AAPT PHYSICS EDUCATION
The Physics Teacher

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Eugene Hecht

Citation: The Physics Teacher **41**, 486 (2003); doi: 10.1119/1.1625210
View online: http://dx.doi.org/10.1119/1.1625210
View Table of Contents: http://scitation.aip.org/content/aapt/journal/tpt/41/8?ver=pdfcov
Published by the American Association of Physics Teachers

An Historico-Critical Account of Potential Energy: Is *PE* Really Real?

Eugene Hecht, Adelphi University, Garden City, NY

This paper critically explores the familiar concept of potential energy (*PE*), with the intent of addressing the issue of whether it is "real" or not. We begin with an historical account of the development of the idea of energy, examining the original motivations for the introduction of the notion of *PE*. This is followed by a sample of the arguments existing in the literature (from the 1880s through the 20th century) against the legitimacy of *PE*; that is, arguments maintaining that potential energy is not a real observable physical quantity. Today potential energy is so widely and unquestioningly accepted that it seems almost unthinkable that anyone ever seriously challenged its veracity. Using relativistic considerations it will be shown that *PE* is as real as mass is real. Nonetheless it will be argued that the concept of potential energy, however real, is actually superfluous.

Historical Origins of *PE*

The modern concept of potential energy developed out of, and in a kind of competitive tension with, the older idea of momentum. Jean Buridan (c1295–c1358), in his impetus theory, introduced the prescient notion that the true measure of the motion of an object was not speed alone, but the product of speed and quantity of matter (*quantitas materiae*).[1] That was around 1330, and it would take more than three centuries for the rather ill defined concept of quantity of matter to evolve into the only slightly better defined concept of "mass."

A major advance occurred when inertial mass was introduced by Johannes Kepler (c1618), but there was still a great deal of confusion between "weight," *quantitas materiae* (meaning amount of matter), and mass. Indeed, neither Galileo nor Descartes, nor even Leibniz later on, had anything beyond a rudimentary understanding of the modern meaning of mass (which, amazingly enough, is still evolving [2]). After Jean Richer inadvertently discovered (1671) that weight varied with location on the planet, Newton explained that observation, insightfully distinguishing between weight and unvarying mass. That was a considerable accomplishment even though Newton's own definition of mass (and he often used *quantitas materiae* and mass interchangeably) left much to be desired.

Buridan's brilliant idea of multiplying quantity of matter by speed was accepted, although in a somewhat muddled fashion,[3] by Galileo, who called it *momento*, and later by Descartes, who spoke of it as *quantity of motion*. Descartes (a man of tremendous imagination, quite unburdened by any intellectual responsibility to carry out confirming experiments) made the next immense breakthrough. Without realizing that his metaphysical conjectures would reverberate into the 21st century and beyond, Descartes wrote of his Creator of the universe:

> He set in motion in many different ways the parts of matter when He created them, and since He maintained them with the same behavior and with the same laws as He laid upon them in their creation, He conserves continually in this matter an equal quantity of motion.

DOI: 10.1119/1.1625210

In other words, the total momentum (i.e., quantity of motion) of the universe persists unchanged and will continue to be preserved forever. That jot of speculative nonphysics would blossom into the all-important law of conservation of momentum and capture the scientific imagination of the age. The very idea of the divine conservation of a dynamical quantity, though it had its roots in the immutability of static matter,[4] transcended the ordinary realm of scientific discourse.

When the Royal Society of London (1668) issued a request for papers on impacting bodies, it was responded to by John Wallis (Nov. 1668), Christopher Wren (Dec. 1668), and Christiaan Huygens (Jan. 1669). Wallis expressed in mathematical terms the concept of conservation of momentum as set out in Descartes's *Principia Philosophiae* (1644), being careful now to account for the signs of the momentum before and after impact. In that way, he was able to derive the familiar equation for the final joint speed resulting from an inelastic collision. Wren (who first tested his ideas experimentally) and Huygens independently treated elastic collisions. The latter arrived at much the same conclusions one finds in a typical modern-day introductory textbook (though how he came to them would prove to be of far greater importance than the conclusions themselves). Momentum was now established as the premiere dynamical quantity; all the while, attracting much less attention, the energy formulation was quietly coming into being.

It shouldn't be surprising then that when Newton in the *Principia* (1687) set out the central concept of his theory — the measure of motion — he defined the *momentum* as the product of an object's mass and velocity: $\mathbf{p} = m\mathbf{v}$. By the way, Newton refers to mass times velocity on one page as *quantity of motion* and on another as *momentum*. This was long before the concept of "vector" was formalized, so he never wrote it in this concise way, but Newton, like Wallis, was well aware of the directional nature of momentum.

And therein lies the seed of the next great development. Two identical cannonballs flying toward each other at the same tremendous speed have momenta that are equal in magnitude and opposite in direction; the net momentum of the two is zero. What kind of essential quality of motion equals zero when the bodies being described are hurtling through space? That thought apparently did not sit well with Huygens, who searched for a different fundamental measure independent of direction, one that would vanish only when motion ceased, one that would, of course, be conserved. Conservation was unmistakably a divine gesture, and so it was the benchmark of the validity of a physical quantity (much as gauge symmetry guides the hands of contemporary theoreticians). Huygens' studies of rigid colliding balls (*On The Motion of Bodies*, 1656) had led him to conclude that there was something special about the product of mass and velocity-squared. Remarkably, adding values of mv^2 for each ball prior to a collision yielded a total that was essentially the same after the collision, even though the velocities had changed.[5] Squaring the velocity removed any dependence on the sign; mv^2 is always positive and only vanishes when the velocity vanishes. Conservation of mv^2 was the crucial insight that would ultimately mature into the all-important principle of conservation of mass-energy (1905).

The earliest traces of the conceptualization of energy go back millennia. The ancient Greeks seem to have had a vague notion of "work"; it appears just beneath the surface in their explanations of how a large weight could be lifted by exerting a small force on a lever. In the early 1600s, Galileo was beginning to grope toward the central idea. He considered the behavior of a pile driver and recognized that the combination of the weight of the hammer and the distance through which it fell determined its effectiveness. And there were those wonderful experiments (*Discorsi*, 1638) where he rolled a ball down one incline and up another, and concluded that the speed acquired in the descent was just enough to raise the ball back to the height from which it had originally been released.[6]

Gottfried Leibniz (1646–1716) picked up on Huygens' idea and showed (1686) that, for a falling body, mv^2 was proportional to Galileo's product of weight and height. Writing in Latin, he called mv^2 the *vis viva* or "living force" to distinguish it from the *vis mortua*, the "dead" or static force of equilibrium. (Given our contemporary understanding of it, the word *force* was widely misused for about two hundred years.[7]) Later on (1695), Leibniz maintained that moving bodies had *vis viva*, whereas bodies at rest that were raised or stretched had *potentia* or "potential force" in that they could bring about further action or change. It wasn't long before Jean Bernoulli proposed the principle of conservation of living forces, and Daniel Bernoulli applied the idea to fluids (1738), producing the now familiar Bernoulli's equation. He talked about the equality between the actual descent (*descensum actualem*) of a fluid and its potential ascent (*ascensum potentialem*). During the next 50 years or so, an intellectual tug-of-war raged between the backers of momentum (Cartesians) and the backers of *vis viva* (Leibnizians), each side trying to establish that its conception was in fact the only true measure of motion.[8]

Though the word *energy* had been used with a variety of meanings for centuries, it was not until 1807 that Thomas Young, an English physicist and physician, spoke of mv^2 for the first time as *energy*. And it took more than half a century for that precise usage to come to prominence in the scientific literature.[9] Young concluded that "labour expended in producing any motion, is proportional to the energy which is obtained." In other words, work that causes motion equals the resulting change in energy. Gustave Coriolis (1829) carried out a calculation of the work done in accelerating a body and arrived at the change in the quantity $\frac{1}{2}mv^2$; *vis viva* had finally matured into its modern incarnation, $\frac{1}{2}mv^2$. By the end of the 19th century,[10] most scientists were avoiding the old phrase "living force" and using instead "kinetic energy" (*KE*), a term introduced (1849) by Lord Kelvin to better distinguish between force and energy.

While what we might call the work-energy theorem[11] (i.e., the relationship between work done and the resulting change in *KE*) was getting a great deal of attention, other complementary lines of thought were also being explored. In the years from 1783 to 1803, Lazare Carnot (father of Sadi Carnot of thermodynamic fame) distinguished between *living force* (mv^2) and the product of weight and height, which he called *latent living force*; Joseph Black[12] had already introduced "latent heat" in c1764. Building on Leibniz's primitive insights, Carnot maintained that a stationary object, by virtue of its height, possesses a form of *vis viva* (i.e., energy). As regards stretched springs, he observed that they "store a certain quantity of living force" and can "convert this latent living force into real living force."

Julius Mayer (1842) and Hermann von Helmholtz (1847) are credited with independently formulating the principle of conservation of energy. Helmholtz originally spoke about the sum of *vis viva* and *Spannkraft* (quantity of strain or tension, as produced, e.g., in a stretched spring), but later (1882) he adopted the English usage after William Rankine coined the phrase "potential energy" in 1853. It is Helmholtz who produced the familiar statement that for interacting particles, "the decrease of the potential energy is always equal to the increase of the kinetic energy" and vice versa.[13]

The Dilemma of *PE*

James Clerk Maxwell in his brilliant little book *Matter and Motion* (1877) treated energy in what appears to be a thoroughly modern way, setting out definitions and relationships, many of which are still repeated in classrooms to this day.[14] For example, he maintained that regarding the different interacting masses that compose a system, just as "kinetic energy depends on the motion, the potential energy must depend on the configuration." Even so, there is a subtle dichotomy in the literature between *KE*, or "actual energy," and *PE*, or "potential energy." And herein lies a distinction of considerable theoretical interest.

At one point, Maxwell says of *PE* that it "signifies the energy which the system has not in actual possession, but only has the power to acquire." That's a fascinating point, one very different from the modern view, which is that *PE* is just as real as *KE* (whatever that word *real* might mean). Maxwell's position appears to be that the word *potential* applies to the possibility of acquiring actual energy (*KE*), whereas today we would maintain that the word *potential* pertains to the possibility of delivering energy (e.g., in the form of *KE*) already actually stored in the system. In any event, the critical question has been broached, and it's essentially, "Is *PE* real?"

One highly credentialed Victorian physicist, Professor Thomas Preston, raised the issue in his influential text *The Theory of Heat* (1894):[15]

> When a body is projected vertically upwards its velocity gradually decreases, the kinetic energy which it possessed at the beginning of the flight gradually leaves it as it rises, and when the body reaches its highest point all the initial energy of motion has disappeared. The question then arises, what has become of the energy of motion of

> the body? We say it has become potential, that it has become latent or has disappeared, or ceased to exist as visible motion. ... The word potential energy here is only a name for the difference between the initial kinetic energy of the body when starting in its upward flight, and that possessed at any other point of the path.

To explain how *KE* can go in and out of existence, Preston resorted to an argument first posited by Leibniz (*Acta eruditorum,* Leipzig, 1690). He suggested that the missing *KE* is imparted to the surrounding aether as energy of motion thereof. The aether stores energy; it's the medium that takes up and later gives back *KE* — there is no such thing as *PE*. Of course this solution (though it might call to mind the "force field," which will play the aether's role of invisible energy-storer later in the 20th century) *is* nonsense. Still, the dilemma is real enough — Is *PE* just a computational fiction[16] in an accounting scheme for sustaining conservation of energy?

In reference to potential energy, it's been suggested (1939) "that there has been prevalent a tendency amongst philosophers, and scientists too, to discredit its objective existence, and to deny that there is in corporeal things any real and abiding capacity to do work when they are not actually working."[17] In that same vein, the eminent mathematician John W.N. Sullivan observed, in his very popular book *The Limitations of Science* (1949):[18]

> Potential Energy, it must be admitted, is a somewhat mysterious notion. Other forms of energy, such as energy of motion and heat energy, are obviously "energetic." But potential energy is undetectable until it is transformed. ... Thus the notion of potential energy explains away apparent violations of the principle of the conservation of energy. But is not this the very reason for the importation of the notion of potential energy? Is it not a mathematical fiction, brought in for convenience?

The case against the reality of *PE* is basically that *KE* (the energy of an object in motion) seems, by virtue of that motion, to be directly observable, whereas *PE* (the energy of an object at rest) appears to be quite unobservable. The object itself appears completely unaffected by its acquisition of *PE*. Moreover, as Stace (1934) maintained, "Either energy exists or it does not exist. There is no realm of the 'potential' half way between existence and nonexistence. And the existence of energy can only consist in its being exerted. If energy is not being exerted then it is not energy and does not exist. Energy can no more exist without energizing than heat can exist without being hot."[17]

Speaking about the developers of energetics, E. Hiebert (1962) suggested[19] that

> Their convictions about energy conservation were so strong that they resorted to non-demonstrable explanations, since this was a more acceptable theoretical alternative than to contemplate the outright annihilation of mechanical energy. So they practically invented hidden, potential, latent and virtual forms of energy in order to account for all losses to the whole. By any method of strict logic this seems a strange procedure indeed, to set up a physical law defining a mechanical quantity which remains constant during the motion of a body, and then to apply this law to cases where this constancy is not observed.

Resolving the Dilemma

The idea that there is "energy of motion" and "energy of rest" brings to mind the special theory of relativity where essentially the same language is used. There, the total energy (E) of a free particle of mass (m) is given as the sum of its *rest energy* (E_o) and its kinetic energy (KE):

$$E = E_o + KE.$$

Here $E_o = mc^2$, and we use the more modern formulation in which the mass m, which is Lorentz invariant, is perforce, speed independent.[20]

When the particle increases its speed, it gains *KE* (not mass), and E increases accordingly:

$$E = mc^2 + KE.$$

The speed dependence of the total energy can be expressed explicitly by $E = \gamma mc^2$, where $\gamma = (1 - v^2/c^2)^{-1/2}$, and so when $v = 0$, $\gamma = 1$ and $E = E_o$.

These considerations can be extended to a composite object (presumably even a frog or a taxicab) of mass M consisting of many particles.[21] In that case, the object's total energy, measured in the center-of-mass frame (where it is motionless), is $E_o = Mc^2$. This is the rest energy of the composite body and it encompasses the individual rest energies, kinetic energies, and potential energies of all of the interacting particles that constitute the object.

We could sum up the masses of the individual particles and call that quantity the "intrinsic" or "actual" mass of the object. That would be the object's mass with all the internal particle energy (*KE* and *PE*) removed, but that "actual" mass would not equal the object's inertial mass M. Still, as Einstein put it in 1907, "Since we can arbitrarily assign the zero-point of E_o, we are not even able to distinguish between a system's 'actual' mass and its 'apparent' mass without arbitrariness."[21] In any event, an apple pie sitting on a table has more mass when it's hot than when it's cold. A charged pith ball has more mass in an electric field than it does when there is no field. An atom in an excited state is more massive than when it's in the ground state. A spring, measured at rest, has more mass either compressed or stretched than it has when in its equilibrium configuration. A kilogram of ice takes in energy and melts into more than a kilogram of water. A charged capacitor, which gains electrons on one plate and loses an equal number from the other plate, must increase in *PE* and therefore in mass.

The mass of a composite object as a whole changes with its energy content. If this conclusion seems at all strange, consider an atomic nucleus, which is a well-studied composite object. The measured mass of a nucleus (M) of atomic number Z and mass number A is given by

$$M = Zm_p + (A - Z)m_n - m_\delta ,$$

where the mass of the whole (M) is less than the mass of the sum of the parts, by an amount m_δ known as the *mass defect*. In effect, the nuclear force pulls the nucleons together, the system loses *PE* as it coalesces, and the net inertial mass decreases by an amount m_δ. For example, imagine a neutron and a proton being slowly brought together ($KE = 0$) to produce a deuteron under the attractive influence of the strong force. As they approach one another, the *PE* of the system diminishes and the combined mass is ultimately decreased by 0.002 39 u, or roughly one part in a thousand. The corresponding energy ($E_B = m_\delta c^2$) is the so-called *binding energy*; it's the minimum energy that must be added to the system to dissociate it, to relocate its constituent parts, at rest and far from each other.

Any bound system (i.e., one that requires energy to pull it apart) — from an atom to a galaxy — is such that the mass of the whole is less than the mass of the sum of its separated parts. As a result, when the Earth came together under the influence of the much weaker gravitational force, it "lost" *PE* and thus diminished in mass by about four parts in 10 billion.[22] Of course, the energy associated with even a small amount of mass is immense: 1 g is equivalent to $\approx 10^{14}$ J. Consequently, we are ordinarily not going to be able to observe changes in mass when an everyday system changes its rest energy. To make the point, Max Planck (1907) calculated that when a mole of water (roughly a brimming tablespoonful) forms, its mass decreases by a mere $\approx 10^{-8}$ g due to the chemical binding.

For the sake of completeness, we should mention that it's been argued in this journal, and elsewhere, that energy and mass are parallel but very different, ideas; that they're simply proportional to each other, just as force and acceleration are proportional ($F = ma$) but different.[23] From that perspective it is supposed that mass does not actually transform into energy, and vice versa. But in the end, this interpretation depends on how one defines mass in relativity.[20] In any event, it is certainly in opposition to Einstein's later writings on the subject. In his maturity, Einstein often spoke of (1946) "the equivalence of mass and energy,"[24] stated that (1938) "there is no essential distinction between mass and energy,"[25] and maintained that (1946) "the inert mass of a closed system is identical with its energy."[26]

At this juncture we might well assert that **a change in the *PE* of a system of interacting objects is real in that it is always accompanied by a change in mass** which is, in principle, measurable. The scientists and philosophers who were disturbed because conservation of energy was predicated on unobservable quantities (i.e., all the various forms of *PE*) can now put their doubts aside — *PE* is real.

By equating *PE* with mass, the concept of *PE* becomes as real as mass is real, but at the same time it becomes redundant and perhaps even superfluous. Whenever energy is transferred to a composite system, there will be a change in mass somewhere. In fact, the idea of a mass change is quite general; it encompasses both the action of conservative and nonconservative forces. Thus, if we drag a book across a table, overcoming friction in the process, an amount of work (W_f) will be done. Both the book and the table will warm up, and the masses of both will increase accordingly. The net increase in mass (which we might call the thermal change in mass, m_t) of the table-book system (neglecting radiation losses) will be W_f/c^2. As a rule, that which does positive work will be reduced in mass, or *KE*, or both, whereas that which has positive work done upon it will either gain mass, or *KE*, or both. In short, **when energy is transferred into a composite system it will promptly be manifest as either *KE* or mass.**

Compress a spring a distance x and its mass increases by an amount $\frac{1}{2} kx^2/c^2$ (which we might call the elastic change in mass, m_e). Given that we have a presumably observable quantity m_e, the idea that there is a corresponding amount of elastic *PE*, which is not otherwise directly observable, seems rather redundant. Strike a match and the mass before it bursts into flame will be greater than the sum of the masses afterward. Call that difference the chemical change in mass, m_c. Again, we don't really need the notion of chemical *PE*; after all, the energy associated with the light and sound and *KE* comes from the masses of the atoms that once were the match. The match is like a bunch of compressed springs each tied into that stressed configuration with a string. When the strings snap, the springs more or less explosively pop open and lose mass in the process. That change in mass powers the reaction.

Once again consider a ball of mass m. Suppose that an external force does work on the Earth-ball system, separating the two, raising the ball into the air a height h. Following the leading contemporary introductory textbooks, we might say that an amount of gravitational potential energy ($PE_G = mgh$) was thereby stored in the system. The more thoughtful texts point out that this process depends on the Earth-ball gravitational interaction, and that we are talking about the gravitational *PE* of the composite system and not just of the ball. Even so, what that actually means is not obvious, and yet it's rarely discussed any further, though many questions immediately come to mind. For example, is this gravitational *PE* somehow stored in the gravitational field? After all, the energy of a capacitor is supposed (by the same texts) to be stored in the electric field. All of that aside, it is clear that the Earth-ball composite object is a bound system and hence its mass must increase by roughly mgh/c^2 as the ball rises. Recognizing this observable gravitational change in mass, m_G, there seems to be little need to talk in addition about gravitational *PE*.

Carrying the logic forward, the ball is actually in the solar system and its rest energy ($E_o = mc^2$) at any location is dependent on the extent to which it interacts, not just with the Earth, but also with the Moon, the Sun, the remaining planets, and so forth. In fact, it would seem that the mass of the ball is determined, in whole (or in part), by the interactions it experiences with all the rest of the universe with which it is in interactive contact.[27] This fascinating conclusion is reminiscent of Mach's principle (a designation coined by Einstein in 1918), namely, the inertia of a body is produced by its interaction with the remainder of the material universe. This thesis was first suggested by Ernst Mach on totally different grounds in 1863.

Although the notions of elastic *PE* and chemical *PE* were invented to deal with vastly different behaviors, both are inherently electromagnetic, and there will be a corresponding electromagnetic change in mass. Since there are four fundamental interactions (strong, weak, electromagnetic, and gravitational), there can be four basic forms of *PE* and four presently independent modalities by which the single physical quantity mass can change. This at least suggests that *mass* might well be a more fundamental concept than is *PE*.

Conclusion

Historically, the concept of kinetic energy (*vis viva*) drew its significance from the fact that it was conserved. Because motion was observable, it was reasonable enough to say that *KE* was real. The idea of potential energy was subsequently conceived to account for the disappearance and reappearance of *KE* (as for example, in the case of a swinging pendulum). The problem with *PE* (in the minds of some) was that it was not directly observable, and therefore arguably not real. In the 20th century we learned from the special theory of relativity that a composite system has a rest energy ($E_o = Mc^2$) that depends on its mass, and vice versa. As the rest energy changes, the mass of the system changes. If this changeability of mass were more pronounced, and therefore more readily observable (as it would be if c were much smaller), the concept of *PE* might never have been introduced in the first place. Be that as it may, insofar as the words *potential energy* can efficaciously be replaced by the word *mass*, the notion of *PE*, in all its various incarnations, is superfluous. There is *KE* and there is mass.

References

1. The concept of quantity of matter, what would later become "mass," was introduced in the 13th century by Aegidius Romanus, who applied the already well-accepted notion of conservation of matter to the problem of transubstantiation as it arises in the Eucharist. For more on the subject, see Max Jammer, *Concepts of Mass* (Dover Publications, Mineola, NY, 1997), p. 45.
2. There are those interpreters of the special theory of relativity who maintain that mass is a function of speed, although that seems increasingly to be a minority position. Above and beyond this speed dependence (which is not accepted herein), mass varies with rest energy and so the idea of mass as a fixed quantity is an anachronism. The mass of an object is certainly Lorentz invariant, but it can nonetheless change as its rest energy changes.
3. Classical momentum, mass times velocity, was often erroneously expressed as weight times velocity. And that confusion runs all the way up into the 19th century. See for example G.P. Quackenbos, *Natural Philosophy* (D. Appleton and Co., New York, 1859), p. 29.
4. The primitive medieval notion of conservation of matter (see Ref. 1) no doubt gave impetus to the 17th-century quest for a dynamical conservation principle.
5. Huygens seems to have been aware of the essence of the principle of conservation of kinetic energy as early as 1652; see Ref. 1, p. 63.
6. See, for example, E. Hecht, *Physics: Algebra/Trig* (Brooks/Cole, Pacific Grove, CA, 2003), p. 85, or E. Hecht, *Physics: Calculus* (Brooks/Cole, Pacific Grove, CA, 2000), p. 117. When it came to falling bodies, Huygens might well be considered a successor of Galileo. In the *Horologium Oscillatorium* (1673), he sets out the principle that "when any number of weights starts to fall, the common centre of gravity cannot rise to a height greater than that from which it started." This hypothesis would have a strong effect on Daniel Bernoulli's fluid dynamics.
7. The word *Kraft* in German means force, power, vigor, or energy, and that too contributed to the general confusion in terminology for decades; *vis viva*, living force, wasn't force at all, it was the precursor of kinetic energy. However daunting the task, Newton was very careful to define force, and he did it in a way that still has validity. Nonetheless, the linguistic mess continued for a remarkably long time. In fact, 19th-century authors often equated momentum to force and "impact." Thus, T. Cavallo, in his text *The Elements of Natural or Experimental Philosophy* (T. Dobson & Son, Philadelphia, 1819), p. 19, wrote, "The *momentum* is the force of the body in motion, and equivalent to the impression, it would make on another body at rest, that should be presented to it precisely in the direction of its motion." And J.L. Comstock in *A System of Natural Philosophy* (Pratt, Oakley & Co., New York, 1857), p. 39, states that "this power, or force, is called the momentum of the moving body."
8. See, for example, R. Dugas, *A History of Mechanics* (Editions du Griffon, Switzerland, 1955), p. 235, or Thomas Hankins, *Science and the Enlightenment* (Cambridge University Press, Cambridge, 1985), p. 30.
9. The word *energy* was still being used rather arbitrarily well into the 19th century. For example, W. Peck in his text *Introductory Course of Natural Philosophy for the Use of Schools and Academies* (A.S. Barnes & Co., New York, 1875), p. 25, wrote, "The intensity of a force is the energy with which it acts."
10. See James C. Maxwell, *Matter and Motion* (Dover, New York, 1991), p. 54. Interestingly, there are several popular books in English (e.g., Ref. 3, p. 31) that speak about "striking force" instead of "living force."
11. Ernst Mach (1872), in his *History and Root of the Principle of the Conservation of Energy* (Open Court Pub. Co., IL, 1910), p. 19, called it "the theorem of the conservation of work," and later in 1883 in *The Science of Mechanics* (Open Court Pub. Co., IL, 1960), p. 600, he referred to it as the "principle of *vis viva*." R.B. Lindsay in *Student's Handbook of Elementary Physics* (Dryden Press, New York, 1943), p. 23, calls it "the work-energy theorem." Since the 1980s there have been a number of articles pointing out the failings that arise when applying this theorem to nonpoint masses. See A. John Mallinckrodt and Harvey S. Leff, "All about work," *Am. J. Phys.* **60**, 356 (April 1992) for an extensive bibliography.
12. Daniel Bernoulli earlier used the term *vis potentialis* to contrast with *vis viva.* In the text *Popular Physics* (American Book Co., New York, 1888), p. 35, J.D. Steele says

that “energy may be either active or latent.”

13. Among the earliest texts to incorporate the new vocabulary of energy was W.J. Rolfe and J.A. Gillet, *Handbook of Natural Philosophy for School and Home Use* (Potter, Ainsworth, and Co., New York, 1869). On page 275 in the appendix they distinguish between “*actual* or *dynamical energy*” and “*possible* or *potential energy*.” In 1882 these authors published *Natural Philosophy for the Use of Schools and Academies* (Potter, Ainsworth, and Co., New York), and this time a far more extensive discussion of kinetic and potential energy appears on p. 28.
14. Maxwell (Ref. 10) correctly states (p. 56) that “work, therefore, is a transfer of energy from one system to another,” but alas he had previously (p. 54) said that “Energy is the capacity of doing work” and so creates a tautology. The failure of that often-repeated definition of energy (especially as it relates to the second law of thermodynamics) has been discussed extensively in the contemporary literature. Though it is still doggedly recited in dictionaries and introductory textbooks, energy is not the ability to do work.
15. Thomas Preston, *The Theory of Heat,* 2nd ed. (Macmillan and Co., London, 1904), p. 90.
16. W.T. Stace of Princeton University, in “The present dilemma in philosophy,” *J. Philos.* **31**(14), 365–371 (July 5, 1934), seems to think so: “It is only by the means of the fiction of ‘potential’ energy that it is possible to hold that the same amount of energy is always in existence. All that the *evidence* shows, all that is empirically verifiable, is that where there is a certain quantity of energy which suddenly disappears out of existence at a certain time, the same amount of energy will reappear in the universe at some later time. The gap between the two existences of the energy is filled up by the fictitious supposition that it goes on existing ‘potentially.’”
17. E.M. O’ Connor, *Potentiality and Energy: A Dissertation* (The Catholic University of America Press, Washington, D.C., 1939), p. 37.
18. J.W.N. Sullivan, *The Limitations of Science* (Mentor Books, New York, 1949), p. 155 (first printed by Viking Press in 1933).
19. E.N. Hiebert, *Historical Roots of the Principle of Conservation of Energy* (State Historical Society of Wisconsin, Madison, 1962), p. 102.
20. W.G.V. Rosser, *Introductory Special Relativity* (Taylor & Francis, London, 1991), p. 163. For a bibliography on the issue, see L.B. Okun, “Note on the meaning and terminology of special relativity,” *Eur. J. Phys.* **15**, 403 (1998).
21. Anna Beck, *Collected Papers of Albert Einstein* (Princeton University Press, Princeton, NJ, 1989), Vol. II, Doc. 47, p. 286. See also Leo Sartori, *Understanding Relativity* (University of California Press, Berkeley, CA, 1996), p. 206.
22. For a calculation showing that the mass of the Earth should be reduced by a multiplicative factor of about 4.2×10^{-10} upon compacting into a sphere, see Julian Schwinger, *Einstein’s Legacy* (Scientific American Books, New York, 1986), p. 136. Also look at Bertram Schwarzschild, “Gravitational self-energy and the equivalence principle,” *Phys. Today* **52,** 19 (November 1999).
23. Ralph Baierlein, “Teaching $E = mc^2$: An exploration of some issues,” *Phys. Teach.* **29**, 170–175 (March 1991) and Ralph Baierlein, “Teaching $E = mc^2$,” *Am. J. Phys.* **57**, 391–392 (May 1989). The conceptual dichotomy alluded to above seems to arise out of the distinction between what we have taken as a free particle’s invariant mass (m), and what was once often referred to as its speed-dependent “relativistic mass” (m_r). Thus, if we assume the mass of a particle to be invariant, a photon has zero mass. Alternatively, if mass is assumed (as it is by Baierlein) to be speed dependent, a photon, even though it has zero rest mass (m_o), has a nonzero relativistic mass ($m_r = \gamma m_o = E/c^2$). That, in part, gives the appearance of validity to the notion that mass is never converted into energy. Just think of the decay of a neutral pion (of mass m_π) into two gamma photons. The process can be understood from both perspectives. But the interpretation in which photons have zero mass demands that the pion’s mass be converted into the combined energy of the two photons ($m_\pi c^2$).
24. Albert Einstein, *Out of My Later Years* (Philosophical Library, New York, 1950), pp. 49 and 119.
25. Albert Einstein and Leopold Infeld, *The Evolution of Physics* (Simon and Schuster, New York, 1938), p. 200.
26. A. Einstein, *Philosopher-Scientist*, edited by Paul Schilpp (Harper & Row, Publishers, New York, 1959), p. 61.
27. The ball’s gravitational field travels outward from it at the speed of light and so the ball can only interact with a limited portion of the universe, albeit an ever-increasing one. Much of the universe doesn’t even know the ball has come into existence.

PACS codes: 01.65, 01.70, 03.30

Gene Hecht *is the author of a number of books, including two on the American ceramic artist George Ohr, and six on physics. Among the latter are the introductory texts* Physics: Algebra/Trig *and* Physics: Calculus*, both published by Brooks/Cole, and* Optics*, published by Addison-Wesley. His main interests are the history of ideas and the elucidation of the basic concepts of physics. He spends most of his time teaching, studying physics, and training for his fourth-degree black belt in Tae Kwan Do.*

Department of Physics, Adelphi University, Garden City, NY 11530; genehecht@aol.com