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ARISE: American Renaissance in Science Education

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PREAMBLE

While the dashboards of today's automobiles contain more computer power than the Apollo 13 spacecraft, the classrooms of today all too often appear and function as they did 100 years ago. The world is in a time of unprecedented change, largely driven by science and technology. Yet schools do not teach science well. The demands for science literacy keep increasing whereas the students arriving in the high schools of the nation are increasingly less prepared for science and mathematics instruction. The lack of attention paid by the scientific community to the issue of science education in the schools has contributed to this poor state of affairs. Too many high schools are mired in disconnected, fact-loaded, assembly-line modeled curricula and pedagogy that bear no resemblance to the excitement of true scientific inquiry and discovery. Here and there, exemplary schools and school districts stand out as beacons of illumination and gladden the heart, but the 15,000 districts across the country move chaotically in all possible directions. In any case, schools are <u>not</u> producing:

- Science and mathematics literacy for <u>all</u> students;
- Citizens able to understand issues based in science and technology;
- Citizens able to discriminate between scientific understanding and personal belief;
- A capable work force for a modern technological society;
- People with a joy and pleasure in understanding a complex universe and the individual’s role in it.

Resistance to change is awesome. The national standards and state derivatives must be reinforced by models of curricular reform. In this paper, ARISE presents one model based on a set of principles—coherence, integration of the sciences, movement from concrete ideas to abstract ones, inquiry, connection and application, sequencing that is responsive to how people learn. Others may develop additional reform models that remain true to these principles. So much the better.

INTRODUCTION

Three decades ago, the United States entered and won the space race and launched an aggressive national effort to produce more world-class scientists, mathematicians and engineers. Yet a decade ago, the United States was recognized as a nation at risk due to an inability to deliver a quality education to all students. As a result, increasing numbers of high school graduates were unprepared to meet the demands of business and industry and to play productive roles in a society increasingly dependent on science and technology. The response to this crisis led to a set of national standards that rigorously asserted what all students should learn and be able to do.

Today, the nation has the challenge to ensure that all America's children have the opportunity to learn and understand science, mathematics and technology at the higher levels defined by national standards. The nation can no longer afford to have the fundamental tools of educational, economic and social viability be accessible only to some students. The long-term endurance of the "American Dream"—equal access to opportunities for success—is dependent on a dual commitment to equity and quality, particularly in science and technology education.

This new challenge has higher stakes than the space race with a shorter timeline and involves all students. It is essential that science education programs address the needs of students as future workers and citizens. Nothing short of a bold initiative and a vigorous, high-profile, sustained national commitment will enable us to reach this goal.

NEEDS

Every graduating high school student of the 21st century must be equipped to participate in, and help to shape, a society confronted with accelerating scientific advances. Careers and jobs will be based on those advances and the increasingly wondrous technologies that transform daily lives. The world is changing so dramatically that persons entering the work force with the skills and knowledge that was expected 30 years ago would be overwhelmed by today's technological job requirements. Industries cry out about the lack of adequately-trained workers. State and federal governments are confronted by new technologies that challenge the definitions and precedents of law. New ethical issues arise at every turn, from the Internet, from reproductive technologies, from genetic testing. Schools must respond to these challenges with new approaches that provide the student with a solid knowledge base and prepare the student to continue learning.

The project to map the human genome could not have been imagined 30 years ago. Today, it is in full swing. It promises nothing short of a “user’s manual” for human beings. Tomorrow, it will be the source of new jobs in health care, medicine and agriculture. How will today's high school education prepare students to learn the new fields derived from mapping the human genome? How will they weigh in on the social and legal problems that such knowledge surely will create? And how will they modify their personal behavior to take maximum advantage of this new knowledge? Scientific understanding and habits of mind are essential to reaching these goals.

The nation's success in the 21st century requires that all citizens be scientifically literate and savvy. This changes is a dramatic one for an educational system whose culture rested on the belief that the system must focus on training future scientists and engineers, because science was not for everyone. Today, denying any children these keys to the 21st century would be as foolish as it would be unjust. The science and mathematics in this proposal is for all students. Leaders, parents and workers must:

- Be responsive to accelerating change driven by new technologies.
- Work together to find measured yet creative solutions to problems which are today unimaginable.
- Anticipate the impacts of their actions.
- Communicate effectively about science and technology.
- Maintain the balance among society, economic growth and the environment.

Measured against these needs for students with developed scientific understanding and habits of mind, the nation's high school graduates today emerge largely unprepared. US high school seniors who have taken physics have scored dismally in the international TIMSS tests announced in February, 1998. Fifteen years after the report, *A Nation at Risk*, warned the country about its failure to educate the nation's children, the education systems are fragmented into 50 states and 15,000 school districts often confused by educational ideology, heartened by warm, fuzzy anecdotes of success but seemingly oblivious of the fact that education has changed so little. Although the past five years have indeed shown signs of awareness and even of encouraging improvement, progress is glacially slow. The key question is why do the nation's students (and those who take high school physics are among the best) do so poorly compared to those in other countries? Why is the population so ignorant of science, both the process and the content? Among the most obvious failures:

- Students arrive in high school from K-8 with poor preparation and poor attitudes toward mathematics and science.
- Most states require only two to three science courses in high school (grades 9-12) rather than a coherent sequence.
- In the vast majority of high schools the sequence of study is biology, chemistry and physics. The most frequently taken course is descriptive biology. Only one-half of the students complete chemistry, and only one-fifth complete the entire sequence.

- Most of the science requirement is fulfilled by courses constructed as if they are discrete, disconnected disciplines. These courses are collections of facts and principles to be memorized. The science curriculum is structurally flawed.
- Most students do not have access to important emerging ideas in biology since it is usually offered as a first or second science course without physics or chemistry as prerequisites. Yet modern biology requires knowledge and skills drawn from chemistry and physics.

It is time to critically examine the curriculum that has been offered in US high schools during the past 100 years. High schools overwhelmingly insist that students start their science study (and often end it) with ninth or tenth grade biology, occasionally preceded by a course in descriptive earth science or an introduction to physical sciences.

The sequence of high school study in science—biology, chemistry and physics—was set out in 1894 on the basis of a prestigious national commission (The Committee of Ten). Today’s high school science courses, largely textbook-driven, are treated as independent and unrelated. This, in spite of eloquent voices in the educational literature who have, in vain, called attention to the absurdity of the sequence.[1] The sequence is inappropriate and does not respect developments in the disciplines over the past century, nor does it respect changes in mathematics teaching, with algebra now introduced as early as eighth grade.

As an example, Uri Haber-Schaim selected two popular high school biology texts and searched for items which were used but not otherwise developed, and hence were judged to be prerequisites. Examples from a very long list include acids, activation energy, pH, bases, catalysis, chemical bonding, chemical reactions, conservation of energy, half-life, photosynthesis and absorption spectra. After reading the entire list one gets the idea that chemistry is really a prerequisite for biology. The author continues by studying popular chemistry books to find physics prerequisites in chemistry such as nuclear disintegration, atomic size, electromagnetic radiation, electron spin, energy level transitions, orbital quantum numbers, electric field, radioactivity and so on.

To pursue this mismatch of the biology-chemistry-physics sequence a bit more, consider the following statement: “The transmission of sodium and potassium positive ions through cell membranes is crucial to the functioning of nerve impulses.” In this one sentence are essential physics and chemical concepts applied to a vital element of biology. If students do not know physics and chemistry, they are forced to memorize a description of nerve impulses. Without physics and chemistry as prerequisites, it’s the best that can be done.

The science of biology strives for explanations of important processes at the level of cellular events, rather than mere descriptions. That a prerequisite of high school levels of physics and chemistry could provide such explanations is the essence of students learning science like scientists learn science. This teaches the science way of thinking.

Consider another example. The gas laws developed by chemists relate the pressure, temperature and volume of gases, clearly important laws in our understanding of the nature of matter. These are usually given as simple equations (the ideal gas law) suggested by experiments; i.e., increasing the volume of a gas at fixed temperature decreases its pressure or increasing the temperature of a gas at fixed volume increases the pressure. These laws tersely describe the way nature works. The explanation of why these things happen is derived by a simple model of the gas as a collection of atoms, in constant motion, whose average speed is related to the temperature of the entire collection. Now the gas laws become lucid. Pressure is the result of the impact of a huge number of atoms on its confining surfaces. If the volume increases, the lower density of atoms decreases the number of collisions per second; i.e., the pressure is decreased. If the gas is heated, the atoms speed up, increasing the number of impacts on the surfaces; i.e., the pressure is increased. Even though atoms are not visible, the large number of different phenomena are explained by the existence of atoms gradually demonstrates their reality. It is evident from these examples that a hierarchy of explanations should be reflected in the teaching of science.

As an important reaction to the general perception of weakness in our science education, new science and mathematics standards have arisen to determine what American high school graduates should know, understand and be able to do. Standards are based on the belief that given the motivation and resources, the large majority of students can achieve to the level of the standards. Two detailed efforts have achieved wide national consensus: the AAAS Project 2061 Benchmarks and the National Science Education Standards (NSES) published by the National Research Council. Mathematics Standards were developed by the National Council of Teachers of Mathematics (NCTM). Reaching these standards requires that all high school students take at least three year of science and three years of mathematics.

There is a golden opportunity here for a complete reworking of the high school science sequence: new content, new instructional materials, laboratories, assessment tools and teacher preparation requirements. Such reform also implies a new paradigm for American educational practice. Resources must be built in for continuous training of teachers including ample time for teacher-to-teacher communication.

The proposed course sequence that follows respects the new national standards and puts a great deal of emphasis on the methodology for bringing all students at least to the level of the standards, blending in the mathematics sequence so that the science utilizes and exercises the students' increasing mathematical knowledge. Institutionalizing changes of this magnitude will require marshaling new resources and huge systemic support. However, the possibilities of a coherent organization of science education stressing the logical connectivity of the disciplines are exciting. The successful blending of the sciences and mathematics revives the age-old belief in the fundamental unity of knowledge. Also, this approach is compatible with the progress in the neuro and cognitive sciences.

ORGANIC PARADIGM OF LEARNING

The neuro and cognitive sciences are actually able to “see” a living brain as it learns. These sciences teach that the old or mechanistic paradigm of learning does not describe the way the brain develops. This mechanistic paradigm was grounded in three dysfunctional constructs or metaphors: brain as serial computer, learning as information accumulation and mind as *tabula rasa*.

Emergent knowledge about learning shows that:

- The brain does not function in a serial manner, but rather acts more as a parallel processor able to process many different kinds of information simultaneously.
- Learning is not information accumulation, but an internally and socially mediated process of constructing meaning from patterns created through multiple representations of knowledge.
- The mind is not a blank slate, but a dynamic, self-organizing “plastic” neural network that learns best when the context of learning is embedded in the entire physiology—including the body and the emotions.

This new paradigm or more dynamic and organic approach to learning requires that educators create conditions for learning that enable learners to:

- Process many different kinds of information simultaneously.
- Understand information when it is embedded in messy yet relevant, authentic, novel, challenging and information-rich contexts.
- Construct meaning through connections and pattern formulation.
- Organize and associate new information with their existing knowledge.
- Collaborate with peers and adults in challenging (but not threatening) endeavors.

- Actively and continuously engage in the practice of their new learning by constantly revisiting it at increasingly higher levels of complexity over extended periods of time.

This new “learning about learning” effectively frees educators, parents and policymakers to use new knowledge in creating coherent and integrative conditions and environments, inviting the fullness of the students’ capacity.

The human brain is “wired” to learn constantly. But with the mechanistic paradigm of learning, schools have created learning-antagonistic environments stifling children’s innate curiosity about the natural world. The organic paradigm of learning offers a way to create learning communities within classrooms and schools that rekindle the students’ inquisitiveness and desire for exploration and discovery.

VISION OF THE SCIENCE CLASSROOM

There are two aspects of the classroom vision. First, what is the physical arrangement of the classroom? Second, what is going on in that classroom? The following summary of "best practice" teaching and learning describes an environment for implementing new teaching methods based on new information about teaching and learning. As always in this white paper, "best practice" means utilizing teaching and learning strategies advocated in the NSES and Benchmarks. There are many resources listed in the Bibliography that provide detailed information (see for example, Good and Brophy, 1991, and Kober, undated). This section presents an overview.

"Best Practice"

Educators agree that science should be taught in the schools in ways that reflect actual science practice. "Best practice" essentially means engaging students in explorations that reflect real science. Students can do research on what is already known, collect, record and analyze data, propose answers and support their explanations with evidence and communicate results. Real-life scientists and student scientists engage in virtually the same types of behaviors, although perhaps not on the same scale.

In the decades before science education reform, science "laboratory investigations" would engage students in a step-by-step process leading to specific answers. These exercises were called "cookbook activities." Although students may engage in similar exercises in the age of reform, the way students collect, display and analyze data, and use these data to support their explanations, characterizes "best practice" learning. For example, students may measure the density of various objects. But instead of producing the correct measurement as the object of the investigation, they might analyze their measurements (data) to generalize about the relationship between mass and volume as a function of density.

Traditional instructional methods, such as lecture, drill and practice, and the use of textbooks, may still have a place in reform-based classrooms—but with a different spirit. Lecture takes on a Socratic method or includes frequent discussion. Textbooks become a resource rather than defining the curriculum. The classroom spirit is one of inquiry, curiosity, skepticism and open-mindedness, regardless of the instructional method.

"Best practice," then, is characterized by students engaging in authentic science experiences. Teachers facilitate the process. A summary of teachers and student behaviors in reform-based science education may be found in Appendix A. Both the

NSES and Benchmarks clearly delineate what “inquiry” means for students in all grades. This will not be further discussed here.

Classroom View

Reform-based science classrooms show that students are encouraged to work together through the specific arrangement of chairs and tables. The classroom may be noisy due to all the student activity. If the teacher is in front of the room, she or he is probably having a discussion with students. There are posters and student work displayed on the walls. Materials or equipment may be stored in corners, evidence of not-yet-completed ongoing student projects. If students are engaged in an activity, they are clustered in groups or pairs gathering data. The teacher is moving from group to group asking questions to clarify student understanding.

Ideally there are two sections in the room, one a laboratory, the other for discussions and presentations. The laboratory has benches or tables with gas outlets and access to a water supply. Appropriate supplies and instruments are available for every two students, such as test tubes and racks, microscopes and weighing balances. Hoods, emergency showers, and other such devices are available in areas where safety is an issue. There is either a computer area or computer stations for recording, analyzing, and displaying data.

The discussion area has moveable desks or chairs that can be arranged for small group discussions or whole group presentations. There is a demonstration table with gas outlets and sink for laboratory demonstrations and/or presentations. Instructional materials include an overhead projector, whiteboards or chalkboards, video monitor, VCR, flipcharts, display charts and models. The teacher's desk might be in this area with a computer dedicated to his or her needs.

The computer area or computer stations include one computer for every four students. At least two of the computers have telephone links to the Internet. One or more are linked to CD-ROMs. Ideally, most of the computers have microcomputer-based laboratory hook-ups for collecting and displaying data. An LCD or other device is available for displaying computer screens to the whole group. Books, publications and other print materials are available as resources.

By the time any of these concepts is widely accepted, the use of computers in the classroom will have evolved considerably. The high school freshman of the year 2000 may have first encountered computers in kindergarten. This issue is not so much how the technology will have advanced, but how the educational technology has been honed toward the best possible influence on the learning process. This will play a huge role in education's major task—to train the student in "finding out," with the skilled use of library, Internet and other sources.

This is the ideal, but the ideal is not essential for realizing the classroom vision. For example, one of the best teaching and learning situations we encountered in visiting classrooms all over the US was a small classroom with blackboards, a teacher's desk, 20 moveable student desks and a filing cabinet as the only permanent structures. Upon entering the classroom, it took more than one or two minutes to find the teacher who was huddled together with four students around a computer on a rolling cart. Another five students had arranged their desks in a discussion group around a student at the blackboard who was acting as recorder. It turned out that several students were out of the room at the library researching questions that had arisen the previous day. The remaining students were writing in their science journals. It was a twelfth grade physics class of 15 students that had most of its laboratory sessions across the hall in a small laboratory or, often, outside such as when they tested their handcrafted rockets on the football field. The day of the visit all students were working on a collaborative whole class project that, by their own design, required the use of technology such as video cameras and hypertext software.

All tools and materials of the ideal were available to them, just not right in that classroom.

VISION OF THE HIGH SCHOOL SCIENCE CURRICULUM

To satisfy the national standards, high school students need to take at least three years of science and three years of mathematics. The three years, as a core curriculum, should be coherent, reinforcing the disciplines and the connections between them and leading to a student who is comfortable with science, technology and the scientific way of thinking. Thus, schools should devise a coherent core curriculum to stand alongside English, History and Mathematics: Science 1, 2 and 3. Using the scientific advances in Physics, Chemistry, Biology and Earth and Space Science, schools should build a sequence which begins, in ninth grade, with a focus on physics—concrete, addressing problems that students will recognize involving motion and force, replete with examples from their daily experiences but spiced with applications to such “Star Trek” activities as space, galaxies and black holes. Schools should continue to offer AP courses in the core disciplines and fourth-year electives in earth science, astronomy, ecology, school-to-work transitions, and science, technology and society. This proposal for a core science requirement for all students should lead to more students taking more science.

Gradually, physics guides the student to enter the realm of increasingly abstract ideas like energy and ultimately atoms. The end product of Science 1 is a student who understands the atom, its structure and its social behavior, which is a product of electric forces and atomic theory. The mathematics used would be appropriate for ninth grade, offering an added benefit from ninth-grade physics: The early realization that even simple algebra is useful.

To illustrate the progression, students in physics learn qualitatively that atoms exert forces on one another.

> *These forces are sometimes attractive whereupon the atoms can combine to form a molecule. In other cases they repel one another. Two molecules, colliding, can exchange atomic partners in a process which we call a chemical reaction. Atoms are very special: they like certain partners, even certain directions in which connections are made. For example, an oxygen molecule (two atoms of oxygen) can come over to a cluster of carbon atoms. Oxygen atoms love carbon atoms (strong attraction) and the carbon-oxygen system can snap together with a tremendous vengeance and commotion; everything nearby will pick up some of the energy. A large amount of motion energy, kinetic energy, is thus generated. This is of course, burning.*[2]

Science 2 (focused on chemistry) would engage in the combination of atoms: molecule formation—or in more conventional chemical terms, elements combining to make compounds. One branch of chemistry, for example, established that all substances are arrangements of atoms. These are three-dimensional arrangements, and fantastic detective work goes into learning these arrangements. Examples can be drawn from geology and ecology to present students with a base understanding of issues in earth science. It was the study of chemical compounds in the 1800's that led to the first proof of the existence of atoms.

Science 2 graduates go on to deal with complex molecules, which are at the base of modern molecular-based biology: cells, tissues, proteins, genes and DNA in Science 3 (focused on biology). Here arrangements of atoms are crucial to the enormous variety of processes that contribute to living matter. In this sequence, opportunities for emphasizing the connecting themes and principles (e.g., conservation of energy and energy transformations, vibrations from the pendulum to the microwave spectra) are stressed.

The result would be a coherent, integrated three-year sequence. The power of the three-year sequence is in the freedom to modify and distort the disciplinary boundaries and the ability to revisit crucial concepts from different platforms and with increasing sophistication. In the three-year sequence the process of science must be included. One would include historical interludes to pose the questions: “How do we know? Why is this interesting?” Examining the influence of science and technology on human behavior, and human potentialities with both problems and promises, would be part of this three-year program. By taking time to pose unanswered questions, students can experience the excitement of doing science. Also, stories of wrong roads, the tentative nature of scientific theories, the spirit of skepticism, the nature of prediction and some of the passion and beauty of the physical and biological world would manifest themselves.

A major pedagogical advantage of the reversed sequence is that students have the opportunity to apply their new knowledge and thereby value its empowerment. The physics knowledge is applied to chemistry and biology. The physics and chemistry knowledge is applied to biology, and the increasing mathematical sophistication of the student is used in all three years. Of course, in a three-year sequence, teachers can propose some inherently interdisciplinary project (e.g., a space station on Mars or the ecology of a pond) in which each discipline makes its contributions: physics in the first year, physics and chemistry in the second year, and all three in the third year. Here is a splendid opportunity to include the social sciences. Here too, the essential requirement is to demonstrate the intimate weave of science, technology and society.

Teachers should expect students to transfer earlier learning into later applications. Under the current system, students are almost never provided the opportunity to practice this transfer. The very nature of this new design provides a feedback loop to check for knowledge transfer. It would be reasonable to expect that if students have continual practice with an ever-expanding knowledge base, they will get better at it. Ultimately, society needs individuals who can transfer their knowledge of science into informed decision-making and problem-solving.

Goals of equity and social justice lie at the core of the new curriculum. A logical presentation of critical science concepts enables students to succeed without handicaps from previous experiences. The depth of coverage means critical concepts can be learned thoroughly—and retained for a lifetime of work. The inquiry methods of learning, so effective in a primary school setting, will now be used to invite all students to learn science for their own needs. And, finally, by developing a method useful in all schools, the curriculum increases the ability of future voters to make just and responsible decisions about public health, technology and the environment. This approach to teaching and learning science can be crafted into a new and powerful way of preparing <u>all</u> high school graduates for life in the 21st century.

The model sketched above depends on a set of principles: coherence, integration of the sciences, movement from concrete ideas to abstract ones, blending description and explanation, inquiry and sensitivity to how people learn. Other innovative science teaching models respect many of these principles. This reform model represents just one class of examples used successfully in at least two dozen schools around the nation as well as in centralized education systems in Asia and Europe.

STANDARDS-BASED SCIENCE CONTENT: A DESCRIPTIVE MODEL

In order to better understand the relationships among the major science concepts and principles referred to in the NSES and Benchmarks we set out the underlying assumptions for content within and beyond the scope of content standards. (As an example, a descriptive map or format is given in Appendix B as an overview of what might be included in high school science curriculum options.)

Underlying assumptions for content included in the map, within and beyond the scope of the content standards, are based on:

- A finite set of scientific concepts (loci) considered essential for a scientifically literate person.
- A pattern of relationships among these concepts that form intellectually coherent basic principles (scientific laws).
- The fundamental principles of the four scientific disciplines, infinitely related and connected.
- The linkages among disciplines by which the teacher and student can begin at any locus, principle or discipline and effectively access all four quadrants of the map.
- A strategy to present physics first without precluding any one of the disciplines being the point of departure.
- A foundation of mathematics skills based on the NCTM Standards.

Hierarchies

There are many hierarchical relationships among the concepts and principles leading from physics. Most of these relationships should be obvious, but two examples may help.

Example 1: Gravity

"Motions and forces" is a key content standard for all grade levels. Several concepts and principles underlie this standard for grades 9-12. One is the universal force of gravity. Gravity affects the motion of objects near the surface of the earth, e.g., projectiles, and orbits of celestial objects. It accounts for the earth’s rotation. Orbits explain the movement of the planets, the shape of galaxies, the dance of binary stars. Gravity and stars' energy in juxtaposition explain stellar evolution. Earth's rotation, along with energy from the sun and the pu 8 Tc0.-otion explainuhicphenovemaof way life has developed on earth. Feeding into these stories are such concepts as radioactivity, nuclear reactions, chemistry of the upper atmosphere, etc.

Example 2: Living Matter

A key biology content standard is "matter, energy and organization in living systems." All energy used by living systems ultimately comes from the sun through its electromagnetism (light). Energy transformations can be explained using concepts from chemistry. Through energy transformations, plants make food (energy) which flows through the ecosystem. The availability of energy largely determines the distribution of populations (organisms) in the ecosystem. Atomic and molecular reactions with photons (light) and with one another are the underlying phenomena.

The next section relates the guiding philosophy, strategic guidelines and key elements for developing a curriculum framework.

GUIDING PHILOSOPHY

The Physics-Chemistry-Biology progression for science education possesses the stature of a core curriculum, much as a three-year high school plan does for English or language arts. Thus it requires three years of high school science experience to compose a complete and coherent package.

Curriculum guided by this framework benefits from both coordination and integration, where coordination creates linkages between segments, and integration invokes linkages within segments for simultaneous application. Connections between elements may be as important as the elements themselves.

With this approach, portions of a traditional physics course may well extend into the second year, merging seamlessly into chemistry. Analogously, indicators of chemical processes may naturally be invoked in the physics course. Between each of the three years, disciplinary boundaries are somewhat blurred, and will need to be determined to some extent by each local administration. The names “Science 1,” “Science 2” and “Science 3” could be chosen to support this philosophy and would offer districts greater flexibility in the selection of material to include. Fourth year courses, as “Science 4,” remain as more sophisticated, higher level elective opportunities for advanced placement courses or courses in earth science, geology, astronomy, technology or Science, Technology & Society (STS).

Some topics deemed important in traditional courses may have to be reconsidered, modified or omitted to allow students to approach selected topics in depth. Other topics might receive higher priority because they enforce connections and integration within or between disciplines. By fully understanding a strategically selected range of topics, students will more successfully learn how to approach scientific material they will need to grasp in the future.

Topics will be treated to allow students important time to connect the science they learn in school to their lives, to reflect on the material and to examine ethical issues. Students will have time to articulate their personal opinions and take ownership of the science they are studying.

This approach allows strong connections with the mathematics that is being taught concurrently, an advantage also to the mathematics teacher whose students will be presented with concrete applications of the mathematics in their science classes. The mutual reinforcement will improve learning in both disciplines.

Any new reform such as this one should lead to curriculum that incorporates a “learning cycle[3],” where students continually begin learning with exploration and end with application. Learning cycle models developed by Karplus and others can serve as references.

The combination of an inquiry-based approach; appropriate use of lecture, text and other printed or media materials; frequent connections to daily life; insights into career opportunities; appropriate use of technology, communication across the disciplines and active engagement of students in the classroom will prepare students to function as informed citizens of the 21st century, whether their next step is entering the workplace or continuing their studies.

Teachers, schools and districts may eventually be the ones to develop prescriptive frameworks consonant with their state curriculum and institutional needs. A successful prescriptive framework must grow from the knowledge and commitment of the teacher and be respectful of the knowledge and ability of the students who must learn the material.

STRATEGIC GUIDELINES

This framework, based upon a physics-chemistry-biology (P-C-B) sequence, urges an appropriate selection of content elements that is guided in large part by the NSES and the Benchmarks. This framework further recognizes the relationships that exist among the many concepts and principles within those content areas. Schools and districts should consider using a spiral approach in building scientific literacy in order to move from this framework toward a curriculum. These are ways by which this framework gains further strength from strategies that unify and reinforce content throughout and between each year.

Use a Learning Cycle Approach

Curriculum crafted from this framework is to be structured in two dimensions. First, there must be vertical, or grade-to-grade, coherence. To this end, the curriculum looks for major concepts that cross the lines of the science disciplines. The greater the number of these points of integration, the greater the reinforcement over the three years. Second, and no less important, horizontal coherence: the curriculum must be attentive to the internal coherence of each discipline. As Howard Gardner says,

> *The disciplines represent to me the most concerted efforts to provide answers to . . . such questions. History tells us where we came from. Biology talks about what it meant to be alive. Physics talks about the world of objects, alive or not . . . . Some people think the disciplines are irrelevant, and some people think all interesting work is interdisciplinary . . . . I reject both claims. Disciplines are what separate us from barbarians; I don't think you can do interdisciplinary work until you have done disciplinary work.*[4]

VERTICAL COHERENCE

The P-C-B sequence should coexist with story lines or branches which cause students to revisit, reapply, support or even challenge previous experiences and understanding. This process should seek guidance from NSES. Looking bidirectionally—from physics forward and biology back—curriculum choices are informed by numerous logical and appropriate connections within and between disciplines.

To accommodate physics being taught to younger students, the first year should focus on smaller, more concise experiences that can incorporate the exploration-to-application learning cycle within a relatively short period of time. Curriculum generated from this framework will necessarily acknowledge the capability of these students, not just the content to be covered. Some topics will require rethinking exactly how the course is best taught and what concepts are appropriate. Fortunately, there is a solid amount of literature on this subject.

As students become familiar with how to learn during and following Year One, their experiences should expand, incorporating more elaborate experiences or those which require longer periods of processing. Second year activities should be more complex and require more on the part of the students. The third year should focus on larger topics requiring the use of learned tools and content.

HORIZONTAL COHERENCE

There is a coherence and integrity that must be respected within each of the disciplines. Each year's experience best starts at a macroscopic level and with relatively concrete and familiar topics, then progresses appropriately toward greater detail and more abstract subject matter. This may not hold in Science 3 (Biology), which could begin with cells. Each of the three science years provides opportunities for review, integration and reinforcement. Because real situations tend to be far more meaningful and convincing, this spiral sequence should rarely involve conclusions based on faith but rather those built upon observation and a visualization or application of principles. In the spiral revisiting of the topic, the emphasis is on the use or application of the earlier concept rather than repetition.

Students often have gaps or misconceptions in science that are not detected or corrected until later in their education, if at all. Misconceptions developed experientially and reinforced with time can be challenging to correct. Therefore, teaching science should begin with finding out and responding to students' understanding: academically, experientially and otherwise. This implies a benefit to curriculum that offers multiple entry points, and a methodology for allowing teachers to hear from their students in order to assess understanding and attitudes from the beginning.

This curriculum framework seeks units and strands that naturally integrate other sciences, including astronomy, earth and space science and environmental science. It looks for multiple points to affiliate other disciplines, such as mathematics and history. Each year's plan has a "core and more" structure with extensions and enhancements built in for those students who are capable and interested. Such enhancements contain interdisciplinary ties and offer opportunities for long-term projects.

Build Scientific Literacy

A scientifically capable or "literate" person begins with real-world experiences, then builds meaning by interaction with such experiences, to emerge as one equipped to combine prior understanding with the tools and methods of science. In the interest of building scientific literacy, a curriculum guided by this framework uses phenomena from the real world, teaches the purpose and use of science tools, generates important scientific habits of mind and connects science to technology and society.

REAL PHENOMENA FROM THE REAL WORLD

Young people are interested in topics related to their own cares, or to fantasy, romance, power or the exotic. News, case studies and current events should be used as practical examples for learning and as opportunities for students to apply newly acquired knowledge. Students should read and report on books and stories about science. Students should demonstrate their learning with presentations to reaffirm the scholarship of teaching and to show interested public, parents, other students or future employers what students really know. Students should be immersed in community opportunities with resources, experts, events and field sites that demonstrate authentic phenomena.

TOOLS OF SCIENCE

Students need to succeed early to maintain positive attitudes toward science. Toward this end, the first year should emphasize developing student tools such as recording and processing classroom experiences. Tools learned during the first year should be incorporated and expanded during the following two science years. Early experiences should emphasize observation, data collecting and drawing conclusions rather than reporting strict factual knowledge. Additionally, these early experiences should focus more on broad-based principles than on specific concepts.

The curriculum should encourage applications of technology to support different learning styles. Appropriate use of technology will allow students to model materials in ways that will promote understanding and develop students' creativity in science. Science taught in this way will also appeal to students who may not have fared as well in traditional science curricula. More students will experience science, making the discipline accessible to everyone and not just a privileged few.

SCIENTIFIC HABITS OF MIND

Questions the curriculum needs to address are: How do we know this is true? Why do we believe this? By what process did we (and do we) find answers in science? How do scientists ask questions? How do scientists do science? What does history tell us about science and scientists?

To kindle scientific habits of mind[5], educators must present science so as to engender joy and passion about the way the world works. The curriculum incorporates the notion that science infuses itself within society through technology. While technology and science are strongly entwined, they are different activities.

Students should understand this difference. Science is a human endeavor, with both notable successes and notable errors which demonstrate the nature of science and the value of skepticism. Measures of success in this regard should be offered through pre- and post-learning assessment tools for teachers. Students and classrooms should use tools such as concept maps[6] to depict their learning for purposes of assessment and as records of progress and achievement. An example of a concept map is given in Appendix B.

BRIDGES BETWEEN SCIENCE, TECHNOLOGY AND SOCIETY

Building scientific literacy, with its association to real-world events and the acquisition of skills and scientific habits of mind, affords the means to reach beyond the disciplines of science. A scientifically literate person can apply scientific knowledge and understanding to society and technology. The curriculum should attend to the learners' global needs such as health, citizenship, safety, future learning and responsibility. Students discuss risk assessment involving natural and cultural phenomena. They consider the causes and effects of detachment, arrogance and adversity that can exist between individuals, cultures and the natural world. Students should become familiar with predictions, not only those which test theories but also those that assess public policy decisions; e.g., what are the consequences of adding fluorides to drinking water? What would happen if there were a tax on the emission of carbon dioxide into the atmosphere?

KEY ELEMENTS WITHIN THE FRAMEWORK

This discussion presents content recommendations in the form of approaches and topics that should be included within a curriculum guided by this framework. These are presented not as precise plans or sequences for a course of study, but as initial bridges to span the transition from this framework into a corresponding curriculum.

Also listed are topics within each of the disciplines comprising the three-year progression. While neither exhaustive nor exclusive, these lists have been drawn from the Descriptive Map (Appendix B) as topics deemed essential to the curriculum. Many of these topics add strength to a curriculum through their capacity to enforce connections and integration within and between disciplines. Following these topic-specific recommendations is a selection of themes that cut across the disciplines, creating opportunities for links and repetitions throughout the curriculum.

Physics in Year One

The curriculum approaches physics as a foundation of building blocks that both serve to facilitate the three years of science study and honor the subject as a stand-alone discipline. It begins with visible and familiar physical objects, then progresses to abstract levels. A fundamental goal is to elicit student fascination and a desire to discover why something happens and what a given experience means.

SOME IMPORTANT PHYSICS TOPICS

Compared to some traditional physics programs, this curriculum places less emphasis on such topics as mechanics, optics, acoustics and radioactivity, and more upon the following (in alphabetical order):

- Atomic Theory, Structure of Atoms, Molecule Formation, Atomic and Molecular Models
- Conservation of Energy
- Conservation of Mass
- Electricity / Charge

- Energy as a Universal Currency
- Gases
- Gravity
- Kinetic Theory of Gases
- Light and Photosynthesis
- Light as a Wave and Particle
- Matter, Properties of Matter
- Momentum
- Pressure
- Waves

Chemistry in Year Two

Much of Year Two is punctuated by extended laboratory experiences and project-based units that build upon Year One experiences. Again, the curriculum should allow considerable time to elicit student fascination and discovery, combined with insights for relating their chemistry experiences to their physics knowledge.

During this chemistry-based year, the curriculum is a building block for the following year's focus on biology. Atoms and molecules particularly important to biology, such as phosphorus and water, are in the forefront in examining chemical reactivity and the affinity of different substances. Students should also explore chemistry's relationships to such new topics as materials science, and to immunology and cloning in biology.

SOME IMPORTANT CHEMISTRY TOPICS (IN ALPHABETICAL ORDER)

- Acids and Bases
- Atoms
- Bond Geometry, Bond Tension

- Chemical Reactivity and Relationship to Structure
- Equilibrium
- Fundamental Reactions
- Kinetics
- Model Building Models: Visual, Mathematical, Computer
- Organic Chemistry
- Oxidation-Reduction
- Periodicity
- Radioactivity, Atomic Stability
- Simple Chemical Bonding
- Solubility
- Structure and Function, Property Level and Geometric Level
- Thermodynamics
- Three-Dimensional Visualization, Molecular Geometry

Biology in Year Three

In the spirit of the previous years, the biology curriculum should emphasize content-based experiences in field, classroom and laboratory. Students should be capable of processing their experiences with considerable efficiency during this year, given the skills and conceptual frameworks mastered during Years One and Two.

A simple but meaningful departure occurs this third year where, in a general reversal of Years One and Two, studies begin at the microscopic level—cell structure and function—and move toward larger, more systems-based topics. A fundamental goal for this year should be an appreciation for the unity and diversity of life, and the varying quests of science to understand, manipulate or control it. The curriculum should also expand to embrace global, temporal, and societal topics, ethical questions, lifestyles and the future of science.

SOME IMPORTANT BIOLOGY TOPICS (IN ALPHABETICAL ORDER)

- Atoms (Phosphorus, Carbon, etc.)
- Behavior of Organisms
- Biological Diversity: Genetic, Species and Ecosystem
- Cell Structure and Function, Malfunction
- Energy, Flow of Matter and Energy in Living Systems
- Evolution
- Heredity, The Molecular Basis of Heredity
- Interdependence between Living and Non-Living Entities
- Interdependence among Organisms
- Levels of Biological Organization: Cells, Tissue, Organs, Organisms
- Levels of Ecological Organization: Species, Populations, Communities, Ecosystems
- Molecules of Importance (Water, DNA, Carbon-Based Molecules, Proteins, etc.)
- Photosynthesis
- Rate, Scale and Magnitude of Change
- Relationships between Human Population Growth, Industrialization and Regional/Global Ecology
- Reproduction
- Structure and Function
- Surface-to-Volume Ratios of Lifeforms
- Trends and Cycles
- Water: Chemistry of Water, Density, Concentrations

Transdisciplinary Themes

Below are a number of themes that are not necessarily specific to one discipline, but offer opportunities for integration in the three-year sequence.

Approaches

- Case Studies
- Discussions Surrounding Law
- Discussions Surrounding Medicine
- Personal and Societal Choices and Consequences
- Project-Based Learning

Topics

- Ecology
- Energy and Its Influence on Living Systems
- Equilibrium and Perturbation
- Evolution
- Relationships between Structure and Function
- Statistical Reasoning; Estimation and Probability
- Sustainability
- Systems

Earth and Space Science

The fourth important discipline, Earth and Space Science, could serve as a fourth year requirement, since earth sciences depend heavily on the three core disciplines. Earth science also can provide a theme for teaching each of the disciplines, in a sequence discussed later. Conversion of the framework to a curriculum may offer other ways of satisfying this standard.

SOME FRAMEWORK-BASED EXAMPLES

The following vignettes will clarify this vision for the P-C-B sequence. They demonstrate varied approaches to represent the nature of curriculum structure and content that is consistent with the previously outlined philosophy.

Example 1: A Three-Year Story Line

This example presents a three-year P-C-B sequence, with a brief overview, a list of important content elements and an outline of mathematics topics useful to support the curriculum in each year.

YEAR ONE: PHYSICS

The curriculum approaches physics in a way that helps students understand the concepts in terms of the measurements they make. They take as little on faith as is practical. Teachers allow time for genuine inquiry and for students to make connections among topics. The curriculum clearly comes down on the side of informed depth, rather than shallow coverage of a large number of topics.

A novel approach to conceptual physics, though certainly not the only one, is to begin with electricity. Students learn to use electrometers and build circuits. Activities are designed to capture students' interest, using electricity because it is familiar to all students, and they are likely to enjoy learning how everyday appliances work. Conservation of charge is a good first example of a conservation principle. Conservation of mass is also critical, although the curriculum encourages developing this concept in lower grades. If students understand how to measure current and voltage, they will have a practical tool allowing them to measure energy transfers quantitatively. This is actually easier for students to do than the traditional measurement of forces that begins many physics courses. After all, people measure currents and voltages every day, while students measure forces only in the physics lab. This provides a useful introduction to relating phenomena to abstract models. It is important not to burden students with an abstract model of charge in terms of electrons at this point. The curriculum treats electricity on a phenomenological scale.

One could then introduce thermal energy as the product of electric current flowing through materials. By measuring current and voltage, students gain a quantitative understanding of energy as something that can be measured and transferred from one form to another. Once students can quantify thermal energy, they can use thermal energy as a common metric to examine other forms of energy. Production of radiant energy might be an excellent starting point. Experiments include such activities as building a simple electric motor and comparing the heat produced in simple running to the heat produced in lifting a mass. The idea of missing heat is related to other forms of energy produced. In this way the curriculum introduces such concepts as kinetic and potential energy. The curriculum bypasses the abstract definition of energy as “work” by allowing students to construct their own definitions of energy from measurements. Along the way, students will acquire lab skills and practice in interpreting data. If the instructor wishes to introduce the concept of force, this is also a good place to do so in connection with potential energy.

Content Elements for Physics

These physics topics would be included in this model:

- Electrical components and terms: circuits, current, voltages
- Electrical energy and power
- Forces and motion
  Applications to important systems: simple harmonic motion, circular motion
- Energy
  Potential and kinetic energy

  Conservation of energy, simple systems revisited
  Radiant energy, light
  Energy solving the mystery of the missing heat; internal energy
  Change of state
  Stability of simple systems as the question of the lowest energy
  Connections to the atomic theory, dipping into the abstract level
- Spectral lines and a glimpse of quantum phenomena
- Kinetic theory of matter, kinetic energy on an atomic level
  Pressure, gas laws with a simple, operational derivation
  Effusion, balloon with a gas example
- Ways of moving energy
  Particles
  Waves: a Slinky, earthquakes, ripple tanks
  Sound
  Light, photosynthesis
- Structure of the atom
- Possible extensions: gravity, astronomy, convection (weather)

Mathematical Elements Affiliated with Physics in This Model

The following elements are related to the mathematics needed for physics, either as prerequisites or to be concurrently taught:

- Graphing calculators, spreadsheets, computer software: An overarching theme comprises modeling, problem-solving and mathematical reasoning which consistently incorporate appropriate uses of such technology.
- Real numbers: computations involving real numbers, decimals, exponents, scientific notation, order of magnitude, significant digits, scale, estimation, number sense, percent
- Modeling real-world problems
- Ratio and proportion
- Equations and inequalities, properties of equations and inequalities, solving equations

- Functions: the algebra of functions (combining, composing), building, graphing and interpreting graphs, using spreadsheets and graphing calculators as well as paper and pencil
- Data interpretation, including use of spreadsheets to explore, interpret; histograms, line of best fit, errors in measurement
- Statistics, including measures of central tendency
- Introductory probability

YEAR TWO: CHEMISTRY

Chemistry is "the science of change," the study of the properties of substances and of the reactions that create new substances from old. Chemical change occurs constantly in the ordinary, visible world of daily life and has overwhelming practical importance. It is, however, best understood by reference to a rarely-seen microscopic world of atoms and molecules. The two levels (macroscopic and microscopic) interact constantly in the modern practice of chemistry. The curriculum presents chemistry as a discipline that discovers, on the microscopic level, an underlying unity in the wildly diverse macroscopic changes that condition our lives.

The curriculum starts on a concrete, macroscopic level with the classification of materials (as mixture, chemical substance, compound, element, metal/nonmetal, acid/base and so forth). Experiments illustrate important characterizing properties of materials such as density, boiling point, and melting point. The curriculum continues with the classification of chemical reactions with particular attention to the dissolution reaction. Early attention is paid to the energetics of chemical reactions, an approach made possible by the previous year's discussion of energy, its transformations and its conservation. Experiments and examples include organic materials (the stuff of food, fuel and fiber) to connect chemistry to what students see and use daily.

The curriculum takes an historical approach with the beginnings of modern chemistry, recounting the work of Lavoisier on combustion and the conservation of mass. Only then does it move toward the microscopic. It presents the chemical evidence that Dalton used to suggest his atomic theory, and it explains the difficulties encountered by Dalton and others in arriving at consistent chemical formulas and relative atomic masses. This illustrates the building and testing of models and simultaneously furnishes background for setting out the fundamentals of stoichiometry.

Next, the curriculum reviews (from the physics year) the physics of gases. It adds ideas about mixtures of gases and the interactions between chemically different particles in such mixtures. It explains these ideas in terms of the kinetic molecular theory (covered in the previous year). It revisits the difference between heat and temperature, and adds chemical potential energy to the list of energy types discussed in the previous year. The new type of energy is explained in terms of the existence or formation of chemical bonds between atoms.

Returning to a macroscopic level, the curriculum establishes by experience and demonstration that reactions very often stop short of completion. This introduces the concept of a chemical equilibrium. The equilibrium concept is applied to some of the various types of reactions established previously.

The difference between a true thermodynamic equilibrium (in which no further change ever occurs) and kinetic stability (in which further change is possible, but very slow) is introduced with examples and experiments. The time dimension in chemistry is crucial background for understanding enzymes and their biological function.

Finally, the curriculum examines, for review and use, the physicist’s model of the atom. Molecule formation as a potential energy process gives a microscopic view of chemical reactions. Elements of quantum theory may be used, with energy, to provide a sense of the important tools of chemistry: atomic and molecular spectroscopy. Applications are now available to astronomy, e.g., the discovery of helium in the sun, and biology.

Simple chemical bonding theory, electronegativity, electrons and electron dot structures lead to molecular geometries in three dimensions and the introduction to molecular biology.

Content Elements for Chemistry

These chemistry topics would be included in this model:

- Classification of materials: What is the world around us?
  Periodicity
  Metals and nonmetals
- Chemical reactions: How does matter in the world around us interact?
  Avoid chemical/physical change distinction
  Acid (sour)/base (bitter), pH; redox; solubility
  Simple organic reaction, such as dehydration reaction
- Stoichiometry; conservation of matter (downplay, but include to a small degree)
  Number of atoms does not change.
  Use biological examples
  Gas reactions, Dalton's Law
- Chemical reactions move to a lower energy situation; Conservation of Energy
  Bond energies
  Thermodynamics; processes will go one way, but not the other.
  Enough kinetics to understand enzymes; activation energy (qualitative only; concept of an “energy hump”)
- Equilibrium: answers "what is change?" All change involves equilibrium.
  How is an equilibrium affected?, Le Chatelier's Principle
  Equilibrium constant determines the amount of change that takes place.
- Periodicity in the chemical elements

- Chemical bonding; three-dimensional modeling
  What creates a bond? (avoid electron configurations)
  Electronegativity used to describe bonding
  Electron dot structures
  Shapes: geometry, the geometry of a molecule
- Photosynthesis: A discussion of light energy and chemical energy conversion in molecules useful to living things (preparing students for the beginning of the third-year biology course)

Mathematical Elements Affiliated with Chemistry in This Model

The following elements are related to mathematics and needed for chemistry, either as prerequisites or to be taught concurrently:

- Modeling and problem-solving; mathematical reasoning
  Incorporates at all times appropriate use of technology, including graphic calculators, geometry software, and algebra
- Ratio and proportion
- Congruence and similarity
- Data interpretation, geometry and spatial visualization; synthetic and analytic geometry, including rotations, transformations, 2D, and 3D
- Argument and proof
- Logarithms; solutions to several equations in several unknowns; matrices

YEAR THREE: BIOLOGY

Biology as currently taught stresses memorization over understanding. For example, students are asked to memorize molecular structures and reaction pathways rather than learning why these structures work to support the functions of biological processes. In this physics-first approach, students are well grounded in the basics of atomic structure and molecular interactions. This enables the teacher to emphasize how structure naturally supports function. For example, many molecules form polymers: What differentiates one type of polymer from another?

How are these fundamental components used in various combinations leading to the diversity of life? The appreciation of simple principles derived in physics and chemistry enables the students to understand the natural rise of complexity.
This course begins with the molecule and progresses to the cell, on to the organism and finally to the ecosystem. Everything in the course is connected to survival (natural selection). Reproduction is explored at a genetic level, and then content moves to the environmental level.

Understanding the structure and function of the cell—the basic building block of life—is the optimal way for students to understand life at and beyond the level of an organism. Treating cells as the fundamental unit, the curriculum asks: Why are cells useful? How do they respond to changes? What do they need to function properly? What consequences arise from improper functioning? Similar questions can be applied to the organism and the ecosystem. A high school biology course should also include enough human biology to equip students for making informed decisions about their lives.

Overall, this approach aims at enabling students to become decision-makers in an ever-changing world, a world where the tools of molecular biology are so powerful that humans have the unprecedented ability to alter both themselves and the environment that sustains them.

Content Elements for Biology

The biology topics included in this model:

- Molecular components of the cell: students begin with molecules brought into a living system by photosynthesis, which was introduced in the second year.
- Structure and function of a cell, cellular respiration and other cell processes; replication, including DNA structure and function
- Cellular communication; environmental cues that lead to cellular responses, such as growth, development, death

- The role of genetics in cellular function; how mutations alter this role
- Organisms; structure of the body related to function
- Interaction of organisms with, and of organisms with other organisms
- Ethics of humans affecting internal and external environments
- Genetic engineering and environmental management
- Evolution; commonality between organisms

Mathematical Elements Affiliated with Biology in This Model

The following elements are related to mathematics and needed for biology, either as prerequisites or to be taught concurrently:

- 3-D geometric modeling
- Probability
- Statistics for data interpretation
- Spreadsheet modeling for data collection
- Curve fitting
- Exponential functions

Example 2: An Earth Science Integration

Another way to integrate the curriculum horizontally and vertically is to focus each year on the same problem as viewed from the perspective of a different discipline. In the P-C-B progression, the curriculum should be careful to avoid losing earth science as an important constituent, or merely using fragments of this discipline as incidentals or extensions. This example suggests an alternative curriculum approach that makes the earth and its processes the thematic thread for unifying the three-year progression and integrating earth science throughout physics, chemistry and biology studies. Fundamental to this process is the notion that the planet earth is home, and as such, offers pathways to all other disciplines, within science and beyond.

With this model, the earth structures the curriculum. The approach is one of exploring earth through the eyes of a physicist, a chemist and a biologist, respectively. in each year. Obviously, the curriculum would extend each of the disciplines to encompass the standards. Below are connectors to earth science in each of the three years.

EARTH AND PHYSICS

The earth changes and develops as energy is transferred from one form to another, tracking the passage of energy inside the earth's systems, and examining the changes produced in the earth.

The topics include:
Energy as universal currency
Erosion
Geophysics: the structure of the earth and how we know it
Gravity
Light and photosynthesis
Mineral structure and bonding
Momentum
Plate tectonics
Pressure
Snow, from precipitation to snowpack metamorphosis to runoff to avalanches
Surface-to-volume ratios
The sun
Waves

EARTH AND CHEMISTRY

Chemical energy is particularly important in shaping the earth because chemistry governs the formation of the rocks, oceans and atmosphere that constitute the world.

The topics include:

Acid precipitation
Chemical bonds and photosynthesis
Chemistry of water
Energy
Equilibrium
Pollution
Soils
Solubility
The water cycle
Thermodynamics

EARTH AND BIOLOGY

Living systems contain much of the energy found in the earth. Their behavior in turn alters the world in which they exist.

Topics for the curriculum:

Adaptive radiation, speciation
Biogeochemical cycles, flow of matter and energy
Biological diversity
Bird migration mechanisms
Cells, pigments, energy, organisms and photosynthesis
Climate
Ecology of winter
Energy flow
Evolution and adaptation, stress, natural selection
Habitats and biomes
Interdependence of living and non-living entities
Island biogeography
Marine biology

Natural disturbance, stress and succession
Organisms' response to cold, heat
Resources for energy
Soils, plants and nutrients
Structure and function
Thermodynamics

NON-EXAMPLES

Simply using the NSES or Benchmarks does not ensure a well-crafted curriculum. Nor does using "best practice[i]" strategies ensure effective learning. Two non-examples follow from current curricula. They include many "best practice" elements, but have fatal flaws as described in the section *Why it is a non-example.* These illustrations are typical of current practice.

Biology: Second Semester

Human Systems
Ecology
Environmental Health

SEQUENCE

The second semester begins with a unit on human body systems starting with the circulatory system and ending with the endocrine system. All the organs of the body are named and located, and structures are related to function. Students engage in various activities that enable them to relate how the various parts of the body function together.

Next, students engage in a unit on ecology, learning how organisms live and function together in ecosystems while occupying their various niches. Students do numerous activities related to food chains and food webs. They explore their schoolyard and nearby parks to apply what they have learned to real-world ecosystems.

At the end of the semester, there is a short unit on environmental health. Students engage in a long-term project exploring the effects of pollution presented on a CD-ROM. Activities involve students in role-playing, problem-solving and developing group presentations of their projects.

WHY IT IS A NON-EXAMPLE

There is a lot to recommend in this sequence. Students engage in “hands-on, minds-on” activities, exploring their real-world environment while engaging in a long-term project.

There is, however, nothing to tie the units together, nor to integrate what students have learned previously. A slight alteration would provide a more meaningful sequence. By linking environmental health with human body systems, students would cover all topics in the human systems unit but with a larger context of how environmental pollutants affect those systems. The chemistry learned in the previous year would be further expanded in examining chemical pollutants, thus continuing the story line that began in physics. Studying photochemical reactions would carry on the story line that began with the electromagnetic spectrum.

Physics: First Semester

Energy
Motion and Forces
Electricity
SEQUENCE

Students learn about the nature of energy. Through activities that develop their skills of observation, prediction and measurement, they learn to describe how energy changes from one form to another; how potential energy can be converted to kinetic energy and how the law of conservation of energy works.

Next, students learn about forces and motion. They create and interpret graphs, gaining hands-on experiences with speed, velocity, acceleration, momentum and friction. They progress to Newton's laws of motion.

In the electricity unit, students learn about charge and continue their study of forces. They explore the flow of electricity, learning about circuitry, resistance, voltage, and Ohm's law.

WHY IT IS A NON-EXAMPLE

Again, the problem with this illustration is that the sequence does not link conceptual understandings. A sequence designed for conceptual development would relate forces to matter and energy. Forms of energy would act as specific examples to illustrate general ideas. Students would explore a variety of principles to view the workings of nature, learning to predict and infer from data and becoming familiar with scientific habits of mind.

IMPLICATIONS FOR IMPLEMENTATION

Redoing the high school curriculum is not a project to be undertaken in isolation. The effort has significant implications for two key areas affecting the common schools, students’ earlier education and professional development for current and future teachers. In addition, significant institutional barriers must be overcome if the new curriculum is to be successful.

K-8 Prerequisites

The proposed restructuring of the high school science sequence has profound implications for students’ earlier and later education. With regard to the former, the new courses demand that students entering high school possess certain scientific knowledge, skills and attitudes. Fundamentally, the new sequence is aligned with the K-8 interventions that seek to shift the teaching of science to a standards-based format using an inquiry approach.

The present education system all too often allows students to move into high school with fundamental misunderstandings of the nature of science. This is largely a result of the science teaching that K-8 students receive, which, in turn, is predicated on the weakness of the science education that their teachers themselves received. Here again, there are winds of change, but elementary school changes are delphic breezes where tornadoes are needed! Many students leave their elementary years with a view of science as a static collection of disconnected, invariant facts. From their teachers, elementary science texts and tests, many students have developed a warped view that science is essentially a huge and terrifying vocabulary for describing arcane and uninteresting minutiae.

The new high school science sequence must be implemented as one facet of a truly systemic reform cultivating a more accurate view of science as a human endeavor, applicable to many aspects of students' daily lives.

What sorts of knowledge and skills do these curricula expect from students entering high school? To some extent, the answer can be found in NSES and/or Benchmarks. Students should to be able to demonstrate knowledge of at least fundamental scientific categorization schemes; for example, distinguishing among different groups of vertebrates and using similar terminology in describing trajectories, whether of baseballs or rockets. While students need not have elaborate knowledge of taxonomy or systematics, they should be able to sort diverse objects (e.g., leaves from several types of trees) into consistent and meaningful subdivisions, and to elucidate the bases for their classifications (e.g., smooth, lobed, or serrated-leaf edges). They would have some sense of the difference between science and pseudo-science, being able perhaps to list characteristics that make astronomy a science and exclude astrology from this realm. They should be able to describe, at least in broad terms, the work of scientists and how they go about this work. In describing simple physical science phenomena, they should not invoke mysterious or magical forces but should be able to suggest possible ways that features of the environment might influence the observed behavior.

An example may help illustrate the level of skills that students should bring to a high school classroom. Teachers would expect an entering ninth-grade student to make a series of simple, critical measurements around a simple pendulum motion experiment. That is, students should be able to measure the length of a pendulum and the period of its oscillation with reasonable accuracy. They should be able to collect repeated measurements, to compare these skeptically, raising questions about measurements that deviate excessively from the mean. If called for, students should be able to also determine the mass and/or volume of the pendulum (e.g., to ensure that these factors were being held constant among replicate apparatuses). Students should be able to make simple interpretations from the data and predict behavior in replications of their experiments. Teachers would not expect such students to complete complex interpretation of, or extrapolation from, the collected data (such as how the period of oscillation might change with a given change in length). Students should be able to describe the basic experimental set-up and suggest potential extensions or variations on the experiment (e.g., the effect of changing the length of the pendulum’s mass, volume or initial position). Students should be able to discuss why these changes would be interesting and make general predictions about the results manipulating these variables.

With regard to attitudes, teachers would hope that students enter high school with positive views of science, appreciating its appeal, excitement, potential and limitations. To be active learners in the new science classrooms, students should be curious, open to new ideas and conflicting data, and be both skeptical and honest. They should demonstrate their understanding of science as a branch of human endeavor attempting to comprehend the world around them. They should demonstrate their understanding that scientific knowledge changes over time, and that ideas once held to be correct may be found inadequate to explain new phenomena.

Professional Development

This proposal to restructure the high school science sequence provides opportunities to stimulate the creativity and challenge the intellect of current teachers; to open classrooms to practitioners of science; to reform teacher preparation programs and to generate a momentum of its own through a network of teachers acting as mentors for other teachers.

A national recruitment of science teachers is essential, with a built-in component of professional development and collegial activities. Many more secondary teachers are trained in the biological sciences than in chemistry or physics. Teachers must improve their knowledge of scientific content—physics, chemistry, biology, earth and space science—to better demonstrate the interrelation the sciences. Teachers must extend their knowledge of pedagogy—of inquiry, constructivism and problem-based learning. Science teachers must know what their students are learning in mathematics and when they learn it.

Here, too, the answer can be found in the national standards. The vision of professional development is an active, teacher-built process implemented collectively to move forward. The meta-goal is for teachers to be empowered, effective, contributing groups who will push, challenge and support each other. This will evolve differently in each school and each district. Overall, the project framework needs to set goals and provide capacity for people to move towards these goals. Given these needs, professional development is an enormous undertaking that must:

- Apply to virtually every science teacher, including preservice teachers.
- Include summer sessions and workshops—setting the vision, checking out successful programs, people, instructional resources, etc.
- Be continual and ongoing within schools—school structure needs to be adapted so that teachers can meet frequently to discuss the connections between disciplines and the progress of students.
- Include all parties—principals, teachers, parents, community, superintendents, non–teaching staff—to foster a community of sharing, discussion and collaboration.
- Incorporate the use of technology to provide scale-up at reasonable cost and overcome limitations of local expertise.
- Have convenient access to scientists via e-mail, Internet, fax and phone for advice, clarification and help with converting hot news items to high school topics.

Professional development programs are not offered in a vacuum, and an approach that works in one situation may not work in another. There are nine contextual factors that influence professional development design identified by Loucks-Horsley et al., 1998:

- Knowing the students, who they are and what outcomes are desired, is a key starting point for staff development planning.
- Knowing the teachers and being sensitive to their needs; understanding how much they may know about their discipline and how comfortable they are with mathematics; understanding what pressures they may be under and what demands are being placed on them, are all vital to the success of any staff development program.
- Improving classroom practice depends on knowing the current practice. The national standards address four aspects of practice that require attention if reform is to be successful—curriculum, instruction, assessment and learning environment.
- Staff development must take into consideration local, state and federal policies.
- Schools and districts must evaluate resources available to support professional development. Money must be allocated or reallocated for staff time and new instructional materials, classroom upgrades, etc. Districts may be eligible for grants and other community support.
- Schools and districts need to nurture and support teachers working together, trying new ideas and learning from one another.
- Schools and districts need an infrastructure in place to support staff development.
- Staff developers have much to learn from previous experiences in the school or district. What has been successful? What has not? Teachers’ attitudes toward previous efforts can shape how accepting they are of new efforts.
- Staff development that leads to changes in what and how students learn must take into consideration the opinions of parents and the community. Helping them understand why change is needed, and giving them a chance to accept a new vision of science education, will help make them supporters rather than thwarters of professional development efforts.

Barriers to Implementation

Both facilitating and constraining factors must be considered when implementing the revolutionary changes proposed here. The transition from current courses to the new curriculum poses a challenge in itself. In order to CHANGE, the system must address common issues—fear of change, lack of understanding / perceptions, resources, excuses, new paradigms, lack of continuity / mission—affecting all parts of the system including administrators, teachers, students, parents, public, elected officials and commerce.

While the most desirable presentation of science depends on the interweaving and integration of important science themes, many structural conditions mitigate against achieving this form of instruction in the near term, including:

- The absence of a cadre of teachers prepared in the content and skills to teach in this way.
- The absence of materials appropriate to the high school level organized in this way.
- The concerns of parents and policymakers about the acceptance of courses other than the standard ones in the college admission process.
- The lack of assessments geared for other than “standard” courses.
- The reluctance of teachers to work with different age and grade levels, e.g., ninth-grade physics and eleventh-grade biology.

The following examples of implementation barriers depict situations that will certainly differ from one district to another, and from one school to another.

PHYSICAL / ORGANIZATIONAL BARRIERS

Schools will need more classrooms, equipment and instrumentation. Teachers will need a common prep time and meeting location to coordinate the ongoing development of the program. The concept of the “science team” is designed to reduce the barriers between the sciences. However, the “science team” will also need to work to reduce barriers with the non-science disciplines. The school may be so departmentalized that interdepartmental collaboration is virtually impossible. Expectations and criteria for a student's performance may not always be uniform across disciplines and departments. Therefore, students and teachers may not be able to support each others' work, and teachers may be unable to transfer their skills and learning across departments and disciplines.

INTELLECTUAL BARRIERS

In affluent districts which currently produce "successful students," there may be no incentive for parents, teachers or administrators to adopt a new curriculum. Teacher burn-out and "been there-done that" attitudes toward yet another reform initiative may result in lack of teacher cooperation. Teachers may fear being perceived as wrong, stupid, or even as educational “frauds,” stemming from their experiences and lack of support during past initiatives. Teachers may not be empowered to advocate their views. They may not be able to use their experiences in school to implement change. Teachers may not have been treated as professionals. There may often be an inequity of assignments, responsibility and accountability for teachers singled out by the administration; e.g., teachers assigned five classes with four different preps in five different classrooms filled with "difficult" students. Colleges and universities must accept the new curriculum as fulfillment of their admission requirements.

TIME CONSTRAINTS

Teachers will need common time for meeting and planning a coherent science sequence. The common prep time must be unencumbered by the administration's separate agendas. The teachers must be trusted to structure and effectively use the allotted time for their own enrichment.

Students will need sufficient time for inquiry-based instruction. When students are required to take more years of science, there is less time in their schedules for electives and/or arts. Different forms of scheduling and extending the school day or year are ways to address these issues but are difficult to implement.

PROFESSIONAL DEVELOPMENT COSTS

This reform will require more teachers for the additional years of science taught. Schools cannot teach physics first without physics teachers. A very small number of science teachers are trained in physics. Since conceptual-based physics would be taken by all students, up to four times the number of classes might need to be offered than at present. Physics teachers who are used to teaching quantitatively-based rather than conceptually-based courses may be concerned about having to teach all students. They may feel a loss of stature associated with moving away from elite, selective courses for the college-bound. At the same time, there is a lack of teachers prepared to teach modern biology to all students. Also, allowing teachers time for collegial efforts to improve their capabilities will add costs.

The new curriculum must be introduced into the programs for preservice teachers so that schools are not always playing professional development catch-up with their in-service teachers. In districts that cannot compete effectively to attract the best-prepared teachers, the amount of professional development required for the inservicing of teachers may be prohibitive. The certifying of new teachers, and recertifying of current teachers, must stress demonstrable mastery of their field. Professional development must be useful and pertinent. Professional development must be ongoing and provide for guided practice and may include peer coaching as support for ongoing growth and change.

INSTRUCTIONAL BARRIERS

There is a lack of appropriate materials to teach a coherent three-year course that integrates the disciplines. New teaching materials and modifications of laboratory equipment will be needed. Students will need access to course work in science and mathematics at appropriate K-8 levels to thrive in the new high school science sequence.

ASSESSMENT BARRIERS

Schools lack assessment instruments aimed at the appropriate content and level. There must be meaningful, authentic assessment to measure progress and the attainment of objectives. Who will design the assessments? When will the assessments be designed? Assessment must determine student progress as well as achievement. Students must demonstrate an understanding of the connection between the experiential science and the synthesis of the concepts and principles involved in that experience (i.e., the “minds-on” part of “hands-on, minds-on”). It must include the assessment of students' prior knowledge and provide ways to address their misconceptions. Students and teachers must generate and use rubrics which clearly specify the performance outcomes.

FINANCIAL BARRIERS

This proposal is too expensive for schools to implement alone. Who will be responsible for seeking funds from other sources locally? at the state level? nationally? What happens to the supplemental dollars that districts receive in Average Daily Attendance, federal funds and state dollars which don't find their way to the classrooms? The origin of the dilemma is clear. If the nation and the states are to establish new, high-level standards, they must provide the resources for <u>all students</u> to attain those standards.

CONCLUSION

This scaffolding for a set of curricular options would radically change the way high school students learn science. The present system, used in the large majority of schools, is illlogical and drives too many students away from science.
In a world dominated by science and attendant technologies, this is hardly an acceptable situation. Establishing science standards, involving a long process of building a national consensus, was an essential remedial step. This white paper is another step toward establishing a similar national consensus on the elements of a coherent three-year standards-based science curriculum.

This scaffolding points toward a guiding strategy which can be implemented locally in a variety of ways, depending on local talent, local financing, imaginative teaching styles, etc. The need for a central strategy should be obvious. It is here that the scientific knowledge distilled over the past 100 years, the plausible expectation of how knowledge will increase, the current understanding of the interconnections between disciplines and the interaction of science and society can be blended and modulated by experienced science educators. The goal, then, is to establish a notional consensus on a strategy for this piece of school reform. It is probably because of the deep commitment to local educational control that rational modifications of high school science curricula are so long in coming.

At least two dozen high schools (and there are surely many more) now teach the sciences in this suggested rational order, or have otherwise modified the century-old sequence. These schools appear very pleased with the results. But in selling the task of actually producing a curriculum, it will be necessary to spend a lot of time with these and other innovative high schools in order to evaluate their programs. It may also be desirable to know how schools in Europe and Asia deal with science. This is called “research.”

The next step is to circulate this white paper widely, gauging the enthusiasm and resistance it generates. Depending on the availability of modest funding, it would be appropriate to study the successful schools, estimate the incremental costs, address real concerns and build a powerful advocacy group from the scientific, business, university and military communities.

Endnotes:

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APPENDIX A: TEACHER AND STUDENT BEHAVIORS

The National Center for Improving Science Education's *Classroom Practice Framework* translates reform-based science education described in the literature into specific behaviors. It describes the vision of the teacher and student classroom behaviors on which this proposal is based.

The Framework includes 12 student and teacher behaviors:

1. **Students *do* science.**

   Students actively engage in doing science versus learning about science. Students may answer questions or solve problems in order to gain conceptual understanding and/or explore cause-effect relationships in understanding principles. They use manipulatives and engage in hands-on activities. They use process skills such as predicting, inferring, comparing and estimating.
2. **Students engage in inquiry.**

   Students are given open-ended problems to solve or questions to answer through doing an investigation that involves collecting and analyzing data. They may be answering their own questions through experiments they have designed, individually or in groups.
3. **Students communicate.**

   Students communicate findings through laboratory reports, oral reports, discussion, and in journals or logs. Students listen to one another and build on one another's comments during discussions.
4. **Students collect, manipulate, and use data.**

   Students manipulate data collected through their own laboratory investigations and through library and other sources of information. They use this information to provide evidence to support claims in reports and during discussions. Data may be collected and manipulated using computer-based technologies.

5. **Students work collaboratively in groups.**

   Students engage in cooperative/collaborative learning through small-group projects, investigations, and other activities. Students interact around the activity and subject matter; they build on one another's understandings; they work together to complete a project or investigation, in some cases, by having different tasks performed by different students.

6. **Teachers use authentic assessment.**

   Teachers use forms of assessment consistent with "best practice" learning, i.e., testing for understanding and ability to inquire/solve problems versus multiple choice or short-answer tests that probe for knowledge of facts and definitions.

7. **Teachers facilitate learning.**

   The teacher acts as a facilitator by asking students open-ended questions, encouraging students to explain and predict in order to increase their understanding, and by asking probing questions that encourage discussion. Overall, the teacher acts as a consultant to students. Students address one another and often seek help from one another rather than always looking to the teacher for answers. In a classroom where the teacher does not act as a facilitator, students address the teacher; the teacher provides knowledge generally through lectures; and, student-teacher interactions are better defined as "recitation" than "discussion."

8. **Teachers emphasize relations to real-life.**

   Teachers use examples and applications of the subject matter content in daily life, and/or use instructional resources that relate to real-life. Students are able to explain how what they are studying relates to the work of scientists.

9. **Teachers integrate science, technology and mathematics.**

   Teachers integrate subject matter areas to exemplify how the different disciplines co-exist in actual practice. For example, in science class a teacher might include statistics concepts when students are learning ways to organize data. Teachers may even employ other subject areas such as language arts to illustrate communication tools; use history or government for social issues concerning science.

10. **Teachers offer depth versus breadth.**

    Teachers involve students in fewer topics that they cover in depth in their courses rather than briefly considering many topics such as the practice of many teachers who "cover the textbook" during the school year. When involving students in fewer topics, teachers may have students do sustained work, e.g., projects lasting weeks or months.

11. **Teachers build on prior understandings.**

    Teachers relate what students have already learned or what they already know to new understandings. Teachers may do this through an introduction to the day's lesson and/or engage students in discussions of their learnings and understandings prior to introducing a new topic. Teachers try to detect and address possible student misconceptions.

12. **Teachers use a variety of materials for learning.**

    Teachers use a variety of materials and resources rather than rely solely on the assigned textbook for the course. Some of these resources and materials may be computer-based.

Note that the *Framework* is an interrelated set of complex behaviors, many of which overlap. For example, "collecting and manipulating data" can be considered as part of "inquiry" and "doing science." Student behaviors are similar to those of a practicing scientist. Teacher behaviors include methods and strategies found to be most effective for student learning. In this vision, these behaviors would constitute most of what goes on in classrooms.

APPENDIX B: VIEWING THE MAP

Heretofore many science curricula have been based on a potpourri of unrelated topics within the discipline. The map shows relationships between the content standards and their fundamental underlying concepts and principles. Then it goes on to show interrelationships among these overarching as well as underlying concepts and principles. An overarching principle in curriculum construction is to provide options for in-depth coverage of those topics within a discipline which have relevance to applications to the next higher discipline.

The map is most easily read from top to bottom. Note that physics (blue) concepts and principles are presented first in a hierarchy that leads to concepts and principles in chemistry (red), biology (green) and earth/space science (gold). Two overarching concepts, *matter* and *energy*, are at the head of the map. In the middle lies *quantum theory* which explains the relationship between matter and energy. These three lead to virtually every other concept and principle in science. Implicit in the map and underlying all disciplines is the concept of atoms and molecules. Because of the limitations inherent in the map's two dimensions, some ideas appear twice (see dotted lines, e.g., "Energy")

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