Eliciting Big Ideas in Biology

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For educators, researchers and others who are interested in improving learning, and particularly learning of complex skills and knowledge, a fundamental challenge is to understand how isolated skills and pieces of knowledge learned in a variety of classroom contexts can become inter-connected, meaningful, and generalizable. As cognitive science research has convincingly demonstrated, it is the connections among elements of knowledge, understanding of the meaning of important concepts and principles, and the ability to apply knowledge flexibly and effectively in a wide variety of situations, that characterize the development of knowledge toward greater expertise (e.g., Chi & Ceci, 1987; Chi, Glaser, & Rees, 1982; Glaser & Chi, 1988; Larkin, McDermott, Simon, & Simon, 1980; Mayer, 2005; Niemi, 1996; NRC, 2002, 2004). This is true for all domains that cognitive scientists have studied, including mathematics, science, history, reading, writing, other school subjects, and non-school domains such as race-track betting and chess. In fact these characteristics of expert knowledge--interconnectedness, understanding, and ability to transfer—are inextricably linked, a point that is critically important for educators and that constitutes an underlying theme in this paper.

The Importance of Big Ideas

Decades of cognitive research and educational experience have shown that when specific responses to specific tasks or questions are learned by rote, that knowledge does not generalize (e.g., Bassok & Holyoak 1989a, b; Bransford et al., 1999; Carpenter & Franke, 2001; Chi, Glaser, & Farr, 1988; Ericsson, 2002; Larkin, 1983; Newell, 1990;

NRC, 2004). Despite the robustness of this finding, however, science instruction in the U. S. has historically focused on the memorization of specific responses to specific questions, and as a result, the knowledge most students have is extremely context bound and not generalizable. Many students have not constructed the meaning of core concepts and principles and cannot relate concepts to problem solving skills and procedures.

In contrast to the piecemeal, context-bound knowledge that beginning learners have, expert knowledge has a relational structure: this is one of the strongest and most powerful conclusions to be drawn from decades of cognitive science research on the nature and development of knowledge—strongest, in the sense that it has been extensively and compellingly validated in a large number of studies, and powerful, in the sense that it has great explanatory force and broad implications for teaching, learning, and educational practice in general. For someone who has advanced knowledge in a domain, every element of that knowledge is connected to other elements in a highly organized structure, with certain statements, expressing important ideas, dominating and organizing other types of knowledge (e.g., Bereiter & Scardamalia, 1986; Chi & Ceci, 1987; Chi, Glaser, & Rees, 1982; Glaser & Chi, 1988; Larkin, McDermott, Simon, & Simon, 1980; Bransford et al., ; Niemi, 1996; Wineburg, 2002). That certain ideas organize other kinds of knowledge, including problem solving strategies and skills, was first and most dramatically revealed in a series of studies by Glaser and colleagues (Chi & Glaser, 1981; Chi et al., 1982).

In one study, for example, when physics experts and novices were asked to sort problems printed on index cards (Chi et al., 1981), the experts put together problems on the basis of abstract concepts and principles, e.g., Newton’s laws, conservation of energy.

Novices, on the other hand, sorted on the basis of physical features of the problem situation, e.g., “there’s an inclined plane in these problems”. The novices either did not understand the theoretical principles or did not know how and when to apply them to problem solving situations. One effect of representing problems in terms of theoretical concepts is that expert problem solvers can activate and implement problem solving procedures linked to those concepts, e.g., formulas for solving conservation of energy problems. Novices have to resort to remembering how they solved problems with similar surface features, which can lead to ineffective solution strategies as problems with the same surface features (e.g., inclined planes) may be conceptually very different.

A follow-up study (Chi et al., 1982) using a different method, concept mapping, further confirmed that experts’ problem solving schemas were organized primarily around the laws of physics and conditions for applying them, while novice schemas were organized around the surface features of the problems. Chi et al. (1982) concluded that weakness in novices’ problem solving could be attributed primarily to deficiencies in their knowledge base and its organization. A range of studies have replicated these findings in other domains, and in each case researchers have found that experts have highly structured schemas, or knowledge structures, that are organized around central concepts or principles, or “big ideas”. The nature of these concepts differs from domain to domain, but in general they are abstract principles that can be used to organize broad areas of knowledge and make inferences in the domain, as well as determining strategies for solving a wide range of problems.

It has been known for many years that understanding of big ideas leads to more flexible and generalizable knowledge use, improves problem solving, makes it easier to make sense of and master new facts and procedures, and enables transfer (e.g., Ausubel, 1968; Chi & Ceci, 1987; Gelman & Lee Gattis, 1995; Larkin, McDermott, Simon, & Simon, 1980; Silver, 1981). The importance of understanding the core principles of a subject area and using them to organize knowledge (or for schema) has been demonstrated in many different subject areas, from interpreting X-rays, solving navigational problems, or playing chess (Chi, Glaser, & Farr, 1988; Ericsson, 2002; Larkin, McDermott, Simon, & Simon, 1980a,b) to mathematics (Ball & Bass, 2001; Carpenter, Fennema, & Franke, 1996; Carpenter & Franke, 2001; Collis & Romberg, 1991; diSessa & Minstrell; 1998; Lane, 1993; Porter, Kirst, Osthoff, Smithson, & Schneider, 1993).

Identifying Big Ideas

Given the importance of big ideas—organizing concepts and principles--in the organization of expert knowledge and in expert problem solving, the obvious question is how to determine what the big ideas are in a domain. Chi and Glaser ingeniously chose tasks that could be classified in terms of big ideas, but they did not offer a comprehensive list of big ideas in physics. One could follow their lead and administer a lot of tasks to a lot of experts (biologists, for example). Presumably the experts would identify the big ideas represented by those tasks, assuming that the tasks actually reflected and required knowledge of the big ideas. Without knowing what the big ideas are, however, it would be difficult to insure that the tasks comprehensively covered the big ideas in question. There would be no way to guarantee that one had the right set of tasks, without identifying ahead of time the big ideas to be targeted by those tasks. To address this problem, we developed a procedure for eliciting big ideas directly from experts. We did this because we found that neither state standards nor existing curricula make clear what the big ideas in a domain are, nor how other elements of knowledge relate to the big ideas. We reasoned that once we had worked with experts to identify the big ideas for a domain, we would be able to use the big ideas to develop a structured framework of knowledge for each domain, and that framework could then used to build a content blueprint for developing and integrating curriculum, assessment, and instruction.

In this paper we describe how we used this methodology to identify big ideas in biology. In collaboration with experts in several fields of math and science, we have endeavored to use the models of subject area knowledge from studies of expertise in different domains to help guide us in creating lists of big ideas. We have worked closely with different teams to identify key knowledge in a subject area. This knowledge has taken the form of lists of big ideas used to organize knowledge in a domain. Our methods have varied slightly over time and the ideal process has been gradually refined as we have worked to create multiple subject area big ideas documents. There follows a brief description of our general procedure for elucidating big ideas— in this case we were working on the biology big ideas.

For the earth science meeting we recruited two high school teachers and two university biology professors. In order to have a representative sample we selected experts from a range of specialties to allow for different perspectives and broader coverage of all aspects of a domain. Our instinct was that we should have a broader range of experts (within the constraints of the people available to work with us) in order to make sure our big ideas list did not become too focused on one particular sub-area of the discipline. As our stated goal was to arrive at a list of big ideas with which we can organize a large domain of knowledge—breadth of expertise was critical.

To begin, we presented a brief overview of the meeting goals and made sure all participants understood the concepts of big ideas. A short slide presentation was given to the participants outlining some of the key research findings on big ideas, for example, the previously mentioned study by Chi, Feltovich & Glaser (1981) where the problem-solving abilities in experts vs. novices were compared was presented and discussed (see Figure 1).

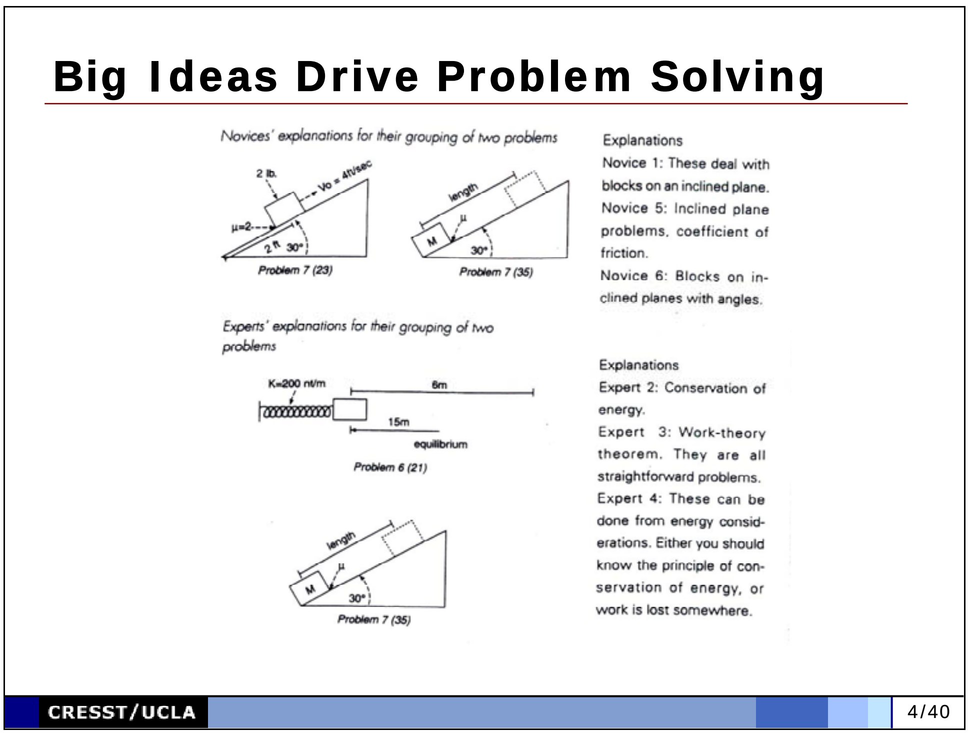

Figure 1: Example slide illustrating how experts and novices classify physics problems.

In this study, novices tended to group problems based on surface features—how the problems actually looked (in this case they classified two problems involving inclined planes together). Experts, on the other hand, grouped problems bases on the underlying theories and ideas needed to solve them (two conservation of energy problems for example). Big ideas were described to participants as concepts or principles used to organize thinking and other activities in a subject area. We emphasized the point that someone who understands the big ideas in a subject area can use them to make sense of and bring together facts that would otherwise be isolated, to identify and solve novel problems, to understand new information, and to create new knowledge.

In contrast, someone who has only memorized facts would not be able to accomplish any of these things, as cognitive science researchers have repeatedly shown. Rote facts can only be used to respond to questions that one has seen before, which is not a hallmark of advanced knowledge. We made clear to participants that we were not looking for a list of facts, or statements that might resemble a standards document, or a blueprint. Instead we were interested in how the participants in the meeting organized their thoughts and ideas about the subject area. Rather than consider how the ideas might be organized for pedagogical purposes, or how ideas are conventionally organized in curricula, the experts were asked to consider which ideas were most important in their own thinking. We provided examples of statements classified already as big ideas and those that would not be considered so (see Figure 2).

Big idea: Living things meet challenges of getting and using energy, reproducing, and maintaining their structure.

Something that would *not* be considered a big idea: Function.

Figure 2: Example Big Idea

The word *function* on its own would not be considered a big idea as it is not clear what about function is the important idea or concept. A better idea, if one wanted to make a statement about functions would be: *A function is a mapping between inputs and outputs such that each input is mapped to one and only one output*.

Following the introduction of the project and the initial presentation, we began a "brainstorming" session. The group was asked to propose some organizing principles within their domain of expertise. These were typed into a computer attached to a projector so all participants could see what was being recorded. This was critical as statements often needed to refined and edited several times before all members of the group were satisfied with them. It was also useful to allow participants to quickly state the ideas they thought were important—and then the language and exact wording could be changed as we went along. A critical component of this process was that these experts did not overly concern themselves with the ordering of concepts, or how they would be taught. Rather the emphasis was on the hierarchy of ideas around which one could design or organize courses of study at a later date. Several times during the meeting we could revisit this idea as participants tended to want to focus on what order you would teach concepts in.

The group of biologists very quickly came up with the theory of evolution as one of the overarching ideas in biology. Another big idea was the characteristics of life. When the preliminary list of big ideas had been determined, we, as a group, attempted to refine the statements and add in some supporting ideas. The supporting ideas are those that help further refine and explain the big ideas. An example of one of the big ideas and initial supporting content notes (in this case in earth science) is shown in Figure 3.

Big Idea: Plate tectonics is the theory that Earth's surface is broken into pieces called plates that move and interact with each other in three basic ways: they collide, pull apart, and slide past each other. Plate tectonics provides the framework for understanding earthquakes, mountain building, volcanoes, and features of the ocean floor.

Supporting Ideas:

a) When earth's surface collides it….

b) When earth's surface pulls apart it…

c) Earthquakes occur when…

d) Volcanoes form when….

Figure 3: Big idea and supporting idea—initial notes.

Discussions took place over two days until a list of ideas was finalized. While there was some discussion on small issues (mostly on how to word, or define the supporting concepts), the experts agreed on the major organizing principles within the domain.

During the meeting, not all of the supporting ideas were fully developed. In most cases, some of the ideas were developed and others were left as rough headings. The experts created a list of headings they thought belonged with a certain big idea and this list was filled out following the session. As the supporting ideas were added, the list was sent around to the participating experts (those who had volunteered) for verification and modification as needed. Figure 4 is an example of a revised big idea and some of the supporting concepts for plate tectonics (the list of supporting ideas is an excerpt of a longer list):

Biological Use of Energy

Living organisms need energy to live. Some living things use sunlight for energy. Others get it from consuming other life forms. Energy from either source is not always directly usable. Living things convert some forms of energy into the chemical energy of those compounds that support life.

Supporting Ideas:

a) Cells perform three main kinds of functions that require energy: mechanical work, transport of molecules, and chemical transformations.

b) Chemical reactions that break bonds in organic molecules such as glucose can provide energy for chemical bonds in other molecules, such as adenosine triphosphate (ATP).

c) Adenosine triphosphate (ATP) is a complex organic molecule with energy stored in its triphosphate "tail." The energy stored in the bonds of these molecules of ATP is the most common direct source of energy for most cellular processes.

Figure 4: Example of big ideas and supporting idea generated by experts

To date big ideas meetings have been held in biology, physics, chemistry, geometry and algebra. These subsequent meetings were held in the same way as the first biology meeting, with the exception that for some subject areas we had a larger number of participants. At each meeting we found the breadth of experience and concentration within a discipline to be very beneficial. In all cases, we included both research-professors and teachers (at the college and high school levels) with different fields and study and areas of expertise. Experts agreed (sometimes after a period of discussion) on the major organizing principals in a domain, across all these subject areas. Much as the earth scientists agreed that plate tectonic theory was a very important big idea, the physicists tended to organize their thinking around the concepts of energy and matter. Similarly, life science experts agreed to on the importance of the theory of evolution and also the concepts of energy and how they relate to living things. Figure 5 shows examples of two big ideas, and related supporting ideas elucidated during the meetings with physicists and life scientists.

Physics: Motion: *Classical motion can be explained by applying Newton's laws of motion*

Supporting ideas:

a) Classical motion is the motion of everyday objects from atoms to galaxies.

b) Mechanics describes motion with velocity and acceleration

c) Acceleration is the rate of change of velocity and is a vector quantity

d) If the speed and/or direction of an object is changing, there will be some acceleration.

Life Science: **Chemical Basis for Life:** *Chemicals structured around carbon are the basis of life. The most important are carbohydrates, proteins, lipids and nucleic acids. Living things use these compounds in a water solution to meet challenges of getting and using energy, reproducing, and maintaining their structure.*

Supporting Ideas:

a) Organic compounds contain carbon. Carbon atoms are the building blocks of molecules. Their ability to combine in many ways with other carbon atoms and with other elements gives them the ability to make many molecules with a wide range of characteristics.

b) The chemistry of life takes place primarily in water solutions, and depends on the presence and properties of the water.

c) Carbon, hydrogen, oxygen, nitrogen, sulfur and phosphorus are the most common elements in organic compounds.

d) The four main classes of large molecules that make up living organisms are carbohydrates, proteins, lipids, and nucleic acids. Large molecules like these are called macromolecules.

Figure 5: Examples of big ideas and supporting statements

Instructional and Assessment Strategies associated with the big ideas

Unfortunately, school curricula, instruction and assessments do not always reflect what we know about subject area knowledge and how it develops. Too often, students are taught in a way that leads them to believe that learning means acquiring a huge number of meaningless facts and skills. As a result, most K-12 students never learn the big ideas in most subject areas (Schmidt, McKnight, & Raizen, 1997; U. S. Department of Education, 2002). Having carried out a rigorous analysis of domains to be taught, we have used them to many purposes including design of instructional materials and assessments. Most students need explicit instruction (e.g., clear definitions and explanations) on the big ideas in order to grasp them. And they need multiple opportunities to:

• Explain the big ideas and get feedback on their explanations

• Use the big ideas to understand and explain phenomena (e.g., how does the theory of plate tectonics account for earthquakes? what makes writing persuasive?)

• Identify situations in which big ideas apply and those in which they don't

• Figure out which facts and skills connect to which big ideas

The list of big ideas for a course can serve as an organizing framework for the course; e.g., as a way to review the objectives of the course to make sure that the big ideas are clearly and fully addressed. The big ideas themselves should be explicitly represented as course, unit, or lesson objectives in many cases it will require several objectives (not necessarily in the same unit) to adequately address a big idea.

The big ideas should also be present in the assessments. Asking a student to explain a situation using the concept of plate tectonics and perhaps apply it to a novel situation, would be allow the student to indicate a deeper level of understanding than would just asking for a definition, or having the student put some numbers into a formula. Figure 6 outlines the assessment strategies that can be used to assess understanding of the big ideas.

A. Define or state the big idea
B. Explain the meaning of each of the terms used to define or state the big idea
C. Explain the idea in their own words
D. Explain why the big idea is important
E. Recognize many different situations in which the big idea applies; e.g., situations that can be explained by the big idea
F. Apply the big idea to relevant situations and problems, including ones not encountered before
G. Use the big idea to solve problems and justify problem solving procedures (e.g., explain why a particular procedure works, using the big idea)
H. Recognize situations in which the big idea does not apply
I. Distinguish true from false statements about the big idea
J. Use the big idea to make inferences (e.g., infer causes) or predict consequences
K. Connect other concepts, facts, and skills with big ideas

Figure 6: Assessment strategies associated with the big ideas:

Further examples of how the big ideas can be used in both instruction and assessment will be addressed, alongside a more comprehensive look at the big ideas list in biology and how we can make a subject area map from these ideas.

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