1. Energy and Power

(updated Jan 21, 2005; typos corrected Jan 26, 2005)

painting by John Dawson

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 world wide.. . .

-- adapted from Nemesis (1987)

Few people are surprised by the fact that an asteroid, the size of Mt. Everest, could do a lot of damage when it hits the Earth. And it is not really surprising that such bodies are out there. 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, there is 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 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 dart board.)

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 US 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 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 into 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 TNT (trinitrotoluene). It is the rapid conversion of this energy into *heat* that is at the heart of most explosions.

You may have noticed that I used a lot of common terms in the previous 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 more clear over the next three chapters.

DEFINITIONS (don't memorize these)

Energy is the ability to do work. (Work is defined numerically as the magnitude of a force multiplied by the amount the force moves in the direction of the force.)
Alternative definition for Energy: anything that can be turned into heat. [1]

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[1] It is likely, as the Universe evolves, that virtually *all* energy will be converted into 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.

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.)

Those definitions are more difficult to understand than you might guess, since they involve other concepts (work, force, energy of motion) that I haven't yet defined. 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, it makes a little more sense. That's also the best way to learn a foreign language: total submersion. 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: it is the chocolate chip cookies that have the greater energy. Not only that, but the energy is *much* greater – eight times greater in the cookies!

That fact surprises nearly everybody, including many physics professors. Try it out on some of your friends who are physics majors.

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, lets consider the amount of energy in one gram of various materials. (A gram is the weight of a cubic centimeter of water; a penny weighs 3 grams.) I'll give the energy in both Calories[2] (that's the famous "food calorie", used in dieting) and in Joules (there are about 4200 Joules in one Calorie).

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[2] Beware: If you have taken a course in biology, chemistry, or physics, you may have encountered an energy unit called a *calorie* spelled with a small c. One calorie (cal) is 1/1000 of a food Calorie (Cal). This is a terrible convention, but I can't change it. It's not my fault. To distinguish the two, the food Calorie should always be capitalized, although in popular writing—including the nutrition information on food-can labels—it often is not. But for us, 1 Cal = 1000 cal = 1 kilocalorie.

Here is the table of 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.

Table 1.2. Relative energy

object	**Energy in one gram** Calories	joules	**compared to TNT**
bullet (moving at speed of sound, 1000 ft per second)	0.01	40 J	0.015
battery (flashlight)	0.01		0.015
battery (computer)	0.1	400 J	0.15
TNT (trinitrotoluene)	0.651	2723 J	1
modern High Explosive (PETN)	1		1.6
chocolate chip cookies	5	21 kJ	8
butter	7	29 kJ	11
gasoline	10	42 kJ	15
methane gas (CH_4)	13	54 kJ	20
hydrogen gas (H_2) for fuel cell	26	110 kJ	40
asteroid or meteor (30 km/sec)	107	450 kJ	165
uranium-235	20 million Cal	84 billion	30 million

Stop reading now, and ponder the table of energies. Look for the numbers that are surprising. How many can you find. (My answers are in the next paragraph.)

I think all of the following are surprises:

the very large amount of energy in chocolate chip cookies, compared to TNT
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 further discussion.

Discussion of the table of Relative Energies

Let's pick out some of the more important and surprising facts shown on Table 1.2 and discuss them in more detail.

TNT vs. 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 they can suddenly expand.

One of the biggest surprises in the Energy Table 1.2 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. [3]

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 (e.g. resulting from mixing the food with acid in the stomach and with enzymes in the intestines), and finally the reaction of the food 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 sledge hammers, 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: When we say there are 5 Cal per gram in CCCs, we are ignoring the weight of the air that combines with the CCCs. Whereas TNT contains all the chemicals needed for an explosion, CCCs need to combine with air, and although air is "free" (you don't have 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, but still much greater than for TNT.

Gasoline

As Table 1.2 shows, gasoline contains more energy per gram than any other everyday substance. That's why it is so valuable as fuel. (This fact will be important when we

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[3] As we'll see in Chapter 3, to calculate the force, you can take the energy and divide it by the distance over which it is released (from chemical to kinetic energy).

consider alternatives to gasoline for automobiles.) Gasoline releases its energy (turns it into heat) by combining with oxygen, and 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."[4] 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 that 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.

Batteries vs. gasoline

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.

Table 1.2 shows that gasoline contains 1000 times as much energy per gram as in a flashlight battery, and 100 times as much as in an expensive computer battery. Those facts explain why most automobiles use gasoline instead of batteries as their source of energy. Batteries are used to start the engine. A typical car carries about 100 lb of gasoline. To carry that much available energy in batteries would take 100 times that weight (10000 lb = 5 tons), much more than the total weight of a typical car. That's not an attractive option, even if the batteries were cheap. But batteries have 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 “snorkeling depth”, the submarines ran on diesel fuel, a form of gasoline. The diesel fuel also ran generators that recharged the batteries. So during WWII, most submarines spent most of their time on the surface, recharging their batteries. Modern nuclear submarines don’t require oxygen, and they can remain submerged for months. That greatly increases their security against detection.

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[4] Engineers like to make a distinction between an *explosion*, in which an abrupt front called a “shock wave” is generated which passes through the rest of the material and ignites it, and a “conflagration”, 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.

Hybrid automobiles

Despite the limitations of batteries, there is a fascinating new 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 into stored chemical energy in the rechargeable battery. Hybrid engines are becoming very popular, and in a few years, they may be the most common type of automobile, particularly if gasoline prices rise.

Figure. Engine of a hybrid automobile (Honda Civic).
A small gasoline engine surrounded by batteries.
(from http://www.insightman.com/press_kit_1.htm)

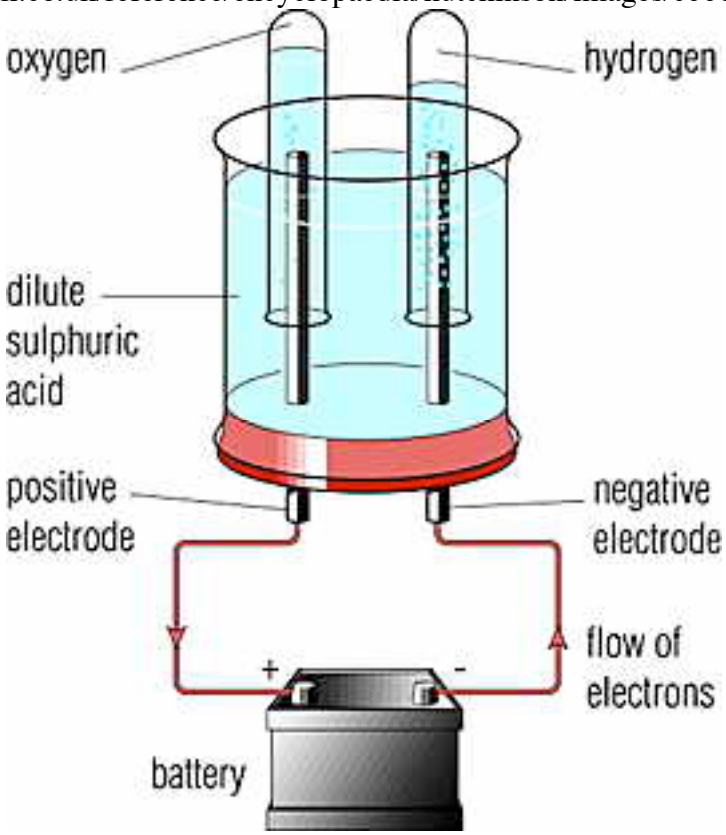
Hydrogen vs. gasoline -- and the fuel cell

Notice from Table 1.2 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.

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). This can be done using an advanced technology called a fuel cell to convert the chemical energy directly into electricity.

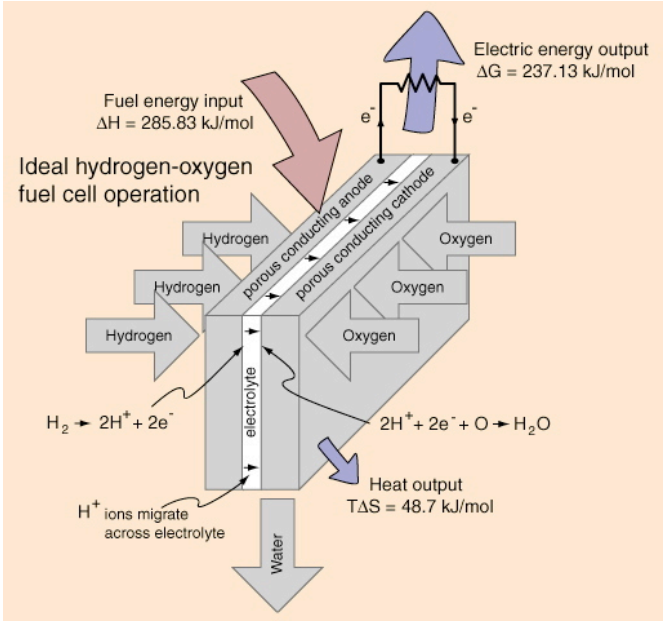
A fuel cell looks very much like a battery, but has a distinct advantage. In a battery, once the chemical is used up, you have to recharge it with electricity produced elsewhere, or throw it away. In a fuel cell, all you have to do is provide more fuel (e.g. hydrogen and oxygen). Perhaps you've seen a demonstration of "electrolysis" in which electricity is

passed between two terminals through water, and hydrogen and oxygen gas are produced at the terminals. I show a diagram of electrolysis below, borrowed from http://www.tiscali.co.uk/reference/encyclopaedia/hutchinson/images/c00879.jpg.



The diagram says the fluid is "dilute sulphuric acid." That is the same as water, with a little acid added to make the electricity flow better. "Flow of electrons" is electricity.

A fuel cell is very similar to an electrolysis apparatus, but it is run backwards. 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.
Below is a diagram (but overly complicated) temporarily borrowed from http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/imgheat/fuelcell.gif showing how a fuel cell works.



The basic idea is simpler than the diagram indicates. Hydrogen and oxygen enter the fuel cell are combined to make electricity and water. That's the basic idea. It is the same as electrolysis (use electricity to turn water into hydrogen and oxygen) but backwards.

The main technical difficulty of the hydrogen economy is that hydrogen is not very dense. Even if liquefied, it has a density of only 0.071 grams per cubic centimeter (cc), a factor of 10 less than gasoline. As we saw in the Energy Table 1.2, per gram, hydrogen has 2.6 times more energy than gasoline. Put these together, and we find that liquid hydrogen stores only 0.071 x 2.6 = 0.18 as much energy per cubic centimeter (or per gallon) as gasoline, a factor of 5 worse. Many experts say the factor is only 3 times worse, since hydrogen can 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 this: Liquid hydrogen (compare to gasoline) has
3 x *more* energy per gram (or lb)
3 x *less* energy per gallon (or cubic centimeter)

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.

A technical difficulty with liquid hydrogen is that it boils at a temperature of –423 degrees F. 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.

Where does the hydrogen come from? There is virtually no hydrogen gas (or liquid) in the environment. Hydrogen gas must be obtained by electrolysis of water, or by breaking apart the hydrogen found in natural (methane) gas. Doing either one 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 into hydrogen and oxygen (through electrolysis, or though 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 only get back out of the hydrogen the energy that you put in to make it. 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. 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, this method of production may not be optimum, but it is probably the cheapest way to make hydrogen. And unlike electrolysis, some net energy is actually released from the process.

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 automobiles (so less carbon dioxide is released); and the power plant can have more elaborate pollution-control devices than an automobile.

Other people like the idea of hydrogen as fuel because it moves the sources of pollution away from the cities, where the high concentration of pollutants can be more dangerous to human health. Of course, it is hard to predict all environmental effects. In June 2003 some environmentalists argued 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 chapters 8 and 10).

The United States has enormous coal reserves (about 2 trillion tons of coal reserves are known; twice as much as this might 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 CO_2 production could be very large.

Gasoline vs. 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? Had an explosion taken place? The answer is: usually not. 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 soaked with gasoline, 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 Nov. 6, 2002, the US started dropping 15,000 lb “fuel-air explosives” on Taliban soldiers in Afghanistan. You can probably guess that this was a liquid fuel similar to gasoline. The fuel is dropped from an airplane, and 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, dispersing the fuel and mixing it with air – but not igniting it. Only when 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 though 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 lbs of fuel, like gasoline, contains the energy equivalent of 225,000 lbs of TNT. So although 15,000 lbs 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 vs. TNT

The most dramatic entry in the table is the enormous energy in the form of uranium known as U-235: 30 million times that of TNT. We will discuss this in detail in chapters 4 and 5. For now, there are only a few important facts to know. The source of energy is the enormous forces inside the atom’s nucleus. 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 1.5 million times as much energy per gram. Compared to chocolate-chip cookies, it releases about 0.75 million times as much. The following approximation is so useful that it is worth memorizing:

Nuclear energy releases about 1 million times that of chemical or food energy, for the same weight of material.

Forms of energy

We have talked about food energy and chemical energy. The energy in a moving bullet or asteroid is called energy of motion, or *kinetic energy*. The energy stored in a compressed spring is called stored 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 into 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 non-technical 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 use, and to be able to use it in the way physicists do. Think of it 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. In equation form:

$$\boxed{\text{power} = \text{energy/time}}$$

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.

The most common unit for power is the watt (named after James Watt, the inventor of the steam engine, the most powerful motor of its time, and the "high tech" of the 1700s. The watt is defined as one joule per second:

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

You'll find that the term kilowatt is usually abbreviated as "kW" since Watt is a person's name. But for some mysterious reason, the term "watt" is usually not capitalized. The same logic applies to the joule and 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.[5] The original "Who's on First" routine is available on the internet.

Energy is "conserved"

When the chemical energy in 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 into 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 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; 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 into 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 called "The conservation of energy." It is one of the most

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[5] 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 dialogue as long as you want.

fundamental and most useful laws of physics.[6] 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. Engineers also use the equations when they design guns and bullet.

But if energy conservation is a law of physics, why are we constantly admonished by our teachers, 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 into 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 in potential energy (e.g. the energy stored in water that has not yet run through a dam to produce electric power).

Measuring Energy

The easiest way to measure energy is to convert it into heat, and see how much it raises the temperature of water. As mentioned earlier, the Calorie is defined as the amount of energy that it takes to raise one kilogram of water by one degree Celsius (also known as one degree Centigrade; one degree Celsius is 1.8 degrees Fahrenheit.), and there are about 4200 joules in a Calorie. Another unit of energy that is widely used is the kilowatt-hour, abbreviated 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 is 1000 joules per second for 3600 seconds (an hour), i.e. it is 3.6 million joules = 860 Calories. You can remember this as: 1 kWh is approximately 1000 Calories. It is tedious (and unnecessary) to memorize all these conversions, and you probably shouldn't bother (except for the cases that I specially mention). A table with conversions appears below. In this table, we use the symbol ≈ (wavy equal signs) to mean "approximately equal to."

Table 1.3 ENERGY UNITS

Note: the symbol "≈" means "approximately equal to"

energy units	**definition and equivalent**
calorie (note little c)	Heats 1 gram of water by 1 C
Calorie (capitalized)	heats 1 kg of water by 1 C 1 Cal = 4182 joules ≈ 4200 J ≈ 4 kJ
joule	1/4182 Calories ≈ Energy to lift 1 kg by 10 cm

[6] When Einstein predicted (with his Theory of Relativity; see chapter 11) that mass can be converted into energy, the law was modified to say that the total of mass and energy is conserved.

	≈ Energy to lift 1 lb by 9 inches
kilojoule	1000 joules 4.2 megaCalories = 4.2 x10^6 Calories
megajoule	1000 kilojoules = 10^6 joules costs about 5 cents from electric utility
kWh (kilowatt-hour)	861 Calories ≈ 1 kiloCalorie 3.6 megajoules costs about 20 cents from electric utility
BTU	British Thermal Unit 1 BTU = 1055 joules ≈ 1 kJ
quad	A quadrillion BTUs = 10^{15} BTU ≈ 10^{12} J Used when discussing the total energy output of a country. The world energy use is about 400 quads per year.

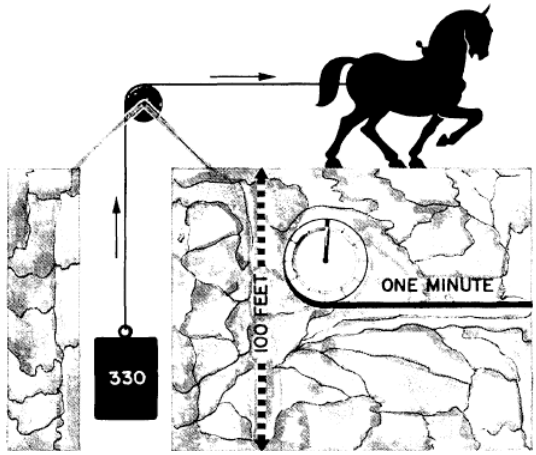
Although you shouldn't bother memorizing this table, it is useful to refer to it often so that you can get a feel for the amount of energy in various issues. For example, if you become interested in the energy usage of countries, then you will read a lot about "quads" and will find them a useful unit.

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 sec (one millionth of a second) the power is 651,000 Calories per second.

Although power can be measured in Calories per second, there are two other units that are in far more common use: 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 100 to 400 horsepower. James Watt, in the 1700s, was the first to actually determine how big one horsepower is (Figure 1.2). One horsepower turned out to be 0.18 Calories per second. (Does that sound small to you? Or does it illustrate that a Calorie is a big unit?) The *watt* was named after him. Watts are the most commonly used unit to measure electric power.

Figure 1.2 Watt's measurement of horsepower



This is a drawing of the method James Watt used to determine how much power a horse could deliver. 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" or 1 hp. (This diagram temporarily borrowed from http://www.tpub.com/home.htm, and may have to be redrafted.) In modern units, 1 hp ≈ 1 kilowatt.

Other common units are

the kilowatt (1 kW = 1000 watts),
the megawatt (1 MW = 1 million watts), and
the gigawatt (1 GW = one billion watts = 1E9 watts = 10^9 watts).

The abbreviation for million 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 approximately 4 kilowatts.

If you need to do engineering calculations, then you need to know that one horsepower is 746 watts. I do not recommend you try to remember this; you can always look it up if you really need it. Instead, remember the approximate equation:

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

where the wavy equal signs " ≈ " means "approximately equal to." It is far more useful to remember this approximate value than it is to fail 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 1.3. Learn the approximate values by visualizing the examples given.

Table 1.3 Power examples

value	equivalent	example of that much power use
1 watt	one joule per second	flashlight
100 watts		bright light bulb;

		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
100 horsepower	≈ 100 kw[C]	small automobile
1 megawatt (Mw)	1 million watts = 10^6 watts	electric power for a small town
45 megawatts		747 airplane; small power plant
1 gigawatt = 1 Gw	1 billion watts = 10^9 watts	large coal, gas, or nuclear power plant
3000 gigawatts = 3 terawatts		total average power use of United States

[A]more precise value: 1 hp = 746 watts
[B]more precise value: 1 kw = 1.3 horsepower
[C]more precise value: 100 hp = 74.6 kw

Power examples

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

Humans and Power Plants

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.)

Here is a brief description of what happens between the power plant and the lighting of a light bulb in your home. The original source of the energy may be chemical (oil, gas, or coal), nuclear (uranium), or kinetic (falling water). In a power plant, energy is converted into 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 a later chapter, 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 1.3). 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. 100 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 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.

Light bulbs

Ordinary household light bulbs (sometimes called "incandescent" or "tungsten" bulbs) work by using electricity to heat a thin wire (called the filament) until it glows white hot. (We'll discuss the glow of such filaments in more detail in Chapters 2 and 10.) 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 light bulb its name) protects the filament from touch (it's 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 into 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* light bulb (we'll discuss these in Chapter 10) is as bright as a 60 watt conventional (incandescent) bulb. Does that mean that a conventional bulb wastes electricity? 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 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).

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 into heat (making the surface warm).

Suppose 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 your experience?

Many environmentalists believe that the best source of energy for the long term future is sunlight. It is "renewable" 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 into electricity. 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 into heat, or reflected.) A more expensive solar cell (such as used on satellites) is about 30% efficient, i.e. it can produce about 300 watts per square meter.

You will sometimes hear someone say that solar power is not practical, since to get enough power you would have to cover the entire country with solar cells. Is this true? A square meter of solar cells can deliver about 150 watts. A gigawatt (a typical nuclear power plant equivalent) would take 7 square kilometers. (Can you verify that number?) 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 (one tenth of one percent) of the 400,000 square kilometer area of California. Besides, the solar plants would probably 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 large hydrogen fuel-cells might provide that.

Remember hydrogen fuel cells? I said that hydrogen is not really a fuel, since it has to be manufactured, and that takes energy. But hydrogen can be a method for storing energy: manufacture it (by electrolyzing water) and store the gas; when you need the energy back, send the hydrogen into a fuel cell.

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?

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 1 kilowatt of power, which is equal to about one horsepower. Since expensive solar cells are only about 30% efficient, that means that you need more than three square meters of solar cell just to get one horsepower, whereas typical automobiles use 100 to 400 hp. To read more about the annual race, go to their homepage http://www.wsc.org.au/index.html.) The race is obviously among very low-powered vehicles!

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 air vehicle"). The aircraft was named the *Centurion*. 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. (Conventional airplanes fly at about 40,000 ft.) The Centurian was built by AeroVironment, a company started by engineer Paul McCready, who designed the Gossamer Condor and the Gossamer Albatross. For more information, see the AeroVironment web page:
http://www.aerovironment.com/area-aircraft/unmanned.html. We'll talk more about the Gossamer Albatross in a moment.

Human power

If you weigh 140 lbs, and run up a 12 foot flight of stairs in 3 seconds, your muscles are generating about 1 horsepower. (Remember: "generating" means 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 1 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 trained cyclist in excellent physical condition can do better: about 0.4 horsepower for several minutes. In 1979, cyclist Bryan Allen used his own power to fly a super-light airplane, the Gossamer Albatross, across the 23 mile wide English Channel (Figure below).

Figure 1.4. The Gossamer Albatross in England in 1979
(AeroVironment photo)

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 light-weight airplane would crash frequently, for example, whenever there was a large gust of wind. It flew only a few feet above the surface.

diet vs. exercise

How much work does it take to lose weight? We have most of the numbers that we need. We said 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.

That's good, if you want to lose weight. Suppose you do continuous strenuous exercise and burn fat at the rate of 4/7 horsepower. Using the fact that one horsepower is 746 watts, that means that in strenuous exercise you use (4/7)x746 = 426 watts = 426 joules per second. In an hour (3600 seconds) you will use 426 x 3600 joules = 1,530,000 joules = 367 Calories. One can of Coca-Cola contains 40 gm of sugar. That endows it with 200 Calories of "food energy." That can be "burned off" with about a half hour of continuous, strenuous exercise.

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, 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.

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, and 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 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 can come from many causes, such as difference in absorption, differences in evaporation, and differences in cloud cover.) Windy places have been used as sources of power for nearly a thousand years. The "windmill" was originally a mill (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.

Wind power

Generating array at Altamont Pass in California (photo c1993, Bill Berte, http://www.pacamera.com/memberGalleries/berte/altamont.html)

A "forest" of windmills has been proposed for construction on the ocean, off the coast of Massachusetts, to supply commercial power. In case you are interested, here are some of the details: there will 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 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 gigawatt. The major opposition to the idea appears to be coming from environmentalists who argue that the array destroys a wilderness area, would kill birds, and creates noise that could disturb marine animals. (Reference: New York Times, "Offshore Harvest of Wind is Proposed for Cape Cod", Karen Lee Ziner, April 16, 2002.)

Wind power ultimately derives from solar, since it is differences in temperature that drive the winds. We'll discuss this further in Chapter 2, in the section called "convection." The windmills cannot be spaced too closely, since when a windmill takes 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.

Cost of Energy

A typical price for electric energy from an electric utility is 20 cents per kWh, If we obtain our electric energy instead by buying batteries, the price goes way up – far more than most people guess: $1000 per kWh![7] That's 5000 times as expensive as the 20 cents

[7] A typical D-cell flashlight battery lights a 1.5 watt bulb for about an hour, so the energy contained is about 1.5 watt-hours. It costs about $1.50, so it delivers energy at a cost of

per kWh charged by the power company. Many people are astonished when they first hear this. But everybody knows intuitively batteries are expensive. That's why people who leave their lights on when they leave their house, will be very careful to turn off their flashlight when they are not using it.

Rechargeable batteries are much less expensive per kWh, since they can be used over and over again. If I take into account the limited lifetime of such batteries, then a typical rechargeable computer battery (one that I own) costs about $3 per kWh.[8] In contrast, gasoline is cheap. The net cost of useful energy from gasoline is about $0.15 per kWh, similar to the cost of electric energy.[9]

Discussion question: is it a coincidence that energy from gasoline costs about the same as energy from an electric power plant?

The California "energy crisis" of 2001

In 2001, the state of California was unable to obtain the electricity that the customers wanted. "Rolling blackouts" were instituted by the state government, and different regions of the state took turns losing their electric power. Note that the State didn't have any simple way to limit the use for any customer, other than by raising the price (which it was loath to do, for fear of unfairly hurting the poorer customers).

A lot has been written about this crisis, including the possibility that companies such as Enron artificially worsened it. But there is an aspect of the crisis that must be understood by anyone who is trying to prevent similar crises, in California or anywhere. If you know the technical difference between energy and power, then you can understand that the crisis was due to an inability to obtain the required power, not due to a shortage of energy. California had plenty of gasoline to use as fuel in electric generating plants. But it didn't have enough electric generating plants – industrial plants that convert gasoline to electricity. Thus, technically, it was a peak power crisis, not an energy crisis.

$1.00 per watt-hour. That means that the cost of one kilowatt-hour from batteries is $1000.

[8] My laptop battery can run a 20 watt computer for about 2 hours, so the energy it stores is 40 watt-hours = 0.04 kWh. The battery costs about $100, can be recharged about 1000 times (I hope; my last one failed after 300). That means that it costs me 10 cents = $0.10 each time I charge it, just to cover the cost of buying the battery (and not including the cost of the electricity from the utility company that I use to recharge it). So it costs $0.10 per 0.04 kWh, equal to $2.50 per kWh. If I add in the $0.20 the electric utility charges me for the electricity I use to recharge it, the price becomes $2.70 ≈ $3 per kWh.

[9] Gasoline costs (US average) about $1.50 per gallon. Using the value of 10 Calories per gram (from Table 1.2), we can calculate that energy from gasoline costs about $0.05 per kWh. But automobiles do not convert all this energy into useful locomotion; about 2/3 is lost to heat (in the exhaust, from the radiator that cools the engine, and from the direct heating of air in contact with the engine). Thus the net cost of *useful* energy from gasoline is about $0.15 per kWh

(Remember, however, that the media and the public often use the terms power and energy to mean the same thing.)

Here is a paradox that might confuse you at first, but will ultimately, deepen your understanding of the crisis. During the crisis, experts realized that it made excellent sense to send electric energy from California to the state of Washington! This was done at night. During the day, Washington sent California electric energy. But the amount California sent at night was twice as much as Washington sent during the day. As a result, both states benefited. How can that be?

The answer is that California was limited in the electric power that it could produce. The crisis hit each day during the hot afternoon, when people throughout the state were using their air conditioning systems at full power. There wasn't enough electric power being generated to provide that demand. So California imported electric power from the state of Washington. Washington gets much of its electricity from hydro power, i.e. from power generated by water flowing downhill through turbines near dams. They had a limited amount of water (generated by the winter snows) and once Washington used it all up, it would have to use more expensive gasoline-generated power. Yet they still decided to generate more power than they needed during the day, using up their dammed water, to send to California (over power lines). It was not due to generosity. In the evening and night, they shut down their dams and saved water, as California supplied their energy needs. The deal was simple: California borrows energy during the day, when it needed the high power, and pays back energy during the night, giving Washington back twice what it had loaned. Washington saved its precious water, and California got the peak power it needed.[10]

Kinetic energy

Let's go back to Table 1.2 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:

---

[10] Note that the return on investment amounted to rate of 100% per day. If you use the formula for compound interest, you can show that that works out to an effective interest rate of 7×10^{107} % per year. Even the Mafia, at its most extreme, never charged interest that high. Was some legal limit on permissible usury exceeded? We'll leave that to the law students. Yet both sides were very happy with the deal. (The energy was actually borrowed for only 1/2 day. Can you work out the true effective interest rate, taking into account that fact? Hint: if you double the value every 12 hours, then the value at the end of 365 days is 2^{730}. Try entering that number on your calculator; some calculators can handle such large numbers, but most can't.)

the kinetic energy equation:

$$E = (1/2)\ m\ v^2$$

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 conversions:

TABLE. Useful conversions

1 mile per hour	= 0.45 meter/sec
1 lb	= 0.5 kilograms

Notice how similar the kinetic equation is to Einstein's famous equation of special relativity, $E = m\ c^2$. In the Einstein equation, c is the speed of light in a vacuum: $3x10^8$ = 3E8 (calculator notation) meters per second. The similarity is not a coincidence, as you will see when we discuss relativity in Chapter 11. 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, In 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 four. A car moving at 60 mph has 4 times the kinetic energy as a similar car moving at 30 mph. Three times the speed means nine times the kinetic energy. For more of the effects of this calculation on automobile and airplane crashes, see Problem 8 at the end of the chapter.)

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

$$\begin{aligned} E &= (1/2)\ m\ v^2 \\ &= (1/2)(0.001)(30000)^2 \\ &= 450000 \text{ joules} = 450 \text{ kJ} \end{aligned}$$

That's the answer given in Table 1.2.

Smart rocks

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 = 7,000 meters/sec. From the point of view of the missile, the rock is approaching it at 7,000 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

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

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. See internet problem #4 at the end of this chapter.)

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? To solve this, take a 1 gm rock, so m = 0.001 kg. (Getting the units right is always the hardest part of these calculations!) According to Table 1.2, the energy in 1 gram of TNT is 0.651 Cal = 2723 joules. We set

$$(1/2)\ m\ v^2 = 2723 \text{ joules}$$

Putting in m = 0.001 (i.e. one gram is 0.001 kilogram), we get v^2 = 5,446,000, so v = sqrt(5446000) = 2300 m/sec = 2.3 km/sec. 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[11], so it is reasonable to

[11] The Earth-Sun distance is $r = 93 \times 10^6$ miles = 150×10^6 km. 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.

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 x10^{12} tons (1.6 teratons)[12]. From Table 1.2, 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)x(1.6 x10^{12}) = 2.6 x 10^{14} tons = 2.6 10^{8} megatons of TNT. Taking a typical nuclear bomb to be 1 megaton of TNT[13], this says that the impact released energy equivalent to over 10^{8} nuclear bombs. That's 10,000 times the entire Soviet-US nuclear arsenal at the height of the cold war.

The asteroid makes a mess, but it stops. The energy is all turned to heat, and that resulted in an enormous explosion. However, an explosion of this 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 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 the impact knock the Earth out of its orbit? We assumed that the asteroid was about 10 km across; that's about one thousandth the diameter of the Earth. A reasonable comparison is between a mosquito and 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 into heat, and that caused the explosion. But what is heat, really? What is temperature? Why does hot gas expand rapidly, in an explosion? These are the questions we will address in the next chapter.

END OF CHAPTER

(Note that the number of seconds in a year is very close to $t \approx \pi$ x10^{7}. That is a favorite approximation used by physicists.)

[12] Taking the radius to be 5 km = 5 x10^{5} cm, we get the volume V = (4/3) πr^3 = 5.2 x10^{17} cubic centimeters. The density of rock is about 3 grams per cubic centimeter, so the mass is about 1.6 x10^{18} grams = 1.6 x 10^{12} metric tons.

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

Quick review

Energy is the ability to do work. It can be measured in Calories and joules with 1 Cal = 4200 joules. Gasoline has about 10 Cal per gram, CCC has about 6, TNT has about 0.6, and expensive batteries hold about 0.1. Uranium has a million times as much per gram, but requires nuclear reactors or bombs to release it in large amounts.

Power is the rate of energy delivery, and can be measured in Cal/sec or in watts, where 1 watt = 1 joule/sec. TNT is valued, not for its energy, but its power, i.e. its ability to deliver energy quickly. A horsepower is 746 watts ≈ 1 kilowatt. A typical small house uses about 1 kilowatt (1 kW). Humans can deliver a horsepower for a short interval, but only about 1/7 horsepower over extended times.

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.

Large nuclear power plants can create electricity with a power of about 1 billion watts, also called 1 gigawatt, abbreviated 1 GW. The power in 1 square km of sunlight is about the same: 1 GW, but solar cells are expensive and can only extract 10% to 30% of that.

Kinetic energy is the energy of motion, and is given by the equation $E = (1/2)\ m\ v^2$. If m is in kg, and v in m/s, then E is in joules. A one gram rock (m = 0.001 kg) moving at 2.4 km/sec (2400 m/s), has kinetic energy is 2645 joules = 0.6 Calories, approximately equal to the chemical energy stored in a gram of TNT. A rock moving about 10 times faster than that hit the Earth 65 million years ago, and its 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.

Homework and quiz questions

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 that are important for future Presidents or just good citizens.

3. In his 2003 State of the Union address, President 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 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."
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 they really meant the "amount of energy in one hour"? Do your best describe what the author must have meant. What impression was the author trying to leave? Was it an accurate impression?[Possible answer in the footnote14.]

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5. Discussion topic: Automobiles carry, typically, 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?
6. According to Table 1.2, a 1-gram bullet moving at the speed of sound (1000 feet per second) has a kinetic energy of 0.01 Calories. Verify this by using the kinetic energy calculation. Hint: most of your effort will be in getting the units right.
7. 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.
8. When an automobile crashes, the kinetic energy of the vehicle is converted into heat, crushed metal, injury and death. From what you have seen (in real life; 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 four times worse? What other factors besides speed could affect the outcome of the crash? Airplane velocities are typically 600 mi/hr, 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?

Internet research questions

1. A 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….

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[14] Since there are typically 30 days per month, that means there are 30x24 = 720 hours per month. So the industrial plant uses 720 times as much energy as 50 houses. We stated in the text that 50 houses typically use 50 kilowatts. So this would imply that the power plant uses 720x50 kilowatts = 36 megawatts.
Recall that a typical large power plant produces 1 GW = 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).

2. What is the current status of hybrid automobiles? How much more efficient are they than gasoline automobiles? What kind of improvements are expected in the next few years?

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 into electricity? Do you think that solar power 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? (A particularly useful site for national defense technology is one run by the Federation of American Scientists, www.fas.org.)

discussion questions

These questions involves issues that are not discussed in the text. That is why they are recommended as a discussion question. 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 answer..

1. Discussion topic: Oil efficiency and national security. Right now, the United States is extremely dependent on oil for its automobiles (and for about 20% of its electric power). Our dependence on oil has turned the Middle East into one of the most important areas in the world. If our automobiles were 60% efficient rather than 30% 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?

Short questions

1. Compare the energy in a kilogram of gasoline to that in a kilogram of a lead-acid (car) battery:
( ) the gasoline has about 400 times as much energy
( ) the gasoline has about 10 times as much energy
( ) the gasoline has about 400 times less energy
( ) the two cannot be honestly compared, since one stores power and the other stores energy

2. Which of the following statements is true?:
( ) Energy is measured in joules and power in calories
( ) Power is energy divided by time
( ) Batteries release energy but TNT releases power
( ) Power signifies a very large value of energy
( ) all of the above

3. Hybrid vehicles run on:
( ) electric and solar power
( ) solar power and gasoline
( ) electric power and gasoline
( ) nuclear power and gasoline

4. A object that has a mass of 10 kg, and is moving at 5 m/sec has what Kinetic energy?
( ) 250 joules
( ) 500 joules
( ) 125 joules
( ) 50 joules

5. What is the main reason that hydrogen-driven automobiles have not replaced gasoline ones?
( ) Hydrogen is too expensive
( ) Hydrogen is too difficult to store in an automobile
( ) Hydrogen is radioactive, and the public fears it
( ) Hydrogen, when combined with oxygen, is explosive

6. In spite of the fact that TNT has very little relative energy per gram, it is a highly effective explosive. Explain why, in a few brief words:

7. One watt is equivalent to :
( ) one joule/sec
( ) one coulomb/sec
( ) one calorie/sec
( ) one horsepower

8. Which is not a unit of energy?
( ) kWh
( ) calorie
( ) Calorie
( ) joule
( ) watt

9. The cost of energy from a battery is closest to:
( ) 14 cents per kWh
( ) 5 cents per kWh
( ) 14 dollars per kWh
( ) 1000 dollars per kWh

10. Kinetic Energy can be measured in:
( ) watts
( ) calories
( ) grams
( ) amperes

11. An object with a speed of 81 km/hr has a kinetic energy of 90 joules. If the speed were reduced to 27 km/hr, the kinetic energy would change by a factor of
( ) 1
( ) 3
( ) 5
( ) 7
( ) 9

12. Which of the following contains the most energy per gram:
( ) TNT

( ) chocolate chip cookies
( ) fusion
( ) battery
( ) fission

13. Next to each of these mark whether it is a unit of energy (E) or power (P)

horsepower _____
kilowatt-hour _____
watt _____
calorie _____

14. The California Energy Crisis (which then didn't happen) was expected because of

( ) low power capacity
( ) low energy reserves
( ) expected cold weather
( ) contracts that required us to export power

15. The kinetic energy of a typical 1 gram meteor is approximately equal to the energy of

( ) 10 grams of TNT
( ) 100 grams of TNT
( ) 1/100 grams of TNT
( ) 10 grams of gasoline

16. "Smart Rocks" are considered for

( ) geologic dating
( ) ballistic missile defense
( ) nuclear power
( ) solar power

17. Compared to TNT, a typical meteor with the same mass has energy that is

( ) 10 x smaller
( ) equal
( ) 10 x larger
( ) 100 x larger

18. The kinetic energy of a bullet, per gram, is (within a factor of 2)

( ) about the same as the energy released from one gram of TNT
( ) about the same as the kinetic energy in a typical one gram meteor
( ) about the same as the energy released by one gram of chocolate chip cookies
( ) none of the above

19. Which of the following statements is true?:

( ) Energy is measured in joules and power in calories
( ) Power is energy divided by time
( ) Batteries release energy but TNT releases power
( ) Power signifies a very large value of energy
( ) all of the above