Energy and the Confused Student III: Language

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Energy is a critical concept in physics problem-solving, but is often a major source of confusion for students if the presentation is not carefully crafted by the instructor or the textbook. Confusion can be caused by the careless use of language in energy discussions. Students consciously or unconsciously imitate a teacher in their use of language and so can confuse themselves and others if they employ or pass on incorrect usage of words and concepts. In this third article in the series, we look at some common examples.

Work Done on . . . by . . .

We must be careful to avoid incomplete statements such as "work was done during this process." While somewhat more valid, "work was done by gravity during this process" is still incomplete because it does not specify the recipient of the work. It is better to specify the force doing the work and the system that is the recipient of the work: for example, consider the statements "work was done by the gravitational force on the ball," "work was done by the electric force on the electron," and "work was done by the force exerted by the piston on the gas." These statements clearly convey that work is done on a system by a force as well as laying the groundwork for the notion that work represents an energy transfer between a system and its environment.

This wording is similar to an equally important specification with earlier discussions of forces. The phrase "the hammer exerted a force" is incomplete. It is important to specify what is applying the force and what the force is applied on: "the force of the hammer on the nail," "the force exerted by the surface on the foot," and the like.

To use the most fully complete language, we should add one more entity to the energy phrasing discussed above: the source of the energy. When the surroundings do work on a system, the system gains energy equal in magnitude to the amount lost by the surroundings. Therefore, "work was done by the spring on the block" is most completely stated as "energy was transferred from the spring to the system of the block by work done by the force exerted by the spring on the block." In many cases, the source of the energy is readily apparent to the student, as in the case of the spring and the block. As another example, when a student pushes on a grocery cart, the kinetic energy of the cart comes from the store of potential energy in the body of the student from recent meals. In some cases, however, the source will not be clear to students. For example, if a ball falling near the surface of the Earth is considered to be a system, what is the environment of the ball that is providing the increasing kinetic energy as it falls faster and faster? The Earth cannot be considered as the answer to this question; in fact, the kinetic energy of the Earth also increases, albeit by a very small amount. We need to identify an environment whose energy is *decreasing*. In cases such as this, it is the gravitational field that is experiencing the decrease in energy. While energy in electric and magnetic fields is discussed in many treatments of electromagnetism, energy in gravitational fields is not often discussed.

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Potential Energy

In discussions of potential energy, a common misleading practice is to use a phrase such as the "potential energy of the ball," in which potential energy is associated with an object rather than with a system of two or more interacting objects. This is misleading conceptually and ignores the importance of the system, as discussed in the second article in this series.[1] It is important to stress that potential energy is a property of a system, not an object. It is associated with a force that acts between members of the system so it cannot be associated with one member only—a single object cannot possess potential energy.[2] Therefore, the better phrase for gravitational potential energy is the "potential energy of the ball-Earth system."

Another common misleading statement is to say that potential energy is related to the *positions* of objects that are interacting within a system. This is a claim that causes little or no trouble in simple mechanics problems but must be revised later on when the student studies electromagnetism. Imagine an electric dipole in an electric field or a magnetic dipole in a magnetic field, either of which can be rotated without a change in position. Even though the position of the center of the rotating dipole remains unchanged, the potential energy of the dipole–field system changes. This change is caused by a change in the *orientation* of the dipole, not a change in *position*. Consequently, it sets the stage for future possibilities to discuss in mechanics that potential energy is associated with the *configuration* of interacting objects in a system. This allows for changes in both position and orientation.

In a related issue, a common statement in mechanics is that the "potential energy is zero at the bottom of the ramp." This suggests that potential energy is like a field, having a unique value at all points in space. It is more proper to say that the "potential energy is zero for the configuration of the system in which the car is at the bottom of the ramp."

Heat

Moving to thermodynamics, we find the most misused physics word in popular language—*heat.* It is important to stress that physicists use this word to refer to (1) a *process* by which energy is transferred and (2) the *amount of energy transferred* by this process, normally denoted as Q. It is *not* the entity that is being transferred (*heat* is not transferred; it is *energy* that is transferred) and, even worse, it is *not* the energy content of a system with a temperature (correctly described as internal energy). Romer[3] claims that heat should not be used as a noun. While I agree with the spirit of using the word *heat* correctly, I disagree that heat is not a noun. Heat is indeed a noun, but it is the name of a process, not the name of what is transferred. Bauman[4] has also discussed the use of the word *heat* and its interpretation as temperature and internal energy.

Consider some phrases used in common language: "heat transfer," "flow of heat," and "the heat radiated outward." These phrases refer to a transfer of energy but represent incorrect uses of the word *heat*. The phrases can be tested by substituting the words "energy transfer" for "heat." Each phrase sounds awkward or redundant when this is done. For example, "heat transfer" becomes "energy transfer transfer." Other common phrases include "the heat of the day" and "too much heat in the air." In these uses, heat is being used to represent temperature. Another common statement is "heat rises." In this case, heat is used to mean warm air!

Barrow[5] makes a radical suggestion that the words *work* and *heat* should "vanish from the thermodynamics scene." He stresses that thermodynamics should focus on energy, and not on work and heat. I wholeheartedly agree that thermodynamics should focus on energy; in fact, *all* branches of physics should focus on energy as the entity that is being transferred. I disagree, however, that we should rid ourselves of the words *work* and *heat*. I think students clearly see a difference between (1) applying a force on a system and (2) placing a cold system in a warm environment, and we need words to differentiate these two very different situations.

While it is not likely that we can turn society around in its use of the word *heat*, we can strive to have a fraction of the population, our students, using the word correctly. For the case in which energy moves between a system at one temperature and its surroundings at a different temperature, the process that occurs is "energy transfer by heat." I dislike the slightly different phrasing "energy transfer in the form of heat" because this suggests that heat is a form of energy storage rather than a method of energy transfer.

Energy Transfer and Transformation

Following on the discussion of the importance of the system in the second article[1] in this series, let us now discuss the important distinction between transfer of energy and transformation of energy. One popular textbook[6] states that (1) energy is *transferred* from kinetic energy to gravitational potential energy. This is an example of a statement that confuses students, especially when compared to an earlier statement in the same textbook that states that (2) energy can be *transformed* from one type to another and *transferred* from one object to another. Statement (2) is correct, albeit incomplete (the emphasis is on an object rather than a system), but statement (1) is incorrect.

It should be made clear to students that *transformations* of energy occur *within* a system and result in one form of energy storage changing to another. For example, in a ball-Earth system, the kinetic energy of the system as the thrown ball rises upward is transformed to gravitational potential energy of the system. In this common situation, the kinetic energy of the system is associated with only one moving object (in the reference frame of the Earth), but in general, it is the energy of the entire system that is transformed. In a stick of dynamite, chemical potential energy transforms to internal energy and kinetic energy of shattered pieces when the stick explodes. When a block slides across a floor and stops, kinetic energy of the block-floor system is transformed to internal energy in the block and floor. If the system is isolated, only transformations of energy can occur and the total energy of the system remains constant.

In contrast, *transfers* of energy occur *across* the system boundary and can result in a change in the total energy of the system. These transfer mechanisms include work, heat, and electromagnetic radiation, as well as others that will be discussed in the fourth article in this series.[7]

Additional careless language includes statements such as "energy enters the light bulb as electricity and turns into light and heat." This statement has three weaknesses in terms of clarity of language. First, energy does not enter any electrical device "as electricity." This suggests that electricity is a form of energy. Similarly, the second and third weaknesses are related to the statement that energy "turns into" light and heat: because "turns into" is equivalent to "transforms into," this statement suggests that light and heat are also forms of energy rather than mechanisms for energy transfer. A stronger, more correct statement is that "energy enters the system of the light bulb by electrical transmission and transfers out of the system by electromagnetic radiation and heat." Notice that changing "as" to "by" is an important step in identifying electricity, light, and heat as transfer mechanisms rather than forms of energy storage.

Energy Dissipation and Loss

The study of electric circuits has an example of an unfortunate but popular word choice—energy is "*dissipated* in a resistor." While physics teachers know that this means that the resistor warms up and energy is transferred to the environment by heat and radiation, students may interpret this word to mean that energy is disappearing. One dictionary definition of *dissipate* is "to cause to spread out to the point of vanishing." The student can apply this notion and come up with the idea that the energy is vanishing in some way.

It is better to say that energy is *delivered* to the resistor, which reinforces the notion of energy transfer to a system. Because of this transfer, the internal energy of the resistor increases. In turn, there is typically a subsequent transfer of energy by heat and electromagnetic radiation from the warm resistor to the cooler environment.

A similar wording that appears in textbooks is "loss" of energy. This is dangerous territory for student confusion, especially when energy has been correctly introduced earlier in these textbooks by saying that energy is neither created nor destroyed. If energy cannot be created nor destroyed, how can it be "lost"? It is far better to be consistent and talk about energy transfers and transformations and to avoid the word "loss" completely.

Conditions for Validity

Another important issue related to language used when discussing energy, as well as any topic in physics, is to present physical principles *along with* the conditions for which they are true. For example, in mechanics, it would be meaningless to state "an object in motion remains in that state of motion" without adding the condition "for the case in which no forces act on the object."

A statement made in some textbooks when discussing a solution to a problem is the vague statement that "energy is conserved," with no reference to the system that is being discussed. It is indeed true that energy is conserved on a universal scale, so this statement is valid for *all* sets of conditions and therefore not useful toward solving the problem. In a specific problem, it is more important to identify the specific conditions for the system in the problem: Is the system isolated or non-isolated? So rather than saying "energy is conserved," it would be more valuable to state "the energy of the isolated system remains constant," or "the system is non-isolated because we can identify one or more energy transfers, so the energy of the system does not remain constant."

The word *general* is often used inappropriately in textbooks. For example, one textbook[6] claims that the general form of the law of conservation of energy for a system is

$$\Delta K + \Delta U + \Delta E_{\text{int}} = 0. \tag{1}$$

This is *not* a general statement of conservation of energy. It is a special-case equation that is only true for an isolated system. A truly general equation for conservation of energy for any system is provided in the fourth article in this series.[7] This general equation includes not only the storage of energy within the system but also the mechanisms by which energy can transfer across the boundary of the system.

As a final comment on conditions for validity, consider the equation $W = \Delta K$. This is often called the *work-energy theorem*, and many students come out of mechanics thinking that this is a fundamental energy equation. It is important to stress to students that this is a specialized equation, as we discuss in the fourth article[7] in this series, that can only be used under the following restrictive conditions: (1) work is the *only* transfer mechanism by which energy is entering the system, and (2) the kinetic energy of the system is the *only* type of energy in the system that is changing. I would argue for the use of the phrase *work-kinetic energy theorem* for this equation to stress that it is a relationship between work and kinetic energy, not energy in general.

Mass Converts to Energy

A common statement in textbook and lecture discussions of relativity includes something like "in this process, mass is converted to energy." This type of statement is misleading for students because it says that one type of entity can change into something completely different. An entity measured in kilograms simply cannot change into something measured in joules.

A better approach to this conversion process is to carefully state that *rest energy* is converted into other types of energy. For example, in a nuclear decay, the rest energy of the system decreases because part of that rest energy is transformed to kinetic energy of outgoing particles. It is true that the mass of the system decreases in addition, but the mass decrease is only *related* to the energy decrease, not *equal* to the energy decrease. Baierlein[8] discusses at length the issue of mass converting to energy.

Questions

In light of these discussions, consider the following true-false questions:

(1) True or False? A 10-kg object is raised to a position 1.0 m above a tabletop. Relative to the tabletop, the object has a gravitational potential energy of 98 J.

(2) True or False? The work done on an object equals the change in the kinetic energy of the object.

The statement in Question (1) is false because the identification of the potential energy is incorrect. The potential energy must be identified with a system of interacting objects, in this case the system of the object and the Earth. So it is better to say, "Relative to the zero-energy configuration when the object is at the tabletop, the system has a gravitational potential energy of 98 J when the object is at the highest position." While this statement requires more words than the statement given in the question, we owe it to our students to present physics properly and correctly, even at the expense of a few more words.

The statement made in Question (2) (the work-kinetic energy theorem) might be true in a specific situation, but it is not true in general. This type of absolute statement that does not refer to the conditions should be avoided because it leads students to believe that, in this case, the work-kinetic energy theorem is a fundamental principle. While the statement is true for a situation in which a horizontal force is applied to an object on a horizontal frictionless surface, it becomes false when the surface has friction or in any case in which the work done on a system does not result in a change in the speed, such as lifting a book from a lower shelf and placing it on a higher shelf.

Conclusion

There are many places where we can lead our students into misinterpretations by careless use of language. Careful and correct use of terms and definitions can go far in improving our students' conceptual understanding and problem-solving ability. In the next article in this series, we will discuss a global approach to energy that can be used to address any energy problem.

References

1. J.W. Jewett, "Energy and the confused student II: Systems," *Phys. Teach.* **46**, 81–86 (Feb. 2008).
2. This statement is made under the assumption that we ignore internal structure of the object. Objects with internal structure can possess potential energy. For example, a spring can possess elastic potential energy and a can of gasoline can possess chemical potential energy. These types of energy are associated with forces between components of the structure of the object, however, not with forces between the object and other objects.
3. R.H. Romer, "Heat is not a noun," *Am. J. Phys.* **69**, 107–109 (Feb. 2001).
4. R.P. Bauman, "Physics that textbook writers usually get wrong: II. Heat and energy," *Phys. Teach.* **30**, 353–356 (Sept. 1992).
5. G.M. Barrow, "Thermodynamics should be built on energy—Not on heat and work," *J. Chem. Educ.* **65**(2), 122–125 (Feb. 1988).
6. As a textbook author myself, I do not specifically identify problematic statements in other authors' textbooks in this series of articles. I do not want this series to appear as a marketing tool, but rather as a professional communication that offers a set of suggestions for improving the teaching of energy to our students. I present items from several textbooks in general terms and not as direct quotes.
7. J.W. Jewett, "Energy and the confused student IV: A global approach to energy," *Phys. Teach.*, to be published in April 2008.
8. R. Baierlein, "Does nature convert mass into energy?" *Am. J. Phys.* **75**, 320–325 (April 2007).

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