Energy and Work

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Letters to the Editor

Energy and Work

Energy is one of the most pervasive and useful concepts in physics. Students surely deserve a clear definition of it, just as they deserve clear definitions of mass, acceleration, etc. But many physics textbooks, along with a recent article in these pages,[1] prefer to leave energy undefined.

It is not difficult to define energy. It's the ability to do work. Quantitatively, a system's energy is the amount of work it can do. Some have objected to this definition on the grounds that mechanical energy is partly transformed into thermal energy in all real processes, and the second law of thermodynamics tells us that thermal energy cannot be entirely used to do work.[2] But, as has been correctly pointed out by others,[3] the definition should be understood as referring to the amount of work a system *could* do under *ideal* conditions. In the case of thermal energy, the idealized conditions include the limit of heat engine exhausts approaching 0K. Other physical laws involve similar idealizations. For example, no material object in the real universe experiences absolutely no external forces, although this is precisely the situation imagined in Newton's first law.

Quantum zero-point energy might be an exception to the "ability to do work" definition, although in light of the accelerating universe and dark energy this situation is murky at present. In any case, this exception can be pointed out to students of quantum physics.

Although most introductory textbooks specializing in energy define energy as the ability to do work,[4] my own quick survey of 22 introductory physics textbooks tallied only six that defined energy this way, and 16 that provided no general definition.[5] Several of these 16 even emphasized that "there is no completely satisfactory definition of energy," and that we can only "struggle to define it." Such statements are likely to discourage students. These 16 textbooks that provided no general definition gave instead formal definitions of the specific individual forms of energy, for example, "kinetic energy is defined as $(1/2)mv^2$." This reduces the principle of conservation of energy to some equivalent of the following statement: "Every physical system has associated with it some conserved quantity having the dimensions of $(1/2)mv^2$." This statement is true enough, but for sophomores it is not physically very meaningful.

The "ability to do work" definition gives students something to hang their hats on, so that specific energy forms take on a physical, as opposed to a formal, meaning. This definition unifies energy's various forms while highlighting its societal importance: It can do work!

References

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3. Mario Iona, "Energy is the ability to do work," *Phys. Teach.* **11**, 259 (May 1973).
4. Harold H. Schobert, *Energy and Society* (Taylor and Francis, New York, 2002); Robert A. Ristinen and Jack J. Kraushaar, *Energy and the Environment* (Wiley, New York, 1999); Roger A. Hinrichs, *Energy*, 2nd ed. (Saunders, Philadelphia, 1996); Gordon J. Aubrecht, *Energy* (Prentice Hall, Englewood Cliffs, NJ, 1995).
5. Including Richard Feynman, Robert Leighton, and Matthew Sands, *The Feynman Lectures on Physics, Vol. I* (Addison-Wesley, Reading, MA, 1963); pp. 4-1 and 4-2.

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Physics *Not* Misfigured

It is apparent from his letter in the March issue of *TPT* that Robert Weinstock[1] did not examine the trajectories in my January "Figuring Physics"[2] carefully enough. I find it difficult to understand how he came to the conclusion that the launching angles were drawn as being equal, especially since my answer explicitly used inequality of the angles. As far as correctness of the art work, all that is necessary is that both trajectories be parabolas, any parabolas, with one taller than the other and with common beginning and ending points.

References

1. Robert Weinstock, "Misfigured physics," *Phys. Teach.* **42**, 132 (March 2004).
2. Paul Hewitt, "Figuring Physics: Projectile speeds," *Phys. Teach.* **42**, 12, 45 (Jan. 2004).

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Editor's Note

Normally when we receive a letter criticizing a published paper, the author is immediately given the opportunity to submit a response. Due to an oversight in our office, Paul Hewitt was not offered that opportunity and so the letter above constitutes his belated reply.

We received another letter dealing with this matter from Robert Romer of Amherst College. Romer examined Hewitt's figures[1] and concluded that they are carefully and correctly drawn, and that Professor Weinstock's assertion that Hewitt's Fig. 2 "represents a physically impossible occurrence" is incorrect.

Weinstock[2] writes that Hewitt's "Fig. 2 shows the two initial velocities to have *the same or very close to the same direction*...." and then argues, in effect, that if $R_A = R_B$ and if $\theta_A = \theta_B$, then it must be the case that $H_A = H_B$, and since Hewitt's Fig. 2 clearly shows that $H_A \neq H_B$, the figure is incorrect.

Romer notes that "the same" and "very close to the same" are not synonymous and that in this case the distinction is all-important. He observes that the two angles drawn by Hewitt are clearly unequal ($\theta_A \neq \theta_B$), and thus Weinstock's criticism is invalid. Romer measured the angles with a protractor and found $\theta_A = 81^\circ$ and $\theta_B = 84^\circ$. As a further check, he used the fairly well-known relationship[3] between the initial launch angle θ, the range R, and the maximum height H reached by a projectile in the case of negligible air resistance, $\tan\theta = 4H/R$. From ruler measurements of H and R on Hewitt's figure, he found $\theta_A = \tan^{-1}(4H/R) = 79^\circ$ and $\theta_B = 84^\circ$, not significantly different from his protractor measurements. Though θ_A and θ_B are equal to within about 5%, their *tangents* differ by a factor of 1.5 or more, and given the uncertainties in the determination of the angles, this is consistent with $H_B/H_A = 1.77$, as found from his ruler measurements on Hewitt's Fig. 2.

Romer goes on to add that this discussion may offer some valuable lessons for all of us. The most obvious one is that the distinction between "equal" and "nearly equal" can be very important. One must be especially careful when the quantity we are interested in depends sensitively on the measured variable, for instance, $\tan\theta$ or $\cos\theta$ when θ is close to 90°. He cautions that a question in the form of: "Is it a good approximation to ...?" is not, by itself, a meaningful question. The first response should always be: "Why do you want to know?" A familiar student question refers to neglecting air resistance, which is often an excellent approximation but often is not — think of yourself as an outfielder positioning yourself to catch a fly ball. He offers another example from less elementary physics: "We know that the magnitudes of the charges of the proton and electron are known to be equal[4] to within one part in 10^{21}, yet a definitive experiment showing even the tiniest deviation from exact equality would have profound implications for physics at the most basic level."

It seems that by drawing the parabolic paths in the way he did, Paul Hewitt created an even better "Figuring Physics" exercise. He might have used launch angles differing by much more than three or four degrees. However, by drawing angles that differ by only a small amount, he led us to do a lot more figuring.

References

1. Paul Hewitt, "Figuring Physics: Projectile speeds," *Phys. Teach.* **42**, 12, 45 (Jan. 2004).
2. Robert Weinstock, "Misfigured physics," *Phys. Teach.* **42**, 132 (March 2004).
3. Robert Resnick, David Halliday, and Kenneth S. Krane, *Physics,* 4th ed. (Wiley, New York, 1992), p.70.
4. John G. King, *Phys. Rev. Lett.* **5**, 562 (1960); John David Jackson, *Classical Electrodynamics*, 3rd ed. (Wiley, New York, 1998), p. 554.