Conserving Energy in Physics and Society: Creating an Integrated Model of Energy and the Second Law of Thermodynamics

Abigail R. Daane, Stamatis Vokos, Rachel E. Scherr

Department of Physics, Seattle Pacific University, Seattle, WA 98119

Abstract. The second law of thermodynamics is typically not a central focus either in introductory university physics textbooks or in national standards for secondary education. However, the second law is a key part of a strong conceptual model of energy, especially for connecting energy conservation to energy degradation and the irreversibility of processes. We are developing a conceptual model of the second law as it relates to energy, with the goal of creating models and representations that link energy, the second law, and entropy in a meaningful way for learners analyzing real-life energy scenarios. We expect this model to help learners better understand how their everyday experiences relate to formal physics analyses. Our goal is to develop tools for use with elementary and secondary teachers and secondary and university students.

Keywords: energy, second law of thermodynamics, conservation, degradation, professional development
PACS: 01.40 Fk, 01.40 E-, 05.70-a

INTRODUCTION

Sociopolitical energy (the energy used to operate electrical grids, run automobiles, etc.) and physics energy are not typically connected in education. Physics energy is conserved: the same quantity of energy exists at the end of any process as at the beginning. Studies investigating student ideas about energy conservation find that generally students rely on the idea that energy is used up [1, 2]. Sociopolitical energy *is* used up, in the sense that it becomes unavailable to perform the same tasks again. Learners' everyday ideas that energy is wasted can be a resource for learning. Teaching about energy spreading and degradation (a decrease in the value of energy) can have the benefit of reconnecting sociopolitical energy to introductory physics classes.

PRIOR RESEARCH ON ENERGY DEGRADATION

Studies recognizing the disconnect between sociopolitical energy and physics energy recommend a greater emphasis on degradation [3]. Some suggest using free energy (energy available for work) to relate to students' ideas of consumable energy [4]. Others recommend a more central focus on the second law of thermodynamics in K-12 education [5]. One study even attempts to teach about entropy in a high school energy unit [6].

When entropy and the second law are a focus of instruction (e.g., in university courses in thermodynamics), students find energy degradation challenging [7]. Many university students view entropy as a conserved quantity after instruction [8].

Our work aims to reconnect energy conservation to degradation by integrating energy, entropy, and the second law into a conceptual model that builds on everyday ideas about energy use. We intend to develop a model that is both responsible to advanced physics concepts and accessible to K-12 teachers.

EXISTING STATEMENTS OF THE SECOND LAW

In introductory physics textbooks, the second law is often stated in terms of entropy: "the total entropy of the universe does not change when a reversible process occurs ($\Delta S_{universe} = 0$ J/K) and increases when an irreversible process occurs ($\Delta S_{universe} > 0$ J/K)" [9]. Entropy is described as a thermodynamic property associated with disorder and multiplicity; it is usually not associated with energy transfers or transformations [10].

A contrasting approach aimed at teachers explains the second law as The Running Down Principle: "In all energy changes there is a running down towards sameness in which some of the energy becomes useless" [11]. Energy in this case is energy unavailable for the performance of work [9], with work defined in terms of forces. In order to avoid requiring our learners to integrate models of force and energy prematurely, we instead define degraded energy as energy unavailable for the process of mechanical energy transfer. In mechanical energy transfer, the form of energy that transfers is kinetic. Thus, degraded energy is the energy that cannot be converted to kinetic energy in a certain scenario without the addition of outside energy or a change in the system.

INSTRUCTIONAL CONTEXT

Seattle Pacific University's Energy Project provides inquiry-based summer professional development courses for K-12 teachers [12] that emphasize energy concepts including conservation and tracking [13]. In these courses, teachers spontaneously consider not only the *amount* and *forms* of energy involved in physical processes (transfers and transformations), but also the energy's *usefulness*. For example, some teachers view energy as losing value during a process, even when they explicitly acknowledge the total amount of energy is constant. Others articulate that the quality, usefulness, or availability of energy decreases when changing form (e.g., kinetic to thermal energy). The teachers' ideas call for a meaningful connection in the K-12 science curriculum between energy that is conserved (in a physics context) and energy that is used up (in a sociopolitical context).

Ideas of energy usefulness emerge when teachers use Energy Tracking Representations (ETRs) including Energy Theater, Energy Cubes, and Energy Tracking Diagrams (ETDs) [13]. Energy Theater is an embodied learning activity that promotes conservation of energy in a scenario (i.e. a box sliding across the floor). Learners' bodies represent chunks of energy. Participants show energy transfers between objects by moving to another location and show transformations by changing their hand signs. Energy Cubes is a variation on this representation, in which chunks of energy are represented by cubes. ETDs are explained in detail in the next section. In what follows, we describe how ETRs can support discussion of energy usefulness and degradation.

MODELING CONSERVATION AND DEGRADATION OF ENERGY

Our model of energy consists of several conceptual statements about energy (energy is conserved, is localized, is located in objects, can change form, is transferred among objects and can accumulate in objects) and representations that embody these statements (ETRs) [13]. ETRs help learners to follow the conservation of energy principle but do not address the concepts of energy usefulness and degradation which relate to learners' everyday experiences. We expect to add features to our ETRs and statements that incorporate sociopolitical energy into the formal physics context by adding the concepts of energy degradation, entropy and the second law to our model. This paper reports on our progress toward this goal. We first describe the representation that is the basis for our development. Next we share principles of energy degradation that hold promise for a role in our integrated model of energy, the second law, and eventually entropy.

Energy Tracking Diagrams

Of all of the ETRs, ETDs provide a permanent, detailed layout of the energy processes involved in a physical scenario. An example of an ETD for a hand compressing a spring at a constant speed is shown in Figure 1. The hand moves and warms as chemical energy in the hand transforms into thermal and kinetic energy. Some of the thermal energy in the hand is transferred to the environment via conduction. Some kinetic energy transfers to the spring, which moves; that kinetic energy is then transformed into elastic energy and thermal energy as the spring compresses and warms. The rules of an ETD are as follows:

- Objects are represented as schematic areas on a whiteboard.
- Individual units of energy are represented as individual letters, with the specific letter representing the form of energy.
- Energy transfers and transformations are represented with arrows. All arrows have a letter at the head and the tail. Arrows that have different letters at the head and the tail indicate transformations. Arrows that cross the boundaries of object-areas indicate transfers.
- The process by which a transfer or transformation occurs (e.g., mechanical work, conduction) is indicated by the color or pattern of the arrow. For example, in Figure 1, striped arrows indicate mechanical work and gray arrows indicate conduction.
- Time order of energy processes is represented by sequences of arrows. (The time order of processes that occur along separate tracks is not represented.)
- Relative amounts of energy may be represented by adding coefficients to the letters representing energy. (Figure 1 does not include coefficients.)

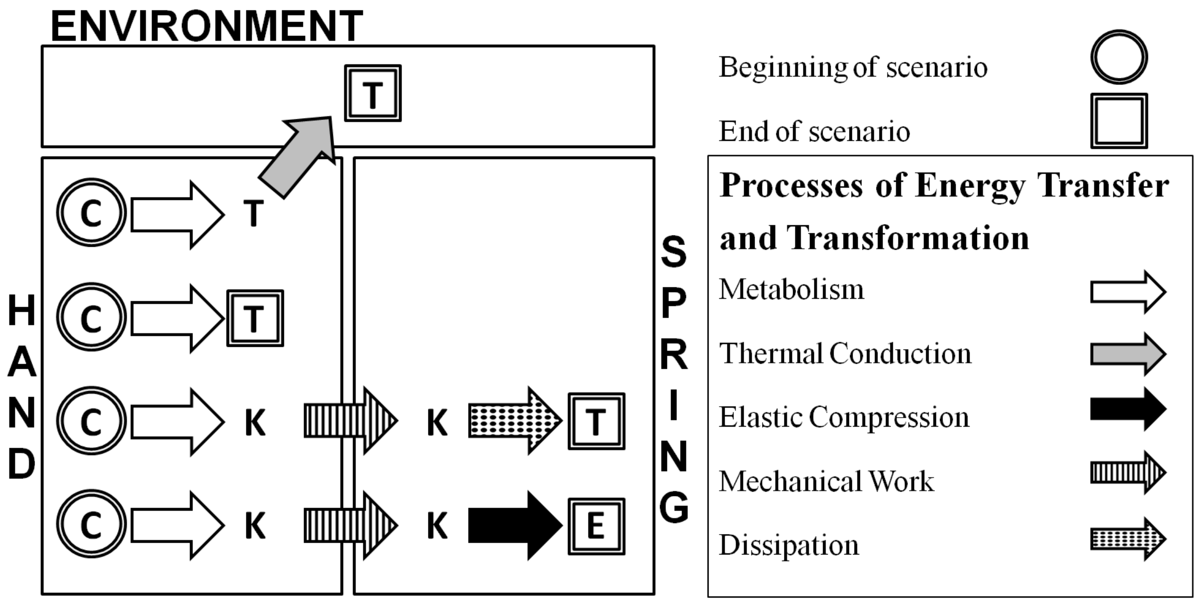

FIGURE 1. Energy Tracking Diagram for a hand compressing a spring at constant speed. C, K, T, and E represent chemical, kinetic, thermal, and elastic energy, respectively.

Principles of Energy Spreading and Degradation

We propose three principles of energy degradation as the beginnings of an integrated model of the concepts of energy, entropy, and the second law. As a result of these three principles, we identify degraded energy as thermal energy at equilibrium. In an ETD, degraded energy is a T (thermal energy) at the end of a track. If the T is not at the end of a track, then the energy is not degraded.

During Physical Phenomena, Energy Tends to Spread

Energy can spread within objects, to other objects, through space, by mixing, and in other ways. The spread always distributes the energy more equitably within the system [14]. In ETDs this can be demonstrated in several ways:

Energy spreads to more and more objects. Energy begins in an object or objects and often ends up in more objects. In Figure 1, the circles indicate the energy locations at the beginning of the scenario (the chemical energy in the hand). The squares indicate the energy locations at the end of the scenario. The energy has spread spatially to three objects (the hand, spring, and environment) from the first object (the hand).

Energy spreads spatially within objects *(and in space).* Within the hand, thermal energy is produced and spreads until it reaches equilibrium in the hand. ETDs do not normally show the spatial features of the hand but can be adapted to show those features, e.g., by dividing the hand into sections. ETDs do not easily represent energy spreading by material expansion (e.g., gas diffusing into a vacuum) or radiation, because they represent objects in energy space rather than configuration space.

Energy spreads spatially during processes. Different processes of energy transfers and transformations, represented in ETDs by different colors/patterns of arrows, are associated with varying degrees of spreading. In Figure 1, conduction (the gray arrow) is a process in which energy both spreads to another object and expands spatially. In contrast, during mechanical work (the striped arrows), energy moves in bulk from the hand to the spring, a transfer not associated with spreading. In general, tracks that end with thermal energy produce larger energy spread.

Leff [14] takes the position that when energy spreads, entropy increases. This qualitative description of entropy could be used in secondary education without the introduction of calculus.

As Energy Spreads, Thermal Energy Never Decreases

Whenever energy spreads, thermal energy does not decrease in quantity. ETDs demonstrate this concept the following ways:

In many scenarios, thermal energy increases. When energy spreads, some energy is transformed into thermal energy, unless it is all already thermal energy. In ETDs, as a process runs down, or returns to the beginning of a cycle, many energy tracks end in thermal energy. In Figure 1, all energy tracks begin as chemical energy and some of the tracks end as thermal energy. The hand, spring, and environment are warmed. Only the elastic energy in the spring is not degraded.

In other scenarios, thermal energy spatially spreads. When the spreading energy is already thermal energy, objects may not get warmer: instead, thermal energy spreads equitably among all objects involved until thermal equilibrium is reached. Though some objects cool during this process, the thermal energy of the system does not decrease. In the example of the hand compressing the spring, thermal energy eventually spreads over the entire system.

As Thermal Energy Increases,
Other Forms of Energy Decrease

For a given system of objects, energy conservation requires that the production of thermal energy occurs together with the reduction of other forms of energy. In Figure 1, all of the energy is initially chemical; as the scenario progresses, a smaller and smaller fraction of the energy is anything other than thermal.

Subsequent processes of the same system of objects will produce more thermal energy and further reduce the prevalence of other forms of energy, making the resulting energy configuration more and more unlike the original. For example, a subsequent process using the system in Figure 1 might be the expansion of the spring back to its uncompressed length against the resistance of the hand. In such a process, the elastic energy in the spring transforms to kinetic energy and then transfers to the hand, transforming into thermal energy as the hand warms (E → K → K → T). At that point, all of the original chemical energy would have transformed to degraded thermal energy and spread equitably among the system. No more energy transformations will occur without additional energy supplied to the system.

CONCLUSIONS AND FUTURE WORK

By understanding how energy spreading and degradation may be indicated in ETDs, we are beginning to create a model that integrates energy conservation with entropy and the second law. Reconnecting sociopolitical and physics energy concepts can increase the relevance of energy instruction for learners. By using ETDs to analyze real-world scenarios, learners can begin to understand the formal physics meanings of conservation and degradation.

Our integrated model is informing the development of instructional activities for K-12 teachers in Energy Project courses. Future work will investigate the usefulness of the conceptual model and the improvement of teachers' understanding of the concept of energy in both a sociopolitical and physics context in those courses. In the long term, we anticipate using the model with secondary and university students as well.

ACKNOWLEDGMENTS

We are grateful to Amy D. Robertson, Lane Seeley, Sarah B. McKagan, and Lezlie S. DeWater for substantive discussions of this work. This work was supported in part by the National Science Foundation (DRL 0822342).

REFERENCES

1. S. Kesidou and R. Duit, *Journal of Research in Science Teaching* **30**(1), 85-106 (1993).
2. J. Solomon, *European Journal of Science Education* **5**(1), 49-59 (1983).
3. R. Duit, *Physics Education* **19**, 59-66 (1984).
4. K. A. Ross, *The School Science Review* **69**(248), 438-445 (1988).
5. H. Goldring and J. Osborne, *Physics Education*, **29**(1), 26-31 (1994).
6. R. Ben-Zvi, *International Journal of Science Education* **21**(12), 1251- 1267 (1999).
7. M. J. Cochran, and P. R. L. Heron, *American Journal of Physics* **74**(8), 734-741 (2006).
8. W. M. Christensen, D. E. Meltzer, and C. A. Ogilvie, *American Journal of Physics* **77**(10): p. 907-917 (2009).
9. J. D. Cutnell and K.W. Johnson, *Physics*, 8 ed, Hoboken: John Wiley & Sons, 2009, pp. 458.
10. D. Schroeder, *An Introduction To Thermal Physics*, San Franscisco: Addison Wesley Longman, 2000.
11. J. Solomon, *Getting to know about energy: In school and society*, Bristol, PA: The Falmer Press, 1992, pp. 128.
12. H. G. Close, et al. "Using the Algebra Project method to regiment discourse in an energy course for teachers" in *AIP Conf. Proc. (2010 Physics Education Research Conference)*. 2010.
13. R. E. Scherr, et al., *Physical Review ST-PER*, submitted.
14. H. S. Leff, *The Physics Teacher* **50**, 87-90 (2012).