Energy Is Not The Ability To Do Work

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It is almost axiomatic that whenever a science teacher introduces a new technical term, he ought to define it. Nevertheless, there are times when it might be better to eschew this usually laudable practice.

In March of 1971, I looked up the definition of energy in each of twelve textbooks designed for use with high school physics classes. In eight of these books I found, either in the glossary or in the main body of the text, a short, pithy definition. Five books told the student that energy is the ability to do work; the other three substituted "capacity" for ability, apparently on the assumption that a word carrying an implication of quantitativeness enhances the usefulness of the definition. The other four books refrained from offering any definition, pending development of a deeper understanding of the physical relationships involved.

In my opinion, the definition of energy as the ability or capacity to do work suffers from three chief defects:

(1) It is so barren of content that it seems to be designed for ease of memorization rather than promotion of understanding.
(2) It grossly distorts the nature of the important social problem of availability of sources of energy.
(3) It is not true.

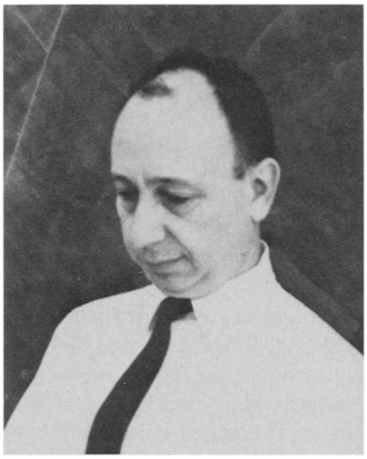
Why does energy exist? This may sound like a foolish question, but it is not at all the same sort of question as, for example, "Why do trees exist?" One does not see or feel energy. You can detect directly and sensorially certain parameters that are related to the quantity called energy: mass, temperature, velocity, shape, phase, position, chemical composition, electric charge separation, *etc.* But none of these is energy. We determine energy by forming combinations of these parameters according to a rigidly specified set of algebraic expressions: mgh, $mv^2/2$, $cm\Delta T$, kqq'/r, *etc.* Each formula, applied to the appropriate physical system, leads to a numerical value having a label with the same dimensions as work.

The formulas are human inventions. No one carried tablets to a mountain top to have the formulas inscribed by a bolt of lightning. Given a different set of definitions of physical quantities, an entirely different set of formulas could result, just as good as the ones we know. What we are really asking is this: Why did people invent these formulas?

Each of these formulas resulted from efforts of physicists to synthesize, to form a broad generalization that could unify a wide variety of phenomena under a single rubric. Many separate conceptual threads were united to form a cord with which to tie together a melange of experimental observations and philosophical speculation. The concept of energy eventually tied these cords into an intricately connected net.

Many cords went into the fabric of the theory of energy, but four stand out as the most important: the theory of mechanics, the technology of machines and engines, the theory of heat, and the theory of electromagnetism.

By the year 1750, a conservation law of sorts had already emerged from the studies of the mathematical physicists and was widely



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accepted.[1] The basis for the theory had been laid by Gottfried Wilhelm Leibniz in 1686. Leibniz proposed that there is a finite quantity of "force" in the universe. This may take the form of a *vis viva* (living force) possessed by objects in motion. Or, an object at rest may have *vis mortua* (dead force) when it possesses some property, such as position or deformation, that endows it with the ability to produce *vis viva*. To this theory, Christiaan Huygens contributed the idea that *vis viva* is conserved in collisions.

The dimensionality of this conserved force was a hot issue in the seventeenth century. Leibniz' most important contribution was his suggestion that the proper measure of *vis viva* is the product of weight and the square of velocity. He was led to this conclusion by the observation that when a falling object strikes the ground, the square of its velocity is proportional to the distance it has fallen. In 1717, John Bernoulli proposed the word energy for this conserved quantity. Conservation of energy became an accepted law, although it applied only to mechanical energy in non-dissipative systems. Furthermore, the law still lacked a precise algebraic expression.

Mathematical formulation of the energy principle resulted from the needs of the engineers of the early industrial revolution. They needed a way to compare the efficacies of water wheels, draft animals, steam engines, and electric motors.[2] It became accepted engineering practice to measure the output of an engine as the product of a weight lifted by distance it is raised, and this quantity was dubbed work. It was already well known that if a non-dissipative machine could be made, work (so defined) would be equal at input and output ends. By 1820, the use of algebra in physics had advanced to the point at which it was possible to equate the quantity called work with the old idea of *vis viva* to arrive explicitly at the statement that

$$\int F ds = \tfrac{1}{2}mv^2.$$

The great movement in physics at the beginning of the nineteenth century was synthesis.[3] The electric battery converted chemical action into electricity which could then be used to produce heat and light. Electromagnetic induction, electric motors, heat engines, photochemical effects, a whole series of new discoveries were revealing hitherto unsuspected connections between physical phenomena. In most cases, electromagnetism was involved at some stage. There was soon a flood of proposals for making quantitative the relationships involved in such transformations. Many workers recognized early that through all these changes, something is conserved. It was referred to as effort, work, force, power, and by a variety of other names. Many efforts were made to define the dimensionality of this elusive fundamental stuff of the universe.

The big breakthrough came about through the study of heat. The seminal work of Joseph Black, in the late eighteenth century, had for the first time established the distinction between heat and temperature.[4] Black invented the relationship $\Delta H = cm\Delta T$ for use in calorimetry, and defined specific heat and latent heat. Count Rumford (Benjamin Thompson) used this relationship to show that the heat evolved in boring cannon is related to the amount of work done, rather than to the amount of shavings produced.[5] As a result of these experiments, Rumford proposed that heat is not an imponderable fluid, but a form of motion.

The final knot that tied together the fabric of the theory of energy conservation was the discovery that heat and work are quantitatively interconvertible. Many workers came to this conclusion independently during the two decades before 1850.[6] Joseph Mayer used the ideal gas law to calculate the amount of work done in the production of a given quantity of heat by the compression of the gas.

In the 1840's, James Prescott Joule performed a series of experiments in which he measured the heat produced from measured amounts of work. This was done in many different ways, but the ratio of work done to heat produced was always the same. He also measured the heat produced from known quantities of electricity, and was able to show that it is proportional to I^2R. He concluded that a quantity having the dimension of work is conserved through all these interactions and hypothesized that the law is universal. Three other men—Mayer, Hermann Helmholtz and, L. A. Colding—independently came to the same conclusion about the same time. Agreement to call this quantity energy came considerably later.

Since that time, experience has abundantly confirmed the hypothesis. With new discoveries (the neutrino, for instance) it became necessary to invent new terms in order to make the energy equation balance. Up to the present, it has always been possible to find the terms necessary to complete the statement that the total energy at the end of any process is the same as it was when the process started. We assume that the reason we have always been able to find such terms is that they describe a general property of natural systems. Conservation of energy seems to be a natural law; the description of this law by means of a set of algebraic formulas is a human invention.

The lesson of this brief history of the concept of energy is clear. Energy has been defined because it is conserved. Any definition of energy that is not rooted in its conservation property is false at its core.

It is sometimes stated that Albert Einstein found an exception to the law of conservation of energy by showing that mass can be converted into energy. While it would be possible to compose a consistent picture of the universe on this basis, it is not convenient to do so.[7] Such a picture would require us to define mass as an invariant, equivalent to what is now called rest mass. This in turn would make new definitions of momentum necessary, and would confuse tremendously the relationship between mass and temperature. Einstein's method was to define relativistic mass, which is a function of the frame of reference. Using this approach, energy and mass are merely two different ways of expressing a certain property of a system—and that property is a conserved quantity.

The equation $E = mc^2$ does not state that mass can be converted into energy. What it says is that the total energy of a system can be found by multiplying its mass by a universal constant. In a frame of reference affixed to the object, multiplying its mass by c^2 yields a quantity called rest mass energy. If the object is in motion, it has additional energy (kinetic energy) which is equal to $mv^2/2$ plus some other terms which are negligible unless v is near the speed of light. It also has additional mass, and the amount of this extra mass can be found by dividing the kinetic energy by c^2. Similarly, an increase in temperature results in increase in mass. The extra mass is found by dividing the increased kinetic energy of the molecules by c^2. In short, any sort of energy has mass, and any mass has energy. The universal constant c^2 is no more than a factor for converting to a different set of units.

The rest mass of an object may include all sorts of energy. It surely includes the kinetic energy of the molecules, electrons, and nucleons, and various forms of potential energy. The high energy physicists will have to find out just how the internal structure of subnucleonic particles contributes to the total energy, and whether there is any residue of rest mass energy when all forms of kinetic and potential energy have been accounted for. Thermodynamics introduced the concept of internal energy, a quantity whose absolute magnitude was never defined, but whose changes are considered in many relationships. It now appears that the best expression for total internal energy is the rest mass energy, m_0c^2.

But is it not true that in a nuclear explosion the mass is converted into energy? Not really. The energy equation of such an event might be written something like this:

rest mass energy of fuel =
    rest mass energy of fission products
  + kinetic energy of fission products
  + increased kinetic energy of other objects
  + radiant energy

where the kinetic energy terms include both a random component (thermal energy) and an organized component (blast). By dividing this whole equation by c^2, we get another equation which expresses the same event in terms of conservation of mass:

rest mass of fuel =
    rest mass of fission products
  + relativistic mass increase of fission products
  + relativistic mass increase of other objects
  + mass of photons produced.

Precisely the same pair of equations could be applied to a chemical explosion; there is nothing different about the mass and energy relationships involved except in amount. Relativity has not changed the fact that energy is conserved. It has merely shown that this law is identical with an older one: the conservation of mass. Energy is conserved, or it is nothing.

Is the ability to do work conserved? Clearly not. The ancestral theory of conservation of *vis viva* was unable to account for dissipative losses, although Leibniz speculated that the lost *vis viva* became the *vis viva* of the internal parts of the systems. The experiments that produced the modern theory demonstrated the quantitative conversion of work to heat, but not vice versa. The question of whether the process works as well the other way had yet to be faced.

If the ability to do work were indeed conserved, we could shut down many of our power plants. To run an elevator, for example, it would be necessary to lift it to the top of the shaft only once. As it descended, its ability to do work would decrease, and this ability could be stored in some other system, such as a flywheel or a storage battery. If undiminished, this ability could be used to raise the elevator to the top of the shaft ready for the next descent. Extend this principle to other systems and it is clear that the problem of diminishing energy resources would disappear.

In fact, even Leibniz would never believe in this elevator, for it is a perpetual motion machine. An important premise in the logic that led him to the theory of the conservation of *vis viva* was the principle, already widely accepted early in the eighteenth century, that a perpetual motion machine is impossible. Yet the perpetual motion elevator implies no contradiction with the law of conservation of energy.

Another great synthesis was needed. When it was found, it solved not only this problem, but another as well. In 1824, the engineer Sadi Carnot had developed a theory of heat engines based on the idea that heat does work in flowing from high temperature to low, just as water does work in flowing downhill or electric charge does work in flowing to lower potential.[8] Carnot was well on the track of the two laws of thermodynamics, but was unable to find them because of his picture of heat as a fluid whose total quantity does not change.

As a result of the development of the first law (conservation of energy), with its assumption that heat is a form of energy rather than a fluid, Rudolph Clausius was able to resolve the contradiction between Carnot's theories and the first law. He accepted Carnot's law that the amount of work done by a heat engine depends on the difference between input and output temperatures. In 1850, Clausius added to this the rule that the heat rejected is less than the heat input, the difference being the amount of work done. This means that total conversion of heat to work would require a system in which heat is added, but none is removed.

Clausius was concerned with the eminently practical problem of finding out how to get the most work out of an engine. He worked with a theoretical system in which some material absorbs heat at a high temperature and rejects a smaller amount of heat at a low temperature. The difference is the amount of work done. He was able to show that if the process is cyclic, a certain fraction of the heat added must be rejected. This fraction is no smaller than the ratio of the low temperature to the high temperature (kelvin, of course). To get total conversion of work to heat, a system would be needed in which the heat rejected is zero, and this could only occur if it is rejected at the absolute zero of temperature. This cannot be achieved.

Complete conversion of input heat to work in a cyclic process is therefore impossible. Every time energy is converted, some of its ability to do work is irretrievably lost. No such limitation applies to the conversion of work to heat; if a short, pithy definition of energy is really needed, it might be described as the ability to produce heat. While this definition is neither elegant nor useful, at least it is true.

The amount of work that can be obtained from energy depends on the degree of organization of the energy. When water percolates downhill through the soil into a reservoir, it is losing gravitational potential energy. Nevertheless, its ability to do work is increasing, for as it accumulates it becomes available for turning a turbine. The force exerted by a rocket engine depends critically on the shape of the nozzle through which the exhaust gas emerges.

If you do 50 Joules of work in accelerating a 1-kg hammer, it will then be going at 10 m/sec. This is highly organized kinetic energy, for all the molecules are moving in the same direction. The hammer can do very nearly 50 Joules of work while coming to rest, returning to its original state. However, if this same amount of energy is added to the *random* motion of the molecules, the result will be a rise in temperature. This is easily found to be about 0.12 K, since the specific heat of iron is about 0.1 cal/g - K. In returning to its original condition—say, room temperature—it might, theoretically, be made to do some work, but it must also reject some heat at the lower temperature. The *maximum* fraction of the input energy that can be turned into work is the ratio of the drop in temperature to the final temperature, or 0.12 K/300 K = 4 x 10^{-4}. Instead of the 50 Joules available to do work when the kinetic energy is organized, we have only 10^{-3} Joules when it is random.

Spurred by the burgeoning industrial revolution, the theoretical physicists, between 1840 and 1860, developed the laws of thermodynamics. These were vital concerns in an epoch when industry was changing over from water power to heat engines and was learning to use electricity to transport energy. The first law (conservation of energy) told the industrialists that they could not get anything for nothing; the second law (increase in entropy) said that they could not even break even.

By 1970,[9] the United States was using nearly 10^{20} Joules of energy a year. Four per cent was derived from hydropower, and the rest by the burning of fossil fuels. Nuclear energy was just beginning to make a contribution. Consumption is doubling roughly every 25 years. Only a small part of this energy is used to do work. Of every 100 Joules used, 25 are consumed in space heating, and another 24 in industrial processes—mostly in processes that are activated by heat, such as smelting and glass-making. Twenty-six Joules are used for generating electricity, but this produces only 7 usable Joules of electric energy. The rest is lost in production and transmission, converted into the inevitable heat. Transportation uses 25 Joules, wasting 19 of them. Counting the useful output of the transportation engines and a part of the electric energy produced, then it seems that only about 10 Joules out of every hundred are used to push things through distances.

Of course, even these 10 Joules eventually end up as heat. Whatever energy you use in starting your car becomes heat when you stop it. One net effect of the use of 10^{20} Joules of energy is the production of 10^{20} Joules of heat. We have recently been made aware of one of the problems that this creates: thermal pollution. Today, an important limitation in the design of any new power plant is the requirement that the waste heat it produces be dispersed widely and quickly so as to minimize local rises in temperature.

Even perfect dispersion of the heat created by industry would not solve the problem. The earth receives from the sun, and reradiates into space, about 5.5 x 10^{24} Joules of energy per year. Industrial activity creates an additional 1.9 x 10^{20} Joules; this is radiated at the expense of an increase in the average temperature of the earth of 0.08 kelvin. But the rate of radiation is proportional to the fourth power of the Kelvin temperature. At the present exponential rate of increase of industrial heat production, we must expect a thousandfold increase within the next 200 years. This could be radiated only by an increase of the earth's average temperature of about 3 kelvins. And this is enough to melt the polar ice caps.

From all this, it is clear that it is misleading to leave heat out of any definition of energy. The concept that energy is the ability to do work dates back to the seventeenth century and was put into question when energy was defined quantitatively as a conserved quantity in the 1840's. Within ten years, the enunciation of the second law of thermodynamics had shown this definition to be false. It is time that it was abandoned. Energy is a quantity having the dimensions of work which is conserved in all interactions. It must be defined in terms of a set of algebraic expressions, written in such a way that their sum does not change when a system is isolated. Energy transferred from one system to another may be called work, heat, radiation, or a variety of other names, depending on the mode of transfer. And at each conversion, the amount of work that can be done diminishes.

A modern definition of energy, then, must be based on both the first and second laws of thermodynamics. Anything less falsifies the picture. If it is not possible to write a satisfactory definition in a few words, we will have to learn to get along without any such neat package.

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