Chapter 14
Looking Through the Energy Lens: A Proposed Learning Progression for Energy in Grades 3–5

Sara Lacy, R.G. Tobin, Marianne Wiser, and Sally Crissman

14.1 Introduction

The *Framework for K-12 Science Education* (National Research Council [NRC] 2012) specifies that by the completion of elementary school students will have basic conceptual understanding of what energy is and how it behaves, including acceptance of the basic ideas of energy conservation. It is expected, for example, that it will make sense to students to use the same term, "energy," to discuss phenomena as varied as a moving ball, a battery, a cup of hot water, a stretched rubber band, and sunlight; and to understand the motion of a pendulum, or the operation of a slingshot, as involving the transfer of this elusive "stuff" from one object and/or one "form" to another.

Here we propose both a general framework for thinking about the goals of pre-college energy education, and a detailed learning progression for Grades 3–5 aimed at getting students to the required level of understanding by the end of the elementary grades. (Following the *Framework* (NRC 2012) we do not envision formal energy instruction in earlier grades.) Our proposal is based on a careful consideration of the role of energy concepts in science and society and on prior research on children's understandings of energy, supplemented and shaped by our own interviews and exploratory interventions with students in 3rd and 5th grades and with teachers.

Learning progressions describe how knowledge in a domain (e.g., energy or matter) can evolve from young students' ideas (which radically differ from

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S. Lacy (✉) • S. Crissman
TERC, Cambridge, MA 02140, USA
e-mail: Sara_Lacy@TERC.edu

R.G. Tobin
Department of Physics and Astronomy, Tufts University, Medford, MA 02155, USA

M. Wiser
Department of Psychology, Clark University, Worcester, MA 01610, USA

R.F. Chen et al. (eds.), *Teaching and Learning of Energy in K-12 Education*,
DOI 10.1007/978-3-319-05017-1_14,

scientists') to a deep and productive understanding of a scientific theory. They articulate *how* students can reach a scientific understanding through specific learning experiences that promote the progressive reconceptualization and integration of students' ideas. A learning progression provides a roadmap for developing curricula that foster "successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" (NRC 2007). We believe that this approach is particularly well suited to the abstract nature of energy. In fact, a learning progression approach has shown promise in teaching energy in middle school (Nordine et al. 2010).

14.2 Foundational Ideas of the Learning Progression

This learning progression focuses on a network of *foundational ideas* about energy carried across grades 3–5 toward productive intermediate understandings (the 5th grade *Stepping Stone*) that can help students progress toward scientific understanding while ensuring that they keep making sense of phenomena. We have identified an "Energy Lens" and four foundational ideas (the "Energy Quartet") that are central to a scientific understanding of energy, essential for an informed citizen, and can progressively and meaningfully evolve, with instruction, from their precursors in childhood to principles endorsed by scientists. While our specific proposal and investigations here are confined to Grades 3–5, we would suggest that the Energy Lens and Energy Quartet could provide a useful organizing structure through all the pre-college years.

14.2.1 The Energy Lens

The principle of conservation is at the very heart of the concept of energy in science (Duit 1981; Elkana 1974; Goldring and Osborne 1994; Millar 2005). It is precisely the fact that energy is conserved that makes it useful. Like any conservation principle, it constrains the possible behaviors of a system, allowing us to say with confidence, across a vast range of natural phenomena, what *cannot* happen (no matter what it's made out of, a dropped ball will not bounce higher than its starting point) and what machines *cannot* be made (e.g., a car that runs on water), no matter how clever we are or how much money we spend. It can lead to scientific discoveries, such as the neutrino, or practical insights, like why you could heat your kitchen by leaving the oven door open but you can't cool it by leaving the refrigerator door open. But the concept of energy conservation is a peculiar tool. It typically does not tell us what *will* happen, or explain the causal mechanisms involved in a phenomenon. It usually focuses on initial and final states of a system, ignoring the messy processes in between, and is most helpful when those processes are at their messiest. Energy arguments can help us to conclude that plants require sunlight to live and grow, or to ask ourselves where the energy for an electric car comes from, but they do little to elucidate the details of photosynthesis or the design of electric cars.

If the principle of conservation of energy is taught without experience in why it is useful, how to reason with it, and what kinds of questions it can and cannot address, the principle is unlikely to be more than empty words, and indeed is unlikely to be believed.

Our proposal is that energy education focus on how scientists use what we call the "Energy Lens" to examine a broad range of phenomena, rather than on definitions, facts, or even equations (though all of those are necessary). "Energy" should be taught not as a discrete topic but as an analytical tool (Jin and Anderson 2012) or intellectual stance that provides partial but powerful insights into many topics in science and society. It differs radically from the force-dynamic, time-sequential, causal reasoning that is more naturally adopted by most students – and most adults (Driver and Warrington 1985; Jin and Anderson 2012). It often requires thinking in terms of systems rather than objects and willfully ignoring striking and fascinating details in favor of a focus on an abstract and invisible quantity. We have observed college physics students who will do a page of dynamic/kinematic calculations rather than two lines of energy analysis, because the causal relationship between force and motion makes more sense to them. Learning to look at phenomena through an "Energy Lens," therefore, is not a matter of a few weeks or even a few years; rather it must develop and be nurtured over a period of many years, and in many different contexts, including chemistry, biology and engineering as well as physical science. Indeed it took the scientific community hundreds of years to come to an understanding of energy (Elkana 1974).

Using the Energy Lens entails asking a set of questions that are appropriate to virtually any phenomenon in the physical world:

- What is the system of interest?
- What observable or measurable changes or other interesting behaviors are taking place?
- Where in the system are energy changes occurring?
- Where does the energy come from?
- Where does the energy go?
- What is the evidence for our answers?

We place the Energy Lens at the intellectual and pedagogical center of our proposal. We believe that through repeated exposure to these questions in various forms and contexts, students will acquire the habit of mind of asking – and tentatively answering – these questions about phenomena they encounter in their daily lives and throughout their science and engineering education. In addition, the Energy Lens provides teachers with an understanding of energy as a crosscutting concept and a straightforward way of bringing energy ideas into other curricular units. (Some teachers have told us that since being exposed to these ideas they see energy everywhere in their science curriculum and have begun to use it as a unifying theme, e.g., *"'Energy' can be viewed as an overarching concept that I can keep revisiting during the school year to connect content as we move through each curricular area."*)

14.2.2 The Energy Quartet

While the Energy Lens represents a powerful analytical stance for the analysis of natural phenomena and technological applications, its use depends on a firm grasp of four key aspects or strands of the energy concept, the "Energy Quartet"[1]:

1. The nature and manifestations ("forms") of energy;
2. Transfer and transformation of energy;
3. Dissipation and degradation of energy;
4. Conservation of energy.

The specific phenomena and experiences that students encounter are aimed at developing their understanding of these aspects of energy, while simultaneously building the habit of mind of looking at diverse phenomena through the Energy Lens.

From a scientific perspective the strands do not have equal status. Understanding energy conservation is the overarching goal, and so stands apart from and above the others. Dissipation and degradation could be viewed as a special case of transfer (to the environment) and transformation (into thermal energy). But our experience with students and teachers has persuaded us that they deserve their own category.

Most importantly, the strands are interconnected, interdependent and concurrent. As Goldring and Osborne (1994) point out, the nature of energy and the principle of conservation cannot be taught sequentially, but must be developed together, "holistically, gradually and over a period of time, with progressively deeper insight leading to the development of a more precise understanding." The idea that the energy stored in a stretched rubber band is the same kind of thing as the energy of a rolling ball makes sense only because one can be transferred to the other. Dissipation makes sense only if "heat" has already been recognized as a form of energy and it has been shown that other forms of energy can be converted into thermal energy. Conservation is believable only once dissipation is fully accepted; yet one is unlikely to accept, or even consider, the idea of dissipation without at least a tentative belief in energy conservation in other contexts. So these four strands must be interwoven and developed in parallel.

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[1] We recognize that some of these terms are controversial, particularly "forms" and "transformations," and we discuss those issues later in this paper.

14.3 What Ideas Do Students Bring to Grade 3? What Should They Know by Grade 5?

The foundational ideas described above are, we believe, relevant for energy education throughout the pre-college curriculum. We turn now specifically to the elementary grades. The Grade 3–5 learning progression builds on students' initial ideas about energy (the Lower Anchor), and teaches students to think of phenomena in terms of energy from the start. The four thematic strands and the Energy Lens develop progressively from the "Lower Anchor" to the "5th grade Stepping Stone" that prepares students for further instruction and learning in middle and high school.

14.3.1 3rd Grade Lower Anchor

The Lower Anchor represents the set of ideas and cognitive resources that most children bring to 3rd grade, prior to any instruction about energy. It is derived from prior research on young children's understanding of energy and our own exploratory interviews. Very young children focus strongly on causal relationships (Leslie 1995; Rovee-Collier et al. 2001; Goswami 2008), so the non-causal perspective of the Energy Lens is likely to be alien.

The literature is largely concerned with middle school students, and does not always differentiate between younger and older students, whose ideas about energy are heavily influenced by instruction. To establish our Lower Anchor, it was important to determine what third-graders think about energy. To investigate children's ideas in more detail, and also to explore how readily they would accept or adopt new ideas, we conducted clinical interviews with eight pairs of 3rd grade students recruited from an urban school in Massachusetts with a high proportion of low-income and non-white families and English language learners. Each interview comprised two 30-min sessions and involved a range of hands-on activities including marble collisions on a horizontal track, a Newton's Cradle, a ball and spring, a balsa wood airplane propeller spun by a twisted elastic, and questions about what it means to "have energy."

Third graders told us that objects such as battery-powered devices and Slinkys have energy because they move by themselves, in unpredictable ways and/or "a lot." They believe that "energy" is the state of being in motion, or the ability to move. This makes "having energy" an inherent, either/or property of a certain class of objects that has the disposition to move in a certain way, as well the state of moving in such a way and the inner resources to do so. This corresponds to the anthropomorphic bias reported in the literature (e.g., Watts 1983; Trumper 1993); children see energy as an intrinsic property of living things and objects that move on their own. This is a correlate of a deeper concept: things that have energy are those with (apparent) agency and intentionality; they have inner resources to move and can be "recharged." In other words, they are the "animates" that children differentiate from “inanimates” starting in infancy (Leslie 1995; Spelke et al. 1995; Gergely et al. 1995; Gelman 2003; Hatano and Inagaki 1999). However, the third graders we interviewed gave no evidence of believing other energy frameworks reported in the literature, e.g., that energy is a causal agent, is in food or fuel, is a product, or is transferred. It is likely that those ideas develop later, as the result of instruction, exposure to media, and everyday language. Most third graders did say that batteries have energy. Batteries are perceived of as *enablers* (as described by Jin and Anderson 2012); switching on the battery allows the battery to “do its job,” i.e., to give energy to a device in the sense of allowing the device to be in a state of energy.

We found that once the interview focused on energy and motion events, students readily adopted the view that all moving objects have motion energy and accepted speed as an indicator of the amount of energy. The interviewer could use language to implicitly and effectively convey “all inanimate objects can have motion energy” by saying, “Let’s look at these colliding marbles. Do you think the blue one has as much energy after it collides with the red one?” This supports our view that language is an important pedagogical tool (Lemke 1990).

14.3.2 5th Grade Stepping Stone

The 5th grade Stepping Stone is the form of the Energy Quartet that students could understand by the end of 5th grade, and the contexts to which they could apply the Energy Lens. To define the stepping-stone we considered the Framework (NRC 2012), draft Next Generation Science Standards (Achieve Inc. 2012) and proposed learning progressions for energy (Jin and Anderson 2012; Nordine et al. 2010). We reviewed existing elementary and middle school curricula and discussed our ideas with a group of elementary school teachers. We also considered empirical evidence of whether and how students’ ideas can progress when they engage in key learning experiences.

At the end of 5th grade, students’ understanding of energy will still be fragmented and incomplete, but they will have a sound experiential and conceptual foundation on which to build a more solid understanding of the Energy Quartet and greater skill, versatility and sophistication in using the Energy Lens, through well-designed instruction in middle and high school. Students will understand that energy is a unitary entity and be able to recognize and characterize its most familiar manifestations, including energy of motion, stored energy of elastic deformation and batteries, stored gravitational energy, and thermal energy. They will be able to trace energy transfers and transformations in a variety of contexts, identifying and representing the gains and losses associated with various phenomena. They will recognize that energy gains in one object or system are consistently accompanied by energy losses in another and that magnitudes of gains and losses are correlated.

They will identify friction,[2] sound, and light as mechanisms for energy transport out of an object or system. They will include the possibility of "leakage" of energy into thermal energy in the environment and recognize that although such energy is not "gone," it is degraded in its usefulness for other purposes.

Since we are not, in these grades, attempting to quantify energy, quantitative conservation is not a goal. By the end of 5th grade, students should spontaneously look for energy losses when they see energy gains, and vice versa, and should expect that the magnitudes of those gains and losses are correlated. Without the means to quantify and compare amounts of energy in different objects and different forms, it is too early to claim that the gains and losses are equal, but students should be familiar with representations of energy (such as energy bars (described in Sect. 5.2) or energy cubes (Scherr et al. 2012)) that embody conservation, and be prepared to consider that possibility. We would not expect 5th graders to apply a strict conservation principle in most situations, particularly those involving subtle or undetectable forms, such as low-grade thermal energy in the environment. Further, we do not expect that students will fully distinguish between a form of energy and its indicator (e.g., thermal energy and temperature) though we expect they will recognize that other factors (e.g., the amount or kind of material) also influence the amount of energy.

The abilities and understandings included in the 5th grade Stepping Stone will provide the foundation for applying the Energy Lens to a variety of systems and phenomena, including those encountered outside the classroom. They will allow students to begin to make predictions and draw inferences based on energy considerations. Since the Energy Lens questions – where does the energy come from and where does it go? – implicitly contain the idea of conservation (energy cannot just appear or disappear), students who have become accustomed to asking and addressing those questions will be well prepared for a more formal treatment of energy conservation in subsequent instruction.

14.3.3 Construct Map

Table 14.1 shows our proposed Construct Map, which indicates possible levels of understanding for each strand from the 3rd grade anchor (L1) towards the 5th grade Stepping Stone (L4). It can serve as a basis for formative assessment. Students start with limited, accessible versions of the four strands and progressively build more general, richer, more complex integrated versions of them. We have

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[2] More precisely, work done by the frictional force. At this grade level we do not think it is productive to focus on the distinction between force and work. "Friction" is used here to refer to a general phenomenon, aspects of which include the frictional force, energy dissipation, and frictional heating.

Table 14.1 Preliminary construct map for the learning progression for energy

Nature/manifestations (“forms”)	Transfer and transformation	Dissipation/degradation	Conservation
L4: Verbal and nonverbal representations show awareness of unitary nature, and distinguish energy from indicators. Can explain thermal phenomena without invoking “cold energy.” Describes gravitational energy and energy of foods/fuels as energy of systems, light and sound as energy carriers. May not fully distinguish food/fuels from associated energy or thermal energy from temperature	**L4:** Recognizes that energy gains in one object/system are consistently accompanied by energy losses in another. Describes gains and losses as transfers and transformations of the same “stuff.” Represents and describes transfers and transformations in a range of situations, including those with multiple objects/forms	**L4:** Consistently includes thermal energy in environment when tracing energy transfers and transformations. Identifies frictional heating, sound and light as mechanisms for energy transport out of object/system. Understands that “lost” energy could exist but not be recoverable	**L4:** Spontaneously asks “Where does energy come from?” and “Where does energy go?” in new situations and includes transfer to/from environment in attempting to answer. Recognizes that magnitudes of energy gains in one object/system and losses in another are correlated. Considers possibility that total energy could be constant, but may not fully believe or consistently apply, especially to real world situations
L3: Describes energy as quantity or substance, and distinguishes energy from indicator in some but not all cases. Recognizes multiple manifestations exist simultaneously. Identifies stored gravitational energy and associates amount with height. Identifies thermal energy and associates amount with temperature. Understands that energy can be transferred without a transfer of matter in some contexts	**L3:** Can qualitatively track and represent energy increases and decreases in processes involving transformations within a single object/system as well as between objects/systems. Uses words like “give,” “take” and “share” to describe energy changes. Shows increased ability to consider multiple objects/forms	**L3:** Shows understanding that in a large system, increases in thermal energy may not produce detectable temperature changes. Includes environment in system and in tracing energy flow in cases involving light, sound or obvious frictional heating. Understands that some forms of energy are less useful than others. May believe “lost” energy is fully recoverable	**L3:** Recognizes constancy of total energy in simple mechanical systems (e.g. pendulum) without dissipation. Recognizes “Where does the energy go?” as meaningful, and begins to include light, sound and frictional heating as possible answers, with guidance, but does not spontaneously ask question and/or thinks “it’s just gone” in many situations

L2: Identifies energy of motion of inanimate objects and stored energy of elastic deformation (springs, elastics), batteries and capacitors, and associates amounts with appropriate indicators. Does not clearly understand that they are different manifestations of the same quantity or consistently differentiate energy from matter. Associates energy with specific objects	**L2:** Can qualitatively track and represent energy increases and decreases in processes involving transfer from one object to two or a few distinct objects, with or without transformations. Recognizes that gains/losses occur in combination, but does not show firm understanding of transfer and does not include multiple energy pathways	**L2:** Recognizes that other forms of energy can be transformed into thermal energy. Understands that light and heat can carry energy away from object. Begins to notice effects such as heating of objects and vibrations. Does not consider energy transfer to wider environment (e.g. air) or possibility of undetected losses	**L2:** Recognizes that energy has to “come from” somewhere to initiate a process, and connects gains and losses, but believes it disappears when visible process ends
L1: Identifies energy as inherent property of animate objects or objects that move on their own or in unusual ways	**L1:** Identifies only presence or absence of energy, not increases or decreases. Can describe processes in terms of gains/losses but does not show awareness of transfer	**L1:** Asserts that energy is just gone when motion stops. Attention is focused on discrete objects; systems/environment are not considered. No awareness of thermal energy	**L1:** Sees energy as inherent property of certain objects that can appear or disappear and is gone when not perceptible

developed this map based on our review of the relevant literature and our preliminary investigations, but like any such map it is a work in progress and will be revised iteratively as the learning progression is implemented and tested in the classroom.

14.4 The Proposed Learning Progression; Start with the Lower Anchor, Aim for the Stepping Stone

In this section we propose a pathway from the 3rd grade Lower Anchor to the 5th grade Stepping Stone. Our proposed learning progression indicates how students' understanding of each of the four strands will broaden and deepen over the course of three curriculum units and includes some productive contexts and experiences within each grade. Although the strands are described sequentially, we emphasize that they develop simultaneously and in parallel. The argument for the unitary nature of energy is inseparable from the ideas of transfer and transformation, for example, and the Energy Lens questions "Where does the energy come from?" and "Where does the energy go?" will be asked throughout. Across the strands there is a progression in the complexity of the phenomena studied and the sophistication of the representations and reasoning used.

14.4.1 Strand 1: Nature and Manifestations ("Forms") of Energy

A central challenge is to convey the idea of energy as a unitary quantity that is manifested in diverse ways. Fixating on a taxonomy of "forms," as many curricula do, can be misleading and confusing, and distract from the more important idea of unity. Some writers advocate abolishing the terms "forms" and "transformations" of energy altogether (Millar 2005; NRC 2012; Swackhamer 2005). Yet it is useful to name the diverse manifestations of energy, just as graphite and diamond have different names even though carbon is carbon. Furthermore, many familiar phenomena, such as a ball rolling down a ramp, are difficult to describe meaningfully at a grade-school level without the idea of transformation.[3] Rather than abandoning "forms" and "transformations" entirely, we propose to limit the number of categories, avoid sorting for its own sake, and construct activities that emphasize the underlying unity of these apparently disparate manifestations (Achieve Inc. 2012; DOE 2012; Jin and Anderson 2012; Nordine et al. 2010).

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[3] The alternative is to describe the energy as being transferred between the gravitational field and the ball (NRC 2012; Swackhamer 2005) but we regard the idea of a field as too abstract to be meaningful in these early grades; in our experience it is difficult enough for college students.

In Grade 3, we begin with manifestations of energy that are familiar and accessible to young children – motion and batteries – and begin developing the ideas of energy amounts (none, less, more), transfer, and transformation. The energy stored in compressed springs and elastics is introduced through the ability to produce motion, such as spinning a propeller (Van Hook and Huziak-Clark 2008). The focus is on simple mechanical systems (colliding marbles, propellers, slingshots), in which the energy is associated with specific objects. All the activities deal with motion in a horizontal plane, intentionally deferring gravitational energy because it cannot (or at least should not) be identified with a specific object. We introduce the term "system" to describe a set of interacting objects (Driver and Warrington 1985; Jewett 2008).

The idea of a system becomes important with the introduction of gravitational energy in Grade 4. (It is also a crucial concept in the study of matter (TERC 2011) and a crosscutting concept in the *Framework* (NRC 2012)). Unlike the stored energy in a compressed spring, gravitational energy is a property not of the object itself, but of the system comprising the object and the earth as they interact through gravity[4] (NRC). Magnets will be used to scaffold this difficult idea, as a more accessible example of energy in a system of interacting objects that does not belong to either object by itself.

Energy in electrical circuits is also explored in Grade 4, allowing the introduction of light and sound as energy carriers[5] (NRC 2012). Heat is mentioned, but not explored in detail until Grade 5. Capacitors are used as sources of stored electrical energy, bringing several pedagogical advantages over batteries: They can easily be charged to various levels, including with a hand-cranked generator; there is a measurable indicator (voltage) for the amount of stored energy; and the stored energy can be exhausted in a few seconds or minutes.

Thermal energy, food, and fuels are introduced last, in Grade 5. We have had success using thermal phenomena as an entry point for energy investigations with adult teachers, but young children associate heat with energy only after some experience and instruction. (Giving up the idea of "cold energy" is challenging for both adults and children.) Understanding heat as energy is critical to the strands of transfer/transformation, dissipation/degradation and conservation, and understanding the relationship among food, fuels, and energy is central to many scientific and everyday applications (DOE 2012; Jin and Anderson 2012).

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[4] Again, the alternative is to describe the energy as residing in the gravitational field (Swackhamer 2005). On a microscopic level, the energy in the compressed spring is due to interactions between the atoms and is not a property of the atoms themselves. So the distinction between the two cases is pedagogical rather than fundamental. Since the interacting atoms are all within the spring, we can describe the stored energy as a property of the spring, due to its compressed state, without reference to any external object.

[5] We do not think it is useful to treat electrical currents as carriers of energy (Millar 2005). It is not accurate to consider the energy as carried by the current, and such a description can contribute to misconceptions such as that the energy is kinetic energy of the electrons and that in a complete circuit the energy returns to the battery.

Accurately describing the energy associated with food and fuels is challenging (Jin and Anderson 2012; Millar 2005; Warren 1983). Since energy is released only when the food/fuel reacts (usually with oxygen) forming new chemical bonds, the energy is properly understood not as a property of the food/fuel itself but of the *system* comprising the food/fuel and oxygen. But a full understanding of the distinction requires an understanding of chemistry, chemical bonds and chemical reactions that very few students achieve even in high school (Jin and Anderson 2012). Further, the idea that energy resides in the food and fuel is pervasive, and in many contexts useful, or at least not harmful. It is far more important, in our view, that students understand that the food or fuel is not itself the energy.

14.4.2 Strand 2: Transfers and Transformations

In our interviews, 3rd grade students saw that decreases in one object's energy coincided with increases in another's (e.g. when a moving marble strikes a stationary one) but they did not conclude that energy had been transferred from one to the other. Adopting the model of energy as a kind of "stuff" that can be transferred is a productive, and perhaps even necessary step towards understanding the unity of energy and the principle of conservation (Millar 2005; Scherr et al. 2012; Swackhamer 2005). In our learning progression students observe, describe, and represent coordinated gains and losses in diverse systems of growing complexity. They begin in Grade 3 with examples of transfer from one object to another, and words such as "give" and "share" are introduced. They move from a view of energy as an "either/or" property to descriptions of amounts of energy as "none," "some," or "a lot."

Transfer and transformation become a central focus in Grade 4, with many examples of increasing complexity, including transformations within a single object or system (e.g., a falling ball), and situations in which energy is transferred to multiple objects and/or forms, as when an electrical circuit drives a propeller and a light bulb. They also begin to observe, and use representations to show, that gains and losses are correlated in magnitude (e.g., a capacitor charged to higher voltage can make a bulb burn brighter and longer). By the end of Grade 4 students should have the expectation that energy gains and losses occur in combination, and the habit of looking for the loss corresponding to an observed gain, and begin to think of those gains and losses as a transfer – that is, that the energy gained is the same "stuff" as the energy lost.

The emphasis in Grade 5 shifts primarily to thermal energy. Purely thermal phenomena, as when a hot object is placed in cool water, provide some of the clearest examples of transfer, but accepting "heat" as energy, rather than a distinct substance, also requires experiences with the transformation of other forms of energy into heat and of heat into other forms. It is also essential that students begin to recognize thermal energy as a ubiquitous byproduct of all the phenomena they study, and to include it in tracing energy transfers.[6]

14.4.3 Strand 3: Dissipation and Degradation

Any successful learning progression for energy must confront the apparent conflict between the scientific principle that energy is conserved and the everyday view of energy as something that is routinely "produced," "consumed," "wasted," and "used up." The statement that "Energy cannot be created or destroyed" stands in apparent conflict not only to the way energy is usually described, but to the universal experience that unless we keep providing them with energy, moving things stop, hot things cool off, and batteries (as well as living things) "die" (Goldring and Osborne 1994; Solomon 1985). The explanation that the energy is still present in the form of slight warming of the environment is not persuasive – unless one is already firmly committed to the principle of conservation – nor is it easily demonstrated. It is simpler, and common (for teachers as well as students), to conclude that conservation of energy applies only in idealized situations (e.g. in the absence of friction). Experiences in which mechanical or electrical energy is transformed into detectable heat – rubbing an eraser on a carpet, heating a resistor with a battery, burning a hole in paper by colliding steel spheres (Nordine et al. 2010) – are necessary, but they do not seem to transfer readily to the more common situation in which the thermal energy is too diffuse to produce a readily detectable temperature change.

This obstacle will not be overcome easily or quickly. The issue of "where does the energy go when it's gone" will need to be raised repeatedly and consistently over the course of years, in many contexts of varying complexity, and students (and teachers) must have multiple experiences that make visible the normally invisible thermal energy associated with dissipation, through the use of such tools as sensitive temperature probes and infrared photography. We hope to help students begin to understand dissipation by the end of 5th grade through such experiences, and by consistently raising the issue of "where the energy goes" while, in parallel, building the idea of energy conservation. But activities and instruction will need to continue to focus on the topic in the higher grades as well.

The question of "where does the energy go when it's gone" arises naturally in the Grade 3 activities, and children will be encouraged to speculate about it; in our exploratory interviews they noticed both vibrations and slight warming. In Grade 4

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[6] We see no benefit to emphasizing or enforcing the thermodynamic distinction between heat and internal energy at this grade level, but we encourage the use of the term "thermal energy" to emphasize that "heat" is a manifestation or form of energy, rather than a distinct quantity or substance.

light and sound provide additional mechanisms by which energy can “leak out” of the system. In Grade 5 there will be activities in which small temperature changes are measured, and students become familiar with the idea of thermal energy in the environment as a sink for the “lost” energy, even if they do not yet fully accept the idea.

At the same time, the everyday idea that something is irreversibly lost when energy is “used” is correct, and we don’t want to replace one misconception (that energy simply disappears) with another (that the dissipated energy could be recovered and reused). A full understanding would require grappling with the Second Law of Thermodynamics and the idea of entropy, but we will acknowledge, beginning in Grade 4, that the “lost” energy is “less useful” than other forms, so that although the total amount of energy does not change, the amount of “usable” energy is diminished in every process (DOE 2012; Goldring and Osborne 1994; Millar 2005; NRC 2012; Nordine et al. 2010).

14.4.4 Strand 4: Conservation

Scientists would not have invented the concept of energy, and we would not teach it, if it were not conserved; conservation is the whole point (Duit 1981; Elkana 1974). The Energy Lens makes no sense without conservation. So this strand is the core of the project, yet it is, deliberately, the one strand that is not explicitly taught, because it cannot be given real meaning until the other strands have been developed, and because a convincing case cannot really be made until one begins to quantify the various forms of energy. Instead, in these early grades we build, largely implicitly, a model of energy as a kind of “stuff,” a body of evidence for such a model, and habits of mind that embody the model, such as asking “Where does the energy come from?” and “Where does the energy go?” and thinking of energy losses being accompanied by energy gains. The ideas of transfer and transformation will continue to be developed across the grades, and the language of the Energy Lens will be used consistently from the beginning – initially as prompts for speculation, but with a growing expectation of meaningful analysis and argumentation. The developing understandings will be reinforced as students are asked to use representations – both student-generated and provided – that will increasingly embody the model of energy as a unitary and conserved quantity (Scherr et al. 2012).

14.5 Exploratory Results from Classroom Research

As a partial test of the feasibility of our learning progression approach, we piloted activities with 3rd and 5th grade students. In each case we began with students’ initial ideas (the Lower Anchor) and developed activities that we hoped would reveal students' conceptual difficulties and help them restructure their ideas toward the 5th grade Stepping Stone. Our findings are helping us to assess both the learning progression and the effectiveness of the learning experiences.

14.5.1 Grade 3 Teaching Experiments

We developed and administered a sequence of "teaching interventions" to investigate if students in Grade 3 could make progress toward the 5th grade stepping stone by using the Energy Lens. Initially, third graders typically think of energy as an all-or-none state, and believe that humans, but not inanimates, can give energy to objects. The idea that a stretched elastic or compressed spring has energy does not make sense to them. Our goal was for students to learn that energy can be transferred between moving objects, from a battery to a moving object, and between a moving object and a spring or elastic band. An interviewer met with pairs of students for four half-hour sessions over the course of 2 weeks. Eighteen 3rd graders participated, most of them from an urban school in Massachusetts serving low-income families.

The interviewer used a flexible script to interact with students over a series of tabletop activities. Students were encouraged to notice and correlate changes in speed and configuration (energy indicators), and to interpret them in terms of energy transfer. Since students easily associate energy with motion, we introduced a simplified version of the Energy Lens questions in the context of colliding marbles:

- Describe what happens. (E.g., Give me a play-by-play description of the changes in motion that you see.)
- Where are there energy changes? (When is there no energy of motion, some energy of motion, or lots of energy of motion? When do you see energy of motion increasing? Decreasing?)
- Where did the energy come from? (If a marble gained energy of motion, where did the energy come from?)
- Where does the energy go? (If one marble lost energy of motion when it hit the other marble, where did the energy go?)

Students were led to see speed as an energy indicator and to associate one marble's energy loss with the other's energy gain. The interviewer then asked students what they thought of the idea that one marble gave some of its energy to the other.

Given what students already know about batteries—they run things, they have energy, they "die"—we hypothesized that a battery-operated toy, in this case a battery-operated propeller, was a fruitful context for introducing the concept of stored energy, and for extending the practice of using the Energy Lens to associate gains and losses of energy (e.g., the energy gained by the propeller is lost by the battery). We also hypothesized that a battery-operated propeller could serve as a useful analogy for one operated by a stretched elastic. Drawing on the analogy between the two propellers, we asked students to consider whether a twisted elastic has stored energy, and encouraged them to apply the Energy Lens to the elastic

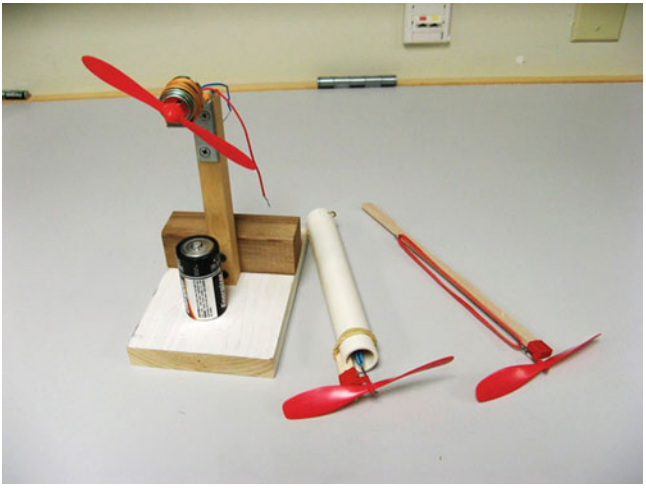

Fig. 14.1 Students explored propellers operated by battery and twisted elastics

operated propeller: the propeller blade begins to move; it gains energy of motion; the energy of motion comes from the twisted elastic. The elastic untwists; when the elastic is less twisted, it has less stored energy; the elastic gives motion energy to the propeller; when the elastic gives motion energy to the propeller it loses stored energy; loss of stored energy is associated with a gain of motion energy (Fig. 14.1).

The excerpt below from the Grade 3 teaching intervention *Can an elastic band store energy*? shows how students use what they have learned about energy stored in batteries, energy of motion, energy gains and losses, and energy transfer to investigate the propeller powered by a twisted elastic band. In a prior investigation, they have learned that stored energy lost from a battery is gained as energy of motion of the propeller.

A pair of students is given a propeller that is attached to an elastic hidden inside a tube: the elastic has been twisted and the propeller is held in place by a skewer that serves as a brake. The interviewer is guiding them to observe and describe what happens and to identify observable indicators of energy changes.

I = Interviewer, S = Student[7]
I: *What about this propeller. Do you think it has any energy?*
S: *No*
S: *Yes*
I: *How can you tell?*
S: *I think it does.*
I: *Can you explain why? It’s not moving.*

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[7] In transcribing the recorded interview we could not consistently distinguish the voices of the two students, so an utterance by either student is indicated by “S” without further identification.

S: *Because there's a rubber band inside it... Actually, no I don't think it has energy right now.*

S: *I don't think it has energy, because it's not moving. And usually when something has energy, it would be moving.*

I: *The battery wasn't moving, but you said it had energy.*

S: *It had stored energy.*

I: *Check this out. [Releases propeller and then stops it with the skewer brake.] Do you think it has energy now?*

S: *Yes*

I: *Why?*

S: *It has stored energy*

I: *How can you tell?*

S: *Because it has a rubber band. It's twisted up. And like, when you take the stick away, it'll go running away.*

I: *[Releases the propeller and lets it run until it stops.] What about now? Does it have stored energy now?*

S: *Not now because now the rubber band is, it's not twisted. Usually when the rubber band is twisted then it's gonna untwist.*

I: *[Shows the propeller without enclosing tube. The elastic is untwisted.] This is what it is like inside. Does this have stored energy?*

S: *Um. No.*

I: *Could you store energy in it?*

S: *Yes.*

I: *How would you do it?*

S: *[Tries to pull and twist the rubber band. Then twists the propeller, which in turn twists the rubber band.] It's working, it's working.*

I: *So now. Tell me why you think there's stored energy.*

S: *Whee .....[releasing the propeller and letting it spin].*

I: *[Winds the propeller.] Now is there energy stored in it?*

S: *Yes*

I: *If I let it go, do you see any energy?*

S: *Yep.*

I: *Did you see any energy pairs? What had no energy and then more energy?*

S: *First it didn't have energy. Before you twisted it.*

I: *You mean the rubber band?*

S: *Yeh. Now it has stored energy.*

I: *What about the red propeller. Does it have energy?*

S: *Not until this gave it energy.*

I: *What's getting energy if I let go?*

S: *This is [the propeller].*

I: *And what loses energy?*

S: *The rubber band loses energy and the propeller gains energy.*

I: *So it lost stored energy and it gained energy of motion.*

I: *Can you make it have more energy than it had the last time?*

S: *I keep twisting. I haven't stopped twisting it since I started.*

I: *How can you tell it has more energy?*
S: *Cause it will run longer and faster.*
I: *Is there any way you can tell by looking at the rubber band?*
S: *Yes. Because it's getting tighter and tighter.*
I: *Did you give it more energy?*
S: *Very.*
I: *What do you think is going to happen when you let go?*
S: *It's gonna go vroom.*
I: *So will it give the propeller more energy if it has more energy?*
S: *Yes, but this is gonna lose more energy.*
I: *I think you should let go now.*

We used a pre/posttest to understand if and how children's ideas progressed before and after the teaching interventions and to assess the promise of the activities. The pre/post was an interview structured around a series of tabletop activities; knocking down bowling pins with a rolling ball, launching a small pom-pom with an elastic-band slingshot, and using a battery-powered milk frother. Students did the activities in pairs, then watched slow-motion videos of the same phenomena and answered open-ended interview questions.

Students made progress from the pre- to posttest in their interpretation of all three events. In the pretest, students did not think that the bowling ball gave energy to the pins. ("*I don't think the ball is giving energy to the pins, I think it's just like making it be forced to fall down.*") In the posttest they were more likely to think that an object's energy can increase because it receives energy from another object; the majority of students believed both that the bowling ball gave energy to the pins and that the battery gave energy to the milk frother, i.e., that inanimate objects can give energy. (Detailed analyses of the test transcripts for all three events reveal that the strong association between humans and energy weakens but does not completely disappear.) In the pretest, students rejected the notion of elastic energy; most third graders told us that the slingshot did not have energy when it was stretched but not moving.

Interviewer: *As you pull it back, while you're pulling, is there any energy?*
Student: *Yes. Because it's moving and before it wasn't moving.*
Interviewer: *Now it's stretched all the way back, is there any energy?*
Student: *No, I don't think there's any energy because it's not moving.*

In the posttest, on the other hand, most students asserted that when energy is given to the slingshot (by stretching it), the slingshot has stored energy. In the posttest, students began to make the association that when energy is gained by one object, it is lost by another. Some students progressed from thinking that giving energy means, e.g., putting another object in a state of energy, to understanding that giving energy is transferring energy; they were more likely to say that the bowling ball slowed down because it gave some of *its* energy to the pins.

Student: *I saw Jimmy give energy to the ball and then the ball give energy to the pins to knock them down.*

Interviewer: *What happens to the ball at the very end?*

Student: *The ball stops, and it lost energy. The ball gained energy, and then the ball gave energy to the pins, and then the ball lost energy.*

In the posttest, some students said energy is transferred from the slingshot to the pompom. Others said that the slingshot gives energy to the pompom, but that is not why it loses energy, noting that the slingshot stops whether or not it launches a pompom.

Thus, we conclude that we are "on the right track." The sequence and goals of our teaching activities seem meaningful and productive: introduce the Energy Lens – beginning with the association of energy with observable indicators and the idea of energy as something that can be transferred between objects—in the context of collisions, extend it to battery-powered objects; and use the energy of batteries as an analogy for elastic energy.

14.5.2 Grade 5 Teaching Experiments

The focus of our work with 5th graders was to develop and test a sequence of activities that would help students think about phenomena involving thermal energy. We piloted two 1-hour sessions in 5th grade classrooms in one urban and one suburban school. Members of the research team led the activities in cooperation with the classroom teachers.

We have found that children of all ages and their teachers (Tobin et al. 2012) have difficulty considering the question "Where did the energy go," a key Energy Lens question that is essential for understanding energy conservation. A 5th grade learning progression target is that students become aware that a system can "lose" energy to its environment; that there are invisible forms of energy (such as low-grade thermal energy) that can make it appear that energy is lost; and that thermal energy is a "sink" for all energy. We know from prior research that not all children believe that heat is energy and that, in some situations, children think that *cold*[8] is transferred rather than heat – elements of the Lower Anchor. We hypothesized that experience with the Energy Lens in the context of motion phenomena, prior to the activities relating to heat, would pave the way for gaining a stronger sense that heat is energy and understanding the correlation between heat gain and heat loss in the context of thermal phenomena.

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[8] This misconception is documented in the AAAS Project 2061 Science Assessment website: "When two objects at different temperatures are in contact with each other, thermal energy is transferred from the warmer object to the cooler object and "coldness" or "cold energy" is transferred from the cooler object to the warmer object." (AAAS n.d.)

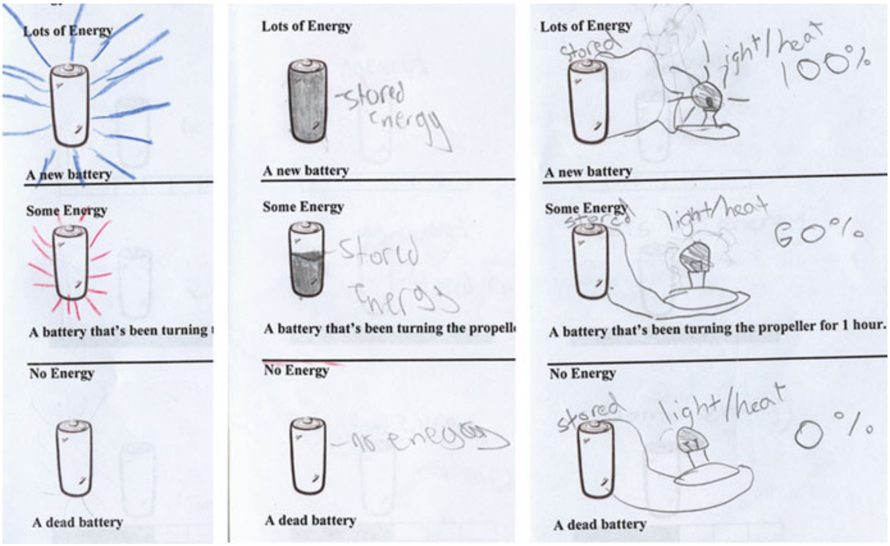


Fig. 14.2 Student representations of "no," "some," and "lots of" energy

We introduced the Energy Lens in the context of marble collisions, and taught students to look for and describe changes in terms of pairs of energy gains and losses in phenomena involving motion energy, "stored energy" of a battery, and "light energy" and "heat energy" of a light bulb. Students designed representations to show situations of no energy, some energy, and lots of energy. We began with an outline drawing of three batteries and asked them to come up with as many ways as they could think of to show "no," "some," or "lots of" energy (Fig. 14.2).

Next, using the same drawing of three batteries, we introduced "energy bars." We filled in energy bars to show "no energy," "some energy," and "lots of energy," and asked students to identify "Which battery has no energy? Some energy? Lots of energy?" (Fig. 14.3).

The next session aimed to extend their use of the Energy Lens to phenomena involving thermal energy, and to make the case that there is no such thing as "cold" energy. Students connected a hand-crank generator and a battery to a resistor and described what happened (heating of the resistor) in terms of energy gains and losses.

To gain insight into how they were thinking about energy transfers, we asked 5th grade students to use "energy bars" to represent energy gains and losses (a) when a resistor is connected to a battery and placed in a beaker of room temperature water and (b) when a room temperature copper cube is placed in a beaker of hot water. (See Fig. 14.4.) As students explained how they decided to fill in the energy bars, they revealed their understanding of energy gains and losses during heat transfer and, in some cases, their understanding of temperature as an indicator of energy and even dissipation. For example, "I gave the [room temperature] water two energy

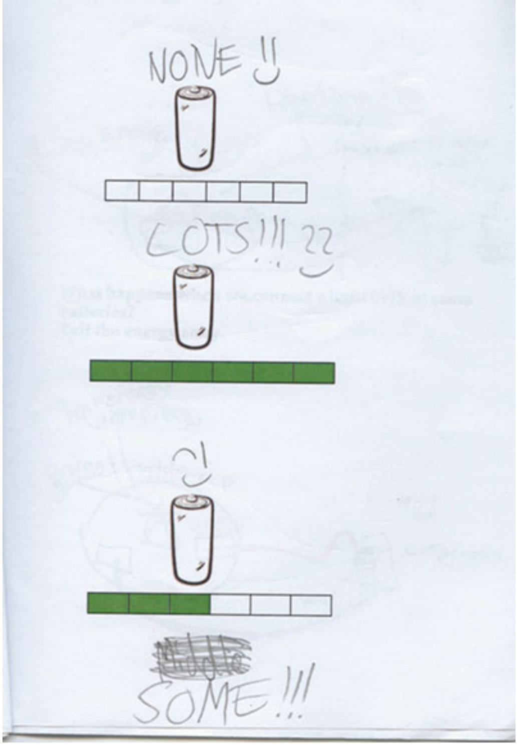
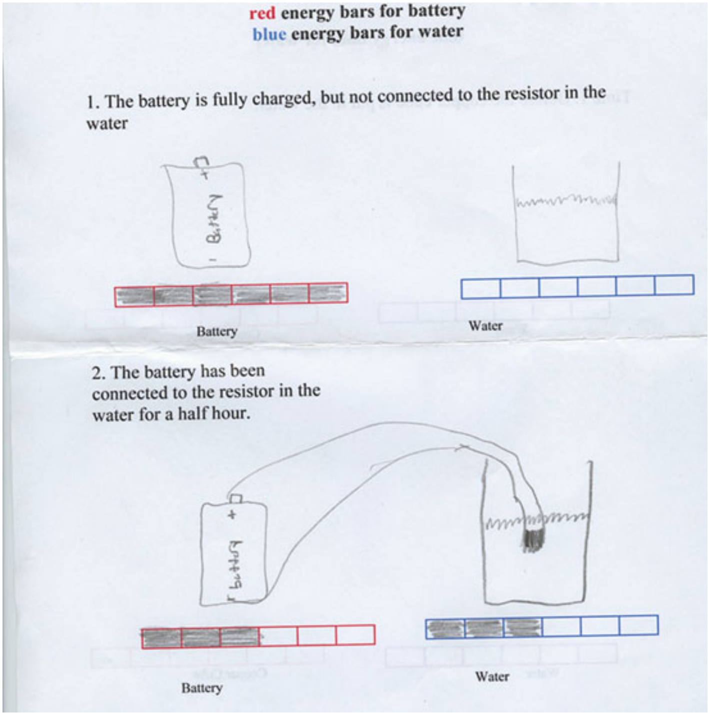


Fig. 14.3 Students label "energy bar" representations of "no," "some," and "lots of" energy

bars because I thought it had some energy before I put in the resistor. I thought the battery must be charged so I colored in all 6. After the resistor heated the water, I added 3 energy bars to the water that gained energy and took away 3 from the battery that lost energy." This student showed the water gaining the same number of bars as the battery lost, but we would not claim that this necessarily indicates an understanding of energy conservation. In general, we did find that students began to recognize that the magnitude of the resistor's energy loss was correlated with the water's energy gain. The energy bars represent a first, partial step in the direction of quantification and towards the idea that, when fully accounted for, the energy gains and losses are not merely correlated but in fact equal.

With such a limited intervention, and without the prior experiences that 5th Graders would have had in a fully implemented learning progression curriculum, we could not hope to fully evaluate whether our postulated Stepping Stone is reachable. We were able, however, to draw some tentative conclusions: By the end of these lessons, most students could describe changes in terms of (a) no, more, or less energy as a property of objects and systems, (b) different manifestations or forms of energy (and exhibited beginning understanding of energy in all its forms as a unitary thing), (c) energy transfer in terms of gains and losses in pairs or multiples, (d) energy transformations, e.g., motion energy to light and heat energy, heat energy to



red energy bars for battery
blue energy bars for water

1. The battery is fully charged, but not connected to the resistor in the water

2. The battery has been connected to the resistor in the water for a half hour.

Fig. 14.4 A student uses "energy bars" to represent energy gains and losses when a resistor is connected to a battery and placed in a beaker of room temperature water

motion energy. Students explained that motion or stored energy can be transferred to an object such as a resistor and manifest itself as heat; heat energy can be transferred to an object and manifest itself as motion. Students were intrigued by the idea that "there is no such thing as cold energy."

A pre/post assessment involving a hands-on activity in which a hot stone was placed in cooler water was used to assess students' progress towards the learning goals. We asked students, "When the stone was in the water, its temperature went down and the temperature of the water went up. Can you explain what was happening?" In the posttest, 20 of the 37 students (compared to 4 of 37 in the pretest) were able to describe the phenomenon in terms of energy gains and losses.

Student #1 (post): *The stone is giving heat energy to the water and the stone losses heat energy and they act as a energy pair. The water gained heat energy while the stone loss heat energy. [sic]*

Before instruction, 80 % asserted the existence of "cold energy." A representative pre-test response was:

Student #2 (pre): *The stone transferred some of its heat energy to the water and the water transferes [sic] some of its cold energy to the stone.*

After instruction the percentage had dropped to 48 %.

Student #2 (post): *Some of the heat energy transferd [sic] to the water so the stone got less warm and the water got warmer.*

After such a limited intervention, however, this understanding is probably fragile and context-dependent. Many students hold on to the idea that "loss of heat energy" can also be described as "gain of cold energy."

The teaching activities also revealed conceptual difficulties that would be addressed in a longer, curricular intervention. The students did not readily look for more than one gain corresponding to a given loss (e.g., in the environment). As in Grade 3, the idea of gains and losses was more readily accessible than that of energy transfer. Students found it easy (and fun) to use graphical representations to show no, a little, or a lot of energy, and qualitatively or semi quantitatively show energy gains and losses. Using representations – both graphical (such as energy bars) and concrete (such as the energy cubes used by Scherr et al. 2012) – may provide a way for students to show that energy is not only gained and lost, but that the same energy is *transferred* from one system to another – that although energy is manifested in many ways, it is all the same "stuff" – as it can all be represented in the same way. Appropriate representational systems, moreover, may help students construct or assimilate – or at least consider – the idea of conservation (Scherr et al. 2012).

These preliminary results give us confidence that the learning goals we envision for the 5th grade, while ambitious, are both accessible and engaging for teachers and children in this age group.

14.6 Conclusion

We have outlined a learning progression for energy in grades 3–5 based on the idea that energy is a powerful analytical tool for thinking about a wide range of phenomena, rather than a discrete topic. Our proposed learning progression is structured around the parallel development of a network of interconnected and interdependent foundational ideas. It builds on young students' intuitive ideas (the Lower Anchor) and is sensitive to prevalent hurdles and misinterpretations revealed by prior research and our own preliminary investigations with children and teachers. Our learning progression is a hypothesis about how relevant instruction could progressively enrich, transform, and integrate students' knowledge toward a scientific understanding of energy. Exploratory interviews and teaching interventions provide preliminary evidence for the promise of this approach. The next step will be to use these ideas to develop the complex system of curriculum, assessment, and teacher professional development that will provide elementary students with the resources to develop a more sophisticated understanding of energy in middle school.

Acknowledgement This work was supported by National Science Foundation Awards #1020013 and #1020020.

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