POLICY FORUM: SCIENCE EDUCATION

Coherence in Science Education

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There is widespread consensus on national standards for science and mathematics. The Project 2061 Benchmarks of the American Association for the Advancement of Science (AAAS) (*1*) and the National Science Education Standards (NSES) (*2*) published in 1996 by the National Research Council set out what high school graduates need to know, understand, and be able to do. They describe an educational system in which all students can achieve reasonable scientific, mathematical, and technological literacy.

In a world of exploding science-based technology, our citizens need a vastly better command of scientific knowledge than they now have. Since the 1983 report *A Nation At Risk* (*3*) questioned the quality of science education in the United States, hundreds of studies, panels, committees, and analyses of international tests have confirmed the deep systemic problems facing our educational system. The latest confirmation was the low rating achieved by 12th graders in the Third International Mathematics and Science Study (TIMSS).

High schools (there are about 15,000 nationwide) vary in how much mathematics and science they require for graduation. In fact, only half of high school graduates take as much as 2 years of science and less than a quarter of high school students take 3 years of science. To satisfy the NSES or Benchmarks requirements, a minimum of 3 years of science is needed. It is encouraging that there is a slowly growing movement across the nation to insist on at least 3 years of science and 3 years of mathematics.

We argue that there will never be a better time than now to construct a 3-year, coherent, integrated science sequence, appropriately blended with 3 years of mathematics. The objective is to build knowledge of science and the concurrent use of mathematics, following the hierarchical nature of science as it has unfolded over the past century. Today, students take biology first, then chemistry, and some 25% of the survivors go on to physics. The subjects are treated as completely independent and unrelated, to be learned (and forgotten) in the sequence taken. This is in spite of eloquent voices in the educational literature (*4*), who have in vain called attention to the absurdity of this sequence.

As an example, the noted physics educator Uri Haber-Schaim (*4*) selected two popular high school biology texts and searched for items that were used but not otherwise explained and hence were judged to be prerequisites. Examples, from a very long list, include acids, activation energy, pH, bases, catalysis, chemical bond, chemical reactions, conservation of energy, half-life, photosynthesis, and absorption spectra. The conclusion, after reading the entire list, is that chemistry is really a prerequisite for biology. The author continues by studying popular chemistry books to find physics prerequisites in chemistry and enumerates nuclear disintegrations, atomic size, electromagnetic radiation, electron spin, energy level transitions, orbital quantum numbers, electric field, radioactivity, and so on.

A group of scientists and science educators (*5*) has organized an informal alliance to begin the design of a coherent sequence that we call Science I, Science II, and Science III, as a 3-year core curriculum to stand alongside English, mathematics, and the social sciences. There are a variety of proposals in the educational literature that would satisfy the demand for coherence and integration. We will only discuss here what emerged from a recent workshop held in Chicago (*6*).

In our proposal, Science I has a focus on physics, taught conceptually but with enough mathematics to put to use the algebra learned in eighth and ninth grades. The use of algebra in practical problems not only advances mastery but should spark a realization that "Hey, this stuff is useful!" The curriculum here will start with the large world of physics that surrounds the students; it will be inquiry-based and will emphasize, in the spirit of Benchmarks' "less-is-better" mode, topics in physics that will have the most relevance to chemistry, biology, and earth sciences. This approach does not, however, neglect the integrity and coherence of physics as a discipline. A challenge to the detailed curricula that may evolve is to blend the concepts that cross and connect disciplines with the concepts that respect and extend disciplines. Common threads are stressed—including energy transformations, from electrical and mechanical to atomic, molecular, and nuclear; vibrations, from the simple pendulum to microwave spectroscopy; and circular motion, from atomic orbits to flywheels to planetary trajectories.

Ultimately, students will move on to Science II (focused on chemistry) with a good sense of the structure and properties of atoms and with experience in such applications as the kinetic theory of gases. Again, the chemistry sequence will encourage the use of higher-level mathematics, such as the solution of several equations with several unknowns or the use of graphing calculators. The students will use the content of Science I in a spiral learning cycle in which topics are not so much repeated as used. Science II will step back

The Cell Membrane

The cell membrane is made up of two layers of lipid molecules that form a flexible "sandwich" called a lipid bilayer (Figure 4.10). Each lipid molecule has an **electrically charged (polar)** head region and an **uncharged (nonpolar)** tail. The polar heads on both sides of the membrane are in contact with watery environments: the fluid outside of the cells and the watery cytoplasm inside the cell. Both of these environments, like the lipid molecule heads, are electrically charged. Proteins embedded within and on the bilayer perform a variety of jobs in the membrane. For example, some act as bridges or pumps that move substances into and out of the cell.

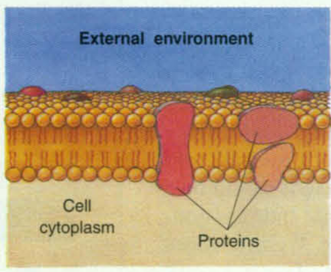

Figure 4.10 *The cell membrane is a lipid bilayer with embedded and surface proteins.*

Which should come first? A figure from an introductory biology textbook (9) that illustrates how knowledge of the chemistry of polar and nonpolar interactions is necessary for understanding biological membranes.

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from atoms to begin with large items: materials and their classifications and properties, chemical change, cycles, and reactions. However, compound formation could be qualitatively related to molecule formation and chemical bonding. The qualitative explanation of the periodic table of the elements in terms of electron shells may go beyond the proposed standard, but its inclusion in the curriculum should be a great temptation.

Science III, focused on biology, would then receive students who are well grounded in the basics of atomic and molecular interactions. For example, many molecules form polymers. What differentiates one polymer from another? How are these fundamental components used in various combinations to lead to the diversity of life? The appreciation of simple principles from physics and chemistry enables students to understand the natural way in which complexity arises. This understanding will facilitate discussions of DNA, in which the complex, three-dimensional structure, with various bonding mechanisms, is critically related to its genetic function.

The 3-year sequence should find the time to concurrently examine the process of science. Examples of this might include i) The nature of theory; how do we know?, ii) How do we learn?, iii) What we can trust and what is tentative?, iv) False roads in science, v) The crucial role of skepticism and of prediction, estimation, and probability, vi) How the role of technology has changed. Today, technology is entwined with modern science, and the connections are an important theme in the process of science.

The 3-year sequence will also introduce some experience of real-world interdisciplinary problems. Topics in earth and space science can serve as a thematic thread that uses physics, chemistry, and biology. For example, upper atmospheric chemistry, ocean solubility, photosynthesis, Earth's rotation, gravity, sources of internal and external energy—all contribute to an understanding of the forces that shape the planet.

Our objective, after all, is to prepare students for all possible futures by arming them with the scientific way of thinking. Out of this kind of curriculum will emerge students who are ready for Advanced Placement sciences, for a fourth-year course in earth and space science, for school-to-work transition courses, or for liberal arts colleges. The prospect of the high school science sequence should encourage school administration to create a seamless K–12 science education process.

We know of about two dozen schools in the nation that have been doing science in the right order with uniform enthusiasm. Experiences in some of these schools point to the new equity that such a sequence installs. The logical presentation of science concepts guides students who do not have the support system in mathematics and science that customarily produces good science students. They include girls, minority, and economically disadvantaged students.

The reform we are suggesting will require substantial resources and a new ethic of continuous professional development.

Table III

Modern Chemistry — Holt

Artificial nuclear disintegration, 632	Energy level transition, 102
Aston mass spectograph, 66	Fission, 643
Avogadro numbers, 69	Hybridization, 125
Atomic size, 535	Ionization energy, 101
Dipole attraction, 207	Isotope, Hydrogen, 64
Conservation of atoms, law, 162	Mechanical energy, 11
Conservation of electrons, 498	Neutron, 63
Conservation of energy, law, 12	Orbital quantum number, 79
Electromagnetic radiation, 76	Partial pressure, 217
Electron spin, 80	Potential energy, 11
Emission spectra, 543	Radiation energy, 217
	Radioactivity, 629

Physical underpinnings. Examples of physics prerequisites for understanding chemistry.

SOURCE: U. HABER-SCHAIM, *PHYS. TEACHER* **22**, 331 (1984)

We envision new teaching materials; new laboratories; enhanced educational technology; and new teacher training; but most dramatically, time for teachers to engage each other about teaching and learning. The new curriculum softens and makes permeable the traditional disciplinary walls and this requires the physics teacher to know more chemistry and biology and so on. These large requirements should not come as a surprise. If the nation wants high standards, it must provide the resources to enable all students to achieve these standards.

We should emphasize that there are other changes one could imagine, including moving the entire sequence earlier, perhaps to seventh grade, and stretching it out over the 6-year period. The suggestion of the Clinton Administration that all students be given an option of two additional years of schooling opens other possibilities. There is some interest in constructing interdisciplinary curricula, often strongly problem-based. In our opinion, the essential issue is the logical common-sense connectivity of the core sciences, what E. O. Wilson (*7*) calls "consilience": the essential hierarchical structure of science that enables teachers to guide students to discovering and hopefully to wondering at the marvelous tapestry of the world that disciplinary threads can weave.

In proposing this model of a coherent integration of the sciences, we are keenly aware of the difficulties of gaining its widespread acceptance. In this war on ignorance, our nation does not have a general staff to set strategy. We, in effect, must convince 15,000 school systems of the principles, at least, by which our model is guided. These are coherence, integration, movement from concrete ideas to abstract concepts, inquiry, logical sequencing to ensure use of concepts, the essential connectivity of disciplines, and societal implications. These principles are designed to ensure that a scientific way of thinking is instilled in all high school graduates.

There is the optimistic, yet reachable, goal in our 21st century schools of learning and teaching the connections among all areas of knowledge. These connections deepen our understanding of various disciplines and fortify one another across many layers. On the grand scale, they tell of the influence of history on science and the influence of science on history and philosophy. They illuminate the mechanisms by which art is created and appreciated, and they honor the humanistic spirit in humankind's quest to understand nature. On the small scale, we learn of the firing of neurons, complex molecules built of atoms obeying the laws of physics and chemistry, which causes our human consciousness to blaze with awareness, joy, and curiosity.

Michael Fullan writes: "As we head for the 21st century.... Teachers' capacity to deal with change, learn from it and help students learn from it, will be critical for the future development of societies" (*8*).

References and Notes

1. AAAS, Project 2061, *Benchmarks for Science Literacy* (Oxford Univ. Press, New York, 1993).
2. National Research Council, *National Science Education Standards* (National Academy Press, Washington, DC, 1996)
3. National Commission on Excellence in Education (NCEE), *A Nation at Risk: The Imperative for Educational Reform* (NCEE, Washington, DC, 1983).
4. Some examples from a larger literature: U. Haber-Schaim, *Phys. Teacher* **22**, 330 (1984); K. Reel, *Science Educ.* (1 April 1995), p. 31; C. R. Nappi, *Phys. Today* (May 1990), p. 32; F. R. Myers Jr., *Phys. Teacher* **25**, 270 (1987); J. Palombi, *ibid.* **9**, 39 (1971).
5. Project ARISE (American Renaissance in American Education) began at a 1995 Workshop in Naperville, IL. Since then, a steering committee consisting of Bruce Alberts and Rodger Bybee of the National Academy of Sciences, Shirley Malcom of AAAS, Gerald Wheeler of the National Science Teachers' Association, Marjorie Bardeen of the Fermilab Education Group, and Leon Lederman of IIT (Pritzker Professor of Science) have met occasionally in Washington, DC, to consult on next steps.
6. ARISE Workshop held in the Knickerbocker Hotel, Chicago, IL (18 to 21 February 1998) and supported by the U.S. Dept. of Education. Report available upon request from D. Koehnke, at Fermilab Education Office, Fermilab MS 226, P. O. Box 500, Batavia, IL 60510–0500 (phone: 630-840-3092).
7. E. O. Wilson, *Consilience: The Unity of Knowledge* (Knopf, New York, 1998).
8. M. Fullan, *Change Forces: Probing the Depths of Educational Reform* (Falmer Press, London, 1993), p. ix.
9. W. H. Leonard and J. E. Penick, Eds., *Biology: A Community Context* (South-Western Educational Publishing, Cincinnati, OH, 1998), p. 207.