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# Modeling Energy Dynamics with the Energy-Interaction Diagram

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Energy is an important cross-cutting concept in all science disciplines, and energy conservation is widely regarded as one of the most important principles in physics.[1–3] Over the years, numerous graphical representations have been proposed that allow learners of physics to visualize energy states and dynamics in a particular situation.[3–7] Each diagram highlights different aspects of energy and therefore may represent different conceptualizations of energy. Bar charts,[8] for example, foreground the idea of multiple *categories* of energy to account for the distribution of energy in a system across those energy types. Similarly, pie charts[5] highlight *relative distribution* of energy among different energy types. While bar charts are able to represent negative energy, pie charts emphasize that there is a certain, total amount of energy available that is distributed over different types. Various energy-tracking diagrams (e.g., PET energy source-receiver diagrams[9], Energy Tracking Diagrams[3]) foreground the *localization* of energy along a chain of energy transfer processes and within the involved objects.[10]

In this paper, we present the Energy-Interaction Diagram, a representation for energy dynamics in a physical system that highlights *energy conservation* and guides users to *derive a mathematical model* for energy changes in a system during a process of interest. The Energy-Interaction Diagram was originally developed by the late Wendell Potter (formerly of the University of California, Davis) for use in the Collaborative Learning through Active Sense-making in Physics (CLASP) curriculum.[11] In our adaptation of the CLASP curriculum at San José State University (SJSU) over several semesters, we have formalized some of the ways the diagram has been used in practice at UC Davis and at SJSU. Our intent here is to provide the reader with the necessary resources to adopt and/or adapt Energy-Interaction Diagrams for instructional use beyond the CLASP curriculum because we think that they are powerful representations for modeling energy dynamics and versatile tools for answering many interesting questions about physical phenomena.

A cornerstone of CLASP is its focus on the scientific practice of *modeling:* creating specific models for the energy dynamics in a particular physical system. For the original developers, the term *model* refers to "the collection of ideas and the relationships among those ideas that, when grouped together, prove useful to [the] students as they make sense of, develop explanations of, and make predictions of phenomena relevant to their needs."[11] We adopt this view of models that takes them as the malleable, ever-changing objects of scientific activity that scientists create and modify to understand the physical world.

When engaging in the process of modeling a physical system in CLASP, students have to make a number of conscious decisions: They have to (1) choose a physical system, (2) choose an appropriate time interval to inspect the process of interest, (3) identify changes in certain properties of the system throughout the process, (4) recognize whether any interactions occur between a system and its environment, or (5) between objects *within* system boundaries. The Energy-Interaction Diagram provides a productive scaffold for students to make those decisions when modeling the energetics of a system and to derive a quantitative model for the energy dynamics in a particular physical system that undergoes a specific physical process.

## I. ENERGY STORES AND TRANSFERS

With Jewett,[2] we find it useful to think of energy as a substance-like quantity[1,12] that can be contained in various *stores*, which are distinguished by their respective observable manifestations (e.g., energy in the "kinetic energy" store is manifested in the motion of an object; energy in the "potential energy" store is manifested in the position of an object relative to another), and transferred from one store to another within a particular physical system (i.e., what is commonly referred to as energy *transformation*) or across system boundaries (i.e., what is commonly referred to as energy *transfer*, with transfer mechanisms like *work* and *heat*). Note, that this understanding of an *energy store* differs from a view of potential energy forms as forms of stored, or static energy that can be readily converted to other forms[13]. Instead, all energy forms are seen as energy stores, including kinetic energy forms, which are associated with motion. A list of energy stores commonly used in CLASP can be seen in Fig. 1

To understand the energy dynamics of any given process, we only need to consider those energy stores which experience a change in the amount of energy contained in them. It can be difficult to determine exactly the amount of energy contained in a system at any given moment, so it is often impossible to know the absolute amounts of energy in each store. However, energy transfers between stores and across system boundaries are manifested in observable changes in the state of the physical system under scrutiny. Those observable (i.e., measurable) state changes then allow us to quantify the *changes* in the energy contained in a system.

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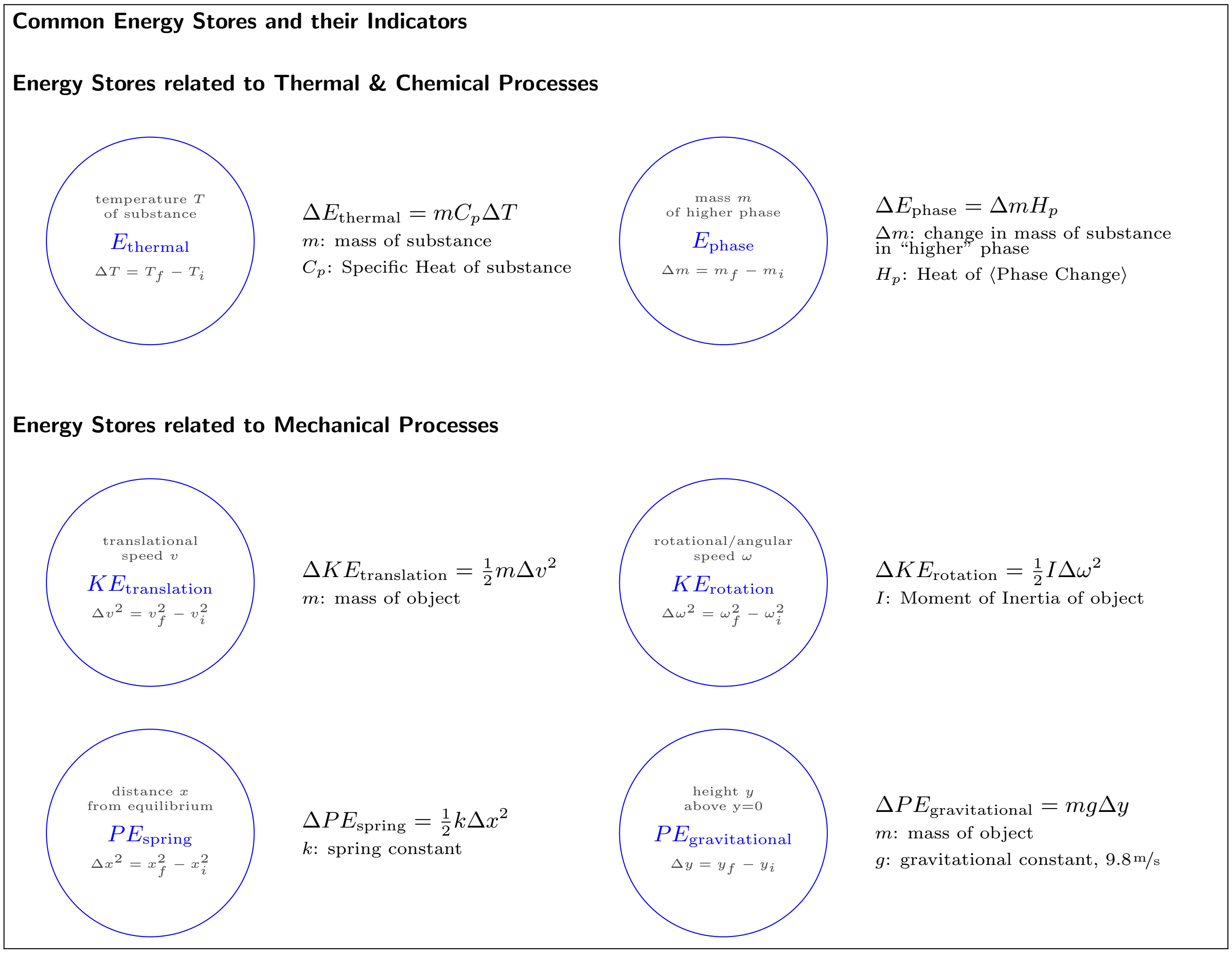



Figure 1. Common energy stores and their indicators, along with corresponding algebraic expressions.

A first step toward understanding the energy dynamics in a physical system is therefore to carefully observe changes in directly observable/measurable state variables of the system (e.g., mass, velocity, temperature, phase) during a given process of interest. Once these observable changes have been recorded, the corresponding energy stores (that undergo a change in the process) can be identified, and the changes in energy within each of these stores can be quantified using simple algebraic relationships between the measurable changes in state variables and the corresponding changes in stored energy. Following Jewett, we find it useful to categorize energy stores in the following way: kinetic (e.g., translational, rotational), potential (e.g., gravitational), and internal energy (e.g., thermal, phase) stores.

When the energy stores undergoing a change have been determined, energy transfers across system boundaries have to be identified, along with the possible mechanisms by which energy may cross the system boundary. Jewett identifies six common mechanisms for energy transfer across system boundaries: work, heat, matter transfer, mechanical waves, electromagnetic radiation, and electrical transmission.[2] For our purposes of a first-semester introductory physics class that discusses only thermal and simple mechanical phenomena, the two mechanisms *work done on the system by external forces* and *energy transferred as heat due to a temperature difference between the system and its surroundings* are sufficient.

Which energy stores (if any) undergo a change and whether a transfer of energy across system boundaries occurs – and what mechanisms are involved – depends on the particular time interval during which a given process is examined. The choice of a suitable time interval is therefore a crucial part of modeling the energy dynamics of a physical system of interest. In the following section, we provide specific examples to introduce the Energy-Interaction Diagram and to illustrate how the choice of time interval may change the particular model of the examined process.

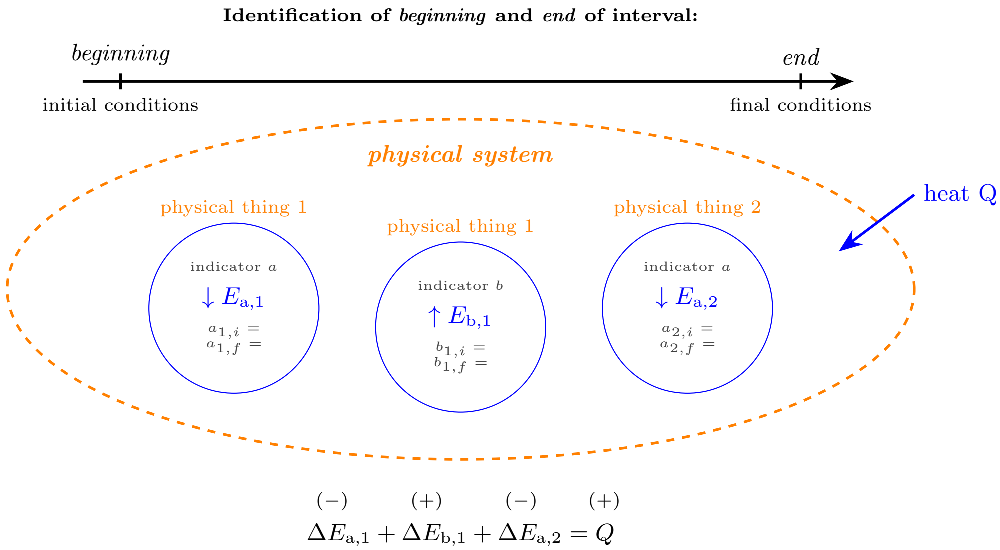



Figure 2. A generic Energy-Interaction Diagram to model a physical system (orange) of two objects, *physical thing 1* and *physical thing 2*, for a process during a specified time interval. Three energy (blue) *stores* and their associated *indicators* (black) undergo a change, and energy is added to the system as *heat Q*.

## II. THE ENERGY-INTERACTION DIAGRAM

Figure 2 shows a generic example of an Energy-Interaction Diagram. The time line at the top specifies the beginning and end points in time for the process under investigation and shows the initial and final states of the observable variables associated with energy stores that undergo a change during the process. The dashed elliptical line represents an *open* system boundary, through which energy can be transferred into the physical system, here in the form of heat Q. The physical system consists of the two objects *physical thing 1* and *physical thing 2*.

For both objects, the energy store $E_a$ changes, while store $E_b$ only undergoes a change for *physical thing 1*. Each of these energy stores is represented as a circle (often colloquially referred to as an "energy bubble") that lists the observable quantity (indicator) associated with this store, as well as the initial and final states of this indicator for the time interval in question. An arrow indicates whether the change is positive or negative. The changes in energy contained in the three energy stores are represented in the algebraic energy conservation equation at the bottom of the diagram with (+) and (−) signs indicating the direction of change for later reference.

If a physical system is isolated with respect to energy transfers from other physical systems, we call the system *closed*. The *total energy* of such a physical system must remain *constant* during the interaction or process under investigation. If system-internal interactions occur, the conservation of energy can be expressed in terms of changes within the energy stores of the physical system: The changes of the energies of *all energy stores* associated with the closed physical system in question must sum to zero.

During an interaction or process in which energy is added or removed from the physical system as heat or work, the changes in energy of all energy stores associated with this *open* physical system must sum to the net energy added (or removed) as heat and/or work. Equivalently, the change in the total energy of that physical system must equal the net energy added (or removed) as heat and/or work.

When using the Energy-Interaction Diagram to model a physical scenario, we first define the physical system and decide what time interval we wish to analyze. Then, we iteratively determine which energy stores are changing (by identifying indicators that undergo a change during the chosen time interval), whether they are increasing or decreasing, and if the system is open or closed. It is important to complete the pictorial part of the diagram first because this allows us to build a mathematical description of energy conservation for the situation at hand. Each energy store (or "bubble") typically represents a term in the equation, and the solid or dashed boundary around the system indicates whether the total changes sum to zero (closed) or another value (open). For an overview of the typical steps to create an Energy-Interaction Diagram, see Fig. 3.

### A. Example 1: Boiling water

One of the simplest scenarios we use to introduce the Energy-Interaction Diagram is the boiling of an amount of water. For example, we use the diagram to determine the amount of energy an electric kettle has to transfer to a cup of water to bring the water to a boil for a cup of hot tea. Estimating the mass of water to be 0.25kg and

**Steps involved in using the Energy-Interaction Diagram**

**Prior to writing anything down:**

1. Tell a story about what happened! Be sure you are clear about what the physical phenomenon or process is.

**Go back and forth through Steps 2-6 until your Energy-Interaction Diagram is complete:**

2. What is the boundary of the physical system you are modeling? What is inside and what is outside?
3. Is the physical system in your particular model open or closed? If open, what energy transfers are occurring (e.g., heat or work)?
4. What is the extent of the process or interaction? What determines the beginning and end?
5. What energy stores do you include in your diagram? Which indicators are changing?
6. What are the values of the indicators at the times corresponding to the beginning and end of the time interval you chose in step 4?

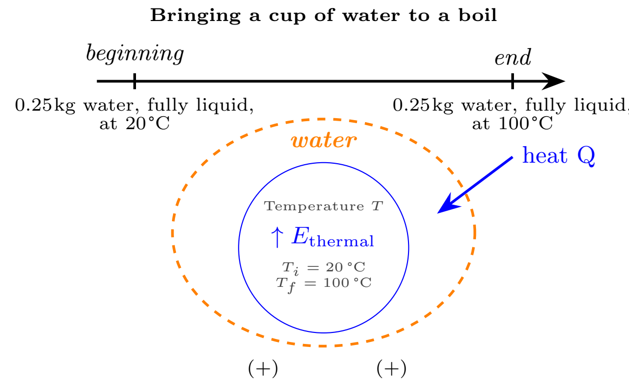
**Only after the diagram is complete, move on to Step 7:**

7. Write down an equation expressing energy conservation for your particular Energy-Interaction Diagram, in terms of the $\Delta E$'s and any $Q$ or $W$. Each term in your conservation of energy equation must correspond to an energy store in your diagram.

Figure 3. Steps involved in creating an Energy-Interaction Diagram. The order of steps depends on the particular situation being modeled and question being answered, so they are not necessarily carried out in the presented sequence.

assuming its initial temperature at 20°C room temperature, we can model the process until the water has just reached 100°C while still being completely liquid (which is an idealized scenario but gives us a lower bound for the amount of energy necessary to bring the water to a boil).

Figure 4 shows an Energy-Interaction Diagram for this simple process. The system is chosen to be the water. The changing indicator is temperature (the system does not undergo a phase change), so we only have to include the thermal energy store in our diagram. Energy is being added to this system in the form of heat. Substituting the algebraic expression for thermal energy and plugging in the values for mass, specific heat, and change in temperature finally allows us to calculate the amount of energy necessary to bring the water to a boil.




$$\Delta E_{\text{thermal}} = Q$$

$$mC_p\Delta T = Q$$

$$Q = 0.25\,\text{kg} \cdot 4.186\,{}^{\text{kJ}}/_{\text{kg }^\circ\text{C}} \cdot 80\,^\circ\text{C} = 84\,\text{kJ}$$

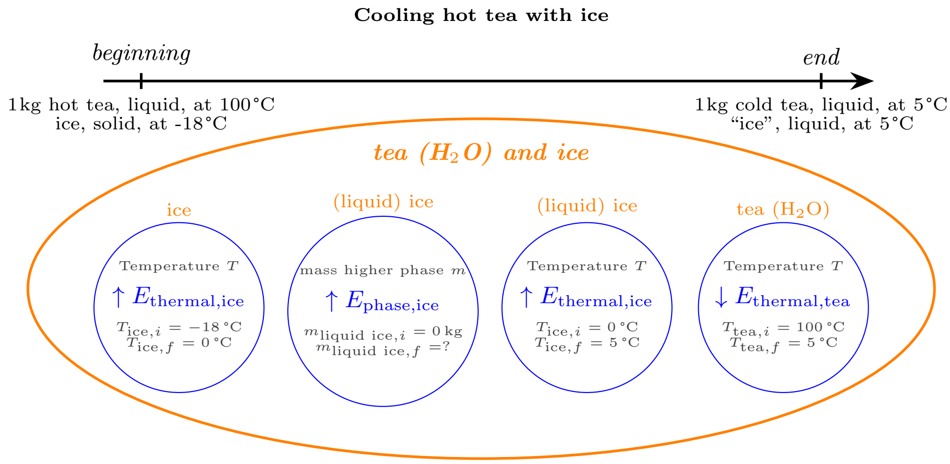
Figure 4. An Energy-Interaction Diagram to model the process of bringing a cup of water at room temperature to boiling temperature (without it actually starting to boil). Only one energy store (*thermal*) and its associated indicator (*temperature*) undergoes a change, and energy is added to the system as *heat* $Q$. Substituting the expression $mC_p\Delta T$ for $\Delta E_{\text{thermal}}$ allows for the calculation of the energy necessary for this process.

### B. Example 2: Making iced tea

In a slightly more complex scenario, we ask students to find out how much ice (completely solid at -18°C) they would have to add to a liter of freshly-brewed tea (completely liquid at 100°C) to cool the tea to a temperature of 5°C. To estimate a lower bound of how much ice would at least be necessary to cool the tea, we ask students to assume that tea and ice were placed in an insulated container and left alone for a while (over the course of the semester, we model the process of making suitable assumptions to determine reasonable estimates for desired quantities). Figure 5 shows an Energy-Interaction diagram for this scenario.

To model this process, we have to introduce a new energy store, *phase energy*. The indicator for phase energy is the *amount of the substance in the "higher phase."* The hierarchy of phases for this determination (from lowest to highest) is solid → liquid → gas. This hierarchy is chosen so that the signs of the algebraic expression are consistent and students do not need to keep track of and correct for sign changes in phase energy.

Another tricky bit in this scenario is the fact that the specific heat ($C_p$) for water has different values for different phases. Therefore, the algebraic expression for $\Delta E_{\text{thermal,ice}}$ has to be broken into two parts, one for the temperature change from -18°C to 0°C and one for the temperature change from 0°C to +5°C. We typically encourage students to include a fourth energy store ("bubble") in their Energy-Interaction diagram to remind themselves of this.




$$\overset{(+)}{\Delta E_{\text{thermal,ice},\leq 0}} + \overset{(+)}{\Delta E_{\text{phase,ice}}} + \overset{(+)}{\Delta E_{\text{thermal,ice},\geq 0}} + \overset{(-)}{\Delta E_{\text{thermal,tea}}} = 0$$

$$m_{\text{ice}} C_{p,H_2O(s)} \Delta T_{\text{ice},\leq 0} + \Delta m_{\text{ice in higher phase}} H_{p,\text{melting},H_2O} + m_{\text{ice}} C_{p,H_2O(l)} \Delta T_{\text{ice},\geq 0} + m_{\text{tea}} C_{p,H_2O(l)} \Delta T_{\text{tea}} = 0$$

Figure 5. Energy-Interaction Diagram to model the cooling of hot tea with ice. Three energy stores and their associated indicators undergo a change, the system is closed. Note that the process for $\Delta E_{\text{thermal,ice}}$ has to be broken up to model the energy change below 0°C and above 0°C because water has different specific heat values for solid vs. liquid phase. We model this with a fourth energy store "bubble" in the Energy-Interaction Diagram, breaking the temperature change up into the two intervals (1) from -18°C to 0°C and (2) from 0°C to +5°C. The indicator for phase energy $E_{\text{phase}}$ is the *amount of the substance in the "higher phase."* The hierarchy of phases for this determination is solid (lowest) → liquid → gas (highest).

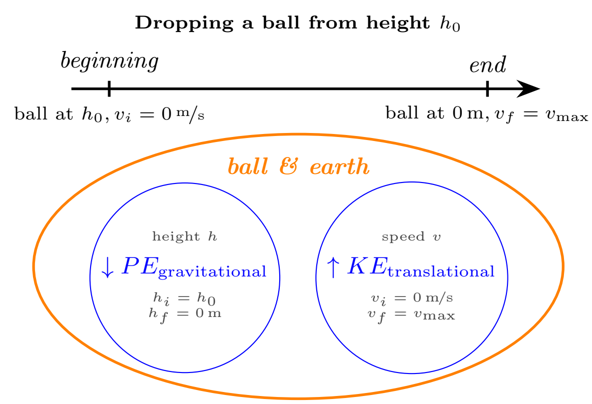
Once the algebraic expressions have been substituted for the different energy changes in the energy-conservation equation, students have to recognize that the mass of the ice that was initially added to the tea, $m_{\text{ice}}$ corresponds to the final mass of now liquid "ice," $m_{\text{liquid ice,f}}$. With this, they can determine the amount of ice necessary to cool the initially hot tea to a cold temperature of 5°C.

## C. Example 3: Dropping a ball

Energy-Interaction Diagrams are also useful to model and understand the energy dynamics in mechanical scenarios. For example, we can examine the case of a ball that is dropped from a specific height $h_0$. A common question one might ask is how fast the ball is just before it hits the ground. To find out, we choose the interval from just when the ball is released at height $h_0$ to just before it hits the ground (moving at maximum speed $v_f$ at height $h = 0\,\text{m}$).

Because we want to determine the maximum speed just before the ball interacts with the floor and stops, we assume that frictional effects are negligible. We also include the earth in our physical system to be able to include the gravitational potential energy store and assume that all interactions of the ball with the environment during the time interval in question can be ignored. Therefore, we can treat the physical system as closed.

Figure 6 shows an Energy-Interaction Diagram for this




$$\overset{(-)}{\Delta PE_{\text{gravitational}}} + \overset{(+)}{\Delta KE_{\text{translational}}} = 0$$

$$mg\Delta h + \tfrac{1}{2} m \Delta v^2 = 0$$

$$mg(0\,\text{m} - h_0) + \tfrac{1}{2} m (v_{\max}^2 - 0\,\text{m/s}) = 0$$

$$v_{\max} = \sqrt{2gh_0}$$

Figure 6. Energy-Interaction Diagram for a ball dropped from height $h_0$. The physical system contains both the ball and the earth. With this assumption and the assertion that frictional effects are negligible, the system does not interact with the environment and can therefore be modeled as closed. This means that all the energy lost from the gravitational potential energy store is transferred to the translational kinetic energy store, and therefore contributes to the ball reaching its maximum speed $v_{\max}$ at height 0m.

situation. With this model, we can answer the question for the final, maximum speed of the ball just before the ground brings it to a full stop.

## III. INTRODUCING ENERGY-INTERACTION DIAGRAMS TO STUDENTS

Unlike traditional physics courses, the CLASP curriculum starts the first semester (or quarter) with thermodynamics. We introduce Energy-Interaction Diagrams as the second graphical representation after Temperature-vs.-Energy Diagrams that display temperature and phase changes of single substances during an energy increase or decrease. As part of their lab manual, students receive "model sheets" that include figures 1-3. We ask students immediately to use complete Energy-Interaction Diagrams to model a variety of scenarios involving temperature and phase changes due to energy transfers within and across system boundaries (similar to the scenarios presented here).

In two weekly discussion lab sections (2 hr 20 min each), students work in small groups on upright whiteboards to familiarize themselves with and use the new representation. They receive individualized feedback from a lab instructor and/or learning assistant. While we initially hold students strictly accountable to the prescribed format and rules of the representation they may make slight changes to the representation later on, as long as the clarity of their representations does not suffer. For example, students may break up processes into several sub-processes and model those separately with individual diagrams, or they may over time include less detailed indices or denote indicators only in one place. Other changes we have seen are the addition of arrows to indicate system-internal energy transfers, or adding descriptors to indicate object properties that are not typically accounted for in the diagrams.

In all assessments, we always require students to go through the steps of modeling a scenario with appropriate graphical representations (including the Energy-Interaction Diagram when appropriate) to derive mathematical models before they start any calculations. While this allows us to reconstruct a students' argument on a written exam, but it also serves to emphasize the importance of modeling situations by understanding and representing the physical phenomena rather than by "hunting equations."

Students willingly take to the use of the Energy-Interaction Diagrams and quickly adjust to the required discipline of generating detailed diagrams. After a few weeks, students often spontaneously turn to the Energy-Interaction Diagrams when they try to make sense of a new phenomenon in our labs.

## ACKNOWLEDGMENTS

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## REFERENCES

[1] B. W. Harrer, "On the origin of energy: Metaphors and manifestations as resources for conceptualizing and measuring the invisible, imponderable," American Journal of Physics **85**, 454–460 (2017).

[2] J. W. Jewett, "Energy and the Confused Student IV: A Global Approach to Energy," The Physics Teacher **46**, 210 (2008).

[3] R. E. Scherr, B. W. Harrer, H. G. Close, A. R. Daane, L. S. DeWater, A. D. Robertson, L. Seeley, and S. Vokos, "Energy Tracking Diagrams," The Physics Teacher **54**, 96–102 (2016).

[4] A. Hobson, "Energy Flow Diagrams for Teaching Physics Concepts," The Physics Teacher **42**, 113–117 (2004).

[5] E. Brewe, "Energy as a substancelike quantity that flows: Theoretical considerations and pedagogical consequences," Physical Review Special Topics - Physics Education Research **7** (2011).

[6] B. Brazzle and A. Tapp, "Using a Ternary Diagram to Display a System's Evolving Energy Distribution," The Physics Teacher **54**, 216–219 (2016).

[7] K. E. Gray and R. E. Scherr, "Drawing energy: Evidence of Next Generation Science Standards for energy in diagrams," in *2016 PERC Proceedings*, edited by D. L. Jones, L. Ding, and A. Traxler (American Association of Physics Teachers, Sacramento, CA, 2016) pp. 128–131.

[8] A. Van Heuvelen and X. Zou, "Multiple representations of work-energy processes," American Journal of Physics **69**, 184–194 (2001).

[9] F. Goldberg, S. Robinson, and V. K. Otero, *Physics & Everyday Thinking* (It's About Time, Armonk, NY, 2008).

[10] Like some of these other representations, the Energy-Interaction Diagram largely aligns with the model for energy expressed in and underlying the Next-Generation Science Standards.[14] Our characterization of this alignment using a list of categories developed by Gray and Scherr (see Ref. 7) can be found in an online appendix.

[11] W. Potter, D. Webb, C. Paul, E. West, M. Bowen, B. Weiss, L. Coleman, and C. De Leone, "Sixteen years of collaborative learning through active sense-making in physics (CLASP) at UC Davis," American Journal of Physics **82**, 153–163 (2014).

[12] R. E. Scherr, H. G. Close, S. B. McKagan, and S. Vokos, "Representing energy. I. Representing a substance ontology for energy," Physical Review Special Topics - Physics Education Research **8**, 1–11 (2012).

[13] See, for example, the treatment of potential energy forms as stored energy in R. D. Knight, B. Jones, and S. Field, *College physics: A strategic approach* (Pearson Education, Inc., San Francisco, CA, 2006); and E. Hecht, *Physics: Algebra/Trig* (Brooks/Cole Publishing Company, Pacific Grove, CA, 1997).

[14] NGSS Lead States, *Next Generation Science Standards: For States, by States* (National Academies Press, Washington, DC, 2013).