Introductory Physics

A Mastery-Oriented Curriculum

John D. Mays

Third Edition

NOVARE
SCIENCE & MATH

Seguin, Texas
2019

Published by Novare Science & Math

novarescienceandmath.com

Printed in the United States of America

ISBN: 978-0-9981699-5-8

Novare Science & Math is an imprint of Novare Science & Math LLC.

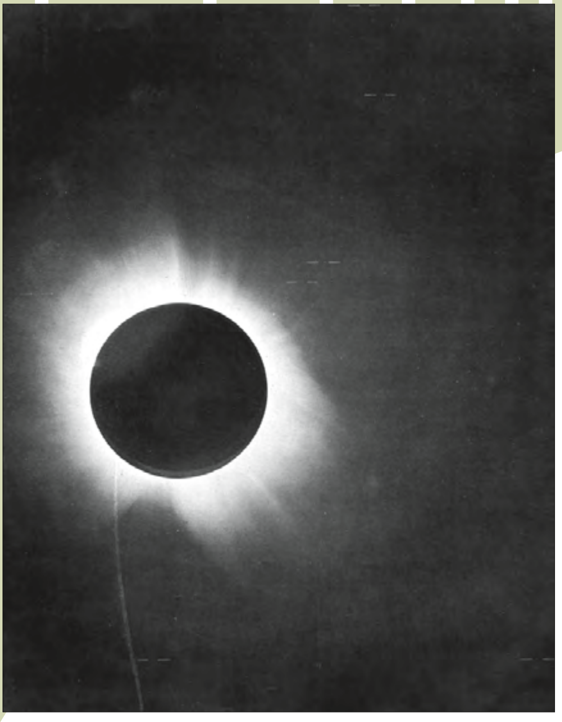
Cover design by Nada Orlic, http://nadaorlic.info/

NOVARE
SCIENCE & MATH

For a catalog of titles published by Novare Science & Math, visit novarescienceandmath.com.

CHAPTER 1

The Nature of Scientific Knowledge



Theory → Hypothesis → Experiment

In 1915, Albert Einstein produced his general theory of relativity. In 1917, Einstein announced an amazing new hypothesis: according to the theory, light traveling through space bends as it passes near a star. In 1919, this hypothesis was confirmed by teams under the leadership of Sir Arthur Eddington, using photographs taken of stars positioned near the sun in the sky during a solar eclipse.

The image above is a positive created from one of Eddington's negatives.

OBJECTIVES

After studying this chapter and completing the exercises, students will be able to do each of the following tasks, using supporting terms and principles as necessary:

1. Define science, theory, hypothesis, and scientific fact.
2. Explain the difference between truth and scientific facts and describe how we obtain knowledge of each.
3. Describe the difference between General Revelation and Special Revelation and relate these to our definition of truth.
4. Describe the "Cycle of Scientific Enterprise," including the relationships between facts, theories, hypotheses, and experiments.
5. Explain what a theory is and describe the two main characteristics of a theory.
6. Explain what is meant by the statement, "a theory is a model."
7. Explain the role and importance of theories in scientific research.
8. State and describe the steps of the "scientific method."
9. Define explanatory, response, and lurking variables in the context of an experiment.
10. Explain why experiments are designed to test only one explanatory variable at a time. Use the procedures the class followed in the Pendulum Experiment as a case in point.
11. Explain the purpose of the control group in an experiment.
12. Describe the possible implications of a negative experimental result. In other words, if the hypothesis is not confirmed, explain what this might imply about the experiment, the hypothesis, or the theory itself.

1.1 Modeling Knowledge

1.1.1 Kinds of Knowledge

There are many different kinds of knowledge. One kind of knowledge is *truth*. As Christians, we are very concerned about truth because of its close relation to knowledge revealed to us by God. The facts and theories of science constitute a different kind of knowledge, and as students of the natural sciences we are also concerned about these.

Some people handle the distinction between the truths of the faith and scientific knowledge by referring to religious teachings as one kind of truth and scientific teaching as a different kind of truth. The problem here is that there are not different kinds of truth. There is only *one* truth, but there *are* different kinds of knowledge. Truth is one kind of knowledge, and scientific knowledge is a different kind of knowledge.

We are going to unpack this further over the next few pages, but here is a taste of where we are going. Scientific knowledge is not static. It is always changing as new discoveries are made. On the other hand, the core teachings of Christianity do not change. They are always true. We know this because God reveals them to us in his Word, which is true. This difference between scientific knowledge and knowledge from Scripture indicates to us that the knowledge we have from the Scriptures is a different kind of knowledge than what we learn from scientific investigations.

I have developed a model of knowledge that emphasizes the differences between what God reveals to us and what scientific investigations teach us. This model is not perfect (no model is), nor is it exhaustive, but it is very useful, as all good models are. Our main goal in the next few sections is to develop this model of knowledge. The material in this chapter is crucial if you wish to have a proper understanding of what science is all about.

To understand science correctly, we need to understand what we mean by scientific knowledge. Unfortunately, there is much confusion among non-scientists about the nature of scientific knowledge and this confusion often leads to misunderstandings when we talk about scientific findings and scientific claims. This is nothing new. Misconceptions about scientific claims have plagued public discourse for thousands of years and continue to do so to this day. This confusion is a severe problem, one much written about within the scientific community in recent years.

To clear the air on this issue, it is necessary to examine what we mean by the term *truth*, as well as the different ways we discover truth. Then we must discuss the specific characteristics of scientific knowledge, including the key scientific terms *fact*, *theory*, and *hypothesis*.

1.1.2 What is Truth and How Do We Know It?

Epistemology, one of the major branches of philosophy, is the study of what we can know and how we know it. Both philosophers and theologians claim to have important insights on the issue of knowing truth, and because of the roles science and religion have played in our culture over the centuries, we need to look at what both philosophers and theologians have to say. The issue we need to treat briefly here is captured in this question: What is truth and how do we know it? In other words, what do we mean when we say something is *true*? And if we can agree on a definition for truth, how can we *know* whether something is true?

These are really complex questions, and philosophers and theologians have been working on them for thousands of years. But a few simple principles will be adequate for our purpose.

As for what truth is, my simple but practical definition is this:

Truth is the way things really are.

Whatever reality is like, that is the truth. If there *really* is life on other planets, then it is true to say, “There is life on other planets.” If you live in Poughkeepsie, then when you say, “I live in Poughkeepsie” you are speaking the truth.

The harder question is: How do we know the truth? According to most philosophers, there are two ways that we can know truth, and these involve either our senses or our use of reason. First, truths that are obvious to us just by looking around are said to be *evident*. It is evident that birds can fly. No proof is needed. So the proposition, “Birds can fly,” conveys truth. Similarly, it is evident that humans can read books and that birds cannot. Of course, when we speak of people knowing truth this way we are referring to people whose perceptive faculties are functioning normally.

The second way philosophers say we can know truth is through the valid use of logic. Logical conclusions are typically derived from a sequence of logical statements called a *syllogism*, in which two or more statements (called *premises*) lead to a conclusion. For example, if we begin with the premises, “All men are mortal,” and, “Socrates was a man,” then it is a valid conclusion to state, “Socrates was mortal.” The truth of the conclusion of a logical syllogism definitely depends on the truth of the premises. The truth of the conclusion also depends on the syllogism having a valid structure. Some logical structures are not logically valid. (These invalid structures are called *logical fallacies*.) If the premises are true and the structure is valid, then the conclusion must be true.

So the philosophers provide us with two ways of knowing truth that most people agree upon—truths can be evident (according to our senses) or they can be proven (by valid use of reason from true premises).

Believers in some faith traditions—including Christianity—argue for a crucial third possibility for knowing truth, which is by revelation from supernatural agents such as God or angels. Jesus said, "I am the way, and the truth, and the life" (John 14:6). As Christians, we believe that Jesus was "God with us" and that all he said and did were revelations of truth to us from God the Father. Further, we believe that the Bible is inspired by God and reveals truth to us. We return to the ways God reveals truth to us at the end of this section.

Obviously, not everyone accepts the possibility of knowing truth by revelation. Specifically, those who do not believe in God do not accept the possibility of revelations from God. Additionally, there are some who accept the existence of a transcendent power or being, but do not accept the possibility of revelations of truth from that power. So this third way of knowing truth is embraced by many people, but certainly not by everyone.

Few people would deny that knowing truth is important. This is why we started our study by briefly exploring what truth is. But this is a book about science, and we need now to move to addressing a different question: what does *science* have to do with truth? The question is not as simple as it seems, as evidenced by the continuous disputes between religious and scientific communities stretching back over the past 700 years. To get at the relationship between science and truth, we first look at the relationship between propositions and truth claims.

1.1.3 Propositions and Truth Claims

Not all that passes as valid knowledge can be regarded as *true*, which I defined in the previous section as "the way things really are." In many circumstances—maybe most—we do not actually *know* the way things really are. People do, of course, often use propositions or statements with the intention of conveying truth. But with other kinds of statements, people intend to convey something else.

Let's unpack this with a few example statements. Consider the following propositions:

1. I have two arms.
2. My wife and I have three children.
3. I worked out at the gym last week.
4. My car is at the repair shop.
5. Texas gained its independence from Mexico in 1836.
6. Atoms are composed of three fundamental particles—protons, neutrons, and electrons.
7. God made the world.

Among these seven statements are actually three different types of claims. From the discussion in the previous section you may already be able to spot two of them. But some of these statements do not fit into any of the categories we explored in our discussion of truth. We can discover some important aspects about these claims be examining them one by one. So suppose for a moment that I, the writer, am the person asserting each of these statements as we examine the nature of the claim in each case.

I have two arms. This is true. I do have two arms, as is evident to everyone who sees me.

My wife and I have three children. This is true. To me it is just as evident as my two arms. I might also point out that it is true regardless of whether other people believe me when I say it. (Of course, someone could claim that I am delusional, but let's just keep it simple here and assume I am in normal possession of my faculties.) This bit about the statement being true regardless of others' acceptance of it comes up because of a slight difference here between the statement about children and the statement about arms. Anyone who looks at me will accept the truth that I have two arms. It will be evident, that is, obvious, to them. But the truth about my children is only really evident to a few people (my wife and I, and perhaps a few doctors and close family members). Nevertheless, the statement is true.

I worked out at the gym last week. This is also true; I did work out last week. The statement is evident to me because I clearly remember going there. Of course, people besides myself must depend on me to know it because they cannot know it directly for themselves unless they saw me there. Note that I cannot prove it is true. I can produce evidence, if needed, but the statement cannot be proven without appealing to premises that may or may not be true. Still, the statement is true.

My car is at the repair shop. Here is a statement that we cannot regard as a truth claim. It is merely a statement about where I understand my car to be at present, based on where I left it this morning and what the people at the shop told me they were going to do with it. For all I know, they may have taken my car joy riding and presently it may be flying along the back roads of the Texas hill country. I *can* say that the statement is correct so far as I know.

Texas gained its independence from Mexico in 1836. We Texans were all taught this in school and we believe it to be correct, but as with the previous statement we must stop short of calling this a truth claim. It is certainly a *historical fact*, based on a lot of historical evidence. The statement is correct so far as we know. But it is possible there is more to that story than we know at present (or will ever know) and none of those now living were there.

Atoms are composed of three fundamental particles—protons, neutrons, and electrons. This statement is, of course, a scientific fact. But like the previous two statements, this statement is not—surprise!—a truth claim. We simply do not know the truth about atoms. The truth about atoms is clearly not evident to our senses. We cannot guarantee the truth of any premises we might use to construct a logical proof about the insides of atoms, so proof is not able to lead us to the truth. And so far as I know, there are no supernatural agents who have revealed to us anything about atoms. So we have no access to knowing how atoms really are. What we do have are the data from many experiments, which may or may not tell the whole story. Atoms may have other components we don't know about yet. The best we can say about this statement is that *it is correct so far as we know* (that is, so far as the scientific community knows).

God made the world. This statement clearly is a truth claim, and we Christians joyfully believe it. But other people disagree on whether the statement is true. I include this example here because we soon see what happens when scientific claims and religious truth claims get confused. I hope you are a Christian, but regardless of whether you are, the issue is important. We all need to learn to speak correctly about the different claims people make.

To summarize this section, some statements we make are evidently or obviously true. But for many statements, we must recognize that we don't know if they actually are true. The best we can say about these kinds of statements—and scientific facts are like this—is that they are correct so far as we know. Finally, there are metaphysical or religious statements about which people disagree; some claim they are true, some deny the same, and some say there is no way to know.

1.1.4 Truth and Scientific Claims

Let's think a bit further about the truth of reality, both natural and supernatural. Most people agree that regardless of what different people think about God and nature, there is some actual truth or *reality* about nature and the supernatural. Regarding nature, there is some full reality about the way, say, atoms are structured, regardless of whether we currently understand that structure correctly. So far as we know, this reality does not shift or change from day to day, at least not since the early history of the universe. So the reality about atoms—the truth about atoms—does not change.

And regarding the supernatural, there is some reality about the supernatural realm, regardless of whether anyone knows what that is. Whatever these realities are, they are *truths*, and these truths do not change either.

Now, I have observed over the years that since (roughly) the beginning of the 20th century, careful scientists do not refer to scientific claims as truth claims. They do not profess to knowing the ultimate truth about how nature *really* is. For example, Niels Bohr, one of the great physicists of the 20th century, said, "It is wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can *say* about nature." Scientific claims are understood to be statements about *our best understanding* of the way things are. Most scientists believe that over time our scientific theories get closer and closer to the truth of the way things really are. But when they are speaking carefully, scientists do not claim that our present understanding of this or that is the truth about this or that.

1.1.5 Truth vs. Facts

Whatever the truth is about the way things are, that truth is presumably absolute and unchanging. If there is a God, then that's the way it is, period. And if matter is made of atoms as we think it is, then that is the truth about matter and it is always the truth. But what we call scientific facts, by their very nature, are not like this. Facts are subject to change, and sometimes do, as new information comes becomes known through ongoing scientific research. Our definitions for truth and for scientific facts need to take this difference into account. As we have seen, truth is the way things really are. By contrast, here is a definition for *scientific facts*:

A scientific fact is a proposition that is supported by a great deal of evidence.

Scientific facts are discovered by observation and experiment, and by making inferences from what we observe or from the results of our experiments.

A scientific fact is *correct so far as we know*, but can change as new information becomes known.

So facts can change. Scientists do not put them forward as truth claims, but as propositions that are correct so far as we know. In other words, scientific facts are *provisional*. They are always subject to revision in the future. As scientists make new scientific discoveries,

Examples of Changing Facts

In 2006, the planet Pluto was declared not to be a planet any more.

In the 17th century, the fact that the planets and moon all orbit the earth changed to the present fact that the planets all orbit the sun, and only the moon orbits the earth.

At present we know of only one kind of matter that causes gravitational fields. This is the matter made up of protons, electrons, and neutrons, which we discuss in a later chapter. But scientists now think there may be another kind of matter contributing to the gravitational forces in the universe. They call it "dark matter" because apparently this kind of matter does not reflect or refract light the way ordinary matter does. (We also study reflection and refraction later on.) For the existence of dark matter to become a scientific fact, a lot of evidence is required, evidence which is just beginning to emerge. If we are able to get enough evidence, then the facts about matter will change.

they must sometimes revise facts that were formerly considered to be correct. But the truth about reality, whatever it is, is absolute and unchanging.

The distinction between truth and scientific facts is crucial for a correct understanding of the nature of scientific knowledge. Facts can change; truth does not.

1.1.6 Revelation of Truth

In Section 1.1.2, we examined the ways we can know truth. Here we need to say a bit more about what Christian theology says about revealed truth.

Christians believe that the supreme revelation of God to us was through Jesus Christ in the incarnation. Those who knew Jesus and those who heard Jesus teach were receiving direct revelation from God. Jesus said, "Whoever has seen me has seen the Father" (John 14:9).

Jesus no longer walks with us on the earth in a physical body (although we look forward to his return when he will again be with us). But Christians believe that when Jesus departed he sent his Holy Spirit to us, and today the Spirit guides us in the truth. According to traditional Christian theology, God continues to reveal truth to us through the Spirit in two ways: *Special Revelation* and *General Revelation*. Special Revelation is the term theologians use to describe truths God teaches us in the Bible, his Holy Word. General Revelation refers to truths God teaches us through the world he made. Sometimes theologians have described Special and General Revelation as the two "books" of God's revelation to us, the book of God's *Word* (the Bible) and the book of God's *Works* (nature). And it is crucial to note that the truths revealed in God's Word and those revealed in his Works *do not conflict*.

Truth is not discovered the same way scientific facts are. Truth is true for all people, all times, and all places. Truth never changes. Here are just a few examples of the many truths revealed in God's Word:

- Jesus is the divine Son of God (Matthew 16:16).
- All have sinned and fall short of what God requires (Romans 3:23).
- All people must die once and then face judgment (Hebrews 9:27).
- God is the creator of all that is (Colossians 1:16, Revelation 4:11).
- God loves us (John 3:16).

Each of these statements is true, and we know they are true because God has revealed them to us in his word. (The reasons for believing God's word are important for all of us to know and understand, but that is a subject for a different course of study.)

1.2 The Cycle of Scientific Enterprise

1.2.1 Science

Having established some basic principles about the distinction between scientific facts and truth, we are now ready to define *science* itself and examine what science is and how it works. Here is a definition:

> Science is the process of using experiment, observation, and logical thinking to build "mental models" of the natural world. These mental models are called *theories*.

We do not and cannot know the natural world perfectly or completely, so we construct models of how it works. We explain these models to one another with descriptions, diagrams, and mathematics. These models are our scientific theories. Theories never explain the world to us perfectly. To know the world perfectly, we would have to know the absolute truth about reality just as God knows it, which in this present age we do not. So theories always have their limits, but we hope they become more accurate and more complete over time, accounting for more and more physical phenomena (data, facts), and helping us to understand the natural world as a coherent whole.

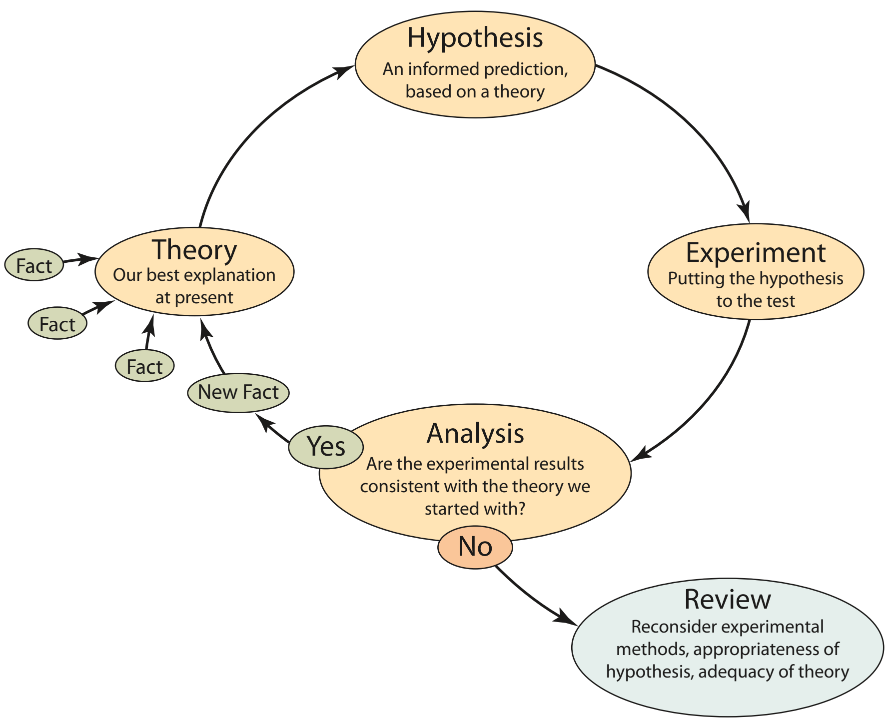
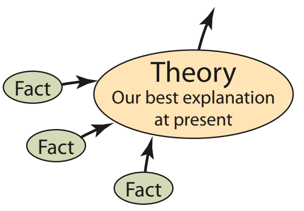


Figure 1.1. The Cycle of Scientific Enterprise.

Scientific knowledge is continuously changing and advancing through a cyclic process that I call the *Cycle of Scientific Enterprise*, represented in Figure 1.1. In the next few sections, we examine the individual parts of this cycle in detail.

1.2.2 Theories

Theories are the grandest thing in science. In fact, it is fair to say that theories are the *glory* of science, and developing good theories is what science is all about. Electromagnetic field theory, atomic theory, quantum theory, the general theory of relativity—these are all theories in physics that have had a profound effect on scientific progress and on the way we all live.[1]



Now, even though many people do not realize it, *all scientific knowledge is theoretically based.* Let me explain. A *theory* is a mental model or explanatory system that explains and relates together most or all of the facts (the data) in a certain sphere of knowledge. A theory is not a hunch or a guess or a wild idea. Theories are the mental structures we use to make sense of the data we have. We cannot understand any scientific data without a theory to organize it and explain it. This is why I write that all scientific knowledge is theoretically based. And for this reason, it is inappropriate and scientifically incorrect to scorn these explanatory systems as "merely a theory" or "just a theory." Theories are explanations that account for a lot of different facts. If a theory has stood the test of time, that means it has wide support within the scientific community.

It is popular in some circles to speak dismissively of certain scientific theories, as if they represent some kind of untested speculation. It is simply incorrect—and very unhelpful—to speak this way. As students in high school science, one of the important things you need to understand is the nature of scientific knowledge, the purpose of theories, and the way scientific knowledge progresses. These are the issues this chapter is about.

All useful scientific theories must possess several characteristics. The two most important ones are:

- The theory accounts for and explains most or all of the related facts.
- The theory enables new hypotheses to be formed and tested.

Theories typically take decades or even centuries to gain credibility. If a theory gets replaced by a new, better theory, this also usually takes decades or even centuries to happen. No theory is ever "proven" or "disproven" and we should not speak of them in this way. We also should not speak of them as being "true" because, as we have seen, we do not use the word "truth" when speaking of scientific knowledge. Instead we speak of facts being correct so far as we know, or of current theories as representing our best understanding, or of theories being successful and useful models that lead to accurate predictions.

An experiment in which the hypothesis is confirmed is said to support the theory. After such an experiment, the theory is stronger but it is not proven. If a hypothesis is not confirmed by an experiment, the theory might be weakened but it is not disproven. Scientists require a great deal of experimental evidence before a new theory can be established as the best explanation for a body of data. This is why it takes so long for theories to become widely accepted. And since no theory ever explains everything perfectly, there are always phe-

1 The term *law* is just a historical (and obsolete) term for what we now call a theory.

nomena we know about that our best theories do not adequately explain. Of course, scientists continue their work in a certain field hoping eventually to have a theory that does explain all of the facts. But since no theory explains everything perfectly, it is impossible for one experimental failure to bring down a theory. Just as it takes a lot of evidence to establish a theory, so it takes a large and growing body of conflicting evidence before scientists abandon an established theory.

At the beginning of this section, I state that theories are mental *models*. This statement needs a bit more explanation. A model is a representation of something, and models are designed for a purpose. You have probably seen a model of the organs in the human body in a science classroom or textbook. A model like this is a physical model and its purpose is to help people understand how the human body is put together. A mental model is not physical; it is an intellectual understanding, although we often use illustrations or physical models to help communicate to one another our mental ideas. But as in the example of the model of the human body, a theory is also a model. That is, a theory is a representation of how part of the world works. Frequently, our models take the form of mathematical equations that allow us to make numerical predictions and calculate the results of experiments. The more accurately a theory represents the way the world works, which we judge by forming new hypotheses and testing them with experiments, the better and more successful the theory is.

To summarize, a successful theory represents the natural world accurately. This means the model (theory) is useful because if a theory is an accurate representation, then it leads

Examples of Famous Theories

In the next chapter, we encounter Einstein's general theory of relativity, one of the most important theories in modern physics. Einstein's theory represents our best current understanding of how gravity works.

Another famous theory we address later is the kinetic theory of gases, our present understanding of how molecules of gas too small to see are able to create pressure inside a container.

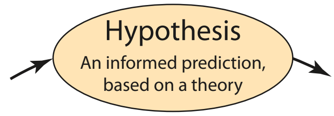
Key Points About Theories

1. A theory is a way of modeling nature, enabling us to explain why things happen in the natural world from a scientific point of view.
2. A theory tries to account for and explain the known facts that relate to it.
3. Theories must enable us to make new predictions about the natural world so we can learn new facts.
4. Strong, successful theories are the glory and goal of scientific research.
5. A theory becomes stronger by producing successful predictions that are confirmed by experiment. A theory is gradually weakened when new experimental results repeatedly turn out to be inconsistent with the theory.
6. It is incorrect to speak dismissively of successful theories because theories are not just guesses.
7. We don't speak of theories as being proven or disproven. Instead, we speak of them in terms such as how successful they have been at making predictions and how accurate the predictions have been.

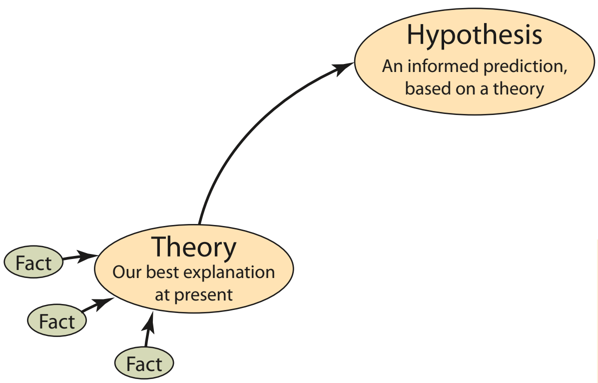
Figure 1.2. Key points about theories.

to accurate predictions about nature. When a theory repeatedly leads to predictions that are confirmed in scientific experiments, it is a strong, useful theory. The key points about theories are summarized in Figure 1.2.

1.2.3 Hypotheses



A *hypothesis* is a positively stated, informed prediction about what will happen in certain circumstances. We say a hypothesis is an *informed* prediction because when we form hypotheses we are not just speculating out of the blue. We are applying a certain theoretical understanding of the subject to the new situation before us and predicting what will happen or what we expect to find in the new situation based on the theory the hypothesis is coming from. Every scientific hypothesis is based on a particular theory.



Often hypotheses are worded as *if-then* statements, such as, "If various forces are applied to a pickup truck, then the truck accelerates at a rate that is in direct proportion to the net force." Every scientific hypothesis is based on a theory and it is the hypothesis that is directly tested by an experiment. If the experiment turns out the way the hypothesis predicts, the hypothesis is confirmed and the theory it came from is strengthened. Of course, the hypothesis may not be confirmed by the experiment. We see how scientists respond to this situation in Section 1.2.6.

Key Points About Hypotheses

1. A hypothesis is an informed prediction about what will happen in certain circumstances.
2. Every hypothesis is based on a particular theory.
3. Well-formed scientific hypotheses must be testable, which is what scientific experiments are designed to do.

Figure 1.3. Key points about hypotheses.

Examples of Famous Hypotheses

Einstein used his general theory of relativity to make an incredible prediction in 1917: that gravity causes light to bend as it travels through space. In the next chapter, you read about the stunning result that occurred when this hypothesis was put to the test.

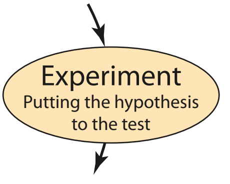
The year 2012 was a very important year for the standard theory in the world of subatomic particles, called the Standard Model. This theory led in the 1960s to the prediction that there are weird particles in nature, now called Higgs Bosons, which no one had ever detected. Until 2012, that is! An enormous machine that could detect these particles, called the Large Hadron Collider, was built in Switzerland and completed in 2008. In 2012, scientists announced that the Higgs Boson had been detected at last, a major victory for the Standard Model, and for Peter Higgs, the physicist who first proposed the particle that now bears his name.

The terms *theory* and *hypothesis* are often used interchangeably in common speech, but in science they mean different things. For this reason you should make note of the distinction.

One more point about hypotheses. A hypothesis that cannot be tested is not a scientific hypothesis. For example, horoscopes purport to predict the future with statements like, "You will meet someone important to your career in the coming weeks." Statements like this are so vague they are untestable and do not qualify as scientific hypotheses.

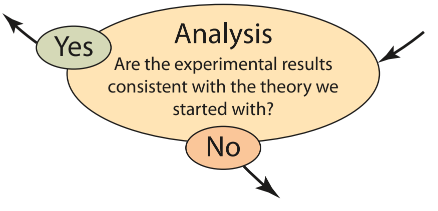
The key points about hypotheses are summarized in Figure 1.3.

1.2.4 Experiments



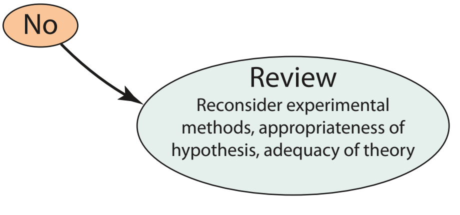
Experiments are tests of the predictions in hypotheses, under controlled conditions. Effective experiments are difficult to perform. Thus, for any experimental outcome to become regarded as a "fact" it must be replicated by several different experimental teams, often working in different labs around the world. Scientists have developed rigorous methods for conducting valid experiments. We consider these briefly in Section 1.3.

1.2.5 Analysis



In the Analysis phase of the Cycle of Scientific Enterprise, researchers must interpret the experimental results. The results of an experiment are essentially data, and data always have to be interpreted. The main goal of this analysis is to determine whether the original hypothesis has been confirmed. If it has, then the experiment has produced new facts that are consistent with the original theory because the hypothesis was based on that theory. As a result, the support for the theory has increased—the theory was successful in generating a hypothesis that was confirmed by experiment. As a result of the experiment, our confidence in the theory as a useful model has increased and the theory is even more strongly supported than before.

1.2.6 Review



If the outcome of an experiment does not confirm the hypothesis, the researchers must consider all the possibilities for why this might have happened. Why didn't our theory, which is our best explanation of how things work, enable us to form a correct prediction? There are a number of possibilities, beginning with the experiment and going backwards around the cycle:

- The experiment may have been flawed. Scientists double check everything about the experiment, making sure all equipment is working properly, double checking the calculations, looking for unknown factors that may have inadvertently influenced the outcome, verifying that the measurement instruments are accurate enough and precise enough to do the job, and so on. They also wait for other experimental teams to try the experiment to see if they get the same results or different results, and then compare.

(Although, naturally, every scientific team likes to be the first one to complete an important new experiment.)

- The hypothesis may have been based on a incorrect understanding of the theory. Maybe the experimenters did not understand the theory well enough, and maybe the hypothesis is not a correct statement of what the theory says will happen.
- The values used in the calculation of the hypothesis' predictions may not have been accurate or precise enough, throwing off the hypothesis' predictions.
- Finally, if all else fails, and the hypothesis still cannot be confirmed by experiment, it is time to look again at the theory. Maybe the theory can be altered to account for this new fact. If the theory simply cannot account for the new fact, then the theory has a weakness, namely, there are facts it doesn't adequately account for. If enough of these weaknesses accumulate, then over a long period of time (like decades) the theory might eventually need to be replaced with a different theory, that is, another, better theory that does a better job of explaining all the facts we know. Of course, for this to happen someone would have to conceive of a new theory, which usually takes a great deal of scientific insight. And remember, it is also possible that the facts themselves can change.

1.3 The Scientific Method

1.3.1 Conducting Reliable Experiments

The so-called *scientific method* that you have been studying ever since about fourth grade is simply a way of conducting reliable experiments. Experiments are an important part of the *Cycle of Scientific Enterprise*, and so the scientific method is important to know. You probably remember studying the steps in the scientific method from prior courses, so they are listed in Table 1.1 without further comment.

We will be discussing variables and measurements a lot in this course, so we should take the opportunity here to identify some of the language researchers use during the experimental process. In a scientific experiment, the researchers have a question they are trying to answer (from the State the Problem step in the scientific method), and typically it is some kind of question about the way one physical quantity affects another one. So the researchers design an experiment in which one quantity can be manipulated (that is, deliberately varied in a controlled fashion) while the value of another quantity is monitored.

A simple example of this in everyday life that you can easily relate to is varying the amount of time you spend each week studying for your math class in order to see what effect the time spent has on the grades you earn. If you reduce the time you spend, will your grades go down? If you increase the time, will they go up? A precise answer depends on a lot

The Scientific Method	
1. State the problem.	5. Collect data.
2. Research the problem.	6. Analyze the data.
3. Form a hypothesis.	7. Form a conclusion.
4. Conduct an experiment.	8. Repeat the work.

Table 1.1. Steps in the scientific method.

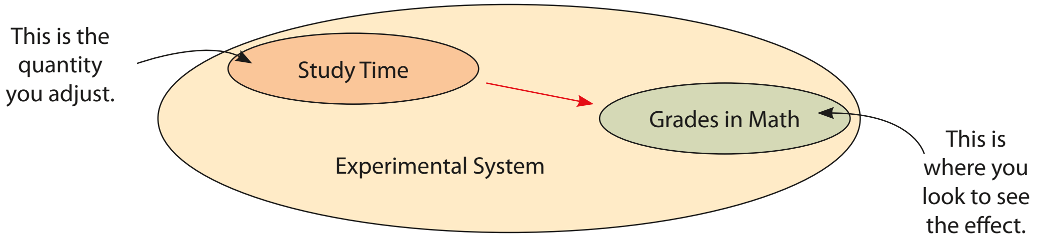


Figure 1.4. Study time and math grades in a simple experimental system.

of things, of course, including the person involved, but in general we would all agree that if a student varies the study time enough we would expect to see the grades vary as well. And in particular, we would expect more study time to result in higher grades. The way your study time and math grades relate together can be represented in a diagram such as Figure 1.4.

Now let us consider this same concept in the context of scientific experiments. An experiment typically involves some kind of complex system that the scientists are modeling. The system could be virtually anything in the natural world—a galaxy, a system of atoms, a mixture of chemicals, a protein, or a badger. The variables in the scientists' mathematical models of the system correspond to the physical quantities that can be manipulated or measured in the system. As I describe the different kinds of variables, refer to Figure 1.5.

1.3.2 Experimental Variables

When performing an experiment, the variable that is deliberately manipulated by the researchers is called the *explanatory variable*. As the explanatory variable is manipulated, the researchers monitor the effect this variation has on the *response variable*. In the example of study time versus math grade, the study time is the explanatory variable and the grade earned is the response variable.

Usually, a good experimental design allows only one explanatory variable to be manipulated at a time so that the researchers can tell definitively what its effect is on the response variable. If more than one explanatory variable were changing during the course of the experiment, researchers may not be able to tell which one was causing the effect on the response variable.

A third kind of variable that plays a role in experiments is the *lurking variable*. A lurking variable is a variable that affects the response variable without the researchers being aware of it. This is undesirable, of course, because with unknown influences present the researchers may not be able to make a correct conclusion about the effect of the known

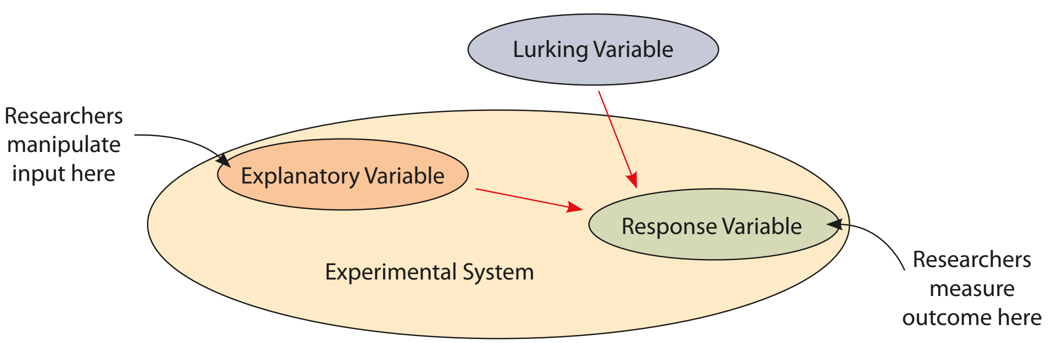


Figure 1.5. The variables in an experimental system.

they do not affect the outcome of the experiment. They do this by making sure there are trees from both the experimental group and the control group in all the different conditions the trees will experience. This way, variations in sunlight, soil type, soil water content, elevation, exposure to wind, and other factors will be experienced equally by trees in both groups.

Chapter 1 Exercises

As you go through the chapters in this book, always answer the questions in complete sentences, using correct grammar and spelling.

Here is a tip that will help improve the quality of your written responses: avoid pronouns! Pronouns almost always make your responses vague or ambiguous. If you want to receive full credit for written responses, avoid them. (Oops. I mean, avoid pronouns!)

Study Questions

Answer the following questions with a few complete sentences.

1. Distinguish between theories and hypotheses.
2. Explain why a single experiment can never prove or disprove a theory.
3. Explain how an experiment can still provide valuable data even if the hypothesis under test is not confirmed.
4. Explain the difference between truth and facts and describe the sources of each.
5. State the two primary characteristics of a theory.
6. Does a theory need to account for all known facts? Why or why not?
7. It is common to hear people say, "I don't accept that; it's just a theory." What is the error in a comment like this?
8. Distinguish between facts and theories.
9. Distinguish between explanatory variables, response variables, and lurking variables.
10. Why do good experiments that seek to test some kind of new treatment or therapy include a control group?
11. Explain specifically how the procedure you followed in the Pendulum Experiment satisfies every step of the "scientific method."
12. This chapter argues that scientific facts should not be regarded as true. Someone might question this and ask, If they aren't true, then what are they good for? Develop a response to this question.
13. Explain what a model is and why theories are often described as models.
14. Consider an experiment that does not deliver the result the experimenters had expected. In other words, the result is negative because the hypothesis is not confirmed. There are many reasons why this might happen. Consider each of the following elements of the Cycle of Scientific Enterprise. For each one, describe

how it might be the driving factor that results in the experiment's failure to confirm the hypothesis.

a. the experiment
b. the hypothesis
c. the theory

15. Identify the explanatory and response variables in the Pendulum Experiment, and identify two realistic possibilities for ways the results may have been influenced by lurking variables.

Do You Know ... *How did Sir Humphry Davy become a hero?*

Sir Humphry Davy (1778–1829) was one of the leading experimenters and inventors in England in the early nineteenth century. He conducted many early experiments with gases; discovered sodium, potassium, and numerous other elements; and produced the first electric light from a carbon arc.

In the early nineteenth century, explosions in coal mines were frequent, resulting in much tragic loss of life. The explosions were caused by the miners' lamps igniting the methane gas found in the mines.

Davy became a national hero when he invented the Davy Safety Lamp (below). This lamp incorporated an iron mesh screen around the flame. The cooling from the iron reduces the flame temperature so the flame does not pass through the mesh, and thus cannot cause an explosion. The Davy Lamp was produced in 1816 and was soon in wide use.

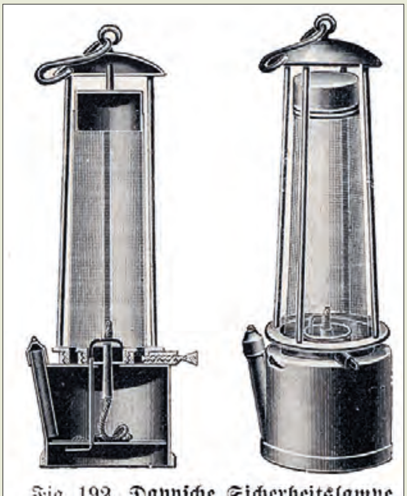


Fig. 192. Davysche Sicherheitslampe

Davy's experimental work proceeded by reasoning from first principles (theory) to hypothesis and experiment. Davy stated, "The gratification of the love of knowledge is delightful to every refined mind; but a much higher motive is offered in indulging it, when that knowledge is felt to be practical power, and when that power may be applied to lessen the miseries or increase the comfort of our fellow-creatures."

CHAPTER 2

Motion

Orrery

Orreries, mechanical models of the solar system, were well-known teaching tools in the 18th century, often forming the centerpiece of lessons on astronomy. They demonstrated Copernicus' theory that the earth and other planets orbit the sun. This example, from around 1750, is smaller but otherwise similar to George II's grand orrery.

This photo of the orrery was taken in the British Museum in London.

OBJECTIVES

Memorize and learn how to use these equations:

$$v = \frac{d}{t} \qquad a = \frac{v_f - v_i}{t}$$

After studying this chapter and completing the exercises, students will be able to do each of the following tasks, using supporting terms and principles as necessary:

1. Define and distinguish between velocity and acceleration.
2. Use scientific notation correctly with a scientific calculator.
3. Calculate distance, velocity, and acceleration using the correct equations, MKS and USCS units, unit conversions, and units of measure.
4. Use from memory the conversion factors, metric prefixes, and physical constants listed in Appendix A.
5. Explain the difference between accuracy and precision and apply these terms to questions about measurement.
6. Demonstrate correct understanding of precision by using the correct number of significant digits in calculations and rounding.
7. Describe the key features of the Ptolemaic model of the heavens, including all the spheres and regions in the model.
8. State several additional features of the medieval model of the heavens and relate them to the theological views of the Christian authorities opposing Copernicanism.
9. Briefly describe the roles and major scientific models or discoveries of Copernicus, Tycho, Kepler, and Galileo in the Copernican Revolution. Also, describe the significant later contributions of Isaac Newton and Albert Einstein to our theories of motion and gravity.
10. Describe the theoretical shift that occurred in the Copernican Revolution and how Christian officials (both supporters and opponents) were involved.
11. State Kepler's first law of planetary motion.
12. Describe how the gravitational theories of Kepler, Newton, and Einstein illustrate the way the Cycle of Scientific Enterprise works.

2.1 Computations in Physics

In this chapter, you begin mastering the skill of applying mathematics to the study of physics. To do this well, you must know a number of things about the way measurements are handled in scientific work. You also need to have a solid problem-solving strategy you can depend on to help you solve problems correctly without becoming confused. These topics are addressed in this chapter.

2.1.1 The Metric System

Units of measure are crucial in science. Science is about making measurements and a measurement without its units of measure is a meaningless number. For this reason, your answers to computations in scientific calculations must *always* show the units of measure.

The two major unit systems you should know about are the SI (from the French *Système international d'unités*), typically known in the United States as the metric system, and

Unit	Symbol	Quantity
meter	m	length
kilogram	kg	mass
second	s	time
ampere	A	electric current
kelvin	K	temperature
candela	Cd	luminous intensity
mole	mol	amount of substance

Table 2.1. The seven base units in the SI unit system.

the USCS (U.S. Customary System). You have probably studied these systems before and should already be familiar with some of the SI units and prefixes, so our treatment here will be brief.

If you think about it, you would probably agree that the USCS is cumbersome. One problem is that there are many different units of measure for every kind of physical quantity. For example, just for measuring length or distance we have the inch, foot, yard, and mile. The USCS is also full of random numbers like 3, 12, and 5,280, and there is no inherent connection between units for different types of quantities.

By contrast, the SI system is simple and has many advantages. There is usually only one basic unit for each kind of quantity, such as the meter for measuring length. Instead of having many unrelated units of measure for measuring quantities of different sizes, fractional and multiple prefixes based on powers of ten are used with the units to accommodate various sizes of measurements.

A second advantage is that since quantities with different prefixes are related by some power of ten, unit conversions can often be performed mentally. To convert 4,555 ounces into gallons, we first have to look up the conversion from ounces to gallons (which is hard to remember), and then use a calculator to perform the conversion. But to convert 40,555 cubic centimeters into cubic meters is simple—simply divide by 1,000,000 and you have 0.040555 m^3. (If you are not clear on the reason for dividing by 1,000,000, just hold on until we get to the end of Section 2.1.3.)

Another SI advantage is that the units for different types of quantities relate to one another in some way. Unlike the gallon and the foot, which have nothing to do with each other, the liter (a volume) relates to the centimeter (a length): 1 liter = 1,000 cubic centimeters.[1] For all these reasons, the USCS is not used much in scientific work. The SI system is the international standard and it is important to know it well.

In the SI unit system, there are seven *base units*, listed in Table 2.1. (In this text, we use only the first five of them.) There are also many additional units of measure, known as *derived units*. All the derived units are formed by various combinations of base units. To illustrate, below are a few examples of derived units that we discuss and use in this book. Note, however, that we won't be working much with the messy fractions; they are simply shown to illustrate how base units are combined to form derived units.

- the newton (N) is the SI unit for measuring force: $1\ \text{N} = 1\ \dfrac{\text{kg}\cdot\text{m}}{\text{s}^2}$
- the joule (J) is the SI unit for measuring energy: $1\ \text{J} = 1\ \dfrac{\text{kg}\cdot\text{m}^2}{\text{s}^2}$
- the watt (W) is the SI unit for measuring power: $1\ \text{W} = 1\ \dfrac{\text{kg}\cdot\text{m}^2}{\text{s}^3}$

1 The liter is not actually an official SI unit of measure, but it is used all the time anyway in scientific work.

Using the SI system requires knowing the units of measure—base and derived—and the prefixes that are applied to the units to form fractional units (such as the centimeter) and multiple units (such as the kilometer). The complete list of metric prefixes is shown in Appendix A in Table A.1. The short list of prefixes you need to know by memory for use in this course is in Table A.2. Note that even though the kilogram is a base unit, prefixes are not added to the kilogram. Instead, prefixes are added to the gram to form units such as the milligram and microgram.

2.1.2 MKS Units

A handy subset of the SI system is the so-called *MKS system*. The MKS system uses only base units—such as the *meter*, *kilogram*, and *second* (hence, "MKS") as units for mass, length, and time—along with other units derived from the base units. The mass, length, and time units, and the symbols and variables used with them, are listed in Table 2.2.

Variable	Variable Symbol	Unit	Unit Symbol
length	*d* (distance) *L* (length) *h* (height) *r* (radius), etc.	meter	m
mass	*m*	kilogram	kg
time	*t*	second	s

Table 2.2. The three base units in the MKS system.

Dealing with different systems of units can become quite confusing. But the wonderful thing about sticking to the MKS system is that *any calculation performed with MKS units produces a result in MKS units*. This is why the MKS system is so handy. The MKS system dominates calculations in physics and we use it almost all the time in this course.

To convert the units of measure given in problems into MKS units, you must know the conversion factors listed in Appendix A in Tables A.2, A.3, and A.4. Table A.5 lists several common unit conversions that you are not required to memorize but should have handy when working problem assignments.

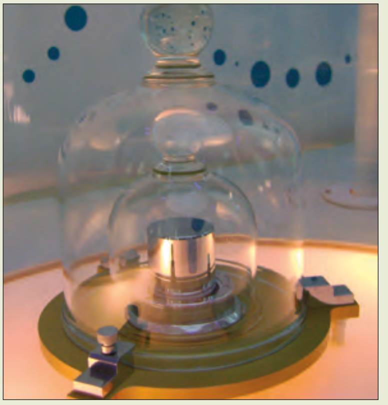
2.1.3 Converting Units of Measure

One of the most basic skills scientists and engineers use is re-expressing quantities into equivalent quantities with different units of measure. These calculations are called *unit conversions*. Mastery of this skill is essential for any student in high school science, and you use it *a lot* in this course. You have studied unit conversions in your math classes for the past few years. But this skill is so important in science that we are going take the time in this section to review in detail how to perform unit conversions.

Let's begin with the basic principle of how this works. First, you know that multiplying any value by unity (one) leaves its value unchanged. Second, you also know that in any fraction if the numerator and denominator are equivalent, the value of the fraction is *unity*, which means *one*. A "conversion factor" is simply a fractional expression in which the numerator and denominator are equivalent ways of writing the same physical quantity. This means a conversion factor is just a special way of writing unity (one). Third, we know that when multiplying fractions, factors that appear in both the numerator and denominator may be "cancelled out." So when performing common unit conversions, what we are doing is repeatedly multiplying our given quantity by unity so that cancellations alter the units of measure until they are expressed the way we wish. Since all we are doing is multiplying by one, the value of our original quantity is unchanged; it simply looks different because it is expressed with different units of measure.

Do You Know ... *How is the kilogram defined?*

The definitions of the base units are fascinating and they all have interesting stories behind them. The official definition of the second is based on the waves of light emitted by cesium atoms. The meter is defined as the distance light travels in a specific tiny fraction of a second (1/299,792,458 second). The kilogram is the only base unit that is still defined by a man-made physical object (an *artifact*). It is also the only base unit that uses a metric prefix. The official kilogram is a golf-ball sized platinum cylinder kept in a vault in Paris, France. There are a number of copies of the official kilogram stored in different countries. One of these replicas is shown to the right. In 2014, officials decided to explore new possibilities for defining the kilogram that use only natural constants.



Let me elaborate a bit more on the idea of unity I mention above, using one common conversion factor as an example. School kids all learn that there are 5,280 feet in one mile, which means 5,280 ft = 1 mi. One mile and 5,280 feet are equivalent ways of writing the same length. If we place these two expressions into a fraction, the numerator and denominator are equivalent, so the value of the fraction is unity, regardless of the way we write it. The equation 5,280 ft = 1 mi can be written in a conversion factor two different ways, and the fraction equals unity either way:

$$\frac{5280\text{ ft}}{1\text{ mi}}=\frac{1\text{ mi}}{5280\text{ ft}}=1$$

So if you have a measurement such as 43,000 feet that you wish to re-express in miles, the conversion calculation is written this way:

$$43{,}000\text{ ft}\cdot\frac{1\text{ mi}}{5280\text{ ft}}=8.1\text{ mi}$$

There are two important comments to make here. First, since any conversion factor can be written two ways (depending on which quantity is placed in the numerator), how do we know which way to write the conversion factor? Well, we know from algebra that when we have quantities in the numerator of a fraction that are multiplied, and quantities in the denominator of the fraction that are multiplied, any quantities that appear in both the numerator and denominator cancel. Most units of measure are mathematically treated as multiplied quantities that can be cancelled out.[2] In the example above, we desire that "feet" in the given quantity (which is in the numerator) cancels out, so the conversion factor is written with feet in the denominator and miles in the numerator.

Second, if you perform the calculation above, the result that appears on your calculator screen is 8.143939394. So why didn't I write down all those digits in my result? Why did I round my answer off to simply 8.1 miles? The answer to that question has to do with the *sig-*

2 An example of a unit that cannot always be treated this way is the degree Fahrenheit.

nificant digits in the value 43,000 ft that we started with. We address the issue of significant digits later in this chapter, but in the examples that follow I always write the results with the correct number of significant digits for the values involved in the problem.

There are several important techniques you must use to help you perform unit conversions correctly; these are illustrated below with examples. You should rework each of the examples on your own paper as practice to make sure you can do them correctly. As a reminder, the conversion factors used in the examples below are all listed in Appendix A. You should study Appendix A to see which ones you must know by memory and which ones are provided to you on quizzes.

1 Use only horizontal bars in your unit fractions. Never use slant bars.

In printed materials, one often sees values written with a slant fraction bar in the units, as in the value 35 m/s. Although writing the units this way is fine for a printed document, you should not write values this way when you are performing unit conversions. This is because it is easy to get confused and not notice that one of the units is in the denominator in such an expression (s, or seconds, in my example), and the conversion factors used must take this into account.

▼ Example 2.1

Convert 57.66 mi/hr into m/s.

Writing the given quantity with a horizontal bar makes it clear that "hour" is in the denominator. This helps you to write the hour-to-seconds factor correctly.

$$57.66\ \frac{\text{mi}}{\text{hr}} \cdot \frac{1609\ \text{m}}{\text{mi}} \cdot \frac{1\ \text{hr}}{3600\ \text{s}} = 25.77\ \frac{\text{m}}{\text{s}}$$

Now that you have your result, you may write it as 25.77 m/s if you wish, but do not use slant fraction bars in the units when you are working out the unit conversion.

▲

2 The term "per" implies a fraction.

Some units of measure are commonly written with a "p" for "per," such as mph for miles per hour or gps for gallons per second. Change these expressions to fractions with horizontal bars when you work out the unit conversion.

▼ Example 2.2

Convert 472.15 gps to L/hr.

When you write down the given quantity, change the gps to gal/s, and write these units with a horizontal bar:

$$472.15\ \frac{\text{gal}}{\text{s}} \cdot \frac{3.785\ \text{L}}{1\ \text{gal}} \cdot \frac{3600\ \text{s}}{1\ \text{hr}} = 6{,}434{,}000\ \frac{\text{L}}{\text{hr}}$$

▲

3 Use the $\boxed{\times}$ and $\boxed{\div}$ keys correctly when entering values into your calculator.

When dealing with several numerator terms and several denominator terms, multiply all the numerator terms together first, hitting the $\boxed{\times}$ key between each, then hit the $\boxed{\div}$ key and enter all the denominator terms, hitting the $\boxed{\div}$ key between each. This way you do not need to write down intermediate results and you do not need to use any parentheses.

Example 2.3

Convert 43.17 mm/hr into km/yr.

The setup with all the conversion factors is as follows:

$$43.17\ \frac{\text{mm}}{\text{hr}} \cdot \frac{1\ \text{m}}{1000\ \text{mm}} \cdot \frac{1\ \text{km}}{1000\ \text{m}} \cdot \frac{24\ \text{hr}}{1\ \text{day}} \cdot \frac{365\ \text{day}}{1\ \text{yr}} = 0.378\ \frac{\text{km}}{\text{yr}}$$

To execute this calculation in your calculator, enter the values and operations in this sequence:

$$43.17 \times 24 \times 365 \div 1000 \div 1000 =$$

4 When converting units for area and volume such as cm^2 or m^3, use the appropriate length conversion factor twice for areas or three times for volumes.

The unit "cm^2" for an area means the same thing as "cm × cm." Likewise, "m^3" means "m × m × m." So when you use a length conversion factor such as 100 cm = 1 m or 1 in = 2.54 cm, you must use it twice to get squared units (areas) or three times to get cubed units (volumes).

Example 2.4

Convert 3,550 cm^3 to m^3.

$$3550\ \text{cm}^3 \cdot \frac{1\ \text{m}}{100\ \text{cm}} \cdot \frac{1\ \text{m}}{100\ \text{cm}} \cdot \frac{1\ \text{m}}{100\ \text{cm}} = 0.00355\ \text{m}^3$$

Notice in Example 2.4 that the unit cm occurs three times in the denominator, giving us cm^3 when they are all multiplied together. This cm^3 term in the denominator cancels with the cm^3 term in the numerator. And since the m unit occurs three times in the numerator, they multiply together to give us m^3 for the units in our result. Notice also that the denominator is $100 \cdot 100 \cdot 100$ = 1,000,000. This is why I write in Section 2.1.1 that to convert from cm^3 to m^3 we just divide by 1,000,000. Pay attention to this and don't make the common (and silly) mistake of dividing by 100!

This issue only arises when you have a unit raised to a power, such as when using a length unit to represent an area or a volume. When using a conversion factor such as 3.785 L = 1 gal, the units of measure are written using units that are strictly volumetric (liters and gallons), and are not obtained from lengths the way in^2, ft^2, cm^3, and m^3 are. Another common unit that uses a power is acceleration, which has units of m/s^2 in the MKS unit system.

▼ Example 2.5

Convert 5.85 mi/hr^2 into MKS units.

$$5.85\ \frac{\text{mi}}{\text{hr}^2}\cdot\frac{1609\ \text{m}}{1\ \text{mi}}\cdot\frac{1\ \text{hr}}{3600\ \text{s}}\cdot\frac{1\ \text{hr}}{3600\ \text{s}}=0.000726\ \frac{\text{m}}{\text{s}^2}$$

With this example you see that since the "hour" unit is squared in the given quantity, the conversion factor converting hours to seconds must appear twice in the conversion calculation.

▲

2.1.4 Accuracy and Precision

The terms *accuracy* and *precision* refer to the limitations inherent in making measurements. Science is all about investigating nature and to do that we must make measurements. Accuracy relates to *error*, which is the difference between a measured value and the true value. The lower the error is in a measurement, the better the accuracy. Error can be caused by a number of different factors, including human mistakes, malfunctioning equipment, incorrectly calibrated instruments, or unknown factors that influence a measurement without the knowledge of the experimenter. All measurements contain error because (alas!) perfection is simply not a thing we have access to in this world.

Precision refers to the resolution or degree of "fine-ness" in a measurement. The limit to the precision obtained in a measurement is ultimately dependent on the instrument used to make the measurement. If you want greater precision, you must use a more precise instrument. The precision of a measurement is indicated by the number of *significant digits* (or significant figures) included when the measurement is written down (see next section).

Figure 2.1 is a photograph of a machinist's rule and an architect's scale set side by side. Since the marks on the two scales line up consistently, these two scales are equally accurate. But the machinist's rule (on top) is more precise. The architect's scale is marked in 1/16-inch increments, but the machinist's rule is marked in 1/64-inch increments.

It is important that you are able to distinguish between accuracy and precision. Here is an example to illustrate the difference. Let's say Shana and Marius each buy digital thermometers for their homes. The thermometer Shana buys cost \$10 and measures to the nearest 1°F. Marius pays \$40 and gets one that reads to the nearest 0.1°F. Note that on a day when the actual temperature is 95.1°F, if the two thermometers are reading accurately Shana's thermometer reads 95° and Marius' reads 95.1°. Thus, Marius' thermometer is more precise.

Now suppose Shana reads the directions and properly installs the sensor for her new ther-

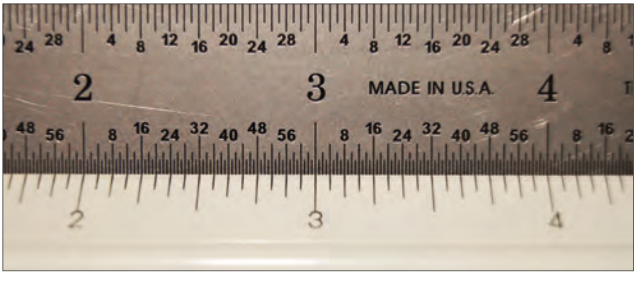


Figure 2.1. The accuracy of these two scales is the same, but the machinist's rule on the top is more precise.

mometer in the shade. Marius doesn't read the directions and mounts his sensor in the direct sunlight, which causes a significant error in the measurement for much of the day. The result is that Shana has lower-precision, higher-accuracy measurements!

2.1.5 Significant Digits

The precision in any measurement is indicated by the number of *significant digits* it contains. Thus, the number of digits we write in any measurement we deal with in science is very important. The number of digits is meaningful because it shows the precision present in the instrument used to make the measurement.

Let's say you are working a computational exercise in a science book. The problem tells you that a person drives a distance of 110 miles at an average speed of 55 miles per hour and wants you to calculate how long the trip takes. The correct answer to this problem *will be different* from the correct answer to a similar problem with given values of 110.0 miles and 55.0 miles per hour. And if the given values are 110.0 miles and 55.00 miles per hour, the correct answer is different yet again. Mathematically, of course, all three answers are the same. If you drive 110 miles at 55 miles per hour, the trip takes two hours. But scientifically, the correct answers to these three problems are different: 2.0 hours, 2.00 hours, and 2.000 hours, respectively. The difference between these cases is in the precision indicated by the given data, which are *measurements*. (Even though this is just a made-up problem in a book and not an actual measurement someone made in an experiment, the given data are still measurements. There is no way to talk about distances or speeds without talking about measurements, even if the measurements are only imaginary or hypothetical.)

When you perform a calculation with physical quantities (measurements), you cannot simply write down all the digits shown by your calculator. The precision inherent in the measurements used in a computation governs the precision in any result you calculate from those measurements. And since the precision in a measurement is indicated by the number of significant digits, data and calculations must be written with the correct numbers of significant digits. To do this, you need to know how to count significant digits and you must use the correct number of significant digits in all your calculations and experimental data.

Correctly counting significant digits involves four different cases:

1. Rules for determining how many significant digits there are in a given measurement.
2. Rules for writing down the correct number of significant digits in a measurement you are making and recording.
3. Rules for computations you perform with measurements—multiplication and division.
4. Rules for computations you perform with measurements—addition and subtraction.

In this course, we do not use the rules for addition and subtraction, so we leave those for a future course (probably chemistry). We now address the first three cases, in order.

Case 1 We begin with the rule for determining how many significant digits there are in a given measurement value. The rule is as follows:

> The number of significant digits (or figures) in a number is found by counting all the digits from left to right beginning with the first nonzero digit on the left. When no decimal is present, trailing zeros are not considered significant.

Let's apply this rule to several example values to see how it works:

15,679 This value has five significant digits.

21.0005 This value has six significant digits.

37,000 This value has only two significant digits because when there is no decimal trailing zeros are not significant. Notice that the word *significant* here is a reference to the *precision* of the measurement, which in this case is rounded to the nearest thousand. The zeros in this value are certainly *important*, but they are not *significant* in the context of precision.

0.0105 This value has three significant digits because we start counting with the first nonzero digit on the left.

0.001350 This value has four significant digits. Trailing zeros count when there is a decimal.

The significant digit rules enable us to tell the difference between two measurements such as 13.05 m and 13.0500 m. Mathematically, of course, these values are equivalent. But they are different in what they tell us about the process of how the measurements were made. The first measurement has four significant digits. The second measurement is more precise. It has six significant digits and would come from a more precise instrument.

Now, just in case you are bothered by the zeros at the end of 37,000 that are not significant, here is one more way to think about significant digits that may help. The precision in a measurement depends on the instrument used to make the measurement. If we express the measurement in different units, this should not change the precision. A measurement of 37,000 grams is equivalent to 37 kilograms. Whether we express this value in grams or kilograms, it still has two significant digits.

Case 2 The second case addresses the rules that apply when you record a measurement yourself, rather than reading a measurement someone else has made. When you take measurements yourself, as you do in laboratory experiments, you need to know the rules for which digits are significant in the reading you are taking on the measurement instrument. The rule for taking measurements depends on whether the instrument you are using is a digital instrument or an analog instrument. Here are the rules for these two possibilities:

Rule 1 for digital instruments

For the digital instruments commonly found in high school or undergraduate science labs, assume all the digits in the reading are significant, except leading zeros.

Rule 2 for analog instruments

The significant digits in a measurement include all the digits known with certainty, plus one digit at the end that must be estimated between the finest marks on the scale of your instrument.

The first of these rules is illustrated in Figure 2.2. The reading on the left has leading zeros, which do not count as significant. Thus, the first reading has three significant digits.

Figure 2.2. With digital instruments, all digits are significant except leading zeros. Thus, the numbers of significant digits in these readings are, from left to right, three, three, five, and five.

The second reading also has three significant digits. The third reading has five significant digits.

The fourth reading also has five significant digits because with a digital display, the only zeros that don't count are the leading zeros. Trailing zeros are significant with a digital instrument. However, when you write this measurement down, you must write it in a way that shows those zeros to be significant. The way to do this is by using scientific notation. Thus, the right-hand value in Figure 2.2 must be written as 4.2000×10^4.

Dealing with digital instruments is actually more involved than the simple rule above implies, but the issues involved go beyond what we typically deal with in introductory or intermediate science classes. So, simply take your readings and assume that all the digits in the reading except leading zeros are significant.

Now let's look at some examples illustrating the rule for analog instruments. Figure 2.3 shows a machinist's rule being used to measure the length in millimeters (mm) of a brass block. We know the first two digits of the length with certainty; the block is clearly between 31 mm and 32 mm long. We have to estimate the third significant digit. The scale on the rule is marked in increments of 0.5 mm. Comparing the edge of the block with these marks, I would estimate the next digit to be a 6, giving a measurement of 31.6 mm. Others might estimate the last digit to be 5 or 7; these small differences in the last digit are unavoidable because the last digit is estimated. Whatever you estimate the last digit to be, two digits of this measurement are known with certainty, the third digit is estimated, and the measurement has three significant digits.

The photograph in Figure 2.4 shows a measurement in milliliters (mL) being taken with a piece of apparatus called a *buret*—a long glass tube used for measuring liquid volumes. Notice in this figure that when measuring liquid volume the surface of the liquid curls up at the edge of the cylinder. This curved surface is called a *meniscus*. The liquid measurement must be made at the bottom of the meniscus for most liquids, including water. The scale on the buret shown is marked in increments of 0.1 mL. This means we estimate to the nearest 0.01 mL. To one person, the bottom of the meniscus (the black curve) may appear to be just below 2.2 mL, so that person would call this measurement 2.21 mL. To someone else, it may seem that the bottom of the meniscus is right on 2.2, in which case that person would call the reading 2.20 mL. Either way, the reading has three significant digits and the last digit is estimated to be either 1 or 0.

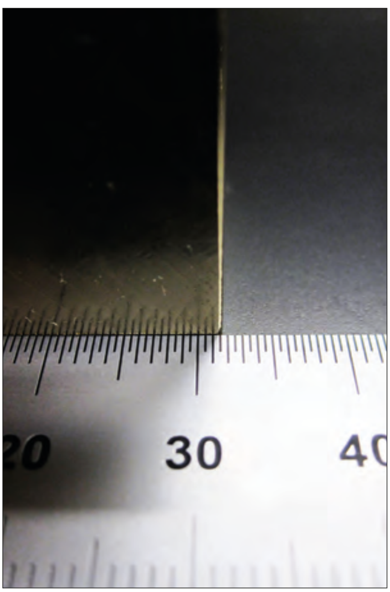


Figure 2.3. Reading the significant digits with a machinist's rule.

As a third example, Figure 2.5 shows a liquid volume measurement being taken with a piece of apparatus called a *graduated cylinder*. (We use graduated cylinders in an experiment we perform later on in this course.) The scale on the graduated cylinder shown is marked in increments of 1 mL. In the photo, the entire meniscus appears silvery in color with a black curve at the bottom. For the liquid shown in the figure, we know the first two digits of the volume measurement with certainty because the reading at the bottom of the meniscus is clearly between 82 mL and 83 mL. We have to estimate the third digit, and I would estimate the black line to be at 40% of the distance between 82 and 83, giving a reading of 82.4 mL. Someone else might read 82.5 mL, or even 82.6 mL.

It is important for you to keep the significant digits rules in mind when you are taking measurements and entering data for your lab reports. The data in your lab journal and the values you use in your calculations and report must correctly reflect the use of the significant digits rules as they apply to the actual instruments you use to take your measurements. Note also the helpful fact that when a measurement is written in scientific notation, the digits written in the stem (the numerals in front of the power of 10) *are* the significant digits.

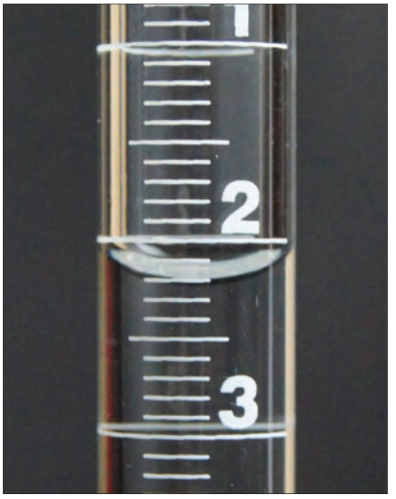


Figure 2.4. Reading the significant digits on a buret.

Figure 2.5. Reading the significant digits on a graduated cylinder.

Case 3 The third case of rules for significant digits applies to the calculations (multiplication and division) you perform with measurements. The main idea behind the rule for multiplying and dividing is that the precision you report in your result cannot be higher than the precision you have in the measurements to start with. The precision in a measurement depends on the instrument used to make the measurement, nothing else. Multiplying and dividing things cannot improve that precision, and thus your results can be no more precise than the measurements that go into the calculations. In fact, your result can be no more precise than the *least precise value* used in the calculation. The least precise value is, so to speak, the "weak link" in the chain, and a chain is no stronger than its weakest link.

There are two rules for combining the measured values into calculated values, including any unit conversions that must be performed. Here are the two rules for using significant digits in our calculations in this course:

Rule 1

Count the significant digits in each of the values you use in a calculation, including the conversion factors you use. (Exact conversion factors are not considered.) Determine how many significant digits there are in the least precise of these values. The result of your calculation must have this same number of significant digits.

Rule 1 is the rule for multiplying and dividing, which is what most of our calculations entail. (As I mentioned previously, there is another rule for adding and subtracting that you will learn when you take chemistry.)

Rule 2

When performing a multi-step calculation, you must keep at least one extra digit during intermediate calculations and round off to the final number of significant digits you need at the very end. This practice ensures that small round-off errors don't add up during the calculation. This extra digit rule also applies to unit conversions performed as part of the computation.

As I present example problems in the coming chapters, I frequently refer to these rules and show how they apply to the example at hand. As you take your quizzes, your instructor might give you a few weeks to practice and master the correct use of significant digits without penalizing you for mistakes. But get this skill down as soon as you can because soon you must use significant digits correctly in your computations to obtain the highest scores on your quizzes.

2.1.6 Scientific Notation

You have probably studied scientific notation before. However, in this course you must master it, including the use of the special key found on scientific calculators for working with values in scientific notation. Mastery of scientific notation is important because working with values in scientific notation is a basic and common occurrence in scientific work. We review the basic principles next.

Mathematical Principles Scientific notation is a way of expressing very large or very small numbers without all the zeros, unless the zeroes are *significant*. This is of enormous benefit when one is dealing with a value such as 0.0000000000001 cm (the approximate diameter of an atomic nucleus). The basic idea will be clear from a few examples.

Let's say we have the value 3,750,000. This number is the same as 3.75 million, which can be written as $3.75 \times 1{,}000{,}000$. Now, 1,000,000 itself can be written as 10^6 (which means one followed by six zeros), so our original number can be expressed equivalently as 3.75×10^6. This expression is in scientific notation. The numerals in front, the stem, are always written as one digit followed by a decimal and the other digits. The multiplied 10 raised to a power has the effect of moving the decimal over as many places as necessary to recreate our original number.

As a second example, the current population of earth is about 7,290,000,000, or 7.29 billion. One billion has nine zeros, so it can be written as 10^9. So we can express the population of earth in scientific notation as 7.29×10^9.

When dealing with extremely small numbers such as 0.000000016, the process is the same, except the power on the 10 is negative. The easiest way to think of it is to count how many places the decimal in the value must be moved over to get 1.6. To get 1.6, the decimal has to be moved to the right eight places, so we write our original value in scientific notation as 1.6×10^{-8}.

Using Scientific Notation with a Scientific Calculator All scientific calculators have a key for entering values in scientific notation. This key is labeled EE or EXP on most calculators, but others use a different label.[3] It is *very* common for those new to scientific calculators to use this key incorrectly and obtain incorrect results. So read carefully as I outline the general procedure.

The whole point of using the [EE] key is to make keying in the value as quick and error-free as possible. When using the scientific notation key to enter a value, you do not press the [×] key, nor do you enter the 10. The scientific calculator is designed to reduce all this key entry, and the potential for error, by use of the scientific notation key. You only enter the stem of the value and the power on the ten and let the calculator do the rest.

Here's how. To enter a value, simply enter the digits and decimal in the stem of the number, then hit the [EE] key, then enter the power on the ten. The value is now entered and you may do with it as you wish. As an example, to multiply the value 7.29×10^9 by 25 using a standard scientific calculator, the sequence of key strokes is as follows:

7.29 [EE] 9 [×] 25 [=]

Notice that between the stem and the power the only key pushed is the [EE] key.

When entering values in scientific notation with negative powers on the 10, the [+/−] key is used before the power to make the power negative. Thus, to divide 1.6×10^{-8} by 36.17, the sequence of key strokes is:

1.6 [EE] [+/−] 8 [÷] 36.17 [=]

Again, neither the "10" nor the "×" sign that comes before it is keyed in. The [EE] key has these built in.

Students sometimes wonder why it is incorrect to use the [10^x] key for scientific notation. To execute 7.29×10^9 times 25, they are tempted to enter the following:

7.29 [×] [10^x] 9 [×] 25 [=]

The answer is that sometimes this works, and sometimes it doesn't, and calculator users must use key entries that *always* work. The scientific notation key ([EE]) keeps a value in scientific notation all together as one number. That is, when the [EE] key is used, then to the calculator 7.29×10^9 is not two numbers, it is a single numerical value. But when the [×] key is manually inserted, the calculator treats the numbers separated by the [×] key as two separate values. This causes the calculator to render an *incorrect* answer for a calculation such as

$$\frac{3.0\times10^{6}}{1.5\times10^{6}}$$

The denominator of this expression is exactly half the numerator, so the value of this fraction is obviously 2. But when using the [10^x] key, the 1.5 and the 10^6 in the denominator are separated and treated as separate values. The calculator then performs the following calculation:

$$\frac{3.0\times10^{6}}{1.5}\times10^{6}$$

3 One infuriating model uses the extremely unfortunate label [$x10^x$] which looks a *lot* like [10^x], a different key with a completely different function.

This comes out to 2,000,000,000,000 (2×10^{12}), which is not the same as 2!

The bottom line is that the EE key, however it may be labeled, is the correct key to use for scientific notation.

2.1.7 Problem Solving Methods

Organizing problems on your paper in a reliable and orderly fashion is an essential practice. Physics problems can get very complex, and proper solution practices can often make the difference between getting most or all of the points for a problem and getting few or none. Each time you start a new problem, you must set it up and follow the steps according to the outline presented in the box on pages 36 and 37, entitled *Universal Problem Solving Method*. It is very important that you always show all your work. Do not give in to the temptation to skips steps or take shortcuts. Develop correct habits for problem solving and stick with them!

2.2 Motion

In this course, we address two types of *motion*: motion at a constant *velocity*, when an object is not accelerating, and motion with a *uniform acceleration*. Defining these terms is a lot simpler if we stick to motion in one dimension, that is, motion in a straight line. So in this course, this is what we will do.

2.2.1 Velocity

Figure 2.6. A car traveling with the cruise control on is an example of an object moving with constant velocity.

When thinking about motion, one of the first things we must consider is how fast an object is moving. The common word for how fast an object is moving is *speed*. A similar term is the word *velocity*. For the purposes of this course, you may treat these two terms as synonyms. The difference is technical. Technically, the term velocity means not only *how fast* an object is moving, but also in what *direction*. The term speed refers only to how fast an object is moving. But since we are only going to consider motion in one direction at a time, we can use the terms *speed* and *velocity* interchangeably.

An important type of motion is motion at a constant velocity, like a car with the cruise control on (Figure 2.6). At a constant velocity, the velocity of an object is defined as the distance the object travels in a certain period of time. Expressed mathematically, the velocity, v, of an object is calculated as

$$v = \frac{d}{t}$$

The velocity is calculated by dividing the distance the object travels, d, by the amount of time, t, it takes to travel that distance. So, if you walk 5.0 miles in 2.0 hours, your velocity is v = (5.0 miles)/(2.0 hours), or 2.5 miles per hour.

Notice that for a given length of time, if an object covers a greater distance it is moving with a higher velocity. In other words, the velocity is proportional to the distance traveled in a certain length of time. When performing calculations using the SI System of units, distances are measured in meters and times are measured in seconds. This means the units for a velocity are meters per second, or m/s.

The relationship between velocity, distance, and time for motion at a constant velocity is shown graphically in Figure 2.7. Travel time is shown on the horizontal axis and distance traveled is shown on the vertical axis. The steeper curve[4] shows distances and times for an object moving at 2 m/s. At a time of one second, the distance traveled is two meters because the object is moving at two meters per second (2 m/s). After two seconds at this speed, the object has moved four meters: (4 m)/(2 s) = 2 m/s. And after three seconds, the object has moved six meters: (6 m)/(3 s) = 2 m/s.

The right-hand curve in Figure 2.7 represents an object traveling at the much slower velocity of 0.5 m/s. At this speed, the graph shows that an object travels two meters in four seconds, four meters in eight seconds, and so on.

To see this algebraically, look again at the velocity equation above. If we multiply both sides of this equation by the time, t, and cancel, we have

$$d = vt$$

This is the same equation, just written in a different form. It still applies to objects moving at a constant velocity. Written this way, t is the independent variable, d is the dependent variable, and v serves as the slope of the line relating d to t. With this form of the velocity equation, we can calculate how far an object travels in a given amount of time, assuming the object is moving at a constant velocity.

Now we work a couple of example problems, following the problem-solving method described on pages 36–37. And remember, all the unit conversion factors you need are listed in Appendix A.

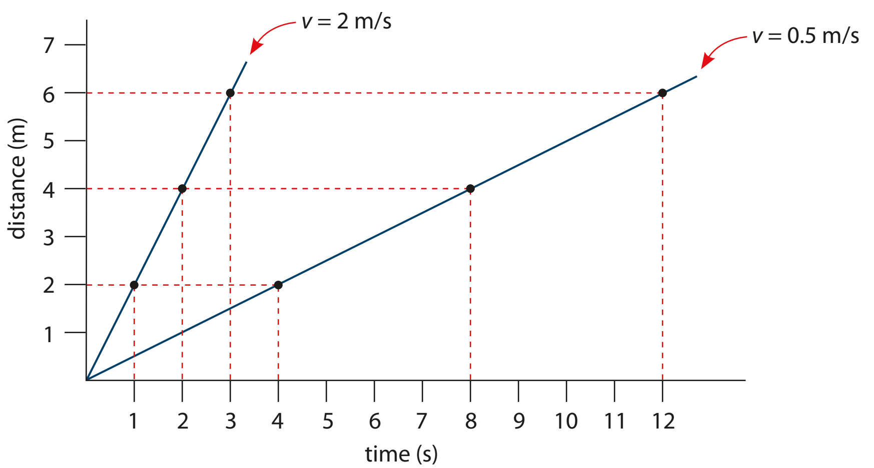


Figure 2.7. A plot of distance versus time for an object moving at constant velocity. Two different velocity cases are shown.

4 Note that when discussing graphs, the lines or curves on the graph are all referred to as *curves*, whether they are curved or straight.

Universal Problem Solving Method

Solid Steps to Reliable Problem Solving

In *Introductory Physics*, you learn how to use math to solve scientific problems. Developing a sound and reliable method for approaching problems is very important. The problem solving method shown below is used in scientific work everywhere. You must follow every step closely and show all your work.

1. Write down the given quantities at the left side of your paper. Include the variable quantities given in the problem statement and the variable you must solve for. Make a mental note of the precision in each given quantity.
2. For each given quantity that is not already in MKS units, work immediately to the right of it to convert the units of measure into MKS units. To help prevent mistakes, always use horizontal fraction bars in your units and unit conversion factors. Write the results of these unit conversions with one extra digit of precision over what you need in your final result.
3. Write the standard form of the equation you will use to solve the problem.
4. If necessary, use algebra to get the variable you are solving for alone on the left side of the equation. Never put values into the equation until this step is done.
5. Write the equation again with the values in it, using only MKS units, and compute the result.
6. If you are asked to state the answer in non-MKS units, perform the final unit conversion now.
7. Write the result with the correct number of significant digits and the correct units of measure.
8. Check your work.
9. Make sure your result is reasonable.

Example Problem

If you want a complete and happy life, do 'em just like this!

A car is traveling at 35.0 mph. The driver then accelerates uniformly at a rate of 0.15 m/s^2 for 2 minutes and 10.0 seconds. Determine the final velocity of the car in mph.

Step 1 Write down the given information in a column down the left side of your page, using horizontal lines for the fraction bars in the units of measure.

$$v_i = 35.0\ \frac{\text{mi}}{\text{hr}}$$

$$a = 0.15\ \frac{\text{m}}{\text{s}^2}$$

$$t = 2\ \text{min}\ 10.0\ \text{s}$$

$$v_f = ?$$

Step 2 Perform the needed unit conversions, writing the conversion factors to the right of the given quantities you wrote in the previous step.

$$v_i = 35.0\ \frac{\text{mi}}{\text{hr}} \cdot \frac{1609\ \text{m}}{\text{mi}} \cdot \frac{1\ \text{hr}}{3600\ \text{s}} = 15.6\ \frac{\text{m}}{\text{s}}$$

$$a = 0.15\ \frac{\text{m}}{\text{s}^2}$$

$$t = 2\ \text{min}\ 10.0\ \text{s} = 130.0\ \text{s}$$

$$v_f = ?$$

Step 3 Write the equation you will use in its standard form.

$$a = \frac{v_f - v_i}{t}$$

Step 4 Perform the algebra necessary to get the unknown you are solving for alone on the left side of the equation.

$$a = \frac{v_f - v_i}{t}$$

$$at = v_f - v_i$$

$$v_f = v_i + at$$

Step 5 Using only values in MKS units, insert the values and compute the result.

$$v_f = v_i + at = 15.6\ \frac{\text{m}}{\text{s}} + 0.15\ \frac{\text{m}}{\text{s}^2} \cdot 130.0\ \text{s} = 35.1\ \frac{\text{m}}{\text{s}}$$

Step 6 Convert to non-MKS units, if required in the problem.

$$v_f = 35.1\ \frac{\text{m}}{\text{s}} \cdot \frac{1\ \text{mi}}{1609\ \text{m}} \cdot \frac{3600\ \text{s}}{1\ \text{hr}} = 78.5\ \frac{\text{mi}}{\text{hr}}$$

Step 7 Write the result with correct significant digits and units of measure.

$$v_f = 79\ \text{mph}$$

Step 8 Check over your work, looking for errors.

Step 9 Make sure your result is reasonable. First, check to see if your result makes sense. The example above is about an accelerating car, so the final velocity we calculate should be a velocity a car can have. A result like 14,000 mph is obviously incorrect. (And remember that nothing can travel faster than the speed of light, so make sure your results are reasonable in this way as well.) Second, if possible, estimate the answer from the given information and compare your estimate to your result. In step 6 above, we see that 3600/1609 is about 2, and $2 \cdot 35.1$ is about 70. Thus our result of 79 mph makes sense.

(Optional Step 10: Revel in the satisfaction of knowing that once you get this down you can work physics problems perfectly nearly every time!)

▼ Example 2.6

Sound travels 1,120 ft/s in air. How much time does it take to hear the crack of a gun fired 1,695.5 m away?

First, write down the given information and perform the required unit conversions so that all given values are in MKS units. Check to see how many significant digits your result must have and do the unit conversions with one extra significant digit. The given speed of sound has three significant digits, so we perform our unit conversions with four digits.

$$v = 1120\ \frac{\text{ft}}{\text{s}} \cdot \frac{0.3048\ \text{m}}{\text{ft}} = 341.4\ \frac{\text{m}}{\text{s}}$$
$$d = 1695.5\ \text{m}$$
$$t = ?$$

Next, write the appropriate equation to use.

$$v = \frac{d}{t}$$

Perform any necessary algebra, insert the values in MKS units, and compute the result.

$$v = \frac{d}{t}$$
$$t = \frac{d}{v} = \frac{1695.5\ \text{m}}{341.4\ \frac{\text{m}}{\text{s}}} = 4.966\ \text{s}$$

Next, round the result so that it has the correct number of significant digits. In the velocity unit conversion and in the calculated result, I used four significant digits. The given velocity has three significant digits and the given distance has five significant digits. Thus, our result must be reported with three significant digits, but all intermediate calculations must use one extra digit. This is why I used four digits. But now we are finished and our result must be rounded to three significant digits because the least precise measurement in the problem has three significant digits. Rounding our result accordingly, we have

$$t = 4.97\ \text{s}$$

The final step is to check the result for reasonableness. The result should be roughly the same as 1500/300 or 2000/400, both of which equal 5. Thus, our result makes sense.

▲

2.2.2 Acceleration

An object's velocity is a measure of how fast it is going; it is not a measure of whether its velocity is changing. The quantity we use to measure if a velocity is changing, and if so, how fast it is changing, is the *acceleration*. If an object's velocity is changing, the object is accelerating, and the value of the acceleration is the rate at which the velocity is changing.

The equation we use to calculate uniform acceleration in terms of an initial velocity v_i and a final velocity v_f is

$$a = \frac{v_f - v_i}{t}$$

where a is the acceleration (m/s^2), t is the time spent accelerating (s), and v_i and v_f are the initial and final velocities, respectively, (m/s).

Did you notice that the MKS units for acceleration are meters per second *squared* (m/s^2)? These units often drive students crazy, and we need to pause here and discuss what this means so you can sleep peacefully tonight. I wrote just above that the acceleration is the *rate* at which the velocity is changing. The acceleration simply means that the velocity is increasing by so many meters per second, per second. Now, "per" indicates a fraction, and if a velocity is changing so many meters per second, per second, we write these units in a fraction this way and simplify the expression:

$$\frac{\frac{\text{m}}{\text{s}}}{\text{s}} = \frac{\frac{\text{m}}{\text{s}}}{\frac{\text{s}}{1}} = \frac{\text{m}}{\text{s}} \cdot \frac{1}{\text{s}} = \frac{\text{m}}{\text{s}^2}$$

Because the acceleration equation results in negative accelerations when the initial velocity is greater than the final velocity, you can see that a negative value for acceleration means the object is slowing down. In future physics courses, you may learn more sophisticated interpretations for what a negative acceleration means, but in this course you are safe associating negative accelerations with decreasing velocity. In common speech, people sometimes use the term "deceleration" when an object is slowing down, but mathematically we just say the acceleration is negative.

Before we work through some examples, let's look at a graphical depiction of uniform acceleration the same way we did with velocity. Figure 2.8 shows two different acceleration curves, representing two different acceleration values. For the curve on the right, after 1 s

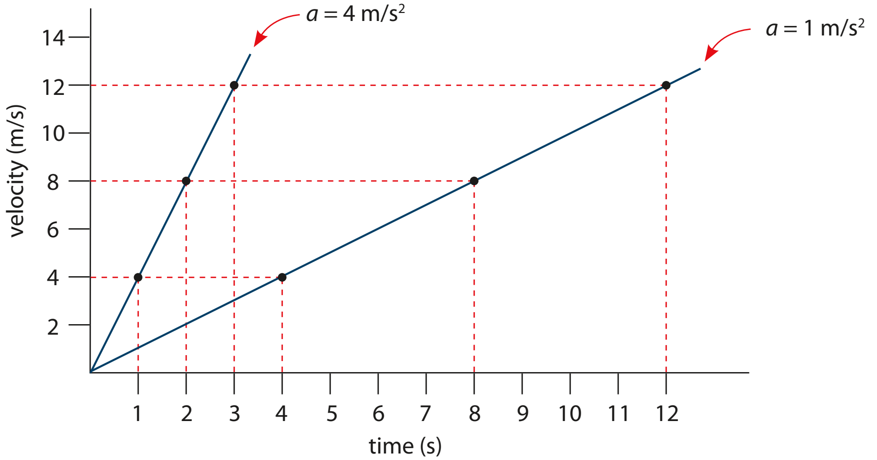


Figure 2.8. A plot of velocity versus time for an object accelerating uniformly. Two different acceleration cases are shown.

the object is going 1 m/s. After 2 s, the object is going 2 m/s. After 12 s, the object is going 12 m/s. You can take the velocity that corresponds to any length of time (by finding where their lines intersect on the curve) and calculate the acceleration by dividing the velocity by the time to get $a = 1$ m/s^2. The other curve has a higher acceleration, 4 m/s^2. An acceleration of 4 m/s^2 means the velocity is increasing by 4 m/s every second. Accordingly, after 2 s the velocity is 8 m/s, and after 3 s, the velocity is 12 m/s. No matter what point you select on that curve, $v/t = 4$ m/s^2.

We must be very careful to distinguish between velocity (m/s) and acceleration (m/s^2). Acceleration is a measure of how fast an object's velocity is changing. To see the difference, note that an object can be at rest ($v = 0$) and accelerating *at the same instant*.

Now, although you may not see this at first, it is important for you to think this through and understand how this counter-intuitive situation can come about. Here are two examples. The instant an object starts from rest, such as when the driver hits the gas while sitting at a traffic light, the object is simultaneously at rest and accelerating. This is because if an object at rest is to ever begin moving, its velocity must *change* from zero to something else. In other words, the object must accelerate. Of course, this situation only holds for an instant; the velocity instantly begins changing and does not stay zero.

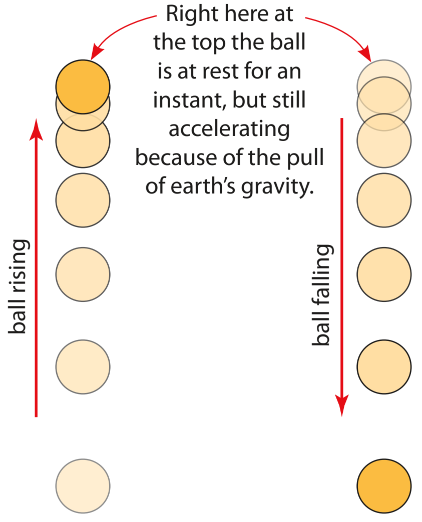


Figure 2.9. A rising and falling ball helps illustrate the difference between velocity and acceleration.

Perhaps my point will be easier to see with this second example. As depicted in Figure 2.9, when a ball is thrown straight up and reaches its highest point, it stops for an instant as it starts to come back down. At its highest point, the ball is simultaneously at rest and accelerating due to the force of gravity pulling it down. As before, this situation only holds for a single instant.

The point of these two examples is to help you understand the difference between the two variables we are discussing, velocity and acceleration. If an object is moving at all, then it has a velocity that is not zero. The object may or may not be accelerating. But acceleration is about whether the velocity itself is changing. If the velocity is constant, then the acceleration is zero. If the object is speeding up or slowing down, then the acceleration is not zero.

And now for another example problem, this time using the acceleration equation.

▼ Example 2.7

A truck is moving with a velocity of 42 mph (miles per hour) when the driver hits the brakes and brings the truck to a stop. The total time required to stop the truck is 8.75 s. Determine the acceleration of the truck, assuming the acceleration is uniform.

Begin by writing the givens and performing the unit conversions.

$$v_i = 42\ \frac{\text{mi}}{\text{hr}} \cdot \frac{1609\ \text{m}}{\text{mi}} \cdot \frac{1\ \text{hr}}{3600\ \text{s}} = 18.8\ \frac{\text{m}}{\text{s}}$$

$$v_f = 0$$

$$t = 8.75\ \text{s}$$

$$a = ?$$

Now write the equation and complete the problem.

$$a = \frac{v_f - v_i}{t} = \frac{0 - 18.8\ \frac{\text{m}}{\text{s}}}{8.75\ \text{s}} = -2.15\ \frac{\text{m}}{\text{s}^2}$$

The initial velocity has two significant digits, so I did the calculations with three significant digits until the end. Now we round off to two digits giving

$$a = -2.2\ \frac{\text{m}}{\text{s}^2}$$

If you keep all the digits in your calculator throughout the calculation and round to two digits at the end, you have –2.1 m/s^2. This answer is fine, too. Remember, the last digit of a measurement or computation always contains some uncertainty, so it is reasonable to expect small variations in the last significant digit. A check of our work shows the result should be about –20/10, which is –2. Thus the result makes sense.

One more point on this example: Notice that the calculated acceleration value came out negative. This was because the final velocity was lower than the initial velocity. Thus we see that a negative acceleration means the vehicle is slowing down.

▲

If you haven't yet read the example problem in the yellow Universal Problem Solving Method box, you should read it now to see a slightly more difficult example using this same equation.

2.3 Planetary Motion and the Copernican Revolution

2.3.1 Science History and the Science of Motion

People have been fascinated with the heavens since ancient times. God's people love to quote Psalm 19:

The heavens declare the glory of God, and the sky above proclaims his handiwork.
Day to day pours out speech, and night to night reveals knowledge.

The psalmist tells us that the glory of the stars and other heavenly bodies reveals the glory of their creator, our God. This means they convey truth to us, the truth we call General Revelation.

The study of motion has always been associated with the motion of the heavenly bodies we see in the sky, so it is particularly fitting in this chapter on motion for us to review the history of views about the solar system and the rest of the universe, referred to as "the