Reinventing the Science Curriculum

The Biological Sciences Curriculum Study proposes a curriculum that puts meaningful learning first.

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As the United States responds to such demands as preparing a 21st-century workforce, implementing rigorous high-stakes tests, and closing achievement gaps in schools, reforming science education becomes increasingly necessary. For many, the dominant model of curriculum development in science includes generating a topic, clarifying science content, identifying activities associated with the topic, and figuring out an assessment. Unfortunately, this approach tends to overemphasize activities and underemphasize mastery of science concepts and the process of scientific inquiry.

The National Science Education Standards (National Research Council [NRC], 1996) defines at specific levels what students should know and be able to do. These standards should stand as the learning outcomes for any science curriculum. In addition, educators need to consider some essentials that are as important to designing and developing an effective curriculum as they are to implementing one. These include focusing on how students learn; integrating laboratory experiences into other classroom activities; and ensuring rigorous, focused, and coherent content within a curriculum that focuses on the process of scientific inquiry and the acquisition of conceptual knowledge.

How Students Learn

Several decades of research in cognitive science have built a significant knowledge base about student learning (see Bransford, Brown, & Cocking, 1999; Donovan & Bransford, 2005). Three principles from this work establish the basis for designing, developing, and implementing an effective science curriculum:

- Students come to class with preconceptions about how the world works. The science curriculum must engage students in a process of conceptual change.

- Competence in science includes a foundation of factual knowledge, a conceptual framework, and a means to organize scientific knowledge. The science curriculum must include all three.
Students can learn to take control of their own learning by defining goals and monitoring their progress in achieving them. The science curriculum must include experiences that require metacognition and provide opportunities for students to engage in metacognitive practices, such as think-aloud problem solving and group work (Martinez, 2006).

Let’s consider an example of how instruction that aligns with these findings might play out in the classroom. Students often misunderstand the process of how plants acquire the energy they need for life and growth. Even though students know that most plants need sunlight to live, they generally do not understand that the process of photosynthesis is the primary means of life and growth for plants.

The following teaching sequence addresses this misconception. After the teacher has introduced the unit on the cell, the students record their ideas about how plants grow on one side of a T-table or in a double-entry journal. As they continue through the rest of the readings and activities, they record new ideas in the second column. Next, the students consider the complex activities that take place in the plant cell. They participate in an activity to explore the idea that plants exchange gases with the atmosphere and that light affects this process.

Through a series of short readings, students learn that plants use light energy, carbon dioxide, and water to make sugars and that these sugars are responsible for the growth and maintenance of the plant. To extend their understanding, students investigate how animals acquire energy for their growth and maintenance. Finally, to evaluate their understanding, the students trace an atom of carbon from the atmosphere to the muscle tissue of an animal. Throughout the learning sequence, students continually track their evolving understanding.

**Integrating the Lab**

A 2006 report published by the National Research Council, *America's Lab Report: Investigations in High School Science*, contributes another dimension to science curriculum development and implementation. The council found that among other problems, such as outdated lab equipment, unclear goals, and teachers’ unfamiliarity with lab work, the high school science lab was poorly integrated into the rest of the curriculum. The council proposed sequencing laboratory experiences with other kinds of science learning activities, such as reading, lectures, discussions, and computer simulations, thereby creating “integrated instructional units.”

For example, in a unit on natural selection, the process through which species evolve, reading about the process or listening to a teacher lecture is insufficient for sustained, enduring understanding. An integrated instructional unit would look somewhat different. After briefly introducing students to the process, a teacher would engage students in an activity designed to model the process. Students might act as predators (using tweezers or forceps) and hunt for organisms (colored dots) that inhabit a specific environment (a large piece of material with a patterned background). Each hunting event lasts 20 seconds. As the students keep track of their hunting success across several generations, keeping track of the survivors as well (those organisms they didn't spot in the amount of time available), they begin to notice that organisms more similar in color to the environment are more likely to survive and reproduce.
than organisms of colors that stand out against the environment. This experience is then reinforced through readings and classroom discussions. This integration of readings, activities, and discussion builds deep understanding and increases student interest. Students more easily master subject matter when they engage in scientific reasoning and grapple with how the natural world works.

**The Content Conundrum**

**Rigor**
Criticisms about the lack of rigor in the U.S. science curriculum center on its content, particularly the lack of a demanding conceptual orientation. For example, is a given curriculum oriented toward scientific concepts fundamental to a discipline or is it chock-full of topics and activities that are interesting and fun but don't emphasize fundamental scientific concepts or processes?

Instructional materials, teaching practices, and classroom climate must promote a learning sequence that allows sufficient time for students to explore concepts in depth, provides opportunities for students to represent their understanding in different formats, builds conceptual understanding, and makes important connections among concepts. The current climate of high-stakes testing is not conducive to this kind of learning because it often reduces content to a patchwork of activities pulled from here and there and reduces teaching to covering topics that may appear on a test. Although students go through the motions of completing activities, in the absence of a thoughtful and coherent sequence of learning experiences, it's doubtful whether they actually learn the targeted concepts.

**Focus**
Science curriculums in the United States also suffer from lack of focus; teachers are expected to cover too many new topics or ideas in a lesson, unit, or course. Focus should be a measure of the opportunities that a class or a course offers its students to master fundamental science concepts and hone inquiry abilities.

To effectively respond to the issues of rigor and focus in school science programs, science curriculums should focus on fundamental scientific concepts and inquiry abilities and develop them in depth. In addition to *The National Science Education Standards* (NRC, 1996), two other documents outline what students should know and be able to do in science: *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993) and the *NAEP 2009 Science Framework* (National Assessment Governing Board, 2006).

**Coherence**
Coherence refers to the organization of concepts and processes developed in a lesson, unit, or course within a school program. Coherence is also a measure of the connectedness among science concepts and processes that students experience during their study of science in the course of a single academic year as well as across several years.

F. James Rutherford of the American Association for the Advancement of Science described it
The topics and activities making up a science lesson or chapter ought to connect with one another to tell a (very limited) story, with, as it were, a discernable beginning, middle, and end. Similarly, the lessons or chapters making up a science unit should connect one another in interesting ways to tell a complete (but still limited) story, and units should connect with one another in interesting ways to tell a more comprehensive story. All of the parts forming a unit or course must be coherent, and all of those parts must join together to form a conceptual whole. (2000, pp. 22–23)

In a yearlong course in biology, for example, this “story” could be considered to have an hourglass shape: broad at the top and bottom and narrower in the center. Students might begin the learning progression with the big picture of the natural world. This would include an introduction to familiar concepts in ecology and ecosystems. Subsequent units of study would uncover in more detail how the natural world works. This would include focused explorations of heredity, cellular processes, and protein synthesis, for example. The final units of study would expand once again to include the broader contexts of evolution, unity, and diversity.

We can see the more comprehensive story in a three-year program in which high school students study multiple branches of science each year. During the first year, in the unit on physical science, for example, students study the structure of the atom and the physical properties of matter. During the second year, in that same unit, they tackle force and motion and the connections to chemical reactions. The third-year unit on physical science includes an in-depth exploration of energy in physical systems. Students are better prepared to grasp this sophisticated, abstract concept because a coherent science curriculum has provided them with solid conceptual understanding.

**Tying It All Together**

A good science curriculum should be rigorous, focused, and coherent; it should effectively integrate lab work; and it should take into account how students learn. What would it look like in action? *BSCS Science: An Inquiry Approach* (Biological Sciences Curriculum Study, 2006) offers an effective alternative to the traditional sequence of biology, chemistry, and physics. This standards-based science program, which is funded by the National Science Foundation, covers three years of high school science. Each year begins with a two-week unit called Science as Inquiry, followed by three core eight-week units that cover physical science, life science, and earth-space science. The final unit of each year is multidisciplinary and explores compelling issues in science and society.

**Science as Inquiry**

To understand science, students need to *do* science by participating in activities, completing projects, investigating questions, and discussing interactive readings. As they model how scientists do their work, students develop a better understanding of the process of scientific inquiry. They learn how to conduct a scientific investigation to answer a question about the natural world and to differentiate between evidence and inference.
In the 9th grade Science as Inquiry unit, students study the questions and concepts that guide scientific investigations—for example, What are the criteria for a scientifically testable question? Tenth graders start their inquiry unit by learning how to design scientific investigations and communicate results. For example, students design an investigation to answer the question, When washing your hands, is an antibacterial soap more effective than regular soap in reducing the number of germs on your hands? Eleventh graders take inquiry one step further by learning how to use evidence as the basis for explanations and models as well as how to create alternative explanations and models. For example, students examine the scientific evidence about global warming and consider how this evidence helps scientists improve the models of global climate change.

**Conceptual Understanding**

Each year, after students explore a component of science as inquiry, they focus on building conceptual understanding. For example, in the 9th grade science curriculum, students begin with the unit on physical science. They explore the building blocks of the universe, beginning with the atom. In the life sciences unit that follows, the 9th graders focus on another building block—the cell—exploring the important processes that take place and how those processes are responsible for living systems. They consider the role these core concepts play in the integrated setting of the natural world—by studying schooling behavior in guppies, for example, or how termites respond to changes in their environment—and they tackle problems and projects that involve these concepts in a context relevant to their lives. They might measure the amount of calories burned during exercise or discuss why a muscle becomes fatigued after lifting heavy weights.

In the earth-space science unit that follows, the 9th graders begin by learning about stars. Although stars represent a vastly different scale from that of the atom or cell, stars are nevertheless fundamental building blocks of the universe. Understanding what they are and how they behave is essential to understanding much about the universe's origin and evolution. The fourth and final 9th grade unit presents an opportunity for the students to build on what they have learned. Students explore ways that science and technology contribute to and affect society—for example, by helping people solve crimes or respond to natural disasters like wildfires or volcanic eruptions.

**Program Results**

We conducted a national field test of the BSCS inquiry approach with 9th and 10th graders from January through June 2002 (Coulson, 2002). The field test included urban, suburban, and rural classrooms across 10 states. Thirty-one teachers, 64 classes, and nearly 1,600 students were involved. Compared with their performance on a pre-test, students showed average gains of 20–25 percent in the post-test. Both general-ability and high-ability students showed significant increases in performance, as did classes that included students from all ability groups.

The past 50 years have taught us a great deal about science curriculum development and
implementation. Our field tests confirm that when the science curriculum includes the components discussed here, students build and deepen enduring understandings in science.

Why I Became a Scientist

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I often wonder whether I would have ended up doing something different if I had not had several outstanding teachers. I first became interested in science when I took a biology course as a high school freshman. John Collins made the subject come alive for me. The highlight of that year was the chance to dissect a frog and see firsthand how all of the organ systems worked together. The following year Harold Everett, a chemist who had spent most of his career at Dupont and had “retired,” taught chemistry at my high school. His enthusiasm for the subject was palpable. He started every class with a dramatic demonstration of what we were to learn that day.

I was convinced that I wanted to pursue a career in science. As a senior at Rensselaer Polytechnic Institute, I conducted independent research with Drs. Lenore Clesceri and George Pierce, studying bacteria from Lake George. I spent every spare moment in the laboratory and realized that I wanted to pursue a career in research. As a result, I have become a strong proponent of giving students the opportunity to experience hands-on science. Our fellowship program at The Institute for Genomic Research places 20 promising high school and college students into one of our research teams every summer.

References


