# Energy Tracking Diagrams

Rachel E. Scherr,[1] Hunter G. Close,[2] Abigail R. Daane,[1] Lezlie S. DeWater,[1]
Benedikt W. Harrer,[3] Amy D. Robertson,[1] Lane Seeley,[1] and Stamatis Vokos[1]

[1] Department of Physics, Seattle Pacific University, Seattle, Washington 98119, USA
[2] Department of Physics, Texas State University, San Marcos, Texas 78666, USA
[3] Cal Teach, University of California, Berkeley, California 94720, USA

*Abstract.* We introduce a representation of energy, the Energy Tracking Diagram, that explicitly represents energy as conserved, flowing among objects, and accumulating in objects (or fields). These features of an energy model promote detailed tracking of energy transfers and transformations in complex real-world scenarios. Learners who use Energy Tracking Diagrams are supported in identifying specific processes of energy transfer and transformation (such as mechanical work, thermal conduction, and metabolism) and thus in recognizing the mechanisms for and constraints on these processes. Energy Tracking Diagrams also support reasoning about the location of potential energy, quantifying relative amounts of energy that are involved in distinct processes, accounting for energy that seems "lost," and disambiguating flows of energy and flows of matter. We illustrate how Energy Tracking Diagrams may be used for assessment of energy conservation, tracking, and transfer and transformation processes.

## I. Introduction

In teaching about energy, we want students to learn that energy cannot be created or destroyed, but only moves from one place to another place: between objects, fields, or systems. We want them to describe changes of energy in a system in terms of energy flows into, out of, and within that system – in other words, to *track* energy as it transfers and transforms in complex natural and human-designed systems [1]. We want students to identify specific mechanisms by which energy is transferred among and transformed within objects, such as mechanical work and incandescence. We hope for learners to be able to optimize systems to maximize some energy transfers and transformations and minimize others, subject to constraints based on 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 describe a set of energy representations – Energy Theater, Energy Cubes, and Energy Tracking Diagrams – that serve these learning goals: that explicitly represent energy as conserved, flowing among objects, and accumulating in objects. These features of an energy model promote detailed tracking of energy transfers and transformations in complex real-world scenarios. We situate these representations in the context of other representations of energy (such as bar charts and pie charts), and compare the affordances of each one for meeting the goals delineated above. In one of our representations, Energy Tracking Diagrams, learners not only conserve and track energy as it transfers and transforms, but also identify specific processes of energy transfer and transformation (such as mechanical work, thermal conduction, and metabolism). Energy Tracking Diagrams thus 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, accounting for energy that seems "lost," and disambiguating flows of energy and flows of matter. They may also provide opportunities to assess learner understanding of energy conservation, tracking, and transfer and transformation processes.

## II. Comparing energy representations

We first critique classic representations of energy, including bar charts, pie charts, and Sankey diagrams, for their limited support of the learning goals of energy conservation and tracking.[1] We next describe dynamic, embodied representations developed specifically to support energy conservation and tracking: Energy Theater and Energy Cubes. Energy Tracking Diagrams, a static, graphic representation that supports these same learning goals, are introduced in Section III.

### *A. Bar charts*

A bar chart, generally speaking, is a representation in which data values are signified by rectangles. Different rectangles indicate different categories of data, and the height (or length) of a rectangle indicates the quantity of data in that category. In energy bar charts, the categories are normally forms of energy (e.g., kinetic, potential); the height of each bar tells the amount of energy that has that form. Some energy bar charts also have a bar indicating the total amount of energy in the represented system; the heights of all the other bars must then sum to the height of the total-energy bar [3]. Energy conservation is indicated by constant height of the total-energy bar during processes that change the heights of the other bars. Animated bar charts can emphasize energy conservation visually by displaying a constant total-energy bar in the presence of dynamically changing bars for individual forms of energy. A particular advantage of bar charts is that they can represent negative energies, which is difficult or impossible in some other representations [4, 5].

A common use of energy bar charts in K-12 classrooms combines a pair of bar charts, representing the initial and final state of the system, with a circle representing the system of interest; energy is shown entering or leaving the system as appropriate. This diagram is called an "LOL chart" because of the shapes formed by the axes and the "system circle" of the three-part diagram. Figure 1 shows an LOL diagram for a cup of coffee that heats the environment.

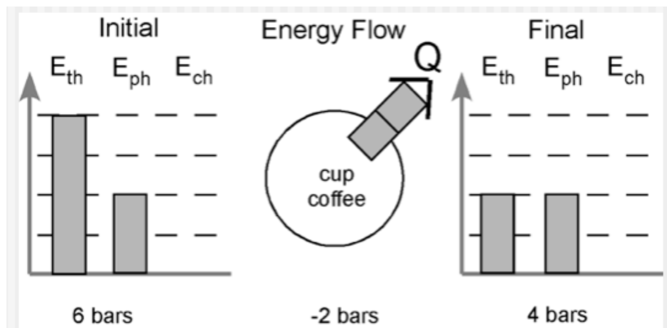


Figure 1. LOL chart for a cup of coffee that heats the environment. The diagram consists of two energy bar charts (initial and final) and an energy flow diagram for the cup-coffee system. $E_{th}$, $E_{ph}$, and $E_{ch}$ reprsent thermal, phase, and chemical energy, respectively; $Q$ represents heat.

As a representational medium, bar charts foreground the idea that there are different categories of energy, thus supporting understanding of forms and transformation of energy. The main task of a user who engages with a bar chart is to determine the relative heights of the bars corresponding to different categories, i.e., the relative amounts of energy that are in different forms at different times. Bar charts are consistent with conservation of energy in that they represent energy as a kind of stuff; this stuff comes in stacks, like towers of books, and is located "in" specific forms (individual bars) as though the forms were containers. These specific forms of energy are themselves "in" a system of objects, as though the system was a super-container. LOL charts additionally show energy traversing the boundary of a system ("going into" or "coming out of" it) in the form of stacked items entering or leaving the "O." Bar charts do not facilitate the representation of energy transfer or flow among objects because they do not depict energy as co-located with specific objects or otherwise configured in space. Thus, they do not support the local tracking of energy transfers and transformations among objects or fields.

### *B. Pie charts*

A pie chart is a circular chart divided into sectors; the size of the sector is proportional to the quantity it represents. Pie charts are generally similar to bar charts in that they indicate the relative amounts of data that are in distinct categories, which, in the case of energy pie charts, are again forms of energy. However, a pie chart communicates distinctly that there is a total amount of energy (the whole "pie"), which is divided into parts (forms). The size of each sector tells the proportion of energy that is in that form. Energy conservation within a system is indicated by a constant-size pie under transformations of its component pieces [4]. As with bar charts, energy in pie charts is not represented as moving among objects or fields.

### C. *Sankey diagrams*

A Sankey diagram is a flow diagram in which flow of a quantity is represented with arrows or pipes. Flow is shown as proceeding from a set of sources (typically arrayed in a column on the left) to a set of destinations (in a column on the right). The amount of energy in a source or destination is represented by the size of each, and the amount of flow is represented by the width of the pipe connecting a source to a destination. Portions of the flow may branch and recombine in the middle of the diagram, representing intermediate processes or categorizations. Figure 2 illustrates a Sankey diagram of energy use in the United States in 2010 [6]. Though Sankey diagrams are difficult to construct by hand, they are common in sociopolitical discussions of energy sources and usage.

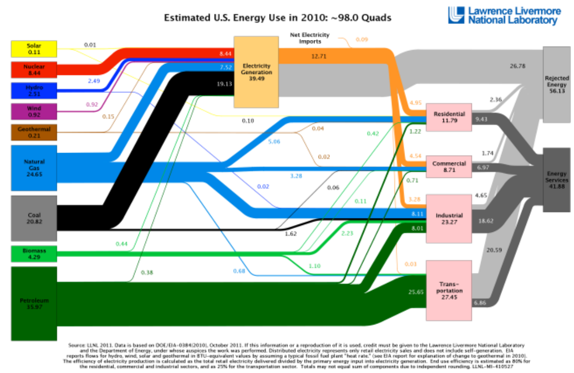


Figure 2. Sankey energy diagram of energy use in the United States in 2010.

Sankey diagrams have some of the same advantages as bar charts and pie charts in that they display the relative proportions of energy in different categories. Additionally, they show energy as having sources and destinations, thus supporting conservation and tracking [7, 8]. In Figure 2, the sources are means of supplying energy to human infrastructure, such as natural gas, coal, and petroleum, and the destinations are the infrastructure "consumers" that require energy to function, such as residential and transportation. In Figure 2, pipes retain the color of their source, suggesting that the pipes represent *energy that was generated by a certain means.* This categorization is different than in introductory university physics, where it is more typical to categorize energy instantaneously by its form than historically by its source.

### D. *Energy Theater and Energy Cubes*[2]

In professional development courses for teachers, we use an embodied representation of energy called Energy Theater [9, 10]. In Energy Theater, each participant identifies as a unit of energy that has one and only one form at any given time. Groups of teachers work together to represent the energy transfers and transformations in a specific physical scenario (e.g., a refrigerator cooling food or a light bulb glowing steadily). Participants choose which forms of energy and which objects in the scenario will be represented. Objects in the scenario correspond to regions on the floor, indicated by circles of rope. As energy moves and changes form in the scenario, participants move to different locations on the floor and change their represented form. The rules of Energy Theater are:

- Each person is a unit of energy in the scenario.
- Regions on the floor correspond to objects in the scenario.
- Each person has one form of energy at a time.
- Each person indicates his or her form of energy in some way, often with a hand sign.
- People move from one region to another as energy is transferred, and change hand sign as energy changes form.

- The number of people in a region or making a particular hand sign corresponds to the quantity of energy in a certain object or of a particular form, respectively.

Figure 3 shows a group of teachers negotiating an Energy Theater representation of a person pushing a box across a floor at constant speed. In this scenario, chemical energy in the hand transforms into thermal and kinetic energy in the hand as it moves and warms. Some kinetic energy transfers from the hand to the box, which moves. That kinetic energy is then transformed into thermal energy in the box and transferred to thermal energy in the floor as the box and floor warm from rubbing. Since the speed of the box is constant, kinetic energy transfers into the box from the hand at the same rate that it is reduced in the box via transformation to thermal energy and transfer to the environment.

Figure 3. Energy Theater representation of a hand pushing a box across a floor at constant speed.

Energy Theater represents energy as being conserved, localized, and changing form; it explicitly shows energy as flowing among objects, and accumulating in objects[3]; and it is a dynamic representation, able to show processes as they unfold as well as ''snapshots'' of energy at specific instants. These are the features of an energy model that promote detailed tracking of energy transfers and transformations in complex real-world scenarios [9, 10]. Teachers work together to negotiate this representation of the energy dynamics in a particular scenario with an end goal of enacting the representation in a final performance for their peers, who critically review the performance according to its representation of the energy transfers and transformations in the scenario.

For teachers who have become comfortable with Energy Theater, we offer a second representational activity called Energy Cubes (Figure 4). This representation is similar to the Energy Theater representation except that units of energy are represented by small cubes that move among object-areas marked on a white board or sheet of paper.[4] Different sides of the cubes are marked to signify different forms of energy. As energy transfers and transforms, learners move and flip the cubes on a whiteboard. The Energy Cubes representation is similar to Feynman's description of energy as a child's set of blocks [11] but with added features: the location of the cube shows the location of the energy and each side of the cube shows a different form of energy.


Figure 4. Energy Cubes representation of a hand lifting a box vertically.

A snapshot of Energy Theater or Energy Cubes illustrates the energy located in each object at the instant of the snapshot, consistent with understanding energy as a state function. Energy is associated with each object based on perceptible indicators that specify the state of that object. An Energy Theater snapshot may also include energy units in transit between objects. Such energy-in-transit is ontologically different than the energy contained in objects: over a time interval, it comprises *processes* of energy transfer. Heating or performing work[5] are processes that imply a choice of time interval – a choice that defines a specified initial state, final state, and connecting story.

In physics, an arbitrarily defined set of objects can comprise the system of interest. In Energy Theater, learners decide which objects are of relevance to particular energy processes, typically including all objects that play whatever the learners judge to be a significant role in the processes. The *system*, therefore, is made up of all interacting objects and is by construction energetically isolated (no energy comes in or out during the time evolution of the system).[6]

A *scenario* is an "energy story" involving the objects comprising the system that has a predetermined time development. Energy Theater and Energy Cubes represent the scenario, including not only the objects, but also the processes by which energy transfers and transforms in the specified time interval. Energy Theater and Energy Cubes do not represent causal agents (forces, temperature gradients, pressure differences, electric potential differences). Coordination of the energy story with the story of these causal agents occurs during the negotiation among the participants.

In our professional development courses, teachers who use these representations consistently produce in-depth analyses of energy scenarios and communicate these analyses in detail to instructors, peers, and researchers [10]. Some of these teachers choose to use Energy Theater and Energy Cubes in their own physics teaching and report that they are appropriate and valuable for use with secondary students [12]. However, these representations may take too much space and time to be practical in university and college physics courses. Their dynamic nature also makes them difficult to assess.

## III. Energy Tracking Diagrams

Partly because Energy Theater and Energy Cubes are dynamic representations of energy, they are ephemeral. An abstract symbolic system for energy can and should include a static component as well, one that can be easily recorded and shared. Energy Tracking Diagrams are a written representation derived from Energy Theater and Energy Cubes. In fact, the diagrams defined here are a formalization of diagrams that teachers in our professional development courses *invented* when invited to make visual representations of Energy Theater [9]. Energy Tracking Diagrams gradually became more standardized in iterations of our courses, and now are formally introduced after teachers have engaged with Energy Theater and Energy Cubes. We imagine, however, that Energy Tracking Diagrams could stand on their own as an independent representation. The rules of an Energy Tracking Diagram are as follows:

- 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 by which a transfer or transformation occurs (e.g., contact force, 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.[7])
- Relative amounts of energy may be represented by adding coefficients to the letters that represent units of energy. (Figure 8 is an example of an Energy Tracking Diagram with coefficients; the other examples below do not include them.)

Like Energy Theater and Energy Cubes, 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 following examples of Energy Tracking Diagrams for various scenarios show how they support learners in identifying transfer and transformation processes (Sec. A), locating potential energy (Sec. B), quantifying relative amounts of energy that are involved in distinct processes (Sec. C), accounting for energy that seems "lost" (Sec. D), and disambiguating flows of energy and flows of matter (Sec. E).

*A. Indicating processes of energy transfer and transformation*

Figure 5 is an Energy Tracking Diagram for a hand compressing a spring at constant speed [13]. In this scenario, chemical energy in the hand transforms into kinetic energy (the hand moves), which transfers to the spring through mechanical work. That kinetic energy is then transformed into elastic energy and thermal energy as the spring compresses and warms. The hand also warms as it moves.[8] 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. (Figure 5 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 hand to the environment via conduction.)

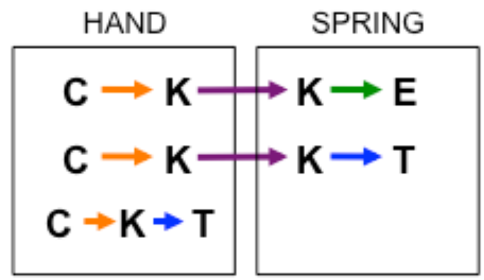


Figure 5. Energy Tracking Diagram for a hand compressing a spring at constant speed. C, K, T, and E represent chemical, kinetic, thermal, and elastic energy, respectively. Orange, purple, green, and blue arrows represent metabolism, mechanical work, elastic compression, and dissipation, respectively.

Constructing Energy Tracking Diagrams includes recognizing how many different tracks are needed to represent the energy processes in the scenario. The spring compression scenario increases elastic energy in the spring, thermal energy in the spring, and thermal energy in the hand. Thus, 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 hand.

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 hand transferring directly to the box as kinetic energy, she might then be unable to label the corresponding arrow, recognizing 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" [14].

Commonly reported difficulties in energy instruction include failure to distinguish work from energy [15, 16] and heat from thermal energy [17-21]. Energy Tracking Diagrams clearly distinguish these quantities with different kinds of symbols: in each case, the energy is represented by a letter, and the process of energy transfer (work or heat) is represented by an arrow. Energy Tracking Diagrams thus have the potential to assist learners in coming to understand these distinctions, though we have not yet studied empirically whether or to what degree this is the case.

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. For example, Figure 5 illustrates the internal (thermal and elastic) energy of the spring increasing by an amount equal to the mechanical work done on the spring (purple arrows).

*B. Locating potential energy*

A possible concern about Energy Theater, Energy Cubes, and Energy Tracking Diagrams is that these representations model energy as being located in objects. This description of energy can be a concern 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 6 is an Energy Tracking Diagram for a pair of attracting magnets that start out in contact; magnet 2 is fixed in place as magnet 1 is pulled away by a hand. This process involves exerting a force over a distance, which transfers kinetic energy (K) from the hand to magnet 1 through mechanical work (purple arrow in Figure 6). The hand moves magnet 1 some distance away and then stops. If kinetic energy is not to accumulate in magnet 1, it must transform into some other kind of energy. In Figure 6, that form of energy is designated as "magnetic energy" (M) and is located in magnet 1. In this model, there is magnetic energy in 1 that can turn into kinetic energy in 1, which is consistent with what we know happens if we release magnet 1: it acquires kinetic energy, flying back toward magnet 2. Gravitational energy is often modeled similarly in introductory physics, by substituting the earth for magnet 2 and an object that we lift away from the earth for magnet 1; objects that have been lifted are said to "have" gravitational energy. We term the process by which K transforms to M "moving relative to a magnet" (green arrow in Figure 6) as we would call the analogous process by which K transforms to G (gravitational energy) "moving vertically."[9] Thus far, the analysis does not require magnetic (or gravitational) energy to be located anywhere but inside the "lifted" object.

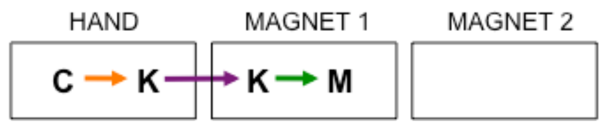


Figure 6. Energy Tracking Diagram for a pair of attracting magnets when magnet 1 is pulled away from magnet 2. C, K, and M represent chemical, kinetic, and magnetic energy. Orange, purple, and green arrows represent metabolism, mechanical work, and motion relative to a magnet. In this model, magnetic energy is located in a single magnet.

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 Figure 6, which shows no energy in 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 Figure 6 is therefore insufficient to account for these simple known phenomena.

Experimentally, the energy that the hand gives to magnet 1 is available to either magnet 1 or magnet 2. We may amend the representation to accommodate this fact by having the kinetic energy in magnet 1 transform into magnetic energy located in a zone between 1 and 2, with the understanding that energy in that zone is accessible to either of the two interacting objects. Figure 7 is an Energy Tracking Diagram using this convention for the scenario of first pulling 1 away from 2 with 2 fixed (upper diagram), then fixing 1 and releasing 2 (lower diagram).[10]

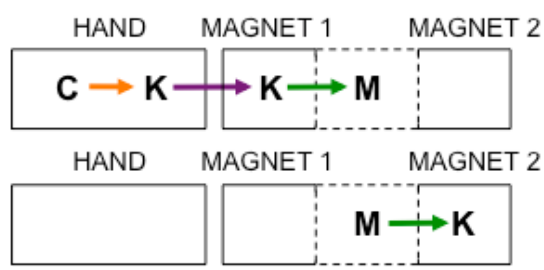


Figure 7. Energy Tracking Diagram for a pair of attracting magnets when magnet 1 is pulled away from magnet 2, (upper diagram), then magnet 2 is released and moves toward magnet 1 (lower diagram). In this model, magnetic energy is located in a zone accessible to either of the two magnets.

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 change its potential energy in the course of the scenario. If the scenario is such that only one object of the pair will be considered to change its potential energy (as is often the case for small masses near the surface of the earth), the potential energy may be represented as being located in the object without logical contradiction within the specific analysis.[11]

### *C. Quantifying energy*

Figure 8 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. (The string connecting the two masses is not shown in Figure 8, but could be included as an intermediary.) 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 movement and mechanical work.

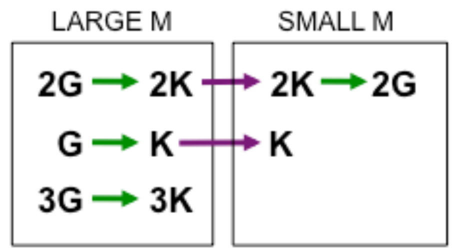


Figure 8. Energy Tracking Diagram for an Atwood's machine of unequal masses suspended over an ideal pulley. G and K represent gravitational and kinetic energy. Green and purple arrows represent vertical movement and mechanical work.

Figure 8 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 Figure 8. 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 $c = 3$.

This scenario illustrates a constraint on energy dynamics that goes beyond the particular scenario: 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.

### *D. Identifying missing energy*

Figure 9 is an Energy Tracking Diagram for a scenario in which a person first raises a ball from waist level to eye level (upper diagram), then lowers it (lower diagram). C, K, G, and T represent chemical, kinetic, gravitational, and thermal energy; orange, purple, green, and blue arrows represent metabolism, mechanical work, vertical movement, and dissipation. On the way up (upper diagram), chemical energy in the person transforms into kinetic energy and then gravitational energy in the person (part of the person's body moves vertically). Some kinetic energy transfers from the person to the ball through mechanical work. That kinetic energy is then transformed into gravitational energy in the ball as the ball rises. The person also warms as he moves. On the way down (lower diagram), gravitational energy in the ball

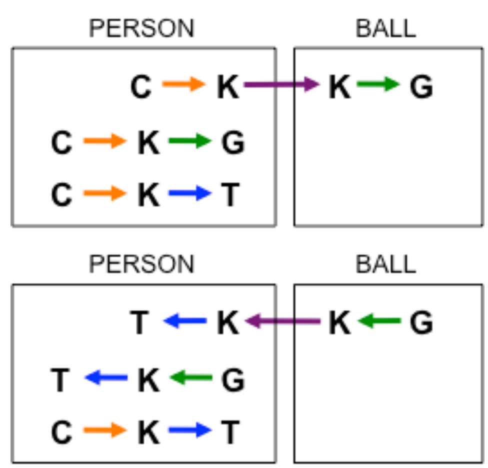


Figure 9. Energy Tracking Diagram for a person raising a bowling ball (upper diagram) and then lowering it (lower diagram). C, K, G, and T represent chemical, kinetic, gravitational, and thermal energy. Orange, purple, green, and blue arrows represent metabolism, mechanical work, vertical movement, and dissipation.

transforms to kinetic energy in the ball as it descends; the person's resistance (work) transfers that kinetic energy from the ball to the hand. Once in the hand, the kinetic energy is transformed to thermal energy by dissipative processes; the hand maintains constant speed and, in the process, warms. In a parallel process, gravitational energy of the person transforms to kinetic energy and then thermal energy as part of the person's body lowers at constant speed. These processes are almost reversals of the processes to raise the ball, but whereas the input to the raising processes was chemical energy, the output is thermal energy. The person warms as he moves (chemical energy transforms to kinetic and then thermal) in both cases.

This scenario is counterintuitive for many learners, who find it difficult to accept that the energy associated with the height and motion of a large, heavy object could all transform into a barely-perceptible quantity of thermal energy in the body [22, 23]. Since the thermal energy in this case is minimally perceptible, some learners argue that thermal energy is not present or that thermal energy cannot account for all of the energy at the end of the process. Others reluctantly acquiesce to the idea that thermal energy must be present, but do not construct a logical explanation to account for it. Energy Tracking Diagrams help learners stay committed to the conservation of energy as they try to figure out where the gravitational energy goes as the ball is lowered.

*E. Disambiguating energy and matter*

In an incandescent bulb glowing steadily (Figure 10), electrical energy (E) flows through electrical conduction (green arrow) from the base of the light bulb into the filament, where some 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).[12] Thus, while the electric current flows in a closed loop around the circuit, some of the energy flows out into the environment.

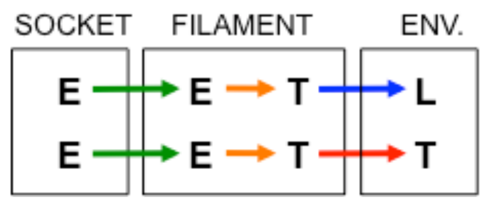


Figure 10. Energy Tracking Diagram for an incandescent bulb glowing steadily. E, T. and L represent electrical, thermal, and light energy. Green, orange, blue, and red arrows represent electrical conduction, Joule heating, incandescence, and thermal conduction.

Some learners are initially tempted to represent energy as flowing around a circuit [10]. While a correct Energy Tracking Diagram should not show electron current (any more than a correct free-body diagram should show the velocity of an object), the fact that current is conserved in a light bulb 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. However, 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 [24-26]. Our instructional perspective on these questions is that Energy Theater and Energy Tracking Diagrams are an excellent context for disciplined model-based reasoning, including disambiguating energy flow and matter flow, as well as theorizing mechanisms of energy transformation [10].

## IV. Assessing energy learning with Energy Tracking Diagrams

Energy Tracking Diagrams can also provide a means to assess learners' use of energy conservation and tracking and 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.

As an analogy, instructors and researchers often use free body diagrams to assess learners' understanding of forces. For example, consider the scenario in which a block slides down an inclined plane at constant speed, and imagine that a student provides the free body diagrams shown in Figure 11 before and after instruction, respectively. After instruction, the 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 pre-assessment response, 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.

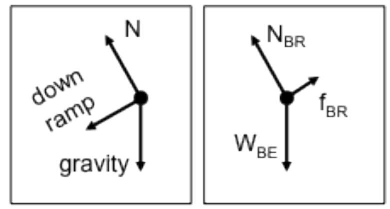

Figure 11. Hypothetical free body diagrams for a block sliding down a ramp, before and after instruction.

Our project has used written assessments that draw on Energy Tracking Diagrams to assess the extent to which our professional development courses advance our learning goals of conservation, tracking, and identification of processes of energy transfer and transformation among in-service K-12 teachers. In 2013, fifteen 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 meter stick),[13] and after instruction, a steam-turbine power plant.[14] 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 meter stick, 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…)."

One teacher offered the pre-instruction (ring slider) response shown in Figure 12. 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.

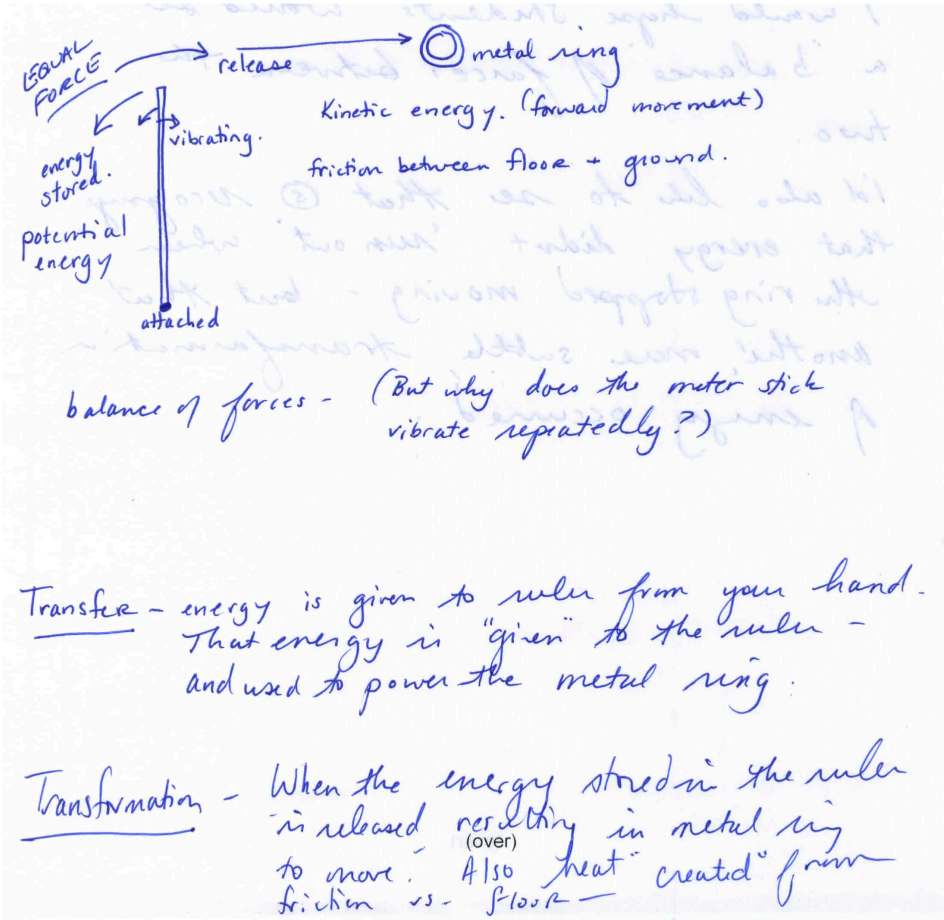


Figure 12. Energy assessment before instruction, in which the respondent analyzes a ring slider scenario.

The same teacher offers the post-instruction (power plant) response shown in Figure 13. 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.

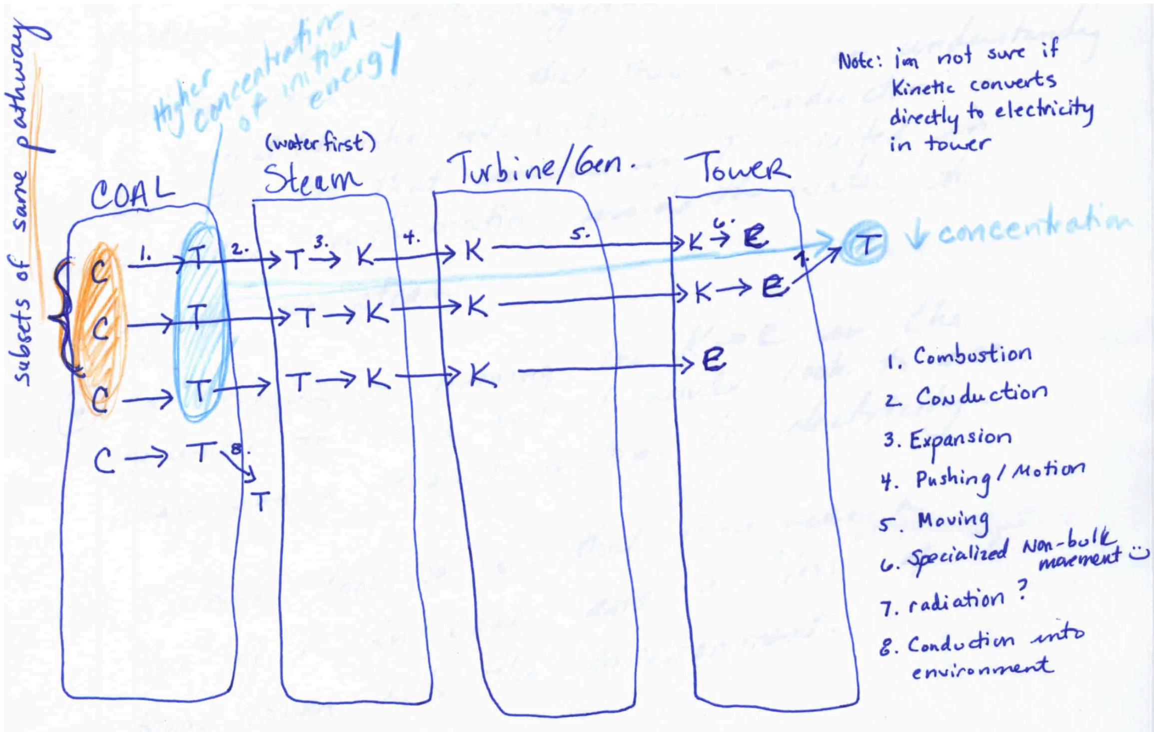


Figure 13. Energy assessment after instruction, in which the respondent analyzes a power plant scenario.

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. We suggest that 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.

## V. 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 representations contribute to the representational repertoire for energy in physical systems, with specific advantages over other representations for tracking energy transfers and transformations.

## Acknowledgments

We gratefully acknowledge all the elementary and secondary teachers who have participated in Energy Project courses for their generosity in making their reasoning accessible to the Energy Project team. We are grateful to Seattle Pacific University's Physics Education Research Group, including Kara Gray and S. B. McKagan, for substantive discussions of this work. This material is based upon work supported by the National Science Foundation under Grants No. 0822342 and 1222732.

## References


1. National Research Council, *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. 2012, Washington, DC: National Academies Press.
2. Scherr, R.E., et al., *Representing energy. I. Representing a substance ontology for energy.* Physical Review - Special Topics: Physics Education Research, 2012. **8**(2): p. 020114 1-11.
3. van Heuvelen, A. and X. Zou, *Multiple representations of work-energy processes.* American Journal of Physics, 2001. **69**(2): p. 184-194.
4. Brewe, E., *Energy as a substancelike quantity that flows: Theoretical considerations and pedagogical consequences.* Physical Review - Special Topics: Physics Education Research, 2011. **7**: p. 020106.
5. Dreyfus, B.W., et al., *Ontological metaphors for negative energy in an interdisciplinary context.* Physical Review - Special Topics: Physics Education Research, 2014 (under review).
6. Lawrence Livermore National Laboratory and Department of Energy, *Estimated U. S. energy use in 2010*. 2012 [cited 2012 April 14]; Available from: https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2010/LLNLUSEnergy2010.png.
7. Swackhamer, G., *Cognitive resources for understanding energy.* 2005.
8. Goldberg, F., V. Otero, and S. Robinson, *Physics and Everyday Thinking*. 2008, Armonk, NY: It's about time, Inc.
9. Scherr, R.E., et al., *Representing energy. II. Energy tracking representations.* Physical Review - Special Topics: Physics Education Research, 2012. **8**(2): p. 020115 1-11.
10. Scherr, R.E., et al., *Negotiating energy dynamics through embodied action in a materially structured environment.* Physical Review - Special Topics: Physics Education Research, 2013. **9**(2): p. 020105 1-18.
11. Feynman, R.P., R.B. Leighton, and M. Sands, *The Feynman lectures on physics*. 1969, Reading, MA: Addison-Wesley.
12. Daane, A.R., L. Wells, and R.E. Scherr, *Energy Theater.* The Physics Teacher, 2014. **submitted**.
13. Daane, A.R., S. Vokos, and R.E. Scherr, *Conserving energy in physics and society: Creating an integrated model of energy and the second law of thermodynamics* in *2012 Physics Education Research Conference*, P. Engelhardt, A.D. Churukian, and N.S. Rebello, Editors. 2013, AIP Conference Proceedings: Philadelphia, PA. p. 114-117.
14. Atkins, L.J. and B.W. Frank, *Examining the products of responsive inquiry*, in *Responsive Teaching in Science*, A.D. Robertson, R.E. Scherr, and D. Hammer, Editors. 2014: in preparation.
15. Lindsey, B.A., P.R.L. Heron, and P.S. Shaffer, *Student ability to apply the concepts of work and energy to extended systems.* American Journal of Physics, 2012. **77**(999): p. 2009.
16. Lindsey, B.A., P.R.L. Heron, and P.S. Shaffer, *Student understanding of energy: Difficulties related to systems.* American Journal of Physics, 2012. **80**(2): p. 154-163.
17. Erickson, G., *Children's conceptions of heat and temperature.* Science Education, 1979. **63**(2): p. 221-230.
18. Harrison, A.G., D.J. Grayson, and D.F. Treagust, *Investigating a grade 11 student's evolving conceptions of heat and temperature.* Journal of Research in Science Teaching, 1999. **36**(1): p. 55-87.
19. Jasien, P.G. and G.E. Oberem, *Understanding of elementary concepts in heat and temperature among college students and K-12 teachers.* Journal of Chemical Education, 2002. **79**(7): p. 889-895.
20. Loverude, M.E., C.H. Kautz, and P.R.L. Heron, *Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas.* American Journal of Physics, 2002. **70**(2): p. 137.

21. Magnusson, S., et al., *The relationship between teacher content and pedagogical content knowledge and student content knowledge of heat energy and temperature*, in *Annual Meeting of the National Association for Research in Science Teaching*. 1992: Boston, MA.
22. Seeley, L., S. Vokos, and J. Minstrell. *Constructing a sustainable foundation for thinking and learning about energy in the 21st century*. in *Energy Summit: Developing a framework for the teaching and learning of energy*. 2012. Lansing, Michigan.
23. Daane, A.R., S.B. McKagan, and R.E. Scherr, *Conservation and tracking of thermal energy in dissipative processes.* Physical Review - Special Topics: Physics Education Research, 2014, in preparation.
24. Davis, B.S. and L. Kaplan, *Poynting vector flow in a circular circuit.* American Journal of Physics, 2011. **79**(11).
25. Chabay, R. and B. Sherwood, *Restructuring the introductory electricity and magnetism course.* American Journal of Physics, 2006. **74**(4).
26. Galili, I. and E. Goihbarg, *Energy transfer in electrical circuits: A qualitative account.* American Journal of Physics, 2005. **73**(2).


---

[1] Some of the material in this section has appeared previously in Ref. 2.
[2] Some of the material in this section and in Section III has appeared in Ref. 9.
[3] Section III.B discusses how learners may discern the appropriate location for potential energy in this kind of representation.
[4] Small wood or acrylic cubes may be obtained from craft supply stores. White board is sold inexpensively at home improvement stores as material for lining shower walls; many such stores will cut white board to custom sizes.
[5] We use the term "work" to refer to the mechanical transfer of energy from one object to another (i.e., a transfer by means of a force), including objects that may both be part of the same system.
[6] Energy Theater is 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 Theater becomes difficult to interpret.
[7] Learners may elect to indicate time ordering by numbering or other means.
[8] Though a physics analysis tends to prioritize the mechanical conversion of kinetic energy into another form of mechanical energy (in this case, the elastic energy in the spring), the metabolic production of thermal energy is often the energetically dominant process in scenarios involving living organisms.
[9] We do not describe either of these processes ("moving relative to a magnet" or "moving vertically") as "work." Work is 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 Figure 7, in which the process in question transfers energy from an object to a field, the term "work" is not 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).
[10] 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.
[11] 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.

[12] 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.

[13] Teachers were told, "A meter stick 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.

[14] 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."