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Energy Tracking Diagrams

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Energy Tracking Diagrams

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Energy is a crosscutting concept in science and features prominently in national science education documents.[1–3] In the *Next Generation Science Standards*, the primary conceptual learning goal is for learners to conserve energy as they *track* the transfers and transformations of energy within, into, or out of the system of interest in complex physical processes.[2–4] As part of tracking energy transfers among objects, learners should (i) distinguish energy from matter, including recognizing that energy flow does not uniformly align with the movement of matter,[5] and should (ii) identify specific mechanisms by which energy is transferred among objects, such as mechanical work and thermal conduction.[6] As part of tracking energy transformations within objects, learners should (iii) associate specific forms with specific models and indicators (e.g., kinetic energy with speed and/or coordinated motion of molecules, thermal energy with random molecular motion and/or temperature)[7] and (iv) identify specific mechanisms by which energy is converted from one form to another, such as incandescence and metabolism.[8] Eventually, we may hope for learners to be able to optimize systems to maximize some energy transfers and transformations and minimize others, subject to constraints based in both imputed mechanism (e.g., objects must have motion energy in order for gravitational energy to change) and the second law of thermodynamics (e.g., heating is irreversible). We hypothesize that a subsequent goal of energy learning—innovating to meet socially relevant needs—depends crucially on the extent to which these goals have been met.

We describe an energy representation, called an *Energy Tracking Diagram*, that incorporates multiple learning targets for energy, including conservation, forms, tracking (transfer and transformation), and appropriate consideration of systems in complex real-world scenarios. Energy Tracking Diagrams prompt learners to recognize the mechanisms for and constraints on energy transfer and transformation processes. They support reasoning about the location of potential energy, quantifying relative amounts of energy that are involved in distinct processes, and disambiguating flows of energy and other flowing quantities. As powerful visual representations, Energy Tracking Diagrams uniquely illuminate learners' understanding of *energy dynamics* and can therefore also be used for assessment purposes.

Energy Tracking Diagrams

Energy Tracking Diagrams are written representations derived from an embodied learning activity called Energy Theater.[9–11] Like Energy Theater, Energy Tracking Diagrams represent energy as being conserved, localized, and changing form. They explicitly show energy as flowing among objects and accumulating in objects. Instead of showing these flows dynamically, Energy Tracking Diagrams represent all the energy transfer and transformation processes that occur in a scenario in a single picture. The rules of an Energy Tracking Diagram are shown in Fig. 1.

- Objects are represented as schematic areas on a whiteboard or on paper.
- 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 cross the boundaries of object-areas indicate energy transfers. Arrows that have a different letter at the head than the tail indicate energy transformations.
- The process or mechanism through which a transfer or transformation occurs (e.g., work, metabolism, conduction) is indicated by the color or pattern of the arrow.
- The time order of energy transfers and transformations 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 that represent units of energy.

Fig. 1. Rules of Energy Tracking Diagrams.

Unlike bar charts, pie charts, and other common energy representations,[12] an Energy Tracking Diagram includes all the interacting objects in the scenario. These objects may be grouped or subdivided according to the goals of the analysis. A system can be specified by designating certain objects as being "inside" and the rest as being "outside": this supports the construction of equations corresponding to transfers of energy across system boundaries, e.g., "increase in energy inside = amount that transferred in." Energy Tracking Diagrams embody the principle of conservation of energy whether an equation is constructed or not: energy units are explicitly shown to persist throughout the time development of the scenario.

The following examples of Energy Tracking Diagrams for various scenarios show how they may support learners in identifying transfer and transformation processes, locating potential energy, quantifying relative amounts of energy that are involved in distinct processes, and disambiguating flows of energy and other flowing quantities. While a combination of other graphical representations might be used to show these features of the scenarios under investigation, Energy Tracking Diagrams uniquely combine all elements into a single visualization.

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Indicating processes of energy transfer and transformation

Figure 2 is an Energy Tracking Diagram for a person compressing a spring at constant speed.[13] In this scenario, chemical energy in the person transforms into kinetic energy (the person moves), which transfers to the spring through mechanical work.[14] That kinetic energy is then transformed into elastic energy and thermal energy as the spring compresses and warms. The person also warms as he or she moves.[15] In the diagram, C, K, T, and E represent chemical, kinetic, thermal, and elastic energy, respectively. Orange, purple, green, and blue arrows represent metabolism, mechanical work, elastic compression, and dissipation, respectively.

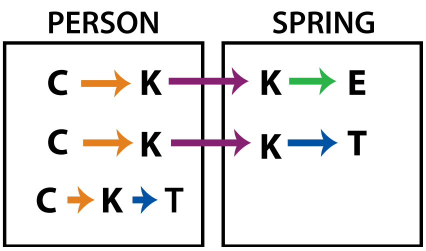

Fig. 2. Energy Tracking Diagram for a person compressing a spring at constant speed. C, K, T, and E represent chemical, kinetic, thermal, and elastic energy. Orange, purple, green, and blue arrows represent metabolism, mechanical work, elastic compression, and dissipation.

Constructing Energy Tracking Diagrams includes recognizing how many different tracks are needed to represent the energy processes in the scenario. In the spring compression scenario, the fact that there are at least three endpoints for sequences of energy processes (elastic energy in the spring, thermal energy in the spring, and thermal energy in the person) indicates that at least three different tracks are required: one ending in E in the spring, one ending in T in the spring, and one ending in T in the person.

Because each arrow in an Energy Tracking Diagram corresponds to a process of energy transfer or transformation, learners creating an Energy Tracking Diagram are prompted to model energy dynamics in terms of identifiable physical processes. In so doing, they have the opportunity to recognize the mechanisms for and constraints on those processes. For example, if a learner initially showed the chemical energy in the person transferring directly to the spring as kinetic energy, she might then be unable to label the corresponding arrow, recognizing that there is no mechanism by which chemical energy in a living organism could transfer directly to another non-living object. Instead, chemical energy may transform to kinetic or thermal energy within the organism, and only then transfer, often by mechanical work or thermal conduction. Learners may also recognize that transfers of kinetic energy from one object to another are typically associated with a contact force. Some learners using this representation have asserted powerful rules such as, "When forces transfer energy, they transfer kinetic energy."[17]

Commonly reported difficulties in energy instruction include failure to distinguish work from energy[18] and heat from thermal energy.[19] Energy Tracking Diagrams clearly distinguish these quantities with different kinds of symbols: energy units are represented by letters, and processes of energy transfer (work or heat) are represented by arrows. Energy Tracking Diagrams thus have the potential to assist learners in coming to understand these distinctions.

Energy Tracking Diagrams support learners in applying mathematical expressions such as the first law of thermodynamics or the work-kinetic energy theorem to specific scenarios. To do so, a learner must specify a system, identify any transfers of energy across system boundaries, and apply the conservation of energy principle to the system in a mathematical form.[20,21] For example, Fig. 2 illustrates the elastic and thermal energy of the spring increasing by an amount equal to the mechanical work done on the spring (purple arrows). This could be written as $\Delta U + \Delta E_{\text{int}} = W$ (using the definitions of these terms offered in Ref. 20).

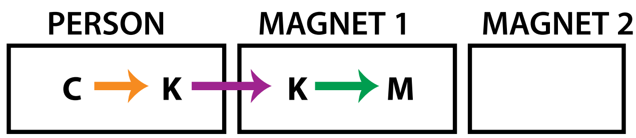

Fig. 3. Energy Tracking Diagram for a pair of attracting magnets when magnet 1 is pulled away from magnet 2. C, K, and M represent chemical, kinetic, and magnetic energy. Orange, purple, and green arrows represent metabolism, mechanical work, and displacement relative to a magnet. In this model, magnetic energy is located in a single magnet.

Locating potential energy

A possible concern about Energy Tracking Diagrams is that they model energy as being located in objects. This description of energy might be problematic for gravitational and other forms of potential energy, which are properly located in a system of objects or in a field, rather than in individual objects. The following scenario can promote conceptual understanding of the circumstances under which it is or is not acceptable to locate energy within objects.

Figure 3 is an Energy Tracking Diagram for a pair of attracting magnets that start out in contact; magnet 2 (M2) is fixed in place as magnet 1 (M1) is pulled away by a person. This process involves exerting a force over a distance, which transfers kinetic energy (K) from the person to M1 through mechanical work (purple arrow in Fig. 3). The person moves M1 some distance away and then stops. If kinetic energy is not to accumulate in M1, it must transform into some other kind of energy. In Fig. 3, that form of energy is designated as "magnetic energy" (M) and is located in M1. In this model, there is magnetic energy in M1 that can turn into kinetic energy in M1, which is consistent with what we know happens if we release M1: it acquires kinetic energy, flying back toward M2. Gravitational energy is often modeled similarly in introductory physics, by substituting the Earth for M2 and an object that we lift away from the Earth for M1; objects that have been lifted are said to "have" gravitational energy. We term the process by which K transforms to M "displacement relative to a magnet" (green arrow in Fig. 3) as we would call the analogous process by which K transforms to G (gravitational energy) "vertical displacement." [22] Thus far, the analysis does not require magnetic (or gravitational) energy to be located anywhere but inside the "lifted" object.

However, if after the magnets were separated magnet 2 were then released, magnet 2 would gain kinetic energy, flying toward magnet 1. This situation is inconsistent with the representation of energy in Fig. 3, which shows no energy in magnet 2 that might be available for transformation. Since no work was done on magnet 2, no kinetic energy was transferred to it and no energy was made available for transformation to magnetic energy. The model in Fig. 3 is therefore insufficient to account for these simple known phenomena.

Experimentally, the energy that the person gives to M1 is available to either M1 or M2. We may amend the representation to accommodate this fact by having the kinetic energy in M1 transform into magnetic energy located in a zone between M1 and M2, with the understanding that energy in that zone is accessible to either of the two interacting objects.

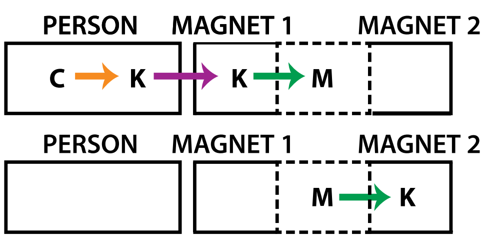

Fig. 4. Energy Tracking Diagram for a pair of attracting magnets when magnet 1 is pulled away from magnet 2 (upper diagram), then magnet 2 is released and moves toward magnet 1 (lower diagram). In this model, magnetic energy is located in a zone accessible to either of the two magnets.

Figure 4 is an Energy Tracking Diagram using this convention for the scenario of first pulling M1 away from M2 with M2 fixed (upper diagram), then fixing M1 and releasing M2 (lower diagram).[23] This representation illustrates what we mean when we say energy is "in the system" without being in a specific object: Its location is such that two or more interacting objects all have access to it.

Alternatively, the shared zone may be termed "the field" and designated as a new object with special properties: it can only contain a certain kind of energy (the shared kind) and it only interacts with certain objects (the ones that do the sharing). In general, it is necessary to locate energy in this shared zone if more than one of the interacting objects will move in the course of the scenario. If the scenario is such that only one object of the pair will be considered to move (as is often the case for small objects near the surface of the Earth), the potential energy may be represented as being located in the moving object without logical contradiction within the specific analysis.[24]

Quantifying energy

Figure 5 is an Energy Tracking Diagram for an Atwood's machine of unequal masses suspended over an ideal pulley, so that the larger mass falls and the smaller mass rises (this diagram uses the convention of locating gravitational potential energy inside the non-Earth object). Coefficients indicate relative amounts of energy along each track for the case that the larger mass is three times the smaller mass. In this scenario, gravitational energy in the large mass transforms into kinetic energy (the mass falls); some of this kinetic energy accumulates in the large mass (it speeds up), and some transfers to the small mass through mechanical work.[25] Some of the kinetic energy in the small mass transforms into gravitational energy as the small mass rises; the rest accumulates in the small mass as it speeds up. In the diagram, G and K represent gravitational and kinetic energy. Green and purple arrows represent vertical displacement in the gravitational field of the Earth and mechanical work.

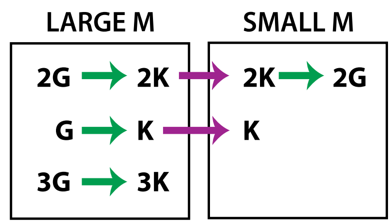

Fig. 5. Energy Tracking Diagram for an Atwood's machine of unequal masses suspended over an ideal pulley. G and K represent gravitational and kinetic energy. Green and purple arrows represent vertical displacement in the gravitational field of the Earth and mechanical work.

Figure 5 includes coefficients representing the relative amounts of energy on different tracks. One means to determine appropriate coefficients is to assign a variable coefficient to each track, such as a, b, and c for the top, middle, and bottom tracks in Fig. 5. Because the quantity of gravitational energy lost by the larger mass is three times that gained by the smaller mass, $a + b + c = 3a$. Because the larger mass has three times the kinetic energy of the smaller mass, $c = 3b$. The result is a system of equations permitting $a = 2$, $b = 1$, and $c = 3$. An advantage of this analysis is that it is independent of the reference point for gravitational energy: It shows the relative amounts of energy gained and lost by each mass without reference to a "zero" of potential energy.

In this model of energy dynamics, each transfer and transformation occurs through a specific mechanism or process. Such a model places constraints on allowed energy transfers and transformations. The Atwood's machine scenario illustrates one such model-based constraint: Because gravitational energy is determined by height (and mass), and changes in height are intrinsically linked to the bulk motion of matter (i.e., kinetic energy), gravitational energy can only transform into kinetic energy in this model. Similarly, in the spring-compression scenario (Fig. 2), chemical energy in the person can only transform into kinetic or thermal energy in

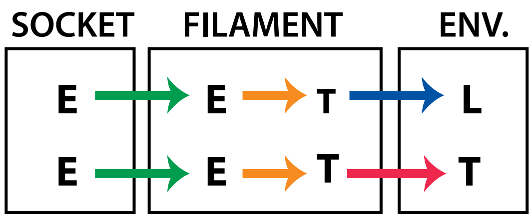

Fig. 6. Energy Tracking Diagram for an incandescent bulb glowing steadily. E, T, and L represent electrical, thermal, and light energy. Green, orange, blue, and red arrows represent electrical conduction, joule heating, incandescence, and thermal conduction.

the person, because those are the only transformations associated with a specific mechanism (metabolism).

Disambiguating energy and other flowing quantities

In an incandescent bulb glowing steadily (Fig. 6), electrical energy (E) flows, through electrical conduction (green arrow), from the base of the light bulb into the filament, where it transforms into thermal energy (T) via the dissipative process of joule heating (orange arrow).

Some of the thermal energy in the filament transfers to the environment through thermal conduction (red arrow), and some transforms to light energy that travels outward to the surroundings (incandescence; blue arrow).[26] Thus, while the electric current flows in a closed loop around the circuit, some of the energy flows out into the environment.

Some learners are initially tempted to represent energy as flowing around an electrical circuit.[7] While a correct Energy Tracking Diagram should not show electric current (just as a correct free-body diagram should not show the velocity of an object), the fact that current is conserved in a light bulb circuit is important to understanding its operation. Reconciling an energy model with a current model in circuits produces challenging questions, such as: By what means does energy enter (and possibly exit) the light bulb? The current appears to be the natural culprit, but the concept of current conservation states that the current is the same quantity when it leaves the bulb as when it entered. How can the current be the same, yet have less energy? Why does an electric circuit require a return of the current to the battery when energy is transformed in the light bulb? These nontrivial questions are discussed in current physics education literature.[27] Our instructional perspective on these questions is that Energy Tracking Diagrams are an excellent context for disciplined model-based reasoning, including disambiguating energy flow and current flow, as well as theorizing mechanisms of energy transformation.[10]

Limitations of Energy Tracking Diagrams

Energy Tracking Diagrams are useful for analyzing a wide variety of scenarios, and uniquely emphasize energy conservation and tracking. There are, however, scenarios and learning goals for which Energy Tracking Diagrams are not ideal.

- Energy Tracking Diagrams do not represent negative energies.
- Energy Tracking Diagrams are not well suited to scenarios in which the integrity of objects is not maintained throughout a scenario. For example, when ice melts into lemonade or an owl eats a mouse, the energy that had once been associated with the lemonade (or owl) becomes difficult to distinguish from energy associated with the melted ice (or mouse), and the associated Energy Tracking Diagram becomes difficult to interpret. For the same reason, Energy Tracking Diagrams are not well suited to scenarios in which energy transfer occurs by means of matter transfer (e.g., filling a car's tank of gas).
- Energy Tracking Diagrams are consistent with quantitative analysis (as shown in Fig. 5), but do not primarily feature quantitative comparisons; bar charts and pie charts serve quantitative analysis more directly.
- When a complex dynamic process is captured in a static diagram, there can be a loss of information about the temporal order of the component processes. Learners who want to represent the time ordering of energy transfer and transformation processes, especially along different tracks, may be better served by Energy Theater,[9-11] which is a dynamic representation. Modeling the time ordering of energy transfers and transformations in Energy Theater may especially promote theorizing mechanisms of energy transfer and transformation.[10-11] Learners who want to simplify their representation by excluding sequential ordering of transfers and transformations may be better served by bar or pie charts.

Assessing energy learning with Energy Tracking Diagrams

Instructors can use Energy Tracking Diagrams to assess learners' use of energy conservation and tracking, including their identification of processes of energy transfer and transformation. For example, if the number of energy units in a learner's Energy Tracking Diagram is the same at the beginning and end of a scenario, energy is being represented as conserved. If the energy units are connected to one another with arrows representing transfers and transformations, energy is being tracked as it flows through the scenario. If arrows are color-coded or labeled, the learner is identifying processes by which energy transfers and transforms in the scenario.

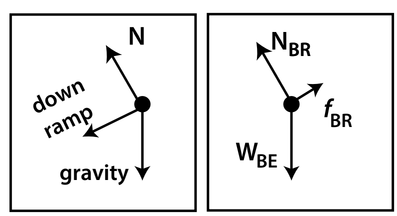

Fig. 7. Hypothetical free-body diagrams for a block sliding down a ramp, before (left) and after (right) instruction.

Analogously, instructors and researchers often use free-body diagrams to assess learners' understanding of forces. For example, imagine that a student provides the free-body diagrams shown in Fig. 7 for a block sliding down an incline at constant speed, one before and one after instruction. After instruction, the

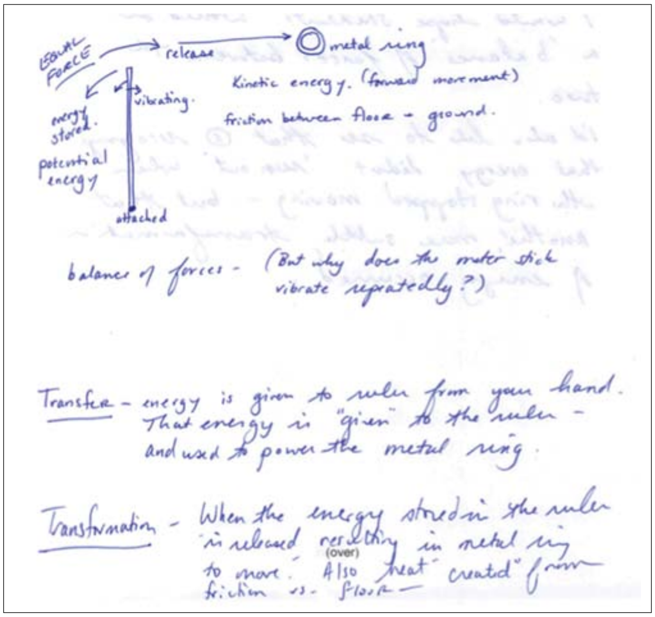

Fig. 8. Energy assessment before instruction, in which the respondent analyzes a ring slider scenario.

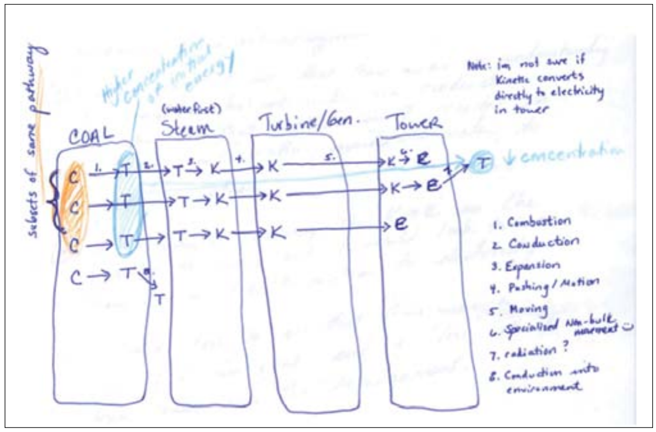

Fig. 9. Energy assessment after instruction, in which the respondent analyzes a power plant scenario. Colors are in the original.

hypothetical student: (i) represents forces as interactions between two objects by indicating the type of force and by including subscripts that denote the entities feeling and exerting the force (B for block, E for Earth, and R for ramp); (ii) reflects the motion of the object in the relative lengths of the arrows (zero net force) and in the direction of the friction force (opposite the motion); and (iii) accounts for all relevant interactions. Since neither (i), (ii), nor (iii) is reflected in the student's response before instruction, one might conclude that this student has learned about the interactional nature of forces and has understood Newton's second law as applied to this scenario.

We have used written assessments that draw on Energy Tracking Diagrams to assess the extent to which our professional development courses advance our learning goals of energy conservation, tracking, and identification of processes of energy transfer and transformation among in-service K-12 teachers. In 2013, 15 secondary teachers in a second-year professional development course were given assessments before and after instruction that requested energy analyses of a real-world scenario—before instruction, a "ring slider" (a metal ring smacked by a bent-back meterstick),[28] and after instruction, a steam-turbine power plant.[29] The assessments asked them to:

(a) "Draw a diagram showing the energy transfers and transformations within and/or among the objects in the scenario." (For the ring slider, teachers were asked to include the meterstick, the ring, the floor, and the surrounding air. For the power plant, they were directed to include the coal in the boiler, the water/steam, the turbine/generator, and the electrical tower.)

(b) "For each transfer and transformation that you indicate in your diagram, describe the mechanism or process by which that transfer or transformation occurred (e.g., metabolism, conduction, compression, melting…)."

Teachers were not asked to quantify the amounts of energy involved in various processes. One teacher offered the pre-instruction (ring slider) response shown in Fig. 8. Analyzing her response for evidence of energy conservation, we observe that she alternates between appropriate language for tracking a conserved quantity (such as "energy is given to the ruler from your hand") and language inconsistent with energy conservation and tracking (such as energy being "released" to an unspecified location). She identifies friction as the process by which "heat" is "created," but does not explicitly identify any processes of energy transfer or transformation. Arrows in the diagram indicate the motion of material objects (the rightward motion of the ring and the bending back of the ruler); the conservation of energy itself is not represented through any of the graphic elements.

The same teacher offers the post-instruction (power plant) response shown in Fig. 9. In this response, the teacher explicitly indicates that energy is conserved by indicating the same number of energy units (four, in this case) at the beginning and end of the scenario. She tracks energy as it moves through the system by laying out the path of transfers and transformations taken by each unit of energy. She identifies processes of energy transfer and transformation for each arrow in her diagram.

This teacher's post-instruction response is incomplete in some senses (e.g., it does not include the energetically important process by which water turns to steam) and flawed in others (e.g., the conversion of kinetic to electric energy is shown as happening in the electrical tower rather than in the generator). Nonetheless, a comparison of this teacher's pre- and post-instruction responses suggests that this teacher has learned to consistently demonstrate energy conservation, to track energy through a scenario, and to identify processes of energy transfer and transformation. This improvement may signify the development of either conceptual understanding or representational competency— it may be that the respondent has learned about energy, or it may be that the respondent has learned to consistently use Energy Tracking Diagrams, which represent a particular model of energy. As with free-body diagrams, learner use of sanctioned representations can (and often does, in practice) serve as a proxy for conceptual understanding. Energy Tracking Diagrams may be useful for assessing learner understanding of energy in the same way that free-body diagrams are useful for assessing learner understanding of forces.

Summary

Energy Tracking Diagrams, like the dynamic representations from which they are derived, articulate a conceptualization of energy as conserved, localized, flowing among objects, accumulating in objects, and changing form. These diagrams contribute to the representational repertoire for energy in physical systems, with specific advantages for tracking energy transfers and transformations. Energy Tracking Diagrams offer a view of learners' understanding of conservation, tracking, and transfer and transformation processes and thus provide a new means of assessing energy concepts, similar to free-body diagrams for force concepts.

Acknowledgments

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6. *Next Generation Science Standards* Crosscutting Concept "Cause and effect: Mechanism and prediction," as well as standards 4-PS3-A, 4-PS3-C, HS-PS3-A, and HS-PS3-B (Ref. 2).
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16. Figure 2 does not include, but could be modified to include, other processes that would be present in real phenomena such as transfer of thermal energy from the person to the environment via conduction.
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22. We do not describe either of these processes ("moving relative to a magnet" or "moving vertically in the gravitational field of the Earth") as "work." We use the term "work" to refer to the mechanical transfer of energy from one object to another (transfer by means of a force), whereas in this model these processes are transformations of energy within a single object. Even in the model shown in Fig. 4, in which the process in question transfers energy from an object to a field, we do not consider the term "work" appropriate, since the energy that transfers out of the object does not transfer by means of a force (the object does not exert a force on the field). The variety of possible definitions of the term "work" is carefully summarized and synthesized in Mallinckrodt and Leff, "All about work," *Am. J. Phys.* **60**, 356–365 (April 1992).
23. In a scenario in which the magnets were pulled apart and then both released simultaneously, both magnets would gain kinetic energy and two distinct tracks would be required in the Energy Tracking Diagram corresponding to the release. Each track would start with an M in the shared zone and end with a K in one of the magnets.
24. An advantage of this approach is that it avoids the attribution of infinite negative energy to closely spaced magnets, due to representing only the magnetic energy associated with the given objects rather than all the magnetic objects in existence. Energy Tracking Diagrams are not suited to representing negative energies.
25. The string connecting the two masses is assumed massless and not shown in Fig. 5, but could be included as an intermediary.
26. Incandescence is distinctive in that energy transfer and transformation are simultaneous aspects of this single process. Light is distinctive in that it may be considered to be either a form of energy or a means of transporting energy. An alternative is to identify "light energy" as "electromagnetic energy," and the blue arrow with radiation.
27. I. Galili and E. Goihbarg, "Energy transfer in electrical circuits: A qualitative account," *Am. J. Phys.* **73**, 141–144 (Feb. 2005); R. Chabay and B. Sherwood, "Restructuring the introductory electricity and magnetism course," *Am. J. Phys.* **74**, 329–336 (April 2006); B. S. Davis and L. Kaplan, "Poynting vector flow in a circular circuit," *Am. J. Phys.* **79**, 1155 (Nov. 2011).
28. Teachers were told, "A meterstick is laid on edge on the floor and one end is fastened down. The other end is pulled back and used to propel a metal ring across a level floor. The metal ring slides to a stop." Teachers also watched a video of the scenario.
29. Teachers were shown a diagram of a power plant and told, "In a 'steam turbine power plant,' coal is burned to produce steam that turns a turbine, generating electricity. The diagram shows various parts of the power plant."

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