

## CHAPTER 10

# Science for All in a Core Curriculum: Frontiers of Science at Columbia University

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### THE PROBLEM

Practicing scientists have strong views about what constitutes good preparation in a particular discipline. While these views shift as science evolves, every molecular biologist would agree that a student needs to understand the genetic code and the way in which proteins are assembled, and every neuroscientist would agree that a student needs to understand how an action potential is generated and how information is transmitted at the synapse. When it comes to preparing science majors outside their particular scientific discipline, we find few areas of agreement; even more contentious is what constitutes science education for non-science majors.

For the future parent, social worker, businessperson, senator, poet, or economist, what should completion of a science requirement confer? Is it important to know facts (the distance to the sun) or to be able to assess whether the facts averred (in the media, on the Internet) are plausible? Should all college graduates be expected to be able to read and understand a scientific article (Watson and Crick's *Nature* paper on the structure of DNA) as they are expected to read a piece of literature (Herman Melville's *Moby-Dick*)? That is, should they be able to explain the question the paper addresses, how the authors address the question, as well as explain what the findings mean?

I believe that the most important skill a science requirement can develop is the capacity for critical analysis. In episode twelve of the seventh season of *West Wing*, a runaway nuclear reactor in California is producing radioactive gas that has to be pumped into a building inadequate for containment. The gas is vented, and the reading just above the smokestack is at first 569 millirems; it then "stabilizes" (two readings) at 561 millirems. The "safe" level of exposure is 500 millirems, so the American people are informed of the exact levels re-

corded. Millions take to the highways. Is this a plausible scenario? Why is 500 millirems considered safe and anything greater not safe? What does exposure mean? How great is the risk that the building will explode (said to occur at 50 psi)? As I watch this episode, I think, “If I were there, should I stay home or set sail? Which way will the Santa Ana winds blow?”

Life has a way of turning hypotheticals into actuals. Your mother has a breast lump; it is biopsied and found to be estrogen-receptor negative. Her doctor prescribes a drug that antagonizes the effects of that hormone. Should you look for a new doctor? The effects of exercise and eating a diet rich in vegetables, fruit, and fish are independently beneficial for warding off Alzheimer’s disease. Does this mean you should choose one strategy or adopt both? What is the probability of a meteor hitting Earth in your lifetime? If one were to hit, where should you be? The ability to analyze data and understand scientific knowledge is essential for an informed citizenry and thus for effective government. How can we achieve this goal within the context of a university education?

## AN APPROACH

In 2001, a group of Columbia University faculty members began to develop a one-semester course, *Frontiers of Science*, that is now taken by every entering Columbia College student. The immediate impetus for developing the course was a survey, undertaken by the University’s Committee on Science Instruction, of the courses students were choosing to satisfy the University’s three-course science requirement. The survey found, for example, that although more than five hundred entering students each year expressed some interest in preparing for a career in medicine, only seventy to eighty graduated having fulfilled the necessary requirements. For the rest, the typical science experience consisted of one introductory chemistry course and a year of calculus. Thus, the majority received a science education that did not even remotely expose them to the driving forces of modern science, such as exciting new discoveries about the way the physical universe and biological worlds work and interact.

The survey found that even for science majors the kind of training typically offered within a given department bore little resemblance to the multidisciplinary flavor of current research. The guild-like mentality of science training presumes that students need to reach the top of the disciplinary pyramid before they can grapple with anything “real.” To ascend the pyramid, they must master a long series of preparatory courses. Because only a handful of majors ever reach the top, only a small percentage of students get to experience how science is really done in a given field and what problems the field is currently investigating. What if we could break the pyramid for students both with and without a professed interest in science? Introducing science across disciplines at the level at which it is actually practiced could set the nascent scientist on an interdisciplinary trajectory and bring the excitement of science to students

whose major impression is that it involves simply memorizing a great many facts and equations.

An introductory, multidisciplinary science course for all students is usually considered impossible. That *Frontiers of Science* was launched in its current form is largely attributable to an existing curricular structure at Columbia College called the Core Curriculum, a series of seminars aimed at critical evaluation of important ideas in philosophy, literature, society, art, and music. All entering students take the Core: the poet takes Literature Humanities, the concert pianist Music Humanities, the accomplished historian Contemporary Civilization, the nascent cosmologist *Frontiers of Science*. The Core provides the required prescription for *Frontiers*: the early stages of a university education should include a common learning experience for a cohort of students with wildly different preparations, gifts, and interests.

#### WHAT IS FRONTIERS OF SCIENCE?

Like other elements of the Core Curriculum, *Frontiers of Science* is taught in small seminars of twenty-two students. However, *Frontiers of Science* is multidisciplinary, with half the subject matter taken from the physical sciences and half from the life sciences. Thus, a number of faculty members are involved in teaching *Frontiers* over the course of the semester. Which sciences are taught—from among physics, chemistry, astronomy, earth science, molecular and evolutionary biology, biodiversity, and neuroscience—changes from semester to semester and from year to year depending on the faculty involved. In addition to teaching science and non-science majors together, *Frontiers* faces the challenge of faculty teaching across disciplines; a cosmologist might teach about molecular evolution.

Each unit of *Frontiers of Science* runs for three weeks; in addition to weekly seminars, a senior faculty member presents a lecture series on exciting discoveries in a particular field. No attempt is made to develop a single theme across the semester. The analytical skills that cut across disciplines are presented in the online text, *Scientific Habits of Mind* (<http://www.fos-online.org/habitsofmind/index.html>). Seminar sections are led by either a senior faculty member or a Columbia Science Fellow, a combined lecturer/postdoctoral position established specifically to meet the teaching needs of *Frontiers of Science*. The development of the curriculum is a joint faculty effort spearheaded by the Science Fellows.

#### THE CHALLENGES OF FRONTIERS: TEACHING AND LEARNING

*Frontiers of Science* comprises twenty-eight seminar sections taught to 550 students each semester by (usually) sixteen members of the faculty. A course director and an assistant director of the Center for the Core Curriculum man-

age the logistics and organizational challenges. Teaching *Frontiers of Science* means mastering current research in at least three disciplines beyond a faculty member's area of expertise. For example, most astronomers have not had significant exposure to biology since high school, and many neuroscientists have never taken a geology course. In the tradition of the Core Curriculum, Columbia does not segregate science majors from non-science majors within *Frontiers of Science*. Teaching a small seminar with a diverse group of students (chemists-, poets-, and economists-to-be) is a significant challenge. The future chemist is chomping at the bit to get into preparative chemistry, and the future poet thinks she has escaped science by choosing Columbia. The Core Curriculum, however, mandates as an educational philosophy that entering students have a common experience in critical analysis.

The two cultures of C. P. Snow are forged in kindergarten. That they are so evident in college students is thus no surprise. *Frontiers of Science* is taught from the perspective of the ways in which scientists carry out their explorations, experiments, observations, and mathematical models; many students are stunned to discover that the memorization skills they so carefully mastered in high school—skills that were instrumental in their gaining admission to Columbia—do not serve them in the course. *Frontiers of Science* emphasizes analysis and problem-solving. Many units rely on mathematical skills (algebra and statistics), and most students are not used to viewing math as a tool to solve problems rather than as a self-contained subject matter. While university-level scientific research is increasingly multidisciplinary, few high school courses reflect this change. Students feel they have barely come to terms with one topic (for example, volcanoes) before they must switch to another (for example, the brain). Aspiring astronomers find three lectures too brief an introduction to the most important subject on the planet, and the assignments may not seem challenging enough—while their classmates may not even know where to begin. Students do not enter college with well-honed skills in group learning, and the day when their classmate from the *Frontiers* seminar is president of the United States and is responsible for deciding whether to vent that containment building described above seems impossibly distant.

## COLUMBIA FACULTY AND CORE COURSES IN SCIENCE

The Columbia science faculty began discussing a general science course in parallel with discussions about *Contemporary Civilization*, the first Core Curriculum course, which was launched in 1919. The motivation then for establishing a core science course was similar to the motivation that drove the development of *Frontiers of Science* beginning in 2001, but the courses that eventually were launched in 1934 bear little resemblance to *Frontiers*. Those courses, Science A (physics and chemistry) and Science B (geology and biology), were to be taken only by non-science students and could not serve as

prerequisites for any “real” courses in any science department. They were terminated at the outbreak of war in 1941, and although we do not have course evaluations for those seven years, the experience must have been unsatisfactory. By 1945, with the Core Curriculum well under way, a general science course was again under discussion, but this time the goal was to create a course that would include all students. The idea was

that a specially constructed and well-integrated two-year course in the natural sciences be a required course for all students who are candidates for a degree from Columbia College, quite irrespective of whether such students plan to enter one of the scientific professions or not . . . [and] that such a course be staffed by men who are prepared to give competent instruction in all of it, and not simply in some fragmentary portion of it.<sup>1</sup>

In her May 2006 address to the Columbia College graduating class, Dean Kathryn Yatrakis noted:

The 1945 Committee was in fact quite emphatic about this general science course being required of all students saying that if it were to restrict the course to non-science students, it would amount to lowering the general standard of interest, enthusiasm, and inquisitiveness, and hence to exclude those who would supply the chief stimulus to both teachers and students.

The new attempt apparently had general support from the faculty as a whole but foundered on the antipathy of the science faculty. The resulting 1946 report amounted to a recommendation for the reinstatement of Science A and Science B when the financial climate permitted. Apparently the climate did not sufficiently improve between 1946 and 1983, the year in which a faculty committee again recommended a single course for all students. The seesaw continued, however: in 1990 another faculty committee recommended against a single science course but did recommend the creation of a standing Committee on Science Instruction (COSI). This committee, in the end, provided the impetus for *Frontiers of Science*.

The university administration (especially the provost and the dean of the college) was from the outset highly supportive of change. A working group adopted the 1983 recommendation, its form was shaped by the members of COSI, and the future directors went forth to sell the idea, first to the science faculties and then to the faculties as a whole. As in 1945, the science faculty was skeptical: one distinguished senior chemist even informed the vice presi-

1. Columbia College Committee on Plans, *A College Program in Action: A Review of Working Principles at Columbia College* (New York: Columbia University Press, 1946), 127.

dent for arts and sciences that the course would be created “over my dead body.” While such a high level of opposition was unusual, the concerns voiced by members of the science faculty were thoughtful and well founded. But from their meetings with the science departments, the course directors usually emerged, like the Pied Piper of Hamelin, trailing at least one enthusiastic faculty member, typically a scientist of extreme distinction with a passion for conveying the beauty and power of science to the public. This initial group recruited another group of more junior faculty members (the Columbia Science Fellows), and after a pilot semester in Fall 2003, *Frontiers of Science* appeared as a five-year experiment in the Core Curriculum in 2004, an experiment renewed for an additional five years in Spring 2009. The chemistry department now feels that “Chemistry is too important not to be in *Frontiers* and *Frontiers* is too important not to include Chemistry,” as James Valenti, director of undergraduate studies and former chair of the Department of Chemistry, put it.

Why the seesaw? What conditions in 1945, 1983, and 2001 made a single course seem important enough to be a possibility, and what in 1933, 1946, and 1990 engendered such grave reservations? The main factor was probably leadership, from both faculty committees and the university administration. However, world events may well have played a role in faculty opinions. In the 1940s, the atomic bomb and the nuclear arms race focused American attention on the power of science, how it should be harnessed, and how it must be constrained. At the millennium, a widespread appreciation of a new threat—global warming—emerged. Determining the causes and consequences of warming requires an extraordinary scientific effort to understand and political will to act; that will must be an informed one. Finally, there is money. In 1933 and 1941, funds for education (and all else) were in short supply because of, respectively, the Great Depression and World War II. Dreams of inclusive education, no matter how important, were a luxury. In the expansive economy of the early 2000s, the financial climate might have been relaxed enough for university leaders to consider seriously the ambitious goals of *Frontiers of Science*.

## FACULTY DEVELOPMENT AND FRONTIERS

A beginning science faculty member at a typical R1 university is expected to develop a research program and a series of graduate and undergraduate courses. Although the new faculty member has been training for the research program for more than ten years, he or she has no explicit preparation for developing a teaching program. “Sink or swim” is often an accurate summary of the new faculty experience. One useful feature of *Frontiers of Science* is that beginning faculty members are mentored in creating a curriculum and teaching small seminars both by more senior faculty and by other Science Fellows. The Fellows work in teams with other faculty members to create seminar materials for each unit, weekly assignments, and the midterm and final examinations. The teams

include scientists both from within the discipline of the unit and from other disciplines. Seminar materials include computer simulations, experimental design, and data analysis—all tied to the unit and that week's lecture. The Fellows also lead a weekly seminar in how one might teach that week's seminar, going through the suggested class exercises and troubleshooting issues that were raised in the Monday lectures.

Columbia currently has eleven Science Fellows and twenty-three former Fellows. Of the latter, thirteen hold a tenure-track assistant professorship or its equivalent, five hold a non-tenure-track research position, one is a high school science teacher, two work in industry, one in policy, and one in educational consulting. Some former Fellows have launched Frontiers-like efforts at their new institutions. The network of former Fellows has great potential as a resource for the development of new faculty. We have also prepared a website (Frontiers of Science Online, or FOSO) with materials (lectures, seminar guides, *Scientific Habits of Mind*) from four representative units in the Frontiers of Science course. The site provides opportunities for faculty outside Columbia to engage in substantive discussions of science education and to share materials and approaches.

Frontiers of Science has also affected the educational approaches of the senior faculty at Columbia. Twenty-six faculty members, representing all the science departments at Columbia College, have taught the course, delivering lectures and leading seminars. An example of the impact of Frontiers of Science on their teaching is the weekly lecture that serves, together with *Scientific Habits of Mind*, as a text for the course. The idea behind the lecture is to present a cutting-edge topic in current research in a way that is comprehensible to any entering student. This goal means that the lecture has to have a clear road map and no jargon. The common themes of the course, embodied in *Scientific Habits of Mind*, are highlighted as they appear.

I give lectures in a unit on neuroscience. The third lecture in this unit explores "The Evolution of Language" (<http://www.fos-online.org/?q=node/390>). This one lecture required more than two hundred hours to prepare, including review of any relevant papers that appeared the week before. All Frontiers of Science lectures are extensively rehearsed and critiqued before and after delivery by the Frontiers faculty members. Through this process (and by observing and critiquing the lectures of other Frontiers faculty), I have learned an enormous amount about clearly and effectively presenting information, lessons that have informed all the other courses I teach. Before my involvement with Frontiers of Science, I was accustomed to lecturing but found the small seminar format challenging. The Frontiers of Science seminar materials, seminar practice, and tutorials on how to engage students in discussion (<http://www.fos-online.org/?q=taxonomy/term/62,61>) were a terrific help in learning how to engage with twenty-two students effectively and collaboratively.

At this point you may wonder why any senior faculty member would choose to teach Frontiers of Science. At Columbia, no department requires its

faculty to participate. All who teach *Frontiers of Science* are volunteers. The faculty who volunteer do so for two major reasons, I believe. The first is that learning about the science you never got to explore while climbing the disciplinary pyramid is enormous fun. Using gravitational lensing to peer back in time to the origins of the universe: who knew? Those pyroclastic flows that consumed Pompeii: awesome! Aside from learning new things (and sharpening one's intellectual skills to be able to teach them), arguing about how to teach science with fifteen other extremely bright people from other disciplines is also enjoyable. It is worth pointing out that I had never discussed how to teach with fellow faculty members before *Frontiers* started, and I expect that I am not alone in this experience. After *Frontiers* was initiated, we started a periodic brown bag luncheon across the sciences to discuss new approaches; the lunches are attended by a very large swath of the faculty from many different disciplines as well as by postdocs preparing for teaching positions.

The second major reason Columbia faculty volunteer for *Frontiers of Science* is the strong feeling among many of the faculty that *Frontiers* represents a significant opportunity to influence how our graduates will view scientific information and its uses in the future. Before *Frontiers of Science*, concerns about Earth's climate had led the Department of Earth and Environmental Sciences to propose that all students be required to take a course on the planet. This concern has translated into sturdy departmental support for *Frontiers of Science*.

## EVALUATING THE IMPACT OF FRONTIERS

*Frontiers* is still evolving as a course, and the major effort in evaluation is to improve its effectiveness for all students. Students have difficulty determining how to approach their assignments, they have difficulty seeing the common threads of scientific analysis that run through different topics, and they find the relation between course readings and course topics opaque. These are the issues we are addressing using data from a thorough evaluation at the end of each semester and from meetings with students who have suggestions for course improvements. We are making progress, but much work remains.

The percentage of students majoring in science at Columbia has remained steady at approximately 20 percent for the past ten years. Within the sciences, we have seen some shift in the choice of courses taken by students to satisfy the science requirement, most notably a doubling of enrollments in earth and environmental sciences courses. We are currently gathering data on course choices and number of science courses taken before and after *Frontiers* by male and female Columbia College students not majoring in a science. Finally, a group of faculty led by David Krantz developed an instrument to survey changes in attitudes and aspirations toward science and scientific literacy. A Web-based questionnaire (<http://www.columbia.edu/cu/psychology/>



Krantzlabweb/Ques/Scienceideas04/scienceideas.html) was administered to coincide with the pilot version of *Frontiers of Science* taken by one-third of Columbia's entering class in Fall 2003. The questionnaire was completed in early Fall 2003 by some of the students enrolled in the course and by some who were not enrolled; it was completed again in Spring 2004 by a separate group of first-year students, again including some who had enrolled in the course and some who had not. The questionnaire included a scale for mathematics confidence, a scale for science confidence and positivity, an assessment of interest in several different careers (some of which were science-related), an assessment of important career goals (personal and social), and a test of "science literacy" adapted in part from a former National Science Foundation survey of scientific literacy.

Among students not enrolled in *Frontiers of Science*, mathematics confidence scores were lower in Spring 2004 than for the group tested in early Fall 2003. The decrease in math confidence was much smaller for students who were enrolled in *Frontiers of Science*. While this result suggests a positive effect of enrollment in the course, the sample was small, and the questionnaire return rate was substantially higher among those enrolled in the course. At Columbia College, approximately one-third of each entering class intends to major in science, but at graduation the actual number is approximately 20 percent. Questionnaire results suggest that substantial attrition takes place in the first year of college: openness to several science-related careers declined between early Fall 2003 and Spring 2004. Because openness to these science-related careers is related to math confidence, part of the attrition might be explained by the decline in math confidence. If *Frontiers of Science* does maintain math confidence in addition to stimulating interest in a variety of scientific fields, it will help Columbia College realize more of its potential in undergraduate science education.

## FRONTIERS FOR ALL?

How to provide a university-level education in the sciences is a persistent question for colleges as they periodically review their undergraduate curricula. The relevant issues have been discussed at a number of recent conferences (for example, [http://www.aacu.org/meetings/engaging\\_science/index.cfm](http://www.aacu.org/meetings/engaging_science/index.cfm) and <http://www.reinventioncenter.miami.edu/conference2006/proceedings.htm>) and are the subject of several studies, including the one sponsored by the American Academy of Arts and Sciences that led to this publication (see <http://www.amacad.org/projects/sciLiberalArts.aspx>). How an individual college or university tackles this issue will differ dramatically depending on its size, resources, students, faculty interests, and educational philosophy. What is generally true, however, is that we need a wealth of approaches and educational resources to meet this challenge. Providing a forum in which those ap-

proaches and resources can be shared among us all is one of the goals of Frontiers of Science Online. At Columbia, we hope to shape Frontiers of Science using discussions and resources from other programs and look forward to sharing what we develop.<sup>2</sup>

2. The 1983 committee that raised the possibility of a “great ideas in science” course was chaired by David Helfand, author of *Scientific Habits of Mind*. The committee on science instruction was chaired by Jacqueline van Gorkom during the period when Frontiers of Science was initiated and shaped. Darcy Kelley and David Helfand were the initial course directors, joined later by Don Hood and, in 2010, Nicholas Christie-Blick. Special thanks to them for their useful comments on this essay. Establishing Frontiers of Science would not have been possible without the strong support of Columbia’s then-provost, Jonathan Cole, and Columbia College’s then-dean, Austin Quigley, as well as the backing of David Cohen, vice president for arts and sciences. The Office for the Core Curriculum, especially Assistant Director Elina Yuffa, provides essential logistical, moral, and intellectual support. Special thanks are due to Dean Kathryn Yatrakis not only for her guidance during various reviews but also for her research into the history of science in the Core Curriculum. Frontiers of Science has a spectacular faculty who make teaching and learning a joy. Last but not least, the students of Columbia College are a special group who have freely shared their good ideas about how Frontiers of Science should evolve.

## CHAPTER 11

# Assessing Scientific Reasoning in a Liberal Learning Curriculum

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A well-rounded college education in the United States is synonymous with liberal education and includes science as one of the liberal arts (American Association for the Advancement of Science, 1990). The experience of learning science as a liberal art should contribute to students' preparation as informed and responsible citizens who think independently, reason analytically, and communicate effectively. Science education is not about learning a litany of facts; rather, it is about developing the thinking skills to engage in twenty-first-century science. To help students achieve this, scientists should teach science as it is practiced and, in particular, teach scientifically by fostering scientific reasoning and quantitative literacy skills in all students (Bybee, 1997; Handelsman et al., 2004; National Leadership Council for Liberal Education and America's Promise, 2007). All college graduates, regardless of their major, should know and be able to engage in the methods of scientific inquiry that lead to scientific knowledge. This capacity includes accessing and analyzing scientific information, using scientific evidence, and constructing reasoned arguments.

As the national interest in liberal learning in undergraduate education has accelerated, goals and outcomes, including the ability to use science as a way of knowing, have appeared on the institutional websites of nearly four in five institutions of higher education (Association of American Colleges and Universities, 2009). Although consensus about the need for scientific reasoning is widespread, few institutions have clearly outlined the curricular pathways and processes that should lead students to achieve scientific reasoning. Generally, we do not have evidence on whether faculty consider the liberal learning goals of their institution when designing their courses, or whether and how they translate these goals into instruction and assessment.