Responsive teaching and the beginnings of energy in a third grade classroom

DAVID HAMMER[1], FRED GOLDBERG[2], SHARON FARGASON[3]

[1]*Departments of Education, and Physics & Astronomy*
Center for Engineering Education & Outreach
Tufts University, USA
David.Hammer@tufts.edu

[2]*Department of Physics*
Center for Research in Mathematics and Science Education
San Diego State University, USA
fgoldberg@sciences.sdsu.edu

[3]*Mary Lanyon Fay Elementary School*
San Diego, USA
sfargason@sandi.net

ABSTRACT

Energy, like "the whole of science…is nothing more than a refinement of everyday thinking" (Einstein, 1936). It is a refinement in two respects, both conceptually, in the particular canonical features of the concept, and epistemologically, in the kind of intellectual pursuit the concept supports. Drawing on data from the third author's third-grade class, we show evidence of children's productive conceptual and epistemological resources for understanding energy. We discuss how responsive teaching can help students tap into and refine these resources, as well as the notion of responsive curriculum and our first steps in designing a prototype.

KEYWORDS

Energy, conceptual resources, epistemological resources, responsive teaching, responsive curriculum

RÉSUMÉ

L'énergie, comme "l'ensemble de la science…. n'est rien de plus qu'un raffinement *de la pensée quotidienne" (Einstein, 1936). C'est un raffinement à deux égards, tant au niveau conceptuel, en particulier les fonctions canoniques du concept, et tant au niveau épistémologique, dans la poursuite intellectuelle que le concept pourrait soutenir. On étudie le cas d'une classe élémentaire de troisième année aux États-Unis (8-9 ans), enseignée par la troisième auteure, pour présenter des exemples de raisonnement qui démontrent la richesse des ressources conceptuelles et épistémologiques des élèves pour comprendre le concept de l'énergie. On discute les caractéristiques d'un enseignement qui "répond" au raisonnement des élèves d'une manière à les aider à identifier et raffiner ces ressources. On présente ainsi le début d'un effort pour conceptualiser un prototype d'un programme d'études "réactif".*

Mots-clés

Energie, ressources conceptuelles, ressources épistémologiques, enseignement réactif, curriculum réactif

Introduction

Discussions about the concept of energy as a target for instruction generally focus on its canonical features: energy is conserved; it can appear in many forms; it represents an 'ability to do work'; it can be "degraded" and so on (Liu & McKeough, 2005; Millar, 2005; Nordine, Krajcik & Fortus, 2011). These aspects of the scientific concept contrast with everyday uses of the term, so researchers have identified a variety of "alternative conceptions" of energy (Duit, 1981; Solomon, 1983a; Driver et al., 1994). While there are a variety of studies documenting the productive beginnings of the concept in children's reasoning (Solomon, 1983b; Watts, 1983; Trumper, 1993; Koliopoulos et al., 2009; Koliopoulos & Argyropoulou, 2011), there are more documenting older students' difficulties and misconceptions (Duit, 1984; Goldring & Osborne, 1994; Papadouris, Constantinou & Kyratsi, 2008).

There has been less attention to another layer of understanding energy. Understanding the concept of energy means, in part, understanding what kind of idea it is and what kind of intellectual pursuit it supports. In one kind of conversation, for example, it would be perfectly reasonable to say and believe, "Coffee gives me energy to work". In another kind of conversation, that statement would be incorrect: There are not many calories in coffee, although there are calories in sugar or cream. In still another kind of conversation, it would be wrong to think of energy as stored in sugar and cream! Energy comes from those molecules reacting with oxygen, so if energy is "stored" somewhere, it is in the initial configuration of the carbon and hydrogen atoms separated from the oxygen.

Each kind of conversation has its own, often tacit criteria for assessing what is valid or makes sense. To introduce criteria from a different conversation would constitute a move to change from one kind of conversation to another - imagine sitting in the cafe, hearing someone say, "Coffee can't give you energy. It doesn't have any calories".

In this way, we argue, "understanding energy" involves not only the canonical features of the concept - that energy is conserved, transformed, etc - but also an epistemological framing (Redish, 2004; Hammer et al., 2005) of a particular kind of conversation. Moreover, learning the one is coupled tightly with learning the other: Trying to learn the scientific concept of energy, without understanding the "game" of science, is like trying to learn the concept of castling without understanding the game of chess. It only has meaning in the context of the larger pursuit.

This is especially important to recognize in elementary science instruction. At the same time that children are learning concepts within science, they are also learning about the kinds of epistemic activity that constitute science. Unfortunately, the epistemic activities children learn in science instruction are generally quite different from those of science itself. The kind of conversation they come to take up has more to do with meeting formal requirements than it has to do with the natural world.

We take scientific inquiry as the pursuit of understanding the natural world and scientific knowledge as the result of that pursuit. More specifically, the pursuit is of coherent, mechanistic understandings- coherent in the sense of 'holding together', that evidence and ideas are mutually consistent and connect with each other in meaningful ways, and mechanistic in the sense that the understanding builds from reliable causes-and-effects (Hammer et al., 2008).[1] Of course there is much more to say about predictive power, about the discovery of new mechanisms, about the role of community in argumentation and consensus, but for our purposes here it is sufficient to recognize that when we think of teaching science, we mean both the pursuit and the body of knowledge.

These are related but different objectives, the pursuit and the body of knowledge. For energy as for other concepts in science, there can be tension between these different kinds of objectives: Students who are free to pursue their own ideas and questions may go in quite different directions than toward the canonical ideas (Hodson, 1988; Hammer, 1997).

1 The concept of energy has a complex history with respect to mechanistic reasoning (see, e.g., Holton & Brush, 2001). Here, we are primarily speaking of the mechanistic reasoning in the children's understandings of the various pushes and pulls that could get the toy car moving, all of which are ultimately related to energy: The pull of a rubber band is related to the concept of elastic potential energy, for example; the downward pull of gravity to the concept of gravitational potential energy. At another level, energy is a powerful construct partly because it taps into rich conceptual resources for understanding conserved "stuff"; the idea of caloric was of a kind of substance.

In what follows we discuss our work to coordinate these objectives in what we describe as responsive teaching and responsive curriculum. In the approach we describe, roughly speaking, the first task for instruction is to tap into those productive resources: Engage students in a kind of epistemic activity that is or can become scientific inquiry and, within that activity, recognize and respond to the beginnings of the concept of energy.

We have two objectives in this article: (1) to show how productive beginnings of understanding energy can emerge in a class taught responsively; and (2) to discuss how responsive teaching can coordinate inquiry and content objectives.

We begin with a description of responsive teaching. Then we provide an overview of the third author's pilot work in her third-grade classroom, which took place over fourteen class periods, from the initial launching question to an extended discussion on the final day. We then discuss some of the many ideas about energy that emerged from the extended class discussion on the final day. Finally we discuss how the students' reasoning could serve as productive beginnings for developing more sophisticated understandings of energy, and how we are using this pilot work to get us started in the design of a responsive curriculum.

Responsive Teaching

Teacher preparation typically mandates that lessons have specific curricular objectives, selected based on the target understanding or abilities. By the end of a lesson in a "Full Option Science System" or "FOSS" unit on Matter and Energy (Lawrence Hall of Science, 2007), the formally adopted curriculum at the third author's school, students are expected to learn that energy can be carried from one place to another by waves, electric current, and moving objects. A supervisor evaluating a lesson would want to see evidence that these objectives were met.

These norms of practice create difficulties for the coordination of inquiry and traditional content oriented objectives. To engage in science as inquiry, students need the autonomy to pose their own questions, have their own ideas, and assess the quality of those ideas (Hodson, 1993; O'Neill & Polman, 2004). Problems arise when students have questions and ideas that the plans did not anticipate: Teachers have to choose whether to pursue student thinking or to keep to the plans. Since professional norms favor plans, students systematically experience the flow of thought in science class as a predetermined set, and they learn a kind of epistemic activity that is in several ways at odds with scientific inquiry (Jiménez-Aleixandre, Rodríguez & Duschl, 2000; Windschitl, 2004). In other words, practices that specify and adhere to conceptual objectives, even in the most "hands-on" curricula, can support students' learning "the classroom game" (Lemke, 1990) of trying to figure out what the teacher wants them to say.

The challenge remains for instruction: How to coordinate the objectives that students take up the pursuit with the objectives that they understand what scientists have established? We are working to meet that challenge with responsive teaching, meaning practices of attending and responding to the substance of student thinking, as it unfolds in the particular class (Levin, Hammer & Coffey, 2009; Coffey et al., 2011).

In general, practices of instruction and curriculum development begin from attention to the established body of knowledge. Designing a lesson means identifying some aspect of that body of knowledge that one expects students are ready to learn and then organizing the experiences and instruction in ways that guide students to the target understanding. That is, the target for the lesson is selected in advance, and reaching that target defines the success of the lesson.

A responsive approach, in contrast, is to adapt and discover instructional objectives responsively to student thinking. The first part of a lesson elicits students' generative engagement around some provocative task or situation (or, perhaps, by discovering its spontaneous emergence). From there, the teacher's role is to support that engagement and attend to it — watch and listen to the students' thinking, form a sense of what they are doing, and in this way identify productive beginnings of scientific thinking. In this way, the teacher may select and pursue a more specific target, in a way that recognizes and builds on what students have begun.

In this way, responsive teaching coordinates the two sorts of objectives. The teacher works first to engage students in the pursuit, and then to support them in their pursuit in ways that afford progress toward canonical practices and ideas. In the end, a responsive approach can "cover" a similar set of topics as in a more traditional one, but the route emerges responsively and may be idiosyncratic (Hammer, 1997).

Again, this approach presumes - in fact it builds from - a view that children are richly endowed with resources for understanding and learning about the physical world: Engage children in a generative activity, and there will be productive beginnings to discover and support. This view, of course, is extensively supported in the literature (e.g. Sodian et al., 1991; Koslowski, 1996; Tytler & Peterso, 2004; Metz, 2011); below we document the productive beginnings of reasoning about energy that emerged in one instance of responsive teaching.

There are numerous examples of responsive teaching in the literature (e.g. Ball, 1993; Roth, 1995; Rosebery et al., 2010), but these are almost exclusively by teachers with unusual expertise, and they tend to occur outside the structure of any particular curriculum. For this reason, it is not clear how responsive teaching can happen at larger scales. We hope to develop responsive curricula that support practices of attending and responding to student thinking; we describe our initial ideas in the final section of this article.

What follows is an extended example, from the classroom of the third author, Sharon, who was working in close interaction with the second author but without any formal curriculum.

At the start of this project Sharon had been teaching for six years, including one previous year in grade three (8-9 year olds). Her school is an elementary school, to grade five (10-11 year olds) located in the inner city. The entire school receives free lunch, 90% of the students are English Language Learners, with a diverse range of primary languages. Although prior to joining our project Sharon had received extensive professional development in mathematics and literacy, as part of the school district's focus on those topics, she had had little professional development in science. Her first experience in our project was a two-week summer workshop in 2009, where she and twelve other project teachers engaged in their own scientific inquiry. They also spent time identifying students' ideas and reasoning from classroom video clips, and discussing possible ways of responding to those ideas.

A few weeks after the workshop, she began piloting a responsive teaching unit for the project, and we videotaped all the science lessons during that time. Sharon was not working from a curriculum, aside from the launching question we describe below; we are using results from her class and two others as material for our development of a prototype. Here we focus mainly on her work as an example of responsive teaching.

THE BEGINNINGS OF ENERGY

We begin with a brief, coarse-grained overview of the children's thinking, with examples of how Sharon responded in day-to-day decisions. We then turn to several transcribed snippets from the final day of activity. These show evidence of productive beginnings in the children's thinking, including evidence and beginnings that may not be obvious. They also show the teacher's attention and responsiveness at a moment-to-moment time-scale during class. Our account here builds on Radoff et al. (2010).

The launching question

Sharon began with what we call a launching question: She showed students a toy car and asked them to think of different things that could happen to get it moving. We chose this question for two reasons. First, we anticipated that it would introduce a rich phenomenology from students' experience relevant to the topic of energy. Second, we expected it would be richly generative of mechanistic reasoning. In all our implementations that has proven to be the case. Students reliably think of a rich variety of mechanisms, from pushing, throwing and kicking the car, to rolling it down a hill, to flinging it with a rubber band, connecting it to an electric motor, and so on and on.

By a launching question, we mean something different from a driving question, one that curriculum developers select to organize a unit as a whole. We choose an initial activity to be generative of many productive possibilities, expecting the class will find some aspects to pursue; we are trying to incite students' intellectual agency. In some classes, for example, students have come up with controversial suggestions, such as hitting the car with a bright light or laser, or playing loud sounds. In some classes, the students have found their own way to disagreements over whether one method would be as effective as another - is it better to use a rubber band or an incline to make the car go faster or farther, for example. In one class, students thought of a particular kind of toy car: If you pull it backward, it then propels itself forward. They then entered a discussion to explore what might be going on inside the car that would make that happen.

A coarse-grained overview

As happened in all of our pilot trials, Sharon's students had many ideas in response to the launching question, including the very typical one to push it with your hand as well as the less typical one to push it with your tongue. Other ideas included rolling the car down a ramp, pulling it with a string, and blowing it with a fan. Sharon decided to have the class break into groups, with each group developing and representing a method on white boards, and the next day she had students take turns presenting their work.

In one example of a responsive move, seeing a variety of ideas that were listed independently but seemed quite similar, Sharon asked the students to categorize the possibilities. They came up with three categories, including

- wind and blowing (wind, air, fan, blowing with mouth);
- pushing (with hand, with train, pushing car down ramp, using rubber band, firecracker);
- going down (dropping car, letting it slide down hill).

It was not until the fourth day that Sharon provided them with simple cars and let the students explore some of the possibilities they had been discussing (Some of their ideas, e.g. rocket boosters, were not options!). From what she saw in their explorations, and selecting one from each of their categories, Sharon organized the students on day five to explore three ways of getting the car moving: ramps, blowing on the car, and rubber bands.

Some students exploring ramps experimented to find the best angle; a few also tried to make the car go up a second ramp. Other students considered whether blowing on a car, by mouth or with a fan, could make it move if it was heavy, and others compared stretching rubber bands either length-wise or laterally.

The explorations of ramps seemed to Sharon the most generative, so she had the whole class focus there, which they did for several days. A long discussion about whether a steep or shallow ramp would make the car go the fastest led to a whole-class experiment, with three ramps: #1 was steep; #2 was less steep; and #3 was the steepest. The cars that went down ramps #1 and #3 crashed at the bottom and rolled over. The car that went down ramp #2 traveled some distance along the carpet before coming to a stop.

For the next several days, the students generated several sorts of questions that Sharon supported them in exploring: If a car rolls farther along on the floor, does that mean it is faster? Which would be faster, a car rolling down a ramp or a car propelled by a rubber band? Is it more effective to stretch the rubber band length-wise or laterally? Sharon ended day 13 by having the children write in their journals around these various questions. As we recount below, one child wrote about "energy," and Sharon used his thinking as the starting point for conversation on day 14.

Our account to this point illustrates the students' thinking and Sharon's responsiveness at a coarse grain-size. She recognized opportunities in their ideas, and she responded by guiding students to pursue them. Seeing a rich variety at the outset, some similar to others, she thought to have students compare and sort them; she used the categories they generated to organize the next phase of their work. Seeing possibilities in their discussions and arguments about ramps, Sharon focused the class's attention there for a while, and so on to this final choice, taking advantage of a student's way of thinking about and using the term energy to introduce it to the class. Throughout, she made decisions informed by what she saw and heard in the students' thinking as well as by her understanding of the disciplinary targets - both practices and the established concept of energy.

Responsiveness also occurs at the finer-grained size of moment to moment interactions, and we turn to that level now. The excerpts that follow are from day 14, and they serve two roles in our presentation. First, they are evidence of students' productive resources for understanding energy. Second, they illustrate how that evidence appears in vivo, not only for us in analyzing video but also for Sharon in the moment, as well as how Sharon responded. We as researchers, of course, have the much easier job: We can have the video transcribed, pause it and replay it, confer with each other. Sharon as the teacher needs to hear and respond in real-time. This has implications for teacher education and for curriculum design, as we discuss in the final section of this article.

Snippets from day 14

Mike had written that a car launched by a rubber band stretched sideways would cause the car to move farther than one launched by a rubber band stretched backwards, and he claimed this was because the former rubber band "had more energy". But in his conversation with Sharon, he was not sure about that claim, and in particular what he meant by that word. Sharon chose to ask the class to talk about this as the opening question for day 14, the final day of work in the responsive teaching pilot study (Later the class would be moving on to the FOSS Matter and Energy unit -Lawrence Hall of Science, 2007-, required in the district).

We only have space for a small portion of what took place. This first excerpt came at the beginning of the period, which Sharon opened by reading what Mike had written in his journal. We use […] to indicate that we have omitted transcript for brevity, and brackets for descriptive comments. The line numbers in the first column are included for easy reference to specific statements. All students' names are pseudonyms.

<u>"A rubber band is just like a steep hill"</u>

1	Sharon	Mike thought this one [the rubber band stretched sideways] would push the car farther and then he said this: "This rubber band has more energy?" Energy. I even, he kinda put a question mark there because he wasn't exactly sure what he meant by that, but he knew he wanted to say that about this rubber band, that it has more energy. So I want to talk more about that and maybe try to answer Kevin's question, so that he doesn't have to have a question mark there anymore. So what do you think that can mean that, that rubber band has more energy? Or why would this rubber band push the car farther? What do we think about that? Jeffrey?
2	Jeffrey	The rubber band is just like a steep hill.
3	Sharon	What do you mean?
4	Jeffrey	By where the car heads down the ramp but it's getting pushed by a rubber band — instead of going down a hill.
5	Sharon	(*Draws a steep ramp on the board at the front of the room*). So a ramp like this and a rubber band like this are similar? And did you say why you think they're similar?
6	Jeffrey	Because they have the same energy.
7	Sharon	They have the, these have, these two have the same energy? What do you mean by that?
8	Jeffrey	They go the same speed.

It is not difficult to recognize nascent understanding of energy in Jeffrey's reasoning. First, he abstracted across a rubber band and a steep hill, recognizing them as similar in a way he described as having "the same energy." Second, he associated energy with speed: the rubber band and a steep hill have the same energy, he seemed to be thinking, because they can both make a toy car go "the same speed". We do not claim that Jeffrey is "almost there"; we suggest only that his reasoning here involves productive conceptual and epistemological resources: In this moment he is thinking of energy as something that can take different forms, and his reasoning about those forms is connected to his sense of mechanism in how a rubber band or a steep hill can make a toy car start moving.

We also note Sharon's responsiveness at this level—here as often she was asking the child "what do you mean" and eliciting more explanation. Her attention was on the meaning Jeffrey was trying to convey, and, in fact, what she heard informed her next moves: She asked the rest of the class whether they thought energy and speed go together. That led to an extended discussion, about cars racing and people racing, and about energy in "fuel" and "gas" as well as water (since a person drinking water can run faster than a person who doesn't).

Is the energy in an energy drink the same?

Not all of the potentially productive aspects of student reasoning are so readily apparent. We pick up a portion of the conversation that began with Stephanie asking about "energy drinks".

9	Stephanie	In the energy drink, is the energy, is (*it*) the same as energy?
10	Sharon	That's a good question, you know the energy drink? Is the energy drink the same as energy?…….
11	Tom	No, it's different. That one's for drinking (*energy drink*) but this one (*fuel in car*) is for racing.….
12	Sharon	Stephanie, what happens when you drink an energy drink?
13	Stephanie	You get hyper.
14	Sharon	You get hyper. What do you mean by hyper? I don't drink energy drinks, so I don't know.
15	Stephanie	Hyper is like when you start jumping up and down a lot.….
16	Sharon	So before we said that energy is the same as gas, right? And we said it's the same as fuel?.… So we've described energy in so many different ways: that there's energy in a ramp, energy in a rubber band, you can drink energy. I want you to think about that for a second. And Stephanie wants to know if this kind of energy (*gas in a car*) is the same kind of energy that's in an energy drink.…. Corrin?

17	Corrin	Um, I could tell the answer to Stephanie because I know that it's not, it's not right because, can I tell Stephanie? (*Sharon nods*). I know the answer to your, um, uh question. The, the energy is not the same as the energy to the car because the energy that you're talking about is a drink, but the energy that we're talking about is like gasoline. But the one that you're talking about is a drink but ours in like the car like gasoline or oil.
18	Sharon	So the drink is different than what goes in the car? …..
19	Corrin	Yes. Because if you put the drink, the energy drink um, in the car, your energy will mess up.
20	Stephanie	I think she's right, I think she's right because there's two different energies, one is to drink and one, like, to make that energy right there, just makes it go fast.
21	Sharon	…Did you say one goes in the car and one makes you go fast?
22	Stephanie	I meant like, one makes you get hyper, like yeah. And then the other one like just makes something go fast or something.

Tom, Stephanie, and Corrin were coming to a consensus that there are multiple kinds of energy–that the "energy" of an energy drink, which can make you "hyper," is not the same thing as the energy they had been discussing. This line of reasoning is not so clearly on a track toward the canonical idea. Nevertheless, we argue, it shows productive thinking important to that development, both conceptually and epistemologically.

Conceptually, if students are to come to understand the scientific concept of energy, they must be able to distinguish it from other ideas, including other ideas connected to the same word. Everyday uses of energy do not always align with scientific uses, and it is important to find that out. At another level, closely related, students need to learn that questions like this are appropriate in science, that they should be looking for such connections and distinctions among different kinds of meaning.

Here, Stephanie, Tom, and Corrin agreed there must be different kinds of energies, giving the simple, clear reason that you can't put an energy drink in a car, and for the somewhat more difficult to articulate reason that they do different things: One "makes you hyper" and the other "makes something go fast," as Stephanie put it (22).

So it was a good question and, to be sure, quite a challenging one. Earlier, the ideas in play were about mechanisms—the car is pushed by the rubber band or rolls down the hill. Discussing gasoline, the students were familiar with the phenomenon at one level: If an automobile has no gasoline, it cannot start moving, and that is consistent with a sense of energy as a kind of stored ability to make something move. It works for the rubber band (when the rubber band is no longer stretched, it can't make the car move) and for the car on the hill (if it is at the bottom of the hill, the hill can't make it move). But energy drinks are different. Drinking an energy drink makes you "hyper" - it changes your behavior - which is not the same as the ability to move the way gasoline does for a automobile or a stretched rubber band does for a toy car.

Sharon responded in several ways, including validating the question as well as supporting their reasoning and summarizing what they had done. She considered it a rich area for further thought and, with the class having been in conversation for about an hour, she asked the students to work individually and write in their science journals what they think energy is, and whether all the kinds of energy they had discussed were the same or different.

<u>"It has more time to gather up energy"</u>

While other students were writing in their journals, Zachary came up to talk with Sharon, who was holding a large, thick rubber band. They talked about the energy in the rubber band. For the first part of their conversation, Sharon asked Zachary about his sense of how the rubber band gets energy- he said, "you just pull it back"-which she had him demonstrate. She checked with him that you could pull the rubber band length-wise or laterally, to give it energy. In this way, through a short series of questions Sharon guided Zachary to establish that the energy is in the stretched rubber band, that the energy would make the toy car move, and that he could give the rubber band more: "You have to go like farther" in pulling it back. This was another instance of student reasoning aligning nicely with the canonical targets.

The next moment is more interesting. Having made that progress in thinking about energy with the rubber band, Sharon then asked Zachary about energy in a ramp. In answering, he referred to the experiment on day 8, when they released cars from the tops of three ramps of different slopes to see which car would end up going fastest (or farthest). In the case of the two steeper ramps, #1 and #3, the cars rolled down fast and crashed at the bottom, tumbling over. Only with the shallowest ramp, #2, did the car make it to the bottom and continue moving along the floor.

23	Sharon	Okay, now how does a ramp get its energy?
24	Zachary	Easy, it needs to be like all the way here, like last time (*He walks over to a table and moves his hand like there was a ramp there*)…… Like last time we did three ramps, number 1, number 2, number 3. Number 2 went the fastest because it was lower, so a ramp, if it's lower, it goes faster.

25	Sharon	So does it have more energy?
26	Zachary	Yes, because it has more time to gather up the energy (*He starts moving excitedly, dancing*).
27	Sharon	So when it's rolling down the ramp, it's gathering up energy? (*She 'dances' a little too*).
28	Zachary	Yes, like a snowball (*Still dancing*).
29	Sharon	Like a snowball! (*smiling*). How it gathers up snow but it's just gathering up more and more and more energy? (*moving her hand in a circle*).
30	Zachary	Yes.

Another student, Natalie, who had been standing nearby, joined the conversation.

31	Sharon	Okay. (*To Natalie*) And Zachary was saying that it's like a snowball. If the ramp is nice and low, it picks up a lot of energy as it goes?
32	Natalie	Sort of, if you make it a little bit higher.
33	Sharon	Oh so you think it gets more energy if it's higher?
34	Natalie	Yeah.
35	Sharon	(*To Zachary, who just said that the car goes fastest down the shallowest ramp*) So you guys disagree.
36	Zachary	I don't disagree
37	Sharon	No, you do disagree with her (*She reminds him that he said there is more energy if the ramp is lower, and Natalie said there's more if it is higher*).
38	Zachary	Yes, I do, but if it's too steep, it will just crash into the bottom, but if it's low, like ramps number 1, number 2, number 3, it will...it will go down faster.

Zachary's answer that the lower ramp has more energy is not so clearly aligned with the canon-or, for that matter, with common sense- so it may be less obvious that, as we argue now, there is evidence of productive resources for learning in his reasoning.

For one, he was drawing on his experience from two weeks earlier, when they had found that a shallower ramp was more effective at making a car roll across the floor.

More impressive, though, and evidently exciting to him, was the idea that as the car rolls down the ramp it "has more time to gather up energy" like, he elaborated, a snowball gathering up snow.

Consider how he was thinking about energy here, rather than focus on the conclusion he reaches. First, he was thinking of energy as a kind of stuff that can be gathered, a kind of thinking that can support understanding energy as a conserved quantity. Second, he was doing that by an analogical connection between the difficult to visualize notion of energy, which he was beginning to form, and his tangible sense of snow. Finally, with that analogy he was thinking of energy-gathering as a process happening over time. Thinking of energy this way, and thinking it is appropriate to approach questions in science this way, are productive conceptual and epistemological resources. There is also evidence of how Zachary was excited by his idea of energy gathering in time. Here, too, is something productive and important, a student taking obvious pleasure in thinking creatively.

In all, there was a great deal of value in Zachary's reasoning, and we see evidence of how Sharon recognized that and responded. Rather than dismiss or reject his first answer, she gave him space to explain it. When she understood his thinking, "it has more time to gather up the energy", she made her appreciation clear, mirroring his excitement and pleasure in the idea. When Natalie expressed her different (and more correct) sense that the steeper ramp would give the car more energy, Sharon took the opportunity to initiate a conversation between her and Zachary. In pointing out their disagreement-insistently to Zachary-she guided them toward a kind of conversation that happens in science, while at the same time arranging for Natalie to challenge Zachary's problematic answer.

Supporting students' progress in understanding energy

The account from Sharon's class illustrates productive beginnings of science in children's thinking, here specifically around the concept of energy, as well as how a teacher can attend, respond and help build from those beginnings. In this section, we review that account, discuss more generally how instruction can work from and with student reasoning to support progress, and finally, present some initial ideas for the design of responsive curriculum.

A resource-based view of knowledge and reasoning

Before we proceed, it is important to be clear about what we do and do not claim based on this data. We certainly do not claim that the students already understand energy, or even that they already understand aspects of energy. Rather, we are claiming that their reasoning shows many productive resources, raw material for constructing an understanding. A central feature of this perspective is that resources activate variously depending on context (Hammer, 2004).

For example, Jeffrey's thinking of a rubber band as like a steep hill in this moment in this conversation shows resources for abstracting across different ways of making the car move, but we do not have evidence or expect that he would think this way consistently, at other moments in other conversations. Stephanie's sense of what "energy" means looking at the label of her drink would be different from her sense of what it means thinking about "saving energy" by turning off lights. And it is quite unlikely that Zachary would be thinking a shallower slope makes something roll faster if he were skateboarding on a hill.

It is clear, too, that the children are capable of participating in a variety of kinds of conversations. While we do not see it here, it is safe to assume that in other contexts they could talk about the energy beams that come out of Iron Man's hands; we do have evidence of how they can think about personal energetics as a feature of behavior as well as think about tangible physical mechanisms for making a car move.

What we see are possibilities in their reasoning, and the initial challenges for instruction are to tap into, to recognize, and support productive possibilities. The heart of our interest in responsive teaching is that it facilitates doing so with respect to both conceptual and epistemological aspects of children's thinking-a teacher can cultivate the kind of conversation that takes place in science as well as, within that conversation, recognize conceptual beginnings.

Emergent beginnings

A conventional approach to teaching energy is to identify features of the concept and then design experiences targeting those features. These include that energy comes in a variety of forms, that it can be transformed from one form to another, that it can be transferred from one place or object to another, and that it is a conserved quantity. To these we add understanding that this use of the term is different from other uses, e.g., when it is used to describe someone's behavior, a feeling, a work of art, etc. That is, understanding the concept is deeply connected to understanding the epistemic activity it supports.

A sophisticated understanding of energy takes time (Liu & McKeough, 2005). Yet, in the conversation that took place on day 14 in Sharon's third grade classroom we can see evidence of productive beginnings in all of these respects.

There is ample evidence of students' associating energy with speed, with location (a toy car on a ramp), the stretch of a rubber band, and in gasoline. There was ample evidence, too, of the students' sense that energy could transform from one form to another, so that a stretched rubber band can cause a car to move; a car moving down a ramp gains speed or energy; how the fuel (gas) in a car is used to make the car move.

The students at least tacitly distinguished between energy associated with motion (speed) and energy that has the potential (or ability) to cause motion (rubber bands, ramps or hills, fuel). This distinction could later lead into a more generalized understanding of kinetic energy and various forms of potential energy.

A number of the students' ideas were evidence of students' sense of energy being transferred from one object to another: A rubber band or a student can give energy to the car by pushing on it; a student can give energy to a rubber band by stretching it. In this way, much of the students' reasoning reflected some sense of it as conserved - it starts somewhere, it ends somewhere. Much reflected a sense of it as existing in different amounts: You can give a rubber band more energy by stretching it more; a car can have more energy if it is moving faster (or, they debated, traveling farther); an automobile with more fuel ("gas") has more energy and can travel farther.

In this we are not identifying stable, established understandings; we are identifying resources that could contribute to their construction. Along with evidence of productive resources, there was also evidence of their varied activation in different particular moments. While there was evidence of resources for thinking of energy as held somewhere and transferred somewhere else, such as from the stretched rubber band to the toy car, there was not evidence of such thinking for the car on the hill - where was the energy located there? Several students argued that the energy in an energy drink is different from the energy in gasoline, because you cannot put the drink in an automobile fuel tank, but nobody applied that kind of thinking to stretched rubber bands (you cannot put stretched rubber bands in a fuel tank either!).

Some of what we argue is evidence of productive resources was in the students' identification of possible inconsistencies. Is "energy" in a drink the same as "energy" in gasoline? One makes you "hyper," which is a kind of movement in one sense, but not quite the same kind of movement as an automobile going fast. Does a car get more energy from a steeper ramp or from a shallower ramp? Does more energy mean something moves faster or farther, or could it be either? Students' recognized and raised these questions, evidence of the beginnings of argumentation in science, of when and how to seek coherence among ideas.

Sharon's instruction, we argue, was effective at tapping into students' productive resources and supporting them, in large ways in how she ran the class and in small ways in asking particular questions. Naturally, we hope to help students build and refine their thinking still further, to help them make progress toward canonical understandings.

Some of that progress should be in stabilizing these beginnings: Students have resources for thinking about energy as conserved stuff; how do we help them apply those resources reliably and systematically? Students have resources for engaging in the pursuit of coherence among ideas, for identifying and trying to reconcile inconsistencies, drawing inferences, using evidence and logic to support their claims; how do we help them become more stable in that pursuit? Some of that progress, too, should be in refining and revising and developing from those beginnings.

Designing responsive curriculum

The pilot study illustrates a basic structure of interaction with students we are working to develop into a new model of responsive curriculum, curriculum that supports teacher attention and responsiveness to student reasoning and participation. What Sharon was doing, we argue, supported student learning, both conceptually and epistemologically.

First and foremost, she was guiding students toward the kind of conversation that is science, engaging them in the pursuit-in their pursuit-of coherent, mechanistic understandings of the natural world. She opened with a launching question, which, it is evident, successfully tapped into rich pools of their knowledge and experience of causes and effects; students had a great many ideas about how to get a toy car moving. What followed reflected the substance of the students' thinking - Sharon drew on their questions and ideas to guide what came next. In that she was selective, taking up aspects of their thinking that were more generative of the scientific conversation she was promoting.

In any class, the teacher's moves signal to students what is important and relevant, and because she could be responsive Sharon could signal to students that their thinking was important. Thus she focused on understanding their reasoning, asking them to reiterate, explain, and elaborate their points to her made in private conversations, as well as to other students. She could also signal to them what kinds of thinking they should be doing, in particular by showing more interest in their reasoning about causes and effects and the consistency among different ideas: What does steepness do to a car? Are energy and speed the same thing? Is the energy of an energy drink the same kind of thing as in gasoline?

At various moments Sharon summarized the class's ideas, posed questions in response to them, and asked students to write down their answers and ideas in their science journals. On the final day, after students had discussed many kinds of energy, Sharon wanted them to think about what energy is, and how it relates to all the different situations they had discussed (ramps, rubber bands, fuel, people running, energy drinks), and whether these were all the same kinds of energy or different kinds. This, in part, is epistemological: Sharon wanted them to think more about what this thing called energy is. She then walked around the class and discussed the writings with as many of the students as possible.

Ultimately, we hope to design curriculum materials that support teachers in such responsive teaching. We are drawing on pilot work in Sharon's class and others' to help us anticipate and recognize different possibilities in student thinking, what might come up and where things might go, from the initial launching question. This has helped us formulate generative launching questions, and from there it helps us design menus of possible follow-up activities. Starting from the toy-car question, a teacher could recognize opportunities for:

- categorizing ideas, as Sharon did here, sorting the many possibilities children generate into similar categories;
- exploring particular mechanisms, such as here in the ramp and rubber band, but in other classes it could be of a propeller, a balloon, or a solar car;
- argumentation, such as here in response to various disagreements that arose;
- experimentation, again when students disagree over some claim that they could test in class;
- the design of representations when students have difficulty understanding each others' ideas and drawing could help;
- student writing, in response to students' having too many ideas to remember, or needing to focus on articulating a particular idea precisely.

These are all possibilities that may emerge immediately from the first discussion about the toy car. Designing the curriculum, we provide examples of what has taken place - including video from Sharon's and other pilot teachers' classes - to support practices of attention to student thinking. We then provide menus of possible activities to help teachers choose and plan what could come next based on what they see and hear in their students thinking.

Later in students' inquiries, we expect, other possibilities will come to the fore, including quantitative experimentation (e.g. if the ramp is twice as long, will the car go twice as fast?) and abstract consideration of "the ability to make the car move" (e.g. to compare a stretched rubber band to a battery to an inflated balloon). There are many different possibilities that could be productive for students' learning both about energy and about kinds of epistemic activities in scientific inquiry.

In teaching with a responsive curriculum, the teacher would make decisions about what to do next in the classroom based on interpreting students' ideas and reasoning. Rather than having a pre-determined agenda for a sequence of activities or a specific set of content learning goals that need to be met, the learning goals in a responsive curriculum can emerge in the context of student discussions. This approach puts new kinds of demands on both the teacher and the students. The teacher needs to listen carefully to the substance of students' ideas, assess the merits of those ideas, and make next-move decisions accordingly. Students need to take on more responsibility for sharing their ideas and critiquing ideas of others.

Rather than have specific learning goals lesson-by-lesson, the teacher could have a set of goals for the unit. Progress comes when the teacher recognizes opportunities in the students' thinking. Correspondingly, rather than a predetermined sequence of activities, the curriculum would be organized around a "menu of possibilities," from which the teacher could choose depending on what has been taking place. In this way, curriculum becomes more of a map of the conceptual terrain, with a variety of possible routes and approaches to navigating that terrain (c.f. Sherin, Azevedo & diSessa, 2005). Teachers become responsive guides for student exploration — and as guides the challenge is to ensure that, by whatever routes the class explores, the students eventually make their way to key landmarks. The development of curriculum is the development of that map.

Conclusion

In this article we have argued that responsive teaching allows teachers to coordinate objectives of student scientific inquiry and progress toward established knowledge. By building on productive conceptual and epistemological resources that they hear in their students' ideas and reasoning, teachers can both empower students to engage in practices of science and help them move forward in their development of understanding the scientific canon. We have illustrated this process by looking at what happened in a third grade classroom where the teacher, Sharon, was teaching responsively. On the last day of a responsive module that Sharon was piloting, she saw the opportunity, generated by a student comment, to engage her students in a substantive conversation about energy. During the conversation students talked about multiple forms of energy, compared them with each other and with everyday meanings of the term, clarified their own thinking and helped clarify the thinking of others, invented analogies to support their thinking, related their ideas to results of prior experiments and debated different interpretations of those results. We argued that when the students were engaging in these kinds of conversations, they were engaging in nascent forms of the practices of science. We also argued that the ideas that emerged from these conversations could serve as productive beginnings toward a deeper understanding of energy: that it can appear in many forms, including its association with motion and the 'ability to cause motion,' that it can be transformed from one form to another, that it can be transferred, and that it can be quantified.

Both the moment-by-moment and day-to-day decisions the teacher makes in a responsive classroom are determined by what she hears and how she interprets the ideas and reasoning of her students. This presents a big challenge for designing a responsive curriculum, since there cannot be any predetermined sequence of activities, either within a science period or between successive periods. In this article we discussed our initial thoughts about designing a responsive curriculum, that it should both provide guidance in attending to students ideas and reasoning in making moment to moment decisions and provide a "menu of possibilities" (annotated with teacher comments) that could be used by the teacher depending on what happens in class on a given day. We are currently working on developing a prototype of a responsive curriculum on energy informed by the pilot work of Sharon and other teachers[2].

REFERENCES

Ball, D. L. (1993). With an eye on the mathematical horizon: dilemmas of teaching elementary school Mathematics. *Elementary School Journal*, 93(4), 373-397.

Coffey, J. E., Hammer, D., Levin, D. M. & Grant, T. (2011). The missing disciplinary substance of formative assessment. *Journal of Research in Science Teaching*, 48(10), 1109-1136.

Driver, R., Squires, A., Rushworth, P. & Wood-Robinson, V. (1994). *Making sense of secondary science: research into children's ideas* (London: Routledge).

Duit, R. (1981). Students' notions about the energy concept - before and after instruction. *Paper presented at conference, Problems concerning students' representation of physics and chemistry knowledge*, Ludwigsburg, W. Germany, 14-16 September.

Duit, R. (1984). Learning the energy concept in school-empirical results from the Philippines and West Germany. *Physics Education*, 19, 59-66.

Einstein, A. (1936). Physics and reality. *Journal of the Franklin Institute*, 221(3), 349-382.

Goldring, H., & Osborne, J. (1994). Students' difficulties with Energy and related concepts. *Physics Education*, 29, 26-32.

Hammer, D. (1997). Discovery learning and discovery teaching. *Cognition and Instruction*, 15(4), 485-529.

Hammer, D. (2004). The variability of student reasoning, lectures 1-3. In E. Redish & M. Vicentini (eds) *Proceedings of the Enrico Fermi Summer School, Course CLVI* (Bologna, Italy: Italian Physical Society), 279-340.

Hammer, D., Elby, A., Scherr, R. E. & Redish, E. F. (2005). Resources, framing, and transfer. In J. Mestre (ed.) *Transfer of learning from a modern multidisciplinary perspective* (Greenwich, CT: Information Age Publishing), 89-119.

Hammer, D., Russ, R., Scherr, R. E. & Mikeska, J. (2008). Identifying inquiry and conceptualizing students' abilities. In R. A. Duschl & R. E. Grandy (eds) *Teaching scientific inquiry: recommendations for research and application* (Rotterdam, NL: Sense Publishers), 138-156.

Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education*, 72(1), 19-40.

Hodson, D. (1993). Philosophic stance of secondary-school science teachers, curriculum experiences, and children's understanding of science - some preliminary findings. *Interchange*, 24(1-2), 41-52.

2 Contact the second author (FG) for links to our project's web based resources for responsive teaching in science and the toy car responsive curriculum. The toy car responsive curriculum site includes the video clips from Sharon's classroom that are discussed in this paper.

Holton, G. J. & Brush, S. G. (2001). *Physics, the human adventure: from Copernicus to Einstein and beyond* (New Brunswick, N.J.: Rutgers University Press).

Jiménez-Aleixandre, M. P., Rodríguez, A. B. & Duschl, R. A. (2000). "Doing the lesson" or "doing science": argument in high school genetics. *Science Education*, 84(6), 757-792.

Koliopoulos, D., Christidou, I., Symidala, I. & Koutsiouba, M. (2009). Pre-energy reasoning in preschool children. *Review of Science, Mathematics and ICT Education*, 3(1), 123-140.

Koliopoulos, D. & Argyropoulou, M. (2011). Constructing qualitative Energy concepts in a formal educational context with 6-7 year old students. *Review of Science, Mathematics and ICT Education*, 5(1), 63-80.

Koslowski, B. (1996). *Theory and evidence: the development of scientific reasoning* (Cambridge, MA: MIT Press).

Lawrence Hall of Science (2007). *Matter and Energy. Full option Science system* (Nashua, NH: Delta Education).

Lemke, J. L. (1990). *Talking Science: language, learning & values* (Norwood NJ: Ablex).

Levin, D. M., Hammer, D. & Coffey, J. E. (2009). Novice teachers' attention to student thinking. *Journal of Teacher Education*, 60(2), 142-154.

Liu, X. & McKeough, A. (2005). Developmental growth in students' concept of Energy: analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching*, 42(5), 493-517.

Metz, K. E. (2011). Disentangling robust developmental constraints from the instructionally mutable: young children's epistemic reasoning about a study of their own design. *Journal of the Learning Sciences*, 20(1), 50-110.

Millar, R. (2005). *Teaching about Energy*, Research Paper 2005/11 (York: University of York, Department of Educational Studies). Retrieved July 27, 2011 from http://www.testsite.lancsngfl.ac.uk/nationalstrategy/ks3/science/files/TeachingAboutEnergy(RobinMillar).pdf.

Nordine, J., Krajcik, J. & Fortus, D. (2011). Transforming Energy instruction in middle school to support integrated understanding and future learning. *Science Education*, 95(4), 670-699.

O'Neill, D. K. & Polman, J. L. (2004). Why educate "little scientists?". Examining the potential of practice-based scientific literacy. *Journal of Research in Science Teaching,* 41(3), 234-266.

Papadouris, N., Constantinou,C. & Kyratsi, T. (2008). Students' use of the Energy model to account for changes in physical systems. *Journal of Research in Science Teaching*, 45(4), 444-469.

Radoff, J., Goldberg, F., Hammer, D. & Fargason, S. (2010). The beginnings of Energy in third graders' reasoning. In C. Singh, M. Sabella & S. Rebello (eds) *2010 Physics Education Research Conference*, Vol. 1289 (Portland OR: American Institute of Physics), 269-272.

Redish, E. F. (2004). A theoretical framework for Physics Education research: modeling student thinking. In E. Redish & M. Vincenini (ed.) *Proceedings of the Enrico Fermi Summer School, Course CLVI* (Bologna, Italy: Italian Physical Society), 1-63.

Rosebery, A. S., Ogonowski, M., DiSchino, M. & Warren, B. (2010). "The coat traps all your body heat": heterogeneity as fundamental to learning. *Journal of the Learning Sciences*, 19(3), 322-357.

Roth, W.-M. (1995). Inventors, copycats, and everyone else - The emergence of shared resources and practices as defining aspects of classroom communities. *Science Education*, 79(5), 475-502.

Sherin, B., Azevedo, F. S. & diSessa, A. (2005). Exploration zones: a framework for describing the emergent structure of learning activities. In R. Nemirovsky, A. S. Rosebery, B. Warren & J. Solomon (eds) *Everyday matters in Science and Mathematics: studies of complex classroom events* (Mahwah, NJ: Lawrence Erlbaum), 329-366.

Sodian, B., Zaitchik, D. & Carey, S. (1991). Young children's differentiation of hypothetical beliefs from evidence. *Child Development*, 62(4), 753-766.

Solomon, J. (1983a). Learning about Energy: how pupils think in two domains. *European Journal of Science Education*, 5, 49–59.

Solomon, J. (1983b). Messy, contradictory, and obstinately persistent: a study of children's out-of-school ideas about Energy. *School Science Review*, 65, 225–232.

Trumper, R. (1993). Children's Energy concepts: a cross-age study. *International Journal of Science Education*, 15(2), 139-148.

Tytler, R. & Peterson, S. (2004). From "try it and see" to strategic exploration: characterizing young children's scientific reasoning. *Journal of Research in Science Teaching*, 41(1), 94-118.

Watts, M. (1983). Some alternative views of Energy. *Physics Education*, 18, 213-216.

Windschitl, M. (2004). Folk theories of "inquiry": how preservice teachers reproduce the discourse and practices of an atheoretical scientific method. *Journal of Research in Science Teaching*, 41(5), 481-512.

ACKNOWLEDGEMENTS

We thank all of our collaborators - teachers, project staff and students - for many conversations and insights. We are also grateful for support by the US National Science Foundation under Grant No. 0732233. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Foundation.