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CHAPTER

Energy and Power

and the Physics of Explosions

At the end of the Cretaceous period, the golden age of dinosaurs, an asteroid or comet about 10 miles in diameter headed directly towards the Earth with a velocity of about 20 miles per *second*, over ten times faster than our speediest bullets. Many such large objects may have come close to the Earth, but this was the one that finally hit. It hardly noticed the air as it plunged through the atmosphere in a fraction of a second, momentarily leaving a trail of vacuum behind it. It hit the Earth with such force that it and the rock near it were suddenly heated to a temperature of over a million degrees Centigrade, several hundred times hotter than the surface of the sun. Asteroid, rock, and water (if it hit in the ocean) were instantly vaporized. The energy released in the explosion was greater than that of a hundred million megatons of TNT, 100 *teratons*, more than ten thousand times greater than the total U.S. and Soviet nuclear arsenals. . . . Before a minute had passed, the expanding crater was 60 miles across and 20 miles deep. It would soon grow even larger. Hot vaporized material from the impact had already blasted its way out through most of the atmosphere to an altitude of 15 miles. Material that a moment earlier had been glowing plasma was beginning to cool and condense into dust and rock that would be spread worldwide.

—from Richard A. Muller, *Nemesis*

Few people are surprised by the fact that an asteroid the size of Mount Everest could do a lot of damage when it hits the Earth. And it is not really surprising that such bodies are out there (figure 1.1). The danger has been the subject of many movies, including *Deep Impact*, *Meteor*, and *Armageddon*. Asteroids and comets frequently come close to the Earth. Every few years, we see a newspaper headline about a "near miss" in which an object misses the Earth by "only a few million miles." That is hardly a near miss. The

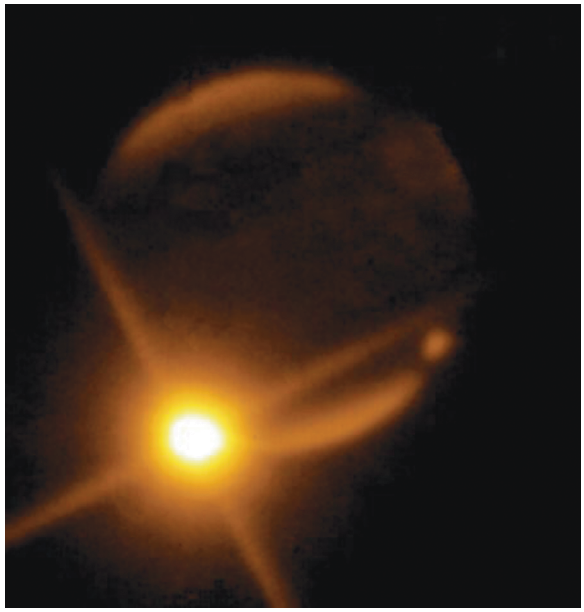

Figure 1.1 Comet Shoemaker-Levy crashes into Jupiter. This explosion is much smaller than the one that occurred when an asteroid or a comet crashed into the Earth 65 million years ago. (Image taken by Peter McGregor at the ANU 2.3m telescope at Siding Spring, Research School of Astronomy and Astrophysics. Copyright Australian National University. Used with permission.)

radius of the Earth is about 4000 miles. So a miss by, say, four million miles would be a miss by a thousand Earth radii. Hitting the Earth is comparable to hitting an ant on a dartboard.

Although the probability of an asteroid impact during your lifetime is small, the consequences could be huge, with millions or maybe even billions of people killed. For this reason, the U.S. government continues to sponsor both asteroid searches, to identify potential impactors, and research into ways to deflect or destroy such bodies.

But why should an asteroid impact cause an explosion? The asteroid was made of rock, not dynamite. And why would it cause such a big explosion? But then what is an explosion, after all?

Explosions and Energy

An *explosion* occurs when a great deal of stored energy is suddenly converted to heat in a confined space. This is true for a grenade, an atomic bomb, or an asteroid hitting the Earth. The heat is enough to vaporize the matter, turning it into an extremely hot gas. Such a gas has enormous pressure—that is, it puts a great force on everything that surrounds it. Nothing is strong enough to resist this pressure, so the gas expands rapidly and pushes anything near it out of the way. The flying debris is what does the damage in an explosion. It doesn't matter what the original form of the energy is—it could be kinetic energy (the result of motion), like the energy of the asteroid, or chemical energy, like the energy in the explosive trinitrotoluene (TNT). It is the rapid conversion of this energy to *heat* that is at the heart of most explosions.

You may have noticed that I used a lot of common terms in the preceding paragraph that I didn't explain. Words such as *energy* and *heat* have everyday meanings, but they also have precise meanings when used in physics. Physics can be derived in a deductive way, just like geometry, but it is hard to learn in that manner. So our approach will be to start with intuitive definitions and then make them more precise as we delve deeper into the physics. Here are some beginning definitions that you may find helpful. The precise meanings of these definitions will become clearer over the next three chapters.

Definitions (Don't Memorize)

- **Energy** is the ability to do work. (*Work* is defined numerically as the magnitude of a force multiplied by the distance that the force moves in the direction of the force.) Alternative definition for energy: anything that can be turned into heat.[1]
- **Heat** is something that raises the temperature of a material, as measured by a thermometer. (It will turn out that heat is actually the microscopic energy of motion of vibrating molecules.)

These definitions sound great to the professional physicist, but they might be somewhat mysterious to you. They don't really help much since they involve other concepts (work, force, energy of motion) that you may not precisely understand. I'll talk more about all these concepts in the coming pages. In fact, it is very difficult to understand the concept of energy just from the definitions alone. Trying to do so is like trying to learn a foreign language by memorizing a dictionary. So be patient. I'll give lots of examples, and those will help you to feel your way into this subject. Rather than read this chapter slowly, I recommend that you read it quickly, and more than once. You learn physics by iteration—that is, by going over the same material many times. Each time you do that, the material makes a little more sense. That's also the best way to learn a foreign language: total immersion. So don't worry about understanding things just yet. Just keep on reading.

Amount of Energy

Guess: How much energy is there in a pound of an explosive, such as dynamite or TNT, compared to, say, a pound of chocolate chip cookies? Don't read any more until you've made your guess.

Here's the answer: The chocolate chip cookies have the greater energy. Not only that, but the energy is *much* greater—eight times greater in the cookies than in TNT! That fact surprises nearly everybody, including many physics professors. Try it out on some of your friends who are physics majors.

[1] It is likely, as the Universe evolves, that virtually *all* energy will be converted to heat. This idea has spawned numerous essays by philosophers and theologians. It is sometimes called the "heat death" of the Universe, since heat energy cannot always be converted back to other forms.

How can it be? Isn't TNT famous for the energy it releases? We'll resolve this paradox in a moment. First, let's list the energies in various different things. There are a lot more surprises coming, and if you are investing in a company, or running the U.S. government, it is important that you know many of these facts.

To make the comparisons, let's consider the amount of energy in 1 gram of various materials. (A *gram* is the weight of a cubic centimeter of water; a penny weighs 3 grams, and there are 454 grams in a pound.) I'll give the energy in several units: the Calorie, the calorie, the watt-hour, and the kilowatt-hour.

CALORIE

The unit you might feel most familiar with is the *Calorie*. That's the famous "food calorie" used in dieting. It is the one that appears on the labels of food packages. A chocolate chip (just the chip, not the whole cookie) contains about 3 Calories. A 12-ounce can of Coca Cola has about 150 Calories.

> **Beware:** If you studied chemistry or physics, you may have learned about the unit called the *calorie*. That is different from the Calorie! A food Calorie (usually capitalized) is 1000 little physics calories. That is a terrible convention, but it is not my fault. Physicists like to refer to food Calories as kilocalories. Food labels in Europe and Asia frequently list kilocalories, but not in the United States. So 1 Cal = 1000 cal = 1 kilocalorie.[2]

KILOWATT-HOUR

Another famous unit of energy is the *kilowatt-hour*, abbreviated kWh. (The W is capitalized, some say, because it stands for the last name of James Watt, but that doesn't explain why we don't capitalize it in the middle of the word kilowatt.) What makes this unit so well known is that we buy electricity from the power company in kWh. That's what the meter outside the house measures. One kWh costs between 5 and 25 cents, depending on where you live. (Electric prices vary much more than gasoline prices.) We'll assume an average price of 10 cents per kWh in this text.

It probably will not surprise you that there is a smaller unit called the *watt-hour*, abbreviated Wh. A kilowatt-hour consists of a thousand watt-hours. This unit isn't used much, since it is so small; however, my computer battery has its capacity marked on the back as *60 Wh*. Its main value is that a Wh is approximately 1 Calorie.[3] So for our purposes, it will be useful to know that:

Wh = 1 Calorie (approximately)
1 kWh = 1000 Calories

[2] I got into trouble in a cake recipe once because I didn't know the difference between a Tsp and a tsp of baking powder. In fact, 1 Tsp = 3 tsp. Ask a cook! (1 Tsp is the standard abbreviation for a tablespoon; 1 tsp is the abbreviation for a teaspoon.)

[3] To an accuracy of 16%.

JOULE

Physicists like to the use energy unit called the *joule* (named after James Joule) because it makes their equations look simpler. There are about 4200 joules in a Calorie, 3600 in a Wh, 3.6 million in a kWh.

Table 1.1 shows the approximate energies in various substances. I think you'll find that this table is one of the most interesting ones in this entire textbook. It is full of surprises. The most interesting column is the rightmost one.

Table 1.1 Energy per Gram

Object	Calories (or watt-hours)	Joules	Compared to TNT
Bullet (at sound speed, 1000 ft/s)	0.01	40	0.015
Battery (auto)	0.03	125	0.05
Battery (rechargeable computer)	0.1	400	0.15
Flywheel (at 1 km/s)	0.125	500	0.2
Battery (alkaline flashlight)	0.15	600	0.23
TNT (the explosive trinitrotoluene)	0.65	2700	1
Modern high explosive (PETN)	1	4200	1.6
Chocolate chip cookies	5	21,000	8
Coal	6	27,000	10
Butter	7	29,000	11
Alcohol (ethanol)	6	27,000	10
Gasoline	10	42,000	15
Natural gas (methane, CH_4)	13	54,000	20
Hydrogen gas or liquid (H_2)	26	110,000	40
Asteroid or meteor (30 km/s)	100	450,000	165
Uranium-235	20 million	82 billion	30 million

Note: Many numbers in this table have been rounded off.

Stop reading now, and ponder this energy table. Concentrate on the rightmost column. Look for the numbers that are surprising. How many can you find? Circle them. I think all of the following are surprises:

- The very large amount of energy in chocolate chip cookies
- The very small amount of energy in a battery (compared to gasoline!)
- The high energy in a meteor, compared to a bullet or to TNT
- The enormous energy available in uranium (compared to anything else in the table)

Try some of these facts on your friends. Even most physics majors will be surprised. These surprises and some other features of the table are worthy of much further discussion. They will play an important role in our energy future.

Discussion of the Energy Table

Let's pick out some of the more important and surprising facts shown in the energy table and discuss them in more detail.

TNT VERSUS CHOCOLATE CHIP COOKIES

Both TNT and chocolate chip cookies store energy in the forces between their atoms. That's like the energy stored in compressed springs—we'll discuss atoms in more detail soon. Some people like to refer to such energy as *chemical energy*, although this distinction isn't really important. When TNT is exploded, the forces push the atoms apart at very high speeds. That's like releasing the springs so that they can suddenly expand.

One of the biggest surprises in the energy table is that chocolate chip cookies (CCCs) have eight times the energy as the same weight of TNT. How can that be true? Why can't we blow up a building with CCCs instead of TNT? Almost everyone who hasn't studied the subject assumes (incorrectly) that TNT releases a great deal more energy than cookies. That includes most physics majors.

What makes TNT so useful for destructive purposes is that it can release its energy (transfer its energy into heat) very, very quickly. The heat is so great that the TNT becomes a gas that expands so suddenly that it pushes and shatters surrounding objects. (We'll talk more about the important concepts of *force* and *pressure* in the next chapter.) A typical time for 1 gram of TNT to release all of its energy is about one *millionth* of a second. Such a sudden release of energy can break strong material.[4] *Power* is the rate of energy release. CCCs have high energy, but the TNT explosion has high power. We'll discuss power in greater detail later in this chapter.

Even though chocolate chip cookies contain more energy than a similar weight of TNT, the energy is normally released more slowly, through a series of chemical processes that we call *metabolism*. This requires several chemical changes that occur during digestion, such as the mixing of food with acid in the stomach and with enzymes in the intestines. Last, the digested food reacts with oxygen taken in by the lungs and stored in red blood cells. In contrast, TNT contains all the molecules it needs to explode; it needs no mixing, and as soon as part of it starts to explode, that triggers the rest. If you want to destroy a building, you can do it with TNT. Or you could hire a group of teenagers, give them sledgehammers, and feed them cookies. Since the energy in chocolate chip cookies exceeds that in an equal weight of TNT, each gram of chocolate chip cookies will ultimately do more destruction than would each gram of TNT.

Note that we have cheated a little bit. When we say there are 5 Calories per gram in CCCs, we are ignoring the weight of the air that combines with the CCCs. In contrast, TNT contains all the chemicals needed for an explosion, whereas CCCs need to combine with air. Although air is "free" (you don't have

[4] As you'll see in chapter 3, to calculate the force, you can take the energy of a substance such as TNT and divide it by the distance over which it is released (from chemical to kinetic energy).

to buy it when you buy the CCCs), part of the reason that CCCs contain so much energy per gram is that the weight of the air was not counted. If we were to include the weight of the air, the energy per gram would be lower, about 2.5 Calories per gram. That's still almost four times as much as for TNT.

THE SURPRISINGLY HIGH ENERGY OF GASOLINE

As table 1.1 shows, gasoline contains significantly more energy per gram than cookies, butter, alcohol, or coal. That's why it is so valuable as fuel. This fact will be important when we consider alternatives to gasoline for automobiles.

Gasoline releases its energy (turns it into heat) by combining with oxygen, so it must be well mixed with air to explode. In an automobile, this is done by a special device known as a *fuel injector*; older cars use something called a *carburetor*. The explosion takes place in a cylindrical cavity known, appropriately, as the *cylinder*. The energy released from the explosion pushes a piston down the axis of the cylinder, and that is what drives the wheels of the car. An internal "combustion" engine can be thought of as an internal "explosion" engine.[5] The *muffler* on a car has the job of making sure that the sound from the explosion is muffled and not too bothersome. Some people like to remove the muffler—especially some motorcyclists—so that the full explosion is heard; this can give the illusion of much greater power. Removing the muffler also lowers the pressure just outside the engine, so the power to the wheels is actually increased, although not by very much. We'll talk more about the gasoline engine in the next chapter.

The high energy per gram in gasoline is the fundamental physics reason why gasoline is so popular. Another reason is that when it burns, all the residues are gas (mostly carbon dioxide and water vapor), so there is no residue to remove. In contrast, for example, most coal leaves a residue of ash.

THE SURPRISINGLY LOW ENERGY IN BATTERIES

A battery also stores its energy in chemical form. It can use its energy to release electrons from atoms (we'll discuss this more in chapters 2 and 6). Electrons can carry their energy along metal wires and deliver their energy at another place; think of wires as *pipes* for electrons. The chief advantage of electric energy is that it can be easily transported along wires and converted to motion with an electric motor.

A car battery contains 340 times *less* energy than an equal weight of gasoline! Even an expensive computer battery is about 100 times worse than gasoline. Those are the physics reasons why most automobiles use gasoline instead of batteries as their source of energy. Batteries are used to start the engine because they are reliable and fast.

[5] Engineers like to make a distinction between an *explosion*, in which an abrupt front called a shock wave is generated that passes through the rest of the material and ignites it, and a *deflagration*, in which there is no shock wave. There is no shock wave in the detonation of gasoline in an automobile, so by this definition, there is no explosion in an automobile engine. Newspapers and the general public do not make this fine distinction, and in this book, neither will I.

Battery-powered cars

A typical automobile battery is also called a *lead–acid battery*, because it uses the chemical reaction between lead and sulfuric acid to generate electricity. Table 1.1 shows that such batteries deliver 340 times less energy than gasoline. However, the electric energy from a battery is very convenient. It can be converted to wheel energy with 85% efficiency—put another way, only 15% is lost in running the electric motor. A gasoline engine is much worse: only 20% of the energy of gasoline makes it to the wheels; the remaining 80% is lost as heat. When you put in those factors, the advantage of gasoline is reduced from 340 down to a factor of 80. So for automobiles, batteries are *only* 80 times worse that gasoline. That number is small enough to make battery-driven autos feasible. In fact, every so often you'll read in the newspaper about someone who has actually built one. A typical automobile fuel tank holds about 100 pounds of gasoline. (A gallon of gasoline weighs about 6 pounds.) To have batteries that carry the energy in 100 pounds of gasoline would take 80 times that weight—that is, 8000 pounds of lead–acid batteries. But if you are willing to halve the range of the car, from 300 miles to 150, then the weight is reduced to 4000 pounds. If you need only 75 miles to commute, then the lead–acid battery weight is only 2000 pounds. (We'll discuss lighter lithium–ion batteries in a moment.)

Why would you trade a gasoline car for a car that could go only 75 miles? The usual motivation is to save money. Electricity bought from the power company, used to charge the battery, costs only 10 cents per kWh. Gasoline costs (as of this writing) about $2.50 per gallon. When you translate that into energy delivered to the wheels, that works out to about 40 cents per kWh. So electricity is four times cheaper! Actually, it isn't quite that good. When most people work out those numbers, they ignore the fact that standard lead–acid car batteries have to be replaced after, typically, 700 charges. When you include the battery expense, the cost per kWh is about 20 cents per kWh. It beats the cost of gasoline by a factor of two. But because batteries take so much space, it's not an attractive option for people who value trunk space.

Batteries have additional advantages in some circumstances. In World War II, when submarines had to submerge and could not obtain oxygen, their energy source was a huge number of batteries stored beneath the decks. When on the surface, or at "snorkeling depth," the submarines ran on diesel fuel, a form of gasoline. The diesel fuel also ran generators that recharged the batteries. So during World War II, most submarines spent most of their time on the surface, recharging their batteries. Watch an old World War II movie, and they don't show that; you get the misimpression that the subs were always below water. Modern nuclear submarines don't require oxygen, and they can remain submerged for months. That greatly increases their security against detection.

Electric car hype

Suppose that we use better batteries, ones that hold more energy per gram. Let's look at the Tesla Roadster, a battery car that has received a lot of attention. It is powered by 1000 pounds of rechargeable lithium-ion batteries, similar to those found in laptop computers. The car range is 250 miles. Tesla Motors claims that if you charge the batteries from your home power plug, driving the car costs 1 to 2 cents per mile. Top speed: 130 miles per hour. Wow!

Can't wait to get one? The cars are built in a factory in England and are currently being sold for about $100,000.

The catch is in the cost of the batteries. Lead–acid batteries, the ones that we considered for the electric car calculation earlier, have a retail cost of about a dollar per pound of battery: $50 for 50 pounds. A good computer battery has a retail price of about $100 per pound—$100,000 for the 1000 pounds in the Tesla Roadster. (When you buy batteries in bulk, the price is about half, so the Roadster batteries cost only $50,000.) When we included replacement costs, the lead–acid batteries cost 10 cents per kWh; a similar calculation shows that computer batteries cost about $4 per kWh. That's 10 times as much as the cost of gasoline! So, when you consider the cost of replacing the batteries, electric cars are far more expensive to operate than our standard gasoline cars. A great deal of research is going into battery improvement, so it is likely that the cost of batteries will come down and that in the future batteries will be made that last longer before they have to be replaced.

There is a lot of hype about "who killed the electric car." Some people say it was the oil industry, because they didn't want a cheaper alternative. But the electric car is not cheaper, unless you are willing to live with the very short range (and heavy) version that uses lead–acid batteries.

HYBRID AUTOS

Despite the limitations of batteries, there is a fascinating technology called *hybrid automobiles*. In a hybrid, a small gasoline engine provides energy to charge a battery; the car then gets its energy from the battery. This has more value than you might guess: the gasoline engine can be run at a constant rate, under ideal conditions, and as a result, it is two to three times as efficient as the engine in ordinary cars. In addition, hybrid engines can convert some of the mechanical motion of the automobile (e.g., its extra speed picked up when descending a hill) back to stored chemical energy in the rechargeable battery. It does this instead of using brakes—which only turn the energy of motion into heat. Hybrid engines are becoming very popular, and in a few years, they may be the most common type of automobile, particularly if gasoline costs go back up to the very high prices of 2008. Hybrid autos can get about 50 miles per gallon (that's what I get with my Toyota Prius, if I drive with low accelerations), considerably better than the 30 miles per gallon that similar nonhybrid autos get.

Many people complain that their hybrids do not have the facility to charge up from the wall plug. The first American version of the Prius got its energy only from its own gasoline engine. In Japan, people can charge the battery from the electric grid, and on the Internet you can find clubs that show you how to change your older Prius to accomplish just that too. The people who do this mistakenly think that they are saving money. They aren't, for the same reason I articulated when discussing all electric autos. It is likely that the batteries in the hybrid can be charged only about 500 to 1000 times. After that, they will have to be replaced, and that will make the average cost per mile much higher. In the current Prius, the batteries are used only during moments when the gasoline engines would be inefficient, such as during rapid acceleration. With this limited use, the batteries will last much longer. It is not clear how much longer that will be, but it could conceivably affect older cars.

HYDROGEN VERSUS GASOLINE—AND THE FUEL CELL

Notice in table 1.1 that hydrogen gas has 2.6 times more chemical energy per gram than gasoline. Popular articles about the future "hydrogen economy" are partially based on this fact. In 2003, President George W. Bush announced a major program with the goal of making hydrogen into a more widely used fuel. But within two years, most of the hydrogen economy programs were cancelled, for the physics reasons we will discuss in a moment.

Another attractive feature of hydrogen is that the only waste product it produces is water, created when the hydrogen is chemically combined with oxygen from the air to make H_2O (water). Moreover, the conversion can be done with high efficiency by using an advanced technology called a *fuel cell* to convert the chemical energy directly to electricity.

A fuel cell looks very much like a battery, but it has a distinct advantage. In a battery, once the chemical is used up, you have to recharge it with electricity produced elsewhere or throw it away. In a fuel cell, all you have to do is provide more fuel (e.g., hydrogen and oxygen). Figure 1.2 shows a setup to demonstrate *electrolysis*, in which electricity is passed between two terminals through water, and hydrogen and oxygen gas are produced at the terminals.

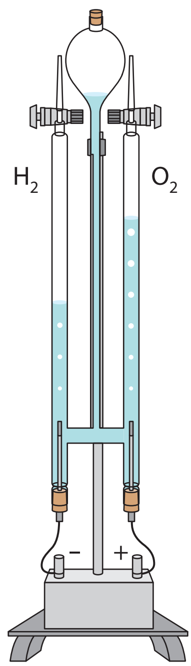

Figure 1.2 Electrolysis. When current is passed through water, it decomposes water into oxygen and hydrogen.

A fuel cell is very similar to an electrolysis apparatus, but it is run backward. Hydrogen and oxygen gas are compressed at the electrodes, they combine to form water, and that makes electricity flow through the wires that connect one terminal to the other. So figure 1.2 can also represent a fuel cell.

The main technical difficulty of the hydrogen economy is that hydrogen is not very dense. Even when liquefied, it has a density of only 0.071 grams per cubic centimeter (cc), a factor of 10 times less than gasoline. As you saw in table 1.1, per gram, hydrogen has 2.6 times more energy than gasoline. Put these together, and we find that liquid hydrogen stores only $0.071 \times 2.6 = 0.18$ times as much energy per cubic centimeter (or per gallon) as gasoline. That is a factor of 5 times worse. However, many experts say that the factor is only 3 times worse, since hydrogen can be used more efficiently than gasoline. It is useful to remember the following approximate numbers; you will find them valuable when discussing the hydrogen economy with other people.

Remember: Compared to gasoline, *liquid hydrogen* has about

3 × *more* energy per gram (or per pound)
3 × *less* energy per gallon (or per liter)

Here's another approximate rule that is easy to remember. In terms of energy that can be delivered to a car:

1 kilogram of hydrogen ≈ 1 gallon of gasoline

Hydrogen liquid is dangerous to store since it expands by a factor of a thousand if warmed. If you protect against that with a thick-walled tank, you might as well store the hydrogen as a high-pressure gas. At a pressure of 10,000 pounds per square inch (66 times atmospheric pressure), the gas is almost half as dense as hydrogen liquid. But that factor of half makes it even harder to fit hydrogen into a reasonable space.

Compared to gasoline, compressed gas hydrogen has
6 × *less* energy per gallon (or per liter).

And the tank to contain the hydrogen typically weighs 10 to 20 times as much as the hydrogen itself. That takes away the weight advantage too.

Because hydrogen takes up so much space (even though it doesn't weigh much), it may be used for buses and trucks before it is used for automobiles. It is also possible that hydrogen will be more valuable as a fuel for airplanes, since for large airplanes the low weight of the hydrogen may be more important than the fact that it takes more volume than gasoline. Fuel cells first achieved prominence in the space program as the energy storage method used by the astronauts (figure 1.3). For the mission to the Moon, low weight was more important than the space that could be saved in the capsule. Moreover, the water that was produced could be used by the astronauts, and there was no waste carbon dioxide to eject.

A technical difficulty with liquid hydrogen is that it boils at a temperature of *minus* 423 degrees Fahrenheit. This means that it must be transported in special thermos bottles (technically known as *dewars*). Either that, or it can be transported in a form in which it is chemically or physically combined with other materials at room temperature, although that greatly increases the weight per Calorie. A more practical alternative may be to transport it as compressed gas, but then the weight of the pressure tank actually exceeds the weight of the hydrogen carried.

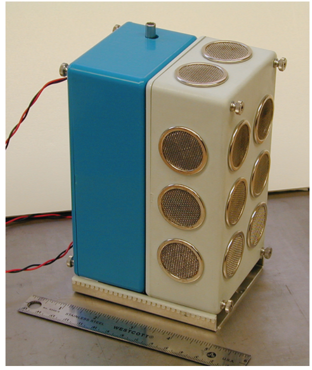

Figure 1.3 Fuel cell developed by NASA. Hydrogen gas enters through the inlet on the top. Air enters through some of the circular openings, and carbon dioxide leaves through the others. The electric power comes from the wires in the back. (Photo courtesy of NASA.)

You can't mine hydrogen! There is virtually no hydrogen gas (or liquid) in the environment. There's lots of hydrogen in water and in fossil fuels (hydrocarbons)—but not "free" hydrogen, the molecule H_2. That's what we want for the hydrogen economy. Where can the hydrogen we need come from? The answer is that we have to "make" it—that is, release it from the compounds of water or hydrocarbons. Hydrogen gas must be obtained by electrolysis of water, by reacting fossil fuels (methane or coal) with water to produce hydrogen gas and carbon monoxide. Doing any of these takes energy.

A typical hydrogen production plant of the future would start with a power plant fueled by coal, gasoline, nuclear fuel, or solar energy. That power plant might use this energy to convert ordinary water to hydrogen and oxygen (through electrolysis, or through a series of chemical reactions known as "steam reforming"). Then, for example, the hydrogen could be cooled until it is turned into a liquid and then transported to the consumer. When hydrogen is obtained in this manner, you get back out of the hydrogen only some of the energy that you put in to make it. A reasonable estimate is that the fraction of the original energy (used to create the hydrogen) that gets to the wheels of the car is about 20%. Thus:

Hydrogen is not a *source* of energy.
It is only a means for *transporting* energy.

Many people who favor the hydrogen economy believe that the source of hydrogen will be methane gas. Methane molecules consist of one carbon atom and four hydrogens. That's why the chemical formula is CH_4. When methane is heated with water to high temperatures, the hydrogen in the methane is released, along with carbon dioxide. Since carbon dioxide is considered an air pollutant (see chapter 11), this method of production may not be optimum, but it is probably the cheapest way to make hydrogen.

Although the fuel cell produces no pollution (only water), it is not quite right to say that a hydrogen-based economy is pollution-free unless the plant that used energy to produce the hydrogen is also pollution-free. Nevertheless, the use of hydrogen as a fuel is expected to be environmentally less harmful than gasoline for two reasons: a power plant can, in principle, be made more efficient than an automobile (so less carbon dioxide is released); and the power plant can have more elaborate pollution-control devices than an automobile. If we use solar or nuclear power to produce the hydrogen, then no carbon dioxide, the most problematic global warming gas, is released.

Hydrogen can also be produced as a by-product of "clean coal" conversion. In some modern coal plants, coal is reacted with water to make carbon monoxide and hydrogen. These are then burned. In such a plant, the hydrogen could be transported to serve as fuel elsewhere, but the energy stored in it originated from the coal.

Other people like the idea of hydrogen as fuel because it moves the sources of pollution away from the cities, where a high concentration of pollutants can be more dangerous to human health. Of course, it is hard to predict all environmental effects. Some environmentalists argue that significant hydrogen gas could leak into the atmosphere and drift to high altitudes. There it could combine with oxygen to make water vapor, and that could affect both the Earth's temperature and delicate atmospheric structure such as the ozone layer (see chapter 9).

The United States has enormous coal reserves. About 2 trillion tons of coal are "known" reserves, but with more extensive searching, geologists expect that about twice as much is likely to be present. Coal could be used to produce all the energy that we would need (at current consumption rates) for hundreds of years. Of course, the environmental consequences from strip mining and carbon dioxide production could be very large. Coal can be converted to liquid fuel for easy pumping and use in automobiles by a technology known as the *Fisher-Tropsch process*; we'll discuss that more in chapter 11.

GASOLINE VERSUS TNT

In most movies, when a car crashes, it explodes. Does this happen in real life? Have you ever witnessed the scene of a car crash? Did an explosion taken place? The answer is: usually not. Cars explode in movies only because they have been loaded with TNT or other explosives for dramatic visual effects. Unless mixed with air in just the right ratio (done in the automobile by the fuel injector or carburetor), gasoline burns but doesn't explode.

In the Spanish revolution, the rebels invented a device that later became known as a "Molotov cocktail." It was a bottle filled with gasoline, with a rag stuck in the neck. The rag was soaked with gasoline and ignited, and then the bottle was thrown at the enemy. It broke upon impact. It usually didn't explode, but it spread burning gasoline, and that was pretty awful to the people who were the targets. This weapon quickly achieved a strong reputation as an ideal weapon for revolutionaries.

I hesitate to give examples from the unpleasant subject of war, but it is important to future presidents and citizens to know of these. On 6 November 2002, the United States started dropping "fuel–air explosives" on Taliban soldiers in Afghanistan. You can probably guess that this was a liquid fuel similar to gasoline. Fifteen thousand pounds of fuel is dropped from an airplane in a large container (like a bomb) that descends slowly on a parachute. As it nears the ground, a small charge of high explosive (probably only a few pounds worth) explodes in the center, destroying the container and dispersing the fuel and mixing it with air—but not igniting it. Once the fuel is spread out and well-mixed with air, it is ignited by a second explosion. The explosion is spread out over a large area, so it doesn't exert the same kind of intense force that it takes to break through a concrete wall, but it has enough energy released to kill people and other "soft" targets. What makes it so devastating is the fact that 15,000 pounds of fuel, like gasoline, contains the energy equivalent of 225,000 pounds of TNT. So although 15,000 pounds sounds bad, in fact it is much worse than it sounds. Once the soldiers had seen the fuel–air explosive from a distance, the mere approach of a parachute induced panic.

URANIUM VERSUS TNT

The most dramatic entry in table 1.1 is the enormous energy in the form of uranium known as *U-235*. The amount of energy in U-235 is 30 million times that of the energy found in TNT. We will discuss this in detail in chapters 4 and 5. For now, there are only a few important facts to know. The enormous forces inside the uranium atom's nucleus provide the energy. For most atoms, this energy cannot be easily released, but for U-235 (a special kind of uranium that makes up only 0.7% of natural uranium), the energy can be released through a process called a *chain reaction* (discussed in detail in chapter 5). This enormous energy release is the principle behind nuclear power plants and atomic bombs. Plutonium (the kind known as *Pu-239*) is another atom capable of releasing such huge energy.

Compared to gasoline, U-235 can release 2 million times as much energy per gram. Compared to chocolate chip cookies, it releases about 3 million times as much. The following approximation is so useful that it is worth memorizing:

> For the same weight of fuel, nuclear reactions release about
> a *million times* more energy than do chemical or food reactions.

More Surprises: Coal Is Dirt Cheap

There are also some amazing surprises in the cost of fuel. Suppose you want to buy a Calorie of energy, to heat your house. What is the cheapest source? Let's forget all other considerations, such as convenience, and just concentrate on the cost of the fuel. It is not easy for the consumer to compare. Prices are constantly changing, so let's just use some average prices from the last few years: Coal costs about $40 per ton, gasoline costs about $2.50 per gallon, natural gas (methane) costs about $3 per thousand cubic feet, and electricity costs about 10¢ per kilowatt-hour. So which gives the most Calories per dollar? It isn't obvious, since the different fuels are measured in different units, and they provide different amounts of energy. But if you put all the numbers together, you get table 1.2. This table also shows the cost of the energy if it is converted to electricity. For fossil fuels, that increases the cost by a factor of 3, since motors convert only about 1/3 of the heat energy to electricity.

The wide disparity of these prices is quite remarkable. Concentrate on the third column, the cost per kWh. Note that it is 25 times more expensive to heat

Table 1.2 Cost of Energy

Fuel	Market cost	Cost per kWh (1000 Cal)	Cost if converted to electricity
Coal	$40 per ton	0.4¢	1.2¢
Natural gas	$3 per thousand cubic feet	0.9¢	2.7¢
Gasoline	$2.50 per gallon	7¢	21¢
Electricity	$0.10 per kWh	10¢	10¢
Car battery	$50 to buy battery	21¢	21¢
Computer battery	$100 to buy battery	$4.00	$4.00
AAA battery	$1.50 per battery	$1000.00	$1000.00

your home with electricity than with coal! Gasoline costs over 2 times as much as natural gas. That has led some mechanics to modify their autos to enable them to use compressed natural gas instead of gasoline.

Note that for heating your home, natural gas *not converted to electricity* is 3 times cheaper than electricity. Back in the 1950s, many people thought that the "all-electric home" was the ideal—since electricity is convenient, clean, and safe. But most such homes have now been converted to use coal or natural gas, just because the energy is considerably cheaper.

Most dramatic on this list is the low price of coal. If energy per dollar were the only criterion, we would use coal for all our energy needs. Moreover, in many countries that have huge energy requirements, including the United States, China, Russia, and India, the reserves of coal are huge—enough to last for hundreds of years. We may run out of oil in the next few decades, but that does not mean that we are running out of cheap fossil fuel.

So why do we use oil instead of coal in our automobiles? The answer isn't physics, so I am only guessing. But part of the reason is that gasoline is very convenient. It is a liquid, and that makes it easy to pump into your tank, and from the tank to the engine. It was once much cheaper than it is now, and so in the past the cost was not as important an issue as convenience, and once we have optimized our auto designs and fuel delivery systems for gasoline, it's not easy to switch. It does contain more energy per gram than coal, so you don't have to carry as many pounds—although it is less dense, so it takes more space in the tank. Coal also leaves behind a residue of ash that has to be removed.

The low price of coal presents a very serious problem for people who believe that we need to reduce the burning of fossil fuels. Countries with substantial numbers of poor people may feel that they cannot switch to more expensive fuels. So the incredibly low price of coal is the real challenge to alternative fuels, including solar, biofuels, and wind. Unless the cost of these fuels can match the low cost of coal, it may be very difficult to convince developing countries that they can afford to switch.

It is odd that energy cost depends so much on the source. If the marketplace were "efficient," as economists sometimes like to postulate, then all these different fuels would reach a price at which the cost would be the same. This hasn't happened, because the marketplace is *not* efficient. There are large investments in energy infrastructure, and the mode of delivery of the energy is important. We are willing to spend a lot more for energy from a flashlight battery than from a wall plug because the flashlight is portable and convenient. Locomotives once ran on coal, but gasoline delivers more energy per pound, and it does so without leaving behind a residue of ash, so we switched from steam to diesel locomotives. Our automobiles were designed during a period of cheap oil, and we became accustomed to using them as if the price of fuel would never go up. Regions of the world with high gas prices (such as the countries of Europe) typically have more public transportation. The United States has suburbs—a luxury that is affordable when gas is cheap. Much of our way of living has been designed around cheap gasoline. The price we are willing to pay for fuel depends not only on the energy that it delivers, but also on its convenience.

The real challenge for alternative energy sources is to be more economically viable than coal. When we talk about global warming (in chapter 11), we'll discuss how coal is one of the worst carbon dioxide polluters that we use. To reduce our use of coal, we could, of course, tax it. But doing that solely in the developed nations would not accomplish much, since the ultimate problem will be energy use by nations such as China and India. Leaders of such countries might choose to get their energy in the cheapest possible way so that they can devote their resources to improving the nutrition, health, education, and overall economic well-being of their people.

Forms of Energy

We have talked about food energy and chemical energy. The energy in a moving bullet or an asteroid is called energy of motion, or *kinetic energy*. The energy stored in a compressed spring is called stored energy or *potential energy*. (Despite its name, potential energy does *not* mean that it is something that can "potentially" be converted to energy; potential energy *is* energy that is stored, just as food that is stored is still food.) *Nuclear energy* is the energy stored in the forces between parts of the atomic nucleus, released when the nucleus is broken. *Gravitational energy* is the energy that an object has at high altitude; when it falls, this energy is converted to kinetic energy. As we will discuss in chapter 2, the heat in an object is a form of energy. All these energies can all be measured in Calories or joules.

Many physics texts like to refer to chemical, nuclear, and gravitational energy as different forms of potential energy. This definition lumps together in one category all the kinds of energy that depend on shape and position—e.g., whether the spring is compressed, or how the atoms in a chemical are arranged. This lumping is done in order to simplify equations; there is no real value in doing it in this text, as long as you realize that all energy is energy, regardless of its name.

In popular usage, the term *energy* is used in many other ways. Tired people talk about having "no energy." Inspirational speakers talk about the "energy of the spirit." Be clear: they have the right to use *energy* in these nontechnical ways. Physicists stole the word *energy* from the English language and then redefined it in a more precise way. Nobody gave physicists the right to do this. But it is useful to learn the precise usage and to be able to use the term in the way physicists do. Think of this as "physics as a second language." The more precise definition is useful when discussing physics.

In the same precise physics language, *power* is defined as the energy used per second. It is the *rate* of energy release, as I mentioned early in this chapter. In equation form:

power = energy/time

Note that in popular usage, the terms of power and energy are often used interchangeably. You can find examples of this if you pay attention when reading newspaper articles. In our precise use of these terms, however, we can say that the value of TNT is that even though it has less energy per gram than chocolate chip cookies, it has greater power (since it can convert its limited energy to heat in a few millionths of a second). Of course, it can't deliver this power for very long because it runs out of energy.

As I mentioned earlier, the most common unit for power is the watt, named after James Watt, who truly developed the science of the steam engine. It was the most powerful motor of its time, and the "high-tech" of the late 1700s and early 1800s. The watt is defined as one joule per second:

1 W = 1 watt = 1 joule per second
1 kW = 1 kilowatt = 1000 joules per second

As you saw earlier, the term *kilowatt* is usually abbreviated as kW since Watt is a person's name, even though *watt* is usually not capitalized. The same logic (or lack of logic) applies to the kilojoule, abbreviated kJ.

There is a physics joke about the watt, inspired by an Abbott and Costello routine called "Who's on First" about baseball names. I relegate it to a footnote.[6] The original "Who's on First" routine is available on the Internet.

Energy Is "Conserved"

When the chemical energy in TNT or gunpowder is suddenly turned into heat energy, the gases that come out are so hot that they expand rapidly and push the bullet out of the gun. In doing this pushing, they lose some of their energy (they cool off); this energy goes into the kinetic energy of the bullet. Remarkably, if you add up all this energy, the total is the same. Chemical energy is converted to heat energy and kinetic energy, but the number of Calories (or joules) after the gun is fired is exactly the same as was stored in the gunpowder. This is the meaning behind the physics statement that "energy is conserved."

The conservation of energy is one of the most useful discoveries ever made in science. It is so important that it has earned a fancy name: the *first law of*

[6] Two people are talking. Costello: "What is the unit of power?" Abbott: "Watt." Costello: "I said, 'What is the unit of power?' " Abbott: "I said, 'Watt.' " Costello: "I'll speak louder. WHAT is the unit of power?" Abbott: "That's right." Costello: "What do you mean, 'that's right?' I asked you a question." Abbott: "Watt is the unit of power." Costello: "That's what I asked." Abbott: "That's the answer."—You can extend this dialog as long as you want.

thermodynamics. Thermodynamics is the study of heat, and we'll talk a lot about that in the next chapter. The first law points out the fact that any energy that appears to be lost isn't really lost; it is usually just turned into heat.

When a bullet hits a target and stops, some of the kinetic energy is transferred to the object (ripping it apart), and the rest is converted to heat energy. (The target and the bullet each get a little bit warmer when they collide.) This fact, that the total energy is always the same, is another example of the *conservation of energy*. It is one of the most useful laws of physics.[7] It is particularly valuable to people doing calculations in physics and engineering. Use of this principle allows physicists to calculate how rapidly the bullet will move as it emerges from the gun; it allows us to calculate how fast objects will move as they fall.

But if energy conservation is a law of physics, why are we constantly admonished by our teachers, by our political leaders, and by our children that we should conserve energy? Isn't energy automatically conserved?

Yes it is, but not all forms of energy have equal economic value. It is easy to convert chemical energy to heat, and very difficult to convert it back. When you are told to conserve energy, what is really meant is "conserve useful energy." The most useful kinds are chemical (e.g., in gasoline) and potential energy (e.g., the energy stored in water that has not yet run through a dam to produce electric power). The least useful form is heat, athough some (but not all) of heat energy can be converted to more useful forms.

Measuring Energy

The easiest way to measure energy is to convert it to heat and then see how much it raises the temperature of water. The original definition of the Calorie was actually based on this kind of effect: one Calorie is the energy it takes to raise one kilogram of water by one degree Celsius (1.8 degrees Fahrenheit). One "little" calorie is the energy to raise one *gram* of water by one degree Celsius. There are about 4200 joules in a Calorie. Another unit of energy that is widely used is the kilowatt-hour (kWh). This is the unit that you pay for when you buy electric energy from a utility company. A kWh is the energy delivered when you get a thousand watts for an hour. That's 1000 joules per second for 3600 seconds (an hour), i.e., 3.6 million joules = 860 Calories. You can remember this as 1 watt-hour (Wh) is approximately 1 Calorie. It is tedious and unnecessary to memorize all these conversions, and you probably shouldn't bother (except for the cases that I specifically recommend). Table 1.3 shows the conversions.

Although you shouldn't bother memorizing this table, it is useful to refer to it often so that you can get a feel for the amount of energy in various issues. For example, if you become interested in the energy usage of countries, then you will read a lot about *quads* and will find them a useful unit. U.S. energy

[7] When Einstein's theory of relativity (see chapter 12) predicted that mass can be converted to energy, the law was modified to say that the total of mass and energy is conserved.

Table 1.3 Common Energy Units

Energy unit	Definition and equivalent
calorie (lowercase)	Heats 1 gram of water by 1°C
Calorie (capitalized), the food calorie, also called kilocalorie	Heats 1 kg of water by 1°C 1 Calorie = 4182 joules ≈ 4 kJ
Joule	1/4182 Calories
	≈ Energy to lift 1 kg by 10 cm
	≈ Energy to lift 1 lb by 9 in
Kilojoule	1000 joules = 1/4 Calorie
Megajoule	1000 kilojoules = 10^6 joules Costs about 5 cents from electric utility
Kilowatt-hour (kWh)	861 Calories ≈ 1000 Calories = 3.6 megajoules
	Costs 10 cents from electric utility
British Thermal Unit (BTU)	1 BTU = 1055 joules ≈ 1 kJ = 1/4 Calorie
Quad	A quadrillion BTUs = 10^{15} BTU ≈ 10^{18} J
	Total U.S. energy use ≈ 100 quads per year;
	total world use ≈ 400 quads per year

Note: The symbol ≈ means "approximately equal to."

use is about 100 quads per year. (Notice that quads per year is actually a measure of power.)

Power

As we discussed earlier, *power* is the rate of energy transfer. The rate at which something happens is the "something" divided by the time—for example, miles/hour = miles per hour, or births/year = births per year. Thus, when 1 gram of TNT releases 0.651 Calories in 0.000001 second (one millionth of a second), the power is 651,000 Calories per second.

Although power can be measured in Calories per second, the two other units that are far more commonly used are the watt (one joule per second) and the horsepower. The horsepower was originally defined as the power that a typical horse could deliver, i.e., how much work the horse could do every second. These days, the most common use of the term is to describe the power of an automobile engine—a typical auto delivers 50 to 400 horsepower. James Watt, in the 1700s, was the first to actually determine how big one horsepower is. One horsepower turned out to be 0.18 Calorie per second. (Does that sound small to you? Or does it illustrate that a Calorie is a big unit?) Watts are the most commonly used unit to measure electric power.

James Watt found that a horse could lift a 330-pound weight vertically for a distance of 100 feet in one minute. He defined this rate of work to be one horsepower (hp). It turns out that 1 hp is about 746 W, which you can think of as approximately 1000 W, or 1 kilowatt (kW). (By now, I hope you are getting used to my approximations, such as 746 is approximately 1000.) Common units are as follows:

kilowatt (1 kW = 1000 watts),
megawatt (1 MW = 1 million watts)
gigawatt (1 GW = 1 billion watts = 10^9 watts = 1000 MW)

The abbreviation for million (*mega-*) is capital *M*, and for billion (*giga-*) is capital *G*. So, for example, 1000 kW = 1 MW = 0.001 GW. One Calorie per second is about 4 kilowatts.

Only if you need to do engineering calculations do you need to know that 1 hp is 746 W. I do not recommend that you try to remember this; you can always look it up if you really need it. Instead, remember the approximate equation:

$$1 \text{ horsepower} \approx 1 \text{ kilowatt}$$

It is far more useful to remember this approximate value than it is to try unsuccessfully to remember the exact value.

Power usage is so important (for future presidents and knowledgeable citizens) that it is worthwhile learning some key numbers. These are given in table 1.4. Learn the approximate values by visualizing the examples.

Table 1.4 Power Examples

Value	Equivalent	Examples of that much power use
1 watt (1 W)	1 joule per second	Flashlight
100 watts		Bright lightbulb; heat from a sitting human
1 horsepower (1 hp)	≈ 1 kilowatt[a]	Typical horse (for extended time); human running fast up flight of stairs
1 kilowatt (1 kW)	≈ 1 hp[b]	Small house (not including heat); power in 1 square meter of sunlight
20 horsepower	≈ 20 kW[c]	Small automobile
1 megawatt (1 MW)	1 million (10^6) watts	Electric power for a small town
45 megawatts		747 airplane; small power plant
1 gigawatt (1 GW)	1 billion (10^9) watts	Large coal, gas, or nuclear power plant
400 gigawatt (0.4 terawatts)		Average electric power use for United States
2 terawatts	$= 2 \times 10^{12}$ watts	Average electric power for world

[a] More precise value: 1 hp = 746 watts
[b] More precise value: 1 kW = 1.3 hp
[c] More precise value: 20 hp = 14.9 kW

Power Examples

Since energy is conserved, the entire energy industry never actually produces or generates energy, it only converts it from one form to another and transports it from one location to another. Nevertheless, the popular term for this is "generating power." (It is an interesting exercise to read the words used in newspaper articles and then translate them into a more precise physics version.)

To give a sense of how much power is involved in important uses, we'll now describe some examples in more detail. Many of these numbers are worth knowing, because they affect important issues, such as the future of solar power.

Here is a brief description of what happens between the power plant and the lighting of a lightbulb in your home. The original source of the energy may be chemical (oil, gas, or coal), or nuclear (uranium). In a power plant, energy is converted to heat, which boils water, creating hot compressed steam. The expanding steam blows past a series of fans called a *turbine*. These fans rotate the crank of a device called an *electric generator*. We'll discuss how electric generators work in more detail in chapter 6, but they turn the mechanical rotation into electric current—that is, into electrons that move through metal. The main advantage of electric energy is that it is easily transported over thousands of miles, just using metal wires, to your home.

A typical large power generating station produces electric power at the rate of about one gigawatt = one billion watts = 10^9 watts = 1 GW (see table 1.4). This is a useful fact to remember. It is true for both nuclear and oil/coal burning plants. If each house or apartment required one kilowatt (that would light ten 100-watt bulbs), then one such power plant could provide the power for one million houses. Smaller power plants typically produce 40 to 100 MW (megawatts). These are often built by small towns to supply their own local needs. One hundred MW will provide power for about 100,000 homes (fewer if we include heating or air conditioning). The state of California is large, and on a hot day it uses 50 GW, so it needs the equivalent of about 50 large electric power plants.

In an electric power plant, not all the fuel energy goes into electricity; in fact, about two-thirds of the energy is lost when it turns into heat. That's because the steam does not cool completely, and because much of the heat escapes into the surroundings. Sometimes this heat is used to warm surrounding buildings. When this is done, the plant is said to be "co-generating" both electricity and useful heat.

Table 1.4 gives the typical power of important devices, ranging from a flashlight (1 watt) up to the total world power (2 terawatts, equal to 2 million million watts).

LIGHTBULBS

Ordinary household lightbulbs, sometimes called *incandescent* or *tungsten bulbs*, work by using electricity to heat a thin wire inside the bulb. This wire, called the *filament*, is heated until it glows white-hot. (We'll discuss the glow of such filaments in more detail in chapters 2 and 8.) All of the visible light comes from the hot filament, although the bulb itself can be made frosted so that it spreads the light out, making it less harsh to look at. The glass bulb (which gives the lightbulb its name) protects the filament from touch (its temperature is over 1000°C ≈ 1800°F) and keeps away oxygen, which would react with the hot tungsten and weaken it.

The brightness of the bulb depends on how much power it uses—that is, on how much electricity is converted to heat each second. A tungsten light that uses 100 watts is brighter than one that uses 60 watts. Because of this, many people mistakenly believe that a watt is a unit of brightness, but it isn't. A 13-watt *fluorescent* lightbulb (we'll discuss these in chapters 9 and 10) is as bright as a 60-watt conventional (incandescent) bulb. Does that mean that a conventional bulb wastes more electricity than does a fluorescent bulb? Yes. The extra electric power used just heats the bulb. That's why tungsten bulbs are much hotter to the touch than equally bright fluorescent bulbs. One kilowatt, the amount of power used by ten 100-watt bulbs, will illuminate your home brightly, assuming that you have an average-size house and are using conventional bulbs.

Memory trick: Imagine that it takes one horse to light your home (one horsepower ≈ 1 kilowatt).

A new kind of light source called a *light-emitting diode*, or *LED*, is now coming on the market. It is almost as efficient as a fluorescent bulb, but it is not yet as cheap. That could change in the near future. LEDs are already being used for traffic lights and flashlights.

SUNLIGHT AND SOLAR POWER

How much power is in a square meter of sunlight? The energy of sunlight is about 1 kilowatt per square meter. So the sunlight hitting the roof of a car (about 1 square meter) is about 1 kilowatt ≈ 1 horsepower. And all of that energy is in the form of light. When the light hits the surface, some bounces off (that's why you can see it), and some is converted to heat (making the surface warm).

Suppose that you placed a kilowatt tungsten bulb in every square meter of your home. Would the home then be as brightly lit as it would be by sunlight? Hint: Recall that a watt is not a unit of brightness, but of energy delivered per second. In sunlight, all of that energy is in the form of light. In an electric bulb, most of the energy goes into heat. Does your answer match what you think would happen with this much light?

Many environmentalists believe that the best source of energy for the long-term future is sunlight. It is "sustainable" in the sense that sunlight keeps coming as long as the Sun shines, and the Sun is expected to have many billions of years left. Solar energy can be converted to electricity by using silicon solar cells, which are crystals that convert sunlight directly to electricity. (We'll discuss these in more detail in chapters 10 and 11.) The power available in sunlight is about one kilowatt per square meter. So if we could harness all of the solar energy falling on a square meter for power production, that energy would generate one kilowatt. But a cheap solar cell can only convert about 15% of the power, or about 150 watts per square meter. The rest is converted to heat, or reflected. A more expensive solar cell (such as those used on satellites) is about 40% efficient, i.e., it can produce about 400 watts per square meter. A square kilometer contains a million square meters, so a square kilometer of sunlight has a gigawatt of power. If 15% is converted to solar cells, then that is 150 megawatts per square kilometer, or about 1 gigawatt for 7 square kilometers. That is about the same as the energy produced by a large modern nuclear power plant.

Here is a summary of the important numbers for solar power:

1 square meter	1 kilowatt of sunlight 150–400 watts electric using solar cells
1 square kilometer	1 gigawatt of sunlight 150–400 megawatts electric

Some people say that solar power is not practical. Even educated people sometimes say that to get enough solar even for a state such as California, you would have to cover the entire country with solar cells.

Is that true? Look at table 1.4. A gigawatt, the output of a typical nuclear power plant, would take 7 square kilometers. This may sound big, but it really isn't. California has a typical peak power use (during the day, largely to run air conditioners) of about 50 gigawatts of electrical power; to produce this would take 350 square kilometers of solar cells. This would take less than one thousandth—that's one-tenth of one percent—of the 400,000-square-kilometer area of California. Besides, the solar plants could be placed in a nearby state, such as Nevada, that gets less rain and doesn't need the power itself.

Others complain that solar energy is available only during the day. What do we do at night? Of course, it is during the day that we have the peak power demand, to run our factories and our air conditioners. But if we are to convert completely to solar cells, then we will need an energy storage technology. Many people think that batteries, compressed air, or flywheels might provide that.

Right now, solar power costs more than other forms, largely because the solar cells are expensive and don't last forever. See what you can find about the costs of solar cells and the cost of building such a plant. (I've talked to contractors who have told me that installation of anything costs $10 per square foot.) Would solar power be more feasible in underdeveloped regions of the world, where construction costs are usually lower?

SOLAR-POWERED AUTOMOBILES AND AIRPLANES

There is an annual race across Australia for solar-powered automobiles. The fundamental problem with such a vehicle can be seen from the fact that one square meter of sunlight has about one kilowatt of power, which is equal to about one horsepower. Since expensive solar cells are only about 40% efficient, that means that you need 2.5 square meters of solar cells just to get one horsepower, whereas typical automobiles use 50 to 400 hp.[8] The race is obviously among very low-powered vehicles!

[8] To read more about the annual race, go to their Web page, at http://www.wsc.org.au/index.html.

Given that low power, it is surprising to discover that a solar-powered airplane has successfully flown. Actually, the vehicle isn't truly an airplane—it doesn't have a pilot or passengers, so it is called an *aircraft*, a *drone*, or an *UAV* (for "unmanned aerial vehicle"). The aircraft was named the *Centurion* (figure 1.4). The solar cells are on the upper and lower surfaces of the wings; the cells on the undersides use light reflected off the Earth. The solar cells have to be big to gather solar power, and yet they also have to be light in weight. The *Centurion* has a wingspan of 206 feet, greater than for a Boeing 747. The total power from the solar cells is only 28 horsepower. The entire weight of the *Centurion* is 1100 pounds. It has already set an altitude record for airplanes of 96,500 feet. (Commercial airplanes fly at about 40,000 ft.) The *Centurion* was built by AeroVironment, a company started by engineer Paul McCready, who designed the *Gossamer Condor* and the *Gossamer Albatross*. We'll talk more about the *Gossamer Albatross* in a moment.[9]

Figure 1.4 *Centurion*, a solar-powered aircraft. (Photo courtesy of NASA.)

HUMAN POWER

If you weigh 140 pounds and you run up a 12-foot flight of stairs in 3 seconds, your muscles are generating about 1 horsepower. (Remember: *Generating* means

[9] For more information, see the AeroVironment Web page at http://www.avinc.com.

converting from one form to another. The muscles store energy in chemical form and convert it to energy of motion.) If you can do this, does that make you as powerful as a horse? No. One horsepower is about as much power as most people can produce briefly, but a horse can produce one horsepower for a sustained period, and several horsepower for short bursts.

Over a sustained period of time, a typical person riding a bicycle can generate power at the rate of about 1/7 = 0.14 = 14% of a horsepower. (Does that seem reasonable? How much does a horse weigh compared to a person?) A world-class cyclist (Tour de France competitor) can do better: about 0.67 horsepower for more than an hour, or 1.5 horsepower for a 20-second sprint.[10] In 1979, cyclist Bryan Allen used his own power to fly a superlight airplane, the *Gossamer Albatross*, across the 23-mile-wide English Channel (figure 1.5).

Figure 1.5 Bryan Allen, about to pedal the *Gossamer Albatross*, with its 96-foot wingspan. It weighed only 66 pounds. Allen was both the pilot and the engine. (Photo courtesy of NASA.)

The *Gossamer Albatross* had to be made extremely light and yet stable enough to control. A key aspect of the design was that it had to be made easy to *repair*. Paul McCready, the engineer who designed it, knew that such a lightweight airplane would crash frequently—for example, whenever there was a large gust of wind. It flew only a few feet above the surface.

DIET VERSUS EXERCISE

How much work does it take to lose weight? We have most of the numbers that we need to calculate this. We saw in the last section that a human can generate a sustained effort of 1/7 horsepower. According to measurements made on such people, the human body is about 25% efficient—i.e., to generate work of 1/7 horsepower uses fuel at the rate of 4/7 horsepower. Put another way, if you can do useful work at 1/7 horsepower, the total power you use including heat generated is four times larger.

[10] I thank bicyclist Alex Weissman for these numbers. Here is a reference: http://jap.physiology.org/cgi/content/full/89/4/1522.

That's good if you want to lose weight. Suppose that you do continuous strenuous exercise and burn fat at the rate of 4/7 horsepower. Since one horsepower is 746 watts (I'm using the more exact value here), that means that in strenuous exercise you use $(4/7) \times 746 = 426$ watts = 426 joules per second. In an hour (3600 seconds), you will use 426×3600 joules = 1,530,000 joules = 367 Calories.

Coca-Cola, for example, contains about 40 grams of sugar in one 12-ounce can. That endows it with about 155 Calories of "food energy." That can be "burned off" with about a half hour of continuous, strenuous exercise. That does not mean jogging. It means running, or swimming, or cleaning stables.[11]

Exercise vigorously for a half hour, or jog for an hour, and drink a can of Coke. You've replaced all the calories "burned" in the exercise. You will neither gain nor lose weight (not counting short-term loss of water). Milk and many fruit juices contain even more Calories per glass. So don't think you can lose weight by drinking "healthy" instead of Coke. They may contain more vitamins, but they are high in Calories.

A typical human needs about 2000 Calories per day to sustain constant weight. Fat (e.g., butter) contains about 7 Calories per gram. So if you cut back by 500 Calories per day—that is, you reduce your consumption by a quarter of the 2000 you otherwise would have eaten—you will consume about 70 grams of your own fat per day, 500 grams per week, equal to a little more than a pound per week. That seems slow, for such a severe diet, and it is, and that's why so many people give up on their diets.

Alternatively, you can lose that pound per week by working out at 1/7 horsepower for one hour every day, seven days per week. Activities that do this include racquetball, skiing, jogging, or very fast walking. Swimming, dancing, or mowing grass uses about half as many Calories per hour. So, to lose a pound per week, exercise vigorously for an hour every day, or moderately for two hours, or cut your food consumption by 500 Calories. Or find some combination.

But don't exercise for an hour, and then reward yourself by drinking a bottle of Coke. If you do, you'll gain back every Calorie you worked off.

WIND POWER

Wind is generated from solar energy, when different parts of the surface of the Earth are heated unevenly. Uneven heating could be caused by many things, such as differences in absorption, differences in evaporation, or differences in cloud cover. Windy places have been used as sources of power for nearly a thousand years. The windmill was originally a mill (a factory for grinding flour) driven by wind power, although early windmills were also used by the Dutch for pumping water out from behind their dikes. Many people are interested in wind power again these days as an alternative source of electricity. Pilot wind generation plants were installed at the Altamont Pass in California in the 1970s. These

[11] Books on exercise physiology tabulate these numbers; the readers tend to be athletes and farm operators—hence the interest in cleaning stables.

Figure 1.6 Wind turbines. (Photo courtesy of New Mexico Wind Energy Center.)

are more commonly called *wind turbines* (figure 1.6), since they no longer mill flour.

Modern wind turbines are much more efficient at removing energy from wind when they are large. This is, in part, because then they can get energy from winds blowing at higher elevations. Some wind turbines are taller than the Statue of Liberty.

Wind power ultimately derives from solar, since it is differences in temperature that drive the winds. We'll discuss this further in the next chapter, in the section "Heat Flow." The wind turbines cannot be spaced too closely, because when they take energy from the wind, the wind velocity is decreased, and the wind is made turbulent—i.e., it is no longer flowing in a smooth pattern. A "forest" of wind turbines has been proposed for construction on the ocean, off the coast of Massachusetts, to supply commercial power (figure 1.7). In case you are interested, here are some of the details: There would be 170 large windmills in a 5-mile-by-5-mile square, connected to land via an undersea cable. Each windmill would rise 426 feet, from water level to the tip of the highest blade (the height of a 40-story building). They would be spaced 1/2 mile from each other. The maximum power this forest can deliver will be 0.42 gigawatts. The major opposition to the idea appears to be coming from environmentalists who argue that the array would destroy a wilderness area, kill birds, and create noise that could disturb marine animals.

Figure 1.7 A map of the proposed offshore wind turbine park in Massachusetts.

Kinetic Energy

Let's go back to table 1.1 again and discuss another surprising fact from that table: The energy of motion of a typical meteor is 150 times greater than the chemical energy of an equal mass of TNT.

Unlike chemical energy, which usually has to be measured (not calculated), there is a simple equation for kinetic energy:

The kinetic energy equation:

$$E = \tfrac{1}{2} mv^2$$

To use this equation, v must be in meters per second, and m in kilograms, and the energy will be in joules. To convert energy to Calories, divide by 4200. Here are useful (approximate) conversions[12]:

1 meter per second (mps) = 2 miles per hour (mph)
1 kilogram (kg) = 2 pounds (lb)

The equation for kinetic energy is optional. It is useful to see it, but because the units may be unfamiliar, the equation is tricky to use.

[12] In many textbooks, kilograms are used solely as a measure of mass. I may be accused of being "sloppy" in not following that physics convention. In fact, scales in both Europe and the United States "weigh" in kilograms. *Kilogram* has become, in common use, a term that denotes the weight of one kilogram of mass.

But notice how similar the kinetic equation is to Einstein's famous equation of special relativity, $E = mc^2$. In the Einstein equation, c is the speed of light in a vacuum: 3×10^8 meters per second. The similarity is not a coincidence, as you will see when we discuss relativity in chapter 12. Einstein's equation states that the energy hidden in the mass of an object is approximately equal to the classical kinetic energy that object would have if it moved at the speed of light. For now, Einstein's famous equation might help you to remember the less famous kinetic energy equation.

Let's take a closer look at what the kinetic energy equation tells us about the relation of kinetic energy to mass and speed. First, the kinetic energy is proportional to the object's mass. This is very useful to remember, and can give you insights even without using the equation. For example, a 2-ton SUV has twice as much kinetic energy as a 1-ton Volkswagen Beetle traveling at the same speed.

In addition, the object's kinetic energy depends on the square of its velocity. This is also a very useful thing to remember. If you double your car's speed, you will increase its kinetic energy by a factor of 4. A car moving at 60 mph has 4 times the kinetic energy as a similar car moving at 30 mph. At 3 times the speed, there is 9 times the kinetic energy.

Now let's plug some numbers into the kinetic equation and see what we get for a very fast object, a meteor. We will express mass in kilograms and velocity in meters/second. We'll do the calculation for a 1-gram meteor traveling at 30 kilometers per second. First, we must convert these numbers: the mass $m = 0.001$ kg; the velocity $v = 30$ km/sec = 30,000 meters/sec. If we plug these numbers into the equations, we get

$$\begin{aligned} E &= \tfrac{1}{2} mv^2 \\ &= \tfrac{1}{2}(0.001)(30000)^2 \\ &= 450000 \text{ joules} = 450 \text{ kJ} \approx 100 \text{ Calories} \end{aligned}$$

SMART ROCKS AND BRILLIANT PEBBLES

For over two decades, the U.S. military has seriously considered a method of destroying nuclear missiles (an "anti-ballistic-missile," or ABM, system) that would not use explosives. Instead, a rock or other chunk of heavy material is simply placed in the missile's path. In some formulations, the rock is made "smart" by putting a computer on it, so that if the missile tries to avoid it, the rock will maneuver to stay in the path

How could a simple rock destroy a nuclear warhead? The warhead is moving at a velocity of about 7 kilometers per second—i.e., $v = 7000$ meters per second. From the point of view of the missile, the rock is approaching it at 7000 meters per second. (Switching point of view like this is called *classical relativity*.) The kinetic energy of each gram (0.001 kg) of the rock, relative to the missile, is

$$E = \tfrac{1}{2}(0.001)(7000)^2 = 25000 \text{ J} = 6 \text{ Cal}$$

Thus, the kinetic energy of the rock (seen from the missile) is 6 Calories. That is 9 times the energy it would have if it were made from TNT. It is hardly necessary to make it from explosives; the kinetic energy by itself will destroy the missile. In fact, making the rock out of TNT would provide only a little additional energy, and it would have very little additional effect.

The military likes to refer to this method of destroying an object as "kinetic energy kill" (as contrasted with "chemical energy kill"). A later invention that used even smaller rocks and smarter computers was called "brilliant pebbles." (I'm not kidding. Try looking it up on the Internet.)

Here is an interesting question: How fast must a rock travel so that its kinetic energy is the same as the chemical energy in an equal mass of TNT? According to table 1.1, the energy in 1 gram of TNT is 0.651 Calories = 2,723 joules. We set $1/2\ mv^2 = 2723$ J. Use 1-gram rock for m, so $m = 0.001$ kilograms (getting the units right is always the hardest part of these calculations!). Then,

$$\begin{aligned} v^2 &= 5446000 \\ v &= \text{sqrt}(5446000) \\ &= 2300 \text{ m/sec} \\ &= 2.3 \text{ km/sec} \end{aligned}$$

That's 7 times the speed of sound.

THE DEMISE OF THE DINOSAURS

Now let's think about the kinetic energy of the asteroid that hit the Earth and killed the dinosaurs. The velocity of the Earth around the Sun is 30 km/sec,[13] so it is reasonable to assume that the impact velocity was about that much. (It would have been more in a head-on collision, and less if the asteroid approached from behind.)

If the asteroid had a diameter of 10 kilometers, its mass would be about 1.6×10^{12} tons (1.6 teratons).[14] From table 1.1, we see that its energy was 165 times greater than the energy of a similar amount of TNT. So it would have had the energy of $(165) \times (1.6 \times 10^{12}) = 2.6 \times 10^{14}$ tons $= 2.6 \times 10^8$ megatons of TNT. Taking a typical nuclear bomb to be 1 megaton of TNT,[15] this says that the impact released energy equivalent to over 10^8 nuclear bombs. That's 10,000 times the entire Russian–U.S. nuclear arsenal at the height of the Cold War.

The asteroid made a mess, but it stopped. The energy was all turned to heat, and that resulted in an enormous explosion. However, an explosion of that size is still large enough to have very significant effects on the atmosphere. (Half of the air is within three miles of the surface of the Earth.) A layer of dirt

[13] The Earth–Sun distance is $r = 93 \times 10^6$ miles $= 150 \times 10^6$ kilometers. The total distance around the circumference is $C = 2\pi r$. The time it takes to go around is one year $t = 3.16 \times 10^7$ seconds. Putting these together, we get the velocity of the Earth is $v = C/t = 30$ km/sec. (Note that the number of seconds in a year is very close to $t \approx \pi \times 10^7$. That is a favorite approximation used by physicists.)

[14] Taking the radius to be 5 km $= 5 \times 10^5$ cm, we get the volume $V = (4/3)\ \pi r^3 = 5.2 \times 10^{17}$ cubic centimeters. The density of rock is about 3 grams per cubic centimeter, so the mass is about 1.6×10^{18} grams $= 1.6 \times 10^{12}$ metric tons.

[15] The Hiroshima bomb had an energy equivalent of 13 kilotons = 0.013 megatons of TNT. The largest nuclear weapon ever tested was a Soviet test in 1961 that released energy equivalent to 58 megatons of TNT.

thrown up into the atmosphere probably blocked sunlight over the entire Earth for many months. The absence of sunlight stopped plant growth, and that meant that many animals starved.

Would that kind of impact knock the Earth out of its orbit? We assumed that the asteroid was about 10 kilometers across—that's about one-thousandth the diameter of the Earth—which makes it one billionth the mass of the Earth. The asteroid hitting the Earth is comparable to a mosquito hitting a truck. The impact of a mosquito doesn't change the velocity of the truck (at least not very much), but it sure makes a mess on the windshield. In this analogy, the windshield represents the Earth's atmosphere. (We'll do a more precise calculation in chapter 3, when we discuss momentum.)

Most of the energy of the asteroid was converted to heat, and that caused the explosion. The impact of a smaller comet (about 1 km in diameter) on the planet Jupiter is shown at the start of this chapter in figure 1.1. Look at it again. It looks pretty dramatic, but the explosion that killed the dinosaurs was a thousand times larger.

But what is heat, really? What is temperature? Why does enormous heat result in an explosion? These are the questions we will address in the next chapter.

Chapter Review

Energy is the ability to do work. It can be measured in food Calories (Cal, also called kilocalories or kcal), kilowatt-hours (kWh), and joules (J). Gasoline has about 10 Cal per gram, cookies have about 5, TNT has about 0.65, and expensive batteries hold about 0.1 Cal. The very high energy in gasoline explains why it is used so widely. The high energy in cookies explains why it is difficult to lose weight. The relatively low energy stored in batteries makes it difficult to use them for electric cars. Hybrid automobiles consist of efficient gasoline engines combined with batteries. The batteries can absorb energy when the car slows down, without forcing it to be wasted as heat. Fuel cells produce electricity like batteries, but they are recharged by adding chemicals (such as hydrogen) rather than by plugging them into the wall. Uranium has 20 million Calories per gram, but requires nuclear reactors or bombs to release it in large amounts.

Coal is the cheapest form of fossil fuel, and it can be converted to gasoline. The major countries that use energy have abundant coal supplies.

Power is the rate of energy delivery and can be measured in Cal/sec or in watts, where 1 watt = 1 J/sec. TNT is valued not for its energy, but for its power—i.e., its ability to deliver energy quickly. A horsepower is about 1 kilowatt (kW). A typical small house uses about 1 kW. Humans can deliver 1 horsepower for a short interval, but only about 1/7 horsepower over an extended period.

Large nuclear power plants can create electricity with a power of about 1 billion watts, also called 1 gigawatt (GW). The power in 1 square kilometer of sunlight is about the same: 1 GW. Solar cells can extract 10% to 40% of that, but the better solar cells are very expensive. A solar car is not practical, but there are uses for solar airplanes, particularly in spying.

Sugar and fat are high in Calories. A half hour of vigorous exercise uses the Calories in one can of soft drink.

Kinetic energy is the energy of motion. To have the same energy as TNT, a rock has to move at about 1.5 miles per second. To destroy an enemy missile, all you have to do is put a rock in its way, since from the point of view of the missile, the rock is moving very fast with lots of energy. If the rock has 10 times the velocity, then it will have $10 \times 10 = 100$ times the energy. The rock that hit the Earth 65 million years ago was moving about 15 miles per second, so it had 100 times the energy of TNT. When it hit, that kinetic energy was converted to heat. The heat caused the object to explode, and we believe that's what resulted in the death of the dinosaurs.

Discussion Topics

These questions involve issues that are not discussed in the text and so they are recommended as discussion questions. You are welcome to express your personal opinions, but try to back your statements with facts and (when appropriate) technical arguments. You might want to discuss these topics with friends before writing your answers.

1. Oil efficiency and national security. Right now, the United States is extremely dependent on oil for its automobile. Our dependence on oil has turned the Middle East into one of the most important areas in the world. If our automobiles were 40% efficient rather than 20% efficient, we would not have to import any oil. The global consequences of our oil inefficiency can reach as far as war in the Middle East. Getting more efficient use of oil is both a technological and a social issue. Who should pay for the research? The U.S. government? Private industry? Is this an economic question or is it a national security one?
2. Automobiles typically carry 100 lb of gasoline. That has the energy content of 1500 lb of TNT. Is gasoline really as dangerous as this makes it sound? If so, why do we accept it in our automobiles? If not, why not? Do we accept gasoline only because it is a "known" evil?

Internet Research Topics

1. Asteroid impacts are rare; a big one hits the Earth only about once every 25 million years. But small ones occur more frequently. In 1908, a small piece of a comet hit the Tunguska region of Siberia and exploded with an energy equivalent to that of about a million tons of TNT. Look on the Internet and find out about the Tunguska impact.
2. What is the current status of hybrid automobiles? How much more efficient are they than gasoline automobiles (in miles per gallon)? What kinds of improvements are expected in the next few years? Are all hybrids fuel efficient? Do any "standard" cars have better mpg?

3. Verify the area that it would take for solar cells to provide sufficient power for the state of California. Look on the Web to see what you can find out about the current cost of solar cells and their expected lifetime. Are there companies working to lower the cost of solar cells? What alternative ways are there to convert solar energy to electricity? Do you think that solar power would be more or less feasible in underdeveloped regions of the world?
4. Look up "smart rocks" and "brilliant pebbles" on the Internet. Are there current programs to develop these for defense purposes? What are the arguments used in favor and against these programs?[16]
5. What is the status of wind power around the world? How large are the current largest wind turbines? How much energy can be obtained from a single wind turbine? Are wind turbines being subsidized by the government, or are they commercially viable?
6. What can you find about electric automobiles? What is their range? Are they less expensive than gasoline autos, when the replacement of batteries is taken into account?
7. Find examples in newspapers and magazines in which the writer uses *power* and *energy* interchangeably, and not in the technical sense we use in this book.
8. Look up the Fisher-Tropsch process for converting coal to diesel fuel. What countries have used it? Are new plants being planned?

Essay Questions

1. Read an article that involves physics or technology that appeared in the last week or two. (You can usually find one in the *New York Times* in the Tuesday Science section.) Describe the article in one to three paragraphs, with emphasis on the technological aspects—not on business or political aspects. If you don't understand the article, then you can get full credit by listing the things that you don't understand. For each of these items, state whether you think the writer understood it.
2. Describe in a page what aspects of this chapter you think are most important. What would you tell your friends, parents, or children are the key points? Which points are important for future presidents or just good citizens?
3. In his 2003 State of the Union address, President George W. Bush announced that the United States will develop a "hydrogen economy." Describe what this means. What mistaken ideas do some people have about such an economy? How will hydrogen be used?
4. When the numbers matter, the confusion between energy and power can be problematical. For example, here is a quote I found on

[16] A particularly useful Web site for national defense technology is run by the Federation of American Scientists at www.fas.org.

the Web site for Portland General Electric: "One very large industrial plant can use as much power in one hour as 50 typical residences use in a month."[17] Can you see the reason for confusion? What do you guess the author means by the "amount of power in one hour"? Do you suppose that they really meant the "amount of energy in one hour"? Do your best to describe what the author meant. What impression was the author trying to leave? Was it an accurate impression?

5. A friend tells you that in 30 years we will all be driving automobiles powered by solar energy. You say to him, "It's hard to predict 30 years ahead. But let me give you a more likely scenario." Describe what you would say. Back up your predictions with relevant facts and numbers whenever they would strengthen your analysis.

6. When an automobile crashes, the kinetic energy of the vehicle is converted to heat, crushed metal, injury, and death. From what you have seen (in real life and in movies), consider two crashes, one at 35 mph, and another at 70 mph. Is it plausible that a crash of the faster automobile is 4 times worse? What other factors besides speed could affect the outcome of the crash? Airplane velocities are typically 600 mph except during take-off and landing, when they are closer to 150 mph. Does the kinetic equation explain why there are few survivors in an airplane crash?

7. Energy is conserved—that is a law of physics. Why then do our leaders beseech us to "conserve energy"?

8. Although TNT has very little relative energy per gram, it is a highly effective explosive. Explain why, briefly.

9. Some people say that the United States is "addicted" to gasoline. Compare gasoline to alternative ways of powering an automobile. Describe both the advantages and disadvantages of the alternatives you discuss, compared to a gasoline engine.

Multiple-Choice Questions

1. "Smart rocks" are considered for
   A. geologic dating
   B. ballistic missile defense
   C. nuclear power
   D. solar power

2. One watt is equivalent to:
   A. one joule/second
   B. one coulomb/second

[17] Since there are typically 30 days per month, that means that there are $30 \times 24 = 720$ hours per month. So the industrial plant uses 720 times as much energy as 50 houses. As stated in the text, 50 houses typically use 50 kilowatts. So this would imply that the power plant uses 720×50 kilowatts $= 36$ megawatts. Recall that a typical large power plant produces 1 gigawatt $= 1000$ megawatts. The usage of the industrial plant seems quite small compared to this. Yet the original statement made the usage appear quite large (at least that was my interpretation).

C. one calorie/second
D. one horsepower

3. The asteroid that killed the dinosaurs exploded because
A. it was made of explosive material
B. it was made out of U-235
C. it got very hot from the impact
D. It didn't explode; it knocked the Earth out of its normal orbit.

4. Kinetic energy can be measured in:
A. watts
B. calories
C. grams
D. amperes

5. Which of the following statements is true?
A. Energy is measured in joules, and power is measured in calories.
B. Power is energy divided by time.
C. Batteries release energy, but TNT releases power.
D. Power signifies a very large value of energy.
E. All of the above.

6. For each of these, mark whether it is a unit of energy (E) or power (P):
A. horsepower
B. kilowatt-hour
C. watt
D. calorie

7. Hybrid vehicles run on:
A. electric and solar power
B. solar power and gasoline
C. electric power and gasoline
D. nuclear power and gasoline

8. What is the main reason that hydrogen-driven automobiles have not replaced gasoline ones?
A. Hydrogen is too expensive.
B. Hydrogen is too difficult to store in an automobile.
C. Hydrogen is radioactive, and the public fears it.
D. Hydrogen mixed with air is explosive.

9. Compared to an equal weight of gasoline, U-235 can deliver energy that is greater by a factor of (choose the closest value)
A. 2200
B. 25,000
C. one million
D. one billion

10. Which of the following contains the most energy per gram?
A. TNT
B. chocolate chip cookies
C. battery
D. uranium

11. Compare the energy in a kilogram of gasoline to that in a kilogram of flashlight batteries:
A. The gasoline has about 400 times as much energy.
B. The gasoline has about 10 times as much energy.
C. The gasoline has about 70 times less energy.
D. They cannot be honestly compared, since one stores power and the other stores energy.

12. Which is least expensive—for the same energy delivered?
A. coal
B. gasoline
C. natural gas
D. AAA batteries

13. The kinetic energy of a typical 1-gram meteor is approximately equal to the energy of
A. 10 grams of TNT
B. 150 grams of TNT
C. 1/100 grams of TNT
D. 10 grams of gasoline

14. Coal reserves in the United States are expected to last for
A. hundreds of years
B. three or four decades
C. 72 years
D. less than a decade

15. A limitation for all electric automobiles is:
A. Low energy density per battery.
B. Batteries explode more readily than gasoline.
C. Electric energy is not useful for autos.
D. Electric motors are less efficient than gasoline motors.

16. Solar power is about (choose all that are correct)
A. 1 watt per square meter
B. 1 kW per square meter
C. 1 megawatt per square km
D. 1 gigawatt per square km

17. The efficiency of inexpensive solar cells is closest to
A. 1%
B. 12%
C. 65%
D. 100%

18. A human, running up stairs, can briefly use power of approximately
A. 0.01 horsepower
B. 0.1 horsepower
C. 0.2 horsepower
D. 1 horsepower

19. A 12-oz can of soft drink (not the “diet” or “lite” kind) contains about
A. 10 Calories
B. 50 Calories
C. 150 Calories
D. 2000 Calories

20. A large nuclear power plant delivers energy of about
A. 1 megawatt
B. 1 gigawatt
C. 100 gigawatts
D. 1000 gigawatts

21. Electricity from a AAA battery costs the consumer about:
A. 1¢ per kilowatt-hour
B. 10¢ per kilowatt-hour
C. $1 per kilowatt-hour
D. $1000 per kilowatt-hour

22. Electricity from a wall plug costs the consumer about:
A. 1¢ per kilowatt-hour
B. 10¢ per kilowatt-hour
C. $1 per kilowatt-hour
D. $1000 per kilowatt-hour

23. The energy per gallon (not per pound) of liquid hydrogen, compared to gasoline, is about
A. 3× less
B. about the same
C. 3× more
D. 12× more

24. Most of the hydrogen we use in the United States comes from
A. pockets of hydrogen gas found underground
B. hydrogen gas extracted from the atmosphere
C. hydrogen produced in nuclear reactors
D. It is manufactured from fossil fuels and/or water.

25. You have 10 tungsten bulbs, and each uses 100 watts. You leave them all on for an hour. The energy used is
A. 10 kilowatt-hours
B. 1 kilowatt-hour
C. 10 kilowatts
D. 1000 watts

26. The kinetic energy of a bullet, per gram, is (within a factor of 2)
A. about the same as the energy released from 1 gram of TNT
B. about the same as the kinetic energy in a typical 1-gram meteor
C. about the same as the energy released by 1 gram of chocolate chip cookies
D. none of the above

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