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Chapter 4

ENERGY

If we reflect on the preceding two chapters, two observations come quickly to mind. First, they cover a considerable span of time: almost two thousand years elapsed from Euclid's Elements to Newton's Principia, published in 1687. Second, they are primarily concerned with the study of motion, particularly the motion of celestial bodies.

In the wake of Newton's stunning triumph, science gained great new impetus. Its pace accelerated and its scope broadened considerably. In a span of little more than three centuries, fundamental aspects of energy, matter and light were explored with great success and whole new fields of investigation were started.

The concept of "energy" is one of the most basic in all of physics. But, what is energy? We might think of it as the currency used to conduct nature's transactions. In any process of nature, we might say, there is always some amount of energy that "changes hands" to "pay" for something.

A certain amount of wealth, initially in dollars, might later be partially converted into German marks, part of which might later still be converted into Japanese yens. In the absence of any losses (or commissions), whatever combination of dollars, marks and yens we may have, it will still represent the original amount of wealth. Similarly, energy may be converted from one form to another, but the total amount remains constant.

Physicists say that, if something, or somebody, performs "work" on a "system", the system gains "energy" of some form. Later, the system may spend some or all of its energy in the performance of work. When we wind a mantle clock, for instance, the work we do goes into energy that is stored in the clock's spring. As the spring slowly unwinds, its energy is spent doing "work" by turning the gears of the clock mechanism.

MECHANICAL ENERGY

Newton's mechanics led to the definition of two forms of energy called gravitational potential energy and kinetic energy.

Suppose you have been hired to hoist a heavy rock, using a rope and pulley. You certainly would want to be paid in proportion to the weight of the rock and the height to which you hoist it: this is how you would measure your work, and so would a physicist.

Having hoisted the rock to some height, you tie your end of the rope to a hook on the ground, and then you ask: Just what kind of energy has the rock acquired because of my work? It is a latent, potential kind of energy, similar to that of a compressed coil spring, ready, but not yet free, to snap. For our rock, it is called *gravitational potential energy*, and is defined as the product of the rock's weight times its height relative to some reference level.

If you now cut the rock loose, you will see that indeed we have energy there. The rock starts falling, accelerating as it goes. Its potential energy is being converted into another kind of energy called *kinetic energy*, defined as half the mass times the square of the speed ("kinetic" derives from the Greek word for motion). By the time the rock reaches the ground, essentially all the energy you put into it has been converted into kinetic energy. This energy can be used to do useful work, if the initial intent was to crunch something on the ground.

In summary, then, an object has (gravitational) potential energy by virtue of the fact that it has weight at some height; it has kinetic energy by virtue of the fact that it has mass moving at some speed.

Let us consider now a swing in a park. If you give it one good push, it will start oscillating. Having reached a high point, it will swing down, converting potential energy into kinetic energy, as it loses height, while gaining speed. When it reaches its low point, it will swing up, converting kinetic energy into potential energy, as it gains height, while losing speed.

Under ideal conditions of no friction and no air resistance, the oscillations of the swing would go on forever. The two forms of mechanical energy would continuously convert into one another without loss, and their sum would remain forever constant.

Under real conditions, however, there will be only a few oscillations, after which the swing comes to rest. You did some work when you gave that push, and you put some energy into the "system". Where has that energy gone? Because of friction and air resistance, heat has been generated. One of the major triumphs of 19th-century physics was the experimental proof that heat is another form of energy to be entered in nature's balance sheet.

HEAT AS ENERGY

During the 18th century and half of the 19th century, heat was thought of as a weightless fluid, called *caloric*, which could not be either created or destroyed. The notion of heat as a fluid provides a convenient mental image: we talk of heat flowing from a higher to a lower temperature, just as we talk of water flowing from a higher to a lower level.

It was later shown that heat could be generated in any amounts at the expense of mechanical work. If, by means of a crank, for instance, you keep turning a paddle wheel inside some container of water, you will generate heat and warm up the water. In the 1840's, an English physicist (and brewer), James Prescott Joule, concluded after extensive measurements that a certain amount of mechanical work consistently produces a corresponding amount of heat, which must thus be viewed as another form of energy.

Measuring temperature

Closely associated with the notion of heat is that of temperature. A familiar way of measuring temperature is by means of a mercury thermometer, using either the Fahrenheit scale, or the "centigrade" (100-degree) scale. In the latter, 0° C is assigned to the level of the mercury when the thermometer is in a bath of melting ice, and 100° C is assigned to the level of the mercury when in a bath of boiling water. The interval in between is divided into 100 equal spaces. The two temperatures, 0° C and 100° C, correspond to 32° F and 212° F, respectively, on the Fahrenheit scale. In either scale, the zero point has been arbitrarily selected, and does not represent the zero value of anything.

The international standard for scientific measurements of temperature is the Kelvin scale, named after the British physicist Lord Kelvin. In this scale, the zero point is "absolute zero", the lowest possible temperature in the universe. The Kelvin scale for absolute temperatures is similar to the centigrade scale except that -273° C becomes 0° K and, therefore, 0° C becomes 273° K.

THERMODYNAMICS

In the early 1800s, the Industrial Revolution, which originated in Britain in the mid-1700s, was in full swing. It was driven by the steam engine, the first practical device to generate mechanical energy from heat. This was the setting for the birth of a new science, called "thermodynamics." It is concerned with how heat, temperature, work and energy are related. The two most important principles of this science are known as the first and second laws of thermodynamics.

The first law of thermodynamics

In 1847, the German physicist Hermann Helmholtz proposed that the definition of energy be generalized to include forms of energy other than mechanical energy in its kinetic and potential forms.

When work is done on a system, it increases the total energy of that system. The additional energy might go into mechanical energy, heat, electrical energy, or some other form of energy. The system, on the other hand, can expend some of its energy to do work. A system is said to be isolated, when it neither receives energy from, nor gives energy to, its surroundings: its total energy in its various forms must then remain constant.

As Helmholtz stated, "... the quantity of energy in nature is just as eternal and unalterable as the quantity of matter". This Principle of Energy Conservation constitutes the first law of thermodynamics.

The Second Law of Thermodynamics

While nature does not restrict the conversion of work into heat, it does impose severe restrictions on the conversion of heat into work. Basically, the second law of thermodynamics states that such restrictions exist.

Consider what happens in a steam engine. Inside a cylinder, the expansion of hot steam under pressure causes the motion of a piston, which in turn causes the wheels of a locomotive to turn. Part of the steam's heat is thus converted into work; the rest is discharged into the surroundings at some lower temperature.

The heat in the exhaust still constitutes energy, but a *degraded* form of energy. It too can be converted into work, but only if we can make it drop to an even lower temperature. Thus, although energy is conserved in an isolated system, the amount of "free energy", i.e., the energy available to do work, keeps on decreasing. This is one of several ways in which the second law of thermodynamics can be stated.

If the universe as a whole is an isolated system, the second law predicts an inevitable doom. In some very distant future, the universe - totally devoid of "free energy" - will have run down completely. The so-called "heat death" will have occurred. All that will be left is a sea of disorganized matter close to absolute zero temperature.

There is a third law of thermodynamics. It states that the absolute zero temperature is unattainable: as we get closer and closer to this minimum temperature, it becomes more and more difficult to extract additional energy and reduce further the temperature.