Supporting Middle School Students' Development of an Accurate and Applicable Energy Concept

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ABSTRACT

Energy is a fundamental unifying concept of science, yet common approaches to energy instruction in middle school have shown little success with helping students develop their naïve ideas about energy into more sophisticated understandings that are useful for making sense of their experiences. While traditional approaches to energy focus on performing calculations in idealized systems, our development team produced a new middle school energy unit that focuses qualitatively on the energy transformations that occur in everyday, non-idealized, systems. This approach uses project-based pedagogy to contextualize instruction with the driving question, "How can I use trash to power my stereo?" In this study, I investigate the effectiveness of our approach by tracking 8th grade students' conceptual development during the unit, following up with students who participated in the unit a year previously, and comparing the energy conceptions and content knowledge between energy unit participants and older students in the same school who learned about energy in an approach that did not emphasize energy transformations in non-idealized systems. Results indicate that during instruction, students' energy conceptions progress from a set of disconnected ideas toward a coherent understanding that is organized around the principle of transformation. After instruction, students who participated in the energy unit were generally more capable of using their understanding of energy to make sense of everyday scenarios than were older non-participants. Furthermore, 9th grade students who participated in the energy unit in their 8th grade year continued to develop more sophisticated understandings of energy during their 9th grade biology course. These 9th grade students seemed better prepared to learn about energy content in their biology course than 10th graders, who did not participate in the energy unit, but took the same biology course during their 9th grade year. Overall, my results suggest that middle school curricula can have a more meaningful and lasting impact on students' energy conceptions and content knowledge by focusing qualitatively on energy transformations that occur in familiar, non-idealized systems.

INTRODUCTION

Energy is one of the most fundamental and far reaching of all scientific concepts. Biologists use energy to describe the relationships between organisms in an ecosystem; chemists routinely interpret chemical reactions by tracking energy changes; geologists use the conservation of energy to build models that describe plate tectonics; astrophysicists rely on energy conservation when deducing the shape and structure of the universe. Regardless of its application, the law governing energy is strikingly simple – the total amount of energy in any closed system must be the same at any two points in time.

It is the simplicity of the law of conservation of energy and its wide applicability that make it a ubiquitous topic in school science, yet it is often addressed superficially in ways that are not likely to promote deep understanding in students. In a review of the most popular textbooks used in middle school science classrooms, Kesidou and Roseman (2002) found most to be inadequate in terms of their ability to promote students' development of coherent understandings of the major ideas in science, such as energy. Among their shortcomings, the most popular school science textbooks failed to model how science concepts and processes can be used in students' lives outside of school. Without making connections between science topics and between school science and students' everyday lives explicit, students are highly unlikely to do it on their own (Brown, Collins, & Duguid, 1989; Lave, 1988).

In order to make such connections and to develop deep understandings of scientific concepts like energy, curricula must provide students with opportunities to refine and reorganize their prior understandings (National Research Council, 2000, 2007). When students enter the science classroom, they have already formed their own ideas related to energy (Driver, Squires, Rushworth, & Wood-Robinson, 1994a; Solomon, 1983; Watts, 1983), but traditional physical science instruction has proven largely ineffective for helping students refine these ideas into more accurate and sophisticated conceptions (Driver *et al.*, 1994a; Solomon, 1983).

Traditional middle school energy instruction often focuses on simple calculations of energy and work idealized systems, offers an operational definition for energy (e.g., "the ability to do work" or "the ability to cause a change"), and focuses on one form of energy at a time without emphasizing the importance of energy transformations in everyday phenomena. This common traditional approach may be a reaction to assertions that young children are not yet capable of dealing with energy as an abstract physical quantity (Piaget & Inhelder, 1971; Warren, 1986), yet recent studies indicate that such a stage-like conception of development is not entirely appropriate (Flavell, 1994). Further, instructional interventions seem to play a key role in developing understandings in young children that many adults never acquire (Klahr & Nigam, 2004; Linn, Lee, Tinker, Husic, & Chiu, 2006; Smith, Maclin, Houghton, & Hennessey, 2000; White & Frederiksen, 1998). When students develop understandings that are coherent rather than a collection of facts, they are more likely to be able to apply their knowledge to new situations and continue to learn more efficiently even after instruction (Linn & Eylon, 2000; National Research Council, 2000, 2007). To help students develop coherent understandings, instruction must be organized around big ideas and involve learners in relevant contexts (National Research Council, 2007; Roseman & Linn, 2007).

A development team (of which I was a part) composed of collaborators from the Center for Highly Interactive Classrooms, Curricula, and Computing in Education at the University of Michigan and the Department of Teacher Education at Michigan State University developed a new curriculum (Fortus, Krajcik, Nordine, Plummer, Rogat, & Switzer, 2005) to introduce middle school students to the scientific concept of energy. The curriculum represents a substantial departure from typical middle school instruction on energy because it involves no calculations of work or energy, makes no attempt to operationally define energy, and focuses on energy transformations that occur in non-idealized phenomena that students are likely to see outside of the classroom. Because of its central focus on energy transformations in everyday phenomena, our approach gives students more of an opportunity to integrate their school science knowledge with their prior experiences into a coherent framework that is organized around the principle of energy transformation. When students are able to use their understanding of energy to interpret everyday phenomena, the explanatory power of their energy concept increases dramatically. By having a concept of energy that is more useful in more contexts, students are well-positioned to use their energy concept to learn and interpret new information. Because our unit is designed to help students develop a more accurate and applicable concept of energy, I believe our approach is a more effective way to introduce middle school students to energy than the traditional alternative of studying energy in a piecemeal fashion using classical idealized phenomena that students are unlikely to experience directly.

In this study, I assessed the effectiveness of our instructional approach by investigating the following research questions:

- How do students' conceptions of energy evolve during the course of their involvement in the energy unit?

- To what extent do students' desirable conceptions of energy attained during their participation in the energy unit persist one year after instruction?
- How do the energy conceptions of students who have participated in the energy unit compare to the energy conceptions of students at the same school who have not participated in the unit?
- What effect does participation in the energy unit have on students' ability to perform on assessment items that are targeted at national standards and benchmarks?

To address these questions, I compared the 8th and 9th grade students who participated in the energy unit at a pilot site to 10th and 11th grade students at the same school who had the same 8th grade teachers but did not participate in the unit. Although the 10th and 11th grade students had also studied energy in 8th grade (the 8th grade science course at the pilot site has been organized around the theme of energy for many years), these students were exposed to an approach that did not emphasize the role of energy transformations in everyday, non-idealized systems. I compared students in terms of their energy conceptions and their ability to perform on assessment items that were developed by members of Project 2061 to assess middle school energy benchmarks from the Benchmarks for Science Literacy (American Association for the Advancement of Science, 1993).

For each of my research questions, I hypothesized the effect of students' participation in the energy unit would be manifest in the following ways:

- I expected that 8th grade students would develop more coherent understandings of energy during instruction that are organized around the principle of transformation. This is the effect I observed in a pilot study (Nordine, Fortus, & Krajcik, 2006).
- Because our unit is likely to produce conceptions that are useful for interpreting everyday phenomena, I expected that students' coherent conceptions would be largely maintained. Therefore, I expected that 9th grade students would exhibit roughly the same quality of energy conception compared to that which they exhibited in a pilot study one year ago, with perhaps some small amount of deterioration.
- Because 10th and 11th grade students have not had energy instruction that is organized around transformations in everyday phenomena, I expected that 8th and 9th grade energy unit participants would be more likely to exhibit coherent energy conceptions organized around the principle of transformation and will be less likely to exhibit alternative conceptions than would 10th and 11th grade students who have not participated in the energy unit
- I expected that 8th and 9th grade students would significantly outperform 10th grade students on energy content assessments targeted at middle school energy benchmarks because energy unit participants would be more likely to have a coherent cognitive framework that better supports energy content knowledge. I expected that 11th grade students, who are the group most highly self-selected for an interest in science and who have recently had energy instruction in physics, will perform at or above the level of 8th and 9th grade students on the energy content knowledge assessment.

The results of this study can inform educators' understanding of how students' conceptual development occurs, the design of *learning progressions* that describe how students' thinking about energy can become successively more sophisticated over an extended period of learning and investigation (National Research Council, 2007), and the development of new curricula that support students' understanding of the big ideas of science. Because over 90% of middle school physical science teachers do not hold a major and certification in their subject (Seastrom, Gruber, Henke, McGrath, & Cohen, 2004), and these teachers are highly likely to rely on curricular materials (Ball & Feiman-Nemser, 1988), putting proven high-quality instructional materials in the hands of teachers is perhaps the most promising way to improve science instruction in middle schools.

THEORETICAL BACKGROUND

Although energy is one of the most central and richly connected ideas in all of science, students often have a great deal of difficulty understanding it (Driver, Squires, Rushworth, & Wood-Robinson, 1994a). While some have suggested that students' difficulty learning about energy is largely due to maturational factors (Warren, 1986), others contend that students' ability to learn about abstract concepts (such as energy) is not as centrally dependent on biological maturation as was once thought (Flavell, 1994), and that instruction can foster scientific understandings in young students that many adults never acquire (Klahr & Nigam, 2004; Linn, Lee, Tinker, Husic, & Chiu, 2006; Smith, Maclin, Houghton, & Hennessey, 2000; White & Frederiksen, 1998). In this section, I describe students' common ways of thinking about energy, how students develop and refine their ideas, and role of curriculum in supporting students' conceptual development.

Common student ideas about energy

Over the past several decades, a line of "misconceptions" research has been aimed at providing insight into the types of common alternative understandings that students bring to the classroom. Many of these researchers did not favor the term *misconception*, because it implied some sort of inappropriate understanding among students, even though their ideas may be entirely consistent with their experiences. For this reason, some researchers use terms such as *preconceptions*, *children's science*, and *alternative frameworks* when describing students' thinking about science concepts that is not congruent with accepted scientific understandings (Confrey, 1990). Regardless of differences in terminology or beliefs about the origin of students' ideas, the body of misconceptions research has served the function of showing empirically that students do not enter the science classroom *tabula rasa*, rather, they bring in their own ideas that will influence the way they interpret new information.

Watts (1983) reported that students' naïve ideas about energy could be categorized according to seven common *alternative frameworks*, which were intended to describe patterns of thinking that are broader than individual misconceptions (Driver & Easley, 1978). He identified these frameworks by interviewing secondary science students using the "interview-about-instances" approach (Osborne & Gilbert, 1980), which is described more in-depth in the methods section. Table 1 identifies each of the seven frameworks, gives a brief description of them, and gives an example quotation from a student that is indicative of each framework. The quotations are from Watts' original student interviews.

Table 1: Description of Watts' original alternative energy frameworks

Framework	Description	Example Quotation
Anthropocentric	Energy is mainly associated with human beings.	(On a person pushing a box up a hill) The person's got a lot of energy in that one…I mean he can push it the whole way up to the top of the hill…but, er, once the box is there it can't do anything so the box definitely hasn't got any energy…whereas the person can walk away back down.
Depository	Some objects 'have' energy, and some 'need' it.	Well, the battery's got the energy…the bulb needs it and the wires…well they're just ordinary wires aren't they.
Ingredient	Energy is dormant within some objects, and can be released by some trigger.	Well, there is energy in things…it's there but it needs another form of energy to make it come out…it's like a seed, it's got energy inside it to

		grow but it needs the sun…well, one chemical needs another chemical to make it react.
Activity	Energy is identified by overt displays, and the display itself is actually called energy.	The [sledgehammer]…is creating energy by moving fast.
Product	Energy is a by-product of some situation and is relatively short-lived.	[The chemicals] might change…in which case they'll release some of their energy and produce heat…in this vapor here.
Functional	Energy is a very general kind of fuel, more or less restricted to technical devices and not essential to all processes.	[Energy is] something that can do something for us…say like gas or something…energy has got to make something else work…like if it was electrical it would make something like a tape recorder work.
Flow-transfer	Energy is some sort of physical fluid that is transferred in certain processes.	…the energy comes out from both leads…because you never get a circuit without the other one…it comes out of the negative end…flows round the circuit…encountering the light bulb on the way…where it can transfer some of the energy…and it goes back to the battery.

Watts' frameworks were later substantiated by Gilbert and Pope (1986) and Trumper (1990). After making some changes to Watt's original definitions, Trumper found that 96% of 14 to 16-year-old students' interview responses were classifiable according to these frameworks. Trumper split the depository framework into two parts: the original depository framework described by Watts (which is of a passive nature), and "the 'active' deposit or 'cause' framework. The energy as 'causes things to happen,' as 'being needed for certain processes to occur' ('The electric bulb needs energy in order to light')" (Trumper, 1990, p. 347). Furthermore, Trumper has defined a "transformation" framework that is intended to describe a desirable concept of energy: "When two systems interact (i.e., when a process takes place), something that we name energy, is transferred from one system to another" (Trumper, 1998, p. 313).

Solomon (1983) found that the most persistent alternative frameworks in young students include the anthropomorphic and activity frameworks, and there seems to be a progression away from these frameworks and towards a conservation-based conception with age. In a synthesis of research into children's ideas, Driver, *et al.*, (1994b) proposed that students' energy conceptions progressed through a fairly common sequence. In this sequence, students start from a conception that is largely defined by their own sense of feeling energetic, extend that sense of energy to other living and then non-living things, become aware of stored energy, and finally become aware of energy conservation and degradation. Because this sequence was constructed from a review of other studies that used a variety of methods in a variety of populations, this sequence was not empirically derived.

Seeking to empirically construct a typical progression through the energy concept, Liu and McKeough (2005) examined United States students' responses to selected items in the TIMSS database. They classified items according to the type of conception that they represented and developed the following categories: activity/work (energy is the cause for activities), source/form (energy is stored in a variety of sources and can exist in various forms), transfer (energy can be transferred), degradation (energy is "lost" during transformations), and conservation (the total energy in a closed system must be constant). After classifying items, they were able to calculate the frequency of correct responses for students in grades 3, 4, 7, 8, and in their final year of high school. Using a 50% correct response rate as a cutoff, they found that all grade levels reached the activity/work competence level, and the source/form level was reached by students in grade 4 and above. An understanding of energy transfer was marginally displayed by 7th, 8th, and high school students.

Liu and McKeough suggest that their results reinforce the neo-Piagetian assertion that maturational factors play a central role in students' ability to acquire the full energy concept, setting an upper limit on students' concept acquisition (Case, 1985, 1992). Recognizing variation within their sample, they acknowledge that students' aptitude and instructional experiences play a role in students' concept development, like the work of Driver, *et al*. (1994b), Liu and McKeough's study did not include an instructional component. Without an instructional component, these studies were unable to detect the effect that instruction can play in helping students develop a deep understanding of energy.

My study is predicated on the idea that instruction plays a crucial role in students' cognitive and conceptual development. Yet, not all instruction is bound to be equally productive in this regard; in fact, students' initial ideas seem quite resistant to change in many instructional contexts (Chi, 2005). The design of instructional interventions has a great deal to do with their success or failure in helping students develop sophisticated understandings. While some have advocated instructional approaches in which students' naïve conceptions should be confronted and overcome (Chinn & Brewer, 1993; Nussbaum & Novick, 1982; Stepans, 2003), others insist that instruction should not focus on highlighting deficiencies in students prior knowledge, rather, it should build upon students' prior knowledge to develop new understandings (Smith, diSessa, & Roschelle, 1993-1994).

Differences in instructional approaches reflect different notions about the nature of students' conceptions and how they reason and learn about the physical world. While some argue that students' naïve conceptions resemble relatively coherent and theory-like (Carey, 1985; diSessa, 1993; Hatano, 2002; McCloskey, 1983; McCloskey, Caramazza, & Green, 1980; Vosniadou, 1994), others suggest that students' naïve conceptions are more fragmented (diSessa, 1993; Smith, *et al*., 1993-1994).

Knowledge in pieces

diSessa argues that children make sense out of the physical world by constructing pieces of knowledge that are minimally abstracted from their experiences (diSessa, 1993). diSessa calls these pieces of knowledge *phenomenological primitives*, or *p-prims*. They are phenomenological because they are based on one's direct experiences, and they are primitive because they represent the type of knowledge that is so fundamental that it is difficult for the knower to elaborate it with words. These p-prims are connected to each other into clusters and broader structures that result in, among other things, a sense of mechanism regarding the physical world.

diSessa claims that individuals' cognitive schema are composed of hundreds or thousands of p-prims. These p-prims are clustered into groups that describe a particular range of phenomena. For example, the three p-prims I have already discussed are likely to be organized within the same cluster that applies to mechanical phenomena that involve force and motion. When people reason about phenomena, particular p-prims are activated, which in turn activate other p-prims to which they are connected. The likelihood that a particular p-prim will be activated by some antecedent is called its *cuing priority*. A p-prim with a high cuing priority requires a small number of antecedents. Furthermore, diSessa defined a p-prim's *reliability priority* to be the likelihood that a p-prim, once activated will remain activated through a reinforcing feedback loop. A p-prim with a high reliability priority is unlikely to be turned off with additional processing about an event or phenomena. The structure of one's cognitive framework is determined by the number and type of p-prims, their connections to each other, and their cuing and reliability priority. As novices develop expertise, they adjust the cuing and reliability priority of their existing p-prims, strengthen or diminish certain connections, and create new p-prims when necessary.

Between p-prims and naïve theories: facets of thinking

The temptation to characterize students' naïve knowledge as either entirely fragmented or entirely coherent most likely reflects a false dichotomy, as students' thinking is not well characterized by either extreme position. Within the knowledge-in-pieces perspective, diSessa and his colleagues have postulated existence of structures such as *clusters* (diSessa, 1993) and *coordination classes* (diSessa & Sherin, 1998; diSessa & Wagner, 2005) in which knowledge pieces may be strongly connected and mutually reinforcing; from the naïve theory perspective, Vosniadou has argued for the existence of *specific theories* that are embedded within larger framework theories (Vosniadou, 1994). It seems clear that the advocates of both the coherent and fragmented knowledge perspectives recognize the need to account for students' understanding at different grain sizes.

In the classroom, teachers would be well-served to understand the implications of both perspectives, as they can offer valuable insight into students' thinking (Hammer, 1996; Minstrell, 2001). Minstrell is a teacher-researcher who has developed a system of *facets*, which assume a knowledge-in-pieces perspective, but are designed to describe students' understandings with a grain size that is somewhere between diSessa's p-prims and the naïve theories advocated by McCloskey. The facets were designed to reflect what a teacher might actually hear students say in the classroom as they progress in their understanding (Minstrell, 2001, 2004; National Research Council, 2001). While facets are not intended to directly describe the small knowledge pieces (p-prims) that students possess, they are useful for grouping student responses, which are the manifestations of their underlying cognitive structure.

The categorization scheme provided by the facets makes it practical for teachers to understand common ways that students think about particular concepts and to roughly classify students' responses according to how close they are to the learning goal that is reflected by the content standard. In this study, I use Watts' frameworks as a sort of facet cluster for energy (Minstrell and his colleagues have not yet developed a facet cluster for middle school students' understanding of energy), because the frameworks are useful for categorizing students' common ways of thinking. In doing so, I do not intend to assert that students' thinking is theory-like or constrained by an adherence particular alternative frameworks; I am simply using the frameworks as "bins" by which to categorize students' constructed responses in order that students' conceptual development can be efficiently categorized and evaluated.

Conceptual change

When conceptual development occurs, students' understandings are not likely to progress in an ordered fashion from more problematic to less problematic ideas. Rather, their process of conceptual change will likely be a nonlinear process that reflects a complex interplay of both intuitive and instructed ideas of different grain sizes. From a knowledge-in-pieces perspective, students' knowledge networks consist of a large number of ideas, existing in different grain sizes, that are connected in various ways. These ideas may be intuitive or instructed and may include p-prims that are not easily articulated, facts, previous experiences, and scientific principles. When learning occurs, students' knowledge networks undergo a process of conceptual restructuring (Clark, 2006) and knowledge integration (Linn, Eylon, & Davis, 2004), during which students' ideas and the connections between them are redefined and reorganized. During this process of reorganization, the cuing priority of certain ideas is increased for certain contexts where they hold significant explanatory or decreased when they do not (Smith, diSessa, & Roschelle, 1994). Some ideas may gain a central position within the conceptual structure with high cuing and reliability priorities, while others may be assigned such low cuing and/or reliability priorities that they are almost never used. Additionally, new ideas may be added to the network and existing ones may be changed by coalescing with other ideas or by becoming differentiated into multiple ideas (Clark, 2006).

During the process of conceptual restructuring, not all reorganizations are productive, and students' knowledge networks may not smoothly transition from that of a novice to that of an expert. As students encounter new situations, they modify their ideas and connections between them in order to account for new information. If, over time, the new structures prove themselves to be useful for predicting and explaining students' experiences, they will tend to be reinforced, if not, the structures will continue to be modified as students accumulate experiences. Well before students are exposed to formal science instruction, they have had many experiences with the physical world and have already begun the process of structuring and restructuring their knowledge networks. When they enter the science classroom, students hold many ideas about the physical world, and many of these ideas have been highly congruous with students' experiences, yet are not in line with expert understandings. The "force as a mover" p-prim is an excellent example of such an idea.

Regardless of how predictive students' understanding may be in their own experiences outside of school, there is no question that novices lack the broad explanatory and interpretive power of experts. Unlike experts, novices' understanding is not organized around the central unifying principles of science (Chi, Feltovich, & Glaser, 1981). Science curriculum, then, should be designed such that it supports students' understanding of the unifying principles of science that will allow them to connect between topics and between contexts. In the next sections, I describe the design principles that guided our development of the energy unit to help students develop a deep and coherent understanding of energy.

Promoting coherent understanding with curriculum

From a knowledge-in-pieces perspective, the goal is not to replace students' naïve ideas with more sophisticated ones, rather, it is to fit them into a broader cohesive framework in which the most explanatory and general ideas are assigned a high cuing priority in appropriate contexts. If students develop coherent understandings, they are able to "link their scientific ideas to make sense of experiences and observations and to explain new situations" (Roseman & Linn, 2007, p. 1). Students' coherent understandings may not only be manifest as short term learning, but also as the foundation for future learning (Bransford & Schwartz, 1999; Linn & Eylon, 2000; National Research Council, 1999). In order to support students' development of coherent understanding, curriculum materials must be designed with coherence in mind (Roseman & Linn, 2007).

Roseman and Linn (2007) have identified several characteristics of curriculum that promote coherence. Perhaps most importantly, curricula should focus on the big ideas in science and dispense with unnecessarily distracting ideas. Second, materials should be designed to connect with students' experiences. In order for students to tap into and reorganize their existing prior knowledge networks, they must think critically and analytically about familiar contexts, because it is in contexts familiar to the students where their initial ideas were formed and where they most conspicuously apply. By using new ideas to reason about familiar contexts, students can better understand how the newer ideas learned in school have broader explanatory power than their initial ideas and adjust their thinking accordingly. A third key to promoting coherence with curriculum is to encourage student reflection and metacognition (Davis, 2003; White & Frederiksen, 1998). The process of refining and improving one's initial ideas should include scaffolded opportunities for students to reflect on what they know and why they know it, as well as to examine where to go next. From a social constructivist standpoint, students must also have an opportunity to develop new ideas and to refine existing ones through supported peer interactions such as presenting evidence, forming conclusions, and critiquing each other's ideas.

In the next section, I describe the specific instructional choices the energy unit development team made as we used the principles of learning-goals-driven design using project-based pedagogy (Krajcik *et al.*, in review) to interpret national standards and benchmarks, create learning goals, and design our instructional context and lesson sequence.

THE LEARNING ENVIRONMENT

According our design principles, we first compiled, interpreted, and elaborated the middle school energy standards in the Benchmarks for Science Literacy (BSL) (American Association for the Advancement of Science, 1993) and National Science Education Standards (NSES) (National Research Council, 1995). The standards addressed by our unit are given in Appendix A. During the elaboration phase, our development team chose to change the wording of some standards to exclude some portion of certain standards statements. These changes included using the word “types” in place of “forms” of energy because we were aware that many students hold a misconception that energy has some definite physical form (Driver, Squires, Rushworth, Wood-Robinson, 1994a). Furthermore, we did not address some standards statements based upon a commitment to limiting the amount of prior knowledge required of students. Since the unit was designed for use in all grades of middle school, we could not assume that students would enter the classroom with a particulate view of matter; therefore, we excluded standards that would have required students to possess or develop a particulate nature of matter.

After interpreting and elaborating the standards, we produced seven learning goals, which are scientific ideas that are the focus of learning at some particular stage in the unit. Figure 1 shows these learning goals and the sequence in which they are addressed during the unit.

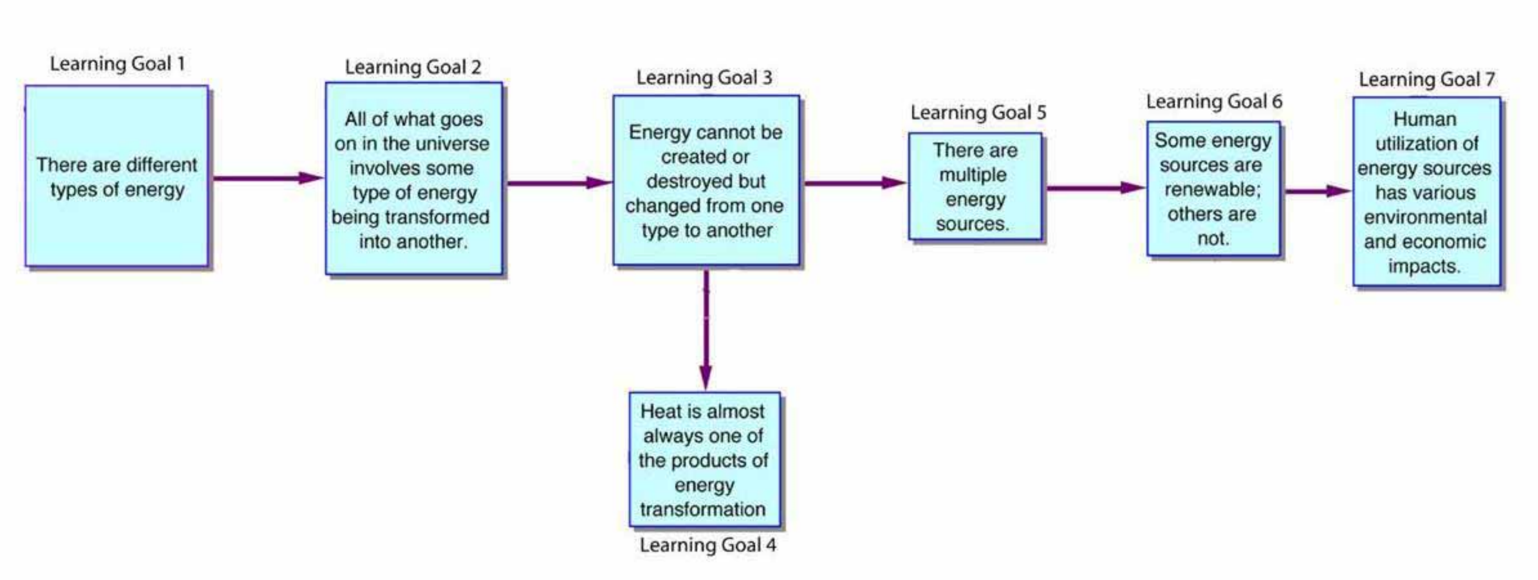

Figure 1. Learning goals of the energy unit and their sequencing.

Instructional sequence

As noted in earlier, we used a project-based model (Krajcik, Czerniak, & Berger, 2003) to organize the unit. In this model, instruction is organized, motivated, and contextualized by a driving question. After considering many options, we chose the driving question, "How can I use trash to power my stereo?" To address this question, students engaged in a series of activities that were organized into six lesson sets, which I describe briefly in Table 2.

Table 2: Description of lesson sets and how learning goals are addressed.

Lesson set	Focal learning goals	Student activities
LS 1	LG 1 – Energy types	Identify types of energy in various phenomena
LS 2	LG 2 – Transformation LG 3 – Conservation LG 4 – Degradation	Identify types of energy in phenomena at various times and track how they change
LS 3	LG 2 – Transformation LG 3 – Conservation LG 4 – Degradation	Formulate preliminary answer to driving question
LS 4	LG 2 – Transformation LG 3 – Conservation LG 4 – Degradation	Design and build an apparatus that exhibits many types of energy transformations en route to performing some task.
LS 5	LG 5 – Energy sources LG 6 – Renewability LG 7 – Human impact	Investigate various energy sources and resources, and develop an energy plan for some location
LS 6	LG 5 – Energy sources LG 6 – Renewability LG 7 – Human impact	Debate energy plans and develop a more sophisticated answer to the driving question

Lesson set one is devoted to introducing students to various types of energy. For each type of energy addressed in this unit, we have defined a set of associated *indicators* and *factors* to help students identify which types of energy are involved in phenomena and to make qualitative judgments about whether their magnitude is increasing or decreasing. An indicator is an observable physical feature of a phenomenon that indicates the involvement of a certain type of energy, while a factor is a characteristic that affects the amount of a particular type of energy. Indicators are a subset of factors, and both factors and indicators were extracted from the mathematical expressions that allow one to calculate the magnitude of each energy type. For example, because kinetic energy is given by the formula $\frac{1}{2}mv^2$, we identify mass and speed as factors for kinetic energy. Because the speed of an object is the observable variable that determines whether an object can be considered to have kinetic energy, this variable is the indicator for kinetic energy. Since mass is necessary for determining the magnitude of kinetic energy, but not sufficient for an object to have kinetic energy, it is a factor. A complete list of energy types addressed in this unit and their associated factors and indicators is shown in Table 3.

Table 3: List of energy types and their associated factors and indicators.

Energy Type	Factors	Indicators
Kinetic energy	Mass	Speed

	Speed	
Light energy	Brightness[1]	Emission of light
Sound energy	Loudness	Emission of sound
Thermal energy	Mass Temperature Type of substance	Temperature
Chemical energy	Type of substances Mass	Substances seeming to appear or disappear
Elastic energy	Compression/elongation Rigidity	Compression or elongation of an elastic substance
Gravitational energy	Mass, height[2]	Height
Electrical energy	Voltage[3]	Complete circuit and a voltage source

During lesson set one, students repeatedly interact with a variety of everyday phenomena in order to classify which energy types are involved in their operation. Such phenomena include toasters, glow sticks, tuning forks, portable music players, candles, and many others that the students were likely to see in their lives outside of school. By choosing everyday objects such as these, students are more likely to connect their school learning with their naïve ideas and intuitive knowledge (diSessa, 2000; Smith, *et al.*, 1993-1994).

In lesson set two, students continue to work with everyday apparatuses, but begin to focus those that are easily delineated by some event, such as a jack-in-the-box, shooting a rubber band, inverted half racquetballs, instant heat packs, and others. The presence of a delineating event allows students to focus easily on types of energy that were present before the event, and those that were present afterwards. This primes students for the idea that any one apparatus or phenomena may exhibit different energy types at different points in time. In order to help students understand that these energy types are transforming into one another, they are asked interact with and classify phenomena that have straightforward "before", "during", and "after" times. For example, students classify the energy types present in a yo-yo before it is dropped, during its fall, and after it has reached the bottom of the string and is spinning. Then, they examine the energy types they listed in the "during" phase and, using their knowledge of the factors for each energy type, determine whether each type of energy was increasing or decreasing. By noticing that any time a type of energy increases, at least one other type of energy must decrease, students begin to see that these types of energy are actually transforming into each other. This activity also lays the groundwork for introducing energy conservation, which also occurs in lesson set two.

There is no feasible low-cost way to introduce middle school students to energy conservation by measuring it empirically, because energy in everyday devices is inevitably transferred to the surroundings as heat. Even if low-cost, specialized devices were available, it is likely that students would have difficulty understanding how their experiences with such an apparatus translates to their out-of-school experiences. Recognizing this, we chose to introduce energy conservation as a quality of energy rather than a mathematical principle. If students accept the idea that an increase in one type of energy is always accompanied with a decrease in another type of energy, and vice versa, it is logical for them to understand that a decrease of all of

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[1] Although the energy of a single photon is dependent upon its wavelength, we wished to describe the light energy emitted by a macroscopic apparatus, which is better described by intensity.

[2] Acceleration of gravity was not included because it is assumed constant for all objects.

[3] Although voltage is a measure of electrical energy per charge, we believed that voltage alone was an adequate factor for electrical energy because in virtually all devices that use electrical energy, the charge-carrying particle is the electron.

the types energy in a system must be accompanied by an increase of some other types of energy. By investigating apparatuses in which energy is clearly not conserved (a bouncing ball and a marble rolling back and forth on a U-shaped track), students begin to recognize that they notice decreases in the amount of energy in the system, but are likely unable to account for the associated increasing energy types that must exist. To help students accept the idea that energy in a system can be transformed to thermal energy in the surroundings, teachers collide a pair of steel spheres (from Educational Innovations, Inc.) with a piece of paper in between them. Heat (we do not introduce this term to students as a noun, instead, we discuss "thermal energy") released during the collision is sufficient to burn a hole in the paper where the spheres collided, and this serves as powerful evidence that thermal energy can be produced during this interaction. By recognizing that an increase in thermal energy must be accompanied by a decrease in another type of energy, students should realize that the thermal energy was transformed from the kinetic energy of the spheres. In lesson set two, the concepts of energy conservation and dissipation (Learning Goals 3 and 4) are developed in conjunction with each other and are built upon the idea of energy transformation.

After lesson set two, students have addressed all learning goals having to do with the energy concept itself: it can exist in different forms (or types), it can be transformed from one form (or type) to another, it cannot be created or destroyed (it is conserved), and it tends to be degraded in macroscopic transformations. Notice that the unit includes no attempt to define for the students what energy *is* or to have students calculate energy in idealized situations, rather, we have attempted to develop students' energy concept by focusing on how energy can be used to describe and interpret the changes that occur during everyday phenomena. Regardless of our curricular design intentions, students are likely to ask what energy *is* – this is a natural question. In response, we suggested that teachers ask students to try to define *time*, which is an equally difficult challenge. By making an analogy to time, students are more likely to understand that it is possible for a concept to be useful even if we cannot satisfactorily define it.

Our approach to interpreting systems by qualitatively tracking energy transformations certainly does not directly prepare middle school students to quantify energy or to verify its conservation through calculations, but it is in line with energy learning progressions outlined by Project 2061 (American Association for the Advancement of Science, 2007) and it is more likely to promote students' ability to interpret complex everyday phenomena without losing their attention in the details of calculations – a common problem with many middle school curricula (Kesidou & Roseman, 2002).

After students have addressed the learning goals related to the energy concept, they are asked to use their understanding of energy to engage in a design project. During this project, students design a Rube-Goldberg-type contraption to accomplish some goal of their choice, such as breaking and frying an egg or peeling a banana. This project provides students with an important opportunity to refine their understanding of energy because it encourages them to reflect on what they know (Davis, 2003) and to iteratively develop and refine plans for a machine that exhibits many energy transformations (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004).

In the last two lesson sets, students turn their attention to the Earth's energy resources. Using what they have learned about energy during the preceding lesson sets, students research the availability of particular resources and the consequences of their use in order to develop an energy plan for a city of their choosing. In the final lesson of the unit, students are given a fictitious newspaper article that asserts, "Energy can be easily defined as the ability to run machines. We are in an 'energy crisis' because we have used so much energy that there is not enough in the world to last for much longer." Students are asked to respond to this article by providing a better explanation of what is meant by the term *energy* and what it means to be in an energy crisis. An ideal response to this prompt will demonstrate students' understanding that the value of energy more what it *does* than what it *is*, that energy is transformed in phenomena, that energy cannot be created or destroyed, and that energy transformations usually produce thermal energy that is difficult to reuse.

By the end of instruction, students will have learned how to identify when certain types of energy are involved in everyday phenomena, investigated the process of energy transformation, used the idea of transformation to explain phenomena, iteratively designed a Rube-Goldberg machine, and applied their knowledge of energy transformation and conservation to the Earth system. Throughout this instructional sequence, students' attention is constantly focused on using the concept of energy transformation qualitatively to describe familiar systems. This approach represents a radical departure from traditional middle school energy curricula.

METHODS

This study was conducted at an independent school, located in a small Midwestern college town, that had enacted the energy unit during the 2004-2005 and 2005-2006 school years. The school, Fairmeadows[†], serves about 200 students in a middle school and about 300 students in a high school, both of which are located on the same campus. The student population at this school is about 75% Caucasian, 6% African-American, 10% Asian, 1% Hispanic American, 3% Middle Eastern, and 5% multiracial. Students at the school come primarily from middle and upper-middle class families and have a relatively low mobility rate.

This low mobility rate allowed me to design a cross-sectional, quasi-experimental study in which I compared students who participated in the energy unit to older student in the same school who had not. I investigated the effects of the energy unit by comparing four different treatment conditions: 8th grade students who just completed the energy unit, 9th grade students who completed the energy unit the previous year and have taken biology, 10th grade students who did not participate in the energy unit and have taken biology and chemistry, and 11th grade students who did not participate in the energy unit and have taken biology, chemistry, and physics. To measure differences between groups, I compared students' performance on energy concept and content measures and conducted interviews with relevant teachers to investigate the energy-related learning opportunities for students in each treatment condition. An overview of my research design is shown in Table 4, and in the following sections I briefly describe each of my student measures.

Table 4. Overview of research design

	RQ1: Conceptual development during unit	**RQ2: Conceptions one year after instruction**	**RQ3: Comparing conceptions across grade levels**	**RQ4:Comparing content knowledge across grade levels**
Data sample	8th	8th, 9th	8th, 9th, 10th, 11th	8th, 9th, 10th, 11th
Relevant measures	A. Student interviews B. Learning goals test C. Energy concept questionnaire D. Energy content questionnaire	A. Student interviews B. Learning goals test C. Energy concept questionnaire D. Energy content questionnaire	A. Student interviews B. Energy concept questionnaire C. Energy content questionnaire	A. Energy content questionnaire
Data collection	A. Before unit/after	A. '04-05	A. End of '05-06	A. End of '05-06

[†] All proper names referring to the research setting, its faculty, and students are pseudonyms.

times (letters correspond to letters of measures above)	LS1/ after LS2/end of '05-'06 B. Pretest/posttest C. Pretest/end of '05-06 D. Pretest/end of '05-06	enactment/end of '05-06 B. Previous enactment pretest/posttest C. End of '05-2006 D. End of '05-2006	B. End of '05-06	
Data analysis (letters in parentheses correspond to the measures used in analysis)	Code interview responses according to energy frameworks (A) One-way ANOVA comparing interviewed and non-interviewed students (ABC) OLS regression to assess effect of prior knowledge, gender, and teacher on student outcomes (BCD)	Code interview responses according to energy frameworks (A) One-way ANOVA comparing interviewed and non-interviewed students (ABC) One-way ANOVA comparing 8th & 9th grade students before and after energy unit (B)	Code interview responses according to energy frameworks (A) One-way ANOVA comparing interviewed and non-interviewed students (BC) One-way ANOVA with orthogonal contrasts between grade levels (B)	One-way ANOVA with orthogonal contrasts between grade levels (A) One-way ANOVA with subscores for physical and life science items (A)

Learning goals test

The learning goals test and its scoring rubric remained identical between the 2004-2005 and 2005-2006 school years. Using this rubric, I scored the pretests and posttests from both years. To establish inter-rater reliability, I recruited a research associate with several years of experience coding interviews and written responses from middle school students who were participating in project-based curricula. After reviewing the rubric together, we randomly selected 10% of the tests and the research associate scored the open-ended questions independently. This process yielded an inter-rater reliability of 97%.

Student interviews

The student interviews were designed using the interview-about-instances approach, which was developed to better understand children's ideas about a particular concept without emphasizing whether these ideas conform to the accepted scientific view (Osborne & Gilbert, 1980). In this approach, students are shown a number of pictures that illustrate various everyday situations and asked whether that picture illustrated *their* idea of the concept under investigation. The pictures are chosen around a single concept and illustrate instances, non-instances, and borderline cases (from a physicist's point of view) of the concept. Once a student identifies whether the picture is an illustration of their idea of the concept, the researcher ask the student to describe his or her reasoning. Student responses are then probed by the researcher, using the students' language when possible. The interview-about-instances approach has been used by many researchers to investigate students' conceptions of energy, force, and light (Gilbert, Watts, & Osborne, 1982; Kruger, 1990; Osborne & Gilbert, 1980; Trumper, 1993, 1998; Watts, 1983, 1985). Watts (1983) used this approach to develop his alternative frameworks for energy and Trumper (1993, 1998) used this approach to verify and extend Watt's frameworks.

The scenarios I used in the interviews have been drawn from past studies that have investigated students' energy conceptions. Because the 8th grade students were interviewed four times, I administered three different sets of scenarios. The scenarios that comprise the first and last round of interviews administered to 8th grade students are identical to each other, and these same scenarios were used to interview students in the 9th, 10th, and 11th grades. The scenarios in the second and third round of interviews administered to 8th graders were unique in order to reduce interview fatigue and to ensure that students continue to think carefully about their responses throughout all four interviews. The order and content of the scenarios used in this study are identical to those I used in a pilot study (Nordine, Fortus, & Krajcik, 2006) that I conducted during the 2004-2005 school year.

To code the interviews according to the energy frameworks students exhibited, I created a coding rubric according to Watts' and Trumper's initial descriptions of the frameworks. To assess the reliability of my classifications, I recruited a research associate with several years of experience coding interviews and written responses from middle school students who were participating in project-based curricula. The research associate was not a part of the development team that produced the energy unit. After reviewing the rubric and discussing several sample interviews to come to a common understanding of the energy frameworks, we randomly selected 12 interviews (>10% of the data set) and the research associate scored these independently. This resulted in an inter-rater reliability of 93%.

Energy concept questionnaire

Authors of past studies investigating students' energy conceptions have used a questionnaire to assess student thinking and to categorize students' responses according to Watts' alternative frameworks (Bliss & Ogborn, 1985; Kruger, Palacio, & Summers, 1992; Trumper, 1993, 1998). I have produced an energy concept questionnaire by adapting items from the instruments used in these studies and from items that appear on the Energy Concept Inventory, which was produced by the developers of the widely-used Force Concept Inventory (Swackhamer & Hestenes, 2003). Figure 2 shows a sample item from the energy concept questionnaire.

The picture below shows an electric heater that is plugged into the wall. The heater is switched on and the bars are glowing.

For the following statements, check the appropriate box.

1. The energy from the power station which supplies this heater did not exist before it was generated at the station.
   ☐Agree ☐Disagree ☐Not sure ☐Don't understand
2. Only some of the energy from the heater goes into heating up the room
   ☐Agree ☐Disagree ☐Not sure ☐Don't understand
3. The energy from the heater goes into the room and disappears.
   ☐Agree ☐Disagree ☐Not sure ☐Don't understand

Figure 2. Sample item from energy concept questionnaire

I recruited physics experts from a variety of specialties to independently complete the energy concept questionnaire, and seventeen of the experts I solicited returned their questionnaire. This group included seven physicists, astronomers, and energy scientists with PhDs in physics, eight science educators with physics bachelor's and/or master's degrees, an aerospace engineer, and a biophysicist. After the questionnaires were returned, I searched for questionnaire items on which experts seemed to have consensus. I defined consensus to be when more than 80% of the experts (14 out of 17) answered a question the same way. Five questions achieved 100% consensus, four questions achieved 90-100% consensus, and six questions achieved consensus of 80-90%. All questions that did not achieve consensus were excluded from all future analyses. I generated quantitative scores for students' questionnaires by giving a point whenever students' responses to items aligned with experts' consensus response. The quantitative scores on the energy concept questionnaire enabled me to assess the extent to which students in different grade levels conceptions of energy aligned with those of physics experts.

Energy content questionnaire

As a development team, we produced a learning goals test (described above) that was designed to measure students' achievement of our learning goals by asking students to apply the knowledge and skills they learned in class to new phenomena. While the learning goals test is an important measure of the unit's effectiveness, it is not a particularly good indication of whether this unit will help students perform on the type of distal items they would see on a large-scale assessment used to determine school accountability. Fortunately, members of Project 2061 at the AAAS have been developing assessment items intended to measure students' achievement of particular benchmarks and were willing to share relevant energy items with me for use in my study. A sample item is shown in Figure 3.

1. A student began a swimming workout by diving straight down into the pool from a 5-meter-high board. At which point in the dive did the student have the most kinetic energy?

   A. At the top of the ladder prior to the dive.
   B. Just after the dive began.
   C. In the middle of the dive
   D. Just prior to entering the water.

Figure 3. Sample item from the energy content questionnaire

While items on the energy concept questionnaire are intended to assess whether students hold certain common conceptions about the nature and behavior of energy, items on the energy content questionnaire are intended to assess whether students have specific knowledge related to how scientists use the energy concept. Together, the energy concept and content questionnaires provide tools to assess the overall quality of students' understanding of energy.

RESULTS

This study was intended to investigate four research questions dealing with students' conceptual development during the energy unit, their retention one year after instruction, and their ability to perform on content and concept measures relative to older students at the same school who did not participate in the unit. In this section, I address each of my research questions in turn.

Conceptual development during the unit (Research question 1)

Figures 4 and 5 show the prevalence of alternative frameworks among 8th grade students during each round of interviews in the 2004-2005 and 2005-2006 enactments.

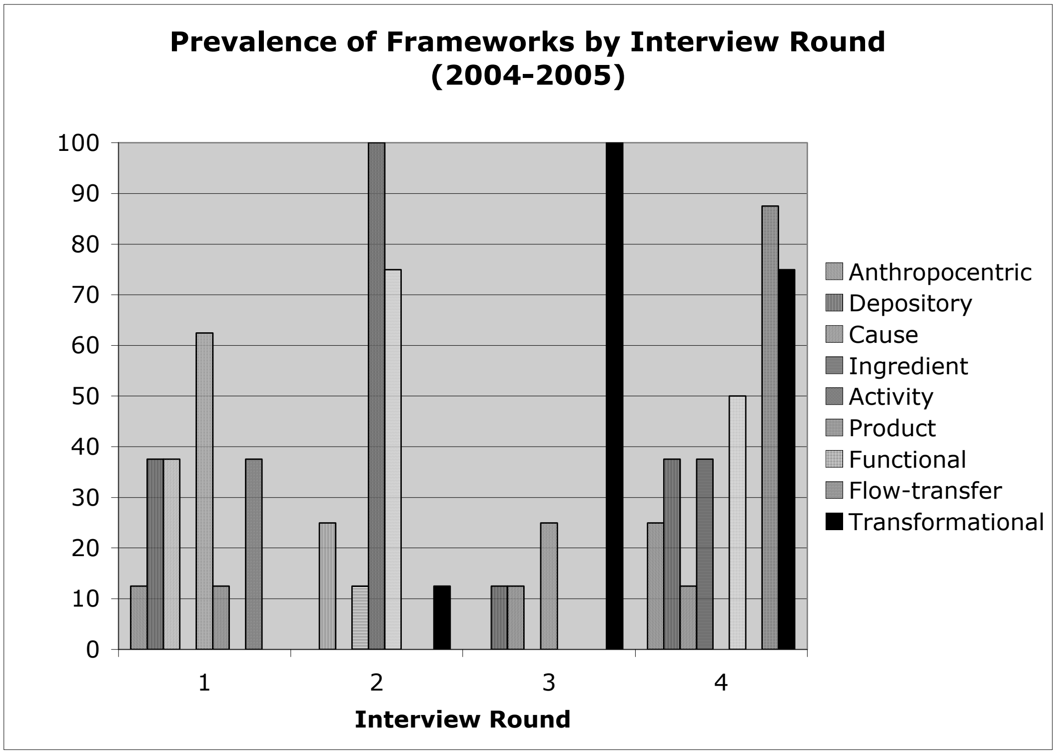
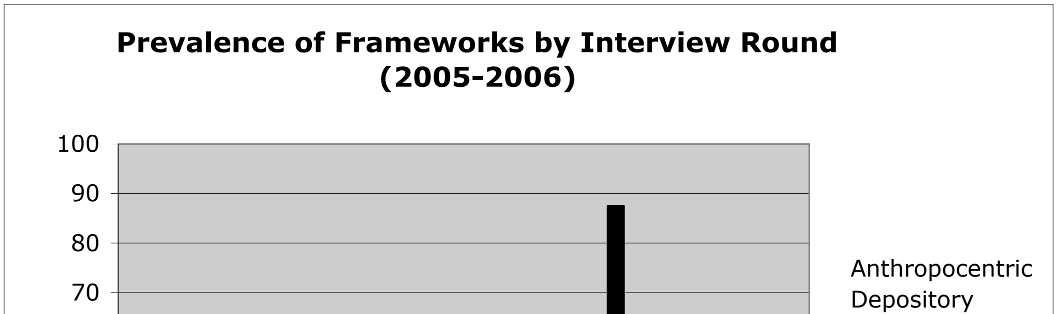


Figure 4. Percentage of students in the interview sample who exhibited particular frameworks, by round, during the first enactment of the energy unit.



While there were caveats, the major themes of students' conceptual movement seemed to hold true from one year to the next. In the remainder of this section, I describe each of these themes and illustrate three case examples to exemplify students who went through varying degrees of conceptual development during the unit.

Theme 1: Student conceptions tend toward the transformation framework

In both years, interviewed students began the unit demonstrating little or no evidence that they understood the role of energy transformations in phenomena. At the end of the unit, most interviewed students exhibited the transformation framework during their interview. This change is almost certainly due to the emphasis the unit places on using the idea of energy transformations to explain and predict the behavior of everyday phenomena.

While many more students exhibited the transformation framework at the end than at the beginning, the number of students exhibiting the transformation framework peaked at round three in both years. The third round of interviews took place immediately after the lesson set in which energy transformations were explicitly introduced and during the lesson set in which students build and explicate their "Rube Goldberg" contraptions. Therefore, the high number of students exhibiting the transformation framework during round three may be a reflection of the activities the students were doing concurrently in class. As students are asked repeatedly to describe the energy transformations that take place during phenomena, it is possible that the idea of energy transformation was temporarily assigned a higher cuing priority when students described the interview scenarios. By round four, the number of students exhibiting the transformation framework had subsided.

It is important to note that the interviews were designed to identify frameworks that seem to hold, and are not a good tool for identifying whether a student does not seem to hold a particular framework. In other words, if a student does not mention the idea of energy transformation in conjunction with some scenario, the student may nonetheless think of energy as something that is transformed during phenomena, but this idea may not have a high cuing priority. This is true for all frameworks – if a student does not exhibit a particular framework, they may still hold that idea, but invoke it less frequently when explaining phenomena. The energy concept questionnaire was intended to address this shortcoming of the interviews by asking students whether they agreed with particular statements that were chosen to align with particular frameworks. However, the concept questionnaire proved to be an unreliable way to assess particular frameworks and I could not use it to qualitatively compare students' conceptions at different points in time.

Although it seems that the idea of energy transformation became less prominent in students' cognitive structures between the third and fourth interview rounds, there is nonetheless unmistakable movement toward the transformation framework over the course of the unit.

Theme 2: Progression toward the transformation framework was not smooth

Although students tended to progress toward the transformation framework, this movement with neither monotonic nor smooth. Simply examining the prevalence of the transformation framework itself reveals that students do not gradually acquire the framework over the course of the unit, rather, it appears suddenly and then fades somewhat. There is little doubt that this occurs because of the instructional sequence of the unit.

In lesson set one, students learn a series of *indicators* and *factors* that they use to determine whether a type of energy is involved in a situation and the amount of that type of energy that is present. After the first lesson set, a student would be expected to know that movement indicates that kinetic energy is present, while the mass and speed of an object determine the amount of kinetic energy it has. Students learn the factors and indicators for kinetic, light, sound, thermal, and chemical energy in the first lesson set (a complete list of the factors and indicators presented in the unit is given in Table 3). The idea of transformation is not introduced until lesson set two, and the second round of interviews was situated after the conclusion of lesson set one and prior to the beginning of lesson set two. It is not surprising, therefore, that students tended not to display the transformation framework in this round. On the other hand, the first lesson set did seem to have some effect on students' energy conceptions by pushing them toward an activity and/or product framework. During both enactments, the most commonly displayed framework in round two was the activity framework, in which energy is viewed as an obvious activity that is not distinct from the action itself. As students learn about the indicators for each energy type, it seems that they can easily adopt the idea that the energy *is* the indicator. For example, Katherine displayed the activity framework during round two when presented with a scenario depicting a lit firecracker.

Katherine: It's because, well, first, if it's lit, the fire is kind of moving down. And it explodes, which is like, light, sound, kinetic, electric. Well, not really, but a lot of different energies.
Jeff Nordine: What happens to those types of energy you mentioned [after the explosion]?
Katherine: Um, they're kind of over. It just kind of stops.

Responding to the same scenario, another student displayed the closely-related product framework.

Lisa: Well, it has like, fire at the end. So that's thermal energy, and it makes a really loud noise, so that's sound energy. And light energy, and kinetic energy. Okay.
Jeff Nordine: What about after the firecracker is exploded, what happens to those types of energy that you mentioned?
Lisa: Um, they're not there anymore.
Jeff Nordine: And where have they gone?
Lisa: No where, I mean, I don't know. They just leave. They aren't being made, so they aren't there.

Neither Katherine nor Lisa seem to be bound by the ideas of energy conservation or transformation, as they indicate that energy types simply pop into and out of existence based upon whether their indicators are present. While Katherine seems to think that there is no difference between the energy and its indicator, Lisa suggests that the energy types are being made by their indicators.

Prior to interview round two, Katherine and Lisa learned how to identify energy types, but they did not learn what happens to energy once its indicator is no longer present. By concentrating on the indicators and factors for each type of energy in the and excluding the idea of energy transformation, the energy unit seems to promote the activity and product frameworks during the first lesson set.

While students moved toward the activity and product frameworks in round two, they moved sharply away from them and toward the transformation framework in round three. Between interview rounds two and three, the students begin to use their indicator and factor framework to trace the types of energy present at different points in phenomena and track whether those types of energy are increasing or decreasing. Students are introduced to the idea of transformation by noticing that any time one type of energy increases, at least one other type must decrease. Then, they are asked to track the energy transformations as they occur in various phenomena. In round three, students tended to talk very readily about the energy transformations that occurred in the interview scenarios, and they tended to account for the "disappearance" of certain energy types by claiming that they had been transformed into other types. It seems possible that the activity and product frameworks serve as a useful intermediate abstraction as students move toward the transformation framework. Although these frameworks did not disappear as the unit progressed, their prevalence relative to the transformation framework decreased. This suggests that students were moving away from the intermediate abstraction, but that some students were more successful than others when it came to moving past the activity and product frameworks and toward a transformation framework exclusively.

Theme 3: Students prefer to reason from a mechanistic perspective

Although nearly all interviewed students exhibited the transformation framework at some point during the energy unit, students' initial responses seldom reflected the transformation framework. Of the nine students in the 2005-2006 sample who exhibited the transformation framework during the fourth round of interviews, only three students invoked the idea transformation in their responses prior to probing. After the second lesson set, the majority of students' initial responses included a list of the types of energy that were present based upon the indicators that they identified in the scenarios. Most of the students who exhibited the transformation framework did so in response to probing. Typical probes included asking students whether the types of energy were related to each other, to describe what happens to the energy types as time goes on, or to clarify language that the student used. The following exchange, which was given as a round three response to a scenario depicting a melting icicle, illustrates how a student might invoke the transformation framework in response to probing:

Angelina:	Well, like the drop of water like, obviously there's thermal, there's heat that's causing the ice to melt and so there's thermal energy, but there's like kinetic energy of the raindrops falling, and probably sound when they hit the ground.
Jeff Nordine:	Are those energies related to each other in any way?
Angelina:	Um, well once the thermal energy like heats the, like makes the icicle, like be heated, and like melt, then maybe some of it, not all of it, cause like (unintelligible) part of it, it's converted into kinetic energy.

In this scenario, Angelina did not initially use the idea of transformation to explain the melting of the icicle, rather, she seemed to organize her response around three major actions: heating of the frozen water, falling toward the ground, and hitting the ground. For each of these three steps, she assigned the appropriate energy (although she did not include the role of gravitational energy as the "raindrops" fall). Although sound energy is nearly irrelevant to core phenomenon of ice melting, Angelina included it in her initial response. This suggests that her initial thinking centers on the scenario as a series of events, to which energy types can be assigned based upon the presence of indicators. Although she demonstrated an understanding that energy transformations are important to the phenomenon, the idea of transformation seemed to be a way to explaining how different energy types can be involved at different times and not a central organizing theme of her thinking.

When students' thinking is primarily focused on the mechanism of action in a scenario rather than the idea of energy transformations, they are prone to suggest energy changes that would violate the law of conservation, even though they may adhere to the idea of energy transformation.

Theme 4: A deep understanding of conservation was elusive for many students

The energy unit does not include a learning goal that deals with energy conservation, and the Benchmarks for Science Literacy recommend that this idea should not be introduced until high school. Still, many students are familiar with the phrase "energy can never be created nor destroyed" even before they begin the energy unit. Yet, this statement seemed far from straightforward to many students. In fact, it seems that some students combined this idea with the indicator and factor framework to construct an understanding of energy that was a hybrid of the activity framework, the ingredient framework, and the idea that energy is never created nor destroyed. In responding to a second round scenario depicting a lit firecracker, Wes explained:

> Jeff Nordine: After the firecracker has exploded, what happens to the types of energy that you mentioned?
>
> Wes: They, well, they don't disappear, but they're not used anymore, like, the heat created by the fuse dies down, and you can touch the firecracker again and throw it away.
>
> Jeff Nordine: When you said that they don't disappear, why did you say that?
>
> Wes: Kinetic energy doesn't just, poof, it's there. It's always going to be there, like, even though that's sitting there, if I kick it, it would move, and that's kinetic energy, but before, it's not in use, but it's there.

Wes seems to believe that the maxim "energy cannot be created nor destroyed" applies to each type of energy individually. That is, when the kinetic energy from the firecracker exploding is no longer there, it simply becomes dormant until it has been activated later by some event that involves motion. This was perhaps the most common misunderstanding of energy conservation among students during both the 2004-2005 and 2005-2006 enactments, and it was not present in students' initial round of interviews. It is possible that learning a fairly in-depth indicator and factor framework prior to learning about energy transformation leaves students to make their own conclusions about where energy comes from or where it goes when they do not observe the indicator for a particular energy type. Students continued to show this type of misunderstanding of energy conservation during the fourth round of interviews, which suggests that transitioning away from an activity/product framework and toward a transformation/conservation framework is challenging for some students.

Although the quantitative conservation of energy was not a learning goal, it is certainly implied. During the unit, students are introduced to the idea of transformation through an activity where they notice that any time an energy type increases or decreases during some phenomenon, at least one other energy type must do the opposite. This activity, as well as the ensuing instruction, is targeted toward learning goals that state, "All of what goes on in the universe involves some type of energy being transformed into another", and, "Energy cannot be created or destroyed but changed from one type to another". Implicit in these learning goals is that the total amount of energy in the universe must not change. Furthermore, this means that the total amount of energy put into a system must equal the energy increase of the system plus the amount that leaves the system in other forms. Angelina is an example of a student who was successful in understanding this idea, who gave the following responses as we discussed the solar car scenario in round three:

> Jeff Nordine: When it slows down and stops, what happens to the energy that was originally there?
>
> Angelina: ...all the energy that it had previously transformed, it still there, it's just in a different form.
>
> Jeff Nordine: Can you compare the amount of solar energy hitting the car to the amount of kinetic energy it has when it's moving, is it more, less, equal?
>
> Angelina: It's probably like, equal, because like none of it is like, lost.

> Well, it may not be the same amount, because there's other types of energy that light is being transformed into like sound...like it's the same amount of energy, just different types, I guess.

Angelina demonstrates not only a sense of quantitative conservation, but also a nascent understanding of energy degradation. Using these ideas, a student would be able to predict the behavior of the car as certain constraints are changed. For example, she would likely be able to assess the impact of adding an air conditioner in the car, because she would know that the energy required to run the air conditioner would have to come from the sunlight, and this would leave less energy available to be transformed into kinetic energy. It is important to note that a student could make these predictions without knowing the inner workings of a solar car – in fact, Angelina requested that I explain what a solar car was before she responded to the scenario. Many students asked for this explanation, and I responded by analogizing a solar car to a solar-powered calculator and explaining that you could drive a solar car around when the sun shines on it. Based on her response to this scenario, Angelina is well positioned to encounter energy-related biological concepts such as energy flow through ecosystems and within organisms.

Moving toward a sense of the quantitative conservation of energy certainly seemed to be the exception rather than the rule, but it seems that most students are moving in the direction of a deep understanding of energy conservation even though they are not there yet.

Energy conceptions one year after instruction (Research question 2)

During both the 2004-2005 and 2005-2006 enactments of the energy unit, students moved from almost uniformly toward a transformation framework in interview round three, but slightly away from it in round four. Also, many alternative frameworks that students held prior to instruction resurfaced (albeit more weakly) in round four after being seemingly absent in round three. Although the overall movement of students' conceptions during instruction was in a desirable direction, the data leave open the possibility that students' conceptions may degrade over time. I investigated this possibility by interviewing the six students who participated in my pilot study and were still enrolled at Fairmeadows.

As I discussed previously, students in the 2004-2005 enactment progressed in a very similar fashion to students in the 2005-2006 enactment. They largely moved toward the transformation framework, tended to reason from a mechanistic perspective, and had difficulty developing a deep understanding of what energy conservation means. When I re-interviewed the students who were interviewed in my pilot study one year after their participation in the energy unit, I found no deterioration in the quality of their conceptions. In fact, I found a decrease in the number of students exhibiting the undesirable anthropocentric, deposit, and product frameworks, and an increase in the number of students exhibiting the desirable transformation framework. Figure 6 shows how the frameworks exhibited by this group of students changed from their final 8th grade interview to their 9th grade interview.

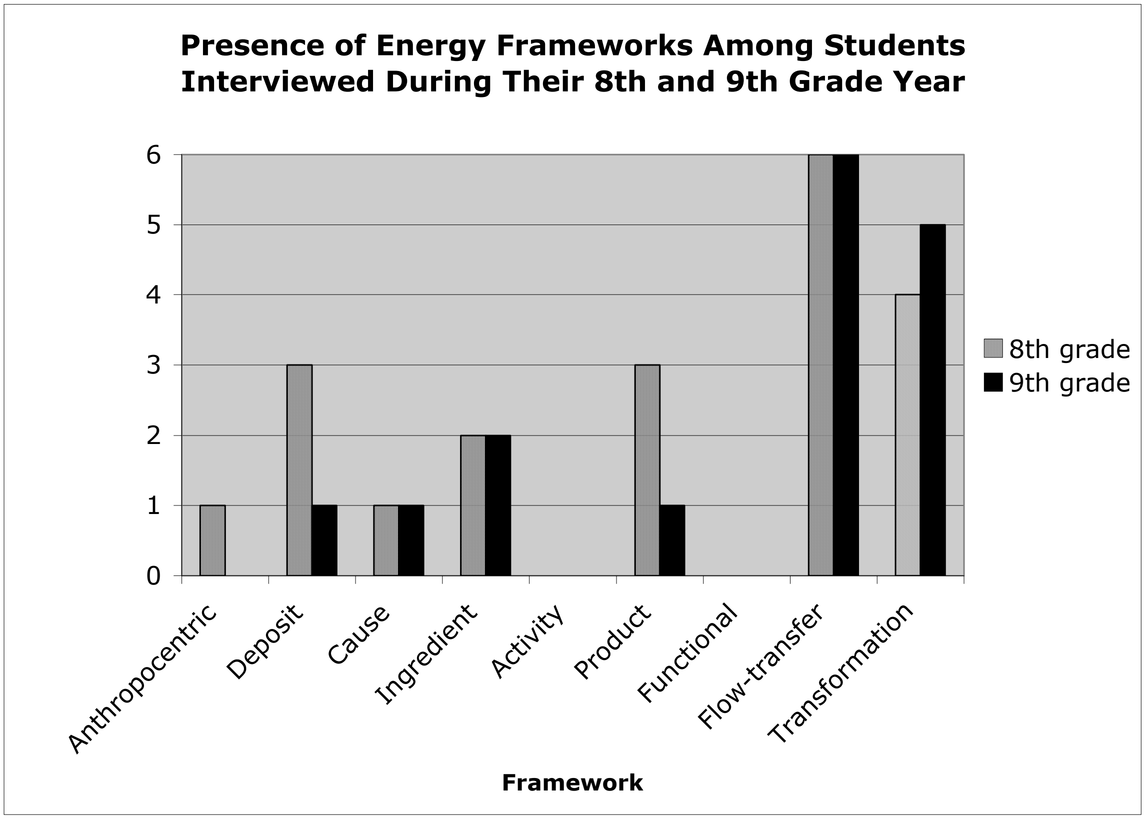


Figure 6. Comparison of energy frameworks present in 8th and 9th grade for students who were interviewed both years.

Rather than degrading, it seems that as a group, the quality of students' conceptions has improved in the year since they participated in the energy unit. Students also seemed to improve individually. Several students exhibited fewer alternative frameworks in 9th grade compared to 8th grade, but the most substantial change seemed to be a more sophisticated view of energy transformation.

Allen is an example of a student who exhibited fewer alternative frameworks and who developed a more sophisticated understanding of transformation. When interviewed immediately after the energy unit, Allen exhibited the transformation framework, but his responses indicated that he held the product, ingredient, flow-transfer, and deposit frameworks as well. When he was interviewed in 9th grade, only the transformation and flow-transfer frameworks remained. Furthermore, his view of transformation seemed to be more closely tied to the idea of quantitative conservation than it had in the past. Responding to the battery, light bulb, and switch scenario in the 8th grade, Allen and I had the following exchange:

Allen:	The battery converts chemical energy to electric energy through some process, which, I have no idea what it does. And since it will burn the chemicals inside of the battery, it will slowly deplete until it has none left.
Jeff Nordine:	After the battery runs out, what happens to the light energy and thermal energy and the other types that you mentioned?
Allen:	They all drop. They're all, well, the light bulb goes out so they all just stop because there's no more electricity. I'm

pretty sure that's what happens.

While he invoked the idea of transformation, he seemed to be teetering on the edge of an activity framework as well, because he indicated that as the battery runs out, the energy types just 'stop'. He did not use the ideas of transformation and conservation to explain what had become of those energy types. In 9th grade, Allen responded to the same scenario:

Allen:	The electrical and I suppose some of the chemical energy in the filament is transferred over to the same amount of energy in light and heat.
Jeff Nordine:	You mentioned 'the same amount of energy'. Why is that the same amount?
Allen:	Energy is never created or destroyed, it is only reassembled, I guess, in the equation. It's an equation, it's equal, like, that's the definition. It also works to a certain extent with mass.

Although his understanding of the function of a light bulb is somewhat flawed, Allen took it upon himself to stress that there is as much energy after the transformation process as before it, and he alluded to the fact that conservation of energy is defined by a mathematical equation.

In addition to exhibiting more sophisticated transformation frameworks, students were more likely to invoke the transformation framework unprompted. In 8th grade, two of the six students invoked the transformation framework prior to prompting, while in 9th grade, four of the six used transformation ideas prior to prompting. This suggests that the idea of energy transformation may have a higher cuing priority for these students than it had the year before.

Anthony is a student who invoked the transformation framework unprompted in his 9th grade interview but did not do so in his final 8th grade interview. In 8th grade, his response to the battery, light bulb, and switch scenario was:

> Well, there's electrical energy in there, and when the switch is turned on, there will be light energy. And when the switch is being flipped on and off, there's kinetic energy.

In his initial response, Anthony did not use the idea of transformation to explain the phenomenon, and he included a reference to kinetic energy that, while true, was almost completely irrelevant to the scenario depicted. In his 9th grade interview, Anthony's initial response was more focused on energy transformations that were central to the phenomenon:

> There's electrical energy in that, and some heat...(unintelligible). The battery has stored chemical energy, the light bulb is converting that energy into light and heat energy to make the light, which is on.

Anthony's 8th grade response indicated that he was reasoning from a mechanistic perspective, in which he searched the scenario for familiar indicators and assigned energy types accordingly, with little regard for the relevance of those energy types. In 9th grade, he seemed to reason from a more transformation-based perspective, in which he considered what kinds of energy transformations are most relevant to the scenario.

Based upon the six students from my pilot study sample who remained at Fairmeadows, it seems that their energy conceptions improved during the year since they completed the energy unit. It seems possible that some of the improvement that I perceived in these six students is due to students' repeated participation in the interview, since this was the third time they have responded to the same interview scenarios. However, a chi-square test revealed no difference between students who were interviewed in both 8th and 9th grade and students who were interviewed only in 9th grade in terms of how many students exhibited the desirable transformation framework, $\chi^2(1,N=15) = 0.069$, p = NS. Table 5 shows the number of students who fell into each category.

Table 5. Students who exhibited the transformation framework in 9th grade, by whether they participated in my pilot study

	Did not exhibit transformation framework	Exhibited transformation framework
Interviewed in 8th and 9th grade	1	5
Interviewed in 9th grade only	2	7

This result, along with the finding that these groups' scores on the energy concept questionnaire were not significantly different, provides evidence that the six students I interviewed are not exceptional among their peers. Therefore, it is reasonable to assume that students' improvement in the year since they took the energy unit is due to continued energy-related learning and not to repeated interview participation.

Energy conceptions across grade levels (Research question 3)

My results indicate that students progress toward the transformation framework while in the energy unit and that the quality of their conception seems to have improved, rather than deteriorated, one year after instruction. While these findings are important, they are insufficient to justify a claim that the energy unit is superior to the energy-related instruction that preceded it at Fairmeadows. To make this comparison, I interviewed samples of 16 students in chemistry and physics who were the most recent classes of students to go through 8th grade science at Fairmeadows before the energy unit was introduced. After classifying the frameworks exhibited by all students in all four grades, I compiled the results into Figure 7.

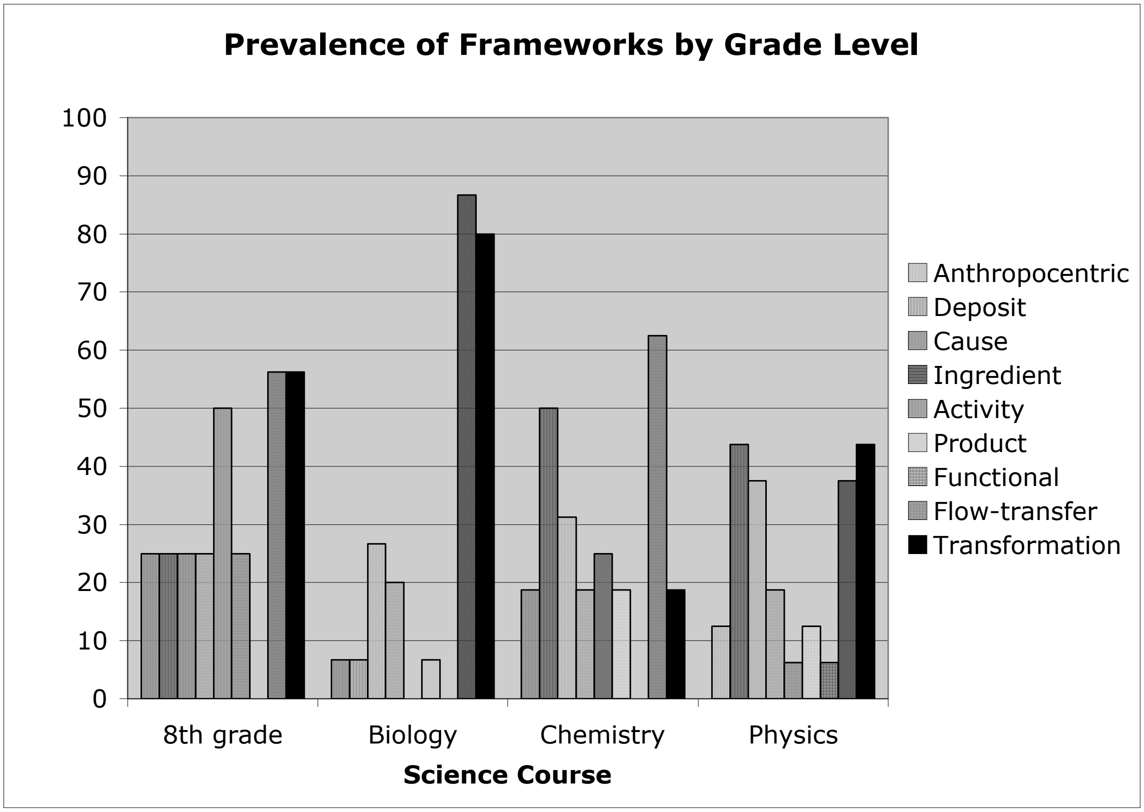


Figure 7. Energy frameworks present in 8th grade science, biology, chemistry, and physics students at Fairmeadows who have been enrolled there since the beginning of their 8th grade year.

Figure 7 shows that differences exist between grade levels in terms of the number and type of frameworks they exhibit. While 56% of 8th grade students and 80% of biology students who were interviewed exhibited the transformation framework, only 19% of chemistry students and 44% of physics students exhibited the transformation framework during their interviews. A chi-square test revealed that this difference is not likely due to chance alone, $\chi^2(3,N=63) = 12.14$, $p \leq .01$. There is little doubt that this difference is due to the heavy emphasis that the energy unit places on interpreting everyday phenomena within an energy transformation perspective. Even though more students in 8th and 9th grade exhibited the transformation framework than students in 11th grade physics, the typical physics student who exhibited a transformation framework demonstrated a far more sophisticated understanding of energy transformation and conservation than did the typical 8th grade student who exhibited the transformation framework. I will devote more attention to the differences between students' understanding of transformation later, when I describe case examples of students from each grade.

Another notable difference between grade levels is that 8th grade students exhibited the activity framework more often that their older counterparts. The results of a chi-square test suggested that this variation was almost certainly non-random, $\chi^2(3,N=63) = 14.96$, $p \leq .01$. It is difficult to use this result to draw a conclusion about the energy unit, since no biology students exhibited the activity framework in their interview. One possibility is that the unit pushes students to adopt the activity framework as a sort of intermediate abstraction on their way to the transformation framework, and students need adequate time to move fully away from the activity framework. My analysis of the longitudinal interview data that I collected while students were participating in the unit suggest that students begin to move away from the activity framework while instruction is ongoing, but that many students have trouble moving fully away from it (and/or the closely-related product framework). The cross-sectional results shown in Figure 7 suggest that students may continue to move away from the activity/product frameworks as they continue to mature and to learn about energy-related concepts in their biology course.

Figure 7 also shows that fewer students who had participated in the energy unit displayed the deposit framework than students who had not participated, and the results of a chi-square test suggest that this variation between grade levels is non-random, $\chi^2(3,N=63) = 8.73$, $p \leq .05$. In the deposit framework, energy is contained within some objects and is used up by other objects when certain processes occur. The difference between energy unit participants and non-participants likely arose due to the emphasis on transformation within the energy unit. Because they are repeatedly asked to account for energy types that are present as phenomena occur, students began to understand that when an object "uses" energy, this really means that it has transformed energy from one type to another. During her interview after the energy unit, Angelina (8th grade) demonstrated that she understands that an object that "uses" energy does not use it up.

Jeff Nordine: If you turn the switch on and leave it on, what happens as time goes on?
Angelina: Well the battery, like it will run, like all of its energy will be used, like in the light bulb, and so yeah, it will be dead then.
Jeff Nordine: And once the energy gets used, what happens to it?
Angelina: Well, it is converted into another thing, I guess, like, so when it left the battery it turned into light and thermal and then, yeah, it's still there, it's just in a different form.

While Angelina exhibited the transformation framework in her response, Michelle (chemistry) exhibited the deposit framework when responding to the same question, posed during the same scenario:

Jeff Nordine: If you were to switch this switch on and leave it for a while, what would happen as time goes on?
Michelle: The energy will run out.
Jeff Nordine: What does it mean for energy to run out?
Michelle: There's a certain amount of energy in the battery that's transferred to the light bulb, but then, um, the energy's just used up.

Buford (physics) also demonstrated the deposit framework when he responded to the same question in the same scenario:

Jeff Nordine: If you turn this switch on and just let it run for a while, what happens as time goes on?
Buford: The energy starts to, it's starts to burn out the energy as it uses it, and it needs to have another source.

Some students who had participated in the energy unit also exhibited the deposit framework, but based on the number of these students compared to the number of students in chemistry and physics who demonstrated this framework, it seems that the energy unit helps students to understand more clearly what it means for objects to "use" energy.

While there seems to be a difference across grade levels in the number and type of energy frameworks students exhibited, these differences alone do not tell the whole story. During the interviews, it was clear that some students held frameworks more strongly or weakly than other students, that there were differences in the cuing priority of certain ideas, and that students' understanding of energy transformation had different levels of sophistication. The case examples that follow are intended to more clearly illustrate the conceptions of individual students who had less developed, moderately developed, and more developed conceptions relative to their grade level peers.

Performance on energy benchmark assessments (Research question 4)

I conducted a one-way ANOVA with orthogonal contrasts to compare the performance of students across grade levels on the energy content questionnaire. Table 6 shows the mean score for each grade level.

Table 6. Grade level means on the energy content questionnaire

	N	**Mean (SD)**
8th grade science	77	9.4 (2.5)
Biology	55	10.3 (2.1)
Chemistry	35	8.6 (1.8)
Physics	29	11.2 (2.3)
Total	195	9.8 (2.4)

The differences in means were strongly significant (*F*(3,191) = 9.20, $p \leq .001$). While the overall results of the one-way ANOVA indicate that the variation between groups is non-random, it does not reveal the source of this variation. Using orthogonal contrasts enabled me to look for variation between specific grade levels. Table 7 shows these results.

Table 7. Contrasts between grade levels on the energy content questionnaire

Contrast	**df**	**t-statistic**
8th grade science vs. biology	191	-2.39*
8th grade science vs. chemistry	191	1.63
8th grade science vs. physics	191	-3.86***
Biology vs. chemistry	191	3.49***
Biology vs. physics	191	-1.83~

*** $p \leq .001$
** $p \leq .01$
* $p \leq .05$
~ $p \leq .1$

The ANOVA results indicate that 8th grade students were significantly outscored by biology students who took the energy unit the previous year, and by physics students who did not participate in the energy unit but had gone through a year of physics instruction. The results also indicate that while 8th graders had a higher mean score than the 10th grade chemistry students, this difference in means was not statistically significant. Besides outscoring the 8th grade science students who had recently completed the energy unit, biology students also outperformed the chemistry students who were a year older and who had studied an extra year of science. Biology students were outscored by physics students, and the difference in their means approached significance.

The ANOVA results suggest that 8th and 9th grade students who have participated in the energy unit are in a better position to succeed on assessments targeted the middle school energy benchmarks than are the older 10th grade chemistry students who did not participate in the energy unit. Physics students, who outperformed all groups, seem to be in the best position to succeed on benchmark assessments.

It is no surprise that physics students performed best on the energy concept questionnaire since they are the oldest, have had the most science instruction, and are likely the most self-selected for an interest in science. While it may be no surprise that physics students performed best on this measure, it is noteworthy that the 9th grade students outscored the 8th grade students. This result suggests that, rather than forgetting what they learned about energy during the 8th grade, 9th grade students may have been better prepared for future energy-related learning in their biology class. To test for this, I separated the energy content questionnaire into two scores: one for items which were targeted to physical science benchmarks and one for items which were targeted to life science benchmarks. I repeated the one-way ANOVA with the same orthogonal contrasts to look for differences between grade levels on physical science items and life science items. The results are shown in Tables 8 and 9.

Table 8. Grade level means on physical science items and life science items from the energy content questionnaire

	N	Mean for physical science items (SD)	Mean for life science items (SD)
8th grade science	77	6.6 (1.7)	2.8 (1.1)
Biology	55	7.1 (1.6)	3.2 (0.9)
Chemistry	35	5.8 (1.5)	2.8 (0.9)
Physics	29	7.9 (1.8)	3.4 (1.0)
Total	195	6.8 (1.8)	3.0 (1.0)

Table 9. Contrasts between grade levels on physical science items and life science items from the energy content questionnaire

Contrast	df	t-statistic for physical science items	t-statistic for life science items
8th grade science vs. biology	191	-1.65	-2.60*
8th grade science vs. chemistry	191	2.37*	-.320
8th grade science vs. physics	191	-3.46***	-2.74**
Biology vs. chemistry	191	3.59***	2.11*
Biology vs. physics	191	-2.02*	-.749

*** $p \leq .001$

** $p \leq .01$

* $p \leq .05$

~ p ≤ .1

While biology students' mean score on physical science items was not significantly higher than 8th grade students, their mean score on life science items was significantly higher (p ≤ .05). Furthermore, biology students significantly outscored chemistry students on physical science items (p ≤ .001) and on life science items (p ≤ .05). Despite the fact that 10th grade students had taken virtually the same biology course as 9th grade students, they were outscored on energy-related life science items by the 9th grade students who had participated in the energy unit during their 8th grade year.

These results suggest that students who had gone through the energy unit learned about energy in their biology course more successfully than students who went through virtually the same biology class but did not participate in the energy unit. To investigate whether the differences between 8th, 9th, and 10th grade students were likely a result of preparation for future learning, I investigated several possible alternative explanations for these results.

The first alternative explanation is that the 9th graders simply learned more about energy when they participated in the energy unit than did the 8th graders. To test for this, I examined 8th and 9th grade students learning goals pretest and posttest scores in an effort to determine whether it was reasonable to assume that the two classes were equal at the end of the energy unit. I ran a one-way ANOVA to test for differences in 8th and 9th graders scores on the learning goals test, and the results of this ANOVA are shown in Table 10.

Table 10. ANOVA results comparing the learning goals test scores of 8th grade students and 9th grade students.

Measure	Mean (SD)		df	t-statistic
	8th grade students	9th grade students		
Learning goals pretest	15.2 (4.0)	13.8 (4.9)	129	1.81~
Learning goals posttest	27.0 (4.9)	27.8 (4.8)	130	.978
Gain	11.7 (4.8)	14.0 (5.8)	125	2.59*

*** p ≤ .001
** p ≤ .01
* p ≤ .05
~ p ≤ .1

The results of this ANOVA indicate that there was likely a difference between students' prior knowledge at the beginning of the unit, but that there was no significant difference between students' scores on the posttest. It is impossible to know for sure why students pretest scores are different, but it seems a likely result of the fact that Mrs. Nelson and Mrs. Geller began incorporating some of the ideas from the energy unit into the weather and life science units that came earlier in the curriculum. Because the 8th grade students had higher pretest scores than the 9th grade students, their gain scores are lower. While it may be true that 8th graders learned more about energy on their own or that 9th graders learned more successfully during their participation in the energy unit, the most plausible scenario is that the 8th and 9th graders did not have significantly different learning experiences during the energy unit and that there was no significant difference between 8th and 9th graders at the conclusion of the energy unit. As a result, it remains possible that the differences that I observed between 8th and 9th grade students on the energy content questionnaire were a result of 9th grade students learning more about energy during their biology class.

The second alternative explanation that I tested for was that the differences in test scores occurred because of a newly increased emphasis on energy during the biology course. In her interview, Mrs. Forest indicated that the biology curriculum remained largely the same during recent years, yet she mentioned that she may have used the term "transformation" more frequently. If the biology course did in fact emphasize energy more than it had in the past, then 9th graders who were new to Fairmeadows should have outscored 10th graders who enrolled at Fairmeadows at the beginning of their 9th grade year. While I do not know anything about these students' experiences prior to their enrollment, I can say for sure that they did not participate in the energy unit. If an increased emphasis on energy in the biology course was responsible 9th grade students scoring higher than 10th grade students among students who have been at Fairmeadows since their 8th grade year, then I would expect to see the same effect for students who enrolled at Fairmeadows at the beginning of their 9th grade year. I used a one-way ANOVA with orthogonal contrasts to compare the scores of students who were new to Fairmeadows in their 9th grade year. Tables 11 and 12 show the results of the contrast between 9th and 10th grade students.

Table 11. Grade level means on physical science items and life science items from the energy content questionnaire for students who were new to Fairmeadows in their 9th grade year.

	N	Mean for physical science items (SD)	Mean for life science items (SD)	Total score
Biology	24	6.4	3.0	9.4
Chemistry	12	5.8	3.6	9.3
Physics	11	7.1	3.6	10.6
Total	47	6.5	3.3	9.7

Table 12. Contrasts between grade levels on physical science items and life science items from the energy content questionnaire for students who were new to Fairmeadows in their 9th grade year.

Contrast	df	t-statistic for physical science items	t-statistic for life science items	t-statistic for total score
Biology vs. chemistry	44	1.12	-1.83~	.110
Biology vs. physics	44	-1.10	-1.66	-1.57

*** $p \leq .001$
** $p \leq .01$
* $p \leq .05$
~ $p \leq .1$

Unlike students who had participated in the energy unit, biology students who were new to Fairmeadows in the 9th grade did not outscore their 10th grade counterparts on the life science items in the energy content questionnaire. This finding refutes the idea that students received more energy instruction in the biology course during the 2005-2006 school year than students received in previous years, and reinforces the assertion that participating in the energy unit prepares students for future learning about energy.

A third alternative explanation for why 9th graders who have gone through the energy unit have outscored 8th graders and 10th graders is that they simply have a higher academic aptitude. I tested for this to some extent when I compared learning goals test scores between 8th and 9th grade students and found that there was no significant difference in their posttest scores. Unfortunately, student-level data for large-scale standardized assessments were not available to me, so I could not compare students between grade levels on such measures. Therefore, it remains possible that students in 9th grade simply have a higher aptitude than their counterparts in 8th and 10th grade.

Although academic aptitude may be a confounding variable in my analyses, it is unlikely any difference between classes fully accounts for the variation I observed across all measures. My results suggest that participation in the energy unit helps Fairmeadows students to be better prepared than they otherwise would have been to succeed on distal assessments targeted at the energy-related benchmarks. Furthermore, evidence suggests that participation in the energy unit prepares students for future energy-related learning.

In the next section, I summarize all of the results from my study and tie them together to discuss how the energy unit seems to have promoted students' development of coherent conceptions of energy and preparation for future energy-related learning.

DISCUSSION

This study explores the effectiveness of a novel approach to middle school energy instruction in terms of its ability to promote students' development a coherent understanding of energy. This approach, which draws upon the guidelines of high quality curricula set forth by Kesidou and Roseman (2002), varies from typical energy instruction because it uses project-based pedagogy to emphasize the role of energy transformations in non-ideal phenomena that students are likely to encounter outside of school. I hypothesized that such a highly-contextualized approach organized around the central idea of transformation would help students to form coherent understandings of energy, that is, to form links between their scientific ideas and their intuitive ideas such that their ability to make sense of their experiences was improved (Linn & Eylon, 2000; National Research Council, 2007; Roseman & Linn, 2007).

I observed that participation in the energy unit had both an immediate effect of improving the coherence of students' energy conceptions and a long-term effect of preparing students for future energy-related learning. In this section, I summarize results suggesting that students developed more coherent conceptions of energy and that they were prepared for future energy-related learning, present a model to explain why coherent understandings may promote future learning, and discuss the features of our energy curriculum that supported students' conceptual development and preparation for future learning. Finally, I outline the implications of this work for future middle school energy curriculum and instruction.

Summary of results

To investigate the effectiveness of our approach, I tracked students' conceptual development during the unit, followed up with students one year after instruction, and compared energy unit participants to older non-participants in the same school in terms of their energy conceptions and ability to perform on distal assessment items targeted at the National Science Education Standards and Benchmarks for Science Literacy standards for energy.

I hypothesized that if students' ideas became more coherent as a result of instruction, this would be manifest in several ways: during instruction, 8th grade students would become more able to link their energy ideas to form consistent responses across a variety of interview scenarios, energy unit participants would be more likely to exhibit the transformation framework and less likely to exhibit alternative frameworks, and students would score higher on the energy concept questionnaire because it measured the degree to which students' responses aligned with expert responses.

Prior to instruction, I observed that 8th grade students' descriptions of the role of energy in interview scenarios were highly context dependent. This finding supports other studies which assert that students' initial ideas are not strongly linked (diSessa, 1993; Smith, *et al.*, 1993-1994) and refutes studies which suggest that students' uninstructed ideas are better described as naïve theories (Carey, 1985; McCloskey, 1983; McCloskey, Caramazza, & Green, 1980; Vosniadou, 1994). Overall, 8th grade students interviewed prior to instruction classified less than 80% of scenarios as illustrative of energy and tended to exhibit different frameworks in different scenarios. As they progressed through the unit, students began to see the role of energy in more scenarios and their ideas seemed to become more connected as they reorganized their cognitive structures. Yet, not all reorganizations are productive (Clark, 2006), and 8th grade students almost uniformly moved toward the alternative activity/product frameworks in interview round two, indicating that the idea of energy as an obvious activity or as a product of an obvious activity was given higher cuing priority during lesson set one. This is not surprising, considering that students had learned a system of *factors* and *indicators* to identify when different types of energy were present or changing, but had not yet learned how to account for energy changes in terms of transformations. During interview round three, students moved dramatically toward the transformation framework, and this movement corresponds with students' participation in activities that emphasize tracking energy transformations in phenomena. After instruction, students' exhibition of the transformation framework had declined somewhat relative to round three, but their responses indicated a strong move toward coherent understanding during the unit. While students interviewed prior to instruction classified less than 80% of scenarios as illustrative of energy, they classified more than 97% of the scenarios in this way after instruction. Also, students' responses demonstrated much more consistency across scenarios. Kyle, the 8th grade student who demonstrated moderate conceptual development, was an excellent example of this. Prior to instruction, Kyle indicated that energy could be used up in some processes, created in others, that people gain energy by "warming up", and that energy was primarily useful for running electronic devices. After instruction, Kyle's ideas were clearly more organized around the principles of transformation and conservation, although he seemed to continue to hold activity/product ideas with relatively high cuing priority.

The conceptual changes that I observed among 8th grade students reinforce the knowledge-in-pieces perspective of conceptual change. Students were clearly not constrained by individual frameworks, as they frequently constructed "hybrid" responses during interviews (such as indicating that energy types were conserved individually by going into a dormant state when their indicators were no longer active – a combination of the activity framework and the idea of conservation), displayed different frameworks in different scenarios, and seemed to reorganize their thinking by emphasizing and de-emphasizing certain ideas (such as transformation and energy as an obvious activity) throughout the course of instruction. In the end, 8th grade students' displayed more conceptual coherence by moving substantially from a set of disconnected ideas about energy toward a understanding in which their ideas were more connected, which helped them to use their energy ideas to interpret a wider range of interview scenarios.

It is important from the perspective of coherence that students' understandings were not merely more connected, but that they were more organized around the central principle of energy transformation. During instruction, the frequency with which 8th grade students exhibited alternative frameworks (non-transformation) decreased relative to the frequency with which they exhibited the transformation framework. Looking across grade levels, students' who had participated in the energy unit were more likely to exhibit the transformation framework relative to the likelihood that they would exhibit an alternative framework. Conversely, the majority of non-participants did not exhibit the transformation framework and exhibited more alternative frameworks more frequently. These results suggest that the energy unit helps students to connect their ideas around the central principle of transformation by assigning it a higher cuing and reliability priority in a wider range of contexts. This productive rearrangement of ideas around the principle of transformation is a hallmark of a coherent conception (Linn & Eylon, 2000; National Research Council, 2007; Roseman & Linn, 2007).

As students develop more connected understandings that are organized around the big ideas of science, their understanding begins to resemble that of an expert (Chi *et al.*, 1981). In this study, I measured the correspondence between students' and experts' ideas with the energy concept questionnaire. These results indicate that students moved toward an expert understanding during instruction and that students who had participated in the energy unit were much more likely than chemistry students, and about as likely as physics students, to have a energy conception that resembled that of an expert. Overall, results suggest that students' ideas about energy become more connected during instruction, that these connections are more organized around the idea of transformation, and that energy unit participants move toward conceptions that resemble expert conceptions of energy – three important manifestations of a coherent energy concept.

My results suggest that instruction can have a powerful effect on students' development of a coherent energy conception. Because younger students who had participated in the energy unit displayed conceptions that were more sophisticated, coherent, and applicable than older students, my results refute the claims of other studies that students' acquisition of the energy concept is primarily mediated by maturational factors (Liu & McKeough, 2005; Warren, 1986). Instead, my results confirm studies which assert that instruction plays a crucial role in students' concept acquisition (Klahr & Nigam, 2004; Linn, Lee, Tinker, Husic, & Chiu, 2006; Smith, Maclin, Houghton, & Hennessey, 2000; White & Frederiksen, 1998). My results extend the findings of these studies by demonstrating that instruction can have a lasting positive effect well after the conclusion of the instructional intervention. This result echoes that of Linn and Eylon (2000), who found that students with coherent understandings of displaced volume continued to develop more predictive views after instruction. Besides developing a more coherent concept of energy during instruction, energy unit participants continued to learn productively about energy in the year after their participation in the energy unit had ended.

Results from the energy content questionnaire indicate that the energy unit helped to prepare students for future energy-related learning in their biology course. On this measure, 9th grade energy unit participants who took the unit one year earlier significantly outscored the 8th graders who had just completed the unit, despite the fact that their learning goals posttest scores at the end of instruction were not significantly different. Furthermore, 9th graders scored significantly higher on life science questions than 8th graders, but not significantly higher on physical science questions, suggesting that differences on the energy content questionnaire were largely due to 9th graders' energy-related learning in their 9th grade biology course. This additional energy-related learning was not simply an effect of the biology course, because 10th graders who had taken a nearly identical biology course were also significantly outscored by 9th graders on the energy-related life science items (and physical science items as well). Finally, among 9th and 10th graders who joined Fairmeadows at the beginning of 9th grade, the 10th graders significantly outscored their 9th grade counterparts, which suggests that the additional energy learning benefit of 9th grade biology existed only for students who had previously participated in the energy unit.

diSessa and Wagner (2005) provide a model that sheds light on why students' participation in the energy unit had the effect of preparing students for future energy-related learning. They argue that future learning is mediated by the extent to which learners' existing ideas are coherent. Because energy unit participants had more coherent understandings of energy, they were better prepared than non-participants to learn about energy in their 9th grade biology course. In the next section, I elaborate diSessa and Wagner's model to explain the mechanism by which coherent understandings operate to prepare students for future learning.

Coherent understanding and preparation for future learning

When people use information learned at one time in one context to reason about new situations at a later time, this is known as *transfer of learning* (Royer, Mestre, & Dufresne, 2005). Bransford and Schwartz (1999) argue for the consideration of a type of transfer that they call *preparation for future learning* (PFL), which focuses on the impact of previous learning on people's ability to continue learning in knowledge-rich environments. Unlike the notion that children can be generally prepared for "learning to learn" (Brown & Kane, 1988), the PFL perspective refers to the relationship between learning in specific content areas and existing prior knowledge.

diSessa and Wagner's (2005) model explains why coherent understandings are likely to promote learners' preparation for future learning. They describe learners' conceptual understandings as *coordination classes* of connected ideas, which function as lenses through which learners can view new information and situations in a way that is consistent with a particular concept. If learners possess a coherent understanding of a scientific concept, then they are capable of using this prior knowledge to discriminate new information, choose what is relevant, and to understand the new context within the framework of their existing cognitive structure. This process is different from the Piagetian notion of *assimilation* (Piaget & Inhelder, 1971), because the PFL perspective emphasizes the role of learners in thinking critically about what they already know in order to formulate appropriate questions to improve their learning (Bransford & Schwartz, 1999).

diSessa and Wagner note that naïve ideas often lack *span* (applicability in different contexts) and *alignment* (the ability to use information reliably across different contexts), while coherent understandings have more span and alignment, which makes them more useful for making sense of new information encountered in new situations (diSessa & Wagner, 2005). Learners will always activate their prior knowledge when they encounter new situations (Brooks & Brooks, 1993; diSessa, 1993; McCloskey, 1983; von Glaserfeld, 1998), but when they possess more coherent understandings, they are more likely to be successful choosing which knowledge to activate and using it to reason about new information.

Schwartz, Bransford and Sears (2005) suggest that the nature of instructional interventions play a large part in determining whether students are prepared for future learning. An important feature of instruction that effectively prepares students for future learning is that it encourages them to grapple with their ideas across many meaningful contexts. When learners activate their prior knowledge to reason in a variety of contexts, they are more likely to transfer their knowledge to new situations (National Research Council, 1999; Schwartz & Bransford, 1998; Schwartz et al., 2005). By focusing on the energy transformations that occur in a wide variety of everyday phenomena, our unit promoted the type of coherent understanding that served as the foundation for students' future energy-related learning. In the next section, I discuss the specific features of the energy unit that supported students' development of coherent conceptions and preparation for future learning.

How does the energy unit promote coherence and future learning?

To support coherent understanding of science concepts, Roseman and Linn (2007) suggest that curriculum should be organized around big ideas, should connect with students' experiences, and should encourage student reflection and metacognition. To address these design principles, we used project-based pedagogy to organize instruction in the energy unit around the driving question, "How can I use trash to power my stereo?" This question was chosen because it met the characteristics of a good driving question outlined by Krajcik, Czerniak, and Berger (2003), but more specifically, because it is most sensibly answered using the idea of energy transformation. By using a project-based approach with a driving question that necessitated the study of energy transformation, we were able to organize instruction within a real-world context and around the big idea of transformation. Furthermore, we were able to encourage students' reflection and metacognition by asking them to use their understanding of energy transformation to iteratively complete the design project and city energy plans. The conceptual development and content knowledge gains that students made during the unit echoed the results of other studies that suggest that project-based pedagogy is an effective way to foster students' ability to interpret and explain real-world phenomena and to understand scientific concepts (Blumenfeld et al., 1991; Geier et al., in press; Kuhn & Reiser, 2005; Marx et al., 2004; McNeill et al., 2006).

It is not project-based pedagogy alone that contributed to the differences between energy unit participants and non-participants at Fairmeadows, because the 8th grade science curriculum consisted entirely of project-based units before the energy unit was introduced. Differences, therefore, must be due to features of smaller grain size than the overall instructional model. These specific design choices relevant to the particular topic of energy were critical in giving students the tools they would need to develop and refine their ideas and to connect these ideas to their out-of-school experiences.

Prior to the introduction of the energy unit, 8th grade science consisted of a year of energy-themed instruction, but the design of this instruction was different from the energy unit in two important ways. First, energy types were treated largely independently of each other without emphasizing the importance of energy transformations. Prior to the introduction of the energy unit, the 8th grade curriculum included the following units: "Where do plants get their energy?" that focused on photosynthesis and green plants, "Where do you get all of your energy?" that focused on digestion and respiration, and "How can you hear what I'm saying?" that focused on sound energy. While each of these units was designed to help students learn about energy, none of them included a specific focus on the role of energy transformations in phenomena. As a result, students were not encouraged to link their ideas across units to consider how sound energy may be related to a plant's energy. Without making this link, students' intuitive and instructed ideas are unlikely to be connected within a coherent framework. It seems, therefore, that the energy unit's emphasis on using energy transformations to predict and explain phenomena is part of the reason why energy unit participants were more likely to display a coherent, transformation-based energy concept than non-participants.

A second important difference between the energy unit and the instruction that preceded it is a focus on everyday, easily observable phenomena. Although previous instruction focused on phenomena that were central to students' lives such as digestion, photosynthesis, and hearing, these phenomena are very difficult for students to interact with and manipulate. On the other hand, energy unit participants study phenomena that are ubiquitous in students' lives and easy to interact with, such as toasters, glow sticks, low-energy firecrackers, and personal music devices. By focusing on phenomena that are real-world, easily observable, and non-idealized, the in-class activities serve as models for how students can use energy concepts to make sense of their everyday experiences, which helps them to connect between their intuitive and instructed knowledge (diSessa, 2000; Kesidou & Roseman, 2002).

A focus on everyday phenomena would not have been productive, however, were it not for the systems of factors and indicators developed within the unit. While a fully quantitative approach would not be practical for interpreting everyday phenomena because students would become overwhelmed with detail, the factor and indicator system provided students with a semi-quantitative tool for recognizing when certain energy types were involved in phenomena and whether their magnitude was increasing or decreasing. Equipped with this tool, students could empirically investigate the idea of energy transformation (as students notice that an increase in one energy type must always be accompanied by the decrease of another, and vice versa) and make sense out of a wide range of familiar contexts while maintaining a focus on the importance of transformations without getting lost in the details of calculation.

A major function of the energy unit is to increase the explanatory power of students' energy concept by providing them with appropriate conceptual tools and modeling the use of energy for making sense of everyday phenomena. Students' ability to use scientific ideas to make sense of their experiences is an indication of coherent understanding (National Research Council, 2007; Roseman & Linn, 2007), and the results of this study suggest that students who participated in the energy unit were more capable of using their knowledge of energy to make sense of the everyday situations depicted in the interview scenarios.

My results indicate that students' coherent understanding has both an immediate effect of enhancing students' ability to make sense of new situations and a lasting positive effect on their future learning about energy. While my study was not specifically intended as a study of students' preparation for future learning, this is an important result because students' future learning happened in an authentic rather than an experimentally contrived context. The energy unit promotes students' preparation for future learning by continuously encouraging them to use their existing understanding of energy and its transformation to make sense of a variety of relevant phenomena. During instruction, this process leads to a more coherent energy concept, and after instruction, students are able to use their coherent energy concept to interpret the new information they encounter in biology within the lens of their existing knowledge. Compared to students with a set of disconnected ideas about energy, students with coherent understandings are much more likely to learn new information effectively. It seems that participation in the energy unit had both a short-term effect of promoting more coherent conceptions of energy and a long-term effect of preparing students for future energy-related learning.

Implications

In this study, I used a cross-sectional design to investigate the impact of a novel, standards-based, energy curriculum on students' energy concept and content knowledge. The results, therefore, have implications for the appropriateness of the standards upon which the curriculum was based and the design of future middle school energy curricula.

We developed the energy unit using a learning-goals driven approach that was intended to address the energy standards in the Benchmarks for Science Literacy (American Association for the Advancement of Science, 1993) and National Science Education Standards (National Research Council, 1995), which advocate middle school energy curricula that are phenomena-rich and focused on the importance of energy transformations. As such, the results of my study provide empirical evidence that this focus is appropriate and useful for middle school students.

Contrary to those who suggest that young students cannot develop rich understandings of energy (Liu & McKeough, 2005; Warren, 1986), my study affirms that the learning trajectory recommended by the national standards documents can promote meaningful understandings of energy in middle school students that many adults never acquire. This result echoes those of other studies that suggest that contextualized instruction plays a major role in developing sophisticated conceptual understandings even in younger students (Blumenfeld et al., 1991; Klahr & Nigam, 2004; Linn, Lee, Tinker, Husic, & Chiu, 2006; Smith, Maclin, Houghton, & Hennessey, 2000; White & Frederiksen, 1998).

Of course, simply focusing on energy transformations or contextualizing instruction through project-based pedagogy is not enough. Besides its focus on energy transformations in everyday phenomena, our unit is different from traditional middle school instruction in two important ways: it uses a qualitative approach to analysis of systems, and it does not provide students with an operational "definition" for energy.

While traditional approaches often focus students attention on performing simple calculations of energy quantities (e.g., work, kinetic energy, gravitational potential energy), such an emphasis necessarily limits the range of phenomena that students are equipped to understand and risks burying the central ideas of energy in detail (Kesidou & Roseman, 2002). In our approach, students are never asked to calculate a numerical value for energy. Instead, our system of factors and indicators provides students with a qualitative tool that is useful for tracing transformation by identifying which energy types are involved and how their magnitudes are changing. Equipped with this tool, students can interpret and explain the behavior of everyday systems without becoming overwhelmed with the details of calculation. Our approach is not intended to suggest that rigorous calculations of energy are unimportant; rather, such calculations are best left for later. This is in line with the learning progression described in the most recent *Atlas for Science Literacy* (American Association for the Advancement of Science, 2007) which recommends that middle school students focus on energy transformation and high school students focus on its quantitative conservation.

Another important between traditional approaches and our unit is that traditional approaches tend to begin by offering a simple "definition" for energy, such as the ability to do work or to cause a change, but our curriculum offered no such definition. While this difference seems somewhat cosmetic, it reflects a fundamental difference between our approach and the traditional approach. In our unit, we focus on using the scientific idea of energy to predict and explain the behavior of phenomena that students are likely to encounter. Rather than focusing on what energy is, the unit focuses on using the concept of energy to predict and explain phenomena. As Richard Feynman noted, "…in physics today, we have no knowledge of what energy *is*. It is just an abstract thing that always comes out with the same numerical value, without telling us anything about a *mechanism* or a *reason*" (Feynman, Leighton, and Sands, 1989). In other words, the value of energy lies not in what it is, but in how it can be used to interpret the behavior of systems. While this is generally true for any scientific idea, focusing students' attention on the behavior of systems rather than the nature of energy has the added educational benefit of grounding the unit more firmly within students' experiences, thereby helping them access their intuitive ideas about energy and to connect them with new instructed ideas into a more explanatory conceptual framework (Clark, 2006; diSessa, 1993, 2000; diSessa & Sherin, 1998).

The results of this study suggest that future middle school energy curriculum will more effectively promote a coherent understanding of energy if it focuses students' attention on using the idea of energy transformation to interpret and explain everyday phenomena. Because energy is a central unifying concept in science, students with a more coherent conception of energy are well positioned for future science learning (National Research Council, 1999) – an effect that I saw in this study. With a coherent conception of energy that promotes future science learning and enhances their understanding of everyday phenomena, students are much better positioned to address the energy-related challenges facing our world, both as scientists working to develop new technologies and as citizens capable of making more informed decisions.

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