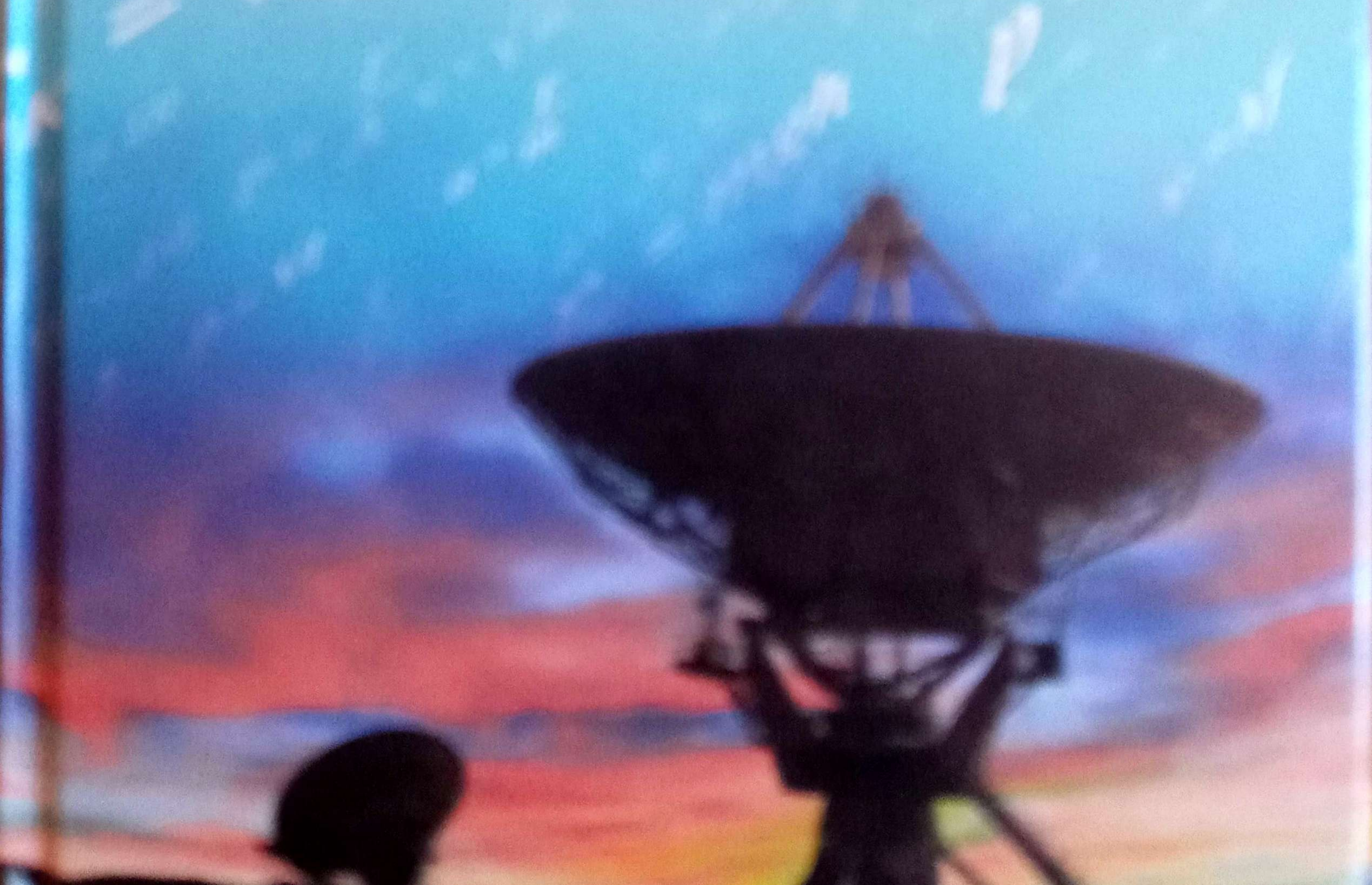
INTRODUCTORY PHYSICS

THIRD EDITION

JOHN D. MAYS



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 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.

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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.

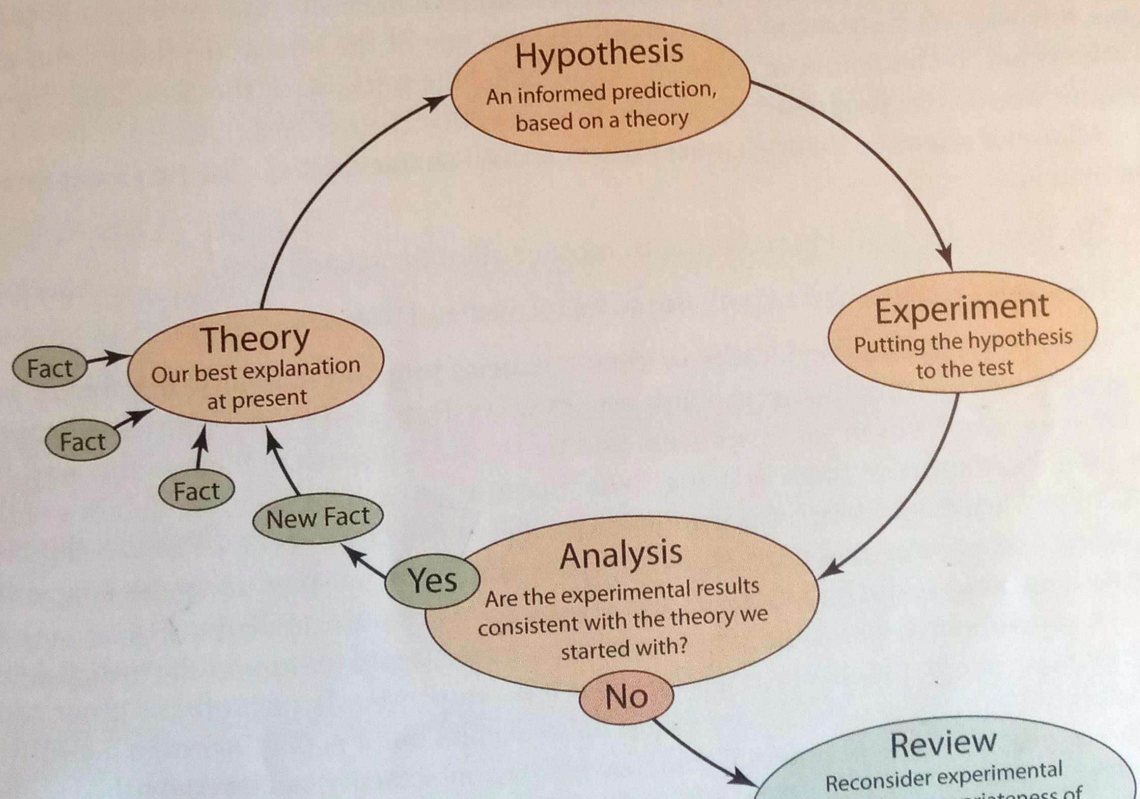
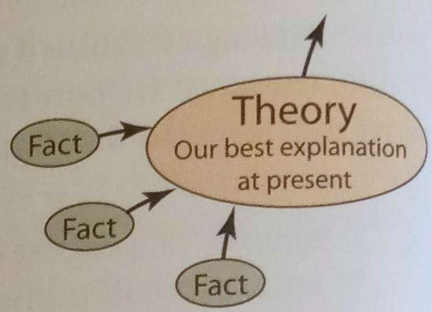


Figure 1.1. The Cycle of Scientific Enterprise.

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.

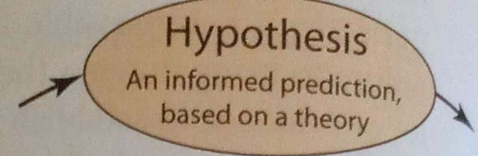
Key Points About Theories

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.

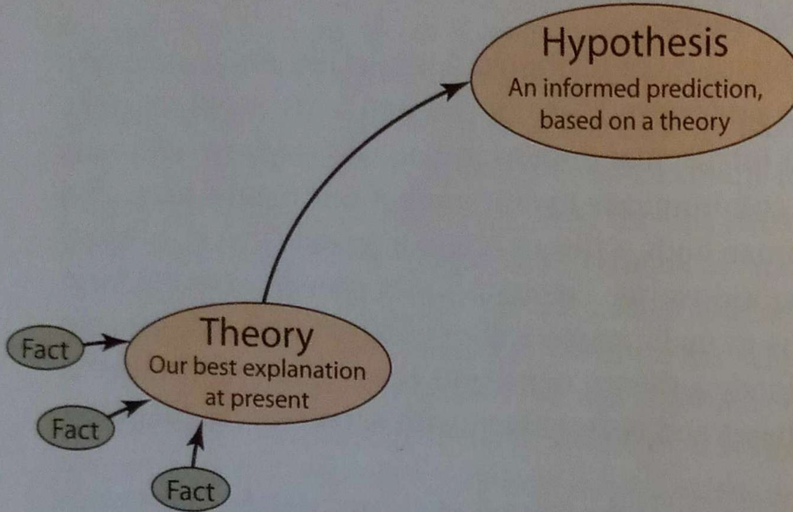
Figure 1.2. Key points about theories.

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 pick-up 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.

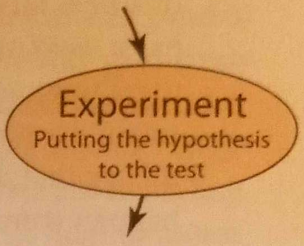
The terms *theory* and *hypothesis* are often used interchangeably in common speech, but in science they mean different things. For this reason you should make note of the distinction.

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.

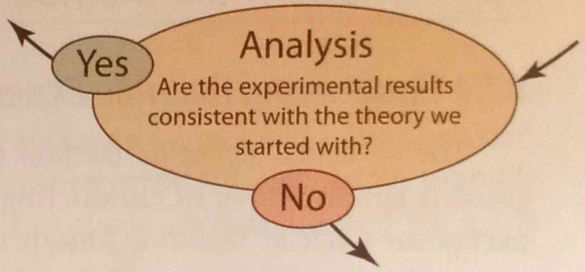
1.2.4 Experiments

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.



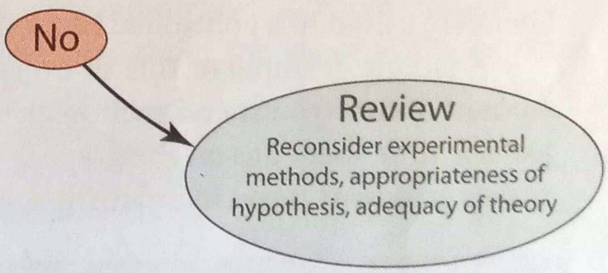
1.2.5 Analysis

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.

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.

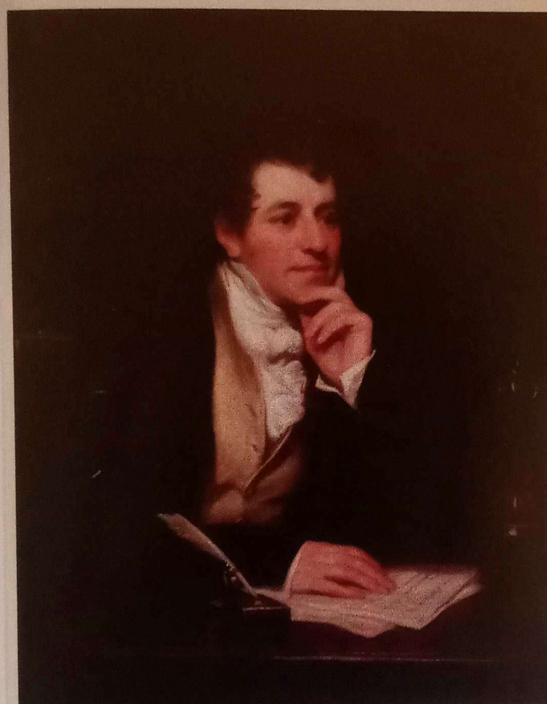
1. Distinguish between theories and hypotheses.
2. Explain why a single experiment can never prove or disprove a theory.
3. Explain how an experiment can still provide valuable data even if the hypothesis under test is not confirmed.
4. Explain the difference between truth and facts and describe the 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.

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."

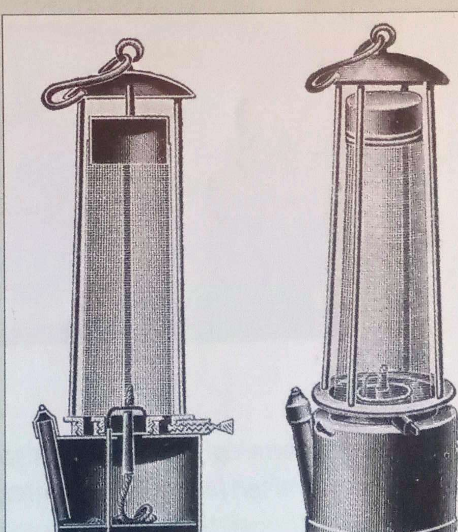


Fig. 192. Davysche Sicherheitslampe

- the team's hypothesis
- an accurate list of materials and equipment, including make and model of any electronic equipment or test equipment used
- tables documenting all the data taken during the experiment, including the units of measure and identifying labels for all data
- all support calculations used during the experiment or in preparation of the lab report
- special notes documenting any unusual events or circumstances, such as bad data that require doing any part of the experiment over, unexpected occurrences or failures, or changes to your experimental approach
- little details about the experiment that need to be written in the report that you may forget about later
- important observations or discoveries made during the experiment

C.3 Experiments

Experiment 1 The Pendulum Experiment

Variables and experimental methods

Essential equipment:

- string
- meter stick
- paper clip
- large steel washers
- clock with second hand

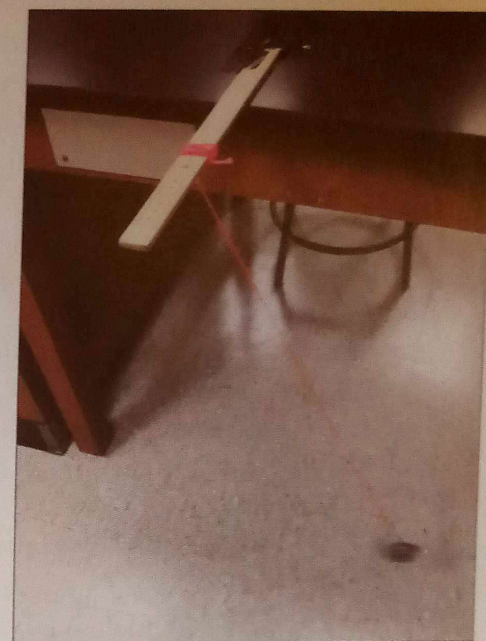
This investigation involves a simple pendulum. The experiment is an opportunity for you to learn about conducting an effective experiment. In this investigation, you learn about controlling variables, collecting careful data, and organizing data in tables in your lab journal.

To make your pendulum, bend a large paper clip into a hook. Then connect the hook to a string, and connect the string to the end of a meter stick. Then lay the meter stick on a table with the pendulum hanging over the edge and tape the meter stick down. Finally, hang one or more large metal washers on the hook for the weight.

Your goal in this experiment is to identify the explanatory variables that affect the period of a simple pendulum. A pendulum is an example of a mechanical system that *oscillates*, that is, repeatedly "goes back and forth" in some regular fashion. In the study of any oscillating system, an important parameter is the *period* of the oscillation. The period is the length of time (in seconds) required for the system to complete one full cycle of its oscillation. In this experiment, the period of the pendulum is the response variable you monitor. (Actually, for convenience you monitor a slightly different variable, closely related to the period. This is explained on the next page.) After thinking about the possibilities and forming your team hypothesis, construct your own simple pendulum from string and some weights and conduct tests on it to determine which variables affect its period and which variables do not.

In class, explore the possibilities for variables that may affect the pendulum's period. Within the pendulum system itself there are three candidates, and your instructor will lead the discussion until the class has identified them. (We ignore factors such as air friction and the earth's rotation in this experiment. Just stick to the obvious variables that clearly apply to the problem at hand.)

Then, as a team, continue the work by discussing the problem for a few minutes with your teammates. In this team discussion, form your own team hypothesis stating which variables you think affect the period. To form this hypothesis, you need not actually do any new research or tests. Just use what you know from your own experience to make your best guess.



The central challenge for this experiment is to devise an experimental method that tests only one explanatory variable at a time. Your instructor will help you work this out, but the basic idea is to set up the pendulum so that two variables are held constant while you test the system with large and small values of the third variable to see if this change affects the period. You must test all combinations of holding two variables constant while manipulating the third one. All experimental results must be entered in tables in your lab journal. Recording the data for the different trials requires several separate tables. For each experimental setup, time the pendulum during three separate trials and record the results in your lab journal. Repeating the trials this way enables you to verify that you have valid, consistent data. To make sure you can tell definitively that a given variable is affecting the period, *make the large value of the variable at least three times the small value in your trials.*

Here is bit of advice about how to measure the period of your pendulum. The period of your pendulum is likely to be quite short, only one or two seconds, so measuring it directly with accuracy is difficult. Here is an easy solution: assign one team member to hold the pendulum and release it on a signal. Assign another team member to count the number of swings the pendulum completes, and another member as a timer to watch the second hand on a clock. When the timer announces "GO" the person holding the pendulum releases it, and the swing counter starts counting. After exactly 10.0 seconds, the timer announces "STOP" and the swing counter states the number of swings completed by the pendulum during the trial. Record this value in a table in your lab journal. If you have four team members, the fourth person can be responsible for recording the data during the experiment. After the experiment, the data recorder reads off the data to the other team members as they enter the data in their journals.

This method of counting the number of swings in 10 seconds does not give a direct measurement of the period, but you can see that your swing count works just as well for solving the problem posed by this experiment, and is a lot easier to measure than the period itself. (The actual period is equal to 10 seconds divided by the number of swings that occur in 10 seconds.)

One more thing on measuring your swing count: your swing counter should state the number of swings completed to the nearest 1/4 swing. When the pendulum is straight down, it has either completed 1/4 swing or 3/4 swing. When it stops to reverse course on the side opposite from where it is released, it has completed 1/2 swing.

When you have finished taking data, review the data together as a team. If you did the experiment carefully, your data should clearly indicate which potential explanatory variables affect the period of the pendulum and which ones do not. If your swing counts for different trials of the same setup are not consistent, then something is wrong with your method. Your team must repeat the experiment with greater care so that your swing counts for each different experimental setup are consistent.

Discuss your results with your team members and reach a consensus about the meaning of your data. Expect to spend at least four hours writing, editing, and formatting your report. Lab reports count a significant percentage of your science course grades throughout high school, so you should invest the time now to learn how to prepare a quality report.

Your goal for this report is to begin learning how to write lab reports that meet all the requirements described in *The Student Lab Report Handbook*. One of our major goals for this year is to learn what these requirements are and become proficient at generating solid reports. Nearly all scientific reports involve reporting data, and a key part of this first report is your data tables, which should all be properly labeled and titled.

After completing the experiment, all the information you need to write the report should be in your lab journal. If you properly journal the lab exercise, you will have all the data, your hypothesis, the materials list, your team members' names, the procedural details, and everything else you need to write the report. Your report must be typed and will probably be around two or three pages long. You should format the report as shown in the examples in *The Student Lab Report Handbook*, including major section headings and section content.

Here are a few guidelines to help you get started with your report:

1. There is only a small bit of theory to cover in the Background section, namely, to describe what a pendulum and its period are. You should also explain the experimental method, that is, why we are using the number of swings completed in 10 seconds in our work in place of the actual period. As stated in *The Student Lab Report Handbook*, the Background section must include a brief overview of your experimental method and your team's hypothesis.
2. Begin your Discussion section by describing your data and considering how they relate to your hypothesis. In this experiment, we are not making quantitative predictions, so there are no calculations to perform for the discussion. We are simply seeking to discover which variables affect the period of a pendulum and which do not. Your goal in the Discussion section is to identify what your data say and relate that to your reader.
3. Consider the following questions as you write your discussion. What variables did you manipulate to determine whether they had any effect on the period of the pendulum? What did you find? According to your data, which variables do affect the period? How do the data show this? Refer to specific data tables to explain specifically how the data support your conclusion. Are your findings consistent with your hypothesis? If not, then what conclusion do you reach about the question this experiment seeks to answer?

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