It is our invention, and we have no doubts about how it is constructed and how every part of it behaves. The construction of the model and the statements about how its parts interact and behave are what we call the *theory*.

Sometimes we will use the word "model" and sometimes the word "theory." They both describe the invented, simplified universe and the relations between quantities in such a universe. If the properties of the model and the relationships in the theory are close to those that are actually observed, then we have succeeded in creating a good model and a good theory.

EXAMPLE 1

Galileo concluded that all objects take the same time to fall to the ground from the top of the leaning tower of Pisa. In light of what we know today, what is the model that is implied by his data, and what are its limitations?
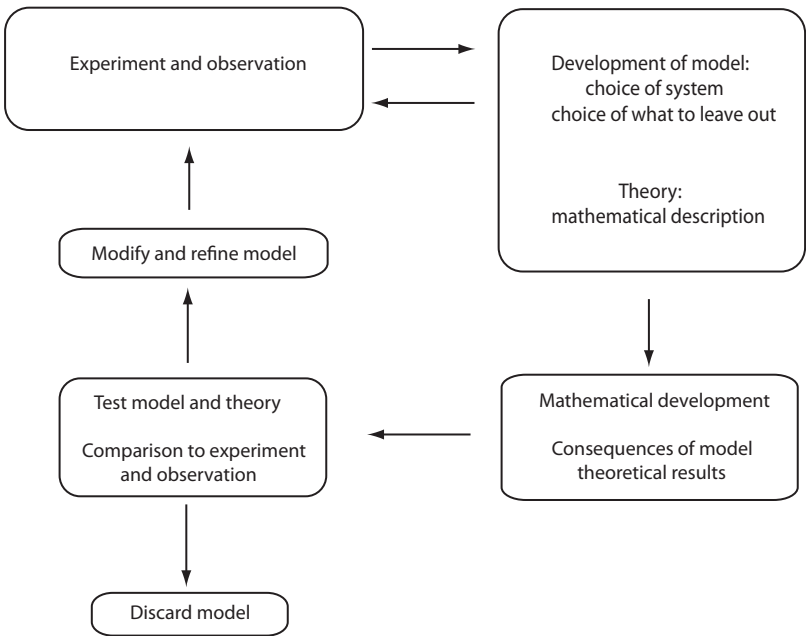
Ans.:

He probably didn't drop a piece of paper or a feather as part of his experiments. He must have known that for them there would be a lot of air resistance, and that this would change the time it takes for these objects to fall.

Galileo's model was that the gravitational interaction was the only one that needed to be considered. A measurable contribution from any other unbalanced forces would have changed his results.

EXAMPLE 2

What assumptions do we make when we use the interaction with the earth, as described by Newton's law of gravitation, with r as the distance to the center of the earth, as the only one that affects the motion of an artificial earth satellite?

Ans.:

The first assumption is that the gravitational interaction is the only one. This will be inappropriate if the satellite's path is so close to the earth that interaction with the atmosphere has a measurable influence. We are also neglecting the presence of all other bodies, such as the moon.

The second assumption is that the earth is spherically symmetrical. (This means that the earth's properties can vary with the distance from its center, but not with its angle, i.e., with the latitude or longitude.) The earth's shape is actually not a sphere. It's an ellipsoid. The distance between the north pole and the south pole is $12,713.6$ km, while the diameter at the equator is $12,756.2$ km. (The difference between these numbers is more than twice as large as the height of the highest mountain.) The mountains and oceans, as well as the uneven distribution of the elements, also limit the symmetry. In addition, each tree, animal, or person represents a departure from spherical symmetry.

"Laws"

Scientists are not very consistent in the way that they use the word "law." We have already used it in situations that are quite different from each other. We have used Newton's second law of motion as the definition of force, so that what it says is exactly true. On the other hand Newton's law of gravitation describes a relation between observed quantities. Its validity depends on whether it is in accord with what is observed.

And we know that although it describes what is observed very well, it is not perfect.

Physical laws that describe the behavior of materials are in a still different category. Hooke's law is the relation between the force (F) on a spring and the amount (x) by which it stretches. It says that these two quantities are proportional. Its validity depends on the particular spring, and we know that this "law" is never exactly true, since with a sufficiently strong force the spring will break. There are many other relations that are called *laws* and that describe the properties of materials. They depend on the interplay of the very large number of atoms in even a small piece of material. This kind of law is often quite approximate.

We see that in physics the word *law* is used in a variety of ways with different meanings. It can be exact, as in a definition. It can be part of a theory that is so well tested that its conclusion is elevated to the status of a *law*. But it is also used for relations that are only approximate, or that are valid only under very restricted circumstances.

Some laws are *empirical*. An empirical law is one that is based on experiment or observation. It describes an observed pattern of results. A law can also be the result of a theory. It then has to be tested by experiment and observation. We would prefer not to call a definition a law, but the term "Newton's laws of motion" is so widely used that we'll stay with it.

If we call a statement a "law" that makes it look as if it were a statement that prescribes what *must* happen. That's not what it means. Scientific theories and models and theoretical laws are attempts to describe natural phenomena. They can never be regarded as final. We have to be ready to find that they are inadequate as better measurements are made or new knowledge is found. If that happens, they may be refined and improved, or they may need to be discarded.

An untested statement or theory is often called a "hypothesis" (plural: hypotheses). Another word that is sometimes used is "postulate." It is a statement or relation that is assumed, usually as the beginning of a theory. A hypothesis or a postulate needs to be tested. Its consequences have to be compared to the results of observations and experiments. Only then can its usefulness and validity be evaluated.

There is some variation in the way that the various terms that we introduce in this chapter

are defined and used. In popular usage, and even among physicists, they are not always used in a consistent fashion. We will use the framework that we have described, but in light of these differences it should not be regarded as rigid and absolute.

Most importantly, we have to remember that the models, the theories, the theoretical and empirical laws, the postulates and hypotheses can be considered to be scientific only if they can be tested by observation and experiment. A statement that is not necessarily wrong, if it cannot be tested it is not part of science.

EXAMPLE 3

The *coefficient of sliding friction* is defined as the force of friction on a sliding object divided by the normal force on it. That this coefficient turns out to be constant in certain situations is sometimes referred to as a *law of friction*.

Describe the nature of the term "law" as it is used here and the likely accuracy of the law.

Ans.:

This is an empirical law, based on the observation of objects pulled along a horizontal surface or sliding down inclined planes. The force of friction, and hence the coefficient of friction, are strongly dependent on the nature of the two surfaces that are in contact. Oil, dirt, and irregularities on the surfaces can cause substantial changes. The "law" can be expected to be a rough guide, at best.

EXAMPLE 4

While you are bowling you watch the ball: is it moving with constant speed, slowing down, or speeding up? How can you decide?

Ans.:

You decide to use Newton's second law of motion, $\Sigma F = Ma$. (You are using the *Newtonian model*.) You postulate that you can neglect the rolling motion so that the ball can be treated as a particle. You now have to think of all the possible forces. You make the hypothesis that friction and air resistance are so small that they can be neglected. You assume that the bowling lane is horizontal.

Based on these assumptions you conclude that there is no net horizontal force once the ball leaves your hand. There is therefore no horizontal acceleration, so that the velocity is constant.

To test this theoretical conclusion you measure the position of the ball at equal time intervals. If the ball moves through equal distances along a straight line in equal time intervals, the velocity is constant. If not, the model with its postulates, hypotheses, and assumptions has to be reevaluated and changed.

(Note that the meanings of the terms *postulate, hypothesis,* and *assumption* are very similar.)

As another example we describe the interplay of theory and observation in the development of our understanding of the motion of the planets.

Observations of the sun and the planets have been made for at least 5000 years. The Greeks thought that the earth is at the center of the universe, with the stars and the planets moving in circles around it. This was their model.

This model made predictions that were inconsistent with the observations. For example, as seen from the earth the planets sometimes appear to move backward. (This is called *retrograde motion*.) Furthermore, the brightness of the planets changes with time, suggesting that their distance from the earth varies. To account for the discrepancies a different model was introduced. It retained the circles with the earth at their center. The planets, however, did not move along these circles, but rather along smaller circles (called *epicycles*) whose center moved along the larger earth-centered circles.

This model was refined by Ptolemy (85–165 A.D.) to the point where it could account for all of the observations of the time, long before the invention of telescopes. However, the model became very complicated, with many epicycles, and with the earth no longer at the center of the large circles. It lasted to the time when Nicolaus Copernicus (1473–1543), in his last year, published a model in which the sun was at the center of the circular motion of the earth and the other planets.

Copernicus' model was not based on new observations, but rather on the simplicity that resulted from putting the sun at the center. It is interesting to note that all models up to that time, including that of Copernicus, were based on circular motion, to a large extent because that was considered motion that was "perfect" or "divine."

Tycho Brahe (1546–1601), still without telescopes, made observations and measurements that were more accurate than any before him, and showed that none of the models could account for their details.

Johannes Kepler (1571–1630) was able to resolve the difficulties. At first he tried a model in which the planets move around the sun in orbits around the five so-called *perfect solids*. (These are the cube, whose six faces are equal squares, the pyramid with its four equilateral triangles, and three others, also with faces that are equilateral polygons.) This model was inadequate in many ways.

After many years of studying the observations he came to the conclusion that the planets move in elliptical orbits, with the sun at one focus of the ellipse. This statement not only describes accurately what was known in Kepler's time, but also accounts correctly for what was subsequently observed after other planets were discovered. It (and two other statements, that together with this one are known as Kepler's laws) can be shown mathematically to follow from Newton's law of gravitation and Newton's second law of motion, as published by him in his major work in 1687.

EXAMPLE 5

Tycho Brahe measured the orbits of the planets closest to the sun. The following table shows their modern values for the period (T) in seconds and the semimajor axis, which we will use instead of the radius, (R) in meters.

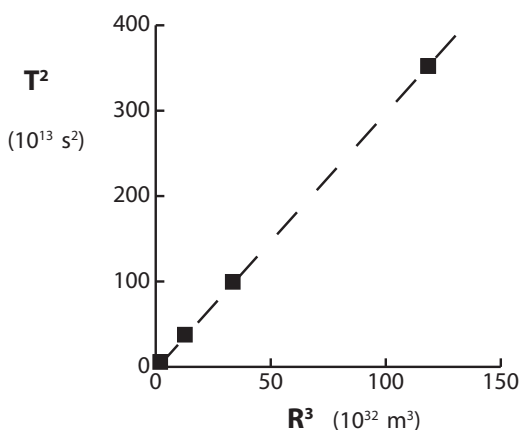| Planet	R	T
Mercury	5.79×10^{10}	7.60×10^6
Venus	1.08×10^{11}	1.94×10^7
Earth	1.50×10^{11}	3.16×10^7
Mars	2.28×10^{11}	5.94×10^7

(a) Plot T^2 vs. R^3 for the data in the table.

(b) Describe in words what Kepler could conclude from the data. (This is now called Kepler's third law. Kepler's laws are empirical. He died before Newton showed their origin to be in the law of gravitation.)

(c) How could his conclusion be tested?

(d) Newton showed that Kepler's third law can be derived from his law of gravitation. Show that this is so for circular orbits.

Ans.:

(a)

(b) Kepler concluded that for the planets in orbit around the sun the square of the period is proportional to the cube of the radius.

(c) Kepler's conclusion could be tested by using data for other planets to see if for them the values of T^2 and R^3 lie along the same line as for those in the table.

(d) Let M be the mass of the sun, m the mass of the orbiting planet, and R the radius of the orbit. For circular orbits there is a centripetal force equal to $\frac{mv^2}{R}$. If we assume that in this case the centripetal force is the gravitational force, then $\frac{mv^2}{R} = \frac{GMm}{R^2}$. We can cancel m and rewrite this relation as $v^2 = \frac{GM}{R}$.

The planet moves with constant speed, v, a distance $2\pi R$ in the time T, so that $v = \frac{2\pi R}{T}$. We can substitute this expression for v to get $(\frac{2\pi R}{T})^2 = \frac{GM}{R}$. This expression can be written as $R^3 = \frac{GM}{4\pi^2}T^2$, showing that $R^3 \propto T^2$.

Constructs: what is real?

In our description of physical phenomena we have used quantities such as *velocity, acceleration*, and *force*. Some are directly observed, such as *distance* and *time*. Others, such as *velocity* and *acceleration*, describe how quantities change. For

still others, such as *energy*, the relation to the observations is less direct.

We have invented these quantities. They are sometimes called "constructs," to emphasize that it is we who construct them and decide what we want them to be. They represent choices that we make. Not all are as obvious as *distance* and *speed*. For *energy* and *momentum* the fact that they are invented is more apparent.

Does that mean that momentum is less "real" than velocity? Is the momentum of a baseball more real than that of an electron, just because we can hold a baseball in our hand, while the electron's properties have to be found more indirectly?

Much of our knowledge is obtained indirectly, often through measuring devices that use needles pointing to numbers, or digital electronic readouts. Is the speed of a car more real than that of an atomic nucleus that we can observe only by indirect means? We can see and hear and touch and smell the car. Is that what makes it real?

The question of what is *real* doesn't have a simple answer. Physicists (and others) often disagree about the meaning of the words "real" and "reality." If we can't agree on a definition, we can't decide where reality begins or ends.

When we ask whether something is real we generally think of how the phenomenon or quantity makes contact with our senses. Do we see it or hear it? Can we feel it or smell it? What if we see only the needle pointing to a number on a dial in a complicated piece of equipment? What if we are talking about a construct that appears only in the equations of a theory? In this book we won't attempt a definition, and will use the word *reality* only rarely, in situations where it doesn't seem to be controversial.

If we go back to the question "how do we know?" we see that there are two main parts. On the one hand, there is observation and experiment. On the other there is the building of models and theories with their constructs. Sometimes the observation comes first. It may be accidental, or it may be carefully planned. In other cases the theory and the model building come first. Often progress is made by going back and forth between these two activities. It is the interaction between the two that most often leads to knowledge and understanding.

From push and pull to operational definition

When we first talked about force we weren't very careful about definitions. The common meaning that force is a push or pull was enough to get us going. Similarly, mass is sometimes said to measure the quantity of matter. These statements give only some vague and incomplete idea of the meaning of the words "mass" and "force." They are too indefinite to be good definitions.

We want to use terms like *force* and *mass* in ways that are more precise and also more fruitful than in ordinary speech. A definition is not very useful if it gives just a rough synonym or general notion. What we need is a definition that gives us a recipe for how to find and measure the quantity, so that we will know it unambiguously. That kind is called an *operational* definition.

The recipe may be one that we can actually carry out, or it may be one that we can only *imagine* carrying out, within the rules and laws that we have already agreed on. That's what we did when we defined both force and mass by using $F = Ma$.

EXAMPLE 6

Give the operational definitions of *force* and *mass*.

(a) Start with two objects and describe each step in the procedure that leads to the operational definition of the ratio of the two masses.

(b) What else is necessary to define mass *absolutely*?

(c) Define *force*.

Ans.:

(a) Apply forces with the same magnitude to the two objects ($F_1 = F_2$). This can be done with a spring that applies the same force each time it is compressed by the same amount. Even better is a spring between the two objects. When it is compressed, and then released, it applies forces with the same magnitude to the two objects.

The two objects then move with accelerations that can be measured, a_1 and a_2. The quantity that decides how large each of the accelerations is is the mass: we define the ratio of the masses to be equal to the inverse ratio of the accelerations: $\frac{a_1}{a_2} = \frac{M_2}{M_1}$, or $M_1 a_1 = M_2 a_2$.

(b) To get a definite value we have to decide on a *standard* mass that everyone agrees to, such as a

kilogram. The same procedure as in part (a) can be used to compare other masses to it.

(c) The force exerted by the spring in part (a) is defined to be equal to M_1a_1 or M_2a_2, or, in general, $F = Ma$.

These definitions tell us first of all what happens *qualitatively*, namely that *the force on an object gives rise to an acceleration*, and that *the mass determines how large that acceleration is*. But they go further; they tell us *quantitatively* how large the force and the mass are. They provide recipes, using only measured quantities, that we can use to determine the mass and the force. That's what makes them *operational definitions*. They are the connection to the real world.

5.2   The Newtonian model and its limitations

Let's go back to Kepler's and Newton's planetary model. Consider a moment when the particles of the model have the same positions as the centers of the actual sun and planets. We can now calculate the subsequent motions of the particles in the model, using Newton's law of gravitation, and compare them to the observed behavior of the sun and the planets.

It turns out that the model is excellent. The motions of the particles of the model and those of the actual planetary system are very closely the same. The equations of the model and the theory can be used to show that in the model the planets (i.e., the particles that represent the planets) move in elliptical orbits about the sun. This is what is observed in the real world. Past motions can be described, and future motions predicted, in great detail.

The model's success goes even farther. It can be used to represent not just the motion of the planets, but also that of their moons and of the many artificial satellites that have been launched.

You can see that we have gone far beyond speculation. The model is supported by many observations. Its success in describing what we observe gives us the confidence to use it to predict what will happen in the future.

We can now ask a number of questions. Is the model complete? What does it leave out?

Is the model unique, or can we think of other models that can describe the same observations?

There is an even more crucial question: is the model in conflict with any observation? No matter how many observations are in accord with the model, even a single one that is in conflict with it casts doubt on the validity and applicability of the model.

This particular model is so good that it is hard to find discrepancies. But there are limits. When Einstein developed the *general theory of relativity* in 1915, and applied it to the motion of *Mercury*, the planet closest to the sun, his calculations showed small differences from the results of the Newtonian equations, i.e., from the *Newtonian model*.

Einstein used a different theory, a different model. Which one is better? No amount of calculation, no amount of thought or discussion can decide. There is only one way to judge: what are the observations? They were made, and Einstein's results turned out to be better.

Does that mean that Newton's equations and model were abandoned? Not at all. For almost all situations Newton's law of gravitation describes what happens as accurately as we can measure, and does so much more simply. It continues to be used to describe the motions of the planets, their moons, and artificial satellites. But we now know more about its limitations and under what circumstances we may need to use Einstein's more complicated model.

When models and theories lead to conclusions that do not correspond to observations, they must be changed or abandoned. There was, for example, a time when it was thought that heat is a kind of substance that is transferred to a body when it is heated. That idea seemed plausible for a time, but was eventually shown to be in conflict with the observation that heat can be generated in unlimited quantity by friction, and so it was discarded.

Newton's law of gravitation describes the gravitational force. In the Newtonian model the planets are represented by particles, and we use only this single law, together with the definitions given by Newton's second law of motion. The motions within the model describe the motions of the real planetary system over a very long span of time. We have put order into a vast number of separate observations. The model describes and predicts what really happens. That's what we

mean when we say that we *understand* the motions of the planetary system.

The success of Newton's law of gravitation goes much further. It was his great insight that it acts between all objects, on earth or elsewhere. That's why it is called the *universal* law of gravitation. This single law describes what happens in a vast variety of situations.

This universality illustrates one of the fundamental aims of science. We try to describe and to explain what happens with as few separate assumptions as possible. If we can describe the motion of the earth around the sun with the same mathematical theory that describes the motion of the falling apple, we have achieved something important, namely an understanding of the relation between two motions that had been thought earlier to be unrelated.

Classical physics and the Newtonian world view

The success of the Newtonian model was so great that the whole world began to be seen as a machine with forces that determine everything that happens. To understand a phenomenon meant to know the forces that were acting and to be able to determine the results of their action, following Newton's laws. The whole universe was looked at as a giant clockwork running according to the laws of Newtonian mechanics, or, as we now call it, "classical" mechanics. Different forces could be incorporated in the model, including the various mechanical pushes and pulls, and later other forces, such as those of electricity and magnetism.

Among the spectacular successes were that the mechanics of wave motion in the air as well as in solid materials could describe the phenomena of sound, and that the mechanics of molecules could describe the phenomena of heat and temperature. Later, as the laws of electricity and magnetism became known, it was recognized that they also lead to a description of the phenomena of the propagation of light and other kinds of "electromagnetic" waves.

Together, the subjects of mechanics, electricity, magnetism, heat, sound, and light were incorporated in the Newtonian model. There seemed to be little reason to doubt that all physical phenomena could be understood and explained within the same framework of what is today called "classical physics." It was tempting to think that the same ideas and methods could be expanded to encompass all of science.

The era of classical physics came to a close near the beginning of the twentieth century, with the development of the theories of relativity, and the realization that classical physics could not account for the existence, the structure, and the behavior of atoms and molecules.

This does not mean that the Newtonian model was then discarded. It continues to be an excellent model. But we now know its limitations. Examples of where we have to go beyond the Newtonian model are at extremely high speeds and very large energies, for which we have to use the special theory of relativity, and at very low temperatures, where quantum effects become important. However, the importance of the theories of relativity and of quantum mechanics goes far beyond these special situations. Our fundamental understanding of structure and interactions, from nuclei to stars, has been profoundly affected by these theories. Still, under many "ordinary" circumstances the Newtonian model and classical physics continue to provide the basic framework and guide to our thinking.

Is the universe programmed?

A peculiar and controversial feature of the Newtonian model is that all motions within it seem to be *determined*: for any particle a knowledge of the initial conditions (the position and velocity at some instant of time) and of the forces (all the forces, for all time) allows the calculation of the position and velocity at any future time. Let's look at that a little further.

The universe is made up of particles. Lots of them. We cannot know the position and velocity of all of them at any given moment. Even if we did they would be different a moment later. But within the framework of classical mechanics each particle *has* a position and a velocity at any moment, whether we know them or not. The forces on a particle depend on its position and velocity with respect to the other particles. It follows that the position and velocity of any particle, at any time, depend on the positions and velocities of all the particles at some moment of time.

The point is not that we might want to know or calculate any or all of the positions and velocities, but rather that they *exist*, and that their values are set and determined. In classical mechanics the set of parameters that describe the universe, i.e., the set of values of the positions and velocities of all of the particles that constitute the universe, is completely determined by the set of these parameters at any given instant of time. Within this framework the future history of the universe develops and unfolds as determined by the state of the universe at the present moment. All of the future is contained in the present.

The urgency and gravity of this question fell away in 1925 when it was realized that classical mechanics does not fully describe the motion of particles (or of any other objects), and has to be extended to include *quantum mechanics*. In quantum mechanics a particle does not have a single path that is determined for it by the forces that act on it. We can only calculate the *probability* of finding the particle at a particular place and moving with a particular velocity at a given time.

There are other questions that first came up in the context of the Newtonian model and its clockwork universe that are still valid today. Do the laws of physics determine everything that we observe? The laws of chemistry are extensions of the laws of physics to systems that are sometimes much more complicated. What about biology? Here the systems are even more complex. Are the laws of physics still applicable? As we have learned more and more about the structures and functions of living matter, we have been able to fit even enormously complex features, such as those of heredity and growth, into the presently known framework of physics.

EXAMPLE 7

(a) A living being, such as a dog, can be thought of as a classical system. Briefly describe the basic elements of the circulatory and digestive systems in terms of this model.

(b) Are there processes that are not well described by this model?

Ans.:

(a) The heart pumps blood through the circulatory system. The lungs take the oxygen from the air, and transport it to different parts of the body by the blood. Food and oxygen undergo chemical changes that result in the action of the muscles and the various organs in the body.

(b) Among the questions that are only partly understood and under active investigation are those of thought, memory, and consciousness. The expectation is that these processes can be described by using the electromagnetic force and the known relations of electromagnetism.

The deterministic character of the Newtonian, classical model seems to require the absence of free will. A more modern model (incorporating quantum mechanics, as developed from 1925 on) does not suffer from this limitation.

It has been speculated that a living organism requires a special "vital" force or ingredient. There is no evidence that this is so. If there are aspects of terms like "soul" and "spirit" that lie outside experimentation and observation, they lie outside the purview of science.

5.3   Mechanics and beyond

So far we have spent most of our time with mechanics, but we have left out quite a lot. There could now be lots of examples and details of techniques. There are many topics in mechanics that we have mentioned, but have not discussed in detail. Projectile motion, circular motion, planetary motion, and oscillating (harmonic) motion come to mind among the more important. We will explore some of these in the problems and projects, and in the next chapters. Electromagnetic forces and the electrical nature of matter will be a major topic later.

With Newton's laws of motion we have the framework for classical mechanics. As long as we stay with this subject, all else is elaboration. There are ramifications and consequences, different quantities, constructs, and relations that illuminate and simplify. We can talk about different kinds of forces. But there will be no other assumptions, no other independent, fundamental physical laws, as long as we stay within the realm of classical mechanics.

With relativity and quantum mechanics we go beyond these limits, with new insights and new and different results. We also go further, in

a different direction, and to different forces, with electromagnetism and with atomic and nuclear physics. But we are finished laying the foundation of classical mechanics, all the mechanics that was known before the invention of the special theory of relativity in 1905. That doesn't mean that we are finished using it. We can apply it to different problems. We can invent new combinations of quantities and units. We will do some of that in the next chapters. And we will use the same basic concepts of displacement, velocity, and acceleration, force, mass, and momentum in every succeeding part of physics.

From elementary particles to composite materials and the edge of the known

We have used the word *particle* to mean *elementary particle*, i.e., an object without internal structure. For particles there are only the four fundamental forces.

Normally, however, we deal with macroscopic objects that consist of large numbers of pieces, such as cells, molecules, and atoms. We speak of other forces between them: friction, pushing, pulling, stretching, squeezing. Are these additional forces that we should add to the fundamental four?

As we look at smaller and smaller scales, we see that these forces are the result of electric forces. When objects touch, some of their atoms come so close that they exert electric forces on each other. These are the forces that we feel and observe, on the larger scale, as friction and as pushes and pulls.

There are good reasons why materials are so difficult to describe. First, quantum mechanics is the basic framework for any interaction between atoms or within them. We will get to this subject later. Second, the number of atoms in even a small piece of matter is huge, of the order of 10^{23} per cm^3. Simplification, approximation, and incompleteness are the rule.

That's very different from what we do when we deal with macroscopic objects, using classical, Newtonian mechanics, where we deal with displacement, velocity, acceleration, and time. In that case, once we know the game, we know the straightforward path from question to answer for each problem. Classical mechanics is so clean, so clear: the model, the assumptions, the methods,

the results—the completeness within its realm of applicability, the reliability, the evident *truth* of it. We have to face the fact that many subjects in physics aren't like that at all.

There is quite a lot of physics that retains the certainty and clarity of Newtonian mechanics. That includes the other subjects that we consider to be parts of classical physics, particularly the electromagnetic theory. It also includes the special theory of relativity and a portion of quantum mechanics.

Some students get the hang of it, learn how to deal with the symbols and equations, feel comfortable with the apparent certainty of the system, and are then surprised, and even disappointed, when they meet physics that is quite different.

It is primarily the science of materials in its broadest sense that is different: atomic and nuclear phenomena, solid and liquid state physics, down to the smallest constituents and up to the stars and galaxies. In each case the object of attention is so complex that we quickly reach the edge of the known. It is not surprising that we need to simplify and approximate. Rather, the surprise should be how much can be said that is simple and straightforward, and at the same time illuminating and descriptive of the essential features.

We need to learn how to move from the well-marked path, with signs that indicate what is allowed and what is forbidden, to the realms where it is not clear which way to go, and where only portions of the way have so far been explored. That's where we are scientists at the frontier of new knowledge.

5.4   Summary

"It's only a theory!" is said often in the newspapers and in politics. We need to remember that most of our scientific knowledge is embodied in theories and models. They are representations of what we observe, with some features left out and some emphasized.

As we look at the ways in which scientific knowledge is accumulated we see that there is no simple "scientific method." There are *observations*, sometimes of specially created situations that we call *experiments*. There is also the analysis of observations, experiments, and other

knowledge, and the creation of *theories* and *models*. A model is an invented representation of a part of the real world. It is simplified and approximate, but attempts to include the essential features of the real system that it is intended to represent. The real system may be so complex that it is difficult or even impossible to analyze. In the model some of the complicating features, such as friction and air resistance, are stripped away.

The word "law" is used for a variety of statements. Most often it is a relation between observed quantities. It may be very general or it may apply only in special situations. It may represent the observations quite precisely or it may be quite approximate. It may be *empirical*, i.e., based on experiments and observation, or it may be *theoretical*, i.e., arrived at by analysis, starting from a *postulate* or *hypothesis*.

In the term "Newton's laws of motion" the word "law" is used differently. We have taken the first two laws to define force and mass. The third law describes the forces between objects that interact with each other.

Velocity, energy, momentum, and others are *constructs* that we have invented to describe observations and quantities derived from observations. We avoid questions of whether one quantity or another is *real* or not, because there is insufficient agreement on the definition of *reality*.

The best definitions are those that provide a definite, quantitative recipe or set of operations for the measurement of a quantity. They are called *operational definitions*.

With Newton's laws of motion and Newton's law of gravitation, a precise description of the solar system, consisting of the sun and its planets, became possible. The success of the procedure and the model led to the notion that other, perhaps all natural phenomena could be described by the forces between the parts of the relevant system and by their motion. A phenomenon would be *explained* by knowing the forces and motions, as in a mechanical clock.

This view was expanded with the knowledge of electric and magnetic forces in the nineteenth century. It formed the basis of what we now call *classical physics*: all motions are determined by the forces, and in fact, so is everything else that

happens. Everything about an object or a system can be predicted by knowing the forces, together with the knowledge of the location of the object and its constituents, and their velocities at some one moment.

The *modern* view is quite different. We now know that what happens cannot be exactly predicted. An inherent uncertainty remains, regardless of how precisely we make the measurements. It is built into the best description that we know, that of *quantum mechanics*, which describes (among other things) how materials are built from atoms and their nuclei.

5.5 Review activities and problems

Guided review

1. When we say that the weight of an object is Mg, and that $g = 9.8$ N/kg, what assumptions are we making, and what model of the earth are we using?

2. Make a list of what we leave out when we calculate the gravitational force between the earth and the moon by using their masses and the relation $F_g = G\frac{M_e M_m}{R^2}$.

3. State Hooke's law. What kind of law is it? What are its limitations? (See also Chapter 6 on Hooke's law.)

4. "A gas consists of molecules that move randomly with a range of speeds."

(a) What would make you say that this is a theoretical statement? What would make you say that this is an empirical statement?

(b) List one or more observations that support it.

5. Explain the circumstances under which T^2 is proportional to R^3 for a planetary system. What are the assumptions that we make when we use this relation?

6. A tree falls in a remote forest, 100 miles from the nearest human being.

You ask your friends Abigail and Beatrice whether the falling tree makes a sound. A. says *yes*, and B. says *no*. Can they both be right? State a definition that makes A.'s answer right and one that makes B.'s answer right.

7. Describe some aspects of a tree as a classical system. Are there aspects that cannot be described this way?

Problems and reasoning skill building

1. "In winter the sun is farther from the earth than in the summer." Describe an observation that supports this hypothesis and one that contradicts it.

2. State Coulomb's law. What kind of law is it? What is its accuracy? What are its limitations?

3. The evaporation of water causes the remaining liquid to cool. List the characteristics of a model that accounts for this observation.

4. Is a theory ever a fact? Describe what each term means.

5. At one time it was thought that "nature abhors a vacuum." Describe the modern model that has replaced this statement.

6. (i) According to the model called "the ideal gas" the volume of a certain amount of gas held at a constant pressure is linearly related to its temperature. (The graph of volume against temperature is a straight line.)

(ii) When the temperature of water vapor decreases, it can "condense" and form liquid water.

Describe the nature of each of these two statements. Do they contradict each other?

Synthesis problems and projects

1. The *greenhouse effect* is the result of two phenomena. One is that all objects radiate electromagnetic energy and absorb some of the electromagnetic energy that falls on them. The radiated energy is different, depending on the temperature of the radiating object. The sun's temperature is such that some of the energy that it radiates is visible. The energy that is radiated by an object at room temperature is not visible. (It is in the "infrared" part of the spectrum.)

The second phenomenon is that some materials allow visible radiation to pass through, but absorb some of the infrared radiation. This is true, for example, for glass and for some gases, including carbon dioxide.

(a) Describe the model that shows how the greenhouse effect may lead to heating of the earth.

(b) What is the hypothesis that links the model to the burning of coal, oil, and natural gas?

(c) What is the nature of the data that are required to investigate the relevance of the model and the hypothesis?

(d) What are some of the limitations of the model?

2. Evolution describes the progression of life forms as a result of mutations and natural selection. Describe the primary features of the theory of evolution and some relevant observations.

3. Describe observations that provide information on the angle between the earth's axis and the ecliptic (the plane in which the earth moves around the sun).

4. Describe the interplay of theory and observation in the development of our understanding of one or more of the following subjects. In each case describe the system, the model, and the testing of the model.

(a) The shape of the earth, beginning with the hypothesis that the earth is flat.

(b) Gravity.

(c) Astrology, i.e., the belief that the positions of the stars and the planets have a significant influence on human beings.

(d) "A broken mirror brings bad luck."

(e) Earthquakes.

5. Last Saturday you had a dish of rice and beans. The next day you had a stomachache that you think might be a result of eating the rice and bean dish.

(a) What is your hypothesis?

(b) Design an experiment to test your hypothesis. What features, will you want to consider?