IV

WHAT IS ENERGY?

-AN OPTIONAL CHAPTER

We must conserve energy. -*President Jimmy Carter*

Energy is conserved. -*Any physics professor*

Energy is like love: you don't have to understand it in order to get involved with it. But unlike love, there is some chance you actually can understand energy. -*Anonymous*

THIS is *a part of the book that you really don't need to read. Feel free to skip* it. Or *even better, read though* it *casually, without feeling you have to learn* it. *Energy* is *a very useful tool, even if you don't deeply understand its* inner *nature. Energy can be commonplace and pedestrian (you can measure* it in *food calories),* or it *can be abstract and ethereal (as when physicists say* it is *the conjugate variable to* time).

The Properties of Energy

ENERGY IN FOODS, FUELS, AND OBJECTS

Let's start with the pedestrian. Table IV.1 shows the available energy in a pound of various foods and fuels and objects. Look at the last column, the energy compared to that of TNT. Do any of the entries surprise you?

Table IV.I. *Energy per pound for various objects and substances.!*

	Food calories	*Kilowatt-hours*	*Compared to TNT*
Bullet (1,000 *ft/s)*	4.5	0.005	0.015
Auto battery	14	0.016	0.046
Computer battery	45	0.053	0.15
Alkaline battery	68	0.079	0.23
TNT	295	0.343	1
High explosive (PETN)	454	0.528	1.5
Chocolate chip cookies	2,269	2.6	7.7
Coal	2,723	3.2	9.2
Butter	3,176	3.7	11
Ethanol	2,723	3.2	9
Gasoline	4,538	5.3	15
Natural gas (methane)	5,899	6.9	20
Hydrogen	11,798	14	40
Asteroid (30 km/s)	48,435	57	165
U-235	9 billion	11 million	32 million

My favorite surprise in this table (it surprised me when I first calculated it) is that chocolate chip cookies deliver 7.7 times more energy than an equal weight of TNT. Amazingly, gasoline has 15 times the energy of TNT! With such low energy per pound, why do we ever use TNT, rather than gasoline or cookies? The answer: TNT can release its energy much faster, so it delivers high power (energy per second); high power can create large force, and that's what is needed to crack rock and concrete. I use this example in my class to illustrate the difference between energy and power; power is the rate of energy delivery. If you want a very big explosion but are limited by the weight you can carry, use gasoline instead of high explosives; that's what our military did with the fuel-air explosives it dropped over Afghanistan.

Is ENERGY A THING?

I still haven't answered the question posed in the title of this chapter: What *is* energy? Let me put that off a little longer and take a moment to remind you of several properties that are truly mysterious but are so common that you might not realize how mysterious they are. When you hit a baseball with a bat, energy is transferred. But no *thing* is transferred; the bat gives up a property (high velocity) to the ball, but it does not transfer an object or material. The situation is similar with a sound wave: the individual molecules in air don't move very far when sound passes, and they wind up in the same location where they started. They moved for a short while and what they passed on was not their mass or their identity, but their pattern of motion. Is this pattern energy?

Certainly a pattern can hold energy, but energy is more complicated. Think about the subcategory of energy that we call heat. *Heat* is the random motion of molecules; at room temperatures, the molecules are vibrating with an average instantaneous velocity of about 770 miles per hour. Some are moving at half that speed; some at twice; 770 is the average. Thus, for a bullet moving at 770 miles per hour, many of the molecules are actually moving backward-those whose random motion is going opposite to the bullet's forward motion. In fact, there is as much energy stored in this random motion as there is in the forward motion of the bullet. The energy in that coherent velocity is what does the damage when the bullet hits; the equal amount of energy in the heat just keeps the bullet warm.

Suppose you have one bullet sitting at rest and another bullet moving at 770 miles per hour. Compare the heat energy of the resting bullet to the kinetic energy of the moving one. They are equal. Unfortunately, most of the heat energy can't be extracted for useful work, because it is *disorganized.* The molecules move in random directions. (The concept of disorganization is formalized in physics in the theory of *entropy.)* There is a general physics theorem about disorganized energy: the fraction that can be converted to useful organized energy-the efficiency-is given by a simple equation called the *Camot equation:*

$$\text{Efficiency} = \left(1 - \frac{\text{Cool temperature}}{\text{Hot temperature}}\right) \times 100\%$$

When you use this equation, the hot temperature is typically the temperature of the combusted fuel, or of the water heated by concentrated sunlight. The cool temperature is typically the temperature of the exhaust gas, or of the cooling tower. The only catch is that for this equation the temperature has to be expressed not in degrees Fahrenheit or Celsius, but in degrees absolute. To do that, either add 459 to the Fahrenheit numbers or add 273 to the Celsius numbers.

The Carnot equation helps explain the limited efficiency of any motor that runs on heat, such as a turbine or internal combustion engine. In the discussion of geothermal energy in Chapter 15, I used this equation to show that water heated by rock by *30* °C can deliver only 9% of its energy. Now consider water heated to boiling: 212°F, a temperature relevant not only for geysers but also for boiling-water nuclear reactors. Assume we extract energy and the water cools to room temperature, 65°F. The hot temperature is 212 + 459 = 671. The cold temperature is 65 + 459 = 524. So the maximum efficiency of energy extraction is

$$\text{Efficiency} = [1 - (524/671)] \times 100\% = 22\%$$

This means that only 22% of the heat in boiling water can be extracted to make electricity or other useful energy.

When President Carter asked us to conserve energy, he was referring to *useful* energy. Electric energy is very useful; it can be converted efficiently to mechanical motion or (if it's what you want) to heat. But once it is heat, only part of it can be transferred back-the percentage given by the Carnot efficiency equation.

The Meaning of Energy

What is energy? There is a short answer, but it is so abstract that we normally take 4 years to prepare physics majors to learn it. I'll condense those years of initiation into a few paragraphs. As you travel through these, you'll get a sense of the intellectual transformation experienced by the maturing physicist.

ENERGY AS TAUGHT TO HIGH SCHOOL STUDENTS AND COLLEGE FRESHMEN

Introductory energy is the least interesting kind. Please don't get so bored with this section that you don't bother reading on; the deeper, more abstract, and exciting definitions of energy are coming up. To the beginner, *energy* is defined as the ability to do work.

Work = force x distance. Force is something that accelerates mass: Force = mass x acceleration; that is, $F = ma$.

Virtually no freshman physics major really understands these equations, for many reasons. The word *ability* is undefined, and perhaps undefinable. The equation $F = ma$ is not really a law but rather just a definition of the term *mass.* (The *law* is that mass, the m in the equation, is a constant independent of velocity.) It doesn't matter; as with this book, the first step is to learn *about* energy, and how to handle the language and the equations. A student who can learn the rules and how to use them can earn an A in the course without truly understanding anything.

ENERGY AS TAUGHT TO SOPHOMORES

Now it gets a little more interesting. Energy can be converted to mass and vice versa. This fact is often expressed by Einstein's equation:

$$E = mc^2$$

Many people are confused by this equation because it works only if you plug in the numbers in the right way. If you express the mass m in kilograms, and the speed of light c in meters per second ($c = 3 \times 10^8$ meters per second), the equation gives the energy in joules. If you want to convert to kilowatt hours, divide by 3,600,000. And the mass m is no longer a constant. If the object has a velocity, the mass increases.[1]

Sophomores also learn the Planck law-that the energy E in quantum physics is related to the quantum frequency f by $E = hf$, where h is a number we call Planck's constant. Although they learn this simple law, most sophomores don't understand what it means just yet. Frequency is measured in cycles per second. The Planck equation seems to be hinting at a deep relationship between energy and time. It is.

ENERGY AS TAUGHT TO JUNIORS

Energy and mass are actually the same thing. If energy is present, not only does it have mass-in fact, it is mass. Energy and mass are not only equal, they are equivalent; that's the real meaning of $E = mc^2$. We see this in atoms. Some kinds of energy are negative, such as the *binding energy* that holds the electron to the nucleus; most amazing, the presence of this negative binding energy lowers the mass of the atom! It's as if negative energy contributes negative mass. Indeed, even the gravitational force-something that originates in mass-from that atom is lower because of that negative mass.

Juniors also get a second glimpse at the deeper meaning of energy-its relation to time. (The first glimpse came from the Planck law.) The only objects that have a unique energy value are those whose quantum mechanical wave function oscillates with time exactly like a sine wave. Again, the energy is given by $E = hf$. If the wave function oscillates differently (like a square wave, or a sum of two beating sine waves), then the energy is "uncertain"-meaning that if you try to measure it, you will get one of a list of possible values, and not one definite predictable value. This is the heart of the Heisenberg uncertainty principle and the Planck equation. And there is another hint at the connection between energy and time: the uncertainty in energy, multiplied by the interval in time used to measure the energy, is always greater than Planck's constant. Energy and time seem to be linked.

ENERGY AS TAUGHT TO SENIORS AND GRADUATES

The most fascinating, precise, and (for the physicist) practical definition of energy is the most abstract one-too abstract to even be discussed in the first few years of a physics education. It is based on the observation that the true equations of physics, such as $E = mc^2$, will be as true tomorrow as they are today.' That's a hypothesis that most people take for granted, although some people continue to test it; if a deviation is found, it will mean a certain Nobel Prize. In the jargon of physics, the fact that the equations don't change is called *time invariance.* It doesn't mean that things in physics don't change; as an object moves, its position varies with time, its velocity varies with time, lots of things in the physical world change with time-but *not* the equations that describe that motion. Next year we will still teach that $E = mc^2$, because it will still be true.

Time invariance sounds trivial, but when you express it mathematically, you can derive an astonishing conclusion: you can prove that energy is conserved. The proof was discovered by Emmy Noether (pronounced NER-ter), a contemporary of Einstein, who called her one of the most "significant" and "creative" mathematicians of all time (Figure IV.1). Like Einstein. she fled Nazi Germany and came to live in the United States.

Following the procedure outlined by Noether, starting with the equations of physics, you can always find a combination of your variables (position, speed, and so on) that will not change with time. When you apply this method in the simple cases (classical physics,

Figure VI.1 Emmy Noether, who discovered the link between time and energy.

with force and mass and acceleration), the quantity that doesn't change with time turns out to be the sum of kinetic and potential energy-in other words, the classical energy of the system.

Big deal. We already knew that energy was conserved. But now there is a fascinating philosophical link. There is a *reason* why energy is conserved! It's because of time invariance.

And there is an even more important result: the procedure works even when we apply the method to the much more complex equations of modern physics. Imagine the following question: In the theory of relativity, what is it that is conserved? Is it energy, or energy + mass energy? Or something else? And what about chemical energy? And potential energy? How do we calculate the energy of an electric field? What about quantum fields, such as those that hold the nucleus together? Should they be included? Question after question with no intuitive answer.

Today, when such questions arise, physicists apply the procedure outlined by Noether and get the unambiguous answer. When Einstein applied the method to his relativistic methods of motion, he derived the new energy, one that contained mass energy, rnc/. When we apply the Noether method to quantum physics, we come up with terms that describe the quantum energy.

Does this mean that the "old energy" was not conserved? Yes it does; if we have improved equations, then not only are the predicted motions of particles different, but also the things we thought were conserved aren't. Classical energy is no longer constant; you *must* include the mass energy-and the energy of the quantum fields. By tradition, we call the conserved quantity the "energy" of the system. So although energy itself doesn't change with time, as we dig and uncover the deeper equations of physics, our *definition* of energy does change with time.