Cycles of Research and Application in Science Education

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In this chapter, we describe the contributions of a research methodology called *developmental maieutics* to 9th grade physical science education. As part of a larger project called the Collaboration for Excellence in Science Education (CESE, Dawson-Tunik, Wenk, & Paulman, 2004), we worked closely with a group of physical science teachers to design developmentally informed activities and assessments for a unit on energy. We then employed embedded (Treagust, Jacobowitz, Gallagher, & Parker, 2003; Treagust, Jacobowitz, Gallagher, & Parker, 2001) assessments as research instruments—to examine the development of energy concepts. Finally, we applied what we learned about the development of energy concepts to (a) address teacher's concerns about students' learning difficulties, (b) describe the pathways through which the energy concept develops, and (c) design scoring rubrics that make it possible for teachers themselves to assess the developmental level of students' conceptions.

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 "novice" and "expert" knowledge states (Bowden, Dall'Alba, Laurillard, Martin, Marton, Masters, Stephanou, & Walsh, 1992; Chi & Slotta, 1993; Clerk & Rutherford, 2000; di Sessa, 1996; Eryilmaz, 2002; Halloun & Hestenes, 1985; Hestenes, Wells, & Swackhamer, 1992; 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 (Duit, 1983; Goldring & Osborne, 1994; Kruger, 1990; Liu, Ebenezer, & Fraser, 2001; Liu & McKeough, 2005; Maloney, 1985; Shymansky, Yore, Treagust, Thiele, Harrison, Waldrip, Stocklmayer, & Venville, 1997; Solomon, 1983; Stylianidou, 1997; Talisayon, 1988; Trumper, 1993; Watts, 1980; Welch, 1984). For a review of this literature, see Dawson-Tunik and Stein (manuscript submitted for publication).

In our view, the most promising research on the development of science conceptions not only identifies correct and incorrect or novice and expert conceptions, but 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.

Developmental Maieutics

From our perspective, the promotion of optimal development, requires that we understand:

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

We have developed an iterative methodological approach designed to accomplish all of these goals. We call this methodology—represented in the spirals shown in Figure 1 — *developmental maieutics*. Employing this methodology, we aim 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 activities intended to promote the development of the concept; and 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 sub-spiral on the right of the figure. The *maieutic* approach to identifying sequences of conceptual development involves submitting interview data to at least two forms of qualitative analysis[i]. First, interview texts are independently analyzed for (1) their developmental level and (2) 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) 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, 2004a; Dawson-Tunik, 2004a; Dawson-Tunik, 2004b; Dawson-Tunik & Stein, 2004a; Dawson-Tunik & Stein, 2004b).

Based on our findings, we then (E) refine the learning activities and assessments designed in steps 2 and 3, above. At this point, our level of understanding of the development of a chosen concept is such that we can develop rubrics for teachers to employ in their own assessments of students' conceptualizations[ii]. These new curricula and assessments can then be further evaluated (F) and refined (G).

-------------------------insert Figure 1 about here-------------------------

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. 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 Fischer's (1980) skill theory and the complexity orders of Commons' General Stage Model (Commons, Trudeau, Stein, Richards, & Krause, 1998).

The Lectical™ Assessment System (LAS)

The LAS (Dawson-Tunik, 2004b) lays out explicit criteria for determining the complexity level of performances in any domain of knowledge. The thirteen complexity levels, which correspond to Fischer's (Fischer & Bidell, 1998) skill levels and the first 13 of Commons' (Commons et al., 1998) 15 stages, are similarly defined. We employ the level names from Fischer's skill theory to label complexity levels (see chapter X).

The scoring procedures employed with the LAS are partially derived from Commons' (Commons, Straughn, Meaney, Johnstone, Weaver, Lichtenbaum, Sonnert, & Rodriquez, 1995) and Rose & Fischer's (1989) assessment systems. 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 are at that complexity level. Thus, it avoids much of the circularity[iii] of many stage scoring systems (Brainerd, 1993), such as the Perry (1970) scheme 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, 2002, 2003, 2004; Dawson & Gabrielian, 2003; Dawson, Xie, &

Wilson, 2003; Dawson-Tunik, 2004a). We have examined inter-analyst agreement rates, compared scores obtained with the LAS with scores obtained with more conventional scoring systems, and examined scale characteristics with statistical modeling. Inter-analyst agreement rates have been high, 80% to 97% within half of a complexity level (Dawson, 2004; Dawson & Gabrielian, 2003; Dawson-Tunik, 2004a)[iv]. Correspondences between the ALS and other developmental scoring systems are also high, consistently revealing agreement rates of 85% or greater within ½ of a complexity level (Dawson, 2002, 2004; Dawson et al., 2003). Employing Rasch scaling, which provides reliability estimates that are equivalent to Cronbach's alpha, we have consistently calculated reliabilities over .95 (Dawson, 2002; Dawson et al., 2003; Dawson-Tunik, 2004a; Dawson-Tunik, Commons, Wilson, & Fischer, in press). Overall, our research shows that the LAS is a valid and reliable general measure of intellectual development from early childhood through adulthood. Detailed information about the LAS can be found at the LAS web site (Dawson-Tunik, 2005).

The energy unit

This research was undertaken by the Collaboration for Excellence in Science Education (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 emerged rapidly. 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 the ability to cause change, and some understanding of energy transformations and transfer and the principle of conservation of energy{, 2004 #6728}. 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 with some evidence of abstract systems. Abstract mappings commonly emerges at around 11-13 years of age and is 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, 2004a; Dawson-Tunik & Commons, in review; Dawson-Tunik et al., in press; Fischer & Bidell, 2005). However, many students in this age group continue to reason at the level of single abstractions, particularly in science and mathematics (Asghar, 2004; Fischer & Bidell, 2005; Fischer & Kenny, 1986). Because comprehension of the course textbook demanded the ability to construct abstract mappings, we hypothesized that students performing at the level of single abstractions would have greater difficulty learning the energy concept as it was presented in class than students performing at the level of abstract mappings.

Based on teachers' observations, we developed an introductory activity for the energy unit, called "Energy on the Rebound", available on the CESE website {Dawson-Tunik, 2005 #6281}, 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' 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. 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*.

Developing energy conceptions

To address these concerns, we had to learn more about students' energy conceptions and how they typically develop. To study their conceptions, we designed the "Energy Teaser". Teachers administered the teaser in all of 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 9th grade sample—were collected by our research team. All interviews were tape-recorded, transcribed, scored with the LAS, and analyzed for their conceptual content. These procedures are described in detail in (Dawson-Tunik & Stein, manuscript submitted for publication).

Table 2 shows the results of our analysis of energy conceptions from the interviews at the elaborated phases of four complexity levels. As shown in the table, we analyzed three of the recurring thematic strands in these interviews: (1) kinetic and potential energy, (2) energy transfer, and (3) gravity. For each of these strands, there is a clear progression in the development of the energy concept (and related concepts). It 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, first observed at representational systems, precedes the differentiation of energy and movement, which begins at single abstractions with the notion that energy is something “behind” motion, and continues at abstract mappings 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*, while 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) facilities movement often served this purpose. This is unfortunate, not because it is an illogical or useless preconception, but because *force* must come to occupy it's 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. For instance, the 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 dictionary defines force as the power, strength, or energy possessed by somebody or something.

We found that *force* and *energy* were more or less synonymous at representational mappings and single abstractions, but for different reasons. At representational systems, the 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, etc. (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? You said, "Yes, the energy present in the ball, absorbed by the spring and then exerted". So, what

does that…?] 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.

Developing an energy scoring rubric

Method

Before developing a rubric for the use of 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 student's 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, since 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 those summarized in Table 1. Each teaser was awarded a single score, based on its highest level conceptions. Table 2 shows the relation between content-based teaser scores and LAS scores from interviews of the same respondents. Kendells tau was .74, scores were identical 56% of the time, and scores were at the same complexity level 81% of the time.

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Encouraged by these results, we then translated the descriptions of conceptions in Table 2 into a more concise and accessible rubric, providing level descriptions for conceptions of energy, forces/gravity, energy forms, energy transfer/transformation, and related concepts, as shown in Table 3. The next step was to test the rubric.

Results

Following an hour of training, a group of 6 physical science teachers with whom CESE had been working for over a year, employed the rubric to score a set of 8 Energy Teasers. As shown in Table 4, all but one of the teachers' scores were within one complexity level of the researchers' scores and 73% were within ½ of a complexity level of the researcher's scores, indicating that teachers were able to employ the rubric reasonably well without extensive instruction.

Discussion

Teachers initially responded to the 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 just never seemed to understand the difference between potential and kinetic energy, and suggested that maybe students weren't 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 want easy to administer and score developmental assessments that are tied to appropriate curricular activities across a wide range of physical science topics. The tools to achieve these goals are available. In fact, a partial solution has been suggested by another project in which we employed developmental maieutics to construct a developmentally informed framework for a decision-making curriculum (Dawson & Stein, 2004b). The federal agency for which we produced this framework required curricula that could be matched to adult students' individual learning needs. This meant matching assessments of students' developmental and conceptual attainments with customized decision-making curricula. To meet this challenge, we first identified and scored (for their developmental level) the learning activities described in ten decision-making texts selected by three international experts in the decision-making field. The result was an electronic database of decision-making lessons and activities organized by their developmental levels. In keeping with the methodological approach of developmental maieutics, we then conducted a content analysis of the same texts, identifying the particular skills (content) emphasized by their authors. These skills were organized into a concept map of sub-skills constituting the decision-making skill domain. Finally, we merged the developmental and content analyses to produce descriptions of each of the major sub-skills as they manifested at each developmental level. The results have been employed to guide the design of decision-making curricula and on-line assessments. The new curricula are currently being evaluated. On-line assessments will be made possible by the implementation of a computerized developmental assessment (Dawson & Wilson, 2004). By coordinating curricula with the developmental needs of students (as revealed in on-line assessments), instructors will be able more effectively to meet the particular learning needs of individual students.

The methods employed to construct the decision-making curricular framework and assessments could readily be adapted to the design of a comprehensive physical science curricular database with complementary on-line assessments. With a system of this kind in place, teachers could obtain on-line assessments of students' learning needs on individual physical science topics, along with class profiles showing the range of learning needs represented in each class. Based upon students' learning needs, the software would then provide suggestions for learning activities, including ideas for presenting concepts to students performing at different developmental levels. Periodically, teachers could employ the on-line assessments to track student development.

Rather than adding to teachers' workload, this system would make it easier for teachers to design effective lesson plans and free up some of the time spent grading student work. Moreover, by tracking and studying student learning as represented in the on-line assessments, researchers would theoretically be able to refine our understanding of the way in which students learn physical science concepts, leading to improvements in assessments and curricula. The research and application spiral of developmental maieutics provides a framework for the cycles of research and application that would be required to implement such a system.

Next steps

Although the results of the cycle of research and application presented here are promising in many ways, there are a number of questions that still must be addressed. First, there was a methodological problem in our initial test of the rubric: the energy concepts employed to describe each level of the rubric were, in part, taken from the interviews of the sample of students on whom the rubric was later tested. We need to conduct additional tests of the rubric on independent samples of students to determine its generality. Second, we need to study the energy conceptions of students from other populations in order to assess the adequacy of the current descriptions of reasoning at each complexity level. Third, we need to take the next step in the research/application cycle and create (and test) curricular materials informed by our findings.

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[i] We have also included lexical analyses (Dawson & Wilson, 2004).

[ii] The energy rubric we designed on the basis of the present research is available at cese.hampshire.edu (Dawson-Tunik, Wenk, & Paulman, 2005).

[iii] When stages are defined in terms of particular conceptual content, it becomes possible to argue that (1) an individual is functioning at a given developmental level because he or she is capable of producing a particular conception, *and* that (2) an individual is capable of producing a particular conception because he or she is functioning at a particular developmental level.

[iv] Certified LAS analysts must maintain an agreement rate of 85% within 1/3 of a complexity level with a Certified Master Analyst (Dawson-Tunik, 2004b).

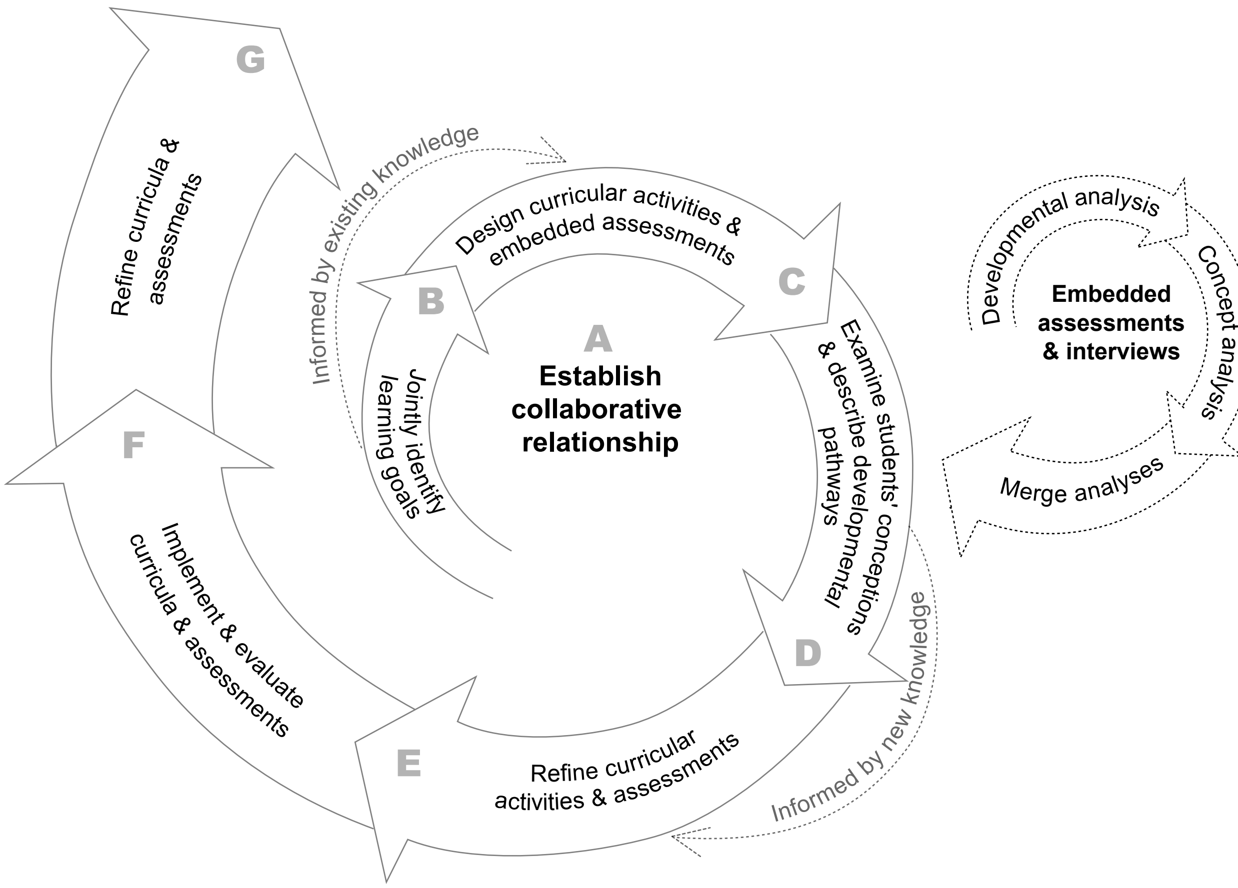
A
Establish collaborative relationship
B
Jointly identify learning goals
C
Design curricular activities & embedded assessments
Examine students' conceptions & describe developmental pathways
D
E
Refine curricular activities & assessments
F
Implement & evaluate curricula & assessments
G
Refine curricula & assessments
Informed by existing knowledge
Informed by new knowledge
Embedded assessments & interviews
Developmental analysis
Concept analysis
Merge analyses

Table 1: Reasoning about energy—representational mappings to abstract mappings

Level	Kinetic & potential energy	Energy transfer	Gravity
Elaborated representational mappings	*Kinetic* and *potential energy* do not appear as meaningful concepts at this level. The only way the word energy is employed is to describe the physical energy of living things. Energy makes it possible for people to run and play. When children performing at this level are asked about the energy of a bouncing ball, they focus on its movement. In particular, they focus on it's *bounciness*. Bounciness makes it possible for balls to bounce.	*Energy transfer* does not appear as a concept at this level. Children performing at this level know that a ball will eventually stop bouncing, but they have no explanation for this phenomenon.	*Gravity* is conceived simply as being that thing that is responsible for pushing, pulling, or holding, things down. The concept is employed as a simple explanation for a ball's movement (falling).
Elaborated representational systems	*Kinetic* and *potential energy* do not appear as meaningful concepts at this level. Children continue to focus on the physical movement of the ball, rarely employing the word energy in their descriptions. When the term energy is used, it clearly means movement or force (as in pushing or pulling). The composition of the ball is often mentioned as a factor in determining its bounciness.	*Energy transfer* does not appear as a meaningful concept at this level. Children performing at this level make detailed observations about the activity of a bouncing ball, almost universally observing that a it bounces lower and lower in a systematic way. They may link this loss of bounce to a loss of energy or force, where energy is equivalent to movement or speed and force is some kind of pushing or pulling.	*Gravity* is conceived as a quasi-physical yet functional entity on par with other concretely describable aspects of a situation. Its function is to pull, push or hold things down, when the other aspects of the situation allow for this. Gravity is analogous to an invisible physical entity, such as wind or air, which is outside and separate from objects, and affects them in ways that are similar to the way they are affected by observable entities. For example, people, horses, and gravity can push or pull.
Elaborated single	*Kinetic* and *potential energy* are used as abstract concepts but without	A this level, *energy transfer* is the movement of energy, which	*Gravity* is categorized as a force (or a type of energy). In some cases gravity

Level	Kinetic & potential energy	Energy transfer	Gravity
abstractions	clearly elaborated relations to other concepts or each other. Kinetic energy is conceptualized as an energy of motion, while potential energy is conceptualized a potential for energy to happen. There no understanding of the ways kinetic and potential energy interact.	is conceived as a substance or a force, between objects via immediate contact or proximity.	is understood as a constant or general aspect of *all* situations, which functions differently under different concrete circumstances. For example, it slows a ball down on a flat surface or speeds a ball up going down a hill.
Elaborated abstract mappings	Descriptions of *kinetic* and *potential energy* are qualified by conceptions of their relations and the notion that there can be greater or lesser amounts of potential or kinetic energy—more of one means less of the other. They are typically related through mediating concepts of *energy transformation* and a partial understanding of *the law of conservation of energy*. Types of potential energy, such as *gravitational potential energy* and *elastic potential energy* may be mentioned in more elaborated performances.	The concept of *energy transfer* is used in conjunction with the notion of *energy forms* such as *heat* and *sound*. Energy transfer results from physical contact between objects.	*Gravity* is consistently and coherently employed in linear abstract explanations of situations. A variety of abstractions can be causally related and explicated relative to *gravity*, which is conceived as a constant force. When definitions are offered, gravity is more clearly classed as a force and understood to be effective in relation to height, weight, etc.

Table 2: Teaser scores compared to LAS interview scores

LAS Interview score	Teaser score: Elaborated RS	Un-elaborated SA	Elaborated SA	Un-elaborated AM	Elaborated AM
Elaborated RS		1			
Unelaborated SA	1	**10**	4		
Elaborated SA		2	**4**	6	
Unelaborated AM				**8**	4
Elaborated AM				1	**2**

Table 3: Scoring rubric for energy conceptions

Level	Energy	Forces/ gravity	Energy forms	Energy transfer/ transformation	Related concepts	For example…
Unelaborated representational systems	Energy is the same thing as motion. Energy can be fast or slow. Energy is something you need for recess, hard work, etc. Energy moves things. Energy is 'in' an object.	Gravity, if mentioned is something that pushes, pulls or holds—like an invisible hand. Force, if mentioned, involves pushing, holding, or pulling on an object.	Energy is in people, moving things.	No concept.	Bounciness, ball composition, weight.	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.
Elaborated representational systems	Energy is something that pushes, pulls, or holds an object. Energy can be strong or weak.	May make a connection between energy and force or gravity without being able to explain the connection. The terms, *gravity*, and *force*, (when they are employed) are used, as the word *energy* is , to explain observed changes in	Energy is in electricity, fuel, etc. The energy makes things work (makes the lights work) or move (makes a car go).	Energy in fuel can be used to make things go. Electricity can make things function.	Bounciness, ball composition, weight.	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

		motion.				(because it is squishy, made of rubber, or has bounciness), and will keep doing this until it stops.
Unelaborated single abstractions	Energy is clearly viewed as “something” that is ‘behind’ motion. This notion is applied inconsistently. Sometimes, energy is still represented as equivalent to motion, especially when describing the energy of stationary objects.	Forces acting on an object change its energy. For example, the *energy* of a dropped object increases due to gravity (a force). This is different from the representational systems argument that gravity makes an object fall or makes it fall faster. 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.”	Particularly in post-tests, the terms *potential* and *kinetic* energy are likely to appear. Potential energy is often conceived as the potential for energy to happen rather than as an actual form of energy.	Energy can move (transfer) from one object to another.	The terms friction, air resistance, and inertia may appear. 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. Students cannot reconcile the effects of inertia and friction.	The student makes a clear attempt to describe what is happening to the *energy* 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 quite believe that potential energy is really energy. Explanations of abstract terms can sound like recitations of textbook definitions.
Elaborated single abstractions	Energy is now rarely spoken of as though	Gravity is still largely viewed as a force that	The terms potential and kinetic energy	Energy can now be transferred to action	Students can provide a good description of	Though relations between energy

	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).	increases the energy of an object by increasing its speed. Concepts of energy and force are often poorly differentiated.	are common in post-tests. Potential energy is now treated as a form of energy rather than as a word for the absence of energy.	(like a bounce) and objects. While energy transformations are not yet described, some students begin to talk about energy getting lost to friction or gravity.	the physical action of friction but do not yet tie this action to a form of energy (heat energy). Friction causes a reduction in 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.

Unelaborated abstract mappings	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. Students may explain that energy is the ability to do work and describe multiple examples of energy doing work.	Gravity is now viewed as a force that is involved in explanations of kinetic and potential energy. *Force* and *energy* are more differentiated than at single abstraction, though confusion may occasionally persist.	Several energy forms, such as heat energy, elastic potential energy, and gravitational energy become common.	The notion that energy undergoes transformations is explained for the first time at this level, and appears in a variety of contexts.	Inertia and friction are commonly evoked to explain changes in the energy of a moving object.	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.
Elaborated abstract mappings	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	*Force* and *energy* are consistently differentiated.	Forms of energy, such as elastic potential energy, are clearly defined and employed in descriptions of energy transformations.	Individuals performing at this level employ well-elaborated notions of energy (kinetic, potential, elastic potential, gravitational potential, thermal	The relation between inertia and friction is fully articulated.	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

	energy, which are now treated as alternating energy states.			energy), friction, gravity, and occasionally, conservation of energy.		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.

Table 4: Teachers' and researchers' scores on a set of 8 Energy Teasers

				Rater			
Teaser #	**Teacher 1**	**Teacher 2**	**Teacher 3**	**Teacher 4**	**Teacher 5**	**Teacher 6**	**Researchers**
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