On the threshold of the 21st century: Comments on science education

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Abstract

Hundreds of students, panels, committees and analyses of international tests have confirmed the deep systematic problems facing our educational system. In a time of increasing need for a science literate population, we are failing our students, the future citizens and workers. Exploding technological advances also increase the gap between rich and poor, between those with access to the evolving knowledge base and those who are without such access. Although international comparisons like the Third International Mathematics and Science Study (TIMMS) appear to have winners and losers, the implications of 21st century life make the educational systems of all nations vulnerable. In the US, equity and common sense would dictate that major resources be deployed to raise the level of all students to at least those of the new science standards. These have achieved national consensus, a new phenomenon in the US obsession with local control of education.

This paper will examine some innovative, even radical reforms in high school science education with obvious implications for K-8 and the first two years of college. The driving force is to prepare students for life in the 21st century, one that will be crowded with opportunities but also dense with threats. On both aspects, our projections of new sciences and new technologies include essentially unforeseeable consequences. This points to a search for educational processes that will strive for capability of adapting and even thriving in an arena of new problems and new opportunities. We like to call this "science thinking."

I will describe some innovative curricula like problem-based learning, integrated science and reversing the traditional sequence of core science courses, i.e. physics-chemistry-biology instead of biology-chemistry-physics. The criteria for a 21st century science curriculum are: coherence, integration, movement from concrete to abstract, inquiry, logical sequencing so that what is learned is used in further learning.

Here we believe that a three-year science sequence should dwell in some depth on the processes of science, its powers, its limitations. Science in the service of mankind serves as a bridge to the social sciences and the humanities. The frontiers of modern neuroscience do encourage a new faith in the old wisdom that there is a fundamental unity to all knowledge.

INTRODUCTION

I bring to this symposium a background in scientific research and a lifetime of university teaching. From the point of view of our theme "The underdevelopment of learning", I believe this combination of experiences is useful. Research implies a continuum of learning experiences. A scientist, often at the frontier of the discipline and always at the frontier of his personal knowledge, must learn in order to survive. This carries over to the teaching, since the teacher, especially in a hard science class, must always ask: Did they learn? Do they understand? Here I use 'understand' in the Gardner/Perkins sense of Teaching for Understanding (Gardner, 1993; Perkins, 1993; Teaching for Understanding, no date).

In the past decade, I have given much attention to science education, science as experienced in primary and secondary schools. I have organized a massive intervention in a large urban (Chicago) public school system: addressing the one issue of the under-preparation of primary school teachers in the content and pedagogy of math and science[1]. I have initiated and served as one of the Directors of a high school for gifted children (the Illinois Mathematics and Science Academy)[2] and have initiated a variety of teacher and student enrichment programs as the Director of a large US National Laboratory (Fermilab)[3]. Finally, my experience has been sharpened by chairing an international committee on Capacity Building under the aegis of the International Council of Scientific Unions (ICSU), which gave me a good perspective on primary school problems around the world. All of this is, obviously, a desperate effort to gain attention to some radical proposals that I feel are needed in the schools.

THE TASK

I begin by posing the question: What is the purpose of schools at this end-of-century epoch? One acceptable response could be: "The purpose of schools is to produce graduates who can cope in the world into which they emerge." Much is hidden in the phrase *"who can cope"* and in the characterization of *"the world into which they emerge"*. It is easy to characterize this as a world of unprecedented pace of change, so much so that it differs, in the requirements on the participants, from the world of teachers, parents, school officials, legislators. It is a world of information technology and the challenge of access. It is a world of globalization, of a paradox of unprecedented global interdependence and, at the same time, of defensive local cultures, nationalism, and community coherence.

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[1] Information on this experience is available online at http://www.tams.org/.
[2] Information available online at http://www.imsa.edu/.
[3] Information on Fermilab available online at http://www.fnal.gov/pub/education.html.

Projections of the human condition, the strength of family, the level of moral and ethical behavior, the economic health, social and political stability are all subject to the explosive advance of science and of technology. Major global problems of population, of environment, the dwindling of natural resources, including fresh water, the habitation of fragile land areas, sensitive to flooding, natural and man-made catastrophes, new pandemic diseases, all speak to the need for a greater understanding and control, i.e. more science and more technology. Advances in our understanding of molecular genetics and of human cognition open vistas of opportunities, which include the possibility of rational manipulation of human evolution. The economic consequences of wealth creation via science and technology also dominate *"the world into which they emerge"*.

This naive sketch of 21st century problems and possibilities is designed to set the stage for what we must do in our schools so that, at age 17 or so, the graduates, no matter what road they choose (work, technical school, liberal arts, science or engineering), will be able to "cope".

THE SCHOOL: GENERAL

Almost any assessment of schools comes up with a list of inadequacies when matched to the needs. Although such international studies as the Third International Mathematics and Science Study (Schmidt, McKnight and Raizen, Eds., 1998; TIMSS United Sates, no date) have winners and losers, one can argue that the standards are far too low. Since we are preparing students for a world strange to teachers and parents, how do we respond? The implication of 21st century life makes the educational systems of all nations vulnerable.

In the education of scientists, one is accustomed to the need to develop the ability to function in entirely unpredictable situations, for such is the nature of scientific exploration. This points to a search for educational processes that will strive for the capability of adapting, and even thriving in areas of new problems and new opportunities. Schools must look across all disciplines, across the knowledge base of the sciences, across the wisdom of the humanities, the verities and explorations of the arts, for the ingredients that will enable our students to continually interact with a world in change, with the imminence of changes bringing essentially unforeseeable consequences. Obviously, a vital component of such education is the habit of life-long learning.

In class after class, we need to confront the students with novel situations and challenge them to "find out". The very mechanisms that are creating this need for adaptability also offer the wherewithal through the technological road maps, available now to millions via home computers, but which can be extended to billions via the economy of silicon.

A LONGER VIEW OF OUR REVOLUTION

A major ingredient in "coping" with a world seemingly gone mad with the exploitation of technology, is the way in which scientists cope with their increasing involvement, as a necessity, in public affairs. They are concerned with values and goals, quite a contrast to the popular image of the scientist as cold, aloof, and "insensitive to the color and tragedy of the human condition", as my mentor, the noted American physicist I. I. Rabi, said.

Can we install, in our minimal three-year science sequence, the concept of scientists who care deeply and passionately for truth and clarification, for the liberating experience of finding order and beauty in a chaotic jumble of natural events? Apologizing for this strident advocacy, I see in the striving for rational explanation and scientific understanding, a standard for humankind's search for a just and meaningful world.

To teach science well to our high school students is to have them learn what science is, is to enable them to see the heritage of our experience in the context of the changes that surround us, born of new revelations, enabled by the very technologies that give us concern and foreboding.

But who can present these ideas to the generations of learners? How do we bridge the gap between the scientific culture and the non-scientific culture? I believe it can at least be started in the high school, but only after a new process is installed. This is the process of daily communication between the teachers of the sciences and the liberal arts. The new conversations between the physics, chemistry, biology and math teachers must expand to include all of the core disciplines. Of course, these conversations will have to be guided by new teaching materials, specifically designed with the grand goal of achieving universal literacy: scientific, cultural and literary. The learning will go on because it is driven by all the usual motivating forces: including a new diploma - that passport and map to economic and cultural comfort in an otherwise, bewildering jungle of confusion and change.

COHERENCE IN SCIENCE EDUCATION

So far, we have indulged in huge generalities. The reality is the school as it is today: a teacher in a classroom of students. Alas, this is only a small part of the learning environment at large (see also Visser, in this collection). Any revolution in education must involve the rest of the system: parents; school officials; teachers colleges teachers unions; local, state and federal legislators; the various organized and unorganized educational associations . . .

I want to focus on a specific, realistic example of a need for change driven by all that went before. This is in the teaching of science in US (and many other nations') high schools.

Some 99% of the US high schools (about 15,000) teach science in the wrong order[4]: Biology in ninth grade (15 year olds), Chemistry in tenth grade, and for the 20% of US high school students who dare, physics in eleventh or twelfth grade. A National Commission (the so-called Committee of Ten) recommended this mad order in 1893. The logic was not, as you may believe, alphabetical. Biology was descriptive, qualitative and more of a natural science. Physics was abstract and mathematical and should wait for the more developed cognitive powers and mathematical preparation of the student. In 1893 or 1930 these arguments made some sense. In 1999, the order is absurd and illustrates the awesome resistance of educational systems to change.

Today, ninth grade biology consists of learning a large vocabulary of names and systems. There is no contact with modern molecular biology, characteristic of the 1950's discovery of DNA. Underlying mechanisms for the structure and function of cells, proteins, and genes cannot be studied because students have no inkling of molecules.

Qualitative biology as a description of biological processes should be a middle school (i.e. ages 11-14) task. In a rational, coherent study of science, we should begin in ninth grade (i.e. the first year of high school, which for US students is age 15) with physics, taught conceptually, i.e. using only the algebra that students are learning. This starts with the world around the students: measurements in space and time, motion of objects, forces, the flight of baseballs, the simple pulley, concepts of energy, conservation, the oscillation of pendula, electricity and magnetism, waves, etc. Slowly, over a year, with numerous excursions to other disciplines where appropriate, we draw the student into the more abstract world of atoms.

After one year of immersion in physics at this level, again <u>using</u> ninth grade algebra, the student has a working model for atoms. As we describe the different numbers of electrons in increasingly heavier atoms, we are already—without knowing it—in the periodic table of the chemists. Some introduction to energy states makes it all sensible. Now we are in sophomore chemistry. We learn the way atoms combine (or don't) to form molecules, as a consequence of the electrical forces or potential energy equivalents.

Chemistry advances through its many phases, with a continuous appeal to physics to understand such crucial chemical processes as bonding, compound formation, photochemistry, electrochemistry, energy transformations and the structure of the periodic table of elements. Again, there is natural progression into large molecules (organic chemistry) and we are soon in biology.

In the most essential elements of sound pedagogy, chemistry *uses* the students' knowledge of physics, and biology *uses* both physics and chemistry to provide the *coherence* of scientific understanding. Mathematics is woven into the pattern of the hierarchy from simple to complex. Unifying themes are stressed: mechanisms, models, conservation of energy, oscillations and vibrations from the simple pendulum to molecular microwave spectroscopy, symmetry, beloved of mathematics, can be appreciated in a spiral learning approach.

And in such a sequence, we must include history: How do we know these things? How does science progress? Something about the heroes and heroines, the influence of social and political forces on the progress of science and the influence of science on society. Connections with cultural history need to be developed. Such scientific traits as skepticism, aesthetics, and intuition are important, as are prediction, probability, risk assessment, uncertainly, and statistics.

These important subjects require careful organization. If done properly, they will convey to students some sense of the essential messiness of science without discouraging them. Case histories of scientific discord and debate may be one way to proceed, especially since they all, by definition, have happy endings. Spontaneous generation, phlogiston, heliocentrism, cold fusion, even the not-yet-completed issue of the expanding universe are possible examples. Validation of scientific discoveries over the centuries, especially when extended to the abstract domains of the molecular, atomic and subatomic world are valuable, even essential learning arenas. The guiding principle is the way science copes with surprise, novelty, and new domains that are revealed by new instruments, themselves a product of scientific advances.

A successful multi-year sequence of the core disciplines will be supplemented by electives in earth sciences; environmental science; astronomy; science, technology and society; and advanced, disciplinary courses taught with a higher level of mathematics. It will require a change in the culture of schools. Teachers of physics, chemistry, biology and mathematics must have time to work collegially together to coordinate and establish the coherence that leads to science as a way of knowing and thinking.

The more profound outcome of such a new high school culture is the inevitable inclusion of the social sciences, the arts and humanities. The connections will emerge in countless ways as teachers and students explore the consequences and the connections of the scientific worldview as it affects human behavior, conditioned by our four hundred-year-old commitment to the enlightenment. Harvard socio-biologist Wilson (1998) revived the word "consilience" to describe the 21st century revision of the age-old belief in the unity of knowledge. This intellectual growth

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[4] See also http://www-ed.fnal.gov/arise/arise.html.

can emerge naturally from a kernel of educational theory if our new criteria include coherence as an essential ingredient in the learning process.

SUMMARY AND CONCLUSIONS

The restructuring of high schools is envisioned as starting from the clear need to revise the traditional science sequence (at least as far as the US is concerned) of biology-chemistry-physics. The obstacles to such a logical change are formidable. In the US it implies the willingness of teachers to change what they teach and how they teach. It implies the willingness of parents to risk their children's admission to colleges, institutions famous for resistance to change. It implies increased costs as teachers must be given several hours a day to work with colleagues to stress the key ideas in this new pedagogy, to invent techniques for improving the learning process, to propose interdisciplinary and transdisciplinary (see also Nicolescu, in this collection) problems that will further use the growing mastery of disciplines. It will require a new effort to marry the knowledge of the physical and biological universes with the wisdom of the humanities and with the essential creativity of art, music and literature. Transdisciplinary challenges must be part of the new pedagogical practice.

This revolution is expensive, requires changes in how teachers are trained, and in societies with a commitment to decentralization and local control, such as the US, will require the support of the movers and shakers of society: the business community, scientists, educators, universities, and political visionaries. It will clearly imply drastic changes in the K-8 curricula (ages 5 to 14) and it will surely influence the liberal arts colleges and professional schools.

Here it is inevitable that law students will have to learn more science. Just examine the issues bedeviling the courts: DNA, gene testing, reproductive technologies, the Internet . . . similar arguments can be made for all professions: business, journalism, political science. The new high schools we are visualizing will aid this task enormously. The 21st century, as we visualize it, is a strange land. They do things differently there!

I conclude with a quotation from the same professor Rabi (1970, p. 62) mentioned above:

> *Plato had an Academy for preparing young men for entry into an equally troubled world. I have often thought in fantasy how interesting it would be if I could put one of our fresh bright Bachelor of Arts complete with Phi Beta Kappa key on a Wellsian time machine and confront him with one of the products of Plato's Academy. What would our twentieth-century paragon be able to tell his opposite number from the dawn of recorded history? Could this product of two millennia of human progress enlighten our Greek youth on philosophy? On the arts of sculpture, of painting, or architecture?*

Could he demonstrate his superiority in poetry, in the drama, or in oratory? Would his language be more pure, his thoughts more elevated? Would he excel in athletic prowess and grace of body and carriage? Would he perform more effectively on a musical instrument? Would he be more prepared to fight for his country and lead men into battle?

We would like to answer Yes, but truth rather than modesty compels us to doubt whether our twentieth-century graduate would make a brilliant showing in these fields which are the special province of what we now call the humanities.

Indeed, only a fraction of our best students could get by the door of the Academy, because the inscription reads, "Let no man enter who does not know mathematics."

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