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Think-aloud interviews were used to investigate college students' cross-disciplinary understanding of energy concepts. Interview subjects were enrolled in a set of four science content courses (physics, biology, geology, and chemistry) for preservice K-8 teachers. These courses, built around the common theme of the flow of energy and matter through interacting systems, use similar vocabulary, modeling tools, and pedagogy to teach energy concepts. The interview tasks were designed to probe how students apply energy concepts originally learned in the physics course in less familiar contexts in geology, biology, and chemistry. Transcripts were analyzed using a coding scheme based on conceptual resources. Thematic analysis was then conducted to identify common patterns in students' cross-disciplinary reasoning, particularly with regard to potential energy. The constructs of disciplinary and situated productivity were used to guide the development of themes. We find that students engage in productive reasoning about energy across disciplines. Students activate ideas related to energy forms and the objects to which these forms are attached with relatively high frequency, and ideas related to physical indicators and mechanisms for energy transfers and transformations with relatively lower frequency. Students apply potential energy concepts across disciplines, but often struggle to identify the physical manifestations of potential energy changes in less familiar contexts. While this study was conducted in a set of courses for preservice teachers, the findings have broader implications for introductory physics courses that serve as prerequisites for other disciplinary coursework.

DOI: [10.1103/hwnw-m3cl](https://doi.org/10.1103/hwnw-m3cl)**I. INTRODUCTION**

A goal of science education is for students to apply foundational principles to explain real-world phenomena. Rather than viewing such principles as isolated or compartmentalized, we want students to recognize the coherence

between different branches of science that overarching ideas provide. One of the most foundational of these ideas is energy. The Next Generation Science Standards (NGSS) include energy as both a cross-cutting concept and a disciplinary core idea [1,2]. Furthermore, the National Research Council's Discipline-Based Education Research (DBER) report [3] identifies transfer—the ability of students to apply ideas and skills in contexts different from those of the original learning—as a “prime goal” and “fundamental assumption” of education (p. 149). The DBER report calls for research into the extent to which this type of learning occurs, and how it occurs, in sequences of college science and engineering courses.

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Many science programs in U.S. higher education involve courses that are disconnected from one another and offered in siloed departments. Such courses often use discipline-specific vocabulary and modeling tools to teach energy concepts [4] and emphasize algorithmic problem solving. These approaches to instruction can lead to a focus on surface features, preventing students from recognizing and applying unifying themes across domains. Research suggests, for example, that introductory chemistry students struggle to apply the fundamental concept of potential energy, previously learned in physics, to chemical systems [5–7].

At Western Washington University, preservice elementary teachers complete a sequence of science content courses in physics, biology, geology, and chemistry. These courses share a common focus on the flow of matter and energy through systems and use shared vocabulary and representational tools related to energy. We have used this course sequence as a laboratory to explore student learning of energy concepts across science disciplines. In this work, we have adopted a novel theoretical construct, *cross-disciplinary learning*, described in detail elsewhere [8] and summarized below in Sec. II. This construct draws on existing theoretical frameworks, including conceptual resources [9], transfer [10,11], and interdisciplinary learning [12].

Our investigation of students' cross-disciplinary learning of energy has involved both quantitative and qualitative studies. A previous publication described a quantitative study that involved a validated instrument pair to gauge the extent to which students successfully apply a basic energy model, learned originally in a physics course, to analyze chemical phenomena [13]. The present article describes a qualitative study that involves think-aloud interviews, in which we explore “what it looks like” when students apply learned energy ideas in novel disciplinary contexts. We have taken an applied approach, seeking to describe themes in student learning in instructionally meaningful ways.

The purpose of this research is not to assess the effectiveness of the curricula in supporting student learning, but rather to document reasoning approaches taken by students as they apply an overarching principle, energy, across disciplinary contexts. We conducted interviews with students who had completed the physics course and were enrolled in the biology, geology, or chemistry course. Our goal was to uncover patterns in reasoning, specifically with respect to cross-disciplinary learning, and to describe those patterns in ways useful to teachers and curriculum developers as they make instructional choices. Two broad questions have guided our research:

Research question 1: What conceptual resources for understanding energy are activated when students are asked to explain phenomena in a novel disciplinary context?

Research question 2: How do students use these resources? What specific conceptual or reasoning difficulties do students encounter?

In the remainder of the introduction, we discuss the role of energy as a unifying concept in the sciences, survey the relevant prior research on the teaching and learning of energy, and describe the instructional context for the present study. Section II summarizes cross-disciplinary learning as the theoretical framework for the study. Sections III and IV describe our interview protocols and share findings. In Sec. V, we summarize our results and discuss implications for instruction.

A. Energy as a cross-cutting concept

Energy is arguably one of the most important unifying explanatory frameworks in science [4]. The same ideas about energy forms, transfer, transformation, and conservation can be used to describe a ball slowing as it travels upward after a toss, a building shaking during an earthquake, a person metabolizing food as they run, and a mixture changing temperature during a chemical reaction. The importance of energy is highlighted by its inclusion as both a disciplinary core idea and a cross-cutting concept in the Next Generation Science Standards (NGSS) [1,2]. The inclusion of energy as a cross-cutting concept reflects an aspiration for students to connect energy concepts across disciplines and to see energy as a universal framework for guiding scientific thinking in all disciplines. Yet each discipline has its own vocabulary and norms surrounding the use of energy concepts to model, investigate, and explain phenomena [4]. Thus, students in traditional, siloed higher education structures may tend to compartmentalize their learning about energy [14,15]. While experts will recognize energy connections across contexts and disciplines, these connections may be less apparent to novices, even when they have developed a deep understanding of energy in one discipline.

B. Prior research on student understanding of energy concepts

Scholarship on the learning and teaching of energy concepts is extensive. Here, we highlight prior studies of postsecondary student learning directly relevant to our own study. Within this domain, three strands of prior work have particular relevance: student (and expert) use of a substance ontology for energy; empirical studies identifying specific difficulties with energy concepts; and application of the resources theoretical framework to identify students' productive conceptual resources for understanding energy.

1. Substance ontology for energy

Many students, and even experts, speak of and reason with energy as a material substance that can flow between

objects [16,17]. In fact, substancelike metaphors for energy are deeply embedded in everyday ways of talking about energy [18,19]. A substance ontology for energy, while perhaps not rigorously consistent with normative scientific models, is nevertheless productive for explaining phenomena [17,20–22]. Gray and colleagues have pointed out that the NGSS model for energy “consistently employs a metaphor in which energy is a substance,” and further that NGSS use of this metaphor is consistent with “how physicists conceptualize energy” [23]. Physics textbook authors have noted that energy, as a fundamental and highly abstract concept, is difficult or impossible to define in terms of more fundamental quantities—and that instruction therefore rightfully focuses on the properties of energy (i.e., instead of the nature of energy) [24]. Some work has identified specific affordances for productive reasoning offered by a substance metaphor for energy [17,20,21,25], while other work has documented difficulties distinguishing energy from matter [26,27] that can stem from this metaphor.

2. Identification of specific difficulties with energy concepts

Empirical research has identified a variety of specific difficulties with energy and energy conservation. In many situations, students may not recognize the central importance of specifying a system when applying an energy model. For example, in physics contexts, students often associate potential energy with a single object (e.g., the “gravitational potential energy of a tossed ball”), perhaps not recognizing that potential energy is defined in terms of the interaction of two objects (i.e., the ball and the Earth) [28]. In our own experience, many students have difficulty applying ideas about potential energy to open systems. For example, students often seem to regard potential and kinetic energy as inverses of each other and struggle with situations in which both increase or both decrease. Difficulties with systems can interfere with the development of functional understanding of the conservation principle; for example, by leading students to “double count” energy quantities [28,29]. Difficulties related to systems may be compounded as students attempt to bridge their energy understanding across disciplines, as different disciplines approach and define systems differently. As discussed by Seeley *et al.*, for example, in biology, a system is often regarded holistically, as a set of interacting objects that form a unified whole, while in physics, a system consists of those objects selected for analysis, with other objects designated to be part of the “surroundings” [29].

Studies have shown that even advanced physics students can struggle to recognize that while energy is a conserved quantity, the choice of system may determine whether or not energy is constant in a given situation. In particular, students have difficulty applying the conservation principle to phenomena involving dissipative interactions (e.g., a pendulum slowly decreasing its swinging motion). Instead of

explicitly identifying an increase in thermal energy, students often explain that mechanical energy is “used up” [30–32]. Finally, we note findings suggesting learners can have greater difficulty identifying changes in thermal energy in situations in which the accompanying changes in temperature are small or imperceptible [33].

3. Identification of conceptual resources for understanding energy

The past decade has seen increasing use of conceptual resources for the analysis of student learning. Like phenomenological primitives (p-prims) [34–36], conceptual resources describe small “pieces” of knowledge that students activate in context-dependent ways. Building from p-prims, which derive from individuals’ lived experiences, conceptual resources can be developed through formal or informal educational experiences as well as everyday lived experiences [9,37]. Fine-grained knowledge elements, such as p-prims or conceptual resources, are not viewed as inherently correct or incorrect but rather can be productively or unproductively activated in a specific context [38–40]. Our work has drawn heavily on that of Robertson and co-workers, who have investigated student activation of conceptual resources when learning physics, including conceptual resources for learning energy [9]. These authors define conceptual resources as “seeds of canonical thinking, sophisticated reasoning, or scientific practices, such that an instructor could conceivably build on these ideas toward an instructional goal.”

In our work, we do not treat conceptual resources as an exclusive or unitary label for an element of student reasoning, but instead, include any instance of reasoning an instructor might recognize as similar in some way to a concept or reasoning an expert might use. Activation of a conceptual resource is not necessarily a moment when a student “gets it right”—but rather, a moment of opportunity, in which an instructor might support the student in extending their reasoning toward a more fully formed physics concept.

Sabo *et al.* have catalogued common conceptual resources related to energy. These include associating energy changes with observable indicators and tracking energy as transfers and transformations occur [9]. We have drawn on these and other documented conceptual resources in developing a scheme for coding our interview transcripts, which we describe in the Methods section.

C. Instructional context for the investigation

The investigation reported here occurred within a science content series for preservice K-8 teachers, consisting of four separate courses in physics, biology, geology, and chemistry. Although each course is situated in its own disciplinary context, all of the courses were designed to support learning about the flow of matter and energy through interacting systems. The physics course is required

for all preservice K-8 teachers and is a prerequisite for the other three courses, which can be taken in any order. The physics course uses the *Next Generation Physical Science and Everyday Thinking* curriculum (NGP) [41], while the biology, geology, and chemistry courses use curricula developed locally. These curricula [42–45] were modeled closely on NGP and were developed in parallel by interdisciplinary teams of science educators.

To support instructional coherence across the courses, the curricula use common vocabulary and modeling tools. For example, all four curricula use *energy diagrams*, a representation to track the flow of energy through interacting systems. In addition, each curriculum situates activities within an explicit, constructivist-based learning cycle. This cycle begins by having students share initial ideas, then guides students to collect and interpret evidence, and finally prompts students to engage in sensemaking and metacognition to develop concepts. “Coherence” here refers to features of the design of the four curricula, not necessarily to student learning. However, other researchers have identified coherence as a necessary but insufficient feature of helping students construct coherent conceptual understanding [46–48]. We thus sought to use the four coordinated courses as a laboratory to study students’ cross-disciplinary learning of energy.

NGP is a guided inquiry curriculum, based on a social constructivist model for learning, and designed to be consistent with the Next Generation Science Standards [41,49]. An instructional goal is to develop and apply an energy-based model to account for real-world phenomena, such as a ball being tossed or a skateboard coming to a stop. In the biology, geology, and chemistry courses, students extend and apply this model to explain new phenomena specific to those disciplines. For example, in geology, students explain the movement of tectonic plates; in biology, cellular respiration; and in chemistry, phase changes and chemical reactions.

The energy-based model, which students develop and apply to account for phenomena in all four courses, includes the following elements:

- Energy comes in various forms; e.g., kinetic, potential, thermal.
- Changes in energy can be observed through changes in physical indicators, such as objects’ movement, temperature, or arrangement in space.
- Energy can be transferred from one object to another.
- Energy can transform from one form to another.
- Energy transfers and/or transformations occur through physical mechanisms that involve interactions between objects and/or fields.
- Amounts of, and changes in, energy can be quantified and expressed numerically.
- Energy can be tracked through systems.
- Energy is conserved and can always be fully accounted for in a given phenomenon.

These elements align closely with the model for energy identified by Gray *et al.* [23] as being embedded in the Next Generation Science Standards [2]. As mentioned, NGSS presents energy as a “cross-cutting concept.” As such, the elements constitute ideas about energy that experts view as spanning the disciplines. Different forms of energy, such as kinetic energy and gravitational potential energy, can, at a surface level, be viewed as independent concepts—each with its own operational definition. The historical development of the energy framework, however, has led to a view of different energy forms as fundamentally interconnected, forming the overarching energy construct [4]. In our work, the elements of the energy-based model listed above form the basis of our coding of interview transcripts for the activation of conceptual resources (see Sec. III).

The energy diagrams students use to model phenomena in all four courses incorporate many of the conceptual elements listed above. As mentioned, these diagrams are introduced and developed explicitly in the physics curriculum [41,49] and are then used in the other three courses. Energy diagrams provide a representational tool for students to apply the energy framework in creating explanations. Examples from the physics and chemistry courses are shown in Fig. 1. Students identify the interaction type (top label), as well as the source and receiver objects (boxes), show how specific energy forms associated with the objects are changing (ovals), indicate the direction of energy transfer (arrow), and in some cases identify the type of energy transfer occurring through a label inside of the arrow.

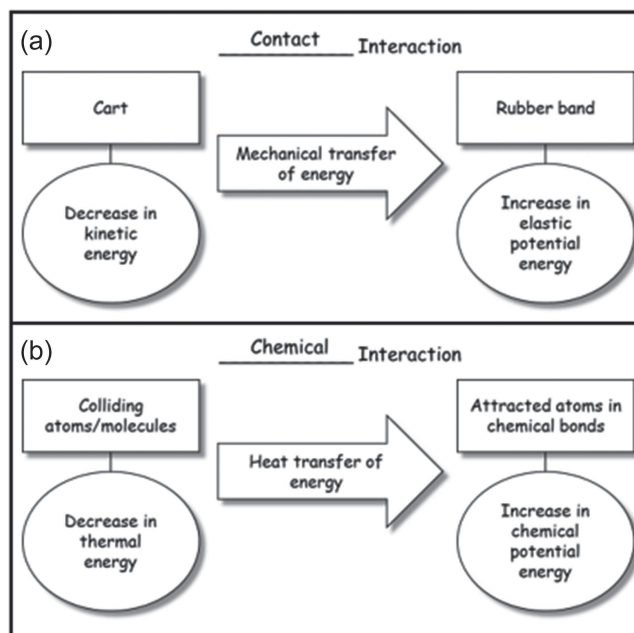


FIG. 1. Sample energy diagrams from: (a) the physics course, representing a cart running into a rubber band bumper, and (b) the chemistry course, representing bonds breaking in a chemical reaction.

II. THEORETICAL FRAMEWORK: CROSS-DISCIPLINARY LEARNING

As discussed, ideas about energy constitute a unifying explanatory framework in STEM. We adopt *cross-disciplinary learning* as the theoretical lens through which we examine student reasoning about energy across physics, biology, geology, and chemistry. Cross-disciplinary learning (CDL), described in detail elsewhere [8], draws on three established theoretical frameworks—transfer, conceptual resources, and interdisciplinary learning. CDL is intended as a theoretical construct or model describing the understanding and reasoning students develop in instructional programs designed around sequential learning, in which foundational concepts are developed in prerequisite courses, and then expanded and applied to more complex systems and processes in later courses.

A vast and growing literature has developed the construct of *transfer* in learning. Transfer frames learning as cumulative and sequential—a process in which ideas are developed first in one context and then later applied to make sense of a novel context (see Ref. [10] for a useful review). Although the sequential nature of most transfer frameworks matches our study context well, we argue that it is limited in utility for understanding productive reasoning across disciplines. Most formulations of transfer involve direct application or mapping of relatively coarse-grained, well-compiled concepts, principles, or modes of reasoning from one context to another. We seek instead to foreground how students transform and integrate finer-grained ideas as they engage in sensemaking across disciplines [8]. Thus, to describe how students combine and transform knowledge when reasoning across disciplines, we find it useful to focus on conceptual resources. Goodhew and colleagues discussed *productiveness* in conjunction with resource activation [39]. Building on work by Harrer [38], they characterized students' activation of resources during problem-solving interviews as having disciplinary productivity, meaning the context in which the resources were activated was appropriate as judged by the disciplinary community, and/or situated productivity, meaning the resource activation helped the student progress toward an intellectual goal.

Experts, at times, use metaphors to understand abstract concepts. Such use, when tempered with knowledge of the limitations of the metaphor, can be viewed as a place where disciplinary and situated productivity overlap. The substance ontology for energy, discussed earlier, is a metaphor used by both experts and novices to support productive reasoning. However, awareness of the limits of this metaphor, i.e., that energy is not literally a substance, may be necessary to prevent the morphing of a productive resource into a non-normative conception.

In our use of a resources framework to describe how students apply learned ideas in novel contexts, we see parallels with the Preparation for Future Learning (PFL) framework of Schwartz and colleagues [11,50]. In contrast

to direct transfer, in which students apply a fully formed idea in the novel domain, in PFL, students draw on previously learned ideas as resources to direct their learning in the new context. Rather than being applied directly to form the response to a novel challenge, resources guide question-asking, sense-making, and the development of new knowledge. Formulated this way, PFL transfer may perhaps be more accessible and ubiquitous, yet also more difficult to detect and characterize than direct transfer.

The idea of interdisciplinary learning also has relevance to our study, as it focuses on some cognitive processes that are relevant to describing how resource activation can be conceptualized in the context of learning in another discipline. Shen *et al.* [12], in their characterization of interdisciplinary learning, recognize two processes: integration and transformation. Transformation involves changing an element of knowledge to enhance its applicability to a new context, while integration involves combining knowledge elements. Shen *et al.* document students' engagement in these practices while working through open-ended interdisciplinary problem-solving tasks [51].

Though the ideas of knowledge integration and transformation are useful to us in our work, our focus differs somewhat from that of Shen *et al.* Instead of bringing knowledge from different disciplines together to solve a problem, we are asking students to bring a set of conceptual resources from a familiar discipline to a new, less familiar discipline. This type of learning is sequential in nature and reflects the structure of many programs of study in higher education, where students are expected to use concepts from prerequisite courses to build understanding in follow-on courses. To formulate cross-disciplinary learning, we have combined the ideas of integration and transformation with the more sequential notion of transfer.

We define cross-disciplinary learning (CDL) as a “process of sequential learning in which students activate, transform, and integrate knowledge from different disciplines, combining previous learning with new learning to construct knowledge within a specific discipline” [8]. The overall sequential nature of CDL has parallels to transfer frameworks. However, with CDL, we regard the activated knowledge as finer-grained in nature and view successful reasoning as involving disciplinary and/or situated productiveness [39] in the activation of these resources in a novel disciplinary context. This view of what constitutes successful reasoning is shared with the PFL transfer framework: rather than privileging (or looking exclusively for) direct mapping of a concept from one discipline to another, CDL regards lines of reasoning that support new learning in the novel context as equally valuable.

Our qualitative analysis of student reasoning using the CDL framework involved two steps. We first coded for conceptual resources to investigate the types of resources students used, as well as the relative frequency with which they used them. This step focused on the *activation* part of the cross-disciplinary learning model [8]. Then, to explore

the difficulties and affordances of students' resource activation, including how students *integrated* and *transformed* resources, we conducted thematic analysis. We describe these methods below.

III. METHODS

This was a qualitative study involving think-aloud interviews with preservice teachers who had taken the prerequisite physics course and were enrolled in a subsequent course in biology, geology, or chemistry. In this section, we describe the development of the interview protocols, how interviews were conducted, the development of a scheme for coding the transcripts, and how thematic analysis was applied. External advisors to the project, who were experts in discipline-based education research but were not involved in the development of the curriculum or in course instruction, provided independent feedback on each of these elements of the research design. This feedback mitigates possible bias stemming from the dual role of the researchers, who also serve as instructors in the course sequence.

A. Developing the interview protocols

To probe students' cross-disciplinary understanding of energy, we developed a separate think-aloud interview protocol for each of the follow-on courses (biology, geology, and chemistry). Interviews were conducted with student volunteers in the first 2–3 weeks of the course. We believed the overall disciplinary context would thus be somewhat familiar to the interview subjects, while energy ideas in this context would be relatively new. We felt this timing would help make cross-disciplinary learning of energy more visible in the interviews.

We modeled the interview protocols after the “summarizing questions” found at the end of each unit in the follow-on curricula [41,42,49]. In these summarizing questions, students synthesize and apply their learning: the questions typically require the coordination of multiple elements of the conceptual framework for energy. To maximize opportunities for students to use a variety of energy resources, we wrote two scenarios for each of the unfamiliar disciplinary contexts. We also wrote one physics scenario to allow us to collect evidence of participants' energy reasoning in the original disciplinary learning context.

The biology, geology, and chemistry interview protocols used different physics scenarios. In each case, the physics scenario was designed to have some similarity to the scenario for the unfamiliar disciplinary context it was matched with. This was done so that we might more readily notice similarities in student approaches to reasoning about energy between the unfamiliar context and the physics context. During the interviews, we presented the physics scenario after the two scenarios in the unfamiliar discipline to avoid cueing students about how to approach the scenarios in the more novel context.

Each scenario described a change in one or more observable indicators tied to energy (e.g., a change in the speed of a moving object, a change in the temperature of an object, or a change in the relative position of two interacting objects). In particular, the biology scenarios involved (1) a person getting hot while running and (2) a person lifting barbells after eating a snack, the geology scenarios involved (1) magma rising to form a hotspot in the ocean and (2) tectonic plates moving toward each other to cause an earthquake, and the chemistry scenarios involved (1) a flask getting warm while an exothermic reaction proceeds inside of it, and (2) a bond between two ions breaking when a collision with a third atom occurs. The physics scenarios involved (A) a block being launched horizontally from a stretched rubber band and slowing down as it moves across a table (end of biology protocol); (B) a cart compressing a spring after sliding across a table and then being launched from the spring in the other direction (end of geology protocol); and (C) two attracting magnets moving away from one another and then stopping and starting to move toward each other (end of chemistry protocol). Each scenario ended with a prompt for the student to create a scientific explanation to account for one or more of the specific observations from the scenario. One instructor from each of the courses (who also happened to be on the development team for the relevant curriculum) reviewed each of their discipline-specific scenarios for accuracy of scientific content and alignment with contexts and energy ideas used or developed in each course. Figure 2 summarizes how the scenarios were organized in each interview protocol and provides an example of one scenario from the geology protocol.

After an initial version of each protocol was developed, it was piloted with 3–5 students as well as one faculty expert in the relevant discipline. During the pilot interviews, we noted the range of responses each scenario elicited, tried different follow-up and probing questions to better understand the participants' thinking, and identified (and revised) parts of the protocols that were difficult for students to interpret. We developed a library of follow-up questions for each protocol, such as “What did you mean when you said X?” to assist with general clarification, “What goes inside the boxes?,” if a participant drew an energy diagram and did not label it, and “What kind of energy is changing?” if a participant mentioned energy changes but did not name a specific energy form. This library included both specific probing questions and criteria for when to ask them. The ultimate goal was to draw out students' thinking without guiding students to any particular idea. The full interview protocols and probing question library are included in Supplemental Material [52].

B. Conducting interviews

Interview participants were enrolled in the biology, geology, or chemistry course. As discussed, most

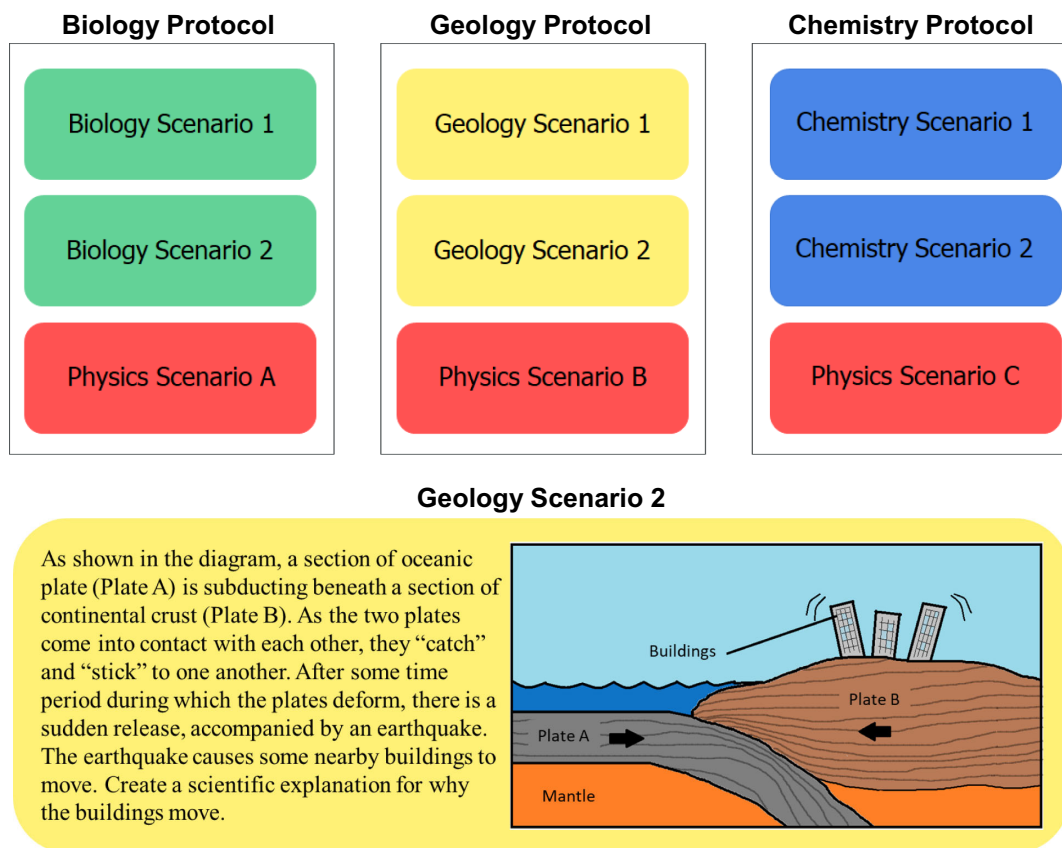


FIG. 2. Organization of the interview protocols (top) and an example scenario from the geology protocol (bottom).

interviews were conducted during week 2 or 3 of the academic term during which the student was enrolled. Participants were recruited by undergraduate research assistants, who used a script to briefly describe the study. The script included general information about studying student thinking about science, and avoided specific mention of transfer, cross-disciplinary learning, or energy concepts. Interested students then completed a paper form and were contacted to schedule interviews. All participants provided informed consent prior to the interview and were compensated with a \$15 stipend or gift card after their interview.

Because of the timing of the development of the interview protocols, as well as the number of offerings of the different classes, we were able to conduct more interviews of students enrolled in the biology course than in geology or chemistry. Results reported here are from 14 biology, 6 geology, and 5 chemistry interviews. Because of concurrent or subsequent enrollment in more than one course, two students participated in more than one interview: One participated in both the biology and chemistry interviews, and the other in all three. Thus, the 25 interviews discussed here were conducted with a total of 23 students.

Most interviews were conducted by at least two interviewers: one faculty member (AB, EB, or TH) and one undergraduate research assistant. No student currently enrolled in a class taught by a faculty member involved

in this project was interviewed by that faculty member. We could not avoid the potential that a participant would later enroll in a course taught by someone who had interviewed them for this study. If they did, they were not interviewed by that professor. In a small number of cases where a faculty member could not be present, the interviews were conducted by one or two undergraduate research assistants, after the RA had co-conducted at least two interviews with a faculty member.

The major goal of the interviews was to draw out and document students' cross-disciplinary reasoning involving energy concepts. Therefore, a semistructured interview methodology [53] was adopted. The interviews were framed for students as an opportunity for researchers to learn about how students create scientific explanations for phenomena they might be unfamiliar with. After the participant was informed of the human subjects' protections and signed a consent form, one interviewer read the first scenario out loud and asked the participant to explain the observed events (e.g., "Can you provide a scientific explanation for why Deb became hot while running?"). If the participant's initial explanation did not involve energy, we asked them to provide an energy-based explanation for the phenomenon. If their energy-based explanation did not include a representation or drawing, we asked if they could provide a representation. To avoid guiding students to any

particular explanation or representation, we used only general language, not language specific to the science education curricula. For example, we avoided the term “energy diagram,” which was a specific representation developed in the physics course. If the participant’s explanation lacked sufficient detail for the interviewers to follow their reasoning, the interviewers applied the criteria from the probing question library to ask one or more of the probing questions. Thus, consistent with established use of think-aloud interviews [53], our interview protocols, provided in Supplemental Material [52], were designed to draw out, but not guide, students’ reasoning about energy.

The interviewers repeated the above process with each scenario. Participants were provided paper and invited to write anything they found helpful for their thinking. A Smart Pen captured students’ audio and written work. Each interview lasted one hour. All interviews were transcribed verbatim, except for the omission of filler words such as “ok” and “um.”

C. Developing the coding scheme

According to our guiding theoretical construct, cross-disciplinary learning, students draw on learned conceptual resources and transform and integrate them in novel ways when sensemaking in a new disciplinary setting [8]. A priority for analysis was thus to recognize instances in which students activated conceptual resources for energy during the interviews. We could then examine the ways in which students reasoned with these resources (including transformation and integration). To accomplish these

analytic goals, we adopted an *a priori* coding scheme, supplementing with emergent codes when necessary, using principles and adapting procedures from Ref. [54] to guide our process. Our choice of an *a priori* coding scheme reflects our desire to build from the extant literature, which describes previously developed, validated coding schemes for students’ understanding of energy. These codes are well aligned with the learning goals of the courses in this study. In cases where the participants’ reasoning was not well characterized with these existing codes, we developed new codes through collaborative examination of the transcripts. We developed an initial set of codes based closely on two sources: (i) the energy-based model for interactions and motion developed in the NGP (physics) curriculum described in Sec. IC, and (ii) the conceptual resources for understanding energy developed previously by Sabo *et al.* [9]. Each establishes a set of discrete conceptual resources, properties, and rules about energy, which are broadly consistent with one another. We then refined these initial codes in several iterative rounds of collaborative coding practice to arrive at a stable coding scheme.

The resulting set of codes is shown in Table I, subdivided into two categories: (a) properties and (b) dynamic behavior of energy. These codes align with previously developed energy resource codes [9], as well as the Next Generation Science Standards, as analyzed by Gray *et al.* [23]. As discussed previously, the interview protocols were intended to be used with students who have completed a physics course using the NGP curriculum. Thus, the conceptual resources for energy are well matched to the learning

TABLE I. Conceptual resource codes for energy.

Code	Description	Sample quotes receiving this code
(a) Properties of energy		
Form	Student indicates energy takes on different forms or has identifiable types. Passage need not identify canonically identifiable energy forms to receive this code.	“Electrostatic potential energy would increase, but the kinetic energy would increase as well” “It’s the same thing ... just becoming a different form through those transformations, is how I see it.”
With object	Student associates energy with an object or set of objects. This code is applied both to explicit associations between an object and a quantity or form of energy, as well as to more metaphorical language that casts objects as containers that can hold energy.	“The block has 450 units of kinetic energy to start with.” “The kinetic energy goes up in the block as [the block] moves away from the rubber band”
Indicator	Student associates a specific form of energy with a physical property that can be directly observed and measured. For this code to apply, the statement must include an explicit connection between the observable indicator and the energy—for example, by using words such as “because” or “so.”	“[The block] is slowing down because it is losing that kinetic energy.” “Nothing about the [tectonic] plates specifically looks like elastic potential energy ... maybe how it is like, squishing on the other plate, I guess.”
Quantity	Student explicitly associates a number with an amount of energy or implicitly makes this association by referring to a unit of measure. This code is also applied when a student refers to a formula or recipe for how to calculate a specific amount of energy.	“So, as you have 100 units [of energy] being released from plate A, that’s all in elastic potential energy.”

(Table continued)

TABLE I. (*Continued*)

Code	Description	Sample quotes receiving this code
(a) Properties of energy		
Accounting	Student implies energy must “add up” or be “accounted for” in a given physical situation. The code is applied both to explicit references to the formal principle (e.g., “energy is conserved”), as well as statements that imply a less formal idea that energy can be or must be accounted for; e.g., statements that energy “must come from somewhere” or “go somewhere,” descriptions of two or more energy quantities along with linking words or phrases such as “if ... then,” or “because,” or statements that imply that all the energy at the beginning of a process can or must be accounted for at the end of the process.	“You can’t just create or destroy energy ... it goes, it comes from one source for another source ... and just transfer[s] and kind of transform[s].” “When there’s a decrease in potential energy, it causes an increase in kinetic energy, an equal increase in kinetic energy.”
(b) Dynamic behavior of energy		
Change	Student indicates the amount or quantity of energy associated with an object can increase or decrease during a process. To receive this code, student must identify the change over time of a single energy quantity, rather than compare the energy associated with two distinct objects or systems.	“When there is a decrease in potential energy, it causes an increase in kinetic energy.” “I tap the first magnet in that direction, that means it is gaining kinetic energy”
Transfer	Student describes the flow of energy from a source to a receiver. To receive this code, the passage must explicitly mention at least two of three facets: (i) an object or substance acting as a source, (ii) another object or substance acting as a receiver, and (iii) movement or motion of energy between them. The mere presence of the word “transfer” or “energy source” or “energy receiver” is not a sufficient criterion to apply the code—two or more of these must be linked together.	“[There is] a huge energy transfer from the magma into the surrounding air ...” “The energy is being transferred to the table.” “The source would be the rubber band ... and then the receiver is the block, because it’s receiving the energy from the rubber band.”
Transform	Student describes a change in energy form (as opposed to a change in quantity, which is described by the Change code). This code can be applied to statements that describe a single object or two different objects; i.e., the transform code may or may not occur in conjunction with a transfer code.	“When you’re pulling it back, it has potential energy ... it turns to kinetic ...” “The energy is being transferred to the block and transformed, I guess into KE”
Mechanism	Student describes a process or sequence of steps through which energy is transferred or transformed. They may include a discussion of a force to account for an energy change. This code is applied when a student is attending to how an energy transfer or transformation occurs and generally reflects causal reasoning. Explicit mention of energy is required for this code to be applied; i.e., isolated force arguments would not receive this code.	“It increases in temperature because there’s friction between the table and block. So that friction creates thermal energy from the movement of kinetic energy.” “In her stomach ... the starches break down to their building block glucose, which increases that chemical potential energy ...”

outcomes for students’ prior energy learning experience. In this way, the resource codes are appropriate for examining the extent to which, and how, students apply prior learning of energy from a physics context to explain novel phenomena in biology, geology, and chemistry settings.

D. Applying the coding scheme

The purpose of developing the codes was to enable us to identify episodes of resource activation, integration, and transformation, as elaborated in our model of cross-disciplinary learning [8]. Once a stable set of codes was

agreed upon by the research team, it was applied systematically to the interview transcripts. The unit of coding was a single talk turn, defined as the set of verbalizations of the interviewee between any questions and comments from the interviewer (except for insubstantial verbalizations such as “ok” or “oh”). We chose talk turns as the coding unit because ideas were often developed by the interviewee over several sentences. With talk turns as the coding unit, we could minimize the inflation of code counts due to the repetition of a term over several sentences as a participant engaged in sensemaking. Coding anything larger than a

single talk turn would not have captured the nuances of the different ways and contexts in which participants used the resources during sensemaking. Coding proceeded by labeling each talk turn with the codes that applied. When necessary, the interviewer's question preceding a talk turn was used to interpret the participant's response. Codes were not mutually exclusive; i.e., a single talk turn could receive more than one code.

Each transcript was coded by two undergraduate research assistants (RAs). After coding a set of 2–5 transcripts independently, the RAs compared their codes and discussed inconsistencies. These discussions led to further refinement in the interpretation and application of codes, and often resulted in updates to the codebook. Interrater reliability (IRR), calculated using Eq. (1), was used to monitor consistency between coders. The RAs proceeded with a second round of independent coding on all transcripts that had an initial IRR below 80%. On final coding, an average IRR of 83% was achieved across all transcripts. Consistent with the coding process outlined in Ref. [9], we recorded only the codes agreed upon by both coders, leading to a single set of codes for each transcript for use in the next stage of analysis, described below.

$$\frac{(n_{\text{total agreements}})}{(n_{\text{RA1 individual codes}}) + (n_{\text{RA2 individual codes}})} \times 100 \quad (1)$$

1. Determining code counts

The codes were tallied across transcripts and aggregated by discipline and scenario to help visualize the relative frequency and contexts in which resources were activated. These tallies were primarily used to address the first research question, “What conceptual resources for understanding energy do students draw on when asked to explain phenomena in a novel disciplinary context?” The tallies were also used to identify specific resources and notable instances of sensemaking for further analysis, to address our second research question, “How do students use these resources? What difficulties do they encounter?”

Code densities. When comparing individual transcripts to each other, we normalized by talk turns to control for the overall amount of verbalization in each interview. This was done by dividing the total code count by the total number of interviewee talk turns. We refer to this as code density, reported as a decimal number. Code densities were calculated for each participant, both for single scenarios and for the entire transcript. For example, if a total of 37 codes were recorded over 17 participant talk turns for scenario 1, and 72 codes were recorded over 34 total talk turns for the entire interview, the code densities would be 2.18 for scenario 1 and 2.11 for the interview. It is plausible that higher code densities indicate conceptual resources being combined or at least used in close proximity. We therefore used code

density as a screening tool to identify passages with potentially rich sensemaking for further thematic analysis. Indeed, Richards *et al.* [55] argue that rich sensemaking is linked to the activation of resources in close proximity.

Code frequencies. To compare code activation across disciplines, code frequencies were calculated. Code frequencies were computed by summing the number of instances of a particular code, then dividing by the total number of codes recorded for the discipline being analyzed. These were multiplied by 100 and are reported as percentages. For example, if the *Form* code was recorded 43 times across all biology transcripts, and there were 367 codes recorded for all biology transcripts, the code frequency for forms across biology interviews would be 12%. Because we were comparing codes rather than transcripts, it was not necessary to normalize code frequencies by number of talk turns.

After code frequencies were calculated, we discovered the *Form* code was one of the most frequently used across disciplines. To further characterize student use of this energy resource, we identified each instance of the form code with the relevant specific energy form, using the categories *kinetic*, *thermal*, *potential*, *gravitational potential*, *chemical potential*, *magnetic potential*, *elastic potential*, or *other*, which was used when the form was not named or easily ascertained by context. The potential energy code was used only when participants referred to potential energy and did not name the specific potential energy form. We note that heat and mechanical energy are referred to explicitly as types of energy transfer, not as forms of energy, in the courses from which we drew interview subjects. Therefore, mentions of mechanical and heat energy in the context of energy transfers (e.g., “There was a heat energy transfer”) were given the transfer code only. However, when it was clear, one of these terms was used as a form of energy associated with an object or system (e.g., “The flask increased in heat energy”), these terms were coded as energy forms, possibly attaching one of the specific form types if it was easily ascertained by the context. (For example, the passage “The flask increased in heat energy” would have been given the *Form* type code, *thermal*.) Form code frequencies were calculated as above, with the numerator being the particular form code count and the denominator being the total number of form codes.

Our sample size does not permit the use of inferential statistics with code frequencies or densities. Instead, we used multiple representations of the data to explore patterns in energy resource use and, as mentioned above, to identify passages for further analysis.

2. Identifying themes in student reasoning

Our second research question, “How do students use energy resources? What difficulties do they encounter?”

required a more descriptive analysis of students' cross-disciplinary learning of energy. Our goal was to understand how and in what contexts students tend to activate conceptual resources, including how students integrate and transform those resources [8]. We employed thematic analysis, in particular to generate illustrative case studies, to address these questions.

Thematic analysis. First, we wanted to unpack student use of *Form* and *With object* resources, as these were the most frequently activated across disciplines and scenarios. We explored how students were linking energy forms to objects and indicators in the different cross-disciplinary scenarios. Using a thematic analysis approach [54], a researcher read all talk turns labeled with *Form* codes in a single scenario for a single participant and wrote analytic memos describing that participant's use of the specific energy forms. Using these memos, the researcher developed themes to characterize individual participants' reasoning. Reading and comparing these memos first across scenarios and then across disciplines, we searched for patterns and generated overall themes. During all levels of analysis, we continuously returned to the transcripts to ensure themes were grounded in participants' interview responses [56,57].

Case studies. The main themes involved the activation of potential energy resources. We searched for cases to vividly illustrate how students reason with potential energy and the nature of the challenges they encounter in doing so. A case study approach [58,59] allowed us to develop detailed insights. We first identified instances of rich sensemaking around potential energy by looking for transcripts with high code densities and multiple *Potential energy* form codes. This led to the identification of three specific sections of the interview protocol for case study analysis, selected because the corresponding transcript excerpts, as a whole, exemplified the identified themes. These sections were from different disciplines and represented one scenario, or part of a scenario, in that discipline: the runner getting hot scenario (scenario 1) for biology; the earthquake scenario (scenario 2) for geology; and the flask getting hot scenario (scenario 1) for chemistry. Two specific transcript excerpts for each protocol section were then selected, based on the frequency of activation of potential energy resources, as well as the research team's judgment of the productivity of the students' reasoning. One transcript in each pair represented a greater level of struggle with potential energy reasoning, while the other represented more coherent reasoning with potential energy. This selection strategy helped to develop a broad picture of the space of possible approaches to reasoning about potential energy captured in the interviews. Once the passages were identified, each member of the research team read each passage carefully and individually wrote a one-page description

and interpretation of the case. We then read the set of analyses and collaboratively identified and elaborated overlapping themes and inferences.

Although thematic analysis and case study methods are presented sequentially here, in our analysis, they progressed iteratively, where the case studies both deepened our understanding of how some of the themes played out and also illuminated new possible themes. When new themes were proposed, we went back to the data corpus and used codes and code densities to locate portions of transcripts where the theme might be present. In this way, we cycled between identifying and further exploring themes, all the while grounding our analysis in the transcripts. Because of the iterative nature of this work, the findings from thematic analysis and case studies are presented together (see Sec. IV B below).

IV. RESULTS AND DISCUSSION

We have described the interview protocols and coding schemes used to investigate how students reason with a basic energy model to explain phenomena in novel disciplinary contexts. In this section, we organize our results into six specific findings, grouped under our two broad research questions. For each finding, we present and discuss supporting evidence from the data corpus, including code frequencies, code densities, and thematic analysis.

A. Research question 1

Our first research question asks, "What conceptual resources for understanding energy are activated when students are asked to explain phenomena in a novel disciplinary context?" To address this question, we examine code counts, densities, and frequencies from interview scenarios involving the less familiar disciplinary contexts of biology, geology, and chemistry (i.e., as opposed to the physics scenario in each interview). We compare measures across interview transcripts, both within and between disciplines. We also compare the unfamiliar disciplinary scenarios to the more familiar ones (physics) to investigate differences between cross-disciplinary reasoning and reasoning within a more familiar discipline. Three of our six overall findings are associated with Research Question 1.

1. Finding 1.1: When applying a basic energy model in a novel disciplinary context, students activate a variety of conceptual resources for understanding energy

When confronted with a phenomenon in an unfamiliar disciplinary context and asked to construct a scientific explanation, we might expect students to struggle or not know how to start. This expectation comes from our experience teaching undergraduate science as well as research that describes far transfer (i.e., the application of learned concepts across disciplines) to be among the most elusive goals of instruction [10]. While a few of the

TABLE II. Average code counts and densities across scenarios for the three interview protocols.

	Average code count (SD)		
	Biology protocol	Geology protocol	Chemistry protocol
Disciplinary scenarios (1 and 2)	39 (13)	51 (17)	58 (16)
Physics scenario (A, B, or C)	25 (6)	22 (8)	34 (9)
	Average code density (SD)		
	Biology protocol	Geology protocol	Chemistry protocol
Disciplinary scenarios (1 and 2)	2.4 (0.56)	2.7 (0.50)	3.4 (0.39)
Physics scenario (A, B, or C)	3.4 (0.70)	2.9 (0.13)	3.5 (0.54)

interview participants generated fully normative energy-based explanations, many students did apply, with little or no prompting, a variety of conceptual resources associated with a basic energy model.

Analysis. Table II presents the average code counts and densities for each protocol broken out by scenario. Recall that scenarios 1 and 2 involve the discipline of the interview protocol, while scenarios A, B, and C involve physics contexts that were presented at the end of each protocol (see Fig. 2). The code count serves as a proxy for participants' activation of conceptual resources related to the energy model from Sec. IC. We found participants activated conceptual resources for energy in a substantial way across all three unfamiliar disciplines: the average code count for each of the unfamiliar disciplinary scenarios was greater than three dozen. The number of resource activations was somewhat lower in biology than in geology and chemistry. This may be because many participants, when working through the biology scenarios, focused their explanations on the flow of matter in metabolic processes and, in some cases, required prompting to attend to energy. The biology curriculum features matter diagrams, alongside energy diagrams, to track the flow of carbon through metabolic processes [42]. Several students made extensive use of matter tracking diagrams during the interviews.

Comparing the amounts of resource activation in unfamiliar and familiar disciplinary contexts requires the use of code densities. These densities are obtained by normalizing code counts over the number of talk turns. For the geology and chemistry interview protocols, we find the code densities are comparable between the unfamiliar disciplinary scenarios and the familiar scenario (physics), while in the biology protocol, the densities are lower in the biology scenarios compared to physics—again, presumably because of the large degree of matter tracking in these interviews (Table II).

Commentary. The results shown in Table II are consistent with the claim that elements of the basic energy model were accessible to students across disciplinary contexts, suggesting that students engaged in the resource activation

stage of the cross-disciplinary learning model (Fig. 1). Other interpretations, however, are also possible. The similarity in instructional models of the four courses may, to some extent, account for similarities in resource activation, or differences in reasoning may be more subtle than the grain size of our codes allows us to observe. Although we cannot distinguish between these possible explanations in this study, we note that students were quite capable of activating conceptual energy resources learned in one disciplinary context when constructing explanations in a more novel context.

2. Finding 1.2: Students activate “Energy forms” and “With objects” more frequently than other conceptual resources for energy

The basic energy model contains multiple conceptual elements, or resources, represented by the different codes in our study. We found that when students constructed explanations for phenomena in unfamiliar disciplinary contexts, *Energy forms* and *With objects* were activated more frequently than other resources.

Analysis. After analyzing the overall activation of conceptual resources for energy, we examined code frequencies (the ratio of an individual code count to the sum of all code counts) to investigate which resources were used most and least often. Figure 3(a) shows the code frequencies by discipline. Although there are notable differences between disciplines (e.g., *Change* is used less frequently in biology than in geology and chemistry), we observed a consistent pattern across all interviews: *Forms* and *With objects* are the most frequently documented codes, constituting 26% and 22% of the total code count, respectively, in the unfamiliar disciplinary scenarios. These two codes individually occur about twice as often as the *Change*, *Transfer*, and *Mechanism* codes, and 4–5 times more often than *Accounting*, *Indicator*, *Transform*, and *Quantity*.

To examine cross-disciplinary learning, we compare the resources used in unfamiliar contexts to those used in the context of physics. Figure 3(b) shows code frequencies for the physics scenario within each protocol. As for the

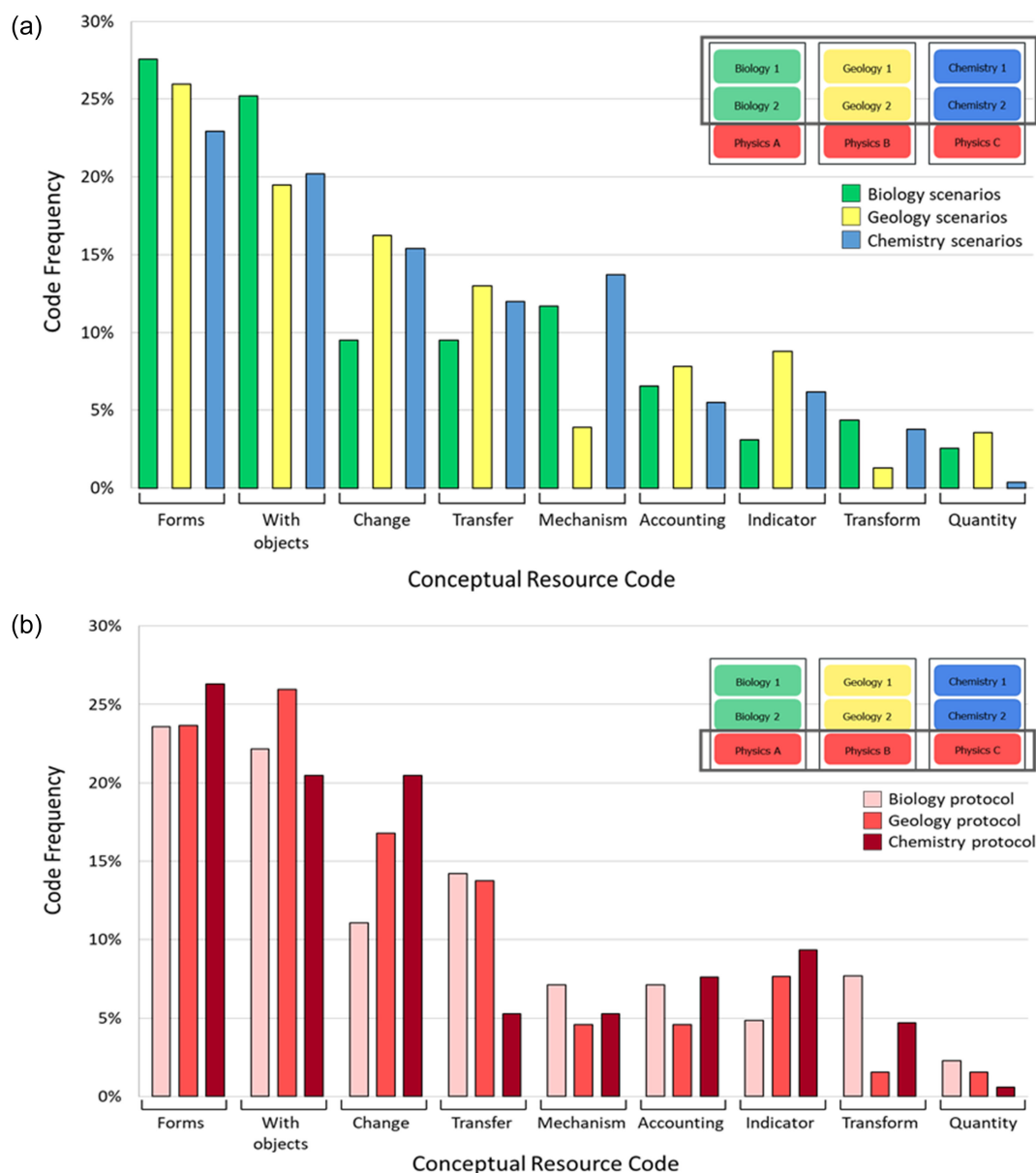


FIG. 3. Code frequencies in: (a) the biology, geology, and chemistry scenarios of the interview protocols, and (b) the physics scenario (scenario 3) of each protocol (biology, geology, and chemistry), ordered by decreasing overall code frequency for these scenarios.

unfamiliar disciplinary scenarios, *Forms* and *With objects* are the most often used codes in the physics scenarios.

Commentary. The high frequency of the *Forms* and *With objects* codes across all disciplines suggests either that these elements of the energy model are more available as conceptual resources to students or that students find these elements more necessary than other resources to activate as part of their energy-based explanations. This finding applies to both the unfamiliar and familiar disciplinary scenarios, and thus to cross-disciplinary learning as well as original learning environments. In the basic energy model, these two codes can be regarded as conceptual resources associated with static properties of material objects, in

contrast with the *Change*, *Transfer*, and *Transformation* codes, which can be regarded as resources associated with dynamic interactions. Thus, the interview results suggest the elements of the energy model most closely associated with interaction and change may be less available to students as they construct energy-based explanations of phenomena. An alternative explanation for the observed differences in frequency is that the *Forms* and *With objects* codes are simply a more foundational part of the energy model—in other words, discussing forms and objects might be necessary in constructing dynamic energy explanations involving ideas about transfer and transformation, while the reverse might not be true. Conducting interviews with disciplinary experts could allow this to be explored further.

We also note that energy forms and objects have a prominent role in the energy diagrams used in all four curricula, and these diagrams were used by all interview participants as anchors for their energy explanations. Thus, these conceptual resources may have been more available to students simply because of their visibility in this energy modeling tool. In Sec. IV B, we further discuss the role of energy diagrams in cueing reasoning with specific conceptual resources.

3. Finding 1.3: Students tend to reason about different specific forms of energy in different disciplinary contexts

The *Energy forms* code marks instances in which students explicitly recognize and apply the general notion that energy takes on different forms and does not include a means for distinguishing the activation of different specific forms of energy (e.g., kinetic energy, thermal energy, or even a non-normative form, such as “motion energy”). After realizing that *Forms* played a dominant role in student reasoning, we decided to explore students’ use of this resource in more detail. We found that the different disciplinary contexts were associated with the activation of different specific forms of energy.

Analysis. Within the overall activation of the *Forms* conceptual resource, we quantified the frequency of various specific forms used by students in their explanations in the biology, geology, and chemistry scenarios (Fig. 4). From this analysis, we see potential energy is the most frequently used energy form in biology, and kinetic energy is the most frequently used energy form in chemistry and geology. In geology, kinetic energy is followed closely by potential and thermal so that these three forms share similar activation frequencies. When potential energy is broken down further, into specific forms, we see even more variation (Fig. 4), with chemical potential energy dominating potential energy forms mentioned in biology, undefined and elastic potential energy dominating in geology, and undefined, chemical, and magnetic potential energy dominating in chemistry explanations.

Commentary. It is perhaps not surprising that different potential energy forms arise in the different scenarios. For each scenario, the energy flows most relevant to the specific phenomenon being explained involve inherently different energy transfers and transformations. It is nonetheless noteworthy that students found ideas about potential energy relevant to these novel contexts, as the concept of potential energy is overall abstract and challenging for learners [5–7]. We note that differences in code use between disciplines emerged only after we reduced the grain size of our coding by distinguishing different forms of potential energy. Differences in the application of the energy model between different disciplines may be nuanced, requiring a deeper analysis of the transcripts to describe fully. Because of the

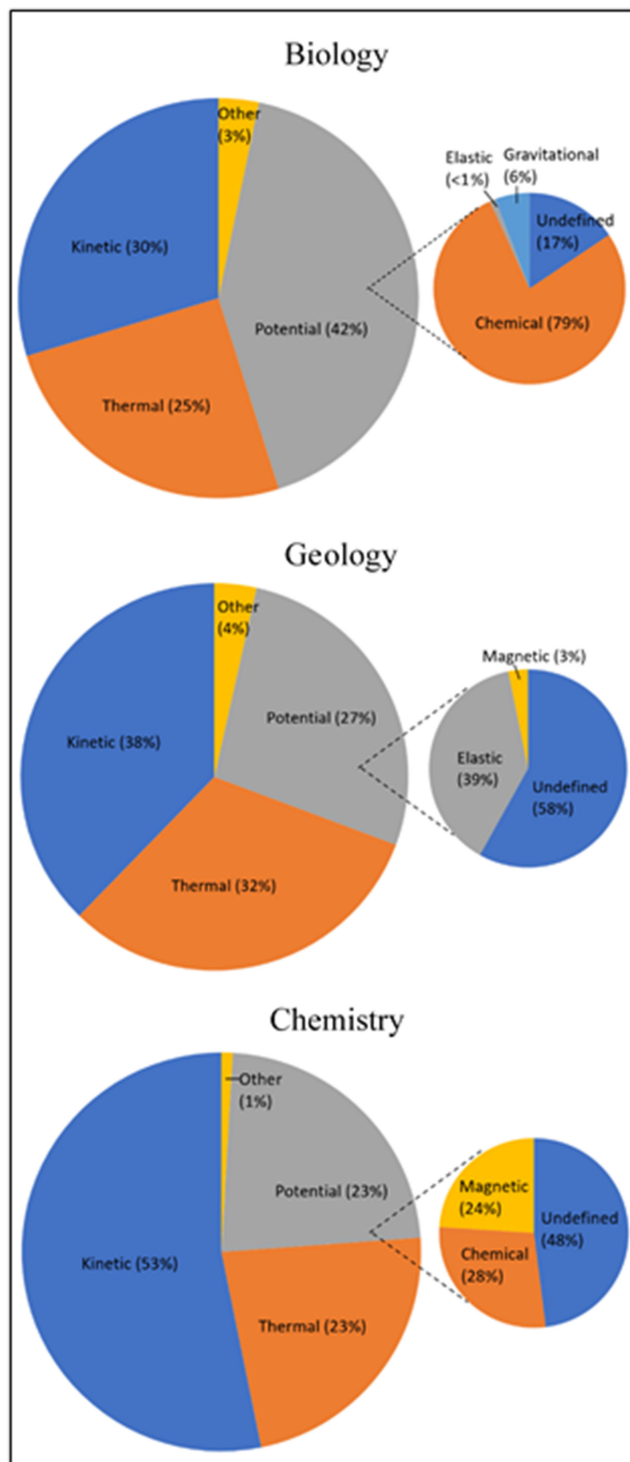


FIG. 4. Form code frequencies in the biology, geology, and chemistry scenarios.

variation in potential energy forms used, as well as the frequency of the activation of undefined potential energy and overall variation in the use of potential energy between protocols, we decided to focus our thematic analysis on students’ use of potential energy across the disciplines. The themes we developed are discussed in the next section.

B. Research question 2

The previous section identifies which conceptual resources for understanding energy students activate as they confront a novel disciplinary challenge. We find, encouragingly, that many of the conceptual elements of the basic energy model taught in the physics course are indeed activated by students as they create energy-based explanations for phenomena in biology, geology, and chemistry contexts. We wanted, however, not only to document resource activation, but also to investigate how students use those resources. Our second research question asks *How do students use conceptual resources for understanding energy? What specific conceptual or reasoning difficulties do students encounter?* In our framework for cross-disciplinary learning [8], productive reasoning involves first the activation of resources, and then the transformation and integration of those resources in context. In this section, we explore these latter processes, examining whether and how students transform and integrate activated resources in an unfamiliar discipline.

In this analysis, we employ the constructs of *disciplinary productiveness* and *situated productiveness* [38,39]. Disciplinary productiveness describes the deployment of a conceptual resource in a manner similar to a normative disciplinary explanation, while situated productiveness refers to the deployment of a resource in a way that allows a student to make progress toward an intellectual goal. Below, we describe selected episodes of resource transformation and integration from our data corpus as having disciplinary or situated productiveness. As discussed above, we focus this analysis on conceptual resources related to potential energy. Using an iterative process of developing analytic memos and reviewing the transcript sections to ensure grounding in the data, as described in Sec. III [54], we developed themes in student reasoning, which we present below as Research Findings 2.1–2.3.

1. Finding 2.1: Students transform and integrate potential energy resources in unfamiliar contexts, displaying situated and disciplinary productivity in their cross-disciplinary reasoning

As seen in Fig. 4, potential energy represented a substantial proportion of the total number of activations of the *Energy forms* resource in each discipline. A close examination of the interview transcripts revealed that students transformed activated potential energy resources to facilitate application of those resources to the unfamiliar disciplinary contexts. Such transformations were generally associated with richer and deeper explanations, suggesting situated productivity [38,39]. Below, we provide examples of students' transformation and integration of conceptual resources for three different potential energy forms: chemical, elastic, and magnetic.

Chemical potential energy. In the biology interviews, students used chemical potential energy (CPE) in ways consistent with their physics learning. The NGP curriculum makes frequent use of CPE to describe decreases in stored energy in situations involving muscle movement (e.g., when a child kicks a ball), so it is perhaps not surprising that this energy form was frequently activated in the biology interview protocol, which involves a person, “Deb,” eating breakfast and then going for a jog or lifting weights. The interview students' use of potential energy in this context involved resource activation and integration but not necessarily transformation. Many of the interview students spontaneously brought up CPE stored in Deb's muscles, together with more general discussions of energy associated with human locomotion, energy stored in food, and digestion and metabolism as processes involving energy transformation.

Students also referred to CPE in the biology interviews in conjunction with descriptions of how ATP is involved in cellular processes. While the biology interview students did not generally describe the relationship between ATP and chemical potential energy in detail, they did often bring up chemical reactions or chemical bonds. In the chemistry interviews, students applied the concept of CPE not in a context of human locomotion but to substances interacting in a chemical reaction. These students sometimes even analyzed chemical potential energy at a submicroscopic level, connecting changes in CPE to the rearrangement of chemical bonds. We argue that this integration of chemical potential energy with the ideas of chemical reactions, bonds, and ATP involves the transformation of CPE as a conceptual resource. Students transformed the resource from a fairly narrow framing, in the original learning context of physics, involving CPE as energy stored in muscles, to a broader scope, involving CPE as energy stored in nonliving materials, sometimes even in submicroscopic entities. This suggests disciplinary productiveness, as these conceptions are generally aligned with canonical ideas about chemical potential energy. Broadening their definitions of chemical potential energy allowed students to integrate this resource with other concepts specific to the scenarios in the unfamiliar disciplines, which in turn suggests situated productivity.

Elastic potential energy. In the geology interviews, some students mentioned elastic potential energy in the context of tectonic plates interacting to produce an earthquake. Not all students who invoked the idea of elastic potential energy in the geology scenarios were able to identify a relevant indicator (i.e., rocks deforming as the plates interact). This is perhaps not surprising, as the notion of rocks deforming is quite a departure from analyzing more readily stretched objects, such as rubber bands, in physics class. Even when students did not make a connection between elastic potential energy changing and rocks deforming, their

willingness to invoke elastic potential energy in this context suggests an attempt to broaden the conception of elastic potential energy, as a conceptual resource, to apply to very different objects and contexts than those from the original learning context of physics. This transformation of the resource in turn suggests situated productiveness, and sometimes disciplinary productiveness, in students' cross-disciplinary reasoning.

Magnetic potential energy. The NGP curriculum introduces the perhaps noncanonical construct (in the physics community) of magnetic potential energy to support students in tracking and accounting for energy in magnetic interactions. Students often activated this resource in the chemistry interviews. When magnetic potential energy was invoked in this context, students used it to track potential energy changes in the context of a bond breaking between ions (scenario 2). None of the interviewees had yet reached the point in the chemistry curriculum that defined electrostatic potential energy, and this form of potential energy is developed only in some sections of the physics course. Although the use of magnetic potential energy in this scenario was not strongly aligned with canonical scientific ideas and was arguably not disciplinarily productive, it does suggest that students were transforming conceptual resources in ways that allowed their integration into a new context. Since electrostatic and magnetic potential energy share some important features and operate in similar ways, students' use of magnetic potential energy in the chemistry scenarios can be seen as exhibiting situated productivity, in that it helped move students forward in their reasoning.

2. Finding 2.2: Students often struggle to associate potential energy changes with physical manifestations of those changes

We found that episodes in which a student struggled to integrate potential energy into a broader "energy story" were often associated with difficulty identifying or describing a physical manifestation of the energy change or transfer. Recall from Sec. III that the *Indicator* code was applied for explicitly connecting a change in a specific form of energy to an observable change or behavior (e.g., relating an increase in thermal energy to an increase in temperature), and the *Mechanism* code was applied for associating an energy change, transfer, or transformation to a linked sequence of physical actions (e.g., relating an energy change directly to the action of a force through some displacement). These two codes, which together relate the unseen, abstract construct of energy to physical processes, were among the least cited codes in our data corpus, suggesting reasoning about the physical manifestations of energy was relatively inaccessible to students (Fig. 3). The relative lack of connections between physical mechanisms and the abstract "story" of what is happening with energy in some cases seemed to prevent students from meaningfully

incorporating potential energy into their explanation. Below, we present examples in each of the three novel disciplinary contexts to illustrate this pattern.

Biology. In the biology interview protocol, students were asked to construct an energy-based explanation for why Deb needs to eat food in order to continue running. One interview volunteer recognized that energy should be a part of their mechanistic description but failed, at first, to specify how:

The food molecules break down into, like, simple sugars and glucose, and then those are transferred from the stomach into, I think—into like either into blood and then into the typical cell ... I'm not entirely sure. But then after they are transferred and stored we use them up as energy.

This passage was not associated with any of our resource codes: The student did not explicitly identify a specific energy form, an object energy is associated with, an increase or decrease in energy, or any physical indicator or mechanism through which energy is changing. While the student seemed confident that energy must form an important part of the explanation for why Deb needs to eat food to continue running, they did not at first seem to connect specific elements of the conceptual model for energy to that explanation.

The student did incorporate potential energy explicitly into their reasoning, but only after more than 40 talk turns. While the eventual activation of a potential energy resource suggests situated and disciplinary productiveness, the student's reasoning subsequently stalled. The student struggled to describe a mechanism or indicator for changes in chemical potential energy:

So we have like potential—probably chemical—energy in the food ... and then it slowly moves into her stomach and small intestine. And then things like glucose and water are all broken down in there and then ... it's transferred into the blood and then into cells but I'm not sure what happens to the energy at that point? I think ... yeah that's something we haven't talked about either. I think the energy ... maybe is in ... I don't know if it's going to be in those molecules though, like in the glucose molecules, but it could be.

On one hand, the student's recognition that potential energy plays an important role in the target explanation was productive. On the other hand, the large number of talk turns required for this activation suggests this was a challenging conceptual step for the student. The last sentence, in which the student associates chemical potential energy with glucose molecules, constitutes a *With objects*

code and may indicate a conceptual step forward in distinguishing energy from matter. However, the lack of a mechanistic explanation connecting potential energy changes to changes in the food molecules (i.e., chemical bond rearrangement) seems to have limited the student's progress. Difficulties connecting bond rearrangement and energy changes, as well as the tendency to conflate matter and energy, are well documented [26,27]. In this interview example, these two reasoning challenges seem interrelated and together may have inhibited the student's progress from productive activation of a previously learned potential energy resource to the transformation and integration of that resource to create an energy-based explanation in the novel context of human metabolism.

Chemistry. In many of the chemistry interviews, participants struggled to describe the mechanism of energy transformation or transfer, and, perhaps as a result, encountered roadblocks in their efforts to incorporate potential energy into their explanations. In the following example, which illustrates a reasoning pattern common in our data, the participant focused solely on the transfer of energy from the reaction mixture to the flask:

The increased temperature due to increased average kinetic energy means that the particles of the mixture inside of the container are colliding with the container, causing the kinetic energy of the particles in the container to speed up, and so their average kinetic energy is going up, so the energy is being transferred in the form of thermal energy from the mixture to the flask itself, which is why the flask warms up.

The student's argument linking submicroscopic particle collisions to the warming of the flask suggests consideration of physical mechanisms for and manifestations of energy transfers and changes. This type of mechanistic reasoning, with its strong disciplinary as well as situated productiveness, did not appear to be as accessible to the student for explaining why the temperature of the reaction mixture increases in the first place. The latter part of the overall explanation for why the flask gets warm involves relating changes in potential energy and changes in kinetic energy of the molecules and atoms that make up the reaction mixture. As in the previous example, the lack of reasoning about physical manifestation was accompanied by difficulty in meaningfully incorporating potential energy into the explanation.

Geology. A final example is drawn from the earthquake scenario in the geology protocol, in which students were asked to construct an energy-based explanation for why buildings start to shake during an earthquake. One interview participant demonstrated situated productiveness of

activated *Energy forms* resources for kinetic and thermal energy by connecting each with a physical indicator: "... that would cause plate B to increase in kinetic energy which causes it to move which then causes the shaking," and, "It's possible there's a thermal energy ... the mantle is transferring energy to the plates which is causing them to increase in temperature." This same student, however, struggled to connect potential energy to the scenario, even when the interviewer asked about the plates "catching and sticking" and causing "deformation" in the rock, in several follow-up questions. The student responded: "I don't know what the catch and stick would necessarily be." The difficulty in recognizing deformation as a physical manifestation of a change in elastic potential energy seemed to hinder the student's progress in incorporating potential energy into their explanation.

Summary. We can view these episodes through the lens of cross-disciplinary learning [8] by noting that students seemed to "get stuck" in situations in which activated conceptual resources associated with potential energy change could be productively transformed to better fit a novel context. In particular, students often struggled to connect observable physical changes in the novel context to changes in potential energy. Without first transforming a conceptual resource in such a way, it would seem less likely that a student would integrate the resource with other elements of the unfamiliar disciplinary context. In general, in the cross-disciplinary learning framework, resource integration may not always be possible without first transforming conceptual resources.

3. Finding 2.3: Specific cues can help students activate conceptual resources for potential energy during cross-disciplinary learning

Notably, in 20 of the 25 interviews discussed in this study (3/5 of the chemistry interviews, 3/6 of the geology interviews, and all 14 biology interviews), students invoked energy ideas spontaneously and did not need to be prompted by the interviewer to provide an energy explanation. For example, early in one of the chemistry interviews, the interviewer asked, "Could you also create an explanation for why the glass would get warm?" In response, the participant said, "I think it's the forming of bonds that releases energy ..." This was the first utterance of the word "energy" in this interview.

While most students spontaneously brought up energy, many struggled to incorporate potential energy into their explanations. We noticed, however, that certain conceptual resources, whether prompted or arising spontaneously, seemed associated with productive activation of potential energy. These included: (a) association of energy changes with physical manifestations of those changes; (b) using accounting-type reasoning to track energy in a scenario; and (c) use of a visual representation to track energy.

Thematic analysis identified illustrative examples of each of these, described in more detail below.

Physical manifestations. We have previously discussed the difficulties students encountered in identifying indicators of, and mechanisms for, potential energy changes. We also, however, observed episodes in which successful identification of indicators seemed to help students incorporate potential energy more strongly into their explanations. For example, two of the geology interview participants brought up elastic potential energy (EPE) relatively early in the Earthquakes scenario. This energy form had been discussed in the physics course, but not yet introduced in the geology course. The students associated changes in EPE with the catching and sticking of rocks as tectonic plates interacted with each other or with the release of a sticking point and the associated elastic deformation of rocks back to their “original” state. One participant associated a change in elastic potential energy with a sudden release: “I think the sudden release is due to this increase in elastic potential energy that it gets so great, that it causes an earthquake.” Another student related changes in the rocks’ shapes to a transformation of EPE to kinetic energy:

That spot [student gestures to a diagram showing interaction of two tectonic plates] increases in ... elastic potential energy I believe. And so that’s the sticking, and then the release would be the elastic potential energy turning ... back into kinetic energy, bouncing back out and shaking the ground and that’s what shakes the buildings.

In each case, the student identified a physical manifestation of a change in potential energy and incorporated potential energy productively into an explanation for why the buildings shake.

In one of the chemistry scenarios focused on an exothermic reaction, the participant identified potential energy early on, but later, when they considered the bonds in the reaction mixture, identified the type of potential energy as chemical: “so it’s like the bonds are decreasing. I think the term they used in [physics] and [geology] is chemical potential energy.” This is an example of the activation of a conceptual resource from physics and integration into the new chemistry context to explain the increase in temperature of an exothermic reaction. The interviewee appeared to use the idea of bonds as a cue to specify the type of potential energy as chemical. For these and other interviewees, physical manifestations of changes in energy, whether arising spontaneously or prompted by the interviewer, served as a stepping stone to incorporate potential energy into their explanations.

Accounting. The geology protocol included a prompt to consider how an extended period of deformation of rocks in

the Earth’s crust would impact the resulting earthquake’s intensity. In response, one participant explained:

The longer [the rocks] are stuck together the more deformed they are. And if they are more deformed maybe the release is larger ... There is probably stored energy, potential energy in the rocks and the longer there is potential energy maybe the potential energy increases and then when it isn’t potential anymore and it is actually an earthquake, because you can’t just get rid of that energy, it would all turn into that earthquake kinetic energy.

Previously in the scenario, the student had focused on kinetic and thermal energy. This episode, in which the student activates the *Accounting* resource (“you can’t just get rid of that energy”), was the first instance the student explicitly mentioned potential energy.

Similarly, during one of the biology scenarios, an interviewee had been focusing their reasoning exclusively on kinetic and thermal energy, until the interviewer referred back to a previous episode in which the participant discussed the energy of a source object decreasing during a transfer:

Interviewer: “So you said that if energy is being transferred that one [energy form] has to decrease right?”

Student: “I guess food, the food she ate in the morning would ... this would be chemical potential energy? So those would go down.”

The realization that a transfer must result in a change in energy of an object, expressed originally by the student and brought up again by the interviewer, was coded as an instance of the *Accounting* resource and seemed to cue the student to incorporate potential energy into their explanation.

These examples suggest that students activate energy accounting as a conceptual resource and integrate it with energy forms resources in their cross-disciplinary reasoning. This integration is associated with both disciplinary and situated productiveness, as students build mechanistic reasoning chains involving changes in potential energy.

Energy representations. In all the interviews, participants drew, with little or no prompting, energy diagrams of the form presented in the physics course. These diagrams seemed to help students activate potential energy resources and integrate them into their explanations.

One biology interview participant associated energy with food early on, but did not explicitly mention potential energy until they referenced the unprompted energy diagram they had drawn earlier (see Fig. 5). The interviewer

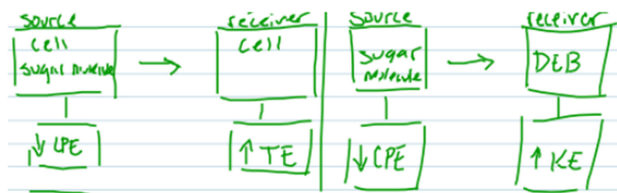


FIG. 5. A biology interview participant's energy diagram.

asked, “How would what you drew connect to your answer about [Deb] being able to keep running?” The participant responded:

I don't know exactly what the energy type would be but I think it's ... a decrease in chemical potential energy and then an increase in kinetic energy maybe? ... I guess it would be kinetic energy if she's running still but whatever energy she is running on I think is from the decrease in chemical potential energy cause that still lines up with the law of energy conservation.

Like the geology examples above, the activation of an accounting resource, in this case mediated by the student's energy diagram, served as a catalyst for incorporating potential energy productively into their overall explanation.

Another biology participant had spontaneously activated potential energy, but then productively transformed this resource as they constructed an energy diagram:

Student: “Ok, I'm making up my own kind of thing here (drawing an energy diagram). So the energy going in would be the food and that would turn into a stored energy, like a potential energy.”

Interviewer: “You wrote the initial CPE there. CPE is ...?”

Student: “Chemical Potential Energy.”

While this explanation conflates matter and energy and is not fully normative, we see situated productiveness of a potential energy resource, in this case, both mediated by and expressed through the energy tracking diagram (Fig. 6). The student has incorporated changes in chemical potential energy into an explanation relating the consumption of food to Deb's running and becoming warm.

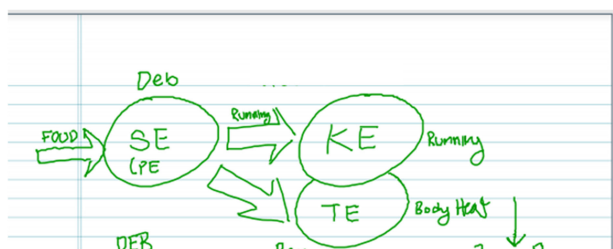


FIG. 6. The energy diagram of another biology interview participant.

These examples illustrate how energy representations, particularly the energy diagrams used in the four curricula, may cue some students to activate and productively integrate conceptual resources for potential energy. Our findings suggest energy diagrams may have functioned as ways to engage the other cues discussed above (physical manifestations and accounting). As a modeling tool, the diagrams provided participants a means to visualize abstract ideas, consistent with prior studies [21–23].

Summary. Viewing these episodes through the lens of cross-disciplinary learning [8], we speculate that conceptual resources, such as mechanism, indicator, and accounting, as well as representational resources, such as energy tracking diagrams, facilitate the activation of additional, necessary resources, such as potential energy, which otherwise seem to be relatively inaccessible to students. The potential energy resource is then available to students to transform and integrate with new resources, from the unfamiliar disciplines, in the service of cross-disciplinary learning.

V. CONCLUSION

A. Summary

We have analyzed transcripts from think-aloud interviews with preservice K-8 teachers enrolled in science content courses to characterize the cross-disciplinary learning of energy concepts. We find that students activate conceptual resources for energy developed in a prior physics course when confronted with a novel challenge in a less familiar disciplinary context. Student reasoning in the less familiar context was often incomplete, as might be expected given that, by design, they were interviewed early in their follow-on disciplinary coursework. Similar to the Preparation for Future Learning transfer framework [11,50], we consider students' ability to activate learned resources in relatively unfamiliar contexts as evidence of productive reasoning across disciplines, even if their reasoning is not fully correct or complete. Thematic analysis using a conceptual resources framework [9,38,39] indicates situated, if not disciplinary, productiveness of conceptual resources for energy, as students activate such resources when constructing explanations, including identifying and relating relevant energy forms, transfers, and transformations.

The *Energy forms* and *With objects* resources are the most frequently activated resources across all disciplines. We were encouraged to find that students activated conceptual resources for specific energy forms in disciplinary contexts that were presumably less familiar to them. Among the different types of energy forms, kinetic, thermal, and potential energy were used with some regularity. Potential energy tended to be more difficult for students to describe, perhaps because, as one student expressed, “potential energy is a hard thing for me to

grasp just because it's not a physical thing." Although students in many cases brought up a specific potential energy form, it was less common for them to associate a change in that type of potential energy with a physical indicator or mechanism. In some cases, participants were not able to identify the type of potential energy involved, even when prompted by the interviewer. Nevertheless, students cited potential energy forms with comparable frequency to kinetic and thermal energy. This suggests an ability to activate a conceptual resource when sense-making in a new disciplinary context, even in the presence of considerable uncertainty and corresponding absence of a fully formed explanation.

With energy forms in particular, but also with many of the other conceptual resources for energy, we found students not only *activated* resources but also *transformed* and *integrated* them with other ideas in the new context, as our construct for cross-disciplinary learning posits [8]. We regard this as evidence of productive cross-disciplinary learning [39]. For example, some students activated an elastic potential energy resource in the earthquake scenario, broadening the notion of elasticity to apply to rocks. In these cases, students also combined ideas about elastic potential energy with ideas about interacting tectonic plates, integrating the activated and transformed energy resource into a novel disciplinary context. In the chemistry scenarios, students transformed and integrated potential energy resources by connecting potential energy to changes in submicroscopic entities.

Although few of the participants produced fully complete and correct potential energy explanations, we found that some cues seemed to help them move forward in their reasoning. When students activated an energy accounting resource, they often subsequently recognized that a form of energy besides kinetic or thermal energy must be changing. In these cases, our participants often used potential energy as a placeholder: While not necessarily naming a specific type of potential energy, students realized that some other type of energy must be involved. In other cases, recognizing a physical indicator or mechanism seemed to trigger activation of a potential energy resource. These physical manifestations, whether correctly assigned or not, helped students consider how and what type of potential energy was changing. Finally, students' drawn representations, especially the particular type of energy tracking diagram introduced to students in the physics course, also spurred the activation of potential energy as a resource in their explanations. It is possible that the energy diagrams activated an energy accounting resource, which in turn led to the activation of the potential energy resources.

B. Implications

When we design programs of study in which students complete sequential courses in different disciplines, we expect certain cross-cutting concepts to serve as a

foundation for students to reason across disciplines. Our findings suggest students are indeed capable of such cross-disciplinary learning, although students' initial reasoning attempts may often be incomplete. These findings are consistent with prior frameworks involving conceptual resources and preparation for future learning [9,11,39], and more broadly are consistent with constructivist theories of learning [60–62]. If educators recognize the conceptual resources students activate in new contexts, they can support students in transforming and integrating these resources to build explanations. Open-ended formative assessment tasks can provide opportunities for students to activate and express relevant conceptual resources, whereas focusing only on students' ability to arrive at correct answers might not be as effective in revealing the resources students are activating [8,10,50].

In our study, some of the richest sensemaking episodes occurred as students engaged and grappled with potential energy. We found that students can be supported in developing this resource in a number of ways: through cues to apply ideas about energy accounting, physical indicators, and visual representations. For example, the use of the principle of conservation of energy seemed comfortable or even natural to many of our participants, and often cued them to access ideas about potential energy. In practice, instructors can ask students to consider what energy forms might be increasing or decreasing in a scenario in association with other recognized energy changes.

Potential energy may become more accessible if instructors help students build habits of routinely attaching potential energy changes to physical indicators. For example, students can be supported to think about potential energy increasing when two attracting objects move farther apart, whether those be two ions, two magnets, or a projectile and the Earth. As physics and chemistry instructors ourselves, we recognize it is all too easy to focus on determining changes in potential energy in quantitative terms, without connecting observable manifestations to those potential energy changes. This may constitute a lost opportunity to help students ground their potential energy ideas in the real world—for example, connecting changes in chemical potential energy to changes in relative positions of submicroscopic particles.

Students can be supported in identifying and reasoning with potential energy through modeling and representation tools. We found that using energy tracking diagrams helped students identify energy changes for all objects involved in a particular system, and perhaps engage in reasoning about energy accounting. Although the specific energy diagrams used in the curricula tied to this study do not explicitly ask students to connect energy changes to indicators, the act of drawing a representation may have led students to consider indicators in conjunction with energy changes and transfers. The energy tracking diagrams used in this study could

be adapted to provide places for students to identify indicators. (Author E. B. added “indicator triangles” to the diagrams in her most recent iteration of the physics course). Other types of energy modeling tools that specifically ask students to represent indicators may further help students in cross-disciplinary learning of potential energy.

To reason productively with the energy model means to account for the dynamic, ever-changing nature of our world. Energy ideas that are more static in nature, i.e., that energy takes on specific forms and is associated with specific objects, while necessary as foundations for constructing explanations, are (arguably) not themselves the focus of those explanations. Rather, we would like students to center their energy explanations on notions of change, transfer, and transformation, to tell the story of how what we observe is related to the interactions between objects. However, we found that the conceptual resources associated with the more dynamic parts of the basic energy model—energy change, energy transfer, and energy transformation—were activated much less frequently in student explanations than the more static resources of forms and with objects. Instruction and modeling tools that push students to foreground these dynamic resources may help students to further integrate multiple conceptual resources to develop more complete energy explanations.

C. Limitations

This study used interviews to elicit and document patterns in student reasoning about energy. We assume such patterns, to a large extent, have origins in students' prior learning experiences. Two students participated in multiple interviews, resulting in an overrepresentation of their ideas in the dataset and introducing a possible cueing effect from one interview to the next.

Because our study involved qualitative analysis, we do not generalize our findings to populations. Instead, we use our findings to begin to map a “possibility space” for student cross-disciplinary learning of energy. While multiple interpretations of the transcript data are possible, and other themes could be developed, it is plausible that the themes in student cross-disciplinary reasoning about energy we have identified would arise in other learning contexts and content subdomains.

Research with larger sample sizes for all three protocols is needed to ascertain the significance of code frequency variation both within and between disciplinary contexts. Further, development of resource productivity codes in this context could allow inferential statistical analysis of energy resource activation patterns that coincide with disciplinary or situated productiveness [38,39]. These could be fruitful directions for further study.

Like any study, the design of our instruments limits and influences what we observed in student reasoning. We posed questions about forms of energy, energy sources and

receivers, and other aspects of the energy model. Such questions may have cued students in various ways. Our quantitative results, for example, the prevalence of the energy forms code, thus stem from both the students' understanding of relevant science content as well as the structure of the interview protocol itself. The results nevertheless offer insights into student reasoning that can help guide instruction.

All participants were drawn from a course series that serves a particular student population (future K-8 teachers) and approaches energy in a particular way. Students from other courses may approach our interview tasks differently, using different vocabulary, modeling tools, and types of reasoning. For example, students with more experience in traditional physics curricula might take more quantitative, and perhaps less conceptual, reasoning approaches. Although we did not explicitly ask the interview subjects to create energy tracking diagrams like those used in the course series, by virtue of their enrollment in the series, these students may have felt cued to do so. Such cueing may have been especially strong when an interview subject was asked to construct a visual representation (even without reference to “an energy diagram”). Coherence with respect to energy content and pedagogy was purposely designed into the course series. We wonder if other populations, from more traditional, siloed programs, might exhibit different patterns of resource activation. Working with additional populations is thus a fruitful direction for future research.

Finally, we cannot assume students were activating resources drawn solely from their physics course. Their consistent and explicit use of the energy tracking diagram developed in the physics course suggests students were activating ideas from this course during the interviews. However, some students had taken prior science coursework in high school or college. Some were concurrently or subsequently enrolled in more than one science education follow-on course. All could have been drawing from their tacit, lived experiences. Nonetheless, our study provides a window into how students activate and reason with some of the conceptual resources they have developed to understand energy.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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