

## **A Science Education that Promotes the Characteristics of Science and Scientists: Features of Content, Activities and Materials**

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*Editor note: This is the second in a series of four articles regarding the nature of science, and how it relates to STEM education.*

Those involved in STEM research are well aware of why what they are investigating is worth pursuing. They also conceptually understand the rationale for the research activities and tasks they undertake and why the equipment and other materials they employ are needed in their work. Similarly, STEM education students should understand what makes the content they are studying worthwhile, the conceptual basis for the activities and tasks they partake, and conceptually understand the role materials play in their work. Moreover, STEM educators at all levels should deliberately think about *their* rationale for all of this, and overtly draw students' attention to, and have them reflect on, the conceptual nature of these issues.

### **DECISION-MAKING FRAMEWORK FOR PROMOTING STEM EDUCATION GOALS**

In the first article of this series, the science education goals appearing in Table 1 were put forward as reflecting the "attitudes, understandings and skills that make for a well-educated (as opposed to trained) self-actualized, caring curious, motivated, responsible and reflective human being" (Clough, 2015, p 25).

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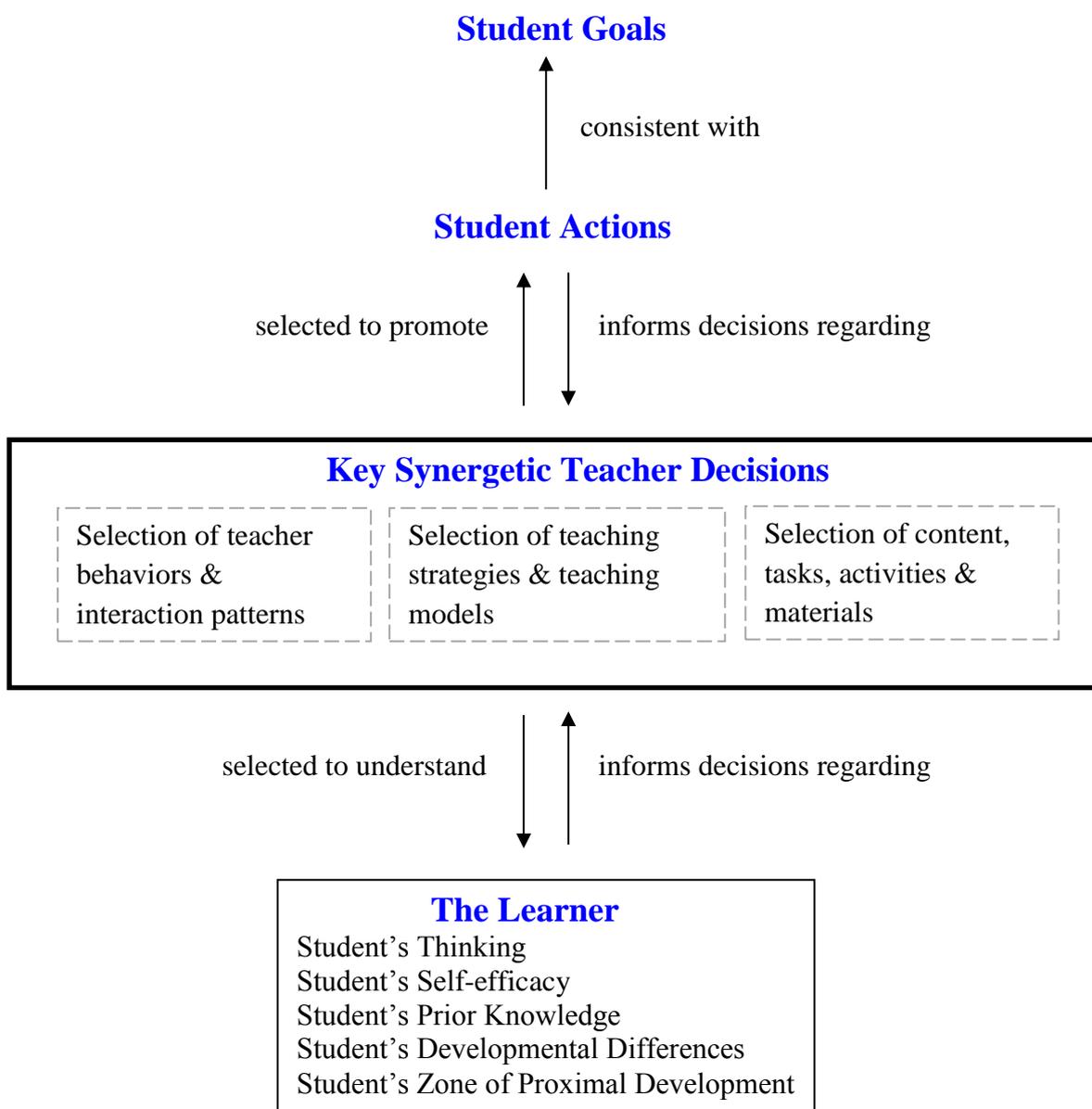
Table 1. Goals for science education

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- Demonstrate deep robust understanding of fundamental science concepts.
  - Exhibit an accurate understanding of the nature of science.
  - Exhibit an accurate understanding of the nature of technology and engineering.
  - Identify and solve problems effectively.
  - Be creative and curious.
  - Use critical thinking skills.
  - Use communication and cooperative skills effectively.
  - Actively participate in working towards solutions to local, national, and global problems.
  - Set goals, make decisions, and accurately self-evaluate.
  - Access, retrieve, and use existing scientific knowledge in the process of investigating phenomena.
  - Convey self-confidence and a positive self-image.
  - Demonstrate an awareness of the importance of science in STEM and STEM-related careers.
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Figure 1 illustrates crucial decisions that STEM educators should deeply consider when planning instruction (Clough, Berg & Olson, 2009). The “Key Synergetic Teacher Decisions” appearing in the center of the figure are, of course, made by all STEM teachers, but too often arbitrarily without assiduous attention to student goals, how people learn, and education research. The arrows in the decision-making framework convey that all teacher decisions regarding the selection of content, tasks and activities, materials, instructional models and strategies, and teacher behaviors should be made in light of desired goals for students and how students learn.

Figure 1. Framework Illustrating Teacher Decisions and their Interactions (Clough *et al.*, 2009)



Articulating student actions consistent with desired student goals is important for establishing and keeping in mind what student activity ought to be pervasive in STEM classrooms. Table 2 lists just some of the many student actions that would be commonplace in a STEM classroom directed at the goals appearing in Table 1. Once established, the desired student goals (and more concrete student actions) along with an accurate understanding of how students learn should together inform teacher decision-making.

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Table 2. Examples of student actions congruent with goals

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Students will:

- generate unique work.
  - express concepts and ideas in their own words and multiple ways.
  - make accurate connections between new and previously learned ideas.
  - ask perceptive questions regarding STEM.
  - accurately express the differences, similarities and interactions between basic science, applied science, engineering and technology.
  - question sources that misportray STEM content and/or the nature of science and technology.
  - express ideas in multiple formats using tight logical sequencing, correct grammar, and spelling.
  - identify inaccurate stereotypes of those in STEM careers.
  - accurately connect STEM ideas to everyday phenomena and socio-scientific decision-making.
  - accurately apply STEM knowledge in inquiry experiences.
  - accurately identify fundamental STEM ideas and what makes those ideas fundamental.
  - exhibit perseverance at tasks, even in the face of setbacks and frustration.
  - acknowledge and respond respectfully to others' ideas.
  - develop action plans for achieving desired STEM education objectives.
  - appropriately use equipment.
  - volunteer for tasks and effectively complete them on time.
  - identify careers that appear not to involve STEM, but how STEM knowledge is required.
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## **A SCIENCE EDUCATION REFLECTING SCIENCE AND HOW STUDENTS LEARN**

Inquiry has in one form or another been part of the science education landscape for at least 150 years, had advocates even further in the past (DeBoer, 2006), and has for some time been at the center of science education reform efforts. Clearly, the longstanding efforts to move science education toward inquiry reflect an earnest desire to have students understand science and how it is done, unlike the many ill-conceived education fads that come and go. However, confusion often exists regarding what inquiry science teaching means and what it looks like in the complex world of classroom teaching. Inquiry science teaching is conceptualized in a variety of ways, but two broad categories are

- 1) teaching science *as* inquiry (helping students understand how scientific knowledge is developed) and
- 2) teaching science *through* inquiry (having students take part in inquiry activities to help them come to more deeply understand science concepts).

When done well, inquiry science teaching accomplishes both while also promoting all student goals appearing in Table 1.

Drawing from an understanding of the counter-intuitive nature of many science ideas and the research of cognitive scientists regarding how students learn, students' struggles to really grasp science ideas make sense.

Importantly, the decisions that students make during inquiry experiences and their rationales for those decisions provide knowledgeable science teachers with what may be the best vantage point for determining students' thinking. Understanding students' thinking and how they learn is the foundation for informed teacher decision-making and effectively teaching science. This information is crucial for making appropriate pedagogical decisions that encourage students to question their prior thinking and move toward an accurate and robust understanding of fundamental science ideas.

Inquiry science experiences, when they are well conceived and effectively implemented by teachers, encourage students to be both mentally and physically engaged in ways that rarely occur in other science education experiences. The decisions that students must make when taking part in inquiry demand that they consider the end in mind, access their prior knowledge, apply it to the situation at hand, and assess their progress. All this requires extensive mental activity reflective of what cognitive scientists have established is central to learning. Inquiry teaching and learning is not a fad! It has a long history, reflects how people learn, and promotes the science education goals we have for students. That is why we must teach science *as* and *through* inquiry.

### **Features of content**

The selection of what science content to teach is crucial and should reflect deep thinking about the structure of the discipline, how students learn, the importance of teaching science through and as inquiry, and other important factors. Too often the selected textbook defines the course scope, sequence, and depth implying that a textbook's inclusion of information alone legitimizes teaching that content (Stake & Easley, 1978; Weiss, 1993; Weiss *et al.*, 2003). Textbooks also exert a significant influence on *how* content is taught—from the sequence of material to the manner in which it is presented (Weiss *et al.*, 2003). The issue here is not the value of textbooks, but rather the role they play in determining the curriculum and mode of instruction. Textbooks can certainly serve as a tool to assist in teaching and learning, but they should not dictate or even play a primary role in determining the scope, sequence, and pedagogy of a course.

Many factors ought to affect what content is taught in a science class. Certainly a district's and/or state's province's or nation's curriculum plays a necessary role, but too often these guides are simply the result of placing in outline format the content contained in adopted textbooks. High-stakes testing plays an increasing role in deciding what content to teach, but it often exerts more influence than the substance of those tests dictate. That teachers predominantly attend to these two prior constraints reflect the reality of teaching in today's schools. However, professional educators must understand and convey to parents, administrators and policymakers more defensible criteria for deciding what content to teach students, and participate in policy decisions regarding high stakes testing. For instance, the first goal in Table 1 calls for studying in depth particular fundamental concepts in a field, rather than glossing over large amounts of material. The *Next Generation Science Standards* (NRC, 2013), *Project 2061* (AAAS, 1989), *Benchmarks for Science Literacy*, (AAAS, 1993), *Atlas Of Science Literacy* (AAAS, 2001) and other science education reform documents are indispensable for identifying such fundamental science ideas. And yet, basing content decisions solely on fundamental science content reflecting the structure of disciplines is also problematic as it ignores or downplays the importance of students' interests, contemporary issues, and content that is germane to particular localities (DeBoer, 2000; Fensham, 1987). All the student goals in Table 2 along with how students learn ought to exert significant influence on what content is chosen for instruction. Students' prior knowledge and skills,

their ability to handle abstractions, and group dynamics all affect what content is within students' zone of proximal development.

The phrase "spiraling curriculum" is often used to convey the forward progress that occurs while at the same time revisiting previously introduced content in new and more complex contexts. This approach encourages students to make more connections between concepts, thus bolstering their stability. However, more robust and long-term learning demands that science content be linked to actual experience. Thus, practical inquiry experiences both within the discipline and also drawn from students' everyday lives must be an integral part of a spiraling science curriculum. Figure 2 (Robinson, 1968) illustrates why both repeated exposure to concepts in different contexts *and* connections to experience are necessary. If learning is thought of as the development of a very complex concept map, ideas having multiple links (e.g. c6) are likely to be well understood and long lasting. Concepts with only one link (e.g. c8, c12 and c13) are more tenuous and easily lost over time. Concepts c9, c10 and c11 convey a set of connected ideas that students are unable to link to experience. Insulated conceptual schemes may be much more elaborate than illustrated in the figure, resulting in declarative knowledge that in the students' minds has no basis in reality. Unable to make connections to the natural world, students must memorize significant amounts of content to pass an exam, but they cannot apply that knowledge to the natural world and social decision-making, resulting in what Resnick (1987) refers to as "in school vs. out-of-school" learning.

A spiraling curriculum that repeatedly revisits science concepts and does so in the context of meaningful concrete experiences (including everyday experiences) will promote connections between concepts, but also ground those concepts in experiences that ensure students link those concepts outside the limited school science setting. In doing so, long-term learning and social decision-making will be enhanced.

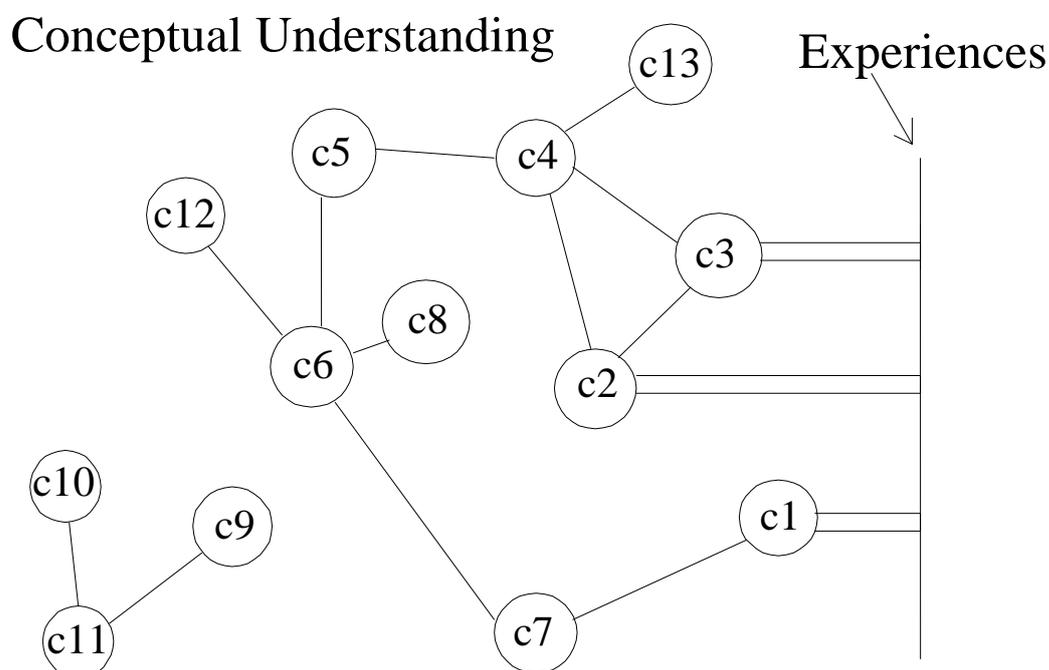
### ***Features of tasks and activities***

Prefabricated cookbook laboratory activities are enticing to both teachers and students because, in making most all the conceptual decisions for students, complexity is significantly reduced. However, as noted earlier, without significant decision making students are not encouraged to be mentally active, express their thinking, and face head on the inadequacies of their initial ideas.

What this means is that hands-on experiences, by themselves, are insufficient for helping students understand the scientific community's explanation for natural phenomena. Pre-fabricated cookbook activities, so ubiquitous in science teaching, rarely engage students in ways necessary to facilitate such an understanding. As Bransford *et al.* (2000) write, "Hands-on experiments can be a powerful way to ground emergent knowledge, but they do not alone evoke the underlying conceptual understandings that aid generalization" (p. 22). Students must also be mentally engaged, and teaching science through inquiry demands that mental engagement.

Developmentally appropriate and carefully created inquiry experiences provide wonderful opportunities for students to experience and understand much about the nature of scientific research. Because students have typically experienced only cookbook activities and highly structured laboratory reports, Colburn and Clough (1997) suggest a gradual approach to moving students toward more decision-making that will, in time, more accurately reflect authentic science. Early in the school year, teachers might have students decide how to convey the results of their laboratory work. This means deciding what to include in the report, whether or not to use data tables and graphs, and the order to present the information.

Figure 2. The Importance of Links between Concepts and Experiences



Lacking prior experience making these sorts of decisions, students will likely ask for clarification, but teachers must refrain from directly answering such requests for help. Rather, they should ask students what questions like, "What would a reader need to know to follow what your work and resulting conclusions?", "How might you present your data in a way that is easiest for the reader to grasp?", and "Who tells a research team exactly how to write their manuscripts for publication?" After students struggle through their initial draft, then have students meld into groups of four and share their reports reflecting on the pros and cons of the different approaches. At this time a classroom discussion regarding students' approaches, the pros and cons of each, and how this process mirrors scientists writing their laboratory reports should occur. Afterwards, students write their final draft to turn in. The process deeply engages students in the content illustrated in the lab experience while also explicitly teaching the nature of science (NOS) in a contextualized manner. And this process begins the journey toward more significant collaboration in class that is so crucial in authentic science research.

In later laboratory experiences, the lab and discussion of results are placed prior to the teacher telling students what "should" occur. Lab procedures may have to be rewritten so that they do not convey what is to be expected. This process is illustrated in detail by Clough and Clark (1994a) and Clark, Clough and Berg (2001). Colburn and Clough (1997) urge post-laboratory discussions where teachers ask questions such as "What were you investigating?", "What were your results?", "How was the lab procedure linked to the question you were investigating?" "What interpretations can be made about the data?", and "What have you learned from doing the activity?" Effective use of students' responses and referring to their lab results sets students up for the questions such as "What does your

struggle to make sense of the lab results indicate about scientific data?”, “Why would scientists looking at data have to go through the same struggle?”, and “What does this experience illustrate about the nature of scientific research?” Clough (1997) argues that “Student skepticism should be directed back to the laboratory procedure, evidence accumulated, and interpretations made” (p. 197). Experiencing aspects of authentic science, students will at times exhibit the frustration, excitement, setbacks, and uncertainty inherent in conducting research regarding the natural world. These same kinds of questions should be posed when analyzing the work of authentic scientists and how they and the scientific community came to the ideas that are too often wrongly communicated in school science as simply final form science (For example, see <http://www.storybehindthescience.org>). Teaching science through inquiry and as inquiry is not limited to conducting laboratory work, but should rather be pervasive throughout science instruction so that students understand how authentic science is done and the creativity, reasoning and evidence that underlie the fundamental science ideas we expect students to deeply understand.

As the school year progresses, more student decision-making should be promoted by having them decide how to go about investigating laboratory research questions. After several such experiences, students can then be encouraged to ask their own laboratory research questions and decide how to answer them. Such experiences will, of course, be limited by mandated curriculum and other constraints, but even AP course work is increasingly expected to include such investigations. For instance, the *AP Biology Course and Exam Description* (College Board 2013, p. 121) states:

Teachers are expected to devote 25 percent of instructional time to lab investigations and conduct at least two investigations per big idea. In conducting lab investigations, students will be encouraged to engage in the following:

- Generate questions for investigation
- Choose which variables to investigate
- Design and conduct experiments
- Design their own experimental procedures
- Collect, analyze, interpret, and display data
- Determine how to present their conclusions.

How this may be accomplished and the accompanying needed change in the teacher’s role (Colburn and Clough, 1997) appears in work by Clough and Clark (1994b), Clark *et al.* (2001) and Clough (2002). These kinds of experiences provide excellent opportunities to teach students the ways in which scientific papers and science textbooks distort how scientific knowledge is created and comes to be accepted by the scientific community.

### ***Features of Materials***

The choice of instructional materials is a more important and nuanced decision than many educators realize. During laboratory activities, materials may easily interfere with understanding targeted concepts or create misconceptions. For instance, in *Minds of Our Own* (1997), students were provided a simple bulb holder during a laboratory activity addressing circuits. Rather than see the bulb holder as merely a device for assisting in connecting wires to the bulb, it was wrongly interpreted as an essential part of a circuit, resulting in the misconception that a bulb could not be lit without it. Both the bulb holder and the bulb itself were, in students’ minds, either misunderstood or were black boxes that clouded the issue of a circuit. These and far more complex materials so common in STEM classrooms need to be examined by teachers and students so that students’ attention may be drawn to the conceptual nature of equipment relevant to the task at hand. Because

materials are designed and used with a purpose in mind, they possess a conceptual nature. Thus, as with the selection of content, tasks and activities, teachers need to examine materials, determine their conceptual appropriateness, and judiciously scaffold instruction to ensure students conceptually understand the role of materials they employ.

## RESEARCH-BASED DECISION-MAKING

Meaningful and effective STEM teaching and learning is complex. Relying on intuition and teaching style will not promote the noble STEM education goals we ardently have for students. The research base regarding teacher decision-making that reflects how students learn and promotes desired STEM education is robust and deserving of teachers' attention. Decisions regarding the selection of STEM content, tasks and activities, and materials should always be made with overt attention to the ends we seek and that research base. The next article in this series will address key features regarding teaching models, strategies and behaviors that reflect how students learn and promote the goals listed in Table 1, thus promoting among students the characteristics of science and scientists.



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