Integrative Computing Education and Research (ICER)
Final Report of the Northwest Regional Meeting

Executive Summary

The United States today faces a growing crisis in computing education. Over the last five years, university enrollments in computing-related disciplines have declined substantially even as the demand for people with these skills continues to grow. This shortfall in the domestic production of a workforce with the necessary technical skills and expertise threatens the competitiveness of the U.S. economy and threatens to compromise our national security.

To maintain the computing workforce necessary to maintain the nation's economic, cultural, and democratic vitality, the CISE Directorate at NSF organized a series of regional workshops that focus on Integrative Computing Education and Research (ICER). The Northwestern Regional ICER workshop was held at Stanford University on Friday and Saturday, January 27-28, 2006. The participants included computing educators from a broad range of institutions along with representatives of other stakeholder groups.

Over the two days of the workshop, the participants identified a set of five strategic initiatives and developed the following recommendations to support the overall goals:

Strategic initiative #1: Improve the quality of computing education
1a. Create more effective repositories for curricular artifacts.
1b. Enlist the community to identify the top ten curricular artifacts in a year.
1c. Encourage curricular experimentation and innovation.
1d. Foster a community that focuses on educational research and assessment.

Strategic initiative #2: Attract more people to the field
2a. Mount a vigorous campaign to change the popular image of computing.
2b. Convene focus groups to get a better sense of what students want.
2c. Increase outreach to high-school students, teachers, and counselors.
2d. Make outreach materials available to faculty.

Strategic initiative #3: Improve retention in the major
3a. Recast introductory courses so that they become "a pump, not a filter."
3b. Make sure introductory students recognize that the field offers many opportunities.
3c. Provide undergraduates with opportunities for research and teaching.
3d. Increase opportunities for collaborative project work.
3e. Encourage the formation of support groups for at-risk students.

Strategic initiative #4: Strengthen interdisciplinary connections
4a. Offer service courses designed for students in other disciplines.
4b. Encourage faculty to develop meaningful collaborative activities across disciplines.
4c. Support development and distribution of interdisciplinary curricula and resources.

Strategic initiative #5: Meet human and infrastructure needs
5a. Eliminate structural barriers to interdisciplinary collaboration.
5b. Provide greater institutional rewards for teaching and curriculum development.
5c. Increase support for curricular development, educational research, and assessment.
5d. Train computing faculty to think strategically both inside and outside the academy.
5e. Strengthen industry involvement in computing education.

These initiative and recommendations are discussed in detail in the accompanying report.

Integrative Computing Education and Research (ICER)
Final Report of the Northwest Regional Meeting
(Stanford University—January 27-28, 2006)

In late 2005 and early 2006, the National Science Foundation sponsored a series of regional workshops under the general title of Integrative Computing Education and Research (ICER). This report describes the outcomes and recommendations of the Northwest Regional Meeting, which was held at Stanford University on January 27 and 28, 2006.

1. The central role of computing in the national economy

In certain respects, it seems unnecessary to spend much time discussing the value of computing and information technology to the U.S. economy, given that pretty much everyone seems to accept that consensus. The growing importance of computing is noted explicitly in the NSF Strategic Plan for 2003-2008 [NSF03]:

> Networking and computing technologies are increasingly important technologies for the American economy, national and homeland security, and progress across science and engineering.

In recent years, other reports have made the same point in even stronger terms. The President's Information Technology Advisory Committee report *Computational Science: Ensuring America's Competitiveness* [PITAC05] begins with the following paragraph:

> Information Technology will be one of the key factors driving progress in the 21st century—it will transform the way we live, learn, work, and play. Advances in computing and communications technology will create a new infrastructure for business, scientific research, and social interaction. This expanding infrastructure will provide us with new tools for communicating throughout the world and for acquiring knowledge and insight from information. Information technology will help us understand how we affect the natural environment and how best to protect it. It will provide a vehicle for economic growth. Information technology will make the workplace more rewarding, improve the quality of health care, and make government more responsive and accessible to the needs of our citizens.

The report goes on to underscore the particular importance of computational science in the following words:

> Computational science is now indispensable to the solution of complex problems in every sector, from traditional science and engineering domains to such key areas as national security, public health, and economic innovation. Advances in computing and connectivity make it possible to develop computational models and capture and analyze unprecedented amounts of experimental and observational data to address problems previously deemed intractable or beyond imagination.

These two sections from the PITAC report—one focusing on the general area of information technology and one focusing on the more specialized field of computational science—emphasize why it is important to begin this report by outlining the value of computing technologies overall. Computing technologies affect the economy in many different ways, and it is all too easy to focus only a particular sector and undervalue how much computing technology contributes to other aspects of the economy.

Broadly speaking, it is useful to identify three areas in which computing technologies have had a significant impact:

1. *Computing technology enables the high-tech industry*. Computer science has a good track record of successful technology transfer from research to the marketplace. In its 2003 report entitled *Innovation in Information Technology* [CSTB03], the Computer Science and Telecommunications Board presents a now-famous timeline showing how innovations developed in academic or industrial research labs move into the commercial world. The report identifies 19 research areas in computing that have subsequently become billion-dollar industries:

Local-area networks	VLSI design	Speech recognition
Graphical user interfaces	Client/server computing	Broadband in last mile
Workstations	Entertainment	Portable communication
Graphics	RAID disk servers	Parallel databases
Timesharing	Relational databases	Parallel computing
Internet	World Wide Web	Data mining
RISC processors		

   That list is already obsolete, as new technologies, such as search tools for the Internet, cross the billion-dollar threshold. These industries—which typically have wide global reach and therefore generate export income to offset some of the U.S. trade deficit—are a critical component of the national economy.

2. *Computational science is an essential component of other application areas in science and technology*. As the 2005 PITAC report makes clear, scientific innovation in almost every field depends on computing. That dependence, moreover, goes well beyond the need to create hardware powerful enough to meet computational needs. In most cases, progress in these other disciplines also depends on advances in computational science. New scientific challenges require new algorithmic strategies that in turn require research and development in computing itself. For example, the sequencing of the human genome required not only new hardware to achieve the necessary speed but also new algorithms to solve problems that were heretofore beyond human reach. This conclusion is underscored by the report of the NSF's Blue-Ribbon Advisory Panel on Cyberinfrastructure, which observes that "scientists in many disciplines have begun revolutionizing their fields by using computers, digital data, and networks to replace and extend their traditional efforts." [Atkins04]

3. *Information technology raises productivity within the economy as a whole*. Even outside the scientific and technological domain, the development of better computing technologies and techniques for managing information systems have led to substantial productivity increases that boost the U.S. economy. In its analysis of the economic impact of information technology, the Congressional Joint Economic Committee concluded that "at least half of the one-percentage point increase in labor productivity growth is attributable to IT," noting at the same time that "in all likelihood the contribution from IT is even greater than this conservative estimate" [JEC01]. Investment in computing and information technology thus has a multiplier effect on the broader economy that extends beyond its immediate contributions to the high-tech industry and science as a whole.

Drawing on economic data assembled from a variety of sources, the 2005 PITAC report on *Ensuring America's Competitiveness* concludes that the high-tech sector has "accounted for a third of the total growth in U.S. economic production since 1992, creating millions of high-paying new jobs" [PITAC05]. To sustain the economic engine that computing technology represents, the United States must find ways to meet the workforce requirements of the many industries that depend on computational skills and talent. As always, the key to creating such a workforce is effective education.

For most of the latter half of the 20th century—fueled by the public investment in science education that began during World War II and continued through the "Sputnik crisis" of the late 1950s—U.S. universities led the world in educating each new generation of scientists and engineers. Countries throughout the world sent their most promising students to study in the United States. A large fraction of those students stayed on to take jobs in this country, where they—along with their U.S. counterparts—made enormous contributions to the national economy. The explosion of the computing field that continued over those years could not have occurred without developing the human capital that education provides. The array of billion-dollar industries cited in the CSTB report would simply not exist without that trained workforce, which has served to enrich both the nation and the world.

In the last few years, however, the privileged position of U.S. success in science and technology has begun to erode, largely because our educational system is no longer as successful in attracting and retaining the best students. Fewer students from the United States are choosing to pursue careers in science and technology; at the same time, other nations have developed vibrant technological sectors and the educational infrastructure necessary to support them. This erosion of U.S. leadership in this area is explicitly recognized in the NSF Strategic Plan [NSF03]:

> The global competition for highly skilled technical workers and S&E [science and engineering] professionals is escalating, while fewer U.S. students are choosing to go into graduate science and engineering programs. Since 1993, enrollment of U.S. students in these programs has dropped nine percent. To maintain the technological lead the United States enjoys throughout the world it will be necessary to recruit greater numbers of U.S. students into the S&E workforce.

2. The crisis in computing education

The decline in student interest in technical subjects is particularly severe in the computing disciplines. After years of soaring popularity during the Internet boom of the 1990s, most colleges and universities in the United States have experienced sharp declines in both computing enrollments and the number of majors. Although delays in federal data reporting make it hard to get comprehensive data covering all U.S. schools, there is nonetheless considerable evidence to substantiate the decline. The research universities that take part in the Taulbee survey, for example, report that enrollments have dropped between 30 and 40 percent between the fall 2000 and fall 2004 [Zweben05].

Paradoxically, the enrollment decline has continued despite strong industrial demand for students with computing skills. While there was a small dip in overall employment in the IT sector following the dot-com collapse in 2000, those numbers bounced back and are now at their highest level ever. That demand, moreover, is projected to increase significantly over the next decade, as shown in Figure 1. In fact, employment prospects

Figure 1. Projected employment by occupation, 2004-2014 (in thousands)

	Employment 2004	Employment 2014	Percentage change
Computer and information systems managers	280	353	+73 (+26.1%)
Computer specialists	3,046	4,003	+957 (+31.4%)
Computer hardware engineers	77	84	+8 (+10.1%)
Total, all professional-level IT occupations	3,403	4,440	+1,037 (+30.5%)
Total, all occupations	145,612	164,540	+18,928 (+13.0%)

Source: Bureau of Labor Statistics. *Monthly Labor Review,* November 2005 [BLS2005] for students completing a bachelor's degree in computing are considerably better than they are for students in other disciplines, as illustrated by the following report in a recent *InfoBrief* [NSF05]:

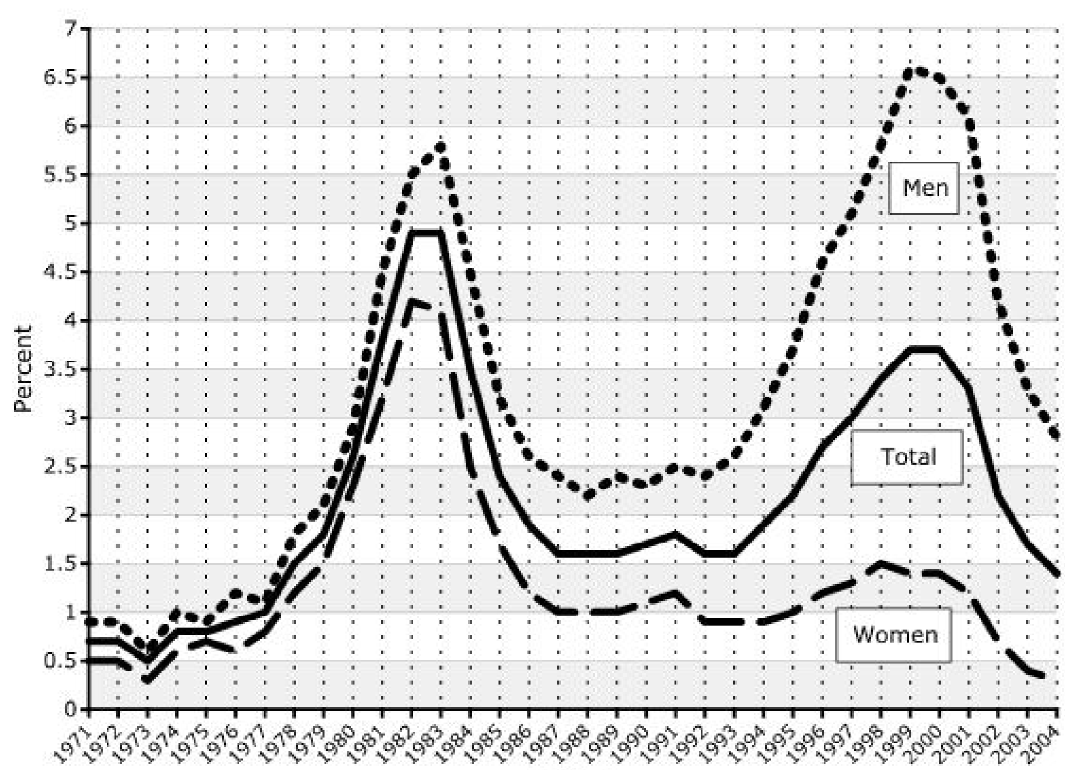
> Continuing a pattern that has been evident for decades, recent bachelor's and master's engineering graduates and computer science graduates at the bachelor's level are more likely than graduates in other fields to be employed full time after graduation, and upon entering the workforce, they are rewarded with higher salaries.

While these comments apply to engineering disciplines as well as computer science, other indicators reveal that computer science graduates in fact command higher salaries than graduates in other scientific fields [CRA05]:

> Among science graduates, the median annual salaries of computer and information sciences (CIS) graduates were the highest as of October 2003. CIS graduates with bachelor's degrees earned a median annual salary of $45,000, and those with master's degrees earned a median annual salary of $60,000.

The decline in the popularity of computing-related majors is revealed in several other statistics as well. For example, the College Board recently reported that the number of students taking the Computer Science Advanced Placement (AP) exam dropped 19 percent between 2001 and 2005—the only AP exam to show a decline [AP06]. An even more disturbing illustration of falling interest levels appears in Figure 2. For many years, the Higher Education Research Institute at UCLA has kept track of the majors that students claim they would like to pursue. As Figure 2 indicates, interest in computer science as a major is highly volatile, with strong upward spikes in the early 1980s and the

Figure 2. Fraction of students expressing interest in computer science as a major



Source: Higher Education Research Institute at UCLA, as cited in [Patterson05] late 1990s. At the moment, however, interest is clearly on the decline. The overall fraction of students has fallen back to what it was in the 1970s—a level that is clearly insufficient to meet the workforce needs of the industry.

Although the low level of interest in computing disciplines is frightening enough in its own right, Figure 2 reveals another important aspect of enrollment trends: enrollments for women are declining even faster than for the population as a whole, and the same appears to be true for minority students as well. The problem, therefore, is not simply that there is an inadequate numbers of students to meet the demands of industry but that computing programs are not seen as attractive to large segments of the population, thereby reducing both the size and diversity of the potential workforce.

In its strategic plan, the National Science Foundation explicitly recognizes the need to develop a more diverse workforce in science and engineering disciplines [NSF03]:

> It will be especially important to tap into the potential evident in previously underutilized groups and institutions of the Nation's human resource pool.

But computing's need to attract a diverse audience is also vital for reasons that go beyond the question of meeting workforce requirements. In his 1998 address to the Annual Meeting of the National Academies, Bill Wulf, president of the National Academy of Engineering, expressed his deeper concerns like this [Wulf98]:

> I believe there is a far deeper reason why we require a diverse work force. Let me give you the argument in a nutshell, and then I'll try to draw it out more carefully. . . . First, engineering is a very creative profession. That is not the way it is usually described, but down to my toes I believe that engineering is profoundly creative. Second, as in any creative profession, what comes out is a function of the life experiences of the people who do it. Finally, sans diversity, we limit the set of life experiences that are applied, and as a result, we pay an opportunity cost—a cost in products not built, in designs not considered, in constraints not understood, in processes not invented.

3. Developing goals and strategies

The ICER regional meetings bring together creative people who have both an understanding of the problems of computing education and a heartfelt desire to assist in the solution to those problems. The agenda for the Stanford workshop appears in Figure 3. Friday's session was devoted to developing a shared understanding of the problems, largely through work in three breakout groups that we assembled based on the white papers each participant had submitted prior to the meeting. The composition and topics for the initial breakout groups look like this:

- *Group 1—Curriculum and Pedagogy:* Dan Garcia (chair), Sarah Douglas (scribe), Kim Bruce, Jim Fix, Cay Horstmann, Kim Kihlstrom, Dave Patterson, Stuart Reges, Mehran Sahami, Larry Snyder
- *Group 2—Outreach and Image:* Bryant York (chair), Judy Cushing (scribe), Lecia Barker, Rob Bryant, Cindy Goral, Tim Sheard, Ellen Spertus, Sharon Tuttle, Brian Walter, Ken Yasuhara
- *Group 3—Integrative Structures:* Judith Gersting (chair), Eric Roberts (scribe), Margaret Burnett, Peter Denning, Clayton Lewis, David Notkin, Jenny Orr, Bobby Schnabel

Each breakout group was asked to identify the top issues facing computing education in that domain, the most promising ideas generated in the brainstorming sessions, and the

Figure 3. ICER Northwest Regional Meeting agenda

Integrative Computing Education and Research (ICER):
Preparing IT Graduates for 2010 and Beyond

Wallenberg Hall, Stanford University
Friday-Saturday, January 26-28

Thursday, January 26

6:30-8:30	Reception at Sheraton hotel

Friday, January 27

8:30-9:00	Continental breakfast at Wallenberg Hall
9:00-9:10	Welcome and opening remarks (Eric Roberts)
9:10-9:35	NSF welcome and setting the charge (Peter Freeman)
9:35-9:45	Charge to the working groups (Judy Cushing)
9:45-11:30	Breakout I groups organized into interest areas based on the white papers – Curriculum and Pedagogy – Outreach and Image – Integrative Structures
11:30-12:00	Preliminary reports back from the Breakout I groups
12:00-1:20	Lunch (Speaker: Sebastian Thrun on the DARPA Grand Challenge)
1:30-3:00	Breakout groups reconvene to revise/refine problem statements
3:00-3:15	Break
3:15-4:00	Reports back from Breakout I groups
4:00-5:00	Plenary Brainstorming session on solution strategies
6:30	Dinner at Zibbibo's, 430 Kipling St., Palo Alto

Saturday, January 28

8:30-9:00	Continental breakfast at Wallenberg Hall
9:00-9:30	Breakout I groups prepare final revision of their recommendations and reports
9:30-11:30	Breakout II groups meet in the following areas: – "Blue Sky" I – "Blue Sky" II – "Next Steps" – Categorization committee to organize solution strategies
11:30-12:15	Reports back from Breakout II groups
12:15-1:30	Wrap-up session to determine priorities
2:00-5:00	Writing team prepares outline of report

most significant barriers that stand in the way of implementing these ideas. The results of this exercise appear in Figure 4.

The sessions on Friday—both in the small groups and in the plenary discussions that followed—also made it possible to define a set of overarching goals:

1. To ensure that the supply of well-trained computing professionals is sufficient to meet the needs of both industry and academia.
2. To increase the diversity of the computing profession so that it more closely reflects the society as a whole.

Articulating these high-level goals is, of course, easier than developing strategies to achieve them. The brainstorming session on Friday afternoon identified many strategic opportunities, which we were later able to organize into the following general categories:

- *Improve the quality of computing education.* Computing has always been a difficult field to teach, partly because the dynamic nature of the discipline forces continuous change not only in curriculum and pedagogy but also in such critical practical matters as keeping up with the evolution of technologies and tools. The rapid pace of change and the enormous fluctuations in enrollments make it impossible to develop a stable

Figure 4. Issues, ideas, and barriers identified by the breakout groups

Group 1: Curriculum and Pedagogy

Top issues:
- Introductory classes that are currently filters, not pumps
- Meeting service responsibilities
- Bringing upper division curriculum into the 21st century

Most promising ideas:
- Find the model courses that work well at universities
- Look for best practices
- Create repository of teaching resources

Most critical barriers and concerns:
- Faculty inertia—will need to show that practices work
- Faculty resources

Group 2: Image and Outreach

Top issues:
- We *do* have an image problem—partly misconception and partly reality—that we need to understand
- We are unaware of the research into the image issue, which is not always well disseminated
- The curriculum must follow through on the image that we want to produce: we currently have some very serious problems in terms of the culture of our curriculum
- We don't understand enough about how to integrate the different strands of our discipline (research and education, computing and domain knowledge, and so on)

Most promising ideas:
- Determine the image we want to create, taking advantage of what social scientists can tell us about the image we currently project
- We need a marketing campaign: I'm a computer scientist, and here's what I do all day
- The community has to do some self-examination to see where the negative images attached to computing actually relates to reality rather than myth

Most critical barriers and concerns:
- Institutional stovepiping: community colleges and high schools often act as impediments to change
- The reward system for faculty undervalues teaching

Group 3: Institutional Structures

Top issues:
- Understanding what kind of integration we are seeking
- Identifying the best opportunities for intellectual engagement with other disciplines, focusing on interdisciplinary connections that offer high synergy
- Making sure that collaboration is done *with* partners, not for them or by them (or to them)
- Recognizing that institutional differences matter: there can be no one-size-fits-all strategy
- Understanding how the computing communities—in collaboration with our interdisciplinary partners—can assess progress

Most promising ideas:
- Articulate a set of core principles that others can understand
- Support initiatives to promote interdisciplinarity
- Create shared curricular modules with other disciplines (in a two-way street)

Most critical barriers and concerns:
- We are overwhelmed and lack resources to address the problems
- Individual and institutional barriers to collaboration
- The pace of change

curriculum of the sort that so many disciplines enjoy. Even so, there are many opportunities to improve the quality of the curriculum, partly by finding better ways to share best practices and resources.

- *Attract more people to the field*. At the current level of student interest in computing disciplines, it will be impossible to meet the workforce needs of the future. Any strategy that seeks to ensure an adequate supply of computing professionals must address the problem of recruitment. In the wake of the high enrollments of the 1990s, some computing programs developed strategies that, consciously or unconsciously, worked to limit the number of students entering the field. Today, it is essential to restructure academic computing programs so that they bring students in as opposed to keeping them out—becoming "a pump, not a filter." To do so, it will be necessary to dispel the negative images surrounding computing careers, not only in terms of changing the stereotypical view of computing professionals as "nerds" chained to their computers but also in terms of countering the widespread popular misperception that the dot-com collapse and the phenomenon of offshoring have reduced the available career opportunities, all statistical evidence to the contrary notwithstanding. It will also be necessary to tailor the message of computing so that it is more attractive to students of today.
- *Improve retention in the major*. At most institutions, getting students into computing majors is only part of the problem; keeping them there is at least as challenging. This problem is particularly severe for women and minorities, who often feel less secure of their own skills. The discipline needs to do a better job of building self-confidence and efficacy in students and eliminating those negative forces that drive so many promising students away.
- *Strengthen interdisciplinary connections*. As section 1 of this report emphasizes, computing is becoming integral to almost every discipline. Unfortunately, too many university departments of computer science take a narrow view of the discipline that makes it more difficult to develop the kind of interdisciplinary programs that would be more attractive to students today. We need to investigate a range of strategies to promote mulidisciplinary activities involving computing, ranging from such formal structures as schools of computing to informal interactions among faculty and students across disciplinary boundaries.
- *Meet human and infrastructure needs*. Even though there are clearly many promising approaches to increasing both the quality and popularity of computing disciplines, there are many barriers that militate against progress in this area. Finding the time to devote to new initiatives remains a huge concern for most faculty members. Any coordinated attempt to address these problems on a national scale will require making sufficient resources available to ensure that faculty can devote real energy to solving these problems. There are, moreover, structural barriers that need to be overcome at most institutions to give both interdisciplinary work and effective teaching the credit they deserve.

In addition to outlining these general strategies, the categorization committee also identified the sets of stakeholders and domains of action:

Stakeholders	**Domains of effort**
• Students • Parents • High schools • Universities and colleges • Funding agencies • Professional societies and other NGOs • Industry	• Enhancing formal and informal learning • Building community • Developing resources • Designing and conducting assessments

4. Recommendations

The workshop participants spent most of Saturday seeking to identify high-leverage activities that would support the goals and strategies that we identified on Friday. We have organized this section of the report along the lines of the strategic opportunities outlined in the preceding section. Within each one of these areas, we have sought to develop specific recommendations to advance that strategy and, where appropriate, to identify the stakeholders and domains of effort involved.

4.1 Improve the quality of computing education

Under this general heading, the group discussed a range of initiatives designed to improve computing education. As is often the case when a group of technologists comes together, much of that discussion focused on technical solutions—most notably the development of online curricular repositories—despite a recognition that past repository projects have met with at most modest levels of success. Even so, there was a strong consensus among the ICER participants that (1) more effective models are possible in this area and (2) developing effective curricular repositories would have a high payoff for educators, many of whom lack the resources and time to develop effective curricular tools on their own.

The group identified several problems with existing repository efforts. Perhaps most importantly, there is a tension over the issue of how large a repository can be. Small repositories, of course, will of necessity be incomplete, so that teachers may be unable to find what they need. Large repositories, on the other hand, are often difficult to navigate, leaving teachers still unable to find what they need, even though it may be there. The materials, moreover, are of varying quality, and existing vetting mechanisms have proven to be inadequate to the task of separating highly effective materials from the background noise. The materials that appear may also fail to meet the needs that teachers have to fit something into a specific hole in their curriculum. Some materials typically require much more time than the syllabus permits, while others do not provide enough material to cover a topic at any depth. Teachers need to be able to select materials at many levels of granularity, ranging from individual examples to an entire course syllabus. Finally, using large or highly sophisticated materials often require training for the teachers, which is typically unavailable today.

Recommendation 1a: Create more effective repositories for curricular artifacts. To be successful, these repositories will need to support the following:

- An interactive review system that makes it easier for the community to develop and share its collective assessment of individual components of the repository.
- A comprehensive range in terms of granularity, making it easy for teachers to adopt anything from a single example to an entire syllabus.
- A supportive infrastructure of workshops and tutorials to train both university faculty and high-school teachers in how to use these materials effectively.

In terms of its effect on stakeholders, this recommendation has implications for funding agencies, professional societies, and for both individual teachers and their institutions. Repositories will not be able to succeed without ongoing funding, nor will it be possible to conduct a sufficient number of workshops in the absence of support. At the same time, the culture of academic institutions will also have to change to reward individual faculty for undertaking this type of work.

The first bullet in Recommendation 1a prompted a more specific recommendation that arose from the recent ACM experience of asking members to select their favorite out-ofprint books. People responded enthusiastically and came up with a huge list of titles, on which the membership was then invited to vote. A similar strategy for selecting the top ten curricular repository submissions each year might elicit a similar response.

Recommendation 1b: Enlist the community to identify the top ten curricular artifacts in a year. This process will presumably involve a nomination phase followed by a balloting phase to select the most highly rated submissions.

The advantages of instituting this review and rating process include:

- The results of the balloting will draw attention to the most effective materials, thereby making it easier for teachers to identify particularly useful entries.
- The competition should improve the quality of submissions by providing more incentives to the creators.
- Establishing a peer-reviewed process for evaluating curricular materials will make it easier for faculty who engage in this activity to secure recognition for that work. The mere fact that someone created some pedagogical tool presumably has far less impact at promotion time than having that submission appear in the top-ten list.

The ACM Education Board will look into initiating this activity.

Although better sharing of materials will help solve some problems, it clear that technical fixes are certainly insufficient to address the full range of challenges facing computing education. The curriculum itself requires periodic updating to adapt to changes in both the technology and the expectation of students. The participants in the ICER workshop offered several proposals for new curricular initiatives, including the following:

- *Curricula organized around the "great principles" of computing.* The ACM Education Board currently has a project to identify these principles and assemble a collection of stories that illustrate them in pedagogically engaging ways [Denning03].
- *Curricula organized around the theme of innovation.* Andrew McGettrick and Peter Denning have argued that some of the decline in student interest is related to the fact that people are increasingly apt to associate the term *programming* with menial forms of low-level coding and not with the more creative aspects of software development. To the extent that students come to equate computing and programming, the negative image attached to programming tends to diminish student interest in the broader discipline. They propose "recentering" computer science so that curricular programs focus on the many innovative aspects of the field [Denning05].
- *Curricula that link computing with other disciplines.* One of the most exciting aspects of computing today is the extent to which computational techniques have become integral to so many other domains. Students who might admit no interest in computing in its own right might nonetheless become excited about opportunities to use computing techniques in another application domain. Such interdisciplinary strategies, moreover, have proven to be effective in boosting retention among women and minority students [Tew05]. Interdisciplinary initiatives of this sort are discussed in more detail in section 4.4.

The theme that underlies these approaches is the need for curricular experimentation.

Recommendation 1c: Encourage curricular experimentation and innovation. The practice of computing evolves rapidly in response to changes in technology, and many of those changes have direct implications for education.

Experimentation alone is not enough. The strategic goal of improving the quality of computing education is advanced only if those experiments can be evaluated in an appropriate way. Curriculum design and pedagogy in the computing disciplines has been surprisingly isolated from the body of research in the educational community that focuses on determining what strategies are successful and enhancing their overall effectiveness.

Recommendation 1d: Foster a community that focuses on educational research and assessment. Achieving this goal will require developing additional expertise within the computing education community about effective research methodology and outcomes analysis but will also require building more effective collaborations with social scientists and educational researchers who already have that expertise.

The following stakeholders are in a position to foster both educational experimentation and the creation of interdisciplinary communities necessary to conduct effective evaluation of those experiments:

- Funding agencies, which can increase support for educational research, particularly in the form of collaborative projects that bring computing educators together with those who have more general educational expertise.
- Academic institutions, which can take this type of research more seriously and remove institutional barriers to conducting it.
- Professional societies, which can include more educational and social science research in their own curricular initiatives. The decision of the National Center for Women in Information Technology (NCWIT) to convene a social science alliance is a useful example along these lines.

4.2 Attract more people to the field

As the discussion in section 2 makes clear, the computing disciplines are facing declining enrollments even though industrial demand for graduates with computing skills remains strong. To reverse this trend, universities and colleges will have to work together with other stakeholders to make computing disciplines more attractive to today's students. Although academic institutions will presumably take the lead in this effort, they are unlikely to succeed alone. Securing an adequate supply of expertise and talent, however, is vital to the success of U.S. industry and to the competitiveness of the nation as a whole. As a result, both industry and government have a direct interest in reversing the decline in computing enrollments.

As a first step toward reversing the enrollment decline of the past five years, it is essential to understand more fully the factors that have led to the erosion in student interest. Shortcomings in computing education and negative stereotypes of computing professionals may explain some of the problems that the field faces in attracting students, but are not sufficient to explain the decline as a whole. After all, many of these factors also applied in the late 1990s when computing enrollments were on the rise.

Given the timing of the enrollment decline, it seems clear that the economic downturn in the computing industry and the continuing increase in the use of offshoring have led to a perception that good jobs are rapidly disappearing in the computing fields. The negative impact of that perception came through clearly in the survey of high-school teachers conducted by the Computer Science Teachers Association in early 2005 [Roberts05]. In that survey, teachers cited both the offshoring phenomenon and the dot-com collapse as significant factors behind the decline of student interest.

As it happens, this perception—widespread though it is—is contrary to fact. As we discuss in earlier sections of this report, statistical data actually show an increase in the number of available jobs, along with strong projections of employment growth over the next decade. That this perception remains so influential in light of a growing need to develop workers with these skills represents an enormous challenge for the United States, as noted in the following recent editorial from the *New York Times* [NYT06]:

> Students may think, Why bother if all the jobs are in India? But the computer sector is booming, while the number of students interested in going into the field is falling. . . . The industry isn't gone, but it will be if we don't start generating the necessary dynamic work force.

At the same time, it is clear that the computing field does have an image problem that goes beyond the incorrect perception of declining opportunities. The stereotype of the computing professional has long been of the antisocial "nerd" who spends all of his—and the image is indeed almost invariably male—time in front of a computer screen. That image is understandably unattractive to many students who seek work opportunities that afford opportunities for social interaction. As with most stereotypes, the popular image in no way represents the range of people who work in the discipline. That image also reflects a misunderstanding of the nature of computing work, which is hardly ever solitary and typically requires extensive interaction with both colleagues and customers. But the popular image, again like most stereotypes, does have some basis in fact, particularly in relation to the cultural homogeneity of the field. Computing students are overwhelming white or Asian and preponderantly male. This lack of cultural diversity impoverishes the discipline in several ways represents a significant barrier to women and minority students. Moreover, as the discussion in section 3 makes clear, computing's ongoing failure to attract a broad spectrum of people not only limits the pool of available talent but also impoverishes the discipline by narrowing its cultural perspective.

We—as an academic discipline, as a profession, and as a nation—must take up the challenge of "generating the necessary dynamic work force" called for in the *New York Times* editorial. In many ways, the largest barrier to creating that workforce in the United States is popular misconceptions about the nature of the field. All stakeholders therefore have a strong interest in supporting a campaign to eradicate that negative image.

Recommendation 2a: Mount a vigorous campaign to change the popular image of computing. This campaign must seek not only to correct widely held impressions of the field that are contrary to fact (such as the idea that all jobs are being moved offshore) but also to promote changes in the discipline to eliminate negative stereotypes (such as the image of computer experts as "nerds").

Turning this general recommendation into concrete initiatives will require significant strategic thought, far beyond the level of what the ICER workshop could accomplish in its limited time. One point that the group thought was critically important was to make sure that the design and implementation of the campaign be as sensitive as possible to its intended audience. Student interests change in response to a wide range of factors, many of which are difficult to understand from the far side of a generational divide. The best way to ensure that curricular programs are attractive to students is to involve them more directly in the design and development of those programs.

Recommendation 2b: Convene focus groups to get a better sense of what students want. To make sure that the process remains forward-looking, these focus groups would need to involve high-school as well as current university students. It is essential, moreover, to work with as diverse a student group as possible to guard against perpetuating existing stereotypes, and to continue these focus groups into the future.

This recommendation remains somewhat vague on the question of who would do the convening of these focus groups. For maximum impact, such studies would need to be conducted by research teams with expertise in both computing education and in this mode of social science research, along the lines suggested earlier in Recommendation 1c. Such studies would, of course, require support from some combination of funding agencies, professional societies, and industry.

The problem of recruitment does not begin at the college level. By the time students graduate from high school, many students already have a sense of what areas they would be interested in exploring as possible careers. If computing is not among that set of possibilities, they will be far less likely to move in that direction once they reach college. Building enrollments in universities and colleges will require focused outreach efforts in high schools, directed not only to students, but also to teachers and guidance counselors who play a large role in giving students a sense of the available options.

Such outreach efforts are not at all new. In recent years, biology, mathematics, and engineering have all undertaken campaigns to increase the visibility of those disciplines. Those initiatives, moreover, have had some success. The number of mathematics and biology majors are both considerably higher than they were ten years ago, in part because entering students have more of a sense of the discipline. Given the fact that computing enrollments were high during the 1990s, academic programs have not always felt the enrollment issue as urgently as those disciplines in which the decline in popularity occurred earlier. Until just a few years ago, most institutions were more worried about how to accommodate the students they had than how to attract others.

Even during the time of high enrollments, however, computing programs were able to conduct focused outreach campaigns that were successful in attracting students to computing majors. In its campaign to increase the number of women in computing, Carnegie Mellon placed considerable emphasis on reaching out to high schools, as described in *Unlocking the Clubhouse* [Margolis01]. The Java Engagement in Teacher Training (JETT) workshops developed by the Computer Science Teachers Association are another model that has proven successful [Stevenson04]. These workshops are particularly interesting in that current undergraduates do much of the training, which has the additional advantage of increasing the undergraduates' own sense of investment in the field, thereby encouraging greater retention. As declining enrollments increase the need for such outreach, these initiatives ought to serve as models for a more broadly based campaign.

Recommendation 2c: Increase outreach to high-school students, teachers, and counselors. These outreach efforts must emphasize not only the continuing demand for well-trained computing professionals but also the intrinsic excitement that comes from the innovative, cutting-edge nature of the discipline. Outreach programs must be designed to appeal to a broad range of students. To this end, it is important to enlist current students in the outreach campaign, since they are likely to be particularly effective at communicating their own excitement to high-school students. Finally, it seems clear that many different strategies and approaches will be necessary to achieve success in this domain.

This recommendation clearly involves most if not all of the stakeholders identified in section 3 of this report. Academic institutions need to reach out to schools in their area both to showcase the exciting opportunities in the field and to offer any programmatic assistance they can to bolster the high-school computing curriculum. Similarly, high schools could benefit substantially from developing more extensive ties with local academic institutions, which typically have more resources and expertise in this area. A particular effective partnership along these lines is to have computing students at colleges and universities engage in service-learning projects in which they teach this material in the schools. Both industry and the professional societies also have clear roles to play. Industry has been active in helping to get schools online through activities such as Net Day. Professional societies have led the development of curricular resources for high schools, along with materials designed to give teachers and students a more accurate picture of the nature of computing.

Although mounting an effective high-school outreach campaign is clearly an enormous task, there are many ways that individual faculty members could contribute to this effort if they had the necessary materials. The participants at the ICER workshop expressed strong support for the idea of making outreach materials available to faculty, not only so that they could pass them along to their own contacts in high schools, but also because those materials would also be useful in recruiting current undergraduates.

Recommendation 2d: Make outreach materials available to faculty. As groups produce outreach material in support of Recommendations 2a and 2c, it is important to make those materials broadly available to faculty, so that they can use them in their own outreach and recruitment efforts.

In the discussion, several participants identified one specific piece of outreach material that may prove particularly effective: the forthcoming brochure being developed by the ACM describing the various subfields of computing—computer science, computer engineering, software engineering, information systems, information technology, and so on—and indicating what opportunities exist in each. This information is sorely lacking in high schools today.

Although this section of the report has focused on outreach at the high-school level, most institutions also need to increase the attractiveness of computing majors to students who are already enrolled. In certain cases—such as the circulation of outreach material to faculty described in Recommendation 2d—efforts developed for the high-school audience may nonetheless offer parallel benefits at the college level. Other aspects of the recruitment process, however, will need to be tailored not only to a college audience but also to the specific structure of the institution. As an illustration of the importance of institution-specific approaches, universities that accept students directly into computing majors clearly face different challenges than universities in which students decide on their major after they arrive. Both models are common in the United States, but in one environment, *retention* is the watchword, while *recruitment* dominates in the other.

Despite such differences, there are nonetheless many commonalities in the strategies that different institutions will need to adopt. In many ways, recruitment and retention are parallel efforts: many of the initiatives one might take to increase retention also serve as recruiting tools, and vice versa. Moreover, it is also clear that improvements in the curriculum and pedagogy and the expansion of interdisciplinary opportunities will affect both recruitment and retention. In light of the fact that it is often hard to separate these two aspects of the enrollment problem, the recommendations in this section must be viewed as only part of a larger campaign to increase the attractiveness of the discipline. To a large extent, the recommendations in the other sections will have a salutary effect on the attractiveness of the field as well.

4.3 Improve retention in the major

As noted in the preceding section, recruitment and retention often act as two sides of the same coin. This is particularly true in terms of our first recommendation in this section, in which we emphasize the philosophy—derived from the “reform calculus” movement in mathematics—that introductory computing courses should act as “a pump, not a filter”

[Steen87]. Particularly during the high enrollments of the 1990s, many departments were primarily concerned with winnowing the mass of interested students to select only the most talented for the major. Many other disciplines have adopted a similar approach. The classic example of this kind of filtering is the premedical curriculum, which typically has extremely high attrition rates. Such a strategy is invariably controversial among people concerned about educational equity; in this case, however, there is no need to argue the general issue, because such a policy makes sense only if there is overproduction of students in the area. In a time when the demand for computing graduates outstrips supply—as it clearly does today—the idea of filtering makes no practical sense.

Recommendation 3a: Recast introductory courses so that they become "a pump, not a filter." Eliminate any vestiges of the "filter course" mentality held over from the time of significantly larger enrollments. If a course is to "pump" additional people into the field, it must address itself to the interests of a broader audience than the traditional pool of computing majors.

Effective retention is also enhanced by making sure that students have a better picture of how the skills that they are learning will serve them in the future. Disciplines in which the introductory courses focus only on providing a foundation for more advanced work have little currency with today's students, who typically have less tolerance for deferred gratification. It is important to include enough contextual material to allow students to "keep their eyes on the prize."

Recommendation 3b: Make sure introductory students recognize that the field offers many opportunities. Introductory courses can no longer afford to serve only as a foundation for courses that follow. Students need to be able to see where they can go in this field, both in the rest of their time at college and in their eventual careers.

In much the same vein, it is important to give undergraduate students a sense of what more advanced work in the field might feel like. Several studies have shown that the opportunity to engage in research as an undergraduate increases the likelihood that students will proceed to graduate school [Cuny01]. And while the evidence is less direct, there is a solid consensus among universities who use undergraduates as teaching assistants that doing so increases the investment that those students have in the discipline.

Recommendation 3c: Provide undergraduates with opportunities for research and teaching. Such activities are valuable not only for retention within the major, but also in encouraging students to consider graduate school.

Another common barrier to retention is the fact that computing programs often emphasize individual work over collaborative opportunities. Although collaborative work can sometimes make it possible for students to muddle through on the work of their partners, individual work is often isolating, particularly when students are less confident of their own abilities [Barker05]. Pair-programming techniques have proven to be successful at many levels of the curriculum, particularly with students perceived to be "at-risk" in terms of completing the major. Similarly, group experiences in project courses—especially if they seek to mirror industrial experience—quickly dispel any misconception that computing is a solitary rather than a social activity.

Recommendation 3d: Increase opportunities for collaborative project work. Many strategies exist to enhance the amount of individual interaction among students in computing courses, ranging from pair programming in introductory courses to group work at the level of a capstone project.

Finally, it is important to emphasize that communities that are underrepresented in computing—women and minority students—may need special attention. It is easy for students who lack role models or a supportive peer community to become isolated and discouraged. To prevent this type of attrition, academic institutions must become more proactive in establishing support structures for those students. Bridge programs and similar initiatives that provide such students with more academic support are important in this regard, but there is also an important social dimension to achieving high retention rates in this population. Students in these targeted communities must be able to achieve a critical mass before they can see themselves as part of the computing major.

Recommendation 3e: Encourage the formation of support groups for at-risk students. These groups provide make it easier for students to see themselves as belonging to the discipline, which has a strong influence on retention. Peer mentoring and coaching have also proven highly effective in this regard.

4.4 Strengthen interdisciplinary connections

The initiative of strengthening interdisciplinary connections is in some respects a particularization of the earlier initiatives and will help to improve the computing curriculum, increase the attractiveness of the field, and encourage greater retention. At the same time, interdisciplinarity—which in certain contexts is more accurately described as multidisciplinarity—stands on its own as a strategy to advance the overall goals outlined in section 3. Computing is now a part of every quantitative discipline, and it is essential for students in those subjects to have at least some familiarity with computation. Modern computing techniques also make it possible to investigate a wide range of research topics that have heretofore been impractical. Bringing students and faculty from computing together with their counterparts in other disciplines will enable the discovery of new knowledge along with the creation of new pedagogy.

The most traditional—and in many respects the least imaginative—opportunity for interdisciplinary teaching lies in the service responsibilities that computing programs have always taken on. Students in other disciplines need computing expertise, which computing programs are in a position to supply. Although service teaching is rarely the most exciting or rewarding activity in a university, there are advantages to computing departments in taking on this role:

- Faculty with expertise in computing can typically do a better job of foregrounding the science and engineering aspects of computing practice than faculty from other disciplines who see computing merely as a means to an end. By keeping these courses in the computing departments, students are able to learn general principles of software use and development that will serve them throughout their careers.
- Taking on additional service teaching may help insulate computing departments from the vicissitudes of the boom-and-bust cycles of computing enrollments. The fact that student enrollments have fallen by more than 50 percent in many institutions is likely to put faculty billets in those disciplines at risk, even though historical patterns suggest that the downturn is cyclical. Departments that find ways to maintain staffing strength through the dips in enrollment will be better positioned to respond when enrollments recover.
- Even the most applied service courses—if taught effectively—can serve as recruiting grounds for computing majors and minors. While the overall goal of such courses cannot be to entice students away from other disciplines, some students will inevitably be attracted to the style of thinking that computing demands. Relatively few students have much formal exposure to computing in high schools and therefore often enter universities planning to major in other disciplines. As students discover that

computing is exciting, scientific, intellectual, and practical, some of them will surely decide to explore the field in greater depth.

> **Recommendation 4a: Offer service courses designed for students in other disciplines.** In addition to providing the computing skills that students need to work effectively in other fields, service courses taught by computing experts also provide an opportunity to introduce students to the excitement that computing holds.

Service courses, however, do not provide true models of interdisciplinarity. To unlock the power of collaborative work across disciplines, faculty and students from distinct disciplines must come together to exploit the synergies that come from bringing different sources of expertise to bear on a common problem. To achieve this more ambitious goal, it will be necessary for faculty to work collaboratively on research and teaching that cross disciplinary boundaries. Courses developed and co-taught by faculty in more than one discipline can be enormously exciting, both for the teachers and the students.

The biggest pitfall to avoid in this area is having one party to the collaboration come to regard the other only for its instrumental value. For example, if biology faculty were to regard computing as a tool, the potential for synergy in biocomputation is significantly reduced. Success in such collaborative efforts depends on updating Morten Kyng's classic principle of participatory design to interdisciplinary efforts: effective collaboration must be done *with* other disciplines, neither for them nor by them.

> **Recommendation 4b: Encourage faculty to develop meaningful collaborative activities across disciplines.** Such activities might include either the team-teaching of courses or research projects that bring together computing students together with those working in other fields. In either case, the collaboration must be focused on true intellectual sharing rather than having one discipline serve the other as a tool.

Such collaborations can occur at many types of institutions. One of the great strengths of small, liberal-arts colleges is that faculty tend to know their colleagues even beyond their own department. These informal connections often provide a foundation for interdisciplinary work. Research universities, on the other hand, have greater depth in their faculty strength that can lead to more focused interactions. Research problems are often intrinsically more interdisciplinary today, particularly in terms of the need to apply computational techniques to problems that arise in some other domain. If solving a particular problem requires people with expertise in some specific area of computing together with an equally focused external area, it is typically much easier to find the right combination of talents in a university setting.

Even though collaborative efforts along these lines could potentially arise in many different institutions, it is equally clear that those collaborations will often be difficult to foster. Particularly in the case of interdisciplinary curricula, it will be essential to exploit those collaborations that do occur by making the products of those efforts available to other institutions. For areas in which collaborative opportunities are particularly rich—such as biomedical computing and computational economic modeling—it would be wonderful if successful curricular experiments could be exported more broadly so that their benefits transcend the institutions at which the collaboration arose.

> **Recommendation 4c: Support development and distribution of interdisciplinary curricula and resources.** Given the institutional barriers to interdisciplinary work, it is impossible to expect each institution to develop interdisciplinary curricula on its own. It is possible to gain far greater leverage by funding a few demonstration projects and then making the materials from those projects widely available.

4.5 Meet human and infrastructure needs

In a perfect world, it might be simple to implement all of the recommendations outlined in the preceding sections. In practice, however, there are many barriers to putting these initiatives into place, including a lack of resources and various institutional disincentives that make it hard to implement changes of this kind. Although most academic institutions today give lip service to interdisciplinary work, individual departments tend to place greater weight on work—both research and teaching—that remains firmly within existing disciplinary boundaries. On the teaching side, a common example of this sort of disincentive is a teaching formula that discourages team teaching by giving each faculty member in a pair credit for only half a course. If faculty are serious about collaboration, team teaching is actually more time-consuming than going it alone. If faculty cannot get credit for their effort, such initiatives will languish.

Recommendation 5a: Eliminate structural barriers to interdisciplinary collaboration. Most institutions today create disincentives to interdisciplinary research and teaching, such as teaching formulas that give less credit for team teaching or tenure evaluations that focus only on excellence within disciplinary boundaries. Changing this culture will be essential to fostering the kind of interdisciplinary work that is so important in today's world.

The lack of sufficient resources also constitutes a significant barrier to institutional change. In the breakout group on institutional structures, the overall consensus was that the greatest impediment is the lack of available time. Time, however, is typically allocated so as to reflect the priorities and culture of the institution. Changing those priorities—in a tangible way that is reflected in the reward structure—can help to liberate time and make it available for these initiatives.

Recommendation 5b: Provide greater institutional rewards for teaching and curriculum development. Computing faculty will not be able to respond to the challenges in computing education as long as universities put a smaller value on teaching than they do on research.

At the same time, eliminating barriers is unlikely—on its own—to jump-start strategic initiatives to improve the computing curriculum. Funding agencies must also ensure that activities like curriculum development, educational research, assessment development, pedagogical experimentation, and interdisciplinary collaboration receive more support than they do at present. Particularly in the case of initiatives that involve interdisciplinary or cross-institutional collaboration, funding agencies may have to adopt new models given that most agencies and foundations have traditionally supported work in a single area. Just as academic institutions must eliminate barriers to interdisciplinarity, funding agencies may need to do the same.

Recommendation 5c: Increase support for curricular development, educational research, and assessment. To the extent that these activities involve interdisciplinary collaborations within and among institutions, it may be necessary to develop new funding models to support that style of activity.

Finally, the ICER participants concluded that the challenges facing education in the computing disciplines are unlikely to be met by academic institutions alone. Every stakeholder has an interest in increasing the number of qualified computing graduates able to meet workforce needs. An effective solution to this problem will require that the many stakeholders work together as effectively as possible.

Unfortunately, most academics—particularly in computing where there are few "elder statesmen" to assume public policy roles—have been relatively disconnected from the policymaking process. By encouraging faculty to develop the political and strategic skills to raise issues effectively at a variety of levels, the field can ensure that more attention is focused on the problems we face.

Recommendation 5d: Train computing faculty to think strategically both inside and outside the academy. Even though the mismatch between educational production and industrial demand is uniquely severe in the computing area, relatively little national attention has been focused on the issue. Computing educators must become more active in raising these issue in the wide range of venues through which change can occur.

As the ultimate consumer of the products of educational institutions, industry has a particular role to play. Partnerships between academic institutions and local industry are particularly well-suited for upper-division courses in areas where the science and technology of computing are advancing rapidly. Bringing industrial perspectives into the curriculum is also likely to have benefits for both the academic institutions and the partner companies, in part because this type of connection will make computing careers more attractive to students who have little sense of how computing disciplines are applied in practice or the range of career opportunities for computing professionals. Such collaborations could take place on many levels, from high schools to graduate programs.

Recommendation 5e: Strengthen industry involvement in computing education. Industry can make a positive contribution to education at many levels, both by bringing cutting edge industrial practice into the classroom but also by making it far clearer to students that interesting opportunities continue to exist in these fields.

5. Long-term visions

The recommendations outlined in section 4 generally proceed from an analysis of the current situation and how it can be improved. That approach tends to support deliberative evolutionary change as opposed to more revolutionary, large-scale restructuring. Planning for more substantive change usually requires thinking in a more expansive way about long-term goals, beginning with an idealized vision of what computing education might be and then continuing with an assessment of how best to move toward that vision from where we are. During the Saturday morning session of the ICER workshop, two different breakout groups sought to define that "blue sky" vision of computing education.

In the ideal future we hope to see, the community of students studying the various computing disciplines will enter universities with far better preparation, thanks to an increased focus on abstract thinking and writing at the K-12 level. Those students will also reflect much more closely the diversity of the population at large. They will also begin their university study with a much more comprehensive picture of what computing is and what opportunities it offers. In particular, students will understand that there are many options available in computing and recognize that they can choose among those options in ways that support their own interests, abilities, and career goals.

The universities that these students enter will also be transformed. Computing programs will be much broader in scope to encompass not only the intellectual growth within the computing disciplines but also the increasing importance of computing across all disciplines. The importance of computing will be understood much more widely throughout the academy, enabling exciting opportunities for interdisciplinary collaboration. Those universities will be more responsive to the needs of their many stakeholders. Industry will play a greater role in supporting education and in providing opportunities for in-service learning through internships and other opportunities for project work similar to what students will encounter on the job. Universities will also be more active in addressing the many challenges in the larger world, both locally and globally. Instead of remaining relatively isolated from the world at large, academic programs in computing can offer their expertise toward finding solutions to those problems in which information technology can plays a positive role.

The computing departments within those universities will continue to offer outstanding programs in traditional computer science, but these programs will be supplemented with others that offer many more options for students. Even within the traditional computing disciplines, the curriculum will be packaged and delivered differently so as to increase both its effectiveness and its attractiveness to students. If students come to this varied curriculum without understanding what it means to be a computer scientist or to work on domain or business problems with a computer scientist, those departments will provide them with opportunities to explore the available range of career paths through the project work that pervades the curriculum, field trips to the "outside world," greater involvement by industry people in classes, and a compendium of inspirational accounts by computing professionals. These personal histories are part of a more general "computing education repository," which is itself distributed, open-source, produced in conjunction with industrial partners, and freely available over the Internet.

While some students will still major in computer science and other traditional fields, students with primary interests in other fields will recognize that computing as integral to their own area and understand that computing has the potential to solve important questions in many domains. We see many educational options, including computing offerings specialized to different fields that engage both students and interdisciplinary teams of faculty in communities of interest. We further envision teaching teams using the solved and unsolved "great problems" of these respective domains to engage in creative collaborative inquiry that often leads to innovative solutions to real-world problems.

In these new computing programs, a well-tuned foundational curriculum focuses on core concepts, great principles, and abstraction. This phase of the curriculum helps students to develop fundamental concepts and skills, which are then reinforced through well-designed collaborative projects. These concepts and skills lay the groundwork for, and are later applied to, individualized and specialized upper-division work. Faculty and students in those programs also have access to a superb teaching repository of ontologies that support the learning of great principles and abstractions at many different levels. The same repository also provides materials that allow customization of upper-division courses to small teams of students and new developments.

In terms of pedagogy, we see faculty who have themselves been coached by master teachers and who understand that delivering content is no longer enough to attract, retain, and educate tomorrow's computer scientists. Those faculty, moreover, work in institutions that respect and support the scholarship of teaching and of computing education. Experts in computing education will collaborate with experts in other domains to develop and refine open-source, peer-reviewed curricular material. The existence of such materials will free faculty for coaching, collaborating, and co-learning, and keep them engaged with their students and colleagues. We also imagine faculty who are run less ragged and have time for greater interpersonal contacts with their students, as well as for a life outside the classroom.

Throughout the curriculum, students will be involved in helping other students through peer-mentoring and peer-coaching activities. Advanced students mentor the less advanced, while lower-division students can serve as role models for younger students through collaborative projects with local high schools.

Students at all levels are also involved in team or individual project work, much of which can be multidisciplinary, distributed, or even global. This model of studio style courses works thanks to faculty who understand how to lead teams, repositories that provide quality materials, and students with solid social skills. Periodic field trips to industry, where students and industry partners present project work, act as recruiting vehicles in two directions: students learn about what it means to be a professional, and industry professionals and faculty see ideas for collaborative teaching advanced courses. Industry mentors serve as evaluators and consultants for advanced projects.

This model of education sees faculty less as purveyors of content and more as coaches developing and carrying out plans jointly with each team. In such a model, motivated students can be brought up to the level needed for their team to succeed. Such teamwork requires the recognition that not all students have the same goals or capabilities, and that faculty need to connect with other disciplines in order to better advise students if lateral moves across the curriculum seem better suited.

We believe that future undergraduate computing education will be significantly different than it is today, but whether that future will fulfill these idealistic visions depends on those with a stake in computing education: computing educators, computing industry, funding agencies, parents, and students. If successful marketing campaigns recruit new and more diverse students and collaborators from other areas, if we realign and sustain a minimal core, and instill problem- and project-oriented curricula in new directions as called for by the changing field, then we see computing education producing an educated citizenry filling key jobs and providing leadership needed for good technology policy decisions in the new global economy.

6. Next steps

In the day and a half that participants spent at the ICER workshop, it was not possible to prioritize the many recommendations outlined in section 4. At the same time, we were able to suggest some immediate steps, both for the ICER participants themselves and for funding agencies looking for ways to jump-start the process. The participants gave themselves the following responsibilities over the next six to twelve months:

- Read and comment on the regional and national reports.
- Maintain the regional ICER web site to include a wiki for report and discussions with our colleagues, references and bibliographies, the final report, and other activities.
- Take on follow-up assignments. As an example, individuals could write up ideas for manageable projects that address the issues identified during the workshop, post these on the wiki, carry these projects out, and then report back to the community.
- Meet informally with faculty colleagues to talk about the state of the discipline.
- Propose and participate in outreach and dissemination efforts of the ICER effort.

For funding agencies, we recommend the following activities:

- Organize follow-on activities to the ICER process to bring more stakeholders into the discussion. One specific suggestion was to convene an ICER workshop with participants primarily from industry.
- Develop interagency structures to fund interdisciplinary curricular development.
- Enable institutional change by supporting research on organizational barriers to change and integration within the academy. Agencies should consider sponsoring workshops to identify vehicles for organizational change and curricular coordination.
- Create more small grants targeted toward curriculum development.

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