Chapter 2

Understanding Physics Fundamentals

In This Chapter

- ▶ Understanding the concept of physics . . . and why it matters
- ▶ Mastering measurements (and keeping them straight as you solve equations)
- ▶ Accounting for significant digits and possible error
- ▶ Brushing up on basic algebra and trig concepts

There you are, working away at a tough, nearly unanswerable physics problem, seeking a crucial breakthrough. The question is tough, and you know that legions of others have struggled with it fruitlessly. Suddenly, illumination strikes, and everything becomes clear.

“Of course,” you say. “It’s elementary. The ball will rise 9.8 meters into the air at its highest point.”

Shown the correct solution to the problem, a grateful instructor awards you a nod. You modestly acknowledge the accolade and turn to the next problem. Not bad.

With physics, the glory awaits you, but you have some hard work waiting for you, too. Don’t worry about the work; the satisfaction of success is worth it. And when you finish this book, you’ll be a physics pro, plowing through formerly difficult problems left and right like nobody’s business.

This chapter starts your adventure by covering some basic skills you need for the coming chapters. I cover measurements and scientific notation, give you a refresher on basic algebra and trigonometry, and show you which digits in a number to pay attention to — and which ones to ignore. Continue on to build a physics foundation, solid and unshakeable, that you can rely on throughout this book.

Don't Be Scared, It's Only Physics

Many people are a little on edge when they think about physics. It's easy to feel intimidated by the subject, thinking it seems like some foreign high-brow topic that pulls numbers and rules out of thin air. But the truth is that physics exists to help you make sense of the world. It's a human adventure, undertaken on behalf of everyone, into the way the world works.

Although the contrary may seem true, there's no real mystery about the goals and techniques of physics; physics is simply about *modeling* the world. The whole idea behind it is to create mental models to describe how the world works: how blocks slide down ramps, how stars form and shine, how black holes trap light so it can't escape, what happens when cars collide, and so on. When these models are first created, they often have little to do with numbers; they just cover the gist of the situation. For example, a star is made up of this layer and then that layer, and as a result, this reaction takes place, followed by that one. And — pow — you have a star.

As time goes on, those models start getting numeric, which is where physics students sometimes start having problems. Physics class would be a cinch if you could simply say, "That cart is going to roll down that hill, and as it gets toward the bottom, it's going to roll faster and faster." But the story is more involved than that — not only can you say that the cart is going to go faster, but in exerting your mastery over the physical world, you can also say how much faster it will go.

REMEMBER

The gist of physics is this: You start by making an observation, you create a model to simulate that situation, and then you add some math to fill it out — and voilà! You have the power to predict what will happen in the real world. All this math exists to help you feel more at home in the physical world and to help you see what happens and why, not to alienate you from your surroundings.

Be a genius: Don't focus on the math

Richard Feynman was a famous Nobel Prize winner in physics who had a reputation during the 1950s and '60s as an amazing genius. He later explained his method: He attached the problem at hand to a real-life scenario, creating a mental image, while others got caught in the math. When someone would show him a long derivation that had gone wrong, for example, he'd think of some physical phenomenon that the derivation was supposed to explain. As he followed along, he'd get to the point where he suddenly realized the derivation no longer matched what happened in the real world, and he'd say, "No, that's the problem." He was always right, which mystified people who, awestruck, took him for a supergenius. Want to be a supergenius? Do the same thing: Don't let the math scare you.

Always keep in mind that the real world comes first and the math comes later. When you face a physics problem, make sure you don't get lost in the math; keep a global perspective about what's going on in the problem, because doing so will help you stay in control. After teaching physics to college students for many years, I'm very familiar with one of the biggest problems they face — getting lost in, and being intimidated by, the math.

And now, to address that nagging question plaguing your mind: What are you going to get out of physics? If you want to pursue a career in physics or in an allied field such as engineering, the answer is clear — you'll need this knowledge on an everyday basis. But even if you're not planning to embark on a physics-related career, you can get a lot out of studying the subject. You can apply much of what you discover in an introductory physics course to real life. But far more important than the application of physics are the problem-solving skills it arms you with for approaching any kind of problem — physics problems train you to stand back, consider your options for attacking the issue, select your method, and then solve the problem in the easiest way possible.

Measuring the World Around You and Making Predictions

Physics excels at measuring and predicting the physical world — after all, that's why it exists. Measuring is the starting point — part of observing the world so you can then model and predict it. You have several different measuring sticks at your disposal: some for length, some for weight, some for time, and so on. Mastering those measurements is part of mastering physics.

To keep like measurements together, physicists and mathematicians have grouped them into *measurement systems.* The most common measurement systems you see in physics are the centimeter-gram-second (CGS) and meter-kilogram-second (MKS) systems, together called *SI* (short for Système International d'Unités), but you may also come across the foot-pound-inch (FPI) system. For reference, Table 2-1 shows you the primary units of measurement in the CGS system. (Don't bother memorizing the ones you're not familiar with now; come back to them later as needed.)

Table 2-1 Units of Measurement in the CGS System

Measurement	*Unit*	*Abbreviation*
Length	centimeter	cm
Mass	gram	g
Time	second	s

(continued)

Table 2-1 *(continued)*

Measurement	*Unit*	*Abbreviation*
Force	dyne	dyne
Energy	erg	erg
Pressure	barye	ba
Electric current	biot	Bi
Magnetism	gauss	G
Electric charge	franklin	Fr

Table 2-2 lists the primary units of measurement in the MKS system, along with their abbreviations.

Table 2-2 Units of Measurement in the MKS System

Measurement	*Unit*	*Abbreviation*
Length	meter	m
Mass	kilogram	kg
Time	second	s
Force	Newton	N
Energy	Joule	J
Pressure	Pascal	Pa
Electric current	ampere	A
Magnetism	Tesla	T
Electric charge	Coulomb	C

Don't mix and match: Keeping physical units straight

Because each measurement system uses a different standard length, you can get several different numbers for one part of a problem, depending on the measurement you use. For example, if you're measuring the depth of the water in a swimming pool, you can use the MKS measurement system, which gives you an answer in meters; the CGS system, which yields a depth in centimeters; or the less common FPI system, in which case you determine the depth of the water in inches.

Suppose, however, that you want to know the pressure of the water at the bottom of the pool. You can simply use the measurement you find for the depth and input it into the appropriate equation for pressure (see Chapters 14 and 15). When working with equations, however, you must always keep one thing in mind: the measurement system.

Always remember to stick with the same measurement system all the way through the problem. If you start out in the MKS system, stay with it. If you don't, your answer will be a meaningless hodgepodge, because you're switching measuring sticks for multiple items as you try to arrive at a single answer. Mixing up the measurements causes problems — imagine baking a cake where the recipe calls for two cups of flour, but you use two liters instead.

Over the years, I've seen people mix up the measurement systems over and over and then scratch their heads when their answers come out wrong. Sure, they had noble intentions, and everything about their solutions was great — and sure, they had masterful insights, masterful applications, and masterful egos. But they also had the wrong answers.

Suppose the solution to a test problem is 15 kilogram-meters per second^2, but a student comes up with the result 1,500 kilogram-centimeters per second^2. The answer is wrong not because of an error in understanding, but because the answer is in the wrong measurement system.

From meters to inches and back again: Converting between units

Physicists use various measurement systems to record numbers from their observations. But what happens when you have to convert between those systems? Physics problems sometimes try to trip you up here, giving you the data you need in mixed units: centimeters for this measurement but meters for that measurement — and maybe even mixing in inches as well. Don't be fooled. You have to convert *everything* to the same measurement system before you can proceed. How do you convert in the easiest possible way? You use conversion factors. For an example, consider the following problem.

Passing another state line, you note that you've gone 4,680 miles in exactly three days. Very impressive. If you went at a constant speed, how fast were you going? As I discuss in Chapter 3, the physics notion of speed is just as you may expect — distance divided by time. So, you calculate your speed as follows:

$$\frac{4{,}680\ \text{miles}}{3\ \text{days}} = 1{,}560\ \text{miles/day}$$

Your answer, however, isn't exactly in a standard unit of measure. You want to know the result in a unit you can get your hands on — for example, miles per hour. To get miles per hour, you need to convert units.

To convert between measurements in different measuring systems, you can multiply by a conversion factor. A *conversion factor* is a ratio that, when multiplied by the item you're converting, cancels out the units you don't want and leaves those that you do. The conversion factor must equal 1.

In the preceding problem, you have a result in miles per day, which is written as miles/day. To calculate miles per hour, you need a conversion factor that knocks days out of the denominator and leaves hours in its place, so you multiply by days per hour and cancel out days:

$$\text{miles/day} \times \text{days/hour} = \text{miles/hour}$$

Your conversion factor is days per hour. When you plug in all the numbers, simplify the miles-per-day fraction, and multiply by the conversion factor, your work looks like this:

$$4{,}680\ \text{miles}/3\ \text{days} = 1{,}560\ \text{miles}/1\ \text{day} = 1{,}560\ \text{miles/day} \times 1\ \text{day}/24\ \text{hours}$$

Note: Words like "seconds" and "meters" act like the variables x and y in that if they're present in both the numerator and denominator, they cancel each other out.

When numbers make your head spin, look at the units

Want an inside trick that teachers and instructors often use to solve physics problems? Pay attention to the units you're working with. I've had thousands of one-on-one problem-solving sessions with students in which we worked on homework problems, and I can tell you that this is a trick instructors use all the time.

As a simple example, say you're given a distance and a time, and you have to find a speed. You can cut through the wording of the problem immediately, because you know that distance (for example, meters) divided by time (for example, seconds) gives you speed (meters/second).

As the problems get more complex, however, more items will be involved — say, for example, a mass, a distance, a time, and so on. You find yourself glancing over the words of a problem to pick out the numeric values and their units. Have to find an amount of energy? As I discuss in Chapter 10, energy is mass times distance squared over time squared, so if you can identify these items in the question, you know how they're going to fit into the solution, and you won't get lost in the numbers.

The upshot is that units are your friends. They give you an easy way to make sure you're headed toward the answer you want. So, when you feel too wrapped up in the numbers, check the units to make sure you're on the right path.

Note that because there are 24 hours in a day, the conversion factor equals exactly 1, as all conversion factors must. So, when you multiply 1,560 miles/day by this conversion factor, you're not changing anything — all you're doing is multiplying by 1.

When you cancel out days and multiply across the fractions, you get the answer you've been searching for:

$$\frac{1{,}560 \text{ miles}}{\text{day}} \times \frac{1 \text{ day}}{24 \text{ hours}} = \frac{65 \text{ miles}}{\text{hour}}$$

So, your average speed is 65 miles per hour, which is pretty fast considering that this problem assumes you've been driving continuously for three days.

You don't *have* to use a conversion factor; if you instinctively know that to convert from miles per day to miles per hour you need to divide by 24, so much the better. But if you're ever in doubt, use a conversion factor and write out the calculations, because taking the long road is far better than making a mistake. I've see far too many people get everything in a problem right except for this kind of simple conversion.

Converting between hours and days is pretty easy, because you know that a day consists of 24 hours. However, not all conversions are so obvious; you may not be familiar with the CGS and MKS systems, so Table 2-3 gives you a handy list of conversions for reference (refer to Tables 2-1 and 2-2 for the abbreviations).

Table 2-3 Conversions from the MKS System to the CGS System

MKS Measurement	*CGS Measurement*
1 m	100 cm
1 km	1,000 m
1 kg	1,000 g
1 N	10^5 dynes
1 J	10^7 ergs
1 Pa	10 ba
1 A	0.1 Bi
1 T	10^4 G
1 C	2.9979×10^9 Fr

Because the difference between CGS and MKS is almost always a factor of 100, converting between the two systems is easy. For example, if you know that a ball drops 5 meters, but you need the distance in centimeters, you just multiply by 100 centimeters/1 meter to get your answer:

$$5.0 \text{ meters} \times \frac{100 \text{ centimeters}}{1 \text{ meter}} = 500 \text{ centimeters}$$

However, what if you need to convert to and from the FPI system? No problem. I include all the conversions you need in the front of this book, on the Cheat Sheet. Keep it on hand when reading through this book or when tackling physics problems on your own.

Eliminating Some Zeros: Using Scientific Notation

Physicists have a way of getting their minds into the darndest places, and those places often involve really big or really small numbers. For example, say you're dealing with the distance between the sun and Pluto, which is 5,890,000,000,000 meters. You have a lot of meters on your hands, accompanied by a lot of zeroes. Physics has a way of dealing with very large and very small numbers; to help reduce clutter and make them easier to digest, it uses *scientific notation.* In scientific notation, you express zeroes as a power of ten — to get the right power of ten, you count up all the places in front of the decimal point, from right to left, up to the place just to the right of the first digit (you don't include the first digit because you leave it in front of the decimal point in the result). So you can write the distance between the sun and Pluto as follows:

$$5{,}890{,}000{,}000{,}000 \text{ meters} = 5.89 \times 10^{12} \text{ meters}$$

Scientific notation also works for very small numbers, such as the one that follows, where the power of ten is negative. You count the number of places, moving left to right, from the decimal point to just after the first nonzero digit (again leaving the result with just one digit in front of the decimal):

$$0.0000000000000000005339 \text{ meters} = 5.339 \times 10^{-19} \text{ meters}$$

If the number you're working with is greater than ten, you'll have a positive exponent in scientific notation; if it's less than one, you'll have a negative exponent. As you can see, handling super large or super small numbers with scientific notation is easier than writing them all out, which is why calculators come with this kind of functionality already built in.

Checking the Precision of Measurements

Precision is all-important when it comes to making (and analyzing) measurements in physics. You can't imply that your measurement is more precise than you know it to be by adding too many significant digits, and you have to account for the possibility of error in your measurement system by adding a ± when necessary. The following sections delve deeper into the topics of significant digits and accuracy.

Knowing which digits are significant

In a measurement, *significant digits* are those that were actually measured. So, for example, if someone tells you that a rocket traveled 10.0 meters in 7.00 seconds, the person is telling you that the measurements are known to three significant digits (the number of digits in both of the measurements).

If you want to find the rocket's speed, you can whip out a calculator and divide 10.0 by 7.00 to come up with 1.428571429 meters per second, which looks like a very precise measurement indeed. But the result is too precise — if you know your measurements to only three significant digits, you can't say you know the answer to ten significant digits. Claiming as such would be like taking a meter stick, reading down to the nearest millimeter, and then writing down an answer to the nearest ten-millionth of a millimeter.

In the case of the rocket, you have only three significant digits to work with, so the best you can say is that the rocket is traveling at 1.43 meters per second, which is 1.428571429 rounded up to two decimal places. If you include any more digits, you claim an accuracy that you don't really have and haven't measured.

When you round a number, look at the digit to the right of the place you're rounding to. If that right-hand digit is 5 or greater, you should round up. If it's 4 or less, round down. For example, you should round 1.428 to 1.43 and 1.42 down to 1.4.

What if a passerby told you, however, that the rocket traveled 10.0 meters in 7.0 seconds? One value has three significant digits, and the other has only two. The rules for determining the number of significant digits when you have two different numbers are as follows:

- **When you multiply or divide numbers,** the result has the same number of significant digits as the original number that has the fewest significant digits.

  In the case of the rocket, where you need to divide, the result should have only two significant digits — so the correct answer is 1.4 meters per second.

- **When you add or subtract numbers,** line up the decimal points; the last significant digit in the result corresponds to the right-most column where *all* numbers still have significant digits.

  If you have to add 3.6, 14, and 6.33, you'd write the answer to the nearest whole number — the 14 has no significant digits after the decimal place, so the answer shouldn't, either. To preserve significant digits, you should round the answer up to 24. You can see what I mean by taking a look for yourself:

  ```
    3.6
  +14
  + 6.33
   23.93
  ```

By convention, zeroes used simply to fill out values down to (or up to) the decimal point aren't considered significant. For example, the number 3,600 has only two significant digits by default. If you actually measure the value to be 3,600, of course, you'd express it as 3,600.0, with a decimal point; the final decimal point indicates that you mean all the digits are significant.

Estimating accuracy

Physicists don't always rely on significant digits when recording measurements. Sometimes, you see measurements such as

$$5.36 \pm 0.05 \text{ meters}$$

The ± part (0.05 meters in the preceding example) is the physicist's estimate of the possible error in the measurement, so the physicist is saying that the actual value is between 5.36 + 0.05 (that is, 5.41) meters and 5.36 – 0.05 (that is, 5.31 meters), inclusive. (It isn't the amount your measurement differs from the "right" answer as given in books; it's an indication of how precise your apparatus can measure — in other words, how reliable your results are as a measurement.)

Fathoming the ± fad

This ± business has become so popular that you see it all over the place now, as in a real-estate ad that announces 35± acres for sale. Sometimes, you even see real-estate ads with numbers such as ±35 acres, which makes you wonder whether the agent realizes that the ad means the actual acreage is in the range of –35 to +35 acres. What if you buy the place and it turns out to be –15 acres? Do you *owe* the agent 15 acres?

Arming Yourself with Basic Algebra

Yep, physics deals with plenty of equations, and to be able to handle them, you should know how to move the items in them around. Time to travel back to basic algebra for a quick refresher.

The following equation tells you the distance, *s,* that an object travels if it starts from rest and accelerates at *a* for a time *t:*

$$s = \tfrac{1}{2}at^2$$

Now suppose the problem actually tells you the time the object was in motion and the distance it traveled and asks you to calculate the object's acceleration. By rearranging the equation, you can solve for the acceleration:

$$a = 2s / t^2$$

In this case, you multiply both sides by 2 and divide both sides by t^2 in order to isolate the acceleration, *a,* on one side of the equation.

What if you have to solve for the time, *t?* By moving the number and variables around, you get the following equation:

$$t = \sqrt{\frac{2s}{a}}$$

Do you need to memorize all three of these variations on the same equation? Certainly not. You just memorize one equation that relates these three items — distance, acceleration, and time — and then rearrange the equation as needed. (For a handy list of many of the equations you should keep in mind, check out the Cheat Sheet at the front of this book.)

Tackling a Little Trig

Besides some basic algebra, you need to know a little trigonometry, including sines, cosines, and tangents, for physics problems. To find these values, you start out with a simple right triangle — take a look at Figure 2-1, which displays a triangle in all its glory, complete with labels I've provided for the sake of explanation (note in particular the angle between the two shorter sides, θ).

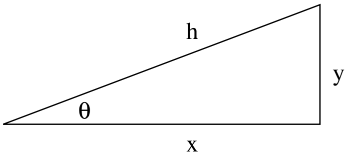

Figure 2-1: A labeled triangle that you can use to find trig values.

To find the trigonometric values of the triangle in Figure 2-1, you divide one side by another. You need to know the following equations, because as soon as vectors appear in Chapter 4, these equations will come in handy:

$\sin \theta = y/r$

$\cos \theta = x/r$

$\tan \theta = y/x$

If you're given the measure of one angle and one side of the triangle, you can find all the others. Here are some examples — they'll probably become distressingly familiar before you finish any physics course, but you *don't* need to memorize them. If you know the preceding sine, cosine, and tangent equations, you can derive the following ones as needed:

$x = r \cos \theta = y/\tan \theta$

$y = r \sin \theta = x \tan \theta$

$r = y/\sin \theta = x/\cos \theta$

Remember that you can go backward with the inverse sine, cosine, and tangent, which are written as $\sin^{-1}$, $\cos^{-1}$, and $\tan^{-1}$. Basically, if you input the sine of an angle into the $\sin^{-1}$ equation, you end up with the measure of the angle itself. (If you need a more in-depth refresher, check out *Trigonometry For Dummies,* by Mary Jane Sterling [Wiley].) Here are the inverses for the triangle in Figure 2-1:

$\sin^{-1}(y/r) = \theta$

$\cos^{-1}(x/r) = \theta$

$\tan^{-1}(y/x) = \theta$