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A Learning Progression for Modeling Energy Flows in Systems

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Summary

This paper outlines development of the Modeling Energy Flows Learning Progression and key indicators for each level of the learning progression. This learning progression is designed to directly support three-dimensional science learning by integrating the crosscutting concept of energy in systems and the science practice of modeling at each level. These two-dimensional levels can then be integrated with individual disciplinary core ideas. In this paper, we describe the foundational literature that informed development of the learning progression, the individual levels, and key indicators that mark transition points between levels. The learning progression is designed for use across scientific disciplines, but is also specific enough to support instructional coherence within disciplines. We posit that learning progressions that are designed in this way can serve to support systems of assessment, instruction, and professional development across multiple grade levels and disciplines.

A Learning Progression for Modeling Energy Flows in Systems

In recent years, the science education community has sought to represent the ways that students come to learn science concepts and practices over time in what have been called learning progressions (Corcoran, Rogat & Mosher, 2009). These learning progressions are bounded at the top by the culturally and scientifically-accepted ideas and practices students are expected to learn; at the bottom, the progressions articulate the ideas and experiences students have when they enter schooling or a sequence of instruction. In the middle, learning progressions include some intermediate sequencing of increasingly sophisticated ideas as they unfold over time (Duschl, Maeng & Sezen, 2011; National Research Council [NRC], 2007).

Learning progressions have been developed for the ways in which student engagement in science practices, disciplinary core ideas, and crosscutting concepts develop over time as part of the *Framework for K-12 Science Education (Board on Science Education [BOSE], 2012)*. This three-dimensional vision for science learning ultimately became the foundation for the *Next Generation Science Standards [NGSS Lead States, 2013)*. However, there is no consensus on the necessary features of a learning progression (Wilson, 2009), and this extends to the process to be used for their development and validation (Duschl, Maeng & Sezen, 2011). In addition, many of the learning progressions that have been developed pre-date the three-dimensional vision of science performance articulated in the *Framework*, and thus are not directly applicable for classroom instruction and assessment.

The three-dimensional structure of the new vision for science learning provides new opportunities to explore the potential of learning progressions as underlying frameworks for curriculum and assessment design, as well as classroom instruction. In particular, we note that the dimension of crosscutting concepts – which include patterns; scale, proportion, and quantity; and matter and energy cycling, among others – provide new opportunities to examine how student understanding progresses over time, not just within units of instruction or within grade bands, but across disciplinary boundaries (Nordine, 2016; Park & Liu, 2014).

In this paper we describe a new learning progression that, building on prior research, interweaves the science practice of modeling with the crosscutting concept of energy flows within systems. In addition, a specific design feature of this progression is that it can be adapted to multiple disciplinary core ideas related to energy. The Modeling Energy Flows learning progression integrates all three dimensions of science learning—science practices, crosscutting concepts, and disciplinary core ideas—described in the *Framework* (BOSE, 2012). This flexible approach to the specification of a learning progression balances the demands of the Framework's vision for three-dimensional learning with the need for applicability across multiple disciplines and content topics.

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Background

In the following sections, we will provide context for the development of our learning progression by describing the structure of NGSS performance expectations. Then, we will describe the ways in which learning progressions have previously been developed for disciplinary core ideas, science practices, and in in some cases, the combination of these two strands. We will then explore the unique position of energy in the NGSS as both a disciplinary core idea and a crosscutting concept before we provide an overview of the foundational research that informed the development of the Energy learning progression.

Three-dimensional Structure of the NGSS

Science and engineering practices, disciplinary core ideas, and crosscutting concepts make up the three dimensions of learning outlined in the *Framework*. The science practices describe the ways in which scientists construct and revise understanding about the natural world. Engineering practices, similarly, describe how engineers design and test systems. Disciplinary core ideas are big ideas in science that make up our current understanding of the world. The crosscutting concepts are those ideas and practices that span across science disciplines.

The *Framework* reflects a recent shift in framing learning goals for science education as part of the 'practice turn' in sociocultural research (Ford & Forman, 2006). This perspective recognizes learning not only as the accumulation of a body of knowledge, but also change in engagement with culturally-valued practices over time. In the *Framework*'s vision, students participate in science practices in order to develop, refine, and apply crosscutting concepts and disciplinary core ideas. This vision for integrated science learning is most explicitly outlined in the performance expectations of the *Next Generation Science Standards (NGSS; NGSS Lead States, 2013)*.

For example, the *NGSS* performance expectation for **HS-LS1-7** illustrates how the three dimensions come together in a single standard. The performance expectation reads, "Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed, resulting in a net transfer of energy" (NGSS Lead States, 2013). The first part of the statement, "Use a model to illustrate that," refers to the science and engineering practice of developing and using models. The middle section of the statement on cellular respiration refers to the disciplinary core idea **LS1.C** about the organization for matter and energy flow in organisms. The final part of the performance expectation on the net transfer of energy refers to the crosscutting concept of energy and matter. Taken together, these three elements make up a single performance expectation that illustrates both the ways high school students should participate in knowledge-building activities (the science and engineering practices) and what content understanding should emerge from that participation (the disciplinary core ideas and crosscutting concepts).

Learning Progressions: Disciplinary Core Ideas and Science Practices

The structure of the NGSS as shown above has implications for the way that researchers take up and use the research base on learning progressions. Some of these progressions are built from logical trajectories of key ideas, based on task and domain analyses and the experiences of teachers and scientists, while others are constructed from evidence of student learning, such as assessments or cognitive interviews (Duschl, Maeng, & Sezen, 2011). Learning progressions have been developed for multiple purposes in science education research, including informing curricular development (Jin & Anderson, 2012; Wiser, Smith, & Doubler, 2012) assessment design (e.g. Alonzo & Steedle, 2009; Neumann, Viering, Boone, & Fischer, 2013), and teacher learning (e.g. Furtak, 2012; Furtak, Thompson, Braaten, & Windschitl, 2012). In addition, the *Framework* used learning progressions to develop benchmarks for learning and create coherence across grade bands.

Gotwals and Alonzo (2012) identified four main strands of research on learning progressions: (a) constructing and defining learning progressions; (b) developing assessments aligned with learning progressions; (c) modelling and inferring student performance on assessments aligned to a learning progression; (d) the use of learning progressions (2012, p. 6). The learning progression described in this paper was designed to support all four of these purposes: first, we seek to construct and define a learning progression, and describe these efforts in this paper. However, we also seek to create a learning progression that will inform a principled approach to assessment design (NRC, 2001; see Briggs & Furtak, 2019). In addition, we ultimately intend to model student performance on these assessments relative to our original, hypothesized learning progression, and also use this progression to inform teachers' classroom assessment design, enactment, and reflection (see Furtak, 2014).

Learning progressions have historically been unidimensional (Wilson, 2003); that is, these progressions focused on one dimension of science learning, either a science concept or a science practice. Concept-focused learning progressions typically describe how student understanding becomes more sophisticated over time in a single content domain or topic. Examples span disciplinary core ideas and grade bands, covering areas such as matter (Adadan, Trundle, & Irving, 2010; Smith, Wiser, Anderson, & Krajcik, 2006), the water cycle (Gunckel, Covitt, Salinas, & Anderson, 2012), energy in carbon transforming processes (Jin & Anderson, 2012), force and motion (Alonzo & Steedle, 2009), natural selection (Furtak, 2012), energy (Neumann et al., 2013), formation of the solar system (Plummer et al., 2015) and genetics (Duncan, Rogat, & Yarden, 2009; Todd & Kenyon, 2015). All of these progressions represent ways that students might think, understand, or reason about a science concept or set of closely-related concepts.

In addition to concept-focused learning progressions, there are also learning progressions that focus on science practices. Although many of these learning progressions pre-date the *Framework*, these learning progressions outline increasingly sophisticated student engagement in science practices. These include modeling (Pierson, Clark, & Sherard, 2017; Schwarz et al., 2009) and argumentation (Berland & McNeill, 2010). All of these practice-focused learning progressions are agnostic to content, and do not take a stance on how these practices might change when used in conjunction with specific disciplinary core ideas or crosscutting concepts. Practice-focused learning progressions are similar in structure to content-focused ones, typically arranged into dimensions or domains of increasing sophistication.

A smaller subset of learning progressions integrate both content and science practices to varying degrees. For example, Songer, Gotwals, and Wenk (2009) described a learning progression that focuses on evidence-based explanations across three years of learning about biodiversity. The authors combined an existing practice-focused learning progression on constructing explanations and use it in the context of biodiversity. The learning progression not only describes how students may engage in more complex evidence-based reasoning over time, but specifies core focal points, classification, ecology, and biodiversity, and how reasoning in those focal points may progress. Similarly, Wyner and Doherty (2017) developed a three-dimensional learning progression for evolution that included multiple practices and crosscutting concepts. The authors had written a curriculum for teaching evolution in middle schools and then collected data from classrooms that used the curriculum to develop the learning progression. In their learning progression, they proposed three progress variables for student learning in evolution and each of these three integrate multiple practices and crosscutting concepts that progress within each variable. Both of these examples, however, anchor the learning progression to a specific content domain, ultimately limiting their applicability across content domains.

Design Context:
Research-Practice Partnership for High School Science Assessment

We have worked in partnership for the past four years with a large school district as it has sought to align its physics, chemistry, and biology curricula with the NGSS. In this partnership, which is focused on supporting teachers through classroom assessment (see Furtak & Briggs, 2018), we have identified the crosscutting concept of Energy and Matter: Flows, Cycles and Conservation (BOSE, 2012) as a thread to follow through these different grade bands.

Our partner school district, which we do not name in accordance with our human subjects agreement, has sought to understand the ways in which their current approach to science instruction with a ‘Physics-First’ model (AAPT, 2006) provides opportunities to deepen students’ understanding of core ideas over time. Specifically, our partner district teaches physics in the 9th grade, chemistry in 10th grade, and biology in 11th grade. In the words of one of the district science coordinators, this sequence begs the question of, “What is gained, and what deeper understandings are possible, when students have physics and chemistry before they take biology?" With this design purpose in mind, and in partnership with the district, we identified Energy as one area in in which student understanding could be traced over time, both as a crosscutting concept, as well as a disciplinary core idea. In addition, the district identified modeling as a priority science practice and provided ongoing professional learning opportunities at regular intervals to support teachers in learning about this practice.

Toward a Progression for Modeling Energy in Systems

Energy occupies a unique position in the NGSS, as it is both a disciplinary core idea within the Physical Science, Life Science, and Earth and Space Science domains, but also part of the Crosscutting Concept of Energy and Matter Cycling. The fact that energy is conserved constrains what can occur in a system. By tracking the flow of energy, one can understand how various observed changes within a system are related. The conservation of energy and its flow into, within, and out of systems is a key concept across disciplines and thus a crosscutting concept. That energy also is a disciplinary core idea in the different domains is due to the fact that the different disciplines have all developed varying ways of describing and tracing energy. Historically, the disciplines each independently developed ways to quantify and describe changes in energy and only later was energy was recognized as a unitary concept (Coopersmith, 2012). These discipline-specific ways of understanding energy have resulted in fragmented energy instruction that can lead students to understand energy in different disciplines as distinct and incompatible concepts (Cooper & Klymkowsky, 2013). As both a disciplinary core idea and crosscutting concept, students can ideally learn both the methods and knowledge that disciplines have developed for tracing energy, and at the same time understand that regardless of the discipline, energy can be traced into, within and out of a system.

Research and Learning Progressions for Energy

In a review of research on energy, Duit (2014) identified four key aspects, transfer, transformation, conservation and dissipation. The exact terms used and combinations for "key aspects" of energy can vary somewhat. For example, Nordine et al. (2016) include energy forms as a fifth aspect, and dissipation is sometimes replaced by or combined with degradation (Herrmann-Abell & DeBoer, 2018; Neumann et al., 2013). On the whole, there appears to be a general consensus that an understanding transfer and transformation generally precedes dissipation and conservation (Duit, 2014; Lee & Liu, 2010; Liu & McKeogh, 2005; Neumann et al., 2013; Nordine et al., 2011). This may be because conservation and dissipation require an integrated understanding of how energy is transferred and transformed (Lee & Liu, 2010). Across disciplines, students have trouble applying concepts of energy across multiple contexts (Park & Liu, 2016; Cooper & Klymkowsky, 2013). These difficulties may be due to differences in how energy is emphasized and taught in different disciplines and a key step in improving energy learning is through greater coherence across the disciplines (Fortus et al., 2015; Kohn, Underwood, & Cooper, 2018)

The development of learning progressions is one possible mechanism for increasing instructional coherence. For example, Neumann et al., (2013) presented a learning progression in physics. They described progress along four different dimensions, forms of energy, transfer and transformation, conservation, and dissipation. Each of these dimensions were mapped so that students built an increasingly complex knowledge base from discrete pieces of knowledge to increasingly connecting and intertwining until ultimately students would build complex knowledge structures about energy. The authors hypothesized that learning should progress both within dimension and that different dimensions may be more or less difficult for students. The authors designed and administered an energy assessment to students in grades 6, 8, and 10. Although they found no differences in how students performed on more or less complex items within dimensions, they found that students developed an understanding of forms first, and then transfers/transformation and dissipation in parallel. Conservation ultimately proved to be the most difficult for students.

Jin and Anderson (2012) developed a progression for K-12 students learning to trace energy in carbon-transforming processes. Their progression describes three dimensions of progress: purpose of energy, association and tracing. How students make progress from thinking of energy as causal to a tool for analysis is captured in *purpose of energy dimension*. The *association dimension* is about students understanding the similarities and differences between forms and processes of energy. Finally, in the *tracing dimension*, students identify what is consistent and what changes with energy in a process. The authors used linguistic analysis of student assessment data from fourth graders through high school students to define four levels of student achievement ranging from everyday and informal understanding to science understanding. The authors identified indicators at each level for tracing and association. Similar to Neumann et al. (2013), they also found that students have difficulty consistently using concepts of energy conservation.

Research and Learning Progressions for Modeling

Early research on modeling in science education often focused on the analogical or representative nature of models. This type of research described how science concepts were represented by textbooks or teachers (Harrison & Treagust, 2000) or by students (Lehrer & Schauble, 2006) or with mathematical models (Hestenes, 1987). More recently, there has been a shift from understanding models as a distinct entity with definable structure toward modeling as a practice with epistemic goals (Passmore, Gouvea, & Giere, 2014). Models are not only ways to represent science knowledge, but rather, modeling is a practice through which students construct new science knowledge. With the shift toward science practice, researchers have called for re-structuring science inquiry in classrooms around constructing and revising models (Passmore, Stewart, & Cartier, 2009; Schwarz & Gwekwerere, 2007; Windschitl, Thompson, & Braaten, 2008). Similar to energy, multiple learning progressions have been developed in modeling.

Schwarz and colleagues (2009) developed a learning progression for modeling that focuses on two key dimensions. The first dimension is that models are productive tools for generating predictions and explanations. This dimension focuses on how students use models, from literal depictions of some phenomenon to using models to generate explanations, predictions, new questions and forward their own thinking about a phenomenon. The second dimension focuses on the changeable nature of models, progressing from seeing models as static entities to ones that are changeable based on evidence or to increase explanatory power.

Pierson and colleagues (2017) identified additional dimensions implicit within the original modeling learning progression. The authors engaged in design-research (DBR collective, 2003) to revise the Schwarz et al. (2009) learning progression and drew on classroom data from co-teaching a semester-long life science unit in 8th grade. The dimensions they identified were salience-generality, audience/user, evidence, mechanistic-generative, and revision. In using this learning progression with middle school students during a semester-long ecology sequence, they found that students do not progress through the learning progression in an ordered sequence but rather move between levels depending on the classroom opportunities available to them.

The preceding research and learning progressions each provided key contributions to our understanding of how student understanding develops in these domains. In the following section we turn to a description of the design of our own learning progression that builds on and combines features of this foundational work.

> "By foregrounding a single science practice and crosscutting concept, we seek to account for how science practices may transform when used with a specific crosscutting concept and how aspects of a crosscutting concept may become more salient in conjunction with a specific science practice."

Modeling Energy Flows Learning Progression

In the context of the research-practice partnership described above, our research team has sought to balance the need for a learning progression that integrates the science practice of modeling and the crosscutting concept of energy with the need for a representation that can be applied across disciplines. Thus, our learning progression foregrounds the science practice of modeling and the crosscutting concept of energy flows. The practice of modeling can take many different forms based on factors such as disciplinary norms, purpose for the model, and the user and audience. This wide spectrum in how modeling can be practiced could potentially contribute to difficulties in learning how to model in classrooms. In this learning progression, students are modeling in a specific context, energy, and for a specific purpose, explanation. By foregrounding a single science practice and crosscutting concept, we seek to account for how science practices may transform when used with a specific crosscutting concept and how aspects of a crosscutting concept may become more salient in conjunction with a specific science practice. For example, as described below, identifying and attending to the systems and surroundings becomes more important when modeling energy flows as compared to when modeling some other concepts. While more general concepts of energy such as forms and transfers are part of the lower anchors of the learning progression, understanding more sophisticated disciplinary core ideas about energy are included only at the upper anchors, such as the mechanistic understanding of how energy is stored or transferred in the context of a specific phenomenon. Through this design, we seek to create a learning progression that can be used to support three-dimensional learning across multiple topics within each discipline, and at the same time provide teachers with a way to create consistent learning experiences for students across years and disciplines.

Development of the Learning Progression

Development of our learning progression was informed by two main bodies of research and our current work with a local school district. First, we built on prior science education research on learning progressions of modeling and energy. As we describe in more detail below, we draw in particular on work from Schwarz and colleagues (2009) and Pierson, Clark, & Sherard (2017) for modeling and the work of Neuman, Nordine, and colleagues (Neumann et al., 2013; Nordine, 2016) for energy. Second, because our learning progression is intended to be used by teachers in schools, we also drew heavily on the *Framework* and the performance expectations and related evidence statements of the *NGSS* for guidance about sequencing, intended learning outcomes, and assessment boundaries. We were also informed by our work as a research team with high school science teachers in a large, comprehensive, public school district around modeling and energy. During this time, we supported physics, biology, and chemistry teachers in developing teaching sequences and assessments on modeling and energy. At the conclusion of the school year, we developed this learning progression by first drawing on our interpretation of the learning expectations outlined in the *Framework* and *NGSS* and the aforementioned research based on how students learn modeling and energy. We then refined our learning progression based on our experiences working with teachers, classroom observations, and data collected from student assessments.

There are three core strands that run throughout the learning progression: energy flows, developing and using models, and systems. We will describe each in more detail below. We also centered this learning progression on the use of phenomena and how models can be used to explain a phenomenon. A phenomenon, which we define as an observable event or state that can be explained or predicted through science activity, serves as a target for students' science practice and knowledge (BOSE, 2012; Achieve, 2016). Students begin with modeling and explaining a single, given phenomenon. As they make progress, they move toward using their model to make predictions about changes in a phenomenon, and then generalizing across multiple phenomena.

Energy flows. The first core strand is the crosscutting concept of tracking the flow of energy into, out of, and within a system. By tracing the flow of energy, students are able to construct explanations for changes in a phenomenon. For energy, we draw on the work of Neumann, Nordine and colleagues and their five "Big Ideas" of energy: forms, transfer, transformation, conservation and dissipation (Neumann et al., 2013; Nordine, 2016). Energy is manifested at the macroscopic level in various forms and one can explain changes in the phenomenon through energy transfer from one object or subsystem to another object or subsystem, and by energy transformation from one form to another. Energy conservation is one of the most important ideas in all of science. That the total energy in any isolated system is conserved is what allows scientists to trace energy in the first place. Any observed increase in one form of energy or subsystem must be accompanied by a decrease in another form or subsystem. The conservation of energy in turn puts limits on the magnitude of change possible in a system. Students can account for any observed changes in the total energy through energy transferring into or dissipating out of the system. We used the five Big Ideas as an initial inspiration for how students might learn about energy across disciplines; first learning simple forms and transfers and transformations before moving on to an understanding about conservation and dissipation.

> We focus on diagrammatic models because of their wide accessibility across content areas and ease of entry for teachers and students.

Although the crosscutting concept itself includes both matter and energy, focusing solely on energy simplifies the learning progression and makes it more widely applicable across each discipline. We integrate matter back into the learning progression when it is appropriate to an NGSS Performance Expectation, such as when students are learning about the carbon cycle in biology.

Developing and using models. The second strand is the science and engineering practice of developing and using models. Although modeling can take many forms, we focus on models with two key features: they are diagrammatic (Pierson et al., 2017) and explanatory (Bokulich, 2011). Diagrammatic models, typically in the form of drawings or pictures, are simplifications of a phenomenon that include both observable and unobservable components and relationships (Pierson et al., 2017; Schwarz et al., 2009). In science and science education, there are models that are constructed from science theory and laws, such as the Ideal Gas Laws or the Bohr model of the atom. Diagrammatic models are different from these kinds of models because they are first constructed from phenomena that are "in the world" rather than purely theoretical. Importantly, models are not simply representations of a phenomenon but are actively constructed and revised by students in order to achieve a science goal, such as making sense of, explaining or making predictions about a phenomenon (Passmore, Gouvea, & Giere, 2014). To construct diagrammatic models, a student must typically go through a process of selecting components, relationships, and interactions observed within the phenomenon that are relevant to their science goal. Students often idealize relationships and abstract out what is not relevant, or that which makes the model too complicated. For example, a student may intentionally omit air resistance in a model of a falling object or idealize a collision between two crashing carts to be perfectly elastic. These abstractions and idealizations are often necessary steps for making models useable for making sense of and explaining a phenomenon.

We focus on diagrammatic models because of their wide accessibility across content areas and ease of entry for teachers and students. Diagrammatic modeling does not require additional materials beyond a pencil and paper, as opposed to, for example, creating computational models that require access to computers and learning how to use software. Diagrammatic models serve science purposes, helping students to make sense of and explain a phenomenon, but also can serve a pedagogical purpose, especially in the area of assessment. Diagrammatic models can be used to make student thinking visible through creating an external and shareable representation of students' conceptual understandings (Gilbert & Justi, 2016; Lehrer, Schauble, Strom, & Pligge, 2001).

We define explanatory models of energy flows as models that depict a mechanism for energy storage, transfer, or transformation. For energy flows, mechanisms are the entities and activities, that facilitate or produce the storage, transfer, or transformation of energy. These mechanistic explanations of energy often involve describing or showing how the actions of cells, molecules, particles, or electromagnetic and gravitational fields facilitate or produce the flow of energy. The *Framework* expresses a clear preference for mechanistic explanations regarding energy. It states that relationships between different forms of energy are “better understood at the microscopic scale, at which all of the different manifestations of energy can be modeled as either motions of particles or energy stored in fields” (BOSE, 2012, pp. 123-124). This preference for a mechanistic explanation is also clear from examining evidence outcomes for Performance Expectations of the *NGSS* (NGSS Lead States, 2013). The evidence statement for HS-PS1-4 includes, “The energy transfer between system and surroundings by molecular collisions” and HS-PS3-2 states, “Thermal energy includes both the kinetic and potential energy of particle vibrations in solids or molecules and the kinetic energy of freely moving particles (e.g., inert gas atoms, molecules) in liquids and gases” as well as, “Chemical energy can be considered in terms of systems of nuclei and electrons in electrostatic fields (bonds).” The *Framework* and the *NGSS* both make clear that students should be working toward developing mechanistic explanations regarding energy at micro- and nanoscopic scales.

These kinds of explanations most closely align with the revised mechanistic-generative category from Pierson and colleagues (2017). This category focuses on students constructing models that do more than just describe a phenomenon. The mechanistic-generative category describes four levels. Level 1 models are simple descriptions of the phenomenon. In Level 2, students begin to illustrate observed patterns within their models. For Level 3, students represent an explanatory mechanism and at Level 4 students are able to make predictions and generate questions about new phenomena. Although our Modeling Energy Flows Learning Progression has a different organization because it integrates modeling with energy flows and systems, its levels maintain the order of the mechanistic-generative category.

Systems. The third core strand is systems. While also a separate crosscutting concept, identifying systems and system boundaries is such a core part of both modeling and energy that it was necessary to foreground systems for our learning progression. To create an explanatory model about a particular phenomenon, one must first identify and bound a system of interest from a larger phenomenon. Without identifying a system, phenomena are too large and complex to be the target of science activity. They need to be bounded, in terms of both space and time, by intentionally defining only a small portion of a phenomenon as the subject of investigation. Students can then use a diagrammatic model to represent the system and immediate surroundings. For energy flows, the crosscutting concept focuses on tracking energy flows “into, out of, and within systems (BOSE, 2012, p. 84).” Identifying the system and surrounding is a necessary step for tracing energy flows, as well as understanding whether or not, for analytic purposes, the system is open or closed to inputs or outputs of energy which is critical for reasoning about conservation and dissipation of energy at later stages.

As an example, when working with modeling in a professional development session, our research team used a typical classroom calorimetry experiment as a guiding activity (Eisenkraft, 2016). In this activity, teachers combusted a corn-based snack underneath a can of water and measured changes in temperature. They then created models to explain the temperature change in the water. Most of the teacher groups created models using the can of water and the corn-based snack as the key components of the system. However, one group also included the farm and the energy from the sun that grew the corn. While both of these models represented accurate depictions of a systems and could both be used to answer questions about energy and the phenomenon, the two different systems are appropriate for answering different questions. The first example is more appropriate for questions about the transfer of energy into the calorimeter and out into the atmosphere, while the latter example being more appropriate for questions about where the initial energy input comes from.

Levels of the Learning Progression

In this section, we describe the learning progression (Figure 1), how it integrates modeling, energy flows, and systems, and key transitions between levels.

Figure 1. A Learning Progression for Modeling Energy Flows

Level	A Learning Progression for Modeling Energy Flows
5	• Students are able to ***generalize their model*** to unknown or multiple phenomena, and can ***explain limitations of applying the model*** to a new phenomenon.
4	• Students ***develop a model*** that illustrates a mechanism that can explain or predict the phenomenon, AND ***use*** the model to make predictions about how changing one part of the model would influence energy flows elsewhere in the system. • Students can explain how the total energy of the system constrains the magnitude of change possible. • Students can ***describe limitations of the model*** in explaining or predicting the phenomenon.
3	• Students ***use*** or ***develop*** a model that relates changes in the phenomenon directly to changes in energy through transfers/transformations by identifying specific indicators. • Students begin to show evidence that their model is accounting for conservation and dissipation. • Model includes energy flows into, within, and out of the system.
2	• Students ***use*** or ***develop*** a model to illustrate a relationship or pattern between the increase in one form of energy and the decrease in another form, or transferred from one location or object to another. • Students identify the most relevant components and relationships in the model and distinguish between the system and surroundings. • Model focuses on energy flows within the system only.
1	• Students ***use*** or ***develop*** a model that shows, through drawings or labels, the components involved in a phenomenon, some (but not necessarily all relevant) energy forms, transfers, or transformations.

Indicator - how changes in energy are manifested. These are the observable differences in a phenomenon, such as when an object speeds up or slows down or temperature increases or decreases, that let students know there is a transfer or transformation of energy.
Mechanism - the entities and activities that produce the changes in energy flow. For example, changes in kinetic energy can best be explained through particle motion. This will usually require changes in scale in a model, such as particle motion, cellular activity, or changes in fields.
Phenomenon - an event or state that we want to explain, in this case, through changes in energy flows.
System/Surroundings - the system includes the part of the universe under investigation and the surroundings include everything outside of the investigation.

Level 1. Level 1 is the literal and descriptive level. Learning at the lowest level focuses on basic skills of diagrammatic modeling. Students learn to observe phenomena, and based on their own motivating questions or external motivating questions provided to them, they identify key patterns, relationships and interactions that might help answer the question, along with selecting components that are likely to be involved in these relationships. Students may omit some critical components or include extraneous ones because they do not yet understand the science principles governing the phenomenon. For example, in the case of students modeling a falling object near to the Earth's surface, a student may not include the Earth as part of the model. This omission may be the result of students not yet understanding how gravitational force works, as opposed to students not yet understanding that their model should include all relevant components. Although included components and relationships are likely to be mostly macroscopic at this point, students are likely to represent some components and relationships that are not directly observed through learning simple representational forms for modeling energy. This can include identifying and labeling forms of energy or drawing simple arrows to show the direction of energy transfers. At this level, students are beginning to identify energy forms, transfers and transformations but they are not being used to explain the phenomenon. While students may include components of both the system and surroundings, the distinction between the two is not explicit.

> "The key transition in understanding relative to level 1 of the learning progression is the ability to demonstrate that energy must be transferred from one object to another object or subsystem or transformed from and to another form."

Level 2. In Level 2, students show an increasing ability to develop models that focus attention on the relationship between energy transfers and transformations and energy flows within the system. The relationship between the relative increase and decrease in forms of energy within the system is a key stepping stone in understanding the cycling of energy, and ultimately, the conservation of energy. When modeling energy flows, students explicitly indicate the source and target of energy transfers or transformations. They may create their model through simple diagrams, such as drawing arrows that clearly begin and end in different objects within the system or graphically (e.g., through energy bar or pie charts), but this could also be accomplished through written description or mathematical calculations. The key transition in understanding relative to level 1 of the learning progression is the ability to demonstrate that energy must be transferred from one object or subsystem to another object or subsystem or transformed from and to another form. In other words, students recognize that energy is not simply increasing (being created) or decreasing (being destroyed) without being accounted for in some way. Students are unlikely to be able to provide a full quantitative accounting at this level, but they understand that such an accounting must exist. At this level, students should also explicitly identify the system and surroundings, although the model only needs to focus on the energy flow within the system.

Level 3. For level 3, the key relationship is between changes in energy and observable indicators in the phenomenon. At this level, students can explicitly link together the unobservable flow of energy with observable indicators in the phenomenon. Students identify key indicators in the phenomenon and relate this back to the energy transfers or transformations they include in their model. When learning about energy, this answers a question about how students know that energy is being transferred or transformed by making connections between observable indicators and energy transfers and transformation. In the calorimetry example, students may have shown thermal energy being transferred as well as temperature changes.

At this level, they would be able to show that the indicator for the transfer of thermal energy is temperature change. This could be shown in multiple ways, such as labels and arrows, displaying data, calculations, or graphs. The critical point is that students at this level would recognize both that (1) the target of thermal energy transfer increased in temperature, and (2) that the source of the thermal energy transfer decreased in temperature. This focus on indicators is an example of modeling that is specific, but not unique, to the energy context.

At Level 3, students also begin to account for energy flow both in and out of the system, which brings in the Big Ideas of conservation and dissipation. Student thinking about dissipation and conservation is conceptually tied to indicators. Students often observe specific indicators, such as light entering the system or being released into the surrounding, and then use these indicators to infer that energy is entering into or exiting out of the system. They are also likely to infer that energy is being brought into the system or that it dissipates based on observations that give the appearance of energy conservation being violated.

Level 4. In Level 4, the student is able to create models that show a mechanistic explanation of the phenomenon through the integration of more complex disciplinary core ideas. In the previous levels of the learning progression, students may model energy flows of an unfamiliar phenomenon while having minimal understanding of the relevant disciplinary core ideas. At Level 4, students are developing models that include the mechanisms by which energy is stored, transferred, or transformed. Depending on the phenomenon, this may include modeling particles, atoms or molecules, cells, or electromagnetic and gravitational fields. While Level 3 is characterized by students using models to link the unobserved with observable indicators, at this level students develop or use models at different scales. Modeling energy at different scales is important for showing how various manifestations of energy at the macroscopic scale are produced or emerge from mechanisms at the micro- and nanoscopic scale and that ultimately these different manifestations arise from similar mechanisms (BOSE, 2012). For example, students would model the transfer of thermal energy through a fluid (convection) by showing how this is produced by the movement of molecules.

In this level, students show how total energy serves as a constraint on the total change in energy that is possible within a system. For example, after dropping a ball, the ball will never bounce equal to or higher than its original height. Students can show this in a model in multiple ways, using graphs or equations that show how the total energy in the system never increases; or that over time, energy dissipates out of the system or degrades into less useful forms.

This level also marks a transition in modeling where students are not just modeling a given phenomenon but are asked to make predictions using their models. Students can use their understanding of the mechanisms that store, transfer, or transform energy to make predictions involving changes in their model. For example, to explain why a cup of coffee will cool down while sitting on a table, students first create a model that shows the movements of molecules in a coffee cup which produces the transfer and dissipation of thermal energy via convection and conduction. Students at this level should also be able to use this model to make predictions about how modifications to the coffee cup would affect how the temperature changes, such as adding insulating sleeves or a lid. Students would use their model to inform these predictions and be able to show in their model how the introduction of a lid would change the movement of molecules, flow of energy, and observable differences in temperature. At this level is also where students are expected to understand the limitations of their model and how decisions made by the student when constructing the model might affect the applicability of the model to the target phenomenon. In the example described in Level 1, students omitted air resistance in order to simplify their model. At this level, students demonstrate how this decision limits the accuracy of the model for making predictions or explanations.

Level 5. In Level 5, students are now capable of using models of energy flows for more than explaining a given phenomenon; they can use them for generative purposes. This includes students applying the model across different phenomena. Any phenomenon is contextual and occurs under specific conditions. However, there are some features of a phenomenon that repeat across nature. A student should be able to apply, with appropriate constraints, an explanation developed for a single phenomenon to other, related, phenomena, For example, students may be initially developing models for a given phenomenon, such as using the transformation of gravitational potential energy to kinetic energy to explain how a free-falling skydiver gains speed. At this upper anchor, students can then use this model of energy transformation to explain and make predictions about new phenomena. In this example, a student would be able to use energy transformation to explain and make predictions about other instances of free fall. They can also describe the conditions and limitations to the generalizability of their model, such as understanding that a model for a free-falling object only applies when gravitational force is the sole force acting on the object, or when the object is relatively close to the Earth's surface.

"A student should be able to apply, with appropriate constraints, an explanation developed for a single phenomenon to other, related, phenomena."

Conclusion

In this paper we have described a learning progression for modeling energy flows. This learning progression maps a possible sequence for students as they learn to develop models that use energy flows to explain phenomena. Building from the *Framework* and *NGSS* performance expectations we developed a learning progression that connects three core strands of student learning: the science practice of modeling and conceptual understanding of energy flows and systems. This learning progression pulls together performance expectations across content areas to help achieve greater coherence across instruction. It is both broad enough that it can be used across multiple disciplines, but also can be mapped onto any performance expectation relating to modeling and energy.

At the writing of this paper, we are collecting data in an effort to validate the levels of this progression across three high school grade bands as part of a larger study with our partner school district. In this study we have used the learning progression described in this paper as the foundation for (1) assessment designs for both formative and summative purposes, (2) the creation of diagnostic score reports for teachers, and (3) to facilitate the iterative design, enactment, and reflection upon formative assessments with science teachers. In this way, we intend to collect multiple forms of evidence to leverage as we understand the validity of the use of this learning progression for multiple purposes (Alonzo & Gotwals, 2012).

Our related writings on the learning progression articulate ways in which the learning progression serves as a foundation for a system of assessment (see Furtak & Briggs, 2018; Briggs & Furtak, 2019), the tools and resources we have designed to support teacher use of the learning progression (e.g. Henson, Chattergoon, & Furtak, 2018) as well as continue to track the ways that teachers work with the learning progression in their school-based professional learning communities.

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