Rethinking Undergraduate Science Education: Concepts and Practicalities
A Traditional Curriculum in a Changed World

Robert T. Yuan, *Professor Emeritus of Cell Biology and Microbiology, University of Maryland, College Park; Consulting Senior Program Officer, Board on Life Sciences, National Research Council*

Science education at the university level has been based on a number of premises. Students that have successfully completed a course of study will have mastery of a scientific discipline. That knowledge should basically be sufficient to take them through a working life of about forty years in a given career track, e.g., industrial research, and project area, e.g., mode of action of antibiotics. And that career takes place within the boundaries, physical and intellectual, of one country.

Let us then turn to the world we actually work and live in. Science and technology is interdisciplinary and most of the work is done by teams composed of individuals from different disciplines. The half life of a project is likely to be in the order of seven years which means that an individual may have to retool him/herself several times in the course of a working life. It will also not be uncommon for that individual to have multiple career tracks, e.g., from academia to industry to venture capital. And new knowledge and multiple collaborations will move across national borders at warp speed.

Given these circumstances, one must conclude that our educational system is preparing our graduates for a world that ceased to exist some time ago. In addition, enrollment in science and engineering in the U.S. continues to decrease and the attrition rates are correspondingly high. In a landmark study by Seymour and Hewitt, it was found that students that received degrees in the sciences were similar in abilities to those that had switched majors. Major reasons given for dropping out of the sciences were the poor quality of the teaching, the sheer boredom of the courses, and a perception that they had little relevance to any career that would be of interest to these students.

Under pressure from industry and government, universities and their faculties have begun to face the need for change in their science, technology, engineering and math (STEM) curriculums. This has been problematic in that many of these efforts focus on the restructuring or creation of a course by an individual professor. This does not necessarily lead to a revision in a course of study nor in the development of a process for sustainable change. Not to mention that dissemination and adoption by other institutions happens rarely and in a random manner.

A New Educational Framework: Concepts and Points to Consider

The fundamental change therefore is to realign the courses with the world of work which university graduates will enter. A novel educational framework for STEM would enable students to learn how to acquire and use an ever expanding body of knowledge where change is occurring at breakneck speed. At the same time, it must expose students to the dynamics of a diverse population, work in teams, and globalization. In a nutshell, it should enable them to work and live in a changed world.

We will present a holistic curriculum that is composed of two bridging concepts. The first one is the "Virtual Workplace" that provides students with a spectrum of thought processes and skills that prepares them for a variety of scientific and science related careers. The second concept is "Journey without Maps." It addresses the challenges associated with the increasing diversity of our student body and faculty. For many minority students finding an educational pathway through a puzzling and complex university or college system is indeed a journey without maps. For non-minority students, using their education and skills in a culturally heterogeneous and constantly changing global economy is also a journey without maps.

The change of an existing STEM curriculum into a "Virtual Workplace" requires us to consider three educational elements: content/process, skills, work environment.

> **Content/process**: The focus should not be so much the learning of a certain body of information. It should rather be the learning of information in relationship to its use for the solution of major scientific problems. The students should be encouraged to seek information from multiple sources including texts, primary papers, laboratory manuals, the Internet, dialogue with specialists. The information should be reviewed critically and be interdisciplinary in nature. And the student should understand that the information will continue to grow and change, and that he/she will continue to learn throughout his/her working life.
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> **Skills:** The classroom environment should provide an opportunity for students to learn and practice certain fundamental skills, e.g., critical thinking, teamwork, peer review, experimental manipulations, computer use, scientific writing and oral presentations.
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> **Work environment:** the tasks assigned in class should mimic those in the workplace, e.g., a paper describing a project should approximate the format of a scientific publication or a grant proposal, class work should be organized around student teams, a project might yield more than one technical solution or that solution might be an imperfect one though an improvement on previous knowledge..

"Journey without Maps" addresses the issue of how to practice science in a global environment which often involves the interface between science, economics and culture. At the same time, the students will face the challenge of working in teams that will be diverse in terms of gender, race/ethnicity, class, and educational background. How does one design a course so that it can effectively deal with:

> **Globalization:** The scientific topics can be presented in the context of different social, economic and cultural environments. For example, immunological assays represent an excellent solution for the detection of HIV in blood samples. This procedure is less satisfactory in developing countries due to reasons of cost, availability of medical

personnel, cultural resistance to drawing of blood. This leads to the development of alternative technologies for working with urine or saliva samples.

Diversity in the workplace: The educational process should expose students to the experience of working together with students of diverse backgrounds. This should result in a rational process for arriving at a consensus and maximizing the contributions of every member of a team. The final outcome should be representative of a team effort. Role playing can be invaluable in exploring the value systems of a different group.

Assessment and Evaluation: This is an integral component of course and curriculum change, both as a measure of the effectiveness of the innovations and also as a means of maintaining quality control over time. This can be done in a manner that is built in into the course by tracking performance with the increasing difficulty in the tasks and by exit surveys of the students. The far more difficult evaluation involves the impact of the new courses on performance in senior level courses and in studies/work following graduation.

The concepts and course features described here are designed to give the student the experience of how a scientist works and thinks in the context of various career tracks. The transformation of the classroom requires a serious consideration of the points described above. Such an initiative runs counter to the existing culture in most universities. First, changes occur mostly at the level of individual courses not of courses of study. Rather than rethinking all the features of a course, it usually addresses one or two elements (e.g., introduction of problem sets, new experiments in the lab). Two, courses that are student centered change the role of the teacher from being master of the classroom to that of a facilitator or arbiter. Third, the teacher becomes the architect and builder of the new course with the resulting investment of time and effort. Fourth, active learning and teamwork increase the difficulty in assessing student performance and puts the teacher in the position of having to deal with personality conflicts in dysfunctional teams. Most faculty members are ill prepared to deal with such problems, and in some cases, they may have chosen science as a way of avoiding such conflicts.

The Practicalities of Implementing Change

The concepts of a “Virtual Workplace” and a “Journey without Maps” may provide answers for our traditional STEM educational approach. They might even be exciting and intellectually challenging but at the end of the day, we have to get real. There are real constraints. Senior administrators may be supportive of STEM reform but they will warn that it must be done in a resource neutral manner. The budgets will remain the same. The demands for teaching time by faculty will also not change. The objective, however, is to establish a process that will lead to comprehensive and sustained change across a series of courses even in the face of such constraints. And as in the case of quality research, this process should be faculty initiated.

Given these fundamental concepts and the set of constraints, the question is how can they be implemented at a research university. This section describes a case study that involves Microbiology courses at the University of Maryland College Park with the participation of roughly ten faculty members over a period of fifteen years. The overall scheme allows for the development of different courses for various student populations.

- Honors seminars: these are interdisciplinary, crosscultural courses with a maximum enrollment of twenty of the university's best students. These seminars represent a test bed for the development of new educational approaches and teaching materials. If change does not work with very intelligent and highly motivated students, it is unlikely to work with the average student population.

- Lower level, large enrollment science courses: in many respects, these courses are built around adaptations of what has been learned in the honors seminars and reach out to the mainstream of the student body.

- Lower level, general education courses: these courses represent adaptations for non-science students and are directed to improving science literacy and providing an understanding of the culture of science.

- Upper level, science courses: these are the specialized courses for majors and represent a ramping up of the tasks embodied in the concepts of a "Virtual Workplace" and a "Journey without Maps."

This array of courses (and students) enables the creation of a sturdy platform that uses developments in one course to be adapted and applied to other ones. While the objective is to come up with a number of constructs that are applicable to all of these courses, we have found that large scale introductory lecture/laboratory courses represent a major challenge of their own. For example, the honors seminars are highly effective in their use of student developed case studies, the use of mixed student teams, and role playing. For example, in a seminar on Traditional Chinese Medicine as a Complementary Approach to Modern Western Medicine, teams may examine the process of scientific and clinical validation as applied to acupuncture for pain management or the use of specific herbal formulations for chronic conditions such as arthritis or dermatitis. However, those course characteristics are only applicable to small classes (i.e., twenty students in the seminars). Major elements such as teamwork, case studies must be adapted for large introductory courses. The following issues while applicable to all courses had special difficulties as applied to the introductory courses.

1. How can a course be designed to be interdisciplinary, provide a window to how scientists work, and give a sense of different career opportunities?

   The basic mechanism is a course module that is presented over a period of several weeks. The module integrates a series of lectures, a case study, mini-quizzes, and a series of laboratory experiments. The case study provides a narrative and a major research question and the student team needs to find information from multiple sources in order to resolve it. In a semester, the three modules can provide an insight into three different career directions: bacteriology, genetic engineering/biotechnology, pathogenesis/medicine.

2. How do you construct the course so that it integrates learning of basic concepts, research and laboratory methods?

   Each module synchronizes a set of activities (lectures, readings, mini-quizzes and laboratory experiments). The case study defines the scientific problem which is then broken down into smaller bite size elements. Information from the various activities needs to be accessed and integrated to resolve the case study. This involves a series of mini-quizzes leading up to a paper at the end of the module and a test. The students learn that different types of information are needed and that only some of it is derived from the textbook. The solutions generated by each team may vary.

3. How can students learn the basic skills that are needed for scientific careers?
   It is generally accepted that knowledge of various laboratory manipulations and familiarity with scientific equipment are an important component of STEM education. There are other skill sets that are equally important and should be built into the courses such as: experimental design, team work, computer skills, communications (oral and written) and critical acquisition of information.

4. How can issues of diversity and globalization be addressed? A diverse workplace presents both opportunities and risks which cannot be ignored. The use of teams that are mixed by gender, race/ethnicity, field of study and grade point average provides a venue for experiencing diversity. Two important elements in our construct has been the inherent difficulty of tasks (requiring maximum effort by every member of the team), evaluation of the task as a team effort and, finally, peer review in the final grading. The idea is that the more effective the team, the better the outcome of a project whether in the lab or the preparation of a paper. One major aspect of globalization is in the way that modules and case studies are constructed to give a broader perspective, e.g., immunomodulators derived from ethnobotany as an alternative to chemically synthesized drugs as a solution to infectious diseases.

The case study provides support for a pedagogical platform that implements the concepts presented earlier and operates within the constraints of our administrative system.. The modification of a set of courses requires components that are, however, not entirely within the domain of faculty members and yet are essential for the success of the enterprise. One of these is evaluation and assessment. Our efforts have focused on building part of the evaluation process into each course. Each successive task in a course is ramped up in difficulty so that proficiency at each stage is necessary to do well in the next one. Class performance in a novel course is compared with that of the traditional version and student surveys are conducted at the end of the semester. Positive results provide some measure of the success of the reforms. Our teaching team feels reasonably satisfied that it has developed a functional model for a large enrollment lecture/lab science course. An early evaluation shows a much higher degree of satisfaction with the new course as compared with its traditional counterpart. Student performance is as good or somewhat better.

We do believe that far more valuable indicators would be performance in successive upper level courses and, ultimately, in graduate/professional school or the workplace. Such projects are clearly beyond the capacity of faculty members or even individual departments.

As pointed out earlier, innovations in the STEM curriculum are expected to be resource neutral, both as regards budget and faculty time. In our case, the solution has been in the use of course design, teaching teams, and technology. Course design incorporates team projects, self-assessment and peer review which reduces the amount of faculty time involved in grading. In the large introductory course, we have used teaching teams composed of faculty who are responsible for lectures, teaching materials, exams and overall grading; graduate TA's who deal with the labs and grading of quizzes and exams, and most importantly, undergraduate TA's who act as facilitators and resource persons (most often in relation to questions arising from the modules and case studies). So while overall staffing has increased, this has not had a major impact on budget. Undergraduate TA's are not paid but receive credits for their time. While faculty time has not increased in a major manner, it probably results in an increase of 2-4 hours/week. The course changes cannot be accommodated in the time allotted to lectures and labs. The use of WebCT allows for a 24/7 access to information and ongoing discussion and access to the members of the teaching team. Student difficulties with concepts or scientific details can be monitored leading to real time adjustments in lectures and lab sessions. Finally, we have made extensive use of university services: computer expertise (from Office of Instructional Technology), access to information (Library Services), and faculty development and assessment (Center for Teaching Excellence). The use of undergraduate TA's and university services increases the effective manpower without affecting the course budget.

Individual Initiatives. Systemic Change

Changes in the STEM curriculum are typically the result of efforts by individual professors and groups of faculty. The biggest challenge still remains and that is systemic change in a campus and dissemination across institutions. As described above, major elements of curriculum change need to be part of the administrative framework in order to maintain momentum and have sustainability. Assessment and evaluation require resources and expertise that are usually not available to an individual professor or department. Furthermore, the procedures should be common to a college if not to an entire university (possibly through a campus wide Center of Teaching Excellence). The creation of a course of study involves several linked courses. Both the knowledge base and skill sets would be ramped up over a period of three years. Such an effort would require the coordination of content, case studies/problem based learning, and strengthening of work skills across courses. We are just beginning to do this with a group of faculty that teaches the principal courses in our Microbiology curriculum.

While curriculum changes are supposed to be financially neutral, the cost and effort for reshaping or creating a new course does require additional funding. Most often that comes from external grant funding. These grants are usually for two years while the process of establishing a new course and integrating it into the curriculum is more in the range of 3-5 years. And as teaching assignments are rotated, there is no provision for faculty development as new instructors are assigned to a course. The funding cycles are not well synchronized with curriculum change.

Even as the curriculum of study for a given major or department undergoes major restructuring, there is seldom a process of harmonizing this across the various departments or colleges that are responsible for STEM teaching. And beyond this is the process of dissemination across different institutions. One significant national effort has been a summer institute organized by the National Research Council and the University of Wisconsin–Madison and supported by the Howard Hughes Medical Institute. The purpose of this five day institute was to bring together faculty teams from various universities to learn new pedagogical approaches to undergraduate STEM teaching. Similar workshops are regularly organized by organizations such as Project Kaleidoscope and the American Society for Microbiology. These activities serve to stimulate grassroots initiatives by faculty. There is little evidence that they lead to systemic change.

A highly educated and skilled workforce lies at the heart of an advanced post-industrial society. Therefore, effective and efficient teaching should have pride of place in our universities and colleges. This paper has argued that we have an increasing understanding of the concepts and tools that can be used for the creation of effective courses and that this can be done in different types of institutions. Such efforts require ingenuity, energy and time that are comparable to those that go into quality research. Unfortunately, the recognition and rewards are not comparable. Creative and sustainable change cannot be based solely on the initiative and effort of individual faculty but must be sustained by radical change in the administrative structure and reward system of our universities and colleges.

There are a number of possibilities as regards systemic change. These include:

- The creation of a new institute designed to carry out basic research, graduate training and undergraduate teaching. The University of Basel (Switzerland) created the Biozentrum which was central to the creation of new Biology II undergraduate curriculum.

- The establishment of a model undergraduate curriculum that includes textbooks and laboratory experiments which is then disseminated to other universities in a national system. The University of Wuhan (China) is doing this in Microbiology under the auspices of the M. of Education.

- The creation of a new technology university incorporating both new faculty and curriculums. Hong Kong built the Hong Kong University of Science and Technology along the lines of a U.S. research university.

These efforts share certain common characteristics: there is a political will that taps into human and financial resources at a regional and, most often, at a national level. The creation of large new institutes or universities also allows for changes in promotion systems and financial rewards. While there may be analogous initiatives in the U.S., our nation differs from other advanced industrial countries in that it does not have a centralized system of education. To put it another way, our system is positioned for innovative approaches to student learning but lacks a framework for sustained and systemic change. This country lacks a lead institution or partnership that can mobilize ideas and resources at a national level. Neither the National Science Foundation nor the Dept. of Education has undergraduate STEM education as a principal component of its portfolio. The absence of a national system does not preclude the creation of a systemic organization for STEM reform that includes its major stakeholders such as educational institutions, government, industry (both high tech employers and those that play an important role in education such as publishing, media, software). Individual initiatives are all important, but the time has come for systemic development and implementation.

Acknowledgments: the work described in this paper was done in collaboration with a group of energetic and committed faculty and staff members at the University of Maryland College Park among which are Ann Smith, Richard Stewart, Patricia Shields, Jennifer Hayes-Klosteridis, Paulette Robinson, Bonnie Chojnacki, Maynard Mack, Jr. (former director of the University Honors Program), Spencer Benson and James Greenberg (director and former director of the Center for Teaching Excellence respectively).