Letters
to the Editor

Work and Energy

I read with interest Carl Mungan's recent paper[1] on the thermodynamics of a block sliding across a frictional surface. I am deeply interested in this topic, as I have noticed how many problems my students have with it. I can remember how confusing it was, even for me, when one of my high school teachers said that static friction does no work. I would like to point out three examples that could be considered straightforward from a work-energy point of view but upon closer examination can show some confusing subtleties.

The first one concerns mountaineering: the 1000-m ascent of a 90-kg person carrying a 10-kg backpack. A common misconception is that the person did approximately 1 MJ of work in raising himself and the backpack to the top of the mountain. A related false conclusion is that the climber has more energy at the top than at the bottom of the mountain. The problem arises when one tries to identify the forces that did the work that supposedly increased his energy. The force exerted by the ground does no work since the point of contact with the person does not move. Also, forces exerted by the climber can do no work on the person himself. The climber does work only on the backpack, lifting it from the bottom to the top of the mountain. The conclusion is that the final energy of the person at the top is *smaller* than it had been at the bottom because of the work done on the backpack, and because some of the person's chemical energy (food) is transformed into thermal energy that is transferred to the surroundings.

The second example is that of an exercise bike with which a person does directly measurable work. The legs push against a preset brake force, and the length of the path is measured by the number of revolutions done by the pedals. This is a nice example of energy transfer from person to bike by the doing of work. The increase of the bike's energy can reveal itself in the increased temperature of the bike, or part of it can be used for something useful like charging batteries.

Finally, consider riding a bicycle uphill at constant speed. One may be tempted to analyze this situation in a manner similar to that of the mountaineer. The person does work on the bicycle, riding it up the hill, and transforms chemical energy partly into potential energy of herself and the bike and partly into thermal energy transmitted to the surroundings. But a careful look reveals no differences between the biker on the road and the person "biking" indoors. In both cases, pedals are pushed against a resistance force. Indoors it is the magnetic brake, while outdoors this same role is played by the incline of the road and by friction and air drag. Work is done on the bike and that results in an increase in the bike's potential energy. In addition, the bike does work on the biker, pushing her up the hill.

The three examples show the range of complications one runs into when applying work, thermal energy, and mechanical energy concepts in analyzing real situations. As has been pointed out,[1] we teachers must be very cognizant of the confusion that is often present in the heads of students when they encounter energy concepts for the first time.

1. C. Mungan, "Thermodynamics of a block sliding across a frictional surface," *Phys. Teach*. **45**, 288-291 (May 2007) and references therein.

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Energy and Work

In the May 2007 paper by Mungan, he questions the relevance of the concepts of work and heat as applied to a an isolated system consisting of a table and a block sliding on top of it. The author notes that in terms of the first law of thermodynamics, the heat transferred to a system "represents energy transferred from hot objects in the surroundings to the cooler system of interest by thermal conduction (including convection) or by blackbody radiation." Since the system he discusses is isolated, naturally it receives no heat by such processes. What the author seems to overlook is that not only may heat be transferred by such processes as those mentioned, it may also be produced. In fact, since the very early days of mankind, friction has been known as an effective source of heat. It follows from the conservation of energy that the heat produced by friction in the process of two surfaces sliding upon each other is equal to minus the total work of the frictional forces. The latter is equal to $-fs$, where f is the size of the frictional forces and s that of the relative displacement of the surfaces. Its sign is negative because for each body the direction of the frictional force on it is opposite to that of its displacement relative to the other body. Hence the heat produced is equal to fs, and the sliding process satisfies the first law.

In the first instance, the frictional heat is deposited in the immediate surroundings of the sliding interface, where it gives rise to a local increase of temperature. It is transferred subsequently by heat conduction to the entire system. At thermal equilibrium, it becomes distributed on the individual components of the system in proportion to their heat capacities. Mungan calculates each of the two bodies' share of the deposited heat and notices that these shares do not balance. Of course they do not. Both of them are positive. And they should not because their origin in the first instance is not heat conduction but heat production.

Mungan suggests that in the process he discusses, individual calculation of heat and work may only be done microscopically. This is not true. Providing that the size of the frictional force is known, we can calculate the kinematics of the bodies and hence the total work of the frictional forces. From that we get the heat produced just by a change of sign. Thus, contrary to the author's opinion, the individual concepts of heat and work are in my view highly relevant to this process.

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Author's Response

Nowadays it is conventional to distinguish energy *transferred* by thermal conduction or radiation from thermal energy *acquired* by an object, rather than referring to both as heat as was done historically.[1] However, the essential thing is to be able to *calculate* the changes in the values of all relevant state variables (temperature, pressure, energy, entropy, velocity, and so on) and this has been my emphasis throughout my writings.[2] Too much "energy" has gone into arguing about the definitions of heat and work, rather than into solving interesting problems in mechanics and thermodynamics. Kai's letter reinforces my view that introducing the notions of heat and work in discussions of dissipative processes often detracts from this bottom line by diverting one's attention to semantics. Even if one *can* self-consistently introduce these notions, it is not *necessary* to do so, nor does it *simplify* any practical calculations, so why bother?

1. Contrast Feynman's statement from the early 1960s that "we have converted work into heat" in the middle of page 44-3 of Volume I of *The Feynman Lectures on Physics* with Arons's warning in December 1999 against this very same wording at the end of page 1065 of *Am. J. Phys.* **67**.
2. Examples include the sudden compression of an insulated ideal gas in *Phys. Teach.* **41**, 450–453 (Nov. 2003), the efficiency of laser cooling in *Am. J. Phys.* **73**, 315–322 (April 2005), and mechanical systems of rolling without slipping and of masses connected by a spring in *Phys. Teach.* **43**, 10–16 (Jan. 2005). Although one can take issue with the details of my definitions of heat and work, they enable one to solve problems efficiently and accurately.

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