

# Cycles of Research and Application in Education: Learning Pathways for Energy Concepts

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**ABSTRACT**—We begin this article by situating a methodology called *developmental maieutics* in the emerging field of mind, brain, and education. Then, we describe aspects of a project in which we collaborated with a group of physical science teachers to design developmentally informed activities and assessments for a unit on energy. Pen-and-paper assessments, called *teasers*, were employed, along with interviews, to study how students learned about the physics of energy. Results were used to describe students' learning pathways and to design a scoring rubric for teacher use. We hypothesized that (a) teasers, by themselves, could be used effectively to evaluate the developmental level of students' reasoning about energy and (b) teachers could employ the scoring rubric with minimal instruction. Encouraged by our findings, we went on to create a freely available online version of the *energy teaser*, including a new rubric designed to improve the accuracy with which teachers can assess the developmental level of students' energy conceptions.

## CYCLES OF RESEARCH AND APPLICATION IN SCIENCE EDUCATION

*Developmental maieutics* is a collaborative methodology that informs curricula, assessment, and evaluation through cycles of research and application. In this article, we describe an application of this methodology that involved partnering with a group of Grade 9 physical science teachers to study

and improve learning in their classrooms. The project was part of a larger initiative called the Collaboration for Excellence in Science Education (CESE; Dawson, Wenk, & Paulman, 2006). During the early weeks of the project, teachers expressed broad agreement that students were not learning the energy concept as it was represented in the ninth-grade curriculum, so we agreed to work with them to design a developmentally informed energy unit that included embedded (Treagust, Jacobowitz, Gallagher, & Parker, 2003; Wilson & Scalise, 2006) assessments that could be used to examine how students were learning the energy concept. These assessments provided us with the data necessary to construct learning sequences for key energy concepts, that is, descriptions of the pathways through which important energy concepts develop. Finally, we applied what we learned about the development of energy concepts and teachers' needs to design two freely available online energy teasers that make it possible for teachers themselves to assess the developmental level of students' energy conceptions (Dawson, 2008a).

We believe that an understanding of how science concepts are learned should be at the center of cooperative efforts between cognitive scientists and educators. There is already a large literature examining the initial schemata children bring into the classroom in the hope of building bridges between "mis/preconceptions" and "accepted conceptions" or between "novice" and "expert" knowledge states (di Sessa, 1996; Eryilmaz, 2002; Marton, 1986; Prosser & Millar, 1989; Slotta, Chi, & Joram, 1995; Stephanou, 1999). Because an understanding of the concept of energy is central to a number of scientific disciplines, including biology, physics, and chemistry, the energy conceptions of children, adolescents, and adults have been the particular focus of numerous investigations. For a review of this literature, see Liu and McKeough (2005).

In our view, the most promising research on the development of science conceptions not only identifies correct and

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incorrect or novice and expert conceptions but also shows how conceptions develop over time. What we learn about the pathways through which concepts typically develop provides useful knowledge that can directly inform curriculum development.

## BACKGROUND AND CONTEXT: DEVELOPMENTAL MAIEUTICS AND MIND, BRAIN, AND EDUCATION

Fischer and colleagues (Fischer, Immordino-Yang, & Waber, 2007) have suggested that research in mind, brain, and education (MBE) should proceed through the establishment of symbiotic relations between research and practice. The idea that the problems teachers face should affect the questions educational researchers ask is not a new one (Dewey, 1929). Nevertheless, it is a requirement of educational research that is rarely satisfied. Because of the complexity of MBE as an emerging field that subsumes a wide array of methodological approaches, issues of quality control are paramount. Fischer's suggestions concerning a *grounded synthesis* point the field toward certain general standards for determining the worth of research efforts, specifically, those conducive to the problem-focused generation of usable knowledge. Here, we present the outline of one methodology that explicitly aims to tie theory and research to issues (and solutions) in educational practice.

A set of key cognitive developmental themes is implicated in what follows. The broad contours of our methodology address issues regarding the relationship between psychology and pedagogy that date back to the birth of psychology (James, 1899/1992). Interestingly, these issues are also concomitant with birth of the cognitive developmental approach. Early on, Piaget (1932) suggested that the psychology of the laboratory could not simply be imported for use in the classroom. Instead, he suggested that only *experimentally implemented educational initiatives* could generate the kind of psychological knowledge teachers can put to use. Over three decades later, Piaget (1965) expanded on this point, remaining convinced that the findings produced by psychologists are of value to educators only if they can be integrated into some kind of *experimental pedagogy* (p. 20).

As explained below, developmental maieutics is a provisional methodological framework addressing the marriage of research and practice in education. Baldwin (1908) and Piaget and Kamii (1978) were guided by philosophical and psychological interests when they pioneered their genetic epistemologies. They were not educationists. And although they spawned a cognitive developmental approach that has proven itself as a framework for conducting educational research and affecting educational practice (Fischer, in press; Griffin, Case, & Siegler, 1994), it is clear that theoretical models of cognitive development need to prove themselves useful in educa-

tion by being put to the test. However, as of yet, there are no fully explicated frameworks for facilitating the generation of usable knowledge at the interface between cognitive developmental theorizing and educational practice. This is one of the goals of developmental maieutics.

Another key issue in cognitive development that is central to our approach is the idea of *learning pathways*. This notion has a history that can be traced back to Baldwin (1908), who offered a speculative model of cognitive development in which several different modes of thought developed through a sequence of hierarchical stages. For Baldwin, different abilities developed along different pathways. A similar idea was expressed by Werner (1948) who outlined a model in which numerous and heterogeneous psychological processes developed in a nonsynchronic fashion but according to common processes of differentiation and integration. Again the image is of different abilities developing along different pathways. Most would assume that Piaget thought nothing of the sort. But as Chapman (1988) demonstrated, Piaget's views regarding the *structure of the whole* are far from clear, and his books are filled with research tracing the distinct developmental trajectories of very specific concepts, such as *causality* and *justice*.

In any case, it was Fischer and his colleagues (Fischer, in press) who brought this idea to the forefront of cognitive developmental theorizing. Research on a variety of fronts has yielded a dynamic picture of cognitive developmental processes where context sensitivity and variability are key (Rappolt-Schlichtmann, Tenenbaum, Koepke, & Fischer, 2007). The acquisition of skills in any domain involves a set of possible learning pathways along which individuals show differentiated, dynamic, and nonsynchronic development trajectories. It is in this tradition that we understand the construction of the learning sequences that form a fundamental part of the approach we offer.

When the two themes outlined above come together, there emerges an educationally oriented cognitive developmental perspective in which the promotion of optimal learning involves understanding:

- The developmental pathways through which concepts typically and optimally develop
- The particular subconcepts required to construct increasingly adequate understandings at each new developmental level
- The range of subconcepts required for an optimal understanding of a given concept
- Effective methods for developing these concepts
- Accurate and reliable assessments of conceptual development that can be employed by classroom teachers.

In this light, we have designed an iterative methodological approach designed to accomplish all these goals. We call this methodology—represented in the spirals shown

in Figure 1—developmental maieutics. The term maieutics is derived from the Greek word for midwifery or the art of facilitating birth. Socrates used the term to refer to the process of facilitating learning, or giving birth to, concepts. This article demonstrates an application of this methodological framework. We offer a partial account of our attempts to improve science learning by collaborating with teachers and schools to (1) conduct basic research on the developmental pathways through which students learn science concepts, (2) design and disseminate curricula and assessments informed by these findings, and (3) enhance teachers' practice by providing opportunities for them to (a) add to their content knowledge, (b) improve their understanding of students' conceptual development, and (c) learn pedagogical practices that promote conceptual development.

The approach begins with (A) the establishment of a collaborative relationship with teachers, with whom we (B) select science topics/concepts with which they and their students are struggling. We then (C) identify the concepts that are essential for mastery of a given science concept, and based on existing knowledge, design and implement (1) activities intended to promote the development of the concept and (2) developmental assessments that can be used to evaluate students' conceptual understanding. These developmental assessments are administered to learners before and after they engage in the learning activities, so we can (D) trace their development within individual learners and evaluate the effectiveness of the learning activities. The method employed to describe the pathways through which concepts are acquired is represented in the small subspiral on the right of the figure. The maieutics approach to identifying sequences of conceptual development involves submitting interview data

to two forms of qualitative analysis,<sup>1</sup> in which interview texts are independently analyzed for (a) their developmental level and (b) their conceptual content. Then, the results of these analyses are examined together to identify trends in conceptual development. To conduct the developmental analysis, we evaluate the hierarchical structure (discussed further below) and degree of elaboration of reasoning performances. To conduct the content analysis, we examine the specific meanings expressed in the same performances. Using this method, we have described developmental sequences for conceptions of leadership, good education, epistemology, learning, morality, and the self, as well as for critical thinking, decision making, and problem solving (Dawson, 2004; Dawson & Gabrielian, 2003; Dawson & Stein, 2004; Dawson-Tunik, 2004).

Based on our findings, we then (E) refine the learning activities and assessments designed in Steps 2 and 3, mentioned above. At this point, our level of understanding of the development of a chosen concept is such that we can design high-quality assessments for teacher use.<sup>2</sup> When administered online, these assessments also allow us to monitor student performance and teacher coding behavior, providing data for their ongoing evaluation (F) and refinement (G).

### Hierarchical Development

Developmental levels, also referred to here as *complexity levels*, are understood as a series of hierarchical integrations of knowledge structures. Many developmental theories employ the notion of hierarchical complexity. In the Piagetian model, for example, each successive hierarchical integration produces novel understandings by employing the operations of the previous order as conceptual elements in its new constructions.

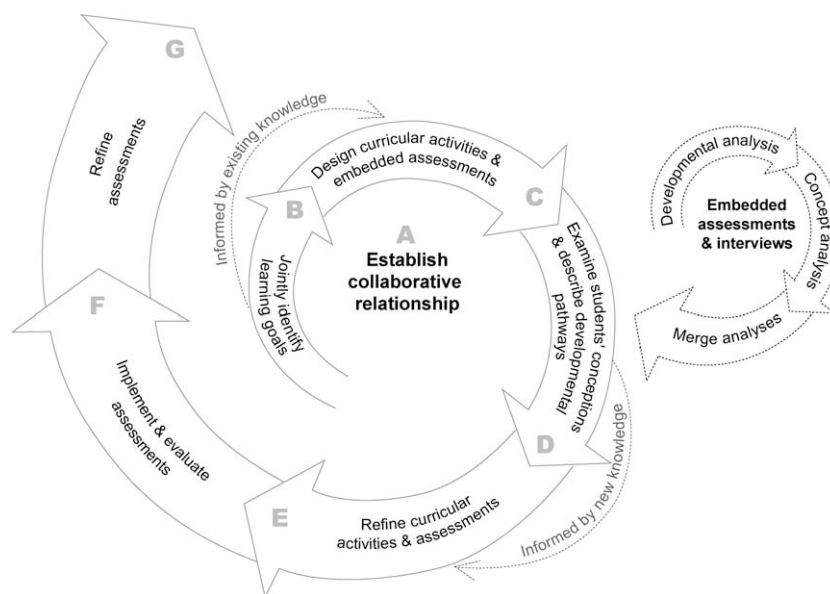


Fig. 1. Cycles of research and application.

This notion is central to several other developmental theories as well, including those of Werner (1948), Case (1985), and Fischer (1980), and underlies a number of developmental scales, such as the levels and tiers of skill theory (Fischer, 1980) and the complexity orders of Commons' General Stage Model (Commons, Trudeau, Stein, Richards, & Krause, 1998).

### The LECTICAL™ Assessment System

The LECTICAL™ Assessment System (LAS; Dawson, 2008b) lays out explicit criteria for determining the complexity level and phase (degree of elaboration within a given level) of verbal performances in any domain of knowledge. Its levels consist of the last 8 of 13 complexity levels (single representations, 6; representational mappings, 7; representational systems, 8; single abstractions, 9; abstract mappings, 10; abstract systems, 11; and single principles, 12), corresponding definitionally to the skill levels of Fischer (1980, in press). Its phases (transitional, 1; unelaborated, 2; elaborated, 3; and highly elaborated, 4) are based on empirical evidence regarding the way learning within levels progresses. This evidence has been derived from a large database of scored interviews and essays (Dawson & Wilson, 2004). Scores are represented in tables and figures as level:phase. For example, elaborated abstract mappings is 10:3.

The scoring procedures employed with the LAS are partially derived from the assessment systems of Commons et al. (1995) and Rose and Fischer (1989). Like its predecessors, this scoring system is designed to make it possible to assess the complexity level of a performance based on its level of differentiation and integration—deep structure—without reference to its *particular* conceptual content. Rather than making the claim that a person occupies a level because he or she has, for example, elaborated a particular conception of justice, the LAS permits us to identify performances of a given complexity level and then to ask (empirically) what the range of justice conceptions is at that complexity level. Thus, it avoids much of the circularity<sup>3</sup> of many stage scoring systems (Brainerd, 1993), such as the Perry (1970) scheme, the Standard Issue Scoring System of Colby and Kohlberg (1987), and the Reflective Judgment Scoring System (King & Kitchener, 1994), which define stages in terms of domain-specific structures like social perspective taking or form of relativism.

We have undertaken several studies of the reliability and validity of the LAS and its predecessors (Dawson-Tunik, 2004). We have examined inter-analyst agreement rates, compared scores obtained with the LAS with those obtained with more conventional scoring systems, and examined scale characteristics with statistical modeling. Inter-analyst agreement rates have been high, 80%–97% within half of a complexity level (Dawson-Tunik, 2004).<sup>4</sup> Correspondences

between the LAS and other developmental scoring systems are also high, consistently revealing agreement rates of 85% or greater within half of a complexity level, although comparisons of the construct validity of the LAS and other systems have shown the LAS to be a more valid measure of cognitive performance (Dawson-Tunik, 2004). Employing Rasch scaling, which provides reliability estimates that are equivalent to Cronbach's alpha, we have consistently calculated reliabilities greater than .95 (Dawson-Tunik, Commons, Wilson, & Fischer, 2005). Overall, our research shows that the LAS is a valid and reliable general measure of intellectual development. Detailed information about the LAS can be found at the LAS Web site (Dawson, 2008b).

### Developmental Maieutics in Action: The Energy Unit

This research was undertaken by the CESE at Hampshire College. We began our work with a group of seven 9th-grade physical science teachers by asking them to tell us about their curricular and instructional needs. A consensus rapidly emerged. All of these teachers were having difficulty teaching the energy concept. Teachers described students' tendencies to confuse energy with motion, to think that potential energy was the potential to have energy, to confuse energy and force, and to demonstrate little understanding of the principle of conservation of energy. These difficulties were common and clearly undermined students' ability to work with the energy concept.

In keeping with the course textbook, the instructional goal of the teachers was to provide students with a scientific conception of energy as a *quantity*, as expressed in the concepts of transformation and transfer and the principle of conservation of energy (*Glencoe Physical Science*, 2004). We employed the LAS to determine the complexity level of the course textbook, primarily finding it to be at the level of elaborated abstract mappings (phase 10:3), with some evidence of unelaborated abstract systems. Abstract mappings commonly emerge at around 11–13 years of age and are elaborated over several years. Previous research has shown that by 14 or 15 years of age, most students demonstrate abstract mappings in at least some domains of knowledge (Dawson-Tunik et al., 2005; Fischer, in press). However, many students in this age-group continue to reason at the level of single abstractions, particularly in science and mathematics (Asghar, 2004; Fischer & Kenny, 1986).

Based on teachers' observations, we developed an introductory activity for the energy unit, called "Energy on the Rebound," a simple activity that required students to make observations about the actions of a bouncing ball and generate hypotheses to explain these observations. The first conceptual goal of the activity was to draw students' attention to the observable changes in the actions of a bouncing ball. Based upon teachers' descriptions of their students'

conceptions, we surmised that all students would be able to describe the observable changes in the bouncing ball system. The second conceptual goal was to help students abstract a generalization about energy from quantitative observations made about the rebound height of the ball following its first bounce. Based upon teachers' and other researchers' descriptions of students' misunderstandings, we thought that most students would attempt to explain the balls' loss of height on the rebound in terms of energy loss (Liu & Collard, 2005). What we did not know was what students would mean by *energy loss* or how to lead students from the notion of *energy loss* to *energy conservation*.

### The Usable Knowledge: Describing Developing Energy Conceptions

To address these concerns, we had to learn more about students' energy conceptions and how they typically develop. To do so, we designed the energy teaser. Teachers administered the teaser in all their classes prior to the beginning of the energy unit and immediately following its completion. A completed teaser is shown in Figure 2. Using the energy teaser as an interview form, we also conducted 96 clinical interviews with volunteers from these classes and 43 interviews with 5- to 13-year-olds attending a local after-school program. All written responses to the teaser—all of which were from the ninth-grade sample—were collected by our research team. All interviews were tape-recorded, transcribed, scored with the LAS, and coded for their conceptual content. We then merged the results of the developmental and concept analyses to describe learning sequences. These procedures are described in detail elsewhere (Dawson, 2006).

It is important to note that these learning sequences are akin to the *rational reconstructions* described by Habermas (1990). With this term, Habermas points to the common core of genetic structuralist renderings of the development of knowledge, such as those offered by Piaget (1971) and Kohlberg (1969), who outline a sequence of ideal types that represent the general developmental logic of the concepts under investigation. Of course, general descriptions of the development of conceptions should not be confused with the actual developmental trajectory of particular individuals, which are undoubtedly highly variable. Learning sequences should be understood as outlining the general structure of the conceptual space through which individuals move in their idiosyncratic ways. In the case of *energy*, for example, one student might quickly develop an understanding of gravity, neglecting or struggling with the concept of kinetic energy, whereas another student might first grasp notions about kinetic energy and use these to scaffold an understanding of gravity. Tracing the course of individual learning trajectories requires longitudinal and microdevelopmental research (Fischer, in press). The rational reconstruction of learning sequences can

be done cross-sectionally because they are inductive generalizations regarding the developmental logic of conceptions within a certain domain. As such, learning sequences make available a variety of useful pedagogical insights, which can ultimately lead to the construction of developmental rubrics that are useful to practitioners.

Table 1 shows some of the results of our analysis of energy conceptions from the interviews. As shown in the table, we analyzed several recurring thematic strands in these interviews, including *kinetic* and *potential energy*, *energy transfer and transformation*, and *forces*, including *gravity*. For each conceptual strand, there is a clear progression in the development of the energy concept (and related concepts). This suggests that the energy concept is constructed through a hierarchical sequence of increasingly adequate conceptions, beginning with observations about the behavior of moving objects in the everyday world.

For example, the conflation of energy and movement at representational systems (Level 8) precedes the differentiation of energy and movement, which begins at single abstractions (Level 9) with the notion that energy is something that causes motion, and continues at abstract mappings (Level 10) with the notion that kinetic and potential energy are alternating energy states.

There is a similar progression in the differentiation of energy and force. From our teachers' point of view, pushing and pulling should be understood as a manifestation of force, whereas the potential or ability to do work (including but not limited to the application of force) should be considered as energy. As noted above, during the transition to single abstractions, the concept of energy begins to emerge as "something" behind movement—something that makes movement possible. We observed a variety of representational systems level conceptions that appear to prepare the way for an abstract conception of energy. In fact, the notion that pushing or pulling (force) facilitates movement often served this purpose. This is unfortunate, not because it is an illogical or a useless preconception but because force must come to occupy its own specific place as a physics concept.

A related confusion involves the use of the word *force* in place of the word *energy*. We suspect this confusion emerges, in part, from the numerous meanings associated with the word *force*. The scientific concept of force is introduced when students are taught Newton's laws. (An object in motion stays in motion until acted upon by an outside force.) The idea of force is also used to describe other intangible entities that have a degree of causal efficacy (force field). To complicate things further, the common dictionary definition of force is the power, strength, or energy possessed by somebody or something.

We found that force and energy were more or less synonymous at representational systems and single abstractions, but for different reasons. At representational systems, the

Student's name (please print)

Student's age

Teacher's name

Date (mm/dd/yy)

## Energy Teaser

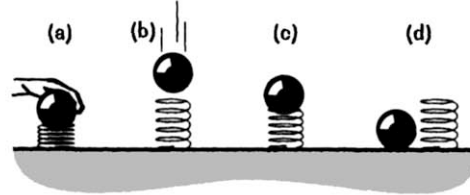
The purpose of this assignment is to find out how much you know about energy. For each of the situations below, first say whether or not you think energy is present. Then, explain your answer.

- (a) A ball is used to press down on a spring.

Is energy present? ☒ Yes ☐ No

Please explain your answer:

Energy is present because the hand is pressing down on the spring. You need energy to keep it down.



- (b) A ball falls toward a spring. Is energy present? ☒ Yes ☐ No Please explain:

Energy is present because the ball has to have energy to go down to the spring. Also, it has energy because the ball will bounce back up.

- (c) A ball sits at rest on a spring. Is energy present? ☐ Yes ☒ No Please explain:

Energy is not present because the ball is not showing energy. It's just sitting there.

- (d) A ball sits at rest next to a spring. Is energy present? ☐ Yes ☒ No Please explain:

Energy is not present because the ball is not in motion. It's just sitting there.

For the two situations below, first say whether you think energy is increasing, decreasing, or staying the same. Then, explain your answer.

- (e) A ball rolls along a horizontal (flat) surface.

Energy is ☐ increasing ☐ decreasing ☒ staying the same

Please explain your answer:

The energy is staying the same because it's a flat surface.



- (f) A ball rolls down a hill.

Energy is ☒ increasing ☐ decreasing ☐ staying the same

Please explain your answer:

The energy increases because the ball can't stop. It's going down a hill.



The ball in the drawing on the right is dropped onto the floor from a height of 100 centimeters. It then bounces to a height of 50 centimeters.

- (g) Explain your theory of what is happening to the energy of the ball as it is falling.

While the ball is falling the energy increases.

- (h) Explain your theory of what happens to the energy of the ball at the moment when it hits the floor.

When it hits the floor, the ball will bounce back.

- (i) Explain your theory of what happens to the energy of the ball after it hits the floor.

It will bounce back to half of the cm.

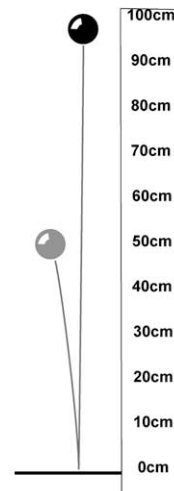


Fig. 2. Sample energy teaser.

**Table 1**  
Scoring Rubric for Energy Conceptions

Level	Energy	Forces/gravity	Energy forms	Energy transfer/ transformation	Related concepts	For example ...
8:1 and 8:2 (8a)	1. Energy is the same thing as motion. Energy can be fast or slow. 2. Energy is something you need for recess, hard work, etc. 3. Energy moves things. 4. Energy is “in” an object	1. Gravity, if mentioned, is something that pushes, pulls, or holds—an invisible hand. 2. Force, if mentioned, involves pushing, holding, or pulling on an object.	1. Energy is in people, moving things.	1. No concept.	1. Bounciness, ball composition, weight.	1. When describing the bouncing of a ball, the student may observe that the ball falls to the ground when it is released, makes a noise when it hits the ground, bounces back up to a lower height (because it is bouncy), and will keep doing this until it stops. Ball composition is often stressed.
8:3 and 8:4 (8b)	1. Energy is something that pushes, pulls, or holds an object. Energy can be strong or weak.	1. May make a connection between energy and force or gravity without being able to explain the connection. 2. The terms gravity and force (when they are employed) are used, as the word energy is to explain observed changes in motion.	1. Energy is in electricity, fuel, etc. The energy makes things work (makes the lights work) or move (makes a car go).	1. Energy in fuel can be used to make things go. 2. Electricity can make things function.	1. Bounciness, ball composition, weight.	1. When describing the bouncing of a ball, the student may observe that the ball speeds up as it falls to the ground (because of gravity or its weight or because everything falls), makes a noise when it hits the ground, bounces back up (because it is squishy, made of rubber, or has bounciness), and will keep doing this until it stops.

9:1 and 9:2 (9a)	<p>1. Energy is clearly viewed as something that is “behind” motion—a cause of motion. This notion is applied inconsistently.</p> <p>Sometimes, energy is still represented as equivalent to motion, especially when describing the energy of stationary objects.</p> <p>1. Forces acting on an object change its energy. For example, the energy of a dropped object increases due to gravity (a force).</p> <p>2. This is different from the representational systems argument that gravity makes an object fall or makes it fall faster.</p> <p>3. Force and energy are often confused. Students may interpret the definition of energy as “the ability to do work,” as “the ability to exert a force.”</p>	<p>1. Particularly in posttests, the terms <i>potential</i> and <i>kinetic</i> energy are likely to appear.</p> <p>2. Potential energy is often conceived as the potential for energy to happen rather than as an actual form of energy.</p>	<p>1. Energy can move (transfer) from one object to another.</p>	<p>1. The terms friction, air resistance, and inertia may appear.</p> <p>2. A student may claim that friction (or air resistance) slows a ball moving along a horizontal surface but does not describe what happens to the energy.</p> <p>3. Students cannot reconcile the effects of inertia and friction.</p>	<p>1. The student makes a clear attempt to describe what is happening to the <i>energy</i> of a bouncing ball, rather than the activity of the ball itself. Energy is no longer equivalent to motion, but the concepts of potential and kinetic energy are not fully grasped. In particular, one gets the sense that the student does not believe that potential energy is really energy.</p> <p>2. Explanations of abstract terms can sound like recitations of textbook definitions.</p>
9:3 and 9:4 (9b)	<p>1. Energy is now rarely spoken of as though it is equivalent to motion. In defining energy, students may emphasize this point by referring to forms or sources of energy in which motion is not observable (electrical).</p> <p>1. Gravity is still largely viewed as a force that increases the energy of an object by increasing its speed.</p> <p>2. Concepts of energy and force are often poorly differentiated.</p>	<p>1. The terms potential and kinetic energy are common in posttests. Potential energy is now treated as a form of energy rather than as a word for the absence of energy.</p> <p>1. Energy can now be transferred to action (like a bounce) and objects.</p> <p>2. Although energy transformations are not yet described, some students begin to talk about energy getting lost to friction or gravity.</p>	<p>1. Students can provide a good description of the physical action of friction but do not yet tie this action to a form of energy (heat energy).</p> <p>2. Friction causes a reduction in energy.</p>	<p>1. Though relations between energy concepts are not yet articulated, there is some understanding that these concepts should be related to one another—that the principle of inertia, for example, influences the energy of a ball as it rolls along a horizontal surface. Attempts to relate these variables are not yet successful. For example, an individual may evoke the concept of inertia inappropriately to explain why a ball loses energy as it moves along a horizontal surface.</p>	

(Continued)

Table 1 (Continued)

Level	Energy	Forces/gravity	Energy forms	Energy transfer/ transformation	Related concepts	For example ...
10:1 and 10:2 (10a)	1. Students may claim that energy occurs in several forms and may explain (rather than simply stating) the idea that energy cannot be created or destroyed. 2. Students may explain that energy is the ability to do work and describe multiple examples of energy doing work.	1. Gravity is now viewed as a force that is involved in explanations of kinetic and potential energy. 2. Force and energy are more differentiated than at single abstraction, though confusion may occasionally persist.	1. Several energy forms, such as heat energy, elastic potential energy, and gravitational energy become common.	1. The notion that energy undergoes transformations is explained for the first time at this level and appears in a variety of contexts.	1. Inertia and friction are commonly evoked to explain changes in the energy of a moving object.	1. Simple transformations between potential and kinetic energy can be described, as can transformations between kinetic and thermal energy. Descriptions of these relations may be somewhat confused, especially if the relations described are complex. For example, it is still somewhat difficult for individuals performing at this level to fully coordinate the effect of friction with the principle of inertia.
10:3 and 10:4 (10b)	1. Students now fully grasp the idea that energy is the ability to do work. This translates into a more complete understanding of the relation between potential and kinetic energy, which are now treated as alternating energy states.	1. Force and energy are consistently differentiated.	1. Forms of energy, such as elastic potential energy, are clearly defined and employed in descriptions of energy transformations.	1. Students employ well-elaborated notions of energy (kinetic, potential, elastic potential, gravitational potential, thermal energy), friction, gravity, and occasionally, conservation of energy.	1. The relation between inertia and friction is fully articulated.	1. Students can accurately describe a number of different energy transformations, such as those that occur in the bouncing ball scenario. If they have not yet learned some of the concepts from the energy unit, individuals performing at this level will borrow pertinent concepts from other units and apply them in meaningful ways.

word energy was often used when the word force was more appropriate. At single abstractions, the confusion was often reversed. There, the word force was often used to describe what should be called energy. For example, a representational systems performance:

[What is this force that is pushing down the ball here?] The energy of air. The air's resistance. It's energy is like the wind pushing it down when you drop it (10115).

Here, the respondent uses the word energy to describe what appears to be a pushing function that causes movement. Although confused, the example demonstrates how, before abstractions emerge, energy, more often than not, was used to describe aspects of a situation that should properly be conceived as examples of force—pushing, pulling, actual physical forcing of movement, and so forth (This quote is also a good example of “downward assimilation,” a process through which the abstract concepts we are trying to teach are converted into concrete versions that often bear little resemblance to the intended concepts.)

As single abstractions emerged, the concept of force often served to signify something behind movement—the thing that makes movement possible. In fact, the word force was used in a number of ways during the emergence of abstractions. For example:

[So, a ball falls towards a spring. Is energy present?] Yes. When the ball falls it will gather force, it will push down the spring, and the spring will just bounce back up (10352).

In this example, the word force is used in a somewhat ambiguous manner. It both takes the place of the word energy and remains a quasi-representational entity. What is clear is that the word force is not used in the manner prescribed by physicists.

To summarize, at representational systems, energy was often used to label instances of pushing and pulling that result in movement, whereas, at single abstractions, force often took on a vague meaning somewhat synonymous with an abstract conception of energy as something behind motion. These

different types of misunderstanding require different teaching interventions. The first misunderstanding, if persistent and accompanied by other, similar downward assimilations, is an indication that a student may require more concrete experience with mechanics before he or she has an adequate experiential repertoire to begin constructing abstract conceptions of force and energy. The second misunderstanding is an indication that the student needs additional exposure to, and opportunities to reflect upon, situations in which force and energy are clearly differentiated.

Interestingly, some confusion about the distinctions between energy and force persisted well into the abstract mappings level, at which students began to articulate the idea of energy transformations. Unfortunately, the sample was too small to allow us to conduct a detailed examination of this phenomenon.

## Using the Usable Knowledge: Developing an Assessment for Teacher Use

### Method

Before developing an assessment for teachers, it was essential to know whether it was possible accurately to assign energy teasers to a developmental level by matching them with the concept descriptions summarized in Table 2. We had already determined that the teasers, due to the lack of justification in most students' responses, could not accurately be scored with the LAS, which requires evidence of the logical structure of students' reasoning. We hypothesized that it might be possible to score many of these teasers based on their conceptual content.

To test this hypothesis, we selected a subset of 43 energy teasers. These teasers were selected from those that had been completed by students who had also participated in interviews. Teasers were rejected if there were missing answers or one-word answers because they did not present enough material for scoring. After selection, and blind to the identity and interview scores of the students, two raters worked together to match the concepts in these teasers to descriptions similar to those summarized in Table 1 as an energy rubric. Each teaser was awarded a single score based on its

**Table 2**  
Teaser Scores Compared to LAS Interview Scores

<i>LAS interview score</i>	<i>Teaser score</i>				
	<i>8:3 and 8:4</i>	<i>9:1 and 9:2</i>	<i>9:3 and 9:4</i>	<i>10:1 and 10:2</i>	<i>10:3 and 10:4</i>
8:3 and 8:4		1			
9:1 and 9:2	1	10	4		
9:3 and 9:4		2	4	6	
10:1 and 10:2				8	4
10:3 and 10:4				1	2

*Note.* LAS = Lectical™ Assessment System.

highest level conceptions. Table 2 shows the relation between content-based teaser scores and LAS scores from interviews of the same respondents. Kendalls tau was .74, scores were identical 56% of the time, and scores were at the same complexity level 81% of the time.

Encouraged by this outcome, we then refined the original descriptions of conceptions into the more concise and accessible rubric shown in Table 1, providing level descriptions for conceptions of energy, forces/gravity, energy forms, energy transfer/transformation, and related concepts. The next step was to test the rubric.

### Results

The rubric was introduced to a group of six physical science teachers with whom CESE had been working for over a year to increase their physical science content knowledge and skills for teaching metacognitive strategies. After the rubric was explained, teachers worked as a group to score three sample teasers. Then, working individually, they employed the rubric to score a set of eight energy teasers. As shown in Table 3, all but one of the teachers' scores were within one complexity level of the researchers' scores and 73% were within half of a complexity level of the researchers scores, indicating that teachers were able to employ the rubric reasonably well without extensive instruction.

Teachers initially responded to the paper version of the scoring rubric with a degree of excitement. First, they were clearly pleased to see that their initial insights into the nature of students' conceptions were supported by research. Second, they immediately began to discuss how they might alter their teaching to accommodate students performing at different complexity levels. One teacher commented that he could see why some students never seemed to understand the difference between potential and kinetic energy and suggested that maybe students were not going to learn much about these abstract forms of energy until they could view energy as something that *explains* motion rather than as motion itself.

Another teacher asked how she could help students see the difference between these two ways of thinking about energy. These initial questions led to a fruitful discussion, in which teachers embraced the new knowledge embedded in the rubrics and discussed methods of applying this knowledge to their teaching. Several weeks following the introduction to the rubric, one of the teachers commented that she finally felt like she understood something about the sources of students' confusion and felt more empowered to "meet students where they are."

But teachers' excitement was tempered by the reality of their jobs and the limitations of the rubric. They wondered when they were supposed to find the time to administer and score teasers, given that their work lives were already overburdened. And they were concerned about the need for a separate rubric for every major concept in physical science and wanted to know if we could either simplify scoring or construct a more general rubric that they could use to score teasers focused on a variety of topics. They also wondered if it would be possible to develop curricula that were tied to the developmental needs of particular students and could easily be accessed and implemented by teachers. In summary, teachers wanted developmental assessments covering a wide range of physical science topics that were easy to administer and score and linked to appropriate curricular activities.

### Discussion

Teachers' response to the scoring rubric was sobering. Despite 2 years of research and analysis, leading to potentially important insights into the development of students' understanding of the physics of energy, meeting teachers' needs would require additional effort. Fortunately, the technologies required to meet teachers' needs are available. We are now using some of them to offer free online teasers, including two versions of the energy teaser (Dawson, 2008a).

The original rubric has informed the design of a coding system comprising straightforward pull-down menus. In the interest of improving accuracy and reliability, rather than

**Table 3**

Teachers' and Researchers' Scores on a Set of Eight Energy Teasers (8a = 8:1–8:2, 8b = 8:3–8:4, 9a = 9:1–9:2, 9b = 9:3–9:4; 10a = 10:1–10:2, 10b = 10:3–10:4)

Teaser number	Rater						Researchers
	Teacher 1	Teacher 2	Teacher 3	Teacher 4	Teacher 5	Teacher 6	
10421	8b	8b	8b	8b	8b	9a	8b
10981	9b	10a	10b	9b	10b	10a	10b
10688	9b	8a	9b	8b	8b	8b	9b
10642	10a	9b	10b	10b	9b	10b	10a
10687	9a	9a	9a	8b	9a	9a	9a
10684	10a	10b	9a	10a	10a	9a	10a
10417	8b	9a	9a	8b	9b	9a	9b
10336	8b	9a	8b	8b	9a	9b	9b

asking teachers to make holistic assessments of students' conceptions across items, the new system asks teachers to make specific assessments of particular concepts within items, resulting in 26 individual judgments that are analyzed to provide a student profile and overall score. Once a teacher is familiar with the contents of the drop-down menus, coding a teaser takes only 5–10 min. Once an adequate number of online assessments have been collected, the extent to which the new system has enhanced the reliability of scores will be examined psychometrically.

Teasers require little more teacher time than administering and scoring conventional tests of factual knowledge and provide considerably more information about student learning. Automatically generated student reports include information about what each student is likely to benefit from learning next, based on his or her performance and current research into learning pathways. Reports also contain suggestions for targeted learning activities.

Because they are delivered online, teasers offer an additional advantage. They deliver data. By tracking and studying student learning and teachers' coding behavior as they are represented in these assessments, researchers can further refine our understanding of the ways in which (a) students learn particular concepts and (b) teachers employ coding rubrics. This knowledge can inform future assessments, curricula, and developmental theory.

Teasers are specifically designed to assess the developmental level at which students' construct content knowledge. They are assessments of how students think about what they know. As such, they may help fill a much discussed void in educational assessment, which tends to focus on content knowledge (Feltovich, Spiro, & Coulson, 1993; Gijbels, Dochy, Van den Bossche, & Segers, 2005). Moreover, teasers can be used in a number of ways. For example, they can be used to assess the level of student thinking before, during, or following instruction. Or, because they require students to organize their new knowledge in *explanations*, they can double as learning tools that can be embedded in curricula to support a deeper understanding of course content (Treagust et al., 2003; Wilson & Sloane, 2000), or they can be completed in groups, with open books, or with teacher support (Rappolt-Schlichtmann et al., 2007). Ongoing research will be required to address the extent to which teasers are useful these roles.

The teacher's role as coder is intended to increase his or her knowledge about student learning and development. When a teacher matches the way in which a student represents a problem to a single item in a pull-down menu of increasingly adequate conceptions, his or her attention is spontaneously drawn to what is and is not present in a given performance. The automatically generated student report reinforces and expands upon these observations. Over time, involving teachers in this way should help build their knowledge of the pathways through which their students learn concepts,

knowledge that can improve teachers' ability to meet the specific needs of individual students. Research will be required to explore these effects.

### Next Steps

Although the results of the cycle of research and application presented here are promising in many ways, there are a number of issues that still must be addressed. First, there were two methodological problems in our initial test of the rubric: (a) the energy concepts employed to describe each level in the original rubric were, in part, taken from the interviews of the sample of students on whom the rubric was later tested and (b) the teachers with whom we tested the rubric had been working with us for over a year, possibly enhancing the speed with which they learned to employ the rubric. To address these concerns, we are now collecting data from online assessments to help us evaluate the modified version of the rubric.

Second, we need to study the energy conceptions of students from other populations in order to assess the adequacy of current descriptions of reasoning at each complexity level. Data from online assessments will also allow researchers to address this issue.

Third, we are aware that online assessments of the kind we are presently able to offer do not meet the needs of all students and teachers. It may take time for students who are unaccustomed to writing about how they are thinking to learn how to convey their ideas. Students with learning disabilities may not be able to use the assessments in their present form. Students without computers will certainly be unable to use them. Still, we view the current assessments as one step toward the goal of tying research to practice in a way that meets the needs of real teachers in real classrooms.

Finally, we need to take the next step in the maieutic cycle and create (and test) curricular materials informed by our findings.

### NOTES

- 1 We have also included lexical analyses (Dawson & Wilson, 2004).
- 2 The assessment we designed on the basis of the present research is available for teachers to use free of charge at <http://DiscoTest.org>.
- 3 When stages are defined in terms of particular conceptual content, it becomes possible to argue that (a) an individual is functioning at a given developmental level because he or she is capable of producing a particular conception and (b) an individual is capable of producing a particular conception because he or she is functioning at a particular developmental level.
- 4 Certified LAS analysts must maintain an agreement rate of 85% within one third of a complexity level with a certified master analyst.

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