The Intertwined Roles of Teacher Content Knowledge and Knowledge of Scientific Practices in Support of a Science Learning Community: Research to Practice

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Lane Seeley
Seattle Pacific University

Eugenia Etkina
Rutgers, The State University of New Jersey

Stamatis Vokos
Seattle Pacific University

The intertwined roles of teacher content knowledge and knowledge of scientific practices in support of a science learning community

Lane Seeley[1], Eugenia Etkina[2] and Stamatis Vokos[3]
[1]*Department of Physics, Seattle Pacific University, Seattle, Washington, 98119, USA*
[2]*Department of Learning and Teaching, Rutgers University Graduate School of Education, New Brunswick, New Jersey, 08901, USA*
[3]*Physics Department, California Polytechnic State University, San Luis Obispo, California, 93407, USA*

Abstract. In this chapter we envision the science classroom as an authentic scientific community. In this vision, student ideas can influence the trajectory of scientific investigation. Teachers serve as experts and guides, but they also can learn alongside their students. To do this, they need to listen to the students and be able to build on students' original ideas to help them learn. What knowledge does a teacher draw on in such a classroom? In this chapter we empirically investigate some ways in which a teacher can utilize both knowledge of the subject matter and knowledge of science practices to respond productively to student thinking. We present data from a large study of knowledge for teaching energy. The subjects of this study were high school physics teachers. We found that in some instructional situations teachers with insufficient content knowledge cannot productively respond to student reasoning. We also found cases where teachers can compensate for lack of content knowledge if they are skilled in science practices. To explain our findings we hypothesize the existence of two types of content knowledge: foundational content knowledge and elaborative content knowledge. Furthermore, we suggest that foundational content knowledge along with knowledge of scientific practices can allow teachers to compensate for insufficient elaborative content knowledge. We discuss the implications of our hypothesis for future research and for the preparation and professional development of physics teachers.

Keywords: PCK, high school physics, foundational content knowledge, elaborative content knowledge, pre-service learning, teacher professional development, content knowledge for teaching, content knowledge for teaching energy, disciplinary content knowledge, systems.

1 Introduction

Ms. Cordova is preparing for her high school physics class tomorrow. She has noticed that her students have used the terms for various forms of energy, but the evidence she has collected suggests that so far only kinetic energy and gravitational potential energy are being associated reliably with observable indicators. As she was leaving class today, a student group mentioned to Ms. Cordova that during a process in which a kicked ball rolls to a stop, its kinetic *energy gradually decreases because its speed decreases, and therefore it must be transforming into potential energy. "It's potential kinetic energy," one of the students in the group exclaimed as she went out the door.*

Ms. Cordova ponders various instructional moves to respond productively to the students' ideas. She notes the students' facility with connecting kinetic energy to its indicator—the speed of the ball. She appreciates the group's intellectual commitment to the idea that energy conservation requires that the decrease in a form of energy in a system be accounted. She is realizing that the imperceptibility of temperature changes in interacting surfaces in many physical processes does not lend itself to students' thinking about thermal energy as a likely increasing form of energy that compensates for a form of energy that is decreasing perceptibly. She is concerned that if the class does not recognize the role of thermal energy in lots of physical phenomena, her students might not be able to connect their school learning of "conservation of energy" to sociopolitical issues associated with efforts to "conserve energy" [1] or even to energy learning in other science disciplines.

The preceding vignette is inspired by multiple classroom discussions in which learners spontaneously bring up the phrase, "potential kinetic energy." To respond productively to student ideas, Ms. Cordova needs to marshal knowledge that is strongly dependent on the specific topic her students are learning. In this example, she needs to know enough (and be curious about her students' ideas) to notice the disciplinary substance of the off-hand comment her students made. She needs to know that the energy of the ball, the floor, and the air will remain constant as no energy is flowing into or out of the system of the three objects, and that the interaction between the ball and the ground converts the kinetic energy of the ball into thermal energy of the ball, the floor, and the air. She also needs to know that in many mechanical contexts, temperature changes are too small to have been experienced by her students in their daily lives. She needs to know of mesoscopic and microscopic models for friction [2] that can help her students develop a causal picture for the "heating up" associated with surfaces rubbing against each other; she also needs to be aware that learners tend to conflate models of processes at different scales (microscopic/macroscopic), whereas even seasoned energy learners have a hard time separating cleanly effects that involve both ordered macroscopic motion (e.g., the "wind" produced by the ball moving through the air) and disordered microscopic motion (e.g., during the dying-down of air currents). The teacher needs to know and prioritize sequences of phenomena whose energy analyses build on the previous ones. She needs to know ways in which mathematization can serve as a tool rather than an impediment to conceptual development in this context. She needs to know multiple energy tracking representations to help her students gain more insight. She needs to know of experiments that are possible to conduct in the classroom and the affordances and limitations of each for specific instructional purposes. In the case that students do not spontaneously bring up the ideas described above, the teacher needs to know enough to judge whether or not eliciting such ideas through a rich question that she will pose is likely to serve her immediate and ultimate learning goals for the students.

The preceding episode illustrates the complexity of the knowledge that is in play when a teacher is committed to responding productively to student ideas.[1] It is not enough for a teacher to "know the content" and "know how to teach." A successful teacher must negotiate pedagogical decisions that are inextricably linked to the content her students are learning. L. Schulman introduced the construct of Pedagogical Content Knowledge (PCK) in order to acknowledge and study the fundamental interaction and inter-dependence of pedagogical and content knowledge [3, 4]. During the past three decades there has been significant progress in defining, categorizing, and assessing PCK domains [5, 6].

There are several instruments that assess teacher's PCK in specific physics domains [7]. The Magnusson, Krajcik, and Borko model of science PCK [8] was the first attempt to detail this knowledge, and recently a new, revised model of PCK has emerged [9]. In this model PCK is just one component of teacher professional knowledge and practice. Most importantly, in this model teacher professional knowledge is not just subject-specific, it is topic-specific.

In this study, we draw on a somewhat different model of teacher knowledge—Content Knowledge for Teaching (CKT) [10]. CKT is operationalized as the specialized disciplinary knowledge that is specifically relevant to the work of teaching. CKT is broader than PCK because it includes both disciplinary knowledge and pedagogical applications of that knowledge. CKT also has a strong empirical focus on the specialized disciplinary knowledge that teachers actually do draw on in real classrooms. In this study we adapt and apply this model (i.e., develop a theoretical framework) to one narrow domain of high school physics and show how to use this theoretical framework to assess teacher knowledge for teaching energy in a first physics course in the context of mechanics. Specifically, in this chapter we aim to answer the following research questions:

- To what degree is the productivity of teacher responses to student thinking contingent on the teacher's disciplinary content knowledge of the relevant physics topic?
- Are there specific aspects of disciplinary content knowledge of the relevant topic that are critical for supporting student thinking?

In order to address these questions empirically we will first briefly introduce CKT as a framework of assessing teacher knowledge. Next, we will describe a written assessment of CKT in the narrow domain of high school physics energy instruction. Finally, we will analyze general and specific patterns of teacher responses on this assessment that provide insight into the preceding questions.

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[1] We do not intend to provide an exhaustive description of the knowledge needed to respond productively to student ideas. In particular, additional knowledge and skills and dispositions are surely needed to engage productively moment-by-moment with real students in a real classroom. We concentrate on important aspects of the disciplinary knowledge that is deployed by the teacher in service of energy instruction.

2 Content Knowledge for Teaching (CKT)

2.1 Tasks of Teaching and Student Energy Targets

The work described in this chapter is one of the products of a multi-year effort to develop and validate a set of substantively coherent measures that assess CKT in physics in the domain of energy, through both tests and evidence from instructional practice. The project focused on one conceptual area so as to forge a tight theoretical and empirical link between CKT and practice.

To establish this link we developed the domain model through an extensive review of the literature and through observations of expert teachers teaching energy. The domain model of Content Knowledge for Teaching Energy (CKT-E) involves two components. The first component is the critical *Tasks of Teaching* (ToTs) [11]. Tasks of teaching describe the key activities through which teachers and students enact practices that promote and support student learning. For our project we developed the following list of broad categories of the Tasks of Teaching (each has several subcategories listed in Appendix A): I) anticipating student thinking around science ideas; II) designing, selecting, and sequencing learning experiences and activities; III) monitoring, interpreting, and acting on student thinking; IV) scaffolding meaningful engagement in a science learning community; V) explaining and using examples, models, representations, and arguments to support students' scientific understanding; and VI) using experiments to construct, test, and apply concepts.

Although we do not expect that teachers engage in all tasks of teaching in every lesson, we should be able to observe a teacher engaged in each of those tasks many times during teaching of the energy unit. Further, while these tasks of teaching are not the only tasks in which teachers engage while teaching, the CKT theory assumes that for students to learn, teachers should engage in all of these tasks across each unit of instruction [11, 12].

The second component of our domain model is the *Student Energy Targets* (SETs). It focuses on the specific content targets of energy in mechanics contexts for students and articulates features that are important in the domain (in our case, energy taught in the context of mechanics in a typical high school physics course), including concepts and skills, critical tasks in which those are manifest, and knowledge representations. Targets are separated into several broad categories: A) connections of energy and everyday experiences [13–15]; B) choice of system [16–19]; C) identification of and differentiation between energy and other physics concepts [20, 21]; D) transfer of energy [1, 22–28]; E) use of mathematics; F) use of representations [1,16, 22–27]; and G) use of science practices [29]. Elaborations of each of these categories are provided in Appendix B.

2.2 CKT-E Residing at the Intersection of ToTs With SETs

We conceptualize CKT-E as "residing" at the intersection of specific tasks of teaching with the content learning targets—in our case, student energy targets. In essence, we ask what knowledge a teacher would need to "have" to execute a particular task of teaching in the domain of energy to support a particular student energy target. We also recognize that when teachers are able to respond to the scientific ideas and questions of their students their responses will often recruit knowledge that lies beyond the learning targets they have set for their students. In these cases teachers may draw on horizon knowledge [11]. The example of Ms. Cordova illustrates how any instructional situation that results from specific ToTs in support of specific SETs can reveal a broad array of CKT.

Ms. Cordova has specific student energy targets in mind. She wants her students to *recognize the important role of internal energy in interpreting or explaining everyday phenomena* (SET A2). She also wants to help them *understand that energy cannot be observed directly and know[s] how different forms of energy correspond to different measurable physical quantities* (SET A1). Finally, she wants them to realize that *equal amounts of energy in different forms are not equally perceptible* (horizon knowledge). The clear and visible motion energy of a rolling ball is much more perceptible than an equal quantity of thermal energy in the ball/environment when the ball rolls to a stop.

In service of these important student energy targets Ms. Cordova undertakes several different tasks of teaching. She is attentive to what her students say about "potential kinetic energy" because she was already *anticipating specific student challenges related to constructing scientific concepts* (ToT Ia) and *anticipating likely partial conceptions and alternate conceptions* (ToT Ib). She needs to understand the ideas behind her student's words and *interpret both productive and problematic aspects of her students thinking* (ToT IIIb). Ms. Cordova anticipates and interprets in order to inform her actions. She is also thinking of what to do the next day to help students "see" the conversion of kinetic energy into internal thermal energy. She wants to *design, select, and sequence a learning experience that will address her students' actual learning trajectories by building on productive elements and addressing problematic ones* (ToT IId).

Ms. Cordova could design a number of different learning experiences to help her students move toward the energy learning targets she has set out for them. For example, she could use an infrared camera or an infrared video to reveal evidence of thermal energy [30] and use this evidence to inform their discussion. Alternatively, she could explore her student's suggestion of "potential kinetic energy" and help the student unpack the ideas behind that phrase. A productive instructional response will draw on domain-specific knowledge. We operationalize CKT as the knowledge that a teacher is likely to draw on in her efforts to carry out specific ToTs in service of specific SETs. Operationalized in this way, CKT extends beyond the student learning targets and includes both disciplinary knowledge and pedagogical knowledge. For example, disciplinary knowledge of infrared photography belongs to what Ball calls "horizon knowledge." Horizon knowledge is beyond the scope of student energy targets but still relevant for a productive instructional response. On the other hand, anticipating why "potential kinetic energy" might make sense to students in this scenario is a pedagogical challenge that is specific to this disciplinary context.

3 Assessing CKT

The specific CKT a teacher recruits will depend on the SETs, the ToTs, the instructional situation, and the instructional decisions. Therefore, fully listing all examples of CKT, even in a narrow domain, is not productive. In constructing a written CKT assessment we have focused on a representative subset of ToT/SET combinations as instantiated through various instructional scenarios. Some of the items assess disciplinary knowledge of physics, which may be relevant for a teaching situation but does not require detailed knowledge of student learning or of the school context to be answered correctly. We designate these items as Content Knowledge for Teaching-Disciplinary (CKT-D). In addition to assessing disciplinary knowledge some items require an understanding of content specific learning trajectories and pedagogical strategies. We designate these items as Content Knowledge for Teaching-Pedagogical (CKT-P). We do not see these distinctions as an effort to measure distinct domains of knowledge. Rather, our goal was to ensure that the tasks we developed represented a range of disciplinary and pedagogical challenges.

The details of test construction, piloting, and revisions are provided elsewhere [31] Here we only describe the final test._The final form of the assessment contained 26 scored items that were associated with 15 unique teaching scenarios. The form included 6 constructed-response (CR) items scored on 3- or 4-point scales, 6 polytomous items in which test-takers could correctly answer between 0 and 5 or 6 items, and 14 multiple-choice items that were dichotomously scored. Every item contained a rationale that was directly connected with specific tasks of teaching and the student energy targets.

3.1 Example Items for Assessing Disciplinary Content Knowledge for Teaching (CKT-D) and Pedagogical Content Knowledge for Teaching (CKT-P)

Examples of CKT-D and CKT-P items are provided in figures 1 and 2. The item shown in Figure 1 is labeled as *Cyclist, CKT-D, SR*. *Cyclist* describes the context of the item. *CKT-D* identifies this item as primarily assessing disciplinary knowledge of physics. In other words, correctly answering this item requires no knowledge of students or pedagogy. *SR* indicates that this item is a selected-response or multiple-choice item rather than a constructed-response item. While this item is not pedagogical in nature it does assess an area of disciplinary knowledge that is particularly relevant to the work of teachers. In order for teachers to give their students full ownership of the energy analysis process they will need to allow their students to select the system for energy analysis. When teachers do this they must be prepared to recognize how different student-generated system choices will affect the energy analysis. In Section 4 we discuss the important role of systems in energy analysis.

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.

Ms. Inez wants to help her students recognize that energy is a conserved quantity but that the energy of a particular system may not be constant, depending on the specific scenario and the choice of system for analysis. She decides to have them focus on the scenario of a cyclist riding up a hill at constant speed.

For each of the following systems indicate whether the energy associated with that system increases, decreases, or remains approximately constant.

	Increases	Decreases	Approximately Constant
A. Bicycle, rider, air, pavement and Earth			
B. Bicycle, rider and Earth			
C. Bicycle, air and pavement			
D. Bicycle and Earth			

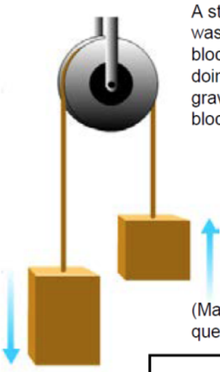
Figure 1 Cyclist, CKT-D, SR item.

Atwood's, CKT-P, CR, shown in Figure 2, 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.

Ms. Santucci's class is already familiar with the concepts of kinetic energy and gravitational potential energy. She wants 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 here, 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 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.)

Figure 2 Atwood's, CKT-P, CR item

While the preceding two items can be readily categorized not all of the items on this assessment are as explicitly CKT-D or CKT-P. Rather, the assessment items are distributed along a continuum of increasing pedagogical challenge. The items that we have categorized as CKT-P are those for which the principal cognitive challenge is directly related to pedagogy. We should also clarify that items that we have classified as CKT-P should not be considered to involve less sophisticated physics knowledge. Many of the CKT-P items require physics knowledge, both sophisticated and subtle.

3.2 General Patterns in Teachers' Performance on CKT-D and CKT-P Items

The online assessment was completed by 362 high school physics teachers from across the country. Among the 50 distinct items on the assessment, 25 could be answered based largely on disciplinary knowledge (CKT-D). Of these 25 items, 24 were selected-response items; 1 was constructed response. The remaining items required a combination of energy subject-matter knowledge and energy-specific pedagogical knowledge (CKT-P). Of these 25 items, 20 were selected response; 5 were constructed response. For the 24 CKT-D selected-response items the average teacher score was 64% with a standard deviation of 18% (see Table 1). For the 20 CKT-P selected-response items, the average score was 71%. For all constructed-response items we developed scoring 3-point rubrics and iteratively found these rubrics to achieve inter-rater reliability of 90% or greater. For example, on *Atwood's, CKT-P, CR* shown in figure 2 we determined whether each of the following elements was present in the teachers response:

- Personally Responsive – Teacher poses a question which is responsive to Taylor's question in a way that might lead her to move forward productively with her thinking.
- Intellectually Responsive – Teacher poses a question that is responsive to Taylor's intellectual need to precisely define her system when analyzing the work done by the gravitational force and changes in gravitational potential energy.
- Productive – Teacher poses a question that can be answered and is likely to lead to increased understanding.

Responses were awarded a single point for each element identified for a maximum possible score of 3. On the single CKT-D constructed-response item the average score was 57%. For the 5 CKT-P constructed-response items the average score was 49%. Standard deviations of teacher scores are also provided in Table 1. On the basis of these findings we see that the teachers found both CKT-D and CKT-P items reasonably challenging and that the teachers achieved similar success rates.

Table 1. *Participant Performance on Test Items by Category, N=362*.

Category	# Items (Points Possible)	Percentage of Points Possible
CKT-D, SR	24 (24)	64% ± 18%
CKT-P, SR	20 (20)	71% ± 13%
CKT-D, CR	1 (3)	57% ± 38%
CKT-P, CR	5 (15)	49% ± 20%

3.3 Contingency of CKT-P on CKT-D Among Teachers and Non-teachers

The CKT-P items on this assessment involve the application of disciplinary knowledge to address a pedagogical challenge. Therefore, it is reasonable to assume that some level of CKT-D would be required for teachers to perform well on the CKT-P items. We also expect that teachers would demonstrate a higher level of CKT-P compared with non-teachers with similar overall disciplinary knowledge of physics. To test the latter expectation we have previously reported the use of a Cognitive Diagnostic Model [32]. CDMs are a type of confirmatory latent class model. Fitting a CDM to the data requires specifying which skills are evaluated by each item, which in turn allows the specification of the latent classes. Here we hypothesize that examinees belong to one of three latent classes - (1) neither type of CKT, (2) CKT-D but not CKT-P, (3) both CKT-D and CKT-P. These latent classes were constrained to be ordered, which reflected our understanding of the hierarchical nature of CKT. That is, for an examinee to have mastered the CKT-P skill, they would also have to have mastered CKT-D. After the specification of the latent classes and their structure, the CDM was fit to the data. CDMs, and latent class models more generally, use the pattern of item responses to assign a probability of each examinee belonging to each latent class. These latent class assignments maximize the likelihood of the observed item responses in a process known as maximum likelihood estimation. The latent class categorizations are summarized in Table 2. This CDM was then used to compare the population of physics teachers with a population of 311 physics majors. The results are shown in Table 3.

Table 2. *Categorization of Test Subjects According to CKT-D and CKT-P*

	CKT Pedagogy		
CKT Disciplinary		Low = 0	High = 1
	Low = 0	00	
	High = 1	10	11

Table 3. *Latent Class Categorization of Teachers and Non-teachers, N teachers = 362, N non-teachers =311.*

	Latent Class 00	**Latent Class 10**	**Latent Class 11**
Both	0.59	0.14	0.27
Teachers (N = 362)	0.44	0.05	0.51
Non-teachers (N = 311)	0.75	0.25	0.00

Among the teacher sample group 51% showed mastery of both CKT-D and CKT-P. In contrast, there were no subjects within the non-teacher group who demonstrated mastery of CKT-P. While the teacher group performed better on the overall assessment, this difference alone does not explain the difference in their mastery of CKT-P. These results strongly suggest that teachers develop CKT-P through their work as teachers. The results also suggest a complex relationship between disciplinary knowledge and the application of that disciplinary knowledge in service of a pedagogical challenge. In the next two sections we will explore that relationship in greater detail. We will specifically focus on the role of supporting disciplinary knowledge as a resource for productively attending to student reasoning.

4 Patterns in Teacher System Energy Reasoning

The example items previously shown in Fig. 1 and Fig. 2 are similar in that they both involve systems reasoning. Systems reasoning in physics involves the ability to strategically select a system for analysis and recognize that the system choice will determine if the energy of that system is constant for a given scenario, recognizing that if the system was defined differently, its energy might not have been constant [17, 19, 33]. On the uphill cycling items many of the teachers taking the test had difficulty interpreting the different system choice options and how the system choice would affect the energy analysis, as suggested here:

> Generally the earth is not needed for inclusion into the calculation of the change in potential energy of the bike. Assuming that $U = mgh$ is being used, the mass of the earth and its subsequent motion is typically ignored. We only really want to analyze the forces and changes in energy of the rider/bike system. If we wanted to treat the Earth as the pavement, and use this in formulating our calculation of the work done by friction, then I suppose this could be useful. This leaves out the air unfortunately,

> which contributes significantly as negative work on the biker, and doesn't help us answer questions about the system effectively.

This teacher does not appear to understand that using the equation, $U = mgh$, implicitly includes Earth in the system for analysis. Several teachers explicitly commented that they did not understand what was meant by the word *system* and how to apply it. Based on those comments the items were revised for clarity and included the following statement explicitly describing how we wanted teachers to interpret the word in responding to the assessment items: "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."

Nevertheless, the role of a system remained difficult for many teachers who took our field test. We suspect that this difficulty can partly be attributed to disciplinary differences in the meaning of the word *system*. In physics, when analyzing a process, specifying a system is the prerogative of the scientist. Specifying a system involves deciding which object or objects to include in the system and which objects will be external to it. A choice of system in physics says nothing about the presence or absence of interactions among objects. That is additional information. In biology or ecology, a system includes all of the relevant objects together with their interactions. If you specify that an object is not within your system, in biology that is taken to mean that the object does not play a significant role in the processes under analysis. In physics, however, it just means that the object in question is in the environment of your chosen system. To get a better understanding of this distinction, compare the following:

- Consider the ecosystem of Yellowstone National Park. Now imagine that wolves are not part of your system. For the ecologist this would suggest that either the wolves have been removed from the park or they do not play a significant role within the ecosystem of the park.
- Now consider a person 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. The person would still play a critical role in the energy story but they would be transferring energy to the system through the process of work. By assigning the person to the environment the physicist is choosing not to track the complex changes in chemical and thermal energy within the person.

The canonical approach to energy analysis in physics is contingent on using the second approach to systems. When the concept of work is introduced to quantify energy transfer into or out of a chosen system this idea implicitly recognizes that objects in the environment are having a significant influence on the chosen system.

4.1 Teacher Performance on Systems Reasoning Items

Systems reasoning is a foundational aspect of energy reasoning. Therefore, we designed several assessment items that directly assess a teacher's ability to apply systems-based disciplinary energy reasoning in an instructional context. The uphill cycling item shown in Fig. 1 provides an example of one of these items in which teachers are asked to match an energy description with the corresponding system choice. From these items we created an 8-point composite index of CKT-D for energy systems reasoning and used it to score teachers' work. Teachers' scores on this composite index varied widely as shown in Figure 3. We classified 163 teachers who scored 3 or less on this composite index as demonstrating low systems CKT-D and 81 teachers who scored 6 or higher as demonstrating high systems CKT-D. The distribution of teacher scores on this composite index illustrates that systems is an area of CKT-D where teachers exhibit wide disparities in understanding.

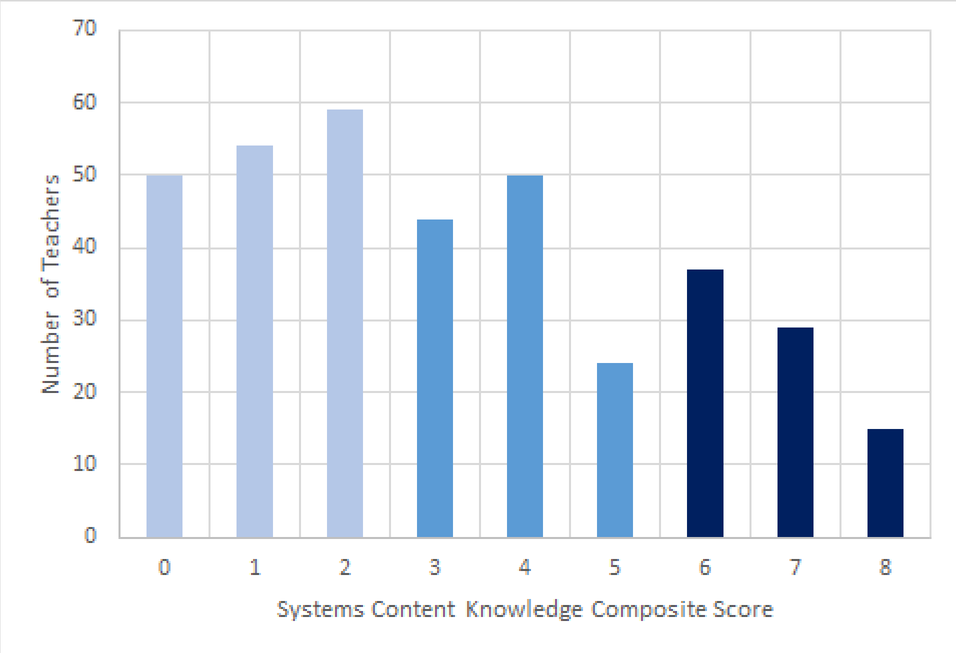


Figure 3. Teachers' systems reasoning composite CKT-D scores.

4.2 Attending Productively to Systems Reasoning

Teaching responsively involves sifting through the multitude of ideas that students voice and recognizing those ideas that provide entry points for additional scientific reasoning [34]. Several items on this assessment present hypothetical classroom situations in which students have expressed scientific ideas that are incomplete yet potentially productive. We then ask teachers to select an instructional response from a list of options and/or describe their response. We classify these items as CKT-P because they assess a teacher's ability to apply subject-matter knowledge and pedagogical knowledge in support of tasks of teaching. In this context we operationalize a productive response according to the following criteria:

- The teacher must be responding to the disciplinary content of a student statement or idea [35].
- The teacher's response must present an idea or strategy that has a reasonable likelihood of helping the students make progress with their statement or idea.

To be sure, in a real-life interaction, a potentially promising first response to *any* student utterance might be, “Tell me more,” or, “What do you mean by that?” Given that the same response could be given in *any* context and in *any* subject-matter domain, we chose not to count this as a complete answer for the purposes of an energy-specific assessment of CKT in physics.

Atwood’s, CKT-P, CR, shown previously in Fig. 2, is a constructed-response item that involves responding to a student’s question about the energetics of an Atwood’s machine. Atwood’s, CKT-P, CR is preceded by Atwood's, CKT-D, SR, which prompts teachers to decide whether the total energy of the large block-Earth system is increasing, decreasing, or remaining roughly constant. Atwood's, CKT-P, CR is the constructed-response item in which a student raises an insightful question that stems from the need to clarify a system in order to apply work and energy reasoning (see Figure X.2). Taylor’s statement demonstrates highly metacognitive scientific thinking as she strives to reconcile her understanding of work and gravitational energy. Specifically, Taylor is primed to recognize that Earth must be included in the system for the system to have significant gravitational energy. Earth can only do work on the system if it is not included in the system. This is an instantiation of a subtle yet fundamental idea in systems-based work and energy analysis. Most high school and college physics teachers introduce the concept of work so it is very likely that thoughtful students will need to work out this subtle distinction at some point.

We have chosen to present *Atwood’s, CKT-P, CR* in this chapter 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. *Atwood’s, CKT-P, CR* is also an item that was relatively difficult for the majority of teachers who participated in our study. We evaluated constructed responses to *Atwood's, CKT-P, CR* on a 3-point rubric in which teachers were awarded one point for productively responding to each component of the item. Productively responding to Taylor’s question about work and gravitational energy teaching was relatively difficult for the teachers in our study (see Figure 4). Only 29% of all teachers completing the field test were able to respond productively to any component of the item. A select group of teachers provided answers that addressed all three questions as illustrated by the following examples:

> Taylor needs to understand that work is only done by external forces. I would ask Taylor to reiterate what makes up the system. If she answers that it is the larger block and the 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 the earth.

> a.) A system cannot do work on itself. We already established that the system includes the block and the earth. Therefore, we can't count the work done by gravity because the earth is in the system .b.) What objects did you include in your system? c.). Hopefully she will answer the 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.

We might suggest that the fish tank analogy is problematic because it suggests that the physical configuration, rather than the physicist, determines the system. Nevertheless, both of these teachers correctly interpret the likely inconsistency with which Taylor is struggling. The second teacher also provides evidence that she recognizes this as a prevalent inconsistency that learners encounter.

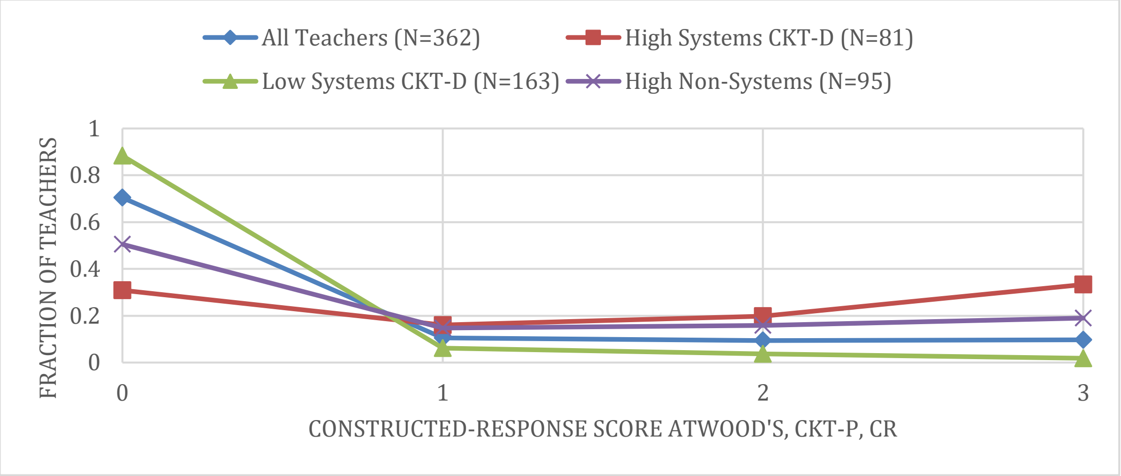


Figure 4. The fraction of teachers who responded productively to student reasoning in *Atwood's, CKT-P, CR.*

The majority of teachers were unable to respond productively to any component of the item as illustrated by this example:

> a. 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 the Earth. b. I would ask Taylor to define work and describe how it can be calculated. c. 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.

The physics content of this response is correct, but it does not address the question Taylor has raised. There is no evidence in Taylor's question to suggest that she does not recognize how work is calculated. In addition, Taylor has explicitly stated 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:

> I don't really understand what she is saying when she says "the gravitational energy of the block and the 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.

4.3 Contingency of Productive Attentiveness on Systems Knowledge

In order to respond to the disciplinary content of Taylor's statement 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. This expectation was confirmed by comparing responses on *Atwood's, CKT-P, CR* for teachers with low and high systems reasoning composite CKT-D scores. Teachers with low systems CKT-D demonstrated very little success navigating this teaching situation. Only 11% of these teachers were able to respond productively to any portion of the constructed-response items as shown in Fig. 4. In contrast, teachers with high systems CKT-D had significantly more success; 69% of them were able to respond productively to some portion of the constructed-response items.[2]

Is it possible 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 maybe systems subject-matter knowledge is a separate aspect of energy knowledge, and one can know lots about energy but without understanding systems cannot respond productively to student difficulties of this sort? To test these two 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 call them non-systems items high-performing teachers. If the first explanation above were correct, then the non-systems items high-performing teachers would do as well on *Atwood's, CKT-P, CR* as the teachers with a high systems score. If the second one were correct, then the performance of non-systems items high-performing teachers should be significantly lower than the performance of the teachers with high systems knowledge. 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 69% of the teachers with high systems knowledge. The difference in performance between each of these two groups was significant at the 0.01 level.

[2] *Atwood's, CKT-D, SR* immediately follows *Atwood's CKT-P, CR* and asks subjects to determine if the energy of the large block-Earth system is increasing, decreasing, or remaining approximately constant. There are multiple ways to correctly answer this item, some of which do not require a deep understanding of systems reasoning. In contrast, a subject is unlikely to answer all parts of *Cyclist, CKT-D, SR* correctly without a deep understanding of systems reasoning. This was our motivation for using a composite systems CKT-D score that provides a clear gauge of a teacher's disciplinary knowledge for systems reasoning.

5 Patterns in Teacher Quantitative Energy Reasoning

In the preceding section we presented an example in which attending productively to student reasoning was highly contingent on supporting disciplinary knowledge. This result is not surprising. One might assume that teachers will always need robust disciplinary knowledge in order to respond productively to the scientific thinking of their students. One might even assume that teachers themselves must know the correct answer in order to help their students make progress toward that answer. In this section, we present an example from quantitative energy reasoning that complicates the first assumption and challenges the second.

5.1 Attending Productively to Quantitative Energy Reasoning

Basketball, *CKT-P*, *SR* and *CR* in Figure 5 are selected-response and constructed-response questions that involve responding to a student dialogue about the energetics of a bouncing basketball. The classroom scenario described in this item was inspired by real classroom experiences. Basketball, *CKT-P*, *SR* and *Basketball*, *CKT-P*, *CR* both assess a teacher's ability to identify an instructional activity that would allow the students to build on and refine their quantitative energy reasoning. The student statements provide some of the essential components of a mathematical approach to this item. For the same exerted force the compression of the object is inversely proportional to the effective spring constant. The resulting elastic energy will then be greater for the object with the lower spring constant and a corresponding greater amount of compression.

This item requires knowledge that is beyond the domain of pure subject-matter knowledge. The teacher should recognize additional ideas that could help the students resolve their debate and identify a specific activity, in this case a specific experiment, that could be feasibly carried out in the classroom and would allow the students to develop these ideas further. Specifically, the students could use two springs with different spring constants, compress them exerting the same force, measure the compressions, and compare the energy of two non-identical springs when they are compressed with the same force. This approach would allow the students to collect data to mathematically compare the elastic energy in the simpler, and more familiar, example of two springs. Once they have worked out the energy comparison for two simple springs they should be able to apply this comparative model to the basketball bouncing on the floor. This item includes both a selected-response portion and a constructed-response portion, the latter of which invites the teacher to explain her choice. Scoring rubrics for the constructed-response answers were developed and refined to achieve an inter-rater reliability at least as large as 90%.

Two students in Ms. Engel's physics class are discussing the energetics of dribbling a basketball on a wooden floor. They agree that all of the kinetic energy gets converted into elastic energy for an instant when the basketball is compressed the most. They also agree that many objects, even basketballs and wooden floors, can be modeled as springs. They are uncertain about whether there would be equal amounts of elastic energy in the ball and the floor. They call Ms. Engel over to share their ideas with her and get some help.

Marcos says, "We were thinking that when the ball compresses against the floor, the forces that the ball and the floor exert on each other would be equal and opposite, so maybe the amount of elastic energy in the floor is the same as the elastic energy in the ball."

Louisa responds, "I get that the forces are the same, but I am thinking that the ball compresses more than the floor, so shouldn't there be more energy stored in the ball?"

Marcos replies, "But the floor is more rigid and would have a higher spring constant. I think the larger k of the floor compensates for the smaller Δx in the $\frac{1}{2}k(\Delta x)^2$ equation, and the elastic energies are the same."

1. Is Marcos correct that the elastic energy of the ball and the floor would be the same?

A. Yes. (31%)
B. No. The elastic energy of the ball would be greater. (51%)
C. No. The elastic energy of the floor would be greater. (1%)
D. There is not enough information to compare these energies. (17%)

2. Which of the following activities would be most likely to provide Ms. Engel's students with additional insights about the relative amounts of elastic energy during the bounce of the basketball?

A. They could measure the spring constants and the displacements of both the floor and the ball and use those to compare the elastic energies. (10%)
B. They could compare the elastic energies of two non-identical springs when they are compressed with the same force. (70%)
C. They could do an experiment to see if a basketball bounces higher on a soft carpet surface or a hard concrete floor. (14%)
D. They could do an experiment to show that the same basketball will not bounce as high off the gym floor if it has first been put in a freezer. (6%)

Explain your selection and how the activity you selected might provide the students with additional insights about the relative elastic energy during the bounce of a basketball

Figure 5. *Basketball, CKT-D, SR and Basketball, CKT-P, CR* questions.

Seventy percent of teachers in our sample selected the most productive instructional response from the choices provided on *Basketball, CKT-P, SR*. Seventy-three percent of teachers provided at least a partially correct explanation of how their chosen instructional response could provide students with additional insights about the energetics of a bouncing basketball as shown in Fig. 6. The following examples both illustrate full explanations of the most productive instructional response:

> Their argument seems to hinge on the difference between the linear relationship in *F=-kx* and the squared relationship in energies. By looking at two springs with measurable and quantifiable spring constants and compressions, they can see that while forces may be equal, relative energies are dominated by the squared term. The other experiments are useful to show how modification to one or the other changes things, but their argument seems to hinge on this mathematical confusion which should first be analyzed with more simplistic and easily quantifiable things. [...]

> Since the floor and the ball aren't identical, but do experience the same force, the chosen scenario is the easiest to actually do an experiment with. If the same force yields the same stored energy for each spring, the

ball and the floor would store the same amount of energy. If the experiment shows that the two springs store different amounts of energy, then the ball and the floor store different amounts. I haven't done the experiment, but I would expect the ball to be the weaker spring and therefore store more energy because of the x^2 in the PE function.

Why were teachers so much more successful in responding productively to this teaching situation than in the case of the Atwood's example? Perhaps the relevant CKT-D of quantitative energy reason is simply much more widely held than the CKT-D, which supports systems reasoning.

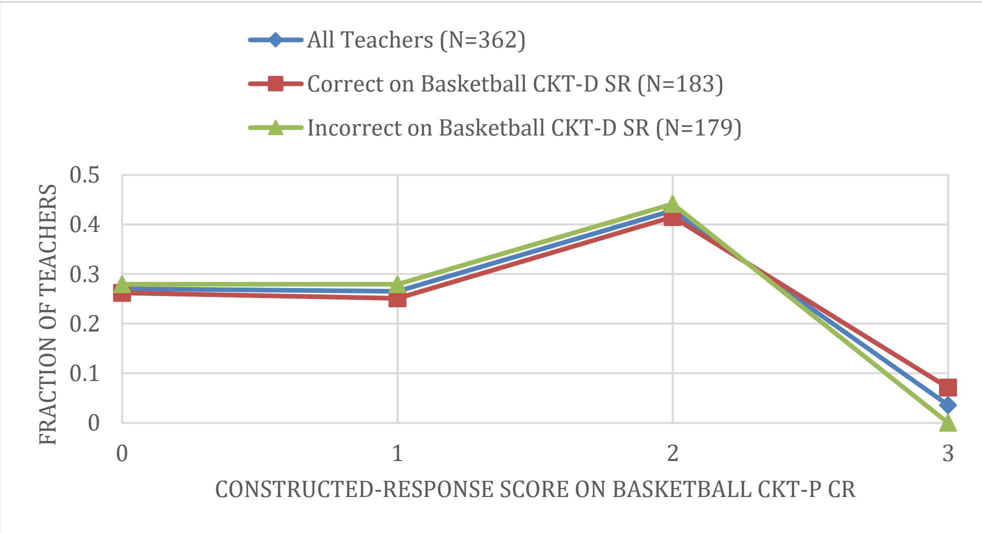


Figure 6. The fraction of teachers who correctly explained in the *CR* question their responses to the *Basketball, CKT-P, SR* question.

5.2 Contingency of Productive Attentiveness on Quantitative Energy Knowledge

Based on our findings for the *Atwood's* item we might expect that a teacher would be better prepared to suggest a productive strategy for comparing the elastic energies of the basketball and the floor if they had a correct understanding of how these elastic energies actually do compare. *Basketball, CKT-D, SR* provides teachers with the opportunity to demonstrate this understanding. Slightly more than half of teachers correctly recognized that the basketball would have more elastic energy during the bounce. We might expect that the teachers who displayed correct content knowledge on *Basketball, CKT-D, SR* would be significantly more likely to select the most productive instructional response on *Basketball, CKT-P, SR*. However, we found that the disciplinary knowledge necessary to correctly answer the *CKT-D* question had relatively little impact on a teacher's likelihood of selecting a productive instructional response on the *CKT-P* question as shown in Table 4. Surprisingly, of the 179 teachers who answered the first SR question incorrectly, 66% were able to select the most productive instructional response on the second SR question.

Table 4. Teachers' Performance on *Basketball, CKT-D, SR* and *Basketball, CKT-P, SR*

Teacher Group	Correct on *Basketball, CKT-P, SR*
All Teachers (N = 362)	255 (70%)
Correct on *Basketball, CKT-D, SR* (N = 183)	136 (74%)
Incorrect on Basketball, CKT-D, SR (N = 179)	119 (66%)

Figure 6 shows that many of these teachers provided at least a partially correct explanation of how their chosen instructional response could provide students with additional insights about the energetics of a bouncing basketball, as one can see from the examples presented below. All of these examples are from the group of teachers who incorrectly agreed with Carlos that the ball and the floor would have the same elastic potential energies.

> The idea that the gym floor has a higher *k* value because it is more stiff than the ball should be obvious to most. Measuring the spring constants of the floor and the ball are probably not feasible in a high school science class, otherwise the first choice would have been the best. The forces are equal based on Newton's 3rd Law. I thought number 2 was the best choice because you could see how different *k* values, but identical forces affect the elastic energies of the springs, but it would also be practical to do in a school.

> Although I like the idea of testing Marcos's hypothesis in option one, the difficulty of finding the displacement of the floor and the very real possibility of having a particular trial happen to have the same elastic energy is a problem. By testing two non-identical springs and the resulting energy from not only the same force but different identical forces, will help eliminate variables out of your control while still addressing the issue of two different spring constants interacting with each other like the ball and the floor.

Surprisingly, the disciplinary knowledge necessary to correctly answer *Basketball, CKT-D, SR* had relatively little impact on a teacher's propensity to select or explain a productive instructional response. The small difference in performance on *Basketball, CKT-P, SR* among the teachers who selected the correct CKT-D response (74%) versus the teachers who did not (66%) was not significant at the 0.05 level. The performance on *Basketball*, *CKT-P*, *CR* was also similar.

6 Summary and Implications for Instruction

In this paper we set out to answer the following research questions in the context of a paper-and-pencil assessment:

1. To what degree is the productivity of teacher responses to student thinking contingent on the teacher's content knowledge of the relevant physics topic?
2. Are there specific aspects of content knowledge of the relevant topic that are critical for supporting student thinking?

6.1 Identifying Foundational and Elaborative CKT-D

Our findings suggest that in some cases responding productively to students is contingent on strong supporting disciplinary knowledge. This may be especially true when disciplinary knowledge relates to a fundamental or axiomatic rather than experimentally testable aspect of the energy model.[3] In our study such a fundamental aspect of the energy model is the concept of a system. In physics, the underlying idea of a system is that there is a choice of objects to be included in the system but once the choice is made, these objects cannot exchange energy with the system. Their interactions and motions contribute to the system's total energy. Only objects that are external to the system can exchange energy with the system. One can write equations for energy types and solve simple problems involving such calculations without a deep understanding of this idea, however, it is often not possible to track energy flow and make real connections between energy and mechanisms for energy transfer without an understanding of this foundational piece of the energy framework. A good example here is knowing when to apply the work-kinetic energy theorem (the work done by the net force exerted on an object is equal to the change of the object's kinetic energy) or a more general energy conservation statement (the change of the energy of the system is equal to the work done by external forces on the system assuming that thermal energy transfer is zero, as it is in our case). Here the subtle difference between a point particle model in the first case and an arbitrarily chosen system of interacting objects in the second case is crucial. Experts understand this difference and do not confuse the two, while novices often do [36, 37]. Can a teacher help a student recognize the difference if she does not have a solid understanding of the concept of a system? Based on our study we answer this question in the negative. The reason here lies in the fundamental, model-based nature of system reasoning in physics, which does not lend itself to experimental tests and yet is the foundation of all further investigations.

However, we also found that in some cases responding productively to student thinking is not contingent on strong subject-matter knowledge. This may be especially true when this kind of knowledge supports a specific elaboration (application) of the energy model. In our study we found that even those teachers who were not successful in applying the mathematical expression for elastic potential energy could still choose a productive teaching approach to help their students understand the difference between force and energy. This approach involved deciding what experiment students could

[3] There is no experiment that one could conduct to decide how one should select a system.

conduct to test their ideas. We found that when the teachers had an option to choose a strategy to help a student understand the nature of the mathematical expression for elastic potential energy, more teachers than in the case of systems were successful in choosing a productive experiment.

6.2 Implications for Teacher Professional Preparation

In a traditional approach to teacher preparation it is assumed that prospective teachers develop content knowledge (everything they need to know about the discipline) while they are taking courses in the science departments and later learn teaching-related knowledge in the schools of education. Research into PCK, and more recently CKT, provides frameworks for understanding the limitations of this traditional approach. The disciplinary knowledge that physics teachers draw on in their classrooms extends beyond the content knowledge of physics majors. Thus, if we wish to prepare and graduate qualified teachers, they need to develop content knowledge for teaching their respective disciplines [10, 11]. This means that we need to develop special methods courses where future teachers learn how to teach their subject matter (e.g., physics, chemistry, biology, mathematics) instead of putting them all together in one generic science methods course [38]. Development of such courses is challenging and should be informed by formative assessment of discipline specific content knowledge for teaching [39]. It is critical to prioritize knowledge and strategies that will best support teachers in responding productively to student thinking. We believe that this study presents a model for identifying specific areas of disciplinary knowledge that are both essential and often deficient among practicing teachers.

The disciplinary knowledge base that teachers deploy to support and respond productively to student thinking is subtle, complex, and extensive. Therefore, we should hope that the requisite knowledge base will be constructed and refined through reflective experience in the classroom. Our results provide both encouraging and cautionary insights into the in-service development of CKT. We are encouraged by cases where teachers are able to utilize their knowledge of pedagogy and scientific practices to compensate for a lack of CKT-D. This provides a promising avenue for continued growth of disciplinary knowledge throughout a teacher's career. In order to prime teachers for this type of ongoing professional growth, teacher preparation programs should emphasize domain-specific pedagogical and scientific practices. Our results also suggest that a greater emphasis on pedagogy and practices is necessary but not sufficient. Even a robust understanding of these practices will not compensate for foundational or axiomatic disciplinary knowledge that cannot be tested empirically, such as the physics-specific relationship of work and systems.

It is very important that those who prepare teachers in a specific content area are in agreement regarding what constitutes foundational content knowledge in their discipline (in the areas relevant to K–12 curriculum) and what science practices are most helpful for responding to student ideas. The Next Generation Science Standards (NGSS) disciplinary core ideas, crosscutting concepts, and science practices provide a framework for enumerating these foundational ideas and practices, but we feel that additional evidence-based refinement is necessary. For example, in physics one of the practices that helps students test their ideas or that helps teachers respond productively to student ideas is experimentation (real or imaginary) and follow-up data analysis and interpretation. Additional attention should be given to this aspect of physics teacher preparation, but an increased emphasis on traditional laboratories will not empower teachers to respond productively to student thinking. We envision modeling the design of experiments to responsively test learner ideas as an integral and extensive component of teacher professional preparation programs. It is unrealistic to expect teachers to establish empirically responsive classrooms if they have not previously participated in such a learning community.

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Appendices

Appendix A: Tasks Of Teaching

Task of Teaching	Description	Specific Tasks
I. Anticipating student thinking around science ideas	*While planning and implementing instruction teachers are able to*	*Teachers:* I. a) anticipate specific student challenges related to constructing scientific concepts, conceptual and

	anticipate particular patterns in student thinking. They understand and recognize challenges students are likely to confront in developing an understanding of key science concepts and mathematical models. Teachers are also familiar with student interests and background knowledge and enact instruction accordingly.	quantitative reasoning, experimentation, and the application of science processes I. b) anticipate likely partial conceptions and alternate conceptions, including partial quantitative understanding about particular science content and processes I. c) recognize student interest and motivation around particular science content and practices I. d) understand how students' background knowledge both in physics and mathematics can interact with new science content
II. Designing, selecting, and sequencing learning experiences and activities	*Classroom learning experiences and activities are designed around learning goals and involve key science ideas, key experiments, and mathematical models relevant to the development of ideas and practices. Learning experiences reflect an awareness of student learning trajectories and support both individual and collective knowledge generation on the part of students.*	*Teachers:* II. a) design or select and sequence learning experiences that focus on sense-making around important science concepts and practices, including productive representations, mathematical models, and experiments in science that are connected to students' initial and developing ideas II. b) include key practices of science including experimentation, reasoning based on collected evidence, experimental testing of hypotheses, mathematical modeling, representational consistency, and argumentation II. c) address projected learning trajectories that include both long-term and short-term goals and are based on evidence of actual student learning trajectories II. d) address learners' actual learning trajectories by building on productive elements and addressing problematic ones II. e) provide students with evidence to support their understanding of short- and long-term learning goals II. f) integrate, synthesize, and use multiple strategies and involve students in making decisions II. g) prompt students to collectively generate and validate knowledge with others II. h) help students draw on multiple types of knowledge, including declarative, procedural, schematic, and strategic II. i) elicit student understanding and help them express their thinking via multiple modes of representation II. j) help students consider multiple alternative approaches or solutions, including those that could be considered to be incorrect
III. Monitoring, interpreting, and acting on student thinking	*Teachers understand and recognize challenges and difficulties students experience in developing an understanding of key science concepts; understanding and applying mathematical models and manipulating*	*Teachers:* III. a) employ multiple strategies and tools to make student thinking visible III. b) interpret productive and problematic aspects of student thinking and mathematical reasoning III. c) identify specific cognitive and experiential needs or patterns of needs and build upon them through instruction

	equations; designing and conducting experiments, etc. This is evident in classroom work, talk, actions, and interactions throughout the course of instruction so that specific learning needs or patterns are revealed. Teachers also recognize productive developing ideas and problem solutions and know how to leverage these to advance learning. Teachers engage in an ongoing and multifaceted process of assessment, using a variety of tools and methods. Teachers draw on their understanding of learners and learning trajectories to accurately interpret and productively respond to their students' developing understanding.	III. d) use interpretations of student thinking to support instructional choices both in lesson design and during the course of classroom instruction III. e) provide students with descriptive feedback III. f) engage students in metacognition and epistemic cognition III. g) devise assessment activities that match their goals of instruction
IV. Scaffolding meaningful engagement in a science learning community	*Productive classroom learning environments are community-centered. Teachers engage all students as full and active classroom participants. Knowledge is constructed both individually and collectively, with an emphasis on coming to know through the practices of science. The values of the classroom community include evidence-based reasoning, the pursuit of multiple or alternative approaches or solutions, and the respectful challenging of ideas.*	*Teachers:* IV. a) engage all students to express their thinking about key science ideas and encourage students to take responsibility for building their understanding, including knowing how they know IV. b) develop a climate of respect for scientific inquiry and encourage students' productive deep questions and rich student discourse IV. c) establish and maintain a "culture of physics learning" that scaffolds productive and supportive interactions between and among learners IV. d) encourage broad participation to ensure that no individual students or groups are marginalized in the classroom IV. e) promote negotiation of shared understanding of forms, concepts, mathematical models, experiments, etc., within the class IV. f) model and scaffold goal behaviors, values, and practices aligned with those of scientific communities IV. g) make explicit distinctions between science practices and those of everyday informal reasoning as well as between scientific expression and everyday language and terms IV. h) help students make connections between their collective thinking and that of scientists and science communities IV. i) scaffold learner flexibility and the development of independence

		IV. j) create opportunities for students to use science ideas and practices to engage real-world problems in their own contexts
V. Explaining and using examples, models, representations, and arguments to support students' scientific understanding	*Teachers explain and use representations, examples, and models to help students develop their own scientific understanding. Teachers also support and scaffold students' ability to use models, examples, and representations to develop explanations and arguments. Mathematical models are included as a key aspect of physics understanding and are assumed whenever the term* model *is used.*	*Teachers:* V. a) explain concepts clearly, using accurate and appropriate technical language, consistent multiple representations, and mathematical representations when necessary V. b) use representations, examples, and models that are consistent with each other and with the theoretical approach to the concept that they want students to learn V. c) help students understand the purpose of a particular representation, example, or model and how to integrate new representations, examples, or models with those they already know V. d) encourage students to invent and develop examples, models, and representations that support relevant learning goals V. e) encourage students to explain features of representations and models (their own and others') and to identify/evaluate both strengths and limitations V. f) encourage students to create, critique, and shift between representations and models with the goal of seeking consistency between and among different representations and models V. g) model scientific approaches to explanation, argument, and mathematical derivation and explain how they know what they know. They choose models and analogs that accurately depict and do not distort the true meaning of the physical law and use language that does not confound technical and everyday terms (e.g., heat and energy). V. h) provide examples that allow students to analyze situations from different frameworks such as energy, forces, momentum, and fields
VI. Using experiments to construct, test, and apply concepts	*Teachers provide timely and meaningful opportunities throughout instruction for students to design and analyze experiments to help students develop, test, and apply particular concepts. Experiments are an integral part of student construction of physics concepts and are used as part of scientific inquiry in contrast with simple verification.*	*Teachers:* VI. a) provide opportunities for students to analyze quantitative and qualitative experimental data to identify patterns and construct concepts VI. b) provide opportunities for students to design and analyze experiments using particular frameworks such as energy, forces, momentum, field, etc. VI. c) provide opportunities for students to test experimentally or apply particular ideas in multiple contexts VI. d) provide opportunities for students to pose their own questions and investigate them experimentally VI. e) use questioning, discussion, and other methods to draw student attention during experiments to key aspects needed for subsequent learning, including the limitations of the models used to explain a particular experiment

		VI. f)	help students draw connections between classroom experiments, their own ideas, and key science ideas
		VI. g)	encourage students to draw on experiments as evidence to support explanations and claims and to test explanations and claims by designing experiments to rule them out

Appendix B: Energy-Specific Student Targets

(ENERGY-RELATED CONTENT AND PRACTICE IDEAS)

A. Connections of energy and everyday experiences

The student:

1) uses energy ideas to interpret or explain everyday phenomena
2) recognizes the important role of internal energy in interpreting or explaining everyday phenomena

B. Choice of system

The student:

1) recognizes that the energy accounting in a phenomenon depends on the choice of system
2) explains the relative advantage of a given system choice (i.e., relative ease of analysis)
3) recognizes that the choice of system determines whether springs or Earth do work (i.e., if the spring or Earth are in the system they do not do any work on the system, but the system can possess elastic or gravitational potential energy)
4) identifies and differentiates between forms of energy and other physics concepts

C. Identification of and differentiation between forms of energy and other physics concepts

The student:

1) recognizes that energy cannot be observed directly and knows how different forms of energy correspond to different measurable physical quantities
2) recognizes and maintains a consistency of scale (microscopic or macroscopic) during energy analysis
3) differentiates between energy and related ideas (e.g., force, power, stimulus, trigger, activation, speed, distance, temperature)
4) distinguishes between forms of energy and energy transfers

D. Transfer of energy (environment→system; system→environment)

The student:

1) recognizes that the energy of a system is always conserved but might not be constant
2) recognizes that work is the way in which energy is transferred mechanically and may result in a change in temperature in some cases
3) avoids double counting when analyzing processes involving work and energy
4) recognizes when to use compensatory models for tracking energy into and out of a system and when quantitative models are of limited use

E. Use of mathematics

The student:

1) understands that when considering potential energy, it is important to think about the change. The zero level of potential energy is arbitrary, but the change is not. The energy of attraction is negative if the zero level is set at infinity.
2) can account for vector and scalar quantities in energy analysis
3) understands that work is a scalar quantity and the positive or negative sign of work does not indicate direction but addition or subtraction
4) connects forms of energy and the factors on which they depend through appropriate linear and non-linear mathematical relationships
5) applies conservation as a mathematical constraint on the outcomes of possible processes
6) recognizes that the mathematical analysis of energy-related processes depends on the choice of initial and final state and the choice of system

F. Use of representations

The student:

1) selects/creates and uses appropriate verbal, mathematical, and graphical/pictorial representations (specific for energy, such as bar charts, energy diagrams, etc.) to describe, analyze, and/or communicate a physical situation or process
2) interprets different representations used to describe, analyze, and/or communicate a physical situation or process
3) understands the relationships between different representations of the same phenomenon and seeks consistency among different representations
4) understands standard technical representations and language used to communicate energy-related ideas

G. Use of science practices

The student:

1) uses a range of representations to communicate ideas and illustrate or defend explanations
2) connects energy ideas to other learning and real-life processes and projects through experimental investigations, energy problem solutions, and engineering designs
3) designs experiments to test competing hypotheses

4) makes choices in data collection and analysis that allow for inferring the amounts and transfers of energy even when they cannot be measured directly
5) connects experiments and data to the mathematical representations of energy
6) evaluates and negotiates choices/options by considering the merits, limitations, and relative advantages of different engineering designs in terms of, for example, different choices of energy models for the same physical process
7) provides evidence-based arguments concerning energy processes and engineering designs
8) demonstrates consistency and coherence in model-based and evidence-based reasoning in making predictions and interpreting results