Energy across the Curriculum: Cumulative Learning Using Embedded Assessment Results

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Abstract: This symposium reports research investigating the design and implementation of curriculum, assessment, and professional development to promote cumulative understanding of energy. Using energy as a core idea, we link topics in 6th and 7th grade including thermodynamics, plate tectonics, global climate change, and photosynthesis. We explore new forms of assessment called MySystem and Energy Stories to capture cumulative understanding. Synthesis of findings across studies illustrates the trajectory of student learning and clarifies the elements of the curriculum that promote coherent views.

Symposium Goals

This symposium synthesizes research exploring cumulative learning of energy concepts across disciplinary project, reflecting the conference theme, *Learning in the Disciplines*. We define cumulative learning following the *Taking Science to School* report that calls for organizing the curriculum around a few key ideas that "connect to many related scientific ideas" (Duschl, Schweingruber, & Shouse, 2007). Using energy transfer and transformations as a core idea, we link topics in 6th and 7th grade including thermodynamics, plate tectonics, global climate change, and photosynthesis. To address this research question the eight posters investigate the design of curriculum and new assessment techniques to emphasize cumulative learning. We also study the impact of professional development and explore effective methods for documenting cumulative learning.

The current curriculum is fragmented and incoherent. The most commonly used middle school science textbooks cover too many topics and neglect connections between topics (Linn, Lewis, Tsuchida, & Songer, 2000; Stern & Roseman, 2004). Furthermore, studies show that textbooks introduce the same topics year after year and neglect links from one year to the next (Roth & Garnier, 2006; Schmidt, McKnight, Valverde, Houang, & Wiley, 1997). High-stakes tests reinforce this practice and reward recall of isolated ideas (Au, 2007). Critics argue that widespread use of multiple-choice items deters development of coherent arguments (National Research Council, 2003).

Our assessments, curriculum materials, and professional development are aligned using the patterns and principles developed to support knowledge integration (Kali & Ronen, 2005; Linn, 2006). We design curriculum using the Web-based Inquiry Science Environment (WISE), a technology-enhanced software system (see Figure 1) that both delivers instruction and keeps track of student responses (see Slotta & Linn, 2009). We incorporate technology tools, visualizations, and simulations created by the Concord Consortium. The WISE system of delivery ensures that teachers can track student progress in real time with embedded assessments, and allows instruction and assessment to be integrated. It supports numerous forms of teacher-student and peer-to-peer learning including interactions with probeware, visualizations, simulations, and virtual experiments.

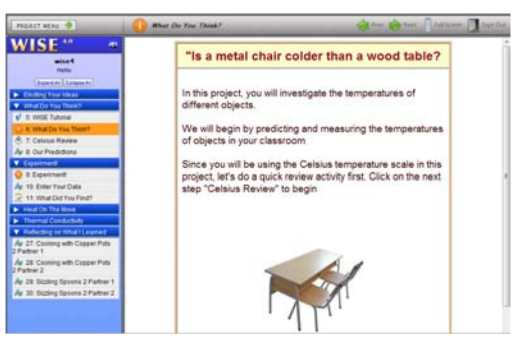

Figure 1. The Web-based Inquiry Science Environment for Thermodynamics

To measure the cumulative learning of energy ideas, we are exploring two new forms of assessment: Energy Stories and MySystem (see Figure 2). Energy Stories ask students to create explanatory narratives about energy phenomena related to the project, such as how plants use light to grow. MySystem, a computer-based modeling environment, enables students to visually represent connections between energy sources, energy transformations, and energy transfer.

Energy Stories	MySystem

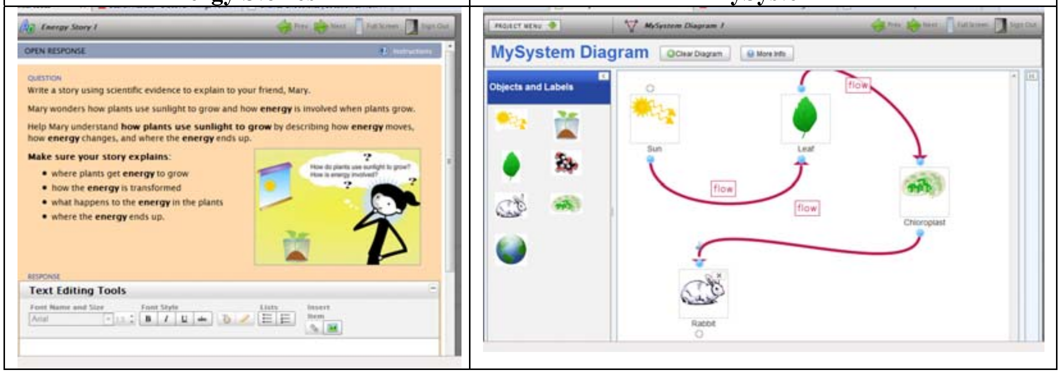

Figure 2. Examples of Energy Stories and MySystem from the Photosynthesis Project

We are implementing the units in the classrooms of twenty middle school teachers and study approximately 1500 students annually. These studies provide evidence in support of organizing the curriculum around core ideas, and explore affordances of incorporating the real world activities and connecting to students' everyday experiences. The symposium will be chaired by Marcia Linn, and discussed by Doug Clark.

Promoting Cumulative Learning

Marcia Linn, University of California, Berkeley; and Chad Dorsey, Concord Consortium

Today most students are tested on the topics they studied in the latest unit and often quite superficially. There is seldom the expectation of applying concepts learned in prior units to the next topic or course. To remedy this situation, Cumulative Learning using Embedded Assessment Results (CLEAR) is leveraging cyberlearning to make science learning more cumulative. Defining cumulative learning raises many issues such as: What sorts of ideas should be retained? What sort of understanding do we desire of students after several years of instruction? How do students use the knowledge gained in one day, topic, or course when they encounter the next day, topic, or course? How can instruction enable students to appreciate the ubiquitous role of fundamental science concepts like energy? How can we help students understand the dependencies and connections across science topics and disciplines? From our prior work on knowledge integration we know that students come to science class with a repertoire of disconnected and often contradictory ideas. We want to spur students to develop more coherent ideas. We would like to enable students to integrate their ideas and promote the most fruitful, generative, and useful ideas. We hope to help students distinguish new ideas from existing ideas and reconcile discrepancies with scientific evidence. We expect that cumulative learners will test and refine their ideas by applying them in situations they encounter in their lives. Ideally cumulative learners would continue to expand, refine, and integrate their understanding all during their lives. This poster defines key features of instruction and assessment for cumulative learning and provides case studies from student work to illustrate how students respond. We argue that all students can become cumulative learners.

Teacher Perspectives on Cumulative Learning

Libby Gerard, University of California, Berkeley

This study explores how teachers use the CLEAR curriculum and assessment materials to foster cumulative learning. What ideas do teachers link? What parts of the curriculum do they revisit? What do they learn about student thinking from the new assessments? And how does that information help guide their teaching?

We report on how the 16 teachers implemented CLEAR inquiry projects (see Table 1). Each project takes between five and fourteen fifty-minute class periods. Energy Stories, MySystem, and other activities are embedded in each project to serve as learning events and assessments. All teachers have a minimum of four years of prior experience teaching with technology-enhanced inquiry science curriculum.

Table 1. Participants, Grade and Projects Taught

Participants (n)	Grade	Projects
10	6^{th}	Eliciting Ideas, Thermodynamics, Plate Tectonics, Global Climate Change
6	7^{th}	Eliciting Ideas, Photosynthesis

Teachers were interviewed at the beginning of the year and after implementing a project in their classroom. They responded to questions about their views of cumulative learning, teaching, and assessment strategies. All teachers also participated as partners in a five-day workshop, in which they used student assessment data from Energy Stories and MySystem to inform the design of CLEAR curriculum projects. Teachers responded in writing at the end of each day of the workshop to four reflection questions focused on analysis of student data, ideas for the curriculum, and anticipated support needs for classroom implementation. The impact of the emphasis on cumulative learning is apparent (see Table 2). Teachers have begun to revisit student ideas when teaching non-CLEAR topics.

Table 2. Data Sources and Teachers' Views

Data Source	Teachers' Views
Baseline interview, Workshop Reflections	Eager to prioritize students' cumulative learning about energy.
	Have done little to support cumulative learning in past due to use primarily of textbook for instruction
	Surprised when analyzing student Energy Stories and MySystem by students' non-normative energy ideas
	Plan to revisit student ideas about energy transformations in CLEAR and non-CLEAR topics
Post Project Interviews	Guided students to revisit ideas from CLEAR virtual experiments and simulations when teaching energy in other contexts
	Added embedded assessments from CLEAR projects to teacher generated end-of-unit and end-of-semester tests to assess students' cumulative learning about energy
	Energy Stories and MySystem provide a valuable summative assessment of the connections students can make whereas explanation questions capture more of learning process
	Energy Stories and MySystem are more open ended than traditional explanations, so they showed how students *apply* what they learned
	Energy Stories generated longer answers from students than traditional explanations because had to explain the whole journey of energy from one point to the end
	MySystem and Energy Stories forced students to assess their own understanding and identify gaps more so than specific explanation items
	Students needed more icons in MySystem (e.g. for energy lost)
	Students needed opportunities to see other MySystem and Energy Stories in a different topic before doing their own because they lack experience using systems and stories in science

Teachers report revisiting elements of the CLEAR units such as virtual experiments and simulations to make connections to new topics. For example, when teaching the Plate Tectonics project, one 6th grade teacher commented that she frequently referred back to a simulation of conduction in the Thermodynamics project to help students understand why heat moves from the core to the mantle and to the Earth's plates. Teachers see the potential of MySystem and Energy Stories as assessments. For example, one teacher remarked:

> "*the MySystem forces [students] to make choices, to ask what direction is energy moving…and have a conversation, you get kids saying well I don't think that should be there, and well why not, and then they have to explain it which really makes them assess what they know and don't know. A lot of times students think they get it but they don't so MySystem diagrams help because it's not just answer a question but create something and then they have to explain it again in the story.*"

Teachers also offered valuable ways to improve the diagrams such as adding icons and giving students a model of an Energy Story and MySystem to critique prior to generating their own. Teachers' views on cumulative learning and assessment can improve the quality of curriculum materials by identifying which ideas from a project students use to help them understand a new topic. Teachers' views can also help us understand how Energy Stories and MySystem can be strengthened and embedded in the projects to guide students to monitor their understanding.

Eliciting Energy Ideas in Thermodynamics

Hilary Swanson, University of California, Berkeley

To explore the impact of typical instruction on student ideas about energy, we asked students to articulate their ideas in assessments administered early in the school year. This embedded activity elicited ideas, the first step in the knowledge integration framework (Linn, 2006). Students articulate their repertoire of ideas and develop criteria to guide the construction of coherent approaches to understanding scientific phenomena. Pretests show that although eighth grade students had greater technological fluency and higher literacy levels than sixth graders, their ideas about energy were not significantly more coherent than the sixth graders' ideas.

Students then participated in a four-day WISE project on thermodynamics, working in dyads (N= 49 dyads). Assessments embedded in the activity were scored using the knowledge integration rubric. In addition a list of specific ideas consistent with Minstrel's facet analysis was identified (Minstrell, 1992). Seventy-four percent of the responses to the first thermal equilibrium prompt were normative, whereas ninety-three percent of responses to a final assessment were normative. For example, on the final assessment, most students correctly identified the sun as the original energy source, and conduction as the means of heat transfer from an object heated by the sun to an object in contact with it. However, some students explained their reasoning by arguing that heat rises. They would correctly or incorrectly answer questions about conduction based upon the relative orientation of the heat source (i.e., hot cup *on top* of counter vs. hot asphalt *under* bare feet). This non-normative idea elicited by the WISE project will be leveraged by the teacher in subsequent projects, which contrast types of energy transfer as they are introduced.

Redesigning Plate Tectonics for Cumulative Learning

Elissa Sato, University of California, Berkeley

Plate tectonics is currently taught as an earth science unit in sixth grade in the state of California. It has traditionally been a difficult concept for middle school students (Gobert & Clement, 1999), requiring students to learn about abstract processes and phenomena that lie outside of their direct experience and to integrate spatial, causal and dynamic information (Gobert, 2000). The California state standards require students to learn that various geological phenomena are different manifestations of a plate movement (Curriculum Development and Supplemental Materials Commission, 2003). To leverage the unifying concept of energy we frame plate tectonics as a disciplinary context for learning about thermal energy transfer by convection. We sought to make connections between previous instruction on energy, students' existing knowledge, and current instruction featuring convection without fragmenting the curriculum. We report on initial teacher concerns: many sixth grade earth science teachers felt it would be difficult to integrate more in-depth coverage of convection into the plate tectonics curriculum when instruction typically focused on geologic events and features on a mechanistic level. Some teachers also questioned how emphasizing energy concepts in plate tectonics would help students make connections with energy concepts in other domains given the abstract nature of the topics.

To investigate students' understanding of energy concepts in plate tectonics, we conducted two pilot studies (N=100) in six middle school classes taught by the same teacher. After completing an existing plate tectonics project, students were asked to write stories about and draw or annotate diagrams to describe how energy causes changes in the mantle, where the energy came from, where the energy goes, and how the energy moves and changes form. Student responses were analyzed using a grounded coding methodology. Most students correctly identified the core as the source of thermal energy within Earth, although several responses attributed the Sun as being the source. Most students were unable to describe the process of convection. Many instead described thermal energy transfer within Earth as a series of pressure-induced bursts of energy escaping from the core without any flow of matter involved. Many students also isolated the movement of thermal energy within Earth as being limited to heat transfer from the core to the mantle.

These results informed the subsequent redesign of the Plate Tectonics project. Based on these studies we strengthened the convection component of the curriculum and the connections between convection and other concepts in plate tectonics and other disciplines. We incorporated multiple activities to help students make connections between the surface and sub-surface processes, as well as between concrete, mechanistic processes and abstract processes involving energy. Whereas the processes involved in convection were described in a single paragraph in the original project, we expanded the section to allow students to explore and visualize the process of convection at both macro- and micro- levels, to contextualize their understanding of convection to plate tectonics, and to extend their understanding of the principles involved in convection to other contexts such as lava lamps and hot air balloons. Preliminary results suggest that the revised project is effective in supporting students' learning of convection and its underlying processes. Students increased their understanding of the processes underlying convection, made connections between thermal energy transfer and surface geologic processes, and reasoned how concepts underlying convection can manifest in different contexts. Many students made references to the role of conduction as an additional means of thermal energy transfer in Earth, suggesting that students were making connections to energy concepts encountered in previous instruction. Future iterations of the Plate Tectonics project will focus on supporting students in building on previous instruction by incorporating activities that will help them better distinguish between conduction and convection.

Redesigning Global Climate Change for Cumulative Learning

Tammie Visintainer and Vanessa Svihla, University of California, Berkeley

To strengthen cumulative learning we redesigned an existing Global Warming project, incorporating concepts of energy and increasing the personal relevancy of the project for students by building on their initial ideas. The goal of the new project design is to present information in a way that will more effectively facilitate an understanding of the relationship between the mechanisms associated with global climate change and student's energy consumption. The new project explores ways to leverage energy stories, advisory roles, and energy consumption surveys to better elicit students ideas based on their everyday experiences. In this way we can push our thinking of cumulative learning beyond the bounds of the science classroom by incorporating how students' social and cultural backgrounds inform their ideas about science phenomena such as global climate change, and the evidence that they use to support these ideas.

A pilot study was conducted in the Spring of 2009 involving four classes of middle school students taught by the same teacher prior to making revisions of the Global Warming project. Students were asked to write stories and draw energy pathways that included where energy comes from and goes, how it changes form, and how energy travels from place to place. Student responses were analyzed using a grounded coding methodology. The majority of students said energy goes to plants, animals, or the ground, and many said that energy travels through the food chain. Most students only referred to energy in the forms of ultra violet and infrared radiation and had difficulty describing mechanism by which energy changes form. No students mentioned human contributions or the role of their energy consumption when describing how energy affects the atmosphere. Revisions to the existing Global Warming project incorporated findings from this pilot study.

We then conducted a pilot study of the new Global Climate Change project in February 2010 with four classes of 6th grade students, including pre and post interviews with five students. Initial analyses of open-ended responses and interviews suggest that the majority of students believe that pollution or gases cause global climate change and that human actions are sources of this pollution. Students cited ice melting, environmental damage, and temperatures rising as evidence of the occurrence of global climate change. Understanding the specific mechanisms driving global climate change as well as the energy transformations that occur during these processes continue to provide challenges for students. Students commonly mentioned exhaust from vehicles as causes of global climate change, but litter which is tangible to 6th graders as a source of pollution, was also commonly mentioned. Students also tended to group all types of environmental issues together (e.g. ozone layer depletion, acid rain) as causes of or evidence of global climate change.

Further redesigns of the Global Climate Change project will build on students' ideas about the causes of global climate change and the evidence they cite to support their ideas. Activities intended to make explicit the mechanisms behind global climate change and why certain types of pollution contribute to this phenomenon while others does not will be added including comparing and researching different human actions. Likewise, activities will be added to make explicit the energy transformations that occur as energy travels from the sun through different pathways to end products (e.g. food sources, electricity) that are tangible to middle school students. Additionally, students will take home and discuss with their families an Energy Consumption Survey containing items that middle school students can relate to such as transportation to school and recycling and then complete an on-line activity related to the project in school. By examining global climate change from an energy consumption perspective and incorporating activities that make explicit the mechanisms and energy transformations involved with this issue, it is our hope that we will increase students' awareness of how their lives connect to greater science phenomena.

New Assessments of Cumulative Learning in Photosynthesis

Kihyun (Kelly) Ryoo, University of California, Berkeley

The role of energy in photosynthesis challenges students because of its complexity and abstract nature. We designed the photosynthesis project using animations, simulations and virtual experiments to make the role of energy more comprehendible. We report on student learning from pretest to posttest and the potential advantages of using the new assessments, Energy Stories and MySystem (Figure 2). Two middle school teachers taught photosynthesis to eight classes of seventh grade students (N=220) using our CLEAR curriculum for approximately two weeks. Students generated pre- and post-project Energy Stories and MySystem diagrams about how energy is involved in photosynthesis. New extended Knowledge Integration rubrics were developed to score the Energy Stories and MySystem. The rubrics have seven levels including full link (one scientifically valid link between energy source, energy transformation, energy storage, and energy transfer), complex link (two scientifically valid links), and advanced complex link (three or more scientifically valid links). In addition to the Knowledge Integration score, we also captured the specific ideas students generated in their Energy Stories and MySystem.

Overall, paired t-tests revealed that students showed significant improvement in their understanding of energy concepts in photosynthesis in both narrative explanations and visual representations (Figure 3). On the pre-project Energy Stories, students demonstrated a limited understanding of energy concepts in photosynthesis (M = 3.96, SD = 1.12). Twenty-eight percent of the students listed fragmented ideas about energy in photosynthesis, such as "the light energy moves to the plant." Although 40% of the students provided one scientifically valid link between energy ideas, most identified the sun as the energy source for photosynthesis but were unable to describe energy transformation and energy transfer during photosynthesis. They also presented a wide range of alternative ideas related to energy in the Energy Stories, such as "plants releasing energy through oxygen" or water as the energy source for photosynthesis. On the post- project Energy Stories (*M*= 5.02, *SD*=0.78), students showed a significant gain ($t(219) = 10.26$, $p < 0.05$) and this effect was large (Cohen's $d = 1.10$), meaning that they provided two or three scientifically valid connections between ideas. Students not only articulated more integrated ideas about energy sources, transformation, and transfer in photosynthesis, but they also provided more detailed examples of this process.

Consistent with the results of Energy Stories, on the pre-project MySystem, students showed some relevant ideas about energy sources in photosynthesis but did not make any correct links between ideas ($M = 3.41$, $SD = 0.94$). Many students made arrows between irrelevant ideas or provided incorrect labels for correct links (Figure 3). By the post-project MySystems, students demonstrated a more coherent understanding of energy flow in photosynthesis by providing more correct links between energy concepts and elaborated descriptions for each link ($t(109) = 14.71$, $p < 0.05$), and this effect was large (Cohen's $d = 1.38$). Students demonstrated a more coherent understanding of energy flows in photosynthesis by linking different energy concepts and elaborated descriptions for each link ($M = 4.86$, $SD = 1.10$). These results show how a technology-enhanced inquiry curriculum can improve students' integrated understanding of abstract concepts in science and potential advantages of explanatory narrative and visual representation as an assessment tool to document student progress in understanding energy concepts.

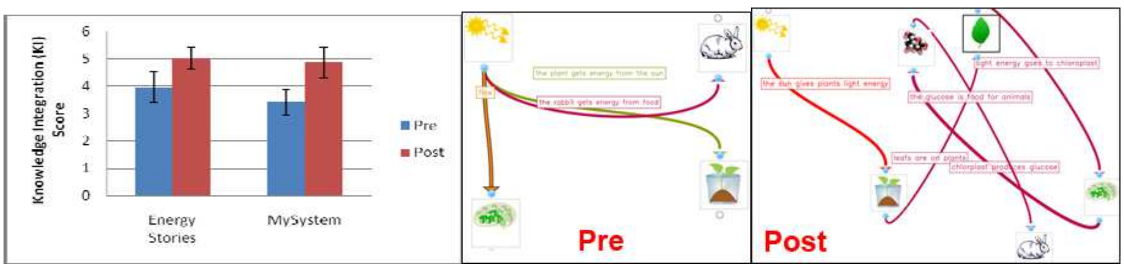

Figure 3. Knowledge Integration Scores of Energy Stories and MySystem on the Pre- and Post-tests

Measuring Cumulative Understanding: Item Formats

Hee-Sun Lee, Tufts University & Ou Lydia Liu, ETS

To measure the learning progression of science ideas, assessment developers have used student alternative conceptions to create multiple-choice items (Alonzo & Steedle, 2009; Briggs, Alonzo, Schwab, & Wilson, 2006; Sadler, 1998; Treagust, 1988). In contrast, we designed multiple-choice items where choices represented various levels of knowledge integration: non-normative ideas, fragmented normative ideas, and integrated normative ideas in order to study whether multiple-choice items can measure students' ability to reason with an increased number of normative and relevant ideas in scientific problems (Lee, Liu, & Linn, in press).

For this study, we selected 10 multiple-choice items from released TIMSS item sets (International Association for the Evaluation of Educational Achievement, 1995, 1999, 2003). These items addressed energy sources, transformation, transfer, and conservation concepts embedded in middle science topics such as heat conductivity, food web, water cycle, plate tectonics, chemical reactions, digestion and respiration. We created a paired item format by adding an explanation part to each of the ten selected multiple-choice items. We designed the explanation part either as selection of an explanation from six choices that represent common student knowledge integration explanation patterns found from a previous study (Lee & Liu, 2010) or as generation of open-ended explanations after a generic prompt, "Explain your choice." We created two online test forms each of which included 10 paired items with alternating selection and generation explanation parts and randomly assigned the two test forms to 794 sixth and seventh grade students.

We used descriptive statistics and a Rasch analysis based on the Partial Credit Model to investigate the compatibility between selection and generation of explanations in measuring knowledge integration. Results show that (1) there appears no systematic advantage for selection explanation items over generation explanation items on the preceding multiple-choice items, (2) student performance on selection explanation items is more aligned when correct answers were chosen in the preceding multiple-choice items than when incorrect answers were chosen, and (3) locations of item thresholds for the fragmented normative idea and the integrated idea explanations are different between generation and selection explanation items. As a result, knowledge integration levels were measured higher when using selection explanation items than generation explanation items. These results indicate that the ability to select an explanation in multiple choice items is not the same as the ability to write one's own explanation. Therefore, relying on multiple choice items to measure knowledge integration will not be accurate and may overestimate students' knowledge integration ability.

Measuring Cumulative Learning Across Disciplines

Vanessa Svihla University of California, Berkeley

Prior research has established effective and reliable ways to measure the coherence of student's repertoire of energy ideas with respect to specific contexts (Lee, et al., in press; Liu, Lee, Hofstetter, & Linn, 2008) and there are promising options for extending these methods of measurement to new open-ended assessment formats (specifically, Energy Stories and MySystem (Ryoo, this session). This poster explores cumulative learning for dyads and methods for resolving individual trajectories of cumulative learning.

Initial analysis of two projects shows that dyads add new ideas and form new scientifically valid links between ideas as they complete a project. For each project, dyad performance on a late, integrative question was modeled as a linear combination of two prior questions, an early question asking students to explain a phenomenon after learning about a type of heat transfer e.g., (conduction or convection) and a later question asking students to provide a more mechanistic explanation of the phenomenon (e.g., conduction relates to rate of heat transfer or heat energy is related to density). A full score on the integrative question would require students to link the description of the heat transfer to the cause.

For the thermodynamics project, modeling the integrative question as a linear combination of prior answers resulted in a significant increase over using the mean (F (2,59)= 6.98, p<0.05) and a positive but not strong relationship (r^2=0.191). For the plate tectonics project, modeling the integrative question as a linear combination of prior answers resulted in a significant increase over using the mean (F (2,62)= 18.28, p<0.05) and a positive relationship (r^2=0.371). Including student pretest scores related to thermodynamics does not explain significant variance (F (2, 59)=0.994, p>0.05). This finding suggests that regardless of starting point, students have potential to learn using these projects, and supports our assertion that all students may become cumulative learners. For the global climate change project, much of the learning is dependent on understanding models in the project. In this case, the integrative question can be modeled as a linear combination of pre-test scores and score on a question reflecting on the first of a series of climate models (F (2,64)= 7.70, p<0.05) and a positive but not strong relationship (r^2=0.194).

Exploring student learning across projects is challenging because students work in different dyads for each project. One approach to analyzing such data is to apply a 2-mode affiliation network approach, identifying clustering across individuals and events (Field, Frank, Schiller, Riegle-Crumb, & Muller, 2006). We are developing models of individual student performance taking into account their various memberships in dyads during the course of the school as they completed CLEAR projects, allowing us to explore the extent to which each individual ensures the relative success of a dyad in reaching coherent understanding of energy transformation. Alternatively, this may be framed as exploring benefits of heterogeneous pairing (Gerard, Tate, Chiu, Corliss, & Linn, 2009; Madhok, 1992; Varma, 2008).

Conclusions

Through these studies, we have demonstrated a design-based approach, incorporating findings from teachers as well as evidence from student pilot data that highlight ways to support cumulative learning of energy ideas. Findings from this initial year of the study include the following:

- Teachers were empowered to support their students in becoming cumulative learners by helping them make further connections across CLEAR and non-CLEAR projects
- Teachers endorsed using personal relevance as a means to increase cumulative learning, a perspective currently being empirically tested
- Pretests show little difference between sixth and eighth grade students in terms of coherence of ideas about energy
- Students show an increase in percent normative ideas over the course of a project
- Students achieve significant gains in developing coherent ideas related to energy across projects

Taken together, empirical evidence from these studies suggests that designing for cumulative learning is promising, but that traditional measures are insufficient for assessing it. Furthermore, cumulative learning as we have framed it provides a means to curricular efficiency, allowing students to learn about a core idea in science with increasing depth. This research, which is in its inaugural year, has potential as an exemplar for practical ways to address challenges common to many educational systems.

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