IBI* SERIES WINNER

Solving Complex Problems

Solving Complex Problems, an IBI prize–winning module, challenges students to use their knowledge creatively in order to design solutions.

K. V. Hodges

Before he became America's first de facto science adviser and before he helped lay the foundation for the National Science Foundation, Vannevar Bush was a professor of Electrical Engineering and, eventually, dean of Engineering and vice president at the Massachusetts Institute of Technology (MIT). In those capacities, he came in contact with some of the nation's best and brightest minds in their formative years. But after two decades in such a rarified academic environment, Bush had become disenchanted by the increasing specialization of undergraduate curricula in science and engineering in America (*1*). He felt that education in these fields placed too much emphasis on information transferral from teacher to student and too little on deep understanding and intellectual synthesis by the student. Bush was among the first to anticipate that massive amounts of information would someday be universally and readily available to all, such that our ability to communicate knowledge through classes would become far less important than our ability to inspire students to do something creative, and valuable, with it.

Invented at MIT some 60 years later and first offered in 2000, "Solving Complex Problems" is a class designed to do just that (*2*). A freshman-year elective for students with a wide range of backgrounds and prospective majors, it typically attracts between 5 and 10% of the MIT freshman class who develop through it an enthusiasm for tackling difficult, multifaceted problems. Students are presented in the first class with a challenge that can be stated simply, but that is deceptively complex and has no straightforward answer. Over the course of the semester, it is their job collectively to "imagineer" a proposed solution, to articulate their solution, and to explain how they arrived at it.

For example, the challenge presented to the first class in 2000 was to design a mission of exploration to Mars to search for signs of past or present life. Some students, who saw themselves as prospective aeronautics or astronautics majors, immediately interpreted this as a simple invitation to solve the ideal rocket equation for the appropriate thrust necessary to transfer a research payload to Mars and back. But it soon became clear that the simplicity of the problem statement masked a spectrum of challenges that would require the development and analysis of complicated decision matrices. Some of the implied questions were fundamental. How should we define "life" for the purpose of this mission? If one uses the life we know on Earth to establish what to look for, how can we be sure that a search for traditional biosignatures is sufficient to conclude that life does not exist on Mars? The phrase "past or present" life adds more complexity to the task. What do we regard as reliable evidence for fossil life? Other questions were more operational. Should the mission be manned or unmanned? How should the spacecraft be designed? What analytical instruments would be best for the required measurements? Still others were eminently practical, including the two most practical of all: How much will all this cost, and who will pay for it?

Establishing the learning environment. Upper-class mentors prepare for the week's student team meetings at MIT.

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Other missions presented challenges of different kinds. In 2001, a sufficiently large number of students enrolled that it became practical to split the core mission—to design a permanently manned, environmentally sensitive undersea research laboratory and to develop research plans for the first 6 months of the operation—into two. The Atlantis I class section was charged with designing a research station that would be located in the Belize barrier reef complex, whereas the Atlantis II station would be on the sea floor at the Edmond hydrothermal vent field in the Indian Ocean at a depth of more than 3000 m. The Atlantis I section soon found that environmental sensitivity would be of paramount importance for success, and the students had to deal with issues as varied as how to deal with waste, how to maintain a stable ocean temperature around the station, and even whether or not the station should be permanently anchored or neutrally buoyant to protect the reef substrate. In contrast, the Atlantis II section had to design for an environment with no natural light and where hull pressures on the station would be extreme. (The students settled on a torus-shaped station with an internal diameter of 6 m and wall thicknesses of 36 cm.) An added value to the two-section structure was that students from both sections met over the course of the semester to compare differences and similarities in their designs and the challenges they faced.

Regardless of topic, the students in a section of Solving Complex Problems all work together in the first few class sessions to predict what challenges will arise and to parse the overall problem into a series of 5 to 10 themes. For example, themes might include the environmental context of the problem, engineering challenges, public relations, budget development, and fund raising. Each student is then assigned, at random, not based on preference, to a team responsible for developing a knowledge base and making preliminary recommendations for their part of the overall solution. Perhaps surprisingly, we have found the approach of randomizing teams very effective because all teams ultimately have to work together on the final design concept; a student particularly interested in one theme—but not assigned to the team associated with it—is encouraged to act as a sounding board (and sometimes friendly critic) for the team. One member from each team is elected to be part of a coordination team to ensure good interteam communications.

In the MIT implementation of Solving Complex Problems, these teams benefit from consultations with upper-class mentors, many of whom are themselves veterans of the class (see the first figure), and alumni mentors with special knowledge of one or

School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA. E-mail: kvhodges@asu.edu
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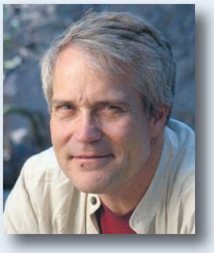
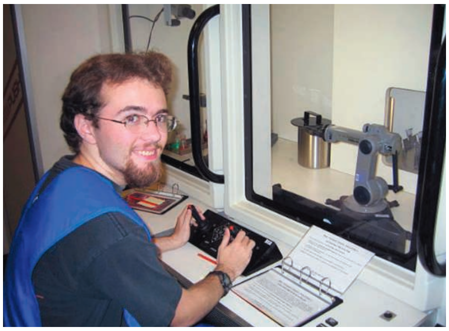
About the author



Kip Hodges is a Foundation Professor at Arizona State University and Founding Director of ASU's School of Earth and Space Exploration. Before 2006, at MIT he was a Professor of Geology in the Department of Earth, Atmospheric, and Planetary Sciences; a MacVicar Faculty Fellow; and a Codirector of both the Earth System Initiative and Terrascope, a freshman learning community in which Solving Complex Problems plays a foundational role. He earned a B.S. in geology at the University of North Carolina at Chapel Hill and his Ph.D. at MIT. His research foci include continental tectonics, noble gas geochronology, and planetary field science (with a special emphasis on developing advanced protocols for scientific exploration of other worlds).

more aspects of the overall problem. Typically, about half of the upper-class mentors receive a small stipend for their participation, whereas the rest earn academic credit. Mentors generally spend 3 to 5 hours per week working in their roles. Alumni all serve on a volunteer basis, and we have found them to be very generous with their time, sometimes volunteering over a number of years to spend an average of an hour or two each month interacting with the students. The upper-class and alumni mentors are instructed to serve as sounding boards and information resources but are asked not to be directly involved in the design process. As the project evolves, the teams naturally coordinate their efforts better to achieve an optimal overall design. At the end of the semester, the design is documented as a content-rich Web site, and the students give a public presentation of the design to one or more experts who deal with such problems as professionals. As an example, the expert panelists for the 2002 class, which had as its focus the design of technological strategies to monitor the Amazon rainforest environment and to devise strategies to ensure its preservation, included (i) Tom Lovejoy, biodiversity chair at the Heinz Center for Science, Economics, and the Environment; (ii) representatives from Raytheon who were working on the Brazilian government's System for the Preservation of the Amazon; and (iii) Larry Linden, founder of the Linden Trust for Conservation. All panelists serve on a volunteer basis. Many of the MIT student Web sites and video archives of final presentations are available on the subject Web site (web.mit.edu/12.000).

The instructor's role in this class is primarily to create an environment conducive to self-directed learning (see the second figure). There are no lectures, although the students are exposed in a casual way to a series of case studies that are germane to their problem. For example, in the Mars problem from 2000, lessons learned from the Apollo program featured prominently. The students are instead encouraged to learn independently using a variety of resources, including the Web (with extensive coaching on how to recognize reliable and unreliable content); libraries; and self-motivated conversations with faculty, graduate students, older undergraduates, and alumni. In the early years of offering this subject, we passed on to the students a list of people who had been recruited by the instructional staff and had volunteered to participate in such discussions. However, we soon found that such recruiting efforts were unnecessary; many at all levels of the academic community are open to such informal interactions when they are precipitated by students asking questions that begin with a phrase like: "What is your take on …." These casual conversations are especially valuable because they impart an appreciation for practical integration of acquired knowledge. For example, freshmen in the "Mars exploration" year of Solving Complex Problems benefited from a brainstorming conversation with alumnus Joe Gavin, who managed the engineering program at Grumman Aircraft that designed and built the Apollo lunar landing module, about the challenges posed by descent to and ascent from other planetary surfaces.



Exploration. An ASU student performs a robotic manipulation experiment at the Challenger Space Center Arizona as background for his team's design task.

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Along the way to arriving at their optimal design, the students learn valuable lessons regarding critical, transdisciplinary thinking, the challenges and rewards of working in teams both large and small, the importance of organizing and synthesizing data from many sources, and the need to justify assumptions and decisions. Early in the development of the class, we learned that a grading scheme was necessary that recognized individual accomplishment but rewarded collaborative problem solving. We allow students to critique their own work, the work of others on their thematic teams, and the class as a whole. But the final grade for the semester depends disproportionately on the quality and sophistication of the overall design as judged by the teaching staff with input from the expert panelists.

The Solving Complex Problems learning environment has proven to be extremely adaptable. Since leaving MIT in 2006 to take up my current position at Arizona State University (ASU), I have used the same approach with more advanced students for a required sophomore-junior–level subject in the B.S. degree in the School of Earth and Space Exploration. In the Spring of 2013, I will use it in teaching the senior capstone subject for our unique B.A. degree in Earth and Environmental Studies, which is designed to emphasize science literacy for liberal arts students who do not anticipate careers in science and engineering. Solving Complex Problems and its curricular descendants provide students with an opportunity to integrate many modes of inquiry, from science and engineering, to public policy, education, economics, and even media affairs. I think Vannevar Bush would approve.

References and Notes

1. G. P. Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (Free Press, New York, 1997).
2. A video introduction to Solving Complex Problems, as well as more information and a general syllabus, are available through MIT's OpenCourseWare site: ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-000-solving-complex-problems-fall-2003

Supplementary Materials
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