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REFORM OF SCIENCE EDUCATION: A CURRICULUM

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SUMMARY

The paper proposes a revision in the way science is taught in high schools, in order to emphasize the hierarchial connections between the core disciplines of biology, chemistry and physics. The proposal is that physics be learned first even though the mathematical preparation of many students is at the level of beginning algebra. However, taught conceptually, physics deals with every day phenomena and its scientific methodology is an ideal introduction to a disciplinary science. The concept of atoms is a natural entry into chemistry and the complex molecules of organic chemistry leads to the third year, molecular biology. Emphasis in this coherent sequence is on the explanations provided by physics to chemistry and physics and chemistry to biology. Mathematics is appropriately woven thought the sequence. The three year curricula includes inquiry based laboratory work and a substantial emphasis on science process: how science works, historical episodes, the role of theory and verification. The objective is to produce high school graduates who will be science literate for their entire lives.

RESUMEN

Este trabajo propone una revisión de la manera en que la ciencia es enseñada en las escuelas secundarias, con el fin de enfatizar las relaciones jerárquicas entre las disciplinas fundamentales de biología, química y física. La propuesta es que la física sea aprendida primero, aunque la preparación matemática de muchos estudiantes sea a nivel inicial de álgebra. Sin embrago, enseñada conceptualmente, la física trata sobre fenómenos de todos los días y su metodología científica es una introducción ideal a una ciencia disciplinaria. El concepto de átomo es un acceso natural a la química, y las moléculas complejas de la química orgánica llevan a la biología molecular del tercer año. En esta secuencia coherente el énfasis está en las explicaciones dadas por la física a la química, y por la física y la química a la biología. Las matemáticas son imbricadas en forma apropiada a través de la secuencia. Los pensa de los tres años incluyen trabajos de laboratorio basados en búsquedas y un énfasis sustancial en el proceso científico: cómo trabaja la ciencia, episodios históricos, el papel de la teoría y la verificación. El objetivo es producir egresados de secundaria alfabetizados en ciencia para toda su vida.

This paper advances the concept that all people living and hoping to thrive in the 21st century need to be literate in their language, need to know how to read, write and communicate –but they also need to be literate in science, mathematics and technology. This is essential in order to earn a living, to make wise decisions about their own behavior and that of their families, in order to participate in decisions made by their communities and their nations. The sweeping advances in democratic societies and the similarly sweeping advances in science and in technology argue forcefully for the importance of science literacy. A crucial component of science literacy is the respect for rationality, for the importance of being able to think critically, of being respectful of history, tradition and the scientific heritage, but with a sense that our understanding of the natural world is always tentative at the frontier.

"Science literacy requires understandings and habits of mind that enable citizens to grasp what... the enterprises... of science and technology are up to, to make some sense of how the natural and designed worlds work, to think critically and independently, to recognize and weigh alternative explanations of events and design trade-offs, and to deal sensibly with problems that involve evidence, numbers, patterns, logical arguments and uncertainties." (AAAS Project 2061, 1993)

In thinking deeply about what qualities of mind we want all students, all future citizens to have, we are led to conclude that there exist large inadequacies in the teaching of science, mathematics and technology and of curricular reforms that may have elements of universal validity.

Although education of students is a major concern of all nations, the details of how we educate and for what purposes are closely attuned to individual cultures and the varied social and economic circumstances of nations.

Still there are some remarkable similarities between national approaches and national educational problems. One of these is the teaching of science and mathematics in the primary schools. Universally, primary school teachers are untrained in both the content and pedagogue of science; the same problems appear in the affluent North and the underdeveloped South, in the industrial West and the rural East.

Here I would like to discuss another problem that bridges cultures and economic disparities and this is

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RESUMO

Este trabalho propõe uma revisão da maneira em que a ciência é ensinada nas escolas secundárias, com o objetivo de enfatizar as relações hierárquicas entre as disciplinas fundamentais de biologia, química e física. A proposta é que a física seja aprendida primeiro, ainda que a preparação matemática de muitos estudantes seja a nível inicial de álgebra. Porém, ensinada em forma de conceito, a física trata sobre fenômenos de todos os dias e sua metodologia científica é uma introdução ideal a uma ciência disciplinar. O conceito de átomo é um acesso natural à química, e as moléculas complexas da química orgânica levam à biologia molecular do terceiro ano. Nesta seqüência coerente a ênfase está nas explicações dadas pela física à química, e pela física e a química à biologia. As matemáticas são imbricadas em forma apropriada através da seqüência. Os programas dos três anos incluem trabalhos de laboratório baseados em buscas e uma ênfase substancial no processo científico: como trabalha a ciência, episódios históricos, o papel da teoria e a verificação. O objetivo é produzir formados de secundária alfabetizados em ciência para toda sua vida.

the teaching of science in the high schools i.e. to children of ages about 13 to ages of about 18. I pick this group because, before university, it includes the bulk of the population whose futures include all occupations: professional, artisans, the industrial workforce, doctors, lawyers, journalists, police and military, political people, bureaucrats… i.e. what we collectively call “the general public”.

Concerns for and interest in “public understanding of science” have been discussed with increasing frequency over the past several centuries as science and technology have advanced. The connections of science and technology to development, to economic advantage and to increases in longevity, health and other human potentialities become ever more evident. Today, many personal decisions, decisions for the family, the local community and the nation have strong scientific components all of which speak to the need for all people to be science literate. We note that such topics as climate change, acid rain, the ozone problem, weapons of mass destruction, genetically engineered foods, are global problems implying a need for global citizenship and decision making. Indeed terrorism, emerging from the breeding grounds of poverty and hopelessness, requires new advances in understanding both the process of creating the terrorists’ suicidal hatreds and the policy issues that allow the root causes to exist.

These issues point to a need for raising the importance of science and mathematics for *all* students and this is the issue I would like to discuss. Here again I believe that most nations do a poor job of producing graduates at the pre-college level that have the needed comfort level with the science and the technology that our 21st century requires. Clearly some national systems do better than others. However, if we use such measures as the public acceptance of anti-science beliefs, the popular success of such false pseudoscience such as astrology, fortune telling, psychic phenomena, etc., we find an almost universal naiveté. In recent years, international measurements of science literacy have become sophisticated and relatively independent of national educational customs. After all, science is the only truly universal culture.

The Third International Mathematics and Science Study (TIMSS) has provided national measures of student achievement in fourth (age ~10 years), eighth and twelfth grades. A rich set of relevant aspects of the educational systems being tested is also becoming available.

One of the universal defects is the failure of school systems to recognize the natural hierarchy of science as a combination of interrelated disciplines. One can imagine a pyramid, the base of which is mathematics which is (supposed to be–) a pure invention of the human mind with its own rationale for existing but which provides the logical structure and the language of the other disciplines. This is followed by physics which requires mathematics as its language and which provides the logical underpinning for other disciplines.

Next in the hierarchy is chemistry. I believe one can defend the assertion that all the laws of chemistry are logically supported by physics. Examples abound. The periodic table lists the atoms (elements) in a regular order that follows from the quantum structure of atoms and the exchange symmetry, i.e. the Pauli Exclusion Principle, provided by the laws of physics.

It may suffice to establish the physics-chemistry ordering in our pyramid by simply noting that all of chemistry depends upon the (quantum) structure of atoms and the resultant forces between atoms. In the case of complex systems and the laws that emerge from complexity, again the understanding involves reduction to atoms or molecules. Some examples are Brownian motion, the concept of temperature and pressure, solutions of salts and electro-chemistry, ion formation. However, we should add that many principles of chemistry are not usefully reduced to underlying atomic and molecular properties.

In a similar manner, we place biology in the hierarchy over chemistry noting that modern, molecular-based biology is underpinned by physics and chemistry. One has to read James Watson’s (1968) book “The Double Helix” to see how powerfully these subjects enter into the discovery of the structure of DNA. Again there are new laws of complex systems which emerge out of the complexity but which can (usefully or not usefully) be reduced to basic properties of atoms and molecules.

The limitation and over-simplifications of this pyramid is underscored by all the hyphenated subjects: astrophysics, physical chemistry, biochemistry, etc., but these do illustrate the unifying

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strands that weave through the sciences.

Much of the above wisdom came out of the results of revolutionary developments in science in the first half of the twentieth century. The ability to study processes involving the action of atoms led to the major revolution in the laws of physics. The data, which led to this major development, began to accumulate in the decade 1890-1900. By 1930, the revolution was essentially over and a new and powerful theory, the Quantum Theory, was in place. By the end of the century, some large fraction of the GNP of the industrial nations was derived from this understanding of the atom. Devices which fall in this class include transistors, microchips, digital computers, cell phones, lasers, CAT scanners, MRI devices, catalytic converters, etc.

The 1950's revolution in biology is symbolized by the discovery of the molecular structure of DNA and the subsequent flowering of the subject of molecular biology, with all of its potential for human advancement and controversy.

Developments in chemistry such as polymers, "bucky balls", carbon tubes, quantum chemistry, computational chemistry, etc. provide a rich background of subjects, which can be adapted to high schools. There are examples of the vast influence that chemistry has on the industrial strength of nations and on the standard of living and quality of life of citizens.

So, now what are the implications of all of this for science education? The hierarchy is one of complexity emerging from simplicity and it should therefore be the guide for pedagogue. To me it primarily calls for the exposure of students, as soon as possible, to the key to this revolution in science and technology, the atom.

It would be useful if students, by the time they reach middle school have a reasonable sense of how small atoms are and, hopefully, some idea of the role of atoms in our understanding of the world. This information should also arrive through powerful out-of-school sources such as museums, science magazines and newspapers that treat science.

Many school systems in Europe and Asia cycle through the core disciplines –for example, they take a month of physics, then chemistry, and then biology. This is an improvement on the US system of a year of biology followed (by about 50% of the population) by a year of chemistry, and then (for only 20%) a year of physics. However, it is my strong conviction that the physics (a full year) must precede chemistry in order to make use of the logical connections– the fact that everything is made of atoms and that the power of physics is the clarification of the structure of atoms, subject to the principles of quantum physics. Obviously, we do not accept the pessimistic view that ninth graders cannot grasp such abstract ideas.

Since it takes about a million atoms, to occupy a speck the size of the period at the end of a sentence, we note that atoms *are* indeed an abstract concept. However, with computers, simulation, imaging and modeling, students can be exposed to the idea of atoms long before ninth grade, the beginnings of high school in the US. Ideas of combination of atoms to make molecules is a process which should replace combination of elements to make compounds. These can be modeled and even the idea of forces binding atoms together can be qualitatively taught before ninth grade. Middle school however should also be where descriptive aspects of science are presented and where students develop mathematical skills such as graphing (slopes and intercepts), introduction to algebra, data tables and mathematical problem solving.

However, by ninth grade, students are learning enough algebra to begin the formal study of conceptual physics. Below I outline briefly a sample three years curriculum that emphasizes the virtues of a sequence in which *all* students (not only future scientists!) study a full year of physics followed by a full year of chemistry, followed by a full year of biology. I stress that there are many examples of other approaches that preserve the important general principles of a coherent science curriculum.

Now, based upon the foregoing, I would like to describe a three year science sequence that would produce high school graduates with a good sense of how science works, a confidence level to reach and enjoy further study, formal or informal, of science and, most importantly, a science way of thinking.

After all, science is the only truly universal culture.

In the beginning of a serious exposure to scientific disciplines (in the U.S., this is ninth grade, age 15) physics must be the first discipline. The level of ninth grade physics depends on the student's mathematics preparation and this in turn requires that the physics teacher and the mathematics teacher must have weekly conversations. Here we insist that physics can be meaningfully taught to students who are simultaneously studying the first year of algebra. Please note that teacher-to-teacher interactions are extremely important in a 21st century high school.

Physics in the First Year

Taking the most pessimistic view, the student is taking beginning algebra. The corresponding physics is usually called Conceptual Physics since concepts must be explained in English (or whatever language) rather than in mathematics. A thorough grounding in concepts is extremely important for all students, even future scientists. Too often, teachers assume that the ability to solve textbook problems is indicative of grasp of concepts. This is just not true!

The subject matter of this year of physics may follow conventional lines of the study of motion, forces and how these produce changes in motion, concepts of kinetic and potential energy, conservation of energy, chemical energy, electrical things: currents, voltages, electrical energy and its interchange with mechanical energies, important systems like the pendulum, circular motion, vibrations, light, heat (energy), useful and not useful energy, gas laws, waves, sound. Finally, at least the last month must be devoted to atoms, the discovery and properties of electrons and nuclei, elements of quantum theory, energy states, photons, forces between atoms and molecule formation.

Laboratory must be closely associated with the subject matter. Although the level of algebra may be quite low, its use in physics is best correlated with its introduction in the algebra class. Examples selected from the world of the student are important e.g. physics in sports, physics around the house, automobiles (horsepower, efficiency), flight of a baseball, "hang-time of Michael Jordan" etc. We proceed from the concrete to the abstract. We recognize a wide flexibility in subjects and in the depth per subject. A priority on subjects that prepare students for chemistry is natural.

Chemistry in the Second Year

In the second year, chemistry may profitably start by reviewing the properties of atoms and relating them to the Periodic Chart of the Elements. The molecule formation is described macroscopically as a reaction in which two elements, encoded by the numbers A and Z combine to form a compound. Its microscopic translation gives it the basic rationale. Properties of materials: compounds, mixtures, metal, acid, base, etc., can be related to atomic structure, which gives the "why" of these differences. Chemical reactions can often shuttle between the macro and the micro descriptions. In this way, the atomic basis enriches the chemistry and the chemistry motivates a deeper understanding of atomic behavior.

Here again, teacher-to-teacher conversations are crucial. Here is a good place to talk about history, which should be included in all three years. In chemistry, Lavoisier is crucial as an organizer of nomenclature, for description of reactions and for his work on combustion. Basic to Lavoisier's contributions is the conservation of mass. Dalton is the discoverer of the atom, which has been popular for 2000 years without any direct proof until Dalton. His adaptation of the ancient Greek idea provided a natural explanation of Lavoisier's chemical ideas. In taking historical excursions we touch on what I believe is a crucial component of science education: namely the process of science. How does it work? Why is science so universal a culture?

I would cheerfully sacrifice 20-30% of course content to the important topic of process including stories of wrong directions, wrong experiments, the relation of theory to experiment and the extraordinary validity of mathematics. The qualities that make for good science: skepticism, curiosity, openness to new ideas from a broad spectrum of contributors, freedom to choose research areas . . . these happen also to be the qualities required for a democratic society.

Other topics include a review of gas laws to do gas reactions, heat and temperature via the kinetic molecular theory, binding energy, chemical equilibrium, reaction rates, the structure of enzymes and their biological function. Organic chemistry is the bridge to biology, but has vast economic applications. The quantum mechanics is also applied to the complex molecules of organic chemistry. Here we are beginning to prepare the student for the transition to biology, with chemical bonding, electron dot structures, and molecular geometries in three dimensions as introduction to molecular biology.

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.

Now we hope we have stimulated another teacher conversation; the biology and chemistry teacher should be in close touch toward the end of chemistry. In the subject of photosynthesis, we involve all three disciplines. A digression on "cold fusion" is a great story of how things can go wrong and how science is self-repairing. Here too we cannot leave out the mathematics which should have progressed beyond algebra to congruence and similarity, to geometry and spatial visualization, to structures like DNA's, double helix, some analytic geometry, logarithms.

Biology in Third Year

In the sequence Biology-Chemistry-Physics, one stresses understanding over memorization. In the physics first approach, students are well grounded in the basics of atomic structure and molecular interactions. As an example of the importance of structure we can have two molecules, which are identical, chemically. The same number of hydrogens, carbons etc. In fact, the shapes are similar in that one is the mirror image of the other. The fancy word is enantiomorphism. But the "twist to the right" molecule works very differently from its mirror twin, the "twist to the left" molecule. This enables the teacher to emphasize how structure naturally supports function. For example, many molecules form polymers. What differentiates one 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 student to understand the natural use 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.

Again, I stress that there are many alternative approaches to a detailed, three-year core curriculum. Let me now summarize and emphasize the key elements in what I believe is a 21^{st} century approach to science literacy.

- There must be a core curriculum consisting of the three core disciplines in the order of physics, chemistry, and biology. Mathematical applications should be continuous so that biology makes use of all the mathematics up to pre-college.
- It is essential that there be

excellent laboratory work which is closely synchronized with the course work.
- Each discipline should spend 20-30% of the time on process, including selected pieces of history, applications to societal problems and the social, political and economic issues that entwine science and society.
- Teachers should have ample time to conference with each other. This *is* professional development in the best sense. If the nations are serious about the importance of science education, this may profitably use up one day a week that might include tutorials on line or by visiting scientists from local universities. The conversations referred to in the text may profitably be regular, weekly meetings of the physics, chemistry, biology and math teachers. The connections between disciplines should be celebrated by many examples.
- A crucial point is that the impact of atoms, atomic structure, and molecule formation be taught early so that students enter chemistry with a fair command of atomic properties. Ideally, we should review the science, math and computer learning curricula in primary and middle school so that there is a match to this dramatically new high school sequence.
- Students can be encouraged to select science electives in say third and fourth year. AP or honors physics would be especially profitable, as would a course in Earth Science, which now makes use of the students' knowledge of the core disciplines. I have of course left out many important subjects which can be inserted into the core curriculum or be offered as electives or even as a required fourth year. One is astronomy, another is statistical theory, prediction, and probability. The detailed folding in of computers and educational technologies is also missing. I know there is more!
- As teacher interactions become a serious component of life in high school, one can imagine inviting in the history teacher and the art and literature teacher to these meetings. Discussions could lead to projects, seminars that would illuminate the fundamental unity of knowledge. We would then be truly educating our young students for all possible futures.

We stress that we believe strongly that the core curriculum sequence should start with physics, enough physics to give students a strong feeling for the structure and properties of atoms. This allows chemistry to follow seamlessly. However, the details of how the core disciplines are taught may have many variations. How the disciplines are connected, how mathematics enters also have many styles.

We are especially excited by the need for continuous professional development and by the prospect of producing high school graduates who will surely forget formulas and prescriptions, but who will be imbued with the power of scientific thinking. Finally, we note that as a real curriculum is developed, school by school, that procedures for measuring the effect of this new reform be devised so that continuous fine tuning, continuous professional development and an increasing ability to connect all fields of learning become an on-going process.

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