Examining physics teacher understanding of systems and the role it plays in supporting student energy reasoning

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In this paper, we argue that the definition of what constitutes a system differs in physics from other sciences, and in particular, biology, and that these differences matter for learning. Furthermore, even within physics, what textbooks (and instructors) mean by the phrase "energy is conserved" is not unambiguous, often giving the impression that whether or not energy is conserved is contingent on the type of system one chooses for analysis, inappropriately, thereby, interweaving conservation with constancy. These discrepancies and ambiguities in the canonical approach to systems as a tool for energy reasoning may, in turn, undermine the knowledge that teachers need to support energy learning among their students. We present data from a validated assessment of the specialized physics knowledge that teachers use to help students make progress in energy learning, which we administered to hundreds of high school physics teachers and senior physics majors. Assessment results support the following claims: (a) Both high school teachers of physics and senior physics majors manifest significant difficulties in applying a consistent systems approach to energy analysis; (b) Teachers who demonstrate a strong understanding of a systems approach to energy analysis are also better equipped to respond productively to student reasoning about a system approach to energy; and (c) Teachers with a strong understanding of a systems approach to energy analysis are also significantly better equipped to respond productively to student reasoning than senior physics majors who demonstrate a similarly strong understanding. Our results have implications for the professional preparation of teachers, graduate Teaching Assistants, Learning Assistants, and physics faculty in their role as instructors.
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I. INTRODUCTION

Energy is a powerful, abstract concept that undergirds a lot of science instruction, both at the precollege and post-secondary levels. The defining characteristic of energy is its conservation, even though it transfers and is converted. The very statement in the previous sentence implies the need to specify some system at the boundary of which energy may transfer. Understanding the role of defining a system in energy analysis is particularly difficult for many physics learners. In this paper, we will explore some reasons for this difficulty. We will also analyze empirical measurements of teacher resources for supporting student use of systems for energy reasoning. Consider the following example:

> *Ms. Santucci's class is discussing the energy associated with an Atwood's machine which consists of two blocks connected by a string that runs over a smooth, lightweight pulley as shown in Fig. 1. The students are discussing the energy related to the larger block as it moves downward and speeds up. Taylor says: "I was thinking about the work done on the larger block. I think both gravity and the string could be doing work on that block, but doesn't the work by gravity come from the gravitational energy of the block and the Earth?"*

This vignette is based on the authors' informal classroom experiences with introductory physics students who are striving to reconcile their ideas about work done by the gravitational force and gravitational potential energy. Understanding the relationship between these two ideas

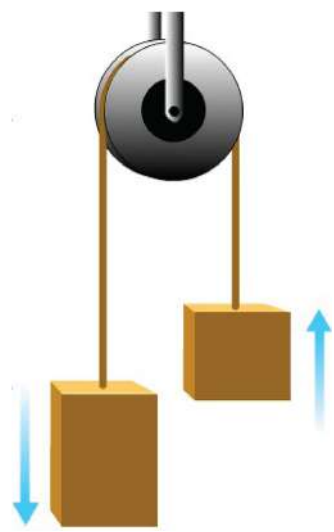


Fig. 1. Atwood's machine.

requires a foundational understanding of the way in which physicists strategically specify a system for energy analysis.[1–4] If the system specified includes Earth, then Earth cannot do work on this system. If the system specified does not include Earth, then there will be no significant amount of gravitational potential energy stored in the system.

This vignette illustrates the complexity of knowledge that is in play when a teacher seeks to respond productively to student ideas. The knowledge that Ms. Santucci needs to marshal strongly depends on the specific topic her students are learning and how she hopes to support their learning. She will likely draw upon specialized knowledge that another professional physicist would not need. Consider an industrial physicist who designs large scale gravitational energy storage projects. They would probably have a standard system choice for characterizing an energy storage reservoir. They would understand the energy analysis based on this system choice very well but they would not need to worry about how different system choices would alter their energy analysis. In contrast, Ms. Santucci needs to know that the role of work and gravitational energy depend on the system that a learner is using in their analysis of a physical scenario. If she wants to empower her students to choose a system strategically, she needs to recognize the implications of various choices they could make. That is to say, she needs to draw upon specialized content knowledge that is specifically relevant to the work of teaching.[5] This specialized content knowledge for teaching (CKT) has been described and studied extensively by Ball and coworkers for subject areas outside of physics.[6] In previously published articles, we described the adaptation and application of the CKT model to the domain of high school physics and showed how to use this theoretical framework to assess teacher knowledge for teaching energy in a first physics course in the context of mechanics.[7,8] In this paper, we specifically focus on the role of CKT in the sub-domain of systems reasoning as a fundamental component of energy analysis. We will argue that the disciplinary approach to systems reasoning about energy in physics is particularly counterintuitive and challenging but also useful. We will present evidence that this approach is not widely understood by teachers or physics majors. Finally, we will show how gaps in a teachers' understanding may undermine their ability to respond productively to student reasoning.

II. BACKGROUND: THE ROLE OF A SYSTEM IN PHYSICS

A. Background: Canonical approaches to systems reasoning in biology and physics

Most physicists and other scientists would likely agree that systems reasoning is both fundamental and cuts across scientific disciplines. The authors of the Next Generation Science Standards (NGSS) emphasize the importance of systems reasoning by including "systems and system models" as one of seven "crosscutting concepts."[9] Learners need to apply systems reasoning to make sense of a wide range of scientific topics from ecology to climate change. While all scientific disciplines recognize the fundamental role of systems, canonical disciplinary approaches to systems-based reasoning are idiosyncratic.

According to a common biological science approach, for example, a system is "a group of related natural objects or forces within a defined zone, a regularly interacting or interdependent group of items forming a unified whole."[10] This definition assumes that when the objects are not in the system, they are not important for the functioning and behaviors of the system. In this example from biology, then a system is established by the interactions themselves. The ecosystem of Yellowstone National Park, for example, includes all of the living and non-living components that interact within this geographical context. From this biological perspective, considering the park system without including wolves would imply an alternative reality in which wolves are extinct or not physically present in the park and, therefore, not interacting with other components of the ecosystem.

The preceding biological approach to systems stands in contrast, however, to the canonical approach in physics where "we will often consider a particular system, by which we mean a particular object or set of objects; everything else in the universe is called the 'environment'."[11] Consider the simple scenario of a child pushing a box on a rough floor. A physicist might strategically decide to include just the box and the floor in their system. In this case, the kinetic energy that is converted into thermal energy through the friction interaction would remain in the system. Although the child plays a critical role in the energy story, the physicist has chosen to include them as part of the environment. According to this analysis, the child adds energy to the system through the process of work. By assigning the child to the environment, the physicist is choosing not to track the complex changes in chemical and thermal energy within the child. To someone with the wolf-free Yellowstone understanding of a system, saying "the child is not part of the system" conjures up the image of a motionless box resting on the table, which is a completely different phenomenon.

The NGSS describe system-based reasoning using both a biological approach to systems and a canonical physics approach. According to the NGSS 5th-grade Earth Systems Standards, "a system can be described in terms of its components and their interactions" (5-ESS2-1). The emphasis here is on the objects and interactions within a system. In the high-school energy standards, the focus shifts to defining a system and identifying interactions with the environment: "When investigating or describing a system, the boundaries and initial conditions of the system need to be defined and their inputs and outputs analyzed and described using models" (HS-PS3-4).

In the preceding paragraphs, we have distinguished a biological and a canonical physics approach to systems. This is, of course, a simplification. Professional physicists certainly see the value of thinking holistically about *all* of the objects and factors that influence a given phenomenon and professional biologists would see the value of focusing on a subset of interacting objects while recognizing inputs and outputs from the environment. It is, however, important to realize that these two approaches to systems are distinctly different.

When learners are first introduced to energy reasoning in physics, they are likely to be more familiar with a biological approach to systems. The first definition of a "system" in the online Merriam-Webster dictionary is "a regularly interacting or interdependent group of items forming a unified whole."[12] Nowhere in the remaining four definitions does Merriam-Webster mention inputs, outputs, or choosing a system. It is the biological approach that aligns more closely with the use of systems language in such non-academic contexts. We do not contend for a moment that students apply the above specific dictionary definition of a system faithfully and consistently. We use this dictionary definition as a typical example of a commonplace use of the term that makes intuitive sense in everyday parlance. For instance, if Kim says that a heat-pump is not part of their home heating system, a person could reasonably assume that Kim does not use a heat pump to raise the house's temperature. A typical person would be unlikely to conclude that Kim had merely defined her home heating system in such a way that her heat pump was external to that system.

The canonical physics approach to systems, in which the system specification just determines which objects are inside the system and which are in the environment of the system *without altering the interactions among objects,* can seem both counterintuitive and arbitrary to novices. Why would we choose to leave the child pushing a box out of the system? Isn't the child essential to the process? Although the expert physicist can make sense of various choices of system, the novice needs to learn why and how to strategically select a particular system based on their energy analysis goals and insights.

In the NGSS era, the development of systems thinking is a very important learning goal of the science curriculum. There is a growing body of research on student understanding of systems thinking in areas such as ecology and earth science. The emphasis there is in helping students recognize that within a complex system (e.g., an ecosystem) feedback loops exist that connect disparate parts of the system, and that changes in one part (e.g., population decrease of one type of organism due to environmental changes) can produce changes in another part of the system (e.g., population collapse in the population of that organism's predator). While important, systems thinking in that literature have a completely different focus than our focus on the canonical physics approach to systems reasoning.

B. Background: Energy is always a conserved quantity but often not constant

Across scientific disciplines, there is widespread agreement that the principle of conservation is a fundamental component of energy reasoning. In fact, conservation is integral to the very definition of energy. Therefore, regardless of the system, energy is always conserved, but in physics we will often choose a system for which the energy is not constant. The system we choose influences the way in which we account for energy conservation.[13] In situations in which there is no net transfer of energy into or out of a specified system, energy conservation implies that the total energy of the system is *constant*. When energy is transferred into or out of *a system*, conservation implies that the change in the total energy of the system *interior* will exactly equal the net transfer of energy through the boundaries of the system. In short, energy is *always* a conserved quantity. The energy of a specified system will be constant if and only if there is no net transfer of energy into or out of the system, and non-constant if there is a net transfer of energy.[14,15]

One productive approach to applying the energy conservation principle in physics involves the following steps: precisely and strategically specifying a system; analyzing energy transfers into or out of the system; and determining whether the total energy of the system increases, decreases, or remains constant. Recognizing the universality of energy conservation even for specific systems and situations where energy is not constant is a subtle yet critical first step in this learning process. Physics learners must gain ownership of two foundational ideas:

(A) the energy is always a conserved quantity regardless of the system chosen for an energy analysis; and
(B) the system chosen for an energy analysis will often determine whether the energy of the system is constant or not.

C. Background: Energy conservation is independent of the choice of system

While the ideas presented in Sec. II B may be familiar and intuitive for many physics faculty, they are not intuitive for novice physics learners. In fact, in Sec. IV, we will see that even many high-school physics teachers and senior physics majors struggle to determine how the choice of system influences the energy analysis for a given scenario. We might simply attribute these difficulties to the inherent challenges of the disciplinary approach to systems reasoning about energy in physics. We would argue, however, that physics educators often fail to introduce energy conservation in a way that is pedagogically responsive to learner needs and resources.

Despite widespread consensus regarding the significance of energy conservation, there is also widespread inconsistency in the language that scientists and science educators use to describe it. Science educators often make statements such as "energy is conserved in isolated systems" or "energy is conserved in closed systems." While both of these statements are true, they suggest that energy is only conserved in scenarios involved closed or isolated systems (i.e., they do not fully distinguish the related yet distinct concepts of conservation and constancy). No qualifier is needed. Energy is conserved in isolated and non-isolated systems. It is conserved in open and closed systems. Energy is *always* conserved.

It may be helpful to consider a contrasting case of a quantity, such as volume, that is sometimes constant but is not a conserved quantity. When various quantities of the liquid water are combined the total volume of water remains constant. In contrast, when liquid water is mixed with ethanol the total liquid volume of the mixture is less than the volume of the original liquids. In this case, it makes no sense to ask where the missing volume can be found because volume is not a conserved quantity. When the energy of a system decreases, it must have transferred out of the system because energy is conserved.

Unfortunately, many excellent introductory textbooks introduce energy conservation in a way that is unlikely to help learners to begin taking ownership of the two foundational ideas listed above. In fact, many textbooks use language that might maintain or even exacerbate confusion between the separate ideas of conservation and constancy. We analyzed eight widely adopted university physics textbooks, and in six of them we found statements similar to those described here, which could likely lead students to think that energy conservation only applies in special cases. For example, a prominent college level introductory physics textbooks states that, "The **law of conservation of energy** states that in a closed, isolated system, energy can neither be created or destroyed; rather, energy is conserved. Under these conditions, energy can change form but the system's total energy in all of its forms remains constant." Another prominent textbook states that, "A closed system of interacting particles has another remarkable property. Each system is characterized by a certain number, and no matter how complex the interactions, the value of this number never changes. This number is called the *energy* of the system, and the fact that it never changes is called the ***law of conservation of energy***. It is, perhaps, the single most important physical law ever discovered."

One could argue that these textbook statements are technically correct but who would fault a student for carefully reading this prose and thinking that the law of conservation of energy only applies to isolated systems. The thoughtful student might wonder why they have been told that the "single most important physics law ever discovered" has little practical relevance. How often do students encounter isolated systems in their everyday lives or their scientific explorations? Imagine trying to make sense of climate change without realizing that the law of energy conservation can be applied to non-isolated systems like Earth or the atmosphere.

In this section, we have argued that the canonical disciplinary approach to systems in physics is both idiosyncratic and counterintuitive. We have also argued that energy conservation is often introduced in a way that does not support learners in recognizing that energy is conserved even when the energy of a specified system is not constant. Perhaps this shortcoming is corrected as learners dig deeper into energy analysis. Perhaps as they analyze energy transfers through work and heat, they come to realize how their choice of system affects their energy analysis. In Sec. IV, we explore these possibilities empirically. We analyze the understanding of the role of system choice in energy analysis among both physics majors and high school physics teachers.

III. METHODS: DEVELOPING AN ASSESSMENT OF CONTENT KNOWLEDGE FOR TEACHING ENERGY

In the introduction to this paper, we discussed the notion of content knowledge for teaching (CKT) and gave an example of a situation in which the teacher, Ms. Santucci, needs this knowledge to respond productively to a student difficulty. Taylor has raised a very insightful question: "Doesn't the work by gravity come from the gravitational energy of the block and the Earth?" Ms. Santucci wants to help Taylor make progress with this question. Ms. Santucci's response will depend on the learning goals she has set for her students. For example, she may want her students to determine whether or not energy is constant for a specified system. She may further want her students to recognize that gravitational potential energy can decrease and kinetic energy can increase without the total energy of a system remaining constant. In service of these goals, Ms. Santucci needs to understand the ideas behind Taylor's words and interpret the productive and potentially problematic aspects of energy understanding that Taylor's question may be revealing.

Ms. Santucci could choose from a number of productive approaches to help Taylor progress. Each instructional response will lean on a teacher's domain-specific knowledge. We have chosen this example to show why we operationalize CKT as the knowledge that teachers are likely to draw on in their efforts to carry out *specific tasks of teaching* in service of *specific learning targets*. (The full lists of both for the domain of energy in the context of mechanics are given in Ref. 7.) Operationalized in this way, CKT extends beyond the student learning targets and includes both disciplinary and pedagogical knowledge. The question is whether such knowledge can be captured and assessed.

Because the specific CKT a teacher recruits will depend on the learning goals she sets for her students, on the instructional situation, and on instructional decisions, it is not feasible to fully list all examples of CKT, even in a narrow domain. In constructing a written CKT assessment, we have focused on a representative subset of learning targets and tasks of teaching as instantiated through various instructional scenarios. Some of the items assessed disciplinary knowledge of physics, which may be particularly relevant for teaching contexts but does not require detailed knowledge of pedagogical strategies or student learning. These have been designated Content Knowledge for Teaching-Disciplinary (CKT-D) items. Some items required an understanding of content-specific learning trajectories and pedagogical strategies along with disciplinary knowledge. We designated these as Content Knowledge for Teaching-Pedagogical (CKT-P) items. We do not view these distinctions as an effort to measure distinct domains of knowledge. Rather, our goal was to ensure that the tasks we developed represent a range of disciplinary and pedagogical challenges related to the learning of energy and documented in the literature.[1,3,16–23] (We have described details of test construction, piloting, and overall results elsewhere.[7]) Our online CKT assessment was completed by 362 high-school physics teachers (information about the teachers is presented in Table I) along with a comparison group of 311 advanced physics majors from across the country. Physics majors were included in this study because we expected that they would have, on average, higher levels of non-teaching specific subject matter knowledge in physics as compared to the teachers. Only 33% of our teacher population sample had an undergraduate degree in physics. Constructed response items were scored based on 3-point rubrics, which were iteratively refined to establish interrater reliability of 90% or greater. In Sec. IV we analyze results for a subset of CKT items focusing on systems energy reasoning.

Table I. Demographics of the teachers in the 362 teacher sample (the percent of those who have a physics major is close to the average in the US).

Demographics	Proportion of sample
Gender	…
Male	0.69
Female	0.31
Race/Ethnicity	…
Caucasian/White	0.92
Other races combined	0.08
Undergraduate major	…
Physics	0.33
Engineering	0.16
Biology	0.10
Other	0.41
Teaching Experience (Years)	…
0–5	0.17
6–10	0.21
>10	0.62

IV. FINDINGS

A. Findings: Identifying the system choice associated with a student's reasoning about energy

Figure 2 shows one of the items that we developed to assess a teacher's ability to identify the system choice that is implicitly assumed in a student's energy reasoning. The questions within this item assess "pure" content knowledge: correctly answering these questions requires only an understanding of the canonical physics approach to systems reasoning about energy. No knowledge of pedagogical strategies or prevalent student ideas is required. That said,

In a situation with a number of interacting objects, one may select any subset of them as the system of interest The objects that have not been selected as belonging to the chosen system are therefore external to the system.

A bowling ball is dropped from a height of 1 m above a small trampoline. It lands and stretches the trampoline downward. Describe the energy changes in this process from the time the ball is dropped until it reaches the lowest point of the motion.

For each of the following student responses, select the system for which the student response is correct.

Student Response	System Choices			
	Ball and Earth	Ball and trampoline	Ball, Earth, and trampoline	None of these systems is consistent with the response.
First there is gravitational potential energy. Then Earth does work and the ball gains kinetic energy. The trampoline does negative work on it and we have elastic energy.				Teachers 30% Phys. Maj. 13%
The gravitational potential energy is converted gradually to kinetic energy as the ball falls and ends up as elastic energy.			Teachers 60% Phys. Maj. 39%	
First there is gravitational potential energy, which is converted to kinetic energy as the ball falls. Finally, the trampoline does negative work and there is no more kinetic energy	Teachers 42% Phys. Maj. 23%			
There is no mechanical energy at the beginning and then Earth does positive work on the ball and it gains kinetic energy. Then the trampoline does negative work on it and kinetic energy decreases to zero.				Teachers 52% Phys. Maj. 31%
There is no mechanical energy at the beginning. Then Earth does positive work on the ball and it gains kinetic energy. Finally, all kinetic energy goes to elastic energy.	Teachers 41% Phys. Maj. 22%			

Fig. 2. *Trampoline, CKT-D, SR* (selected response), percentages are shown for correct choices.

the disciplinary content knowledge assessed by this item is specifically relevant to the work of a teacher. A teacher might want to provide guidance to students after inviting them to select a system for energy analysis. To do this, the teacher would need to recognize how the energy analysis differs depending on the system that a student selects. This will help the teacher guide students in an intentional manner toward coherence in their understanding of energy.

The percentage of teachers and senior physics majors correctly identifying the system choice for each student response is shown in Fig. 2. The data show that the trampoline item turned out to be quite difficult. On average, teachers scored better than physics majors on our CKT-E assessment as a whole.[8] But the difference was especially pronounced on this item. The percentage of teachers answering each question correctly was higher than the percentage among physics majors by an average margin of 20%.

The first student response was the most difficult for both sample groups. Here the respondent must recognize that 'gravitational potential energy' implicitly assumes that Earth is in the system while 'Earth does work' implicitly assumes that Earth is external to the system. Earth cannot be both in the system and external to it. Therefore, no system choice can be consistent with the student response. Only 30% of teachers and 13% of physics majors were able to correctly identify the system implied by this student response. Results on this item reveal a wide range in the level of understanding among both teachers and majors of the canonical physics approach to reasoning about systems. Of the 362 teachers who completed this assessment, 32% identified either 4 or 5 (out of 5) correct answers. This suggests that these teachers were able to recognize how the system choice influences the energy analysis fairly well. A much smaller percentage of senior physics majors (12%) demonstrated a corresponding level of understanding. In contrast, 49% of teachers and 69% of physics majors identified either 0 or 1 correct answers on this item. Selecting either 0 or 1 correct answer is statistically worse than random guessing, which would, on average, yield 1.25 correct out of 5 with 4 answer choices. Our results suggest that approximately 1/3 of high school physics teachers have a fairly robust understanding of the canonical physics approach to systems reasoning about energy, as measured by this item. Unfortunately, nearly one-half of teachers appear to have very little familiarity with this approach to systems reasoning and results are even less encouraging for senior physics majors.

Physics teachers have the task of supporting the next generation of physics learners to use a canonical physics approach to systems reasoning about energy. Therefore, we wish to find out what role disciplinary content knowledge plays in a teacher's ability to respond productively to a challenging teaching situation. To answer that question, we will now look at teacher responses to an item that is based on the Atwood's machine scenario presented in the introduction.

B. Findings: Responding productively to student difficulties with systems reasoning

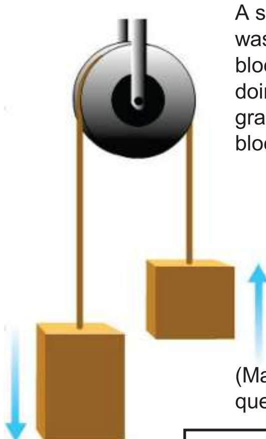
Atwood's, CKT-P, CR (constructed response), shown in Fig. 3, is an item that presents the teacher with a pedagogical challenge and recruits a constructed response. This item is expected to require sophisticated disciplinary knowledge, but it cannot be successfully answered based on disciplinary knowledge alone. The teacher must use her disciplinary knowledge to interpret and evaluate a student statement, plan her instructional response, and anticipate how the student will respond. We have chosen to present *Atwood's, CKT-P, CR* in this paper because it represents a difficulty that thoughtful students will often raise when trying to reconcile the concepts of gravitational energy and work by a gravitational force.[3] Differentiating gravitational energy from work by a gravitational force is directly related to the system choice. If Earth is part of the system then gravitational energy will be stored in the block-Earth system. If Earth is not included in the system then Earth can transfer energy to the system through work.

Teachers' responses to the *Atwood's, CKT-P, CR* were scored based on 3-point rubric which was iteratively refined to establish inter-rater reliability of 90% or greater. We determined whether each of the following elements was present in the teacher's response:

Ms. Santucci's class is already familiar with the concepts of kinetic energy and gravitational potential energy. She wants to challenge them to consider a system for which gravitational energy is decreasing while kinetic energy is increasing, but the sum of these two energies is not constant. She demonstrates an Atwood's machine for her physics students.

In the Atwood's machine shown in the figure, two wooden blocks are connected by a piece of string that runs over a smooth, lightweight pulley. The larger block is moving downward and is increasing in speed. The smaller block is moving upward and is increasing in speed.

In a situation with a number of interacting objects, one may select any subset of them as the system of interest. The objects that have not been selected as belonging to the chosen system are therefore external to the system.



A student, Taylor, shares the following idea. "I was thinking about the work done on the larger block. I think both gravity and the string could be doing work on that block, but doesn't the work by gravity come from the gravitational energy of the block and the Earth?"

a. What specific inconsistency does Taylor need to resolve in her analysis in order to make progress?
b. What question would you ask Taylor, to help her resolve this inconsistency?
c. How might that question help her resolve this inconsistency?

(Make sure your answer addresses all three questions.)

Fig. 3. *Atwood's, CKT-P, CR* item.

(1) Teacher correctly identifies the inconsistency in Taylor's analysis.
(2) Teacher poses a question that can be answered and would likely lead to increased understanding.
(3) Teacher explains how their question could lead to a facet of understanding that would be helpful for Taylor.

A single point was awarded for each element that was present in the teachers' response for a total score of 0 to 3 points for the response as a whole. Productively responding to Taylor's question about work and gravitational energy was relatively difficult for the teachers in our study (see Fig. 3). Only 29% of teachers completing the assessment were able to respond productively to any component of this item. As illustrated by the following examples, a select group of teachers provided answers that addressed all three questions. In the examples below we indicate which part of the response corresponds to which of the three important elements listed above.

Response A (3 points)

Taylor needs to understand that work is only done by external forces (1). I would ask Taylor to reiterate what makes up the system (2). If she answers that it is the larger block and Earth, I would ask her to remember what kinds of forces are necessary to do work on the system. If she answers that the system is only the large block, then I'd ask her how any gravitational energy could be stored in a system not including Earth (3).

Response B (3 points)

A system cannot do work on itself. We already established that the system includes the block and Earth. Therefore, we can't count the work done by gravity because Earth is in the system (1). What objects did you include in your system (2)? Hopefully, she will answer Earth and the block. Then I would ask "Is it possible for an object in the system to do work on the system?" I always relate it back to an aquarium. The fish can do work on each other and the objects inside the fish tank. But the fish can't move the actual tank because they are inside (3).

We might argue that, in response B, the fish tank analogy problematically suggests that the physical configuration, rather than the physicist, determines the system. Nevertheless, both of these teachers have correctly interpreted the likely inconsistency with which Taylor is struggling. The second teacher also provided evidence that she recognized this as a prevalent inconsistency.

Unfortunately, as illustrated by the following example, the majority of teachers were unable to respond productively to any component of the item.

Response C (0 points)

Taylor's inconsistency is that she is not thinking of work as a force multiplied by a distance. The work done by gravity comes from the force of gravity (the weight) acting on the box, not on the "gravitational energy" of the block and Earth. I would ask Taylor to define work and describe how it can be calculated. If she is able to see that work is the product of a force and a displacement, she would be able to understand that both gravity and the string are doing work, but acting in opposite directions.

Although the physics content of response C is correct, it doesn't address the question Taylor is raising. There is no evidence in Taylor's question to suggest that she does not recognize how work is calculated. In addition, Taylor explicitly states that "both gravity and the string are doing work." Because the suggested instructional response does not address Taylor's question, it is unlikely that it would play a significant role in helping her make progress. Some of the teachers were transparent about their own difficulty interpreting the scientific content at the root of Taylor's question:

Response D (0 points)

I don't really understand what she is saying when she says "the gravitational energy of the block and Earth." Does she mean the gravitational force between them, like from $F = GmM/r^2$*? Or is she referring to the smaller block? I can't really answer because I'm not clear on what she is saying.*

Overall, *Atwood's, CKT-P, CR* was an item that was relatively difficult for the majority of teachers who participated in our study. Only 30% of teacher responses contained any of the 3 elements assessed in the rubric. In Sec. IV C, we explore the role of a teacher's understanding of systems in their response to the pedagogical challenge presented by the Atwood's teaching scenario.

C. Findings: Contingency of a productive pedagogical response on systems knowledge

In order to respond to the disciplinary content of Taylor's question, we might expect that a teacher would need a deep understanding of the way in which the choice of system affects work and various potential energies. We confirmed this expectation by comparing responses on *Atwood's, CKT-P, CR* for teachers who had 0 or 1 correct response on the *Trampoline, CKT-D, SR* with responses for teachers who had 4 or 5 correct responses. Teachers with 0 or 1 correct responses on the trampoline item demonstrated very little success navigating the challenging teaching situation simulated by the Atwood's item. Only 3% of these teachers responded productively to a single criterion in our constructed response rubric, as shown in Fig. 4. In contrast, teachers with 4 or 5 correct responses on the trampoline item had significantly more success: 84% of them responded productively to some portion of the constructed-response items, and 29% provided responses that satisfied all three criteria in our rubric.

The results summarized in Fig. 4 can be interpreted in more than one way. It may be that the teachers who responded correctly to the *Atwood's, CKT-P, CR* item just know physics better in general and thus do better on systems-based items. Or perhaps systems subject-matter knowledge is a separate aspect of energy knowledge and teachers who know a great deal about energy, but lack an understanding of systems, cannot respond productively to student difficulties of this sort. To test these two possible explanations, we selected a subgroup of teachers (N = 95) based on high scores on non-systems-related items. The selection criteria for these teachers were entirely independent of their performance on the items assessing systems content knowledge. We identify them as non-systems items, high-performing teachers. These teachers represented a more

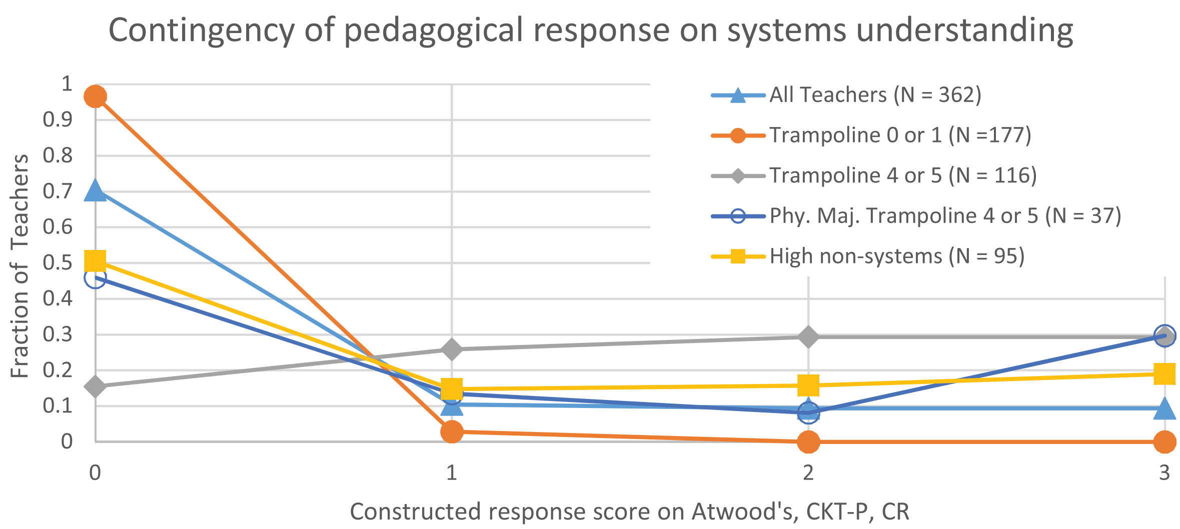


Fig. 4. The fraction of teachers who responded productively to student reasoning in *Atwood's, CKT-P, CR*.

select group than the group of teachers scoring a 4 or 5 on the Trampoline item. The number of teachers in this group was somewhat smaller and they had a higher average CKT-D score. If the first explanation above were correct, then these teachers would do as well or better on *Atwood's, CKT-P, CR* as the teachers with a high score on the Trampoline item. If the second explanation were correct, then the performance of non-systems items high-performing teachers should have been significantly lower. We found that out of the non-systems items high-performing teachers, 49% were able to respond productively to some portion of the constructed-response items compared to 84% of the teachers who scored 4 or 5 on the Trampoline item. The difference in performance between each of these two groups was significant at the $p = 0.01$ level. These results suggest that understanding the concept of a system is indeed a special, separate aspect of energy knowledge. Even if a teacher has a high level of content knowledge for teaching energy, if they lack specific knowledge for teaching a canonical physics approach to energy, they will be unable to respond productively to student difficulties related to a broad spectrum of energy issues.

We also found an interesting difference in performance on the *Atwood's, CKT-P, CR* among the teachers and senior physics majors who provided 4 or 5 correct responses on the *Trampoline, CKT-D, SR* item. Of the 116 teachers who scored 4 or 5 on the *Trampoline* question only 16% scored a 0 on the *Atwood's* question. Of the 37 senior physics majors who scored a 4 or 5 on the *Trampoline* question, 46% scored a 0 on the *Atwood's* question. This finding provides supporting evidence for our claim that disciplinary knowledge of systems is an important but not sufficient condition for effective facilitation of student systems reasoning. Among teachers and physics majors with similar disciplinary knowledge of systems, the teachers were much more likely to be able to leverage this knowledge to support productive student reasoning.

V. CONCLUSIONS AND IMPLICATIONS FOR PHYSICS EDUCATION

In Secs. I–IV, we have explored the critical role of systems reasoning as a foundational concept for teaching and learning about energy. We have proposed the following impediments that learners and teachers face in adopting a canonical physics approach to using systems reasoning for energy analysis.

- The canonical approach to systems in physics is distinctly different from both the popular connotation of the word "system" and the approach to systems that is common in other scientific disciplines.
- Physics curricular materials often introduce the concept of a system approach to energy in inconsistent ways, which likely make it difficult for students to differentiate the meaning of the terms "constant" and "conserved."

One could logically expect that these impediments would lead to inconsistent understandings of systems reasoning among teachers, which would, in turn, compromise those teachers' resources for supporting systems reasoning about energy among their students. In fact, we have presented empirical evidence for the following claims:

- Senior physics majors and high school teachers of physics manifest significant difficulties in applying a consistent systems approach to energy analysis.
- Teachers who demonstrate a strong understanding of a systems approach to energy analysis are also better equipped to respond productively to student reasoning about a system approach to energy.
- Teachers with a strong understanding of a systems approach to energy analysis are also significantly better equipped to respond productively to student reasoning than senior physics majors who demonstrate a similarly strong understanding.

These findings have the following implications:

(1) The difference between physicists' approach to the concept of a system and other disciplinary approaches needs to be foregrounded during instruction, especially in courses that serve students of multiple science disciplines.
(2) In negotiating the physics definition of a system with students learning about energy in the domain of physics, physics instructors and textbook authors need to pay special attention to distinguishing energy constancy (which depends on the system and the physical process) from

energy conservation (which is valid for all system choices and all processes).

(3) As illustrated by our work with senior physics majors and physics teachers, difficulties in applying the systems approach to the analysis of the processes involving energy are prevalent and instructionally consequential. Neither advanced study nor teaching experience appears to significantly develop this foundational knowledge.

(4) The comparison in the performance of senior physics majors and physics teachers in tasks requiring them to respond productively to student reasoning related to the conservation of energy indicate that knowing the right answer for oneself is insufficient for helping to guide others to the correct answer. Therefore, knowing "physics" and "general, non-content specific, pedagogical strategies" is often not sufficient for effective teaching.

Comparing the approach that physicists take to the concept of a system with that of other disciplines, the physics approach is counterintuitive and challenging, and also very useful. It allows physicists to analyze complex situations, focusing on the quantities that are of interest to them, while avoiding complications associated with processes and quantities that are difficult to analyze. Specifically, a physics systems approach allows us to fully understand and apply the concept of conservation (of energy, in our case, although the same is true for other conserved quantities, such as linear and angular momentum, electric charge, etc.) for *any* selected system. Conservation of energy does not imply its numerical constancy; it only means that if the energy in one system changes, we can always track where it went or where it came from *in a local spatial and temporal sense*.

While expert physicists (including textbook authors) are adept in this approach to the analysis of energy-related processes, they often talk and write about it in ways that may lead to confusion between the terms "conserved" and "constant." This naturally contributes to the misunderstanding of the term system by novices. In our study such novices were upper division physics majors who demonstrated little understanding of the concept of energy conservation on the assessment instrument that we designed and validated.

When learners are first introduced to a physics approach to energy conservation, we should explicitly open their perspective to the widespread applicability of this wondrous natural law. Consider the following example from a physics textbook which articulates the universality of energy conservation: "In the 1800s it was experimentally discovered that energy is a conserved quantity. If a system gains energy, the surroundings lose it. If the system loses energy, the surroundings gain the same amount of energy." This statement is a modern update of Enrico Fermi's classic treatise on *Thermodynamics,* which clearly distinguishes the universal principle of energy conservation from specific situations in which the energy of a system is constant:

> *The first law of thermodynamics is essentially the statement of the principle of the conservation of energy for thermodynamical systems. As such, it may be expressed by stating that the variation in energy of a system during any transformation is equal to the amount of energy that the system receives from its environment. In order to give a precise meaning to this statement, it is necessary to define the phrases "energy of the system" and "energy that the system receives from its environment during a transformation."*
>
> *In purely mechanical conservative systems, the energy is equal to the sum of the potential and the kinetic energies, and hence is a function of the dynamical state of the system; because to know the dynamical state of the system is equivalent to knowing the positions and velocities of all the mass-points contained in the system. If no external forces are acting on the system, the energy remains constant.*[24]

Fermi recognized that the conservation principle always applies. One of the reasons for appealing to Fermi here is that he played an important role in the naming of the neutrino, the elusive particle whose existence Wolfgang Pauli had postulated to save conservation of energy when others were promoting the idea of non-conservation of energy in radioactive processes. Fermi also recognized that applying the conservation principle requires careful attention to the system under analysis.

We also found that the physics teachers in our sample, whose physics background we would expect to be on average no stronger than the physics background of senior physics majors, had *slightly* better (though still incomplete) understanding of system reasoning in energy. In addition, the physics teachers showed that they could productively respond to student ideas in this domain *much* better than the senior physics majors who have the same content knowledge. This finding demonstrates that physics teachers possess specialized content knowledge ("content knowledge for teaching"), which goes beyond the pure knowledge of physics content. This finding is in agreement with the finding of Buschang *et al.*[25] who, studying algebra knowledge for teaching, found that while content experts are better than even experienced math teachers in responding to the tasks that require mathematical knowledge for teaching, they were worse in interpreting and responding to student reasoning. However, the dearth of research comparing content experts to teachers in the same content area does not allow us to say whether this is a robust finding or just the beginning of the studies of CKT in different areas.

Content knowledge for teaching is specific to teaching and allows teachers to productively respond to student reasoning. We empirically showed the existence of such knowledge in the narrow domain of system reasoning in energy. The preparation of teachers to help students learn physics (as well as graduate student TAs, Learning Assistants, and physics faculty) should include intentional opportunities for developing this specialized content knowledge, which is topic-specific and cannot be learned through common physics coursework or generic pedagogical education.

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