David Lopatto

Science in Solution:

The Impact of Undergraduate Research on Student Learning

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RESEARCH CORPORATION
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Note from the Publisher

Research Corporation for Science Advancement (RCSA) offers this work by educational psychologist David Lopatto as a means of promoting discussion at the nexus of science and education in America. It is vitally important to keep this conversation going among researchers, scholars, college and university administrators, federal and private funders because the United States simply must provide its citizens with the best possible, and most responsive, science education available in an era of growing global competition. The nation faces a diminishing future if we fail to do so.

For nearly the past century now, RCSA has focused on supporting young scientific researchers—in the process contributing greatly to the shape of our modern world and helping to build the careers of nearly 40 Nobel laureates so far. In doing so the Foundation has come to some general conclusions about science education; until now, however, with the exception of the Academic Excellence Study undertaken in 2001 with our sister foundations (the Camille and Henry Dreyfus Foundation, the Robert A. Welch Foundation, W.M. Kick Foundation and the M.J. Murdock Charitable Trust), the evidence supporting our position on this subject has been based largely on the personal observations of generations of RCSA program officers, and essentially anecdotal in nature.

Thus it is gratifying on many levels to see scholars such as Dr. Lopatto take up the issue of effective science education with renewed vigor and modern, qualitative methodologies. It is not mere wishful thinking, I believe, to say that the conclusions Dr. Lopatto draws in this work seem to confirm RCSA's position that involving undergraduate students in meaningful, authentic scientific research provides a "leg up" for those seeking to make careers in science.

Further research on the topic of science education is essential if we are to hone our collective ability to take advantage of America's bright young minds across the broad spectra of cultural heritage, race, gender, intellectual skills and thinking styles. Only by the attentive and well-informed support of our best and brightest, will the U.S. maintain its security and prosperity in the decades to come.

James M. Gentile
President and CEO
Research Corporation for Science Advancement

Foreword

For years, the science community has debated and discussed whether and if so why a relatively small proportion of the nation's colleges and universities produce a larger than expected share of future scientists and science faculty.[1] It was assumed that small classes and a dedicated teaching-oriented faculty were the reason. But over the past decade or so, the undergraduate research experience in science has been acknowledged as the royal road to a career in science. As Ann Roe, quoted by David Lopatto (infra), puts it "Once [a student] discovers the pleasure of a college project which he [or she] has occasion to do himself, he never turns back."

All very well. But what is it *about* the undergraduate research experience that matters? The small cohort? Problem-based learning? The proximity of the instructor? Student-generated camaraderie? And what of the undergraduate who is just taking a course to learn something about science, not intending to choose science as a career? What's does that student take away from an undergraduate research experience?

David Lopatto, a psychologist at one of the many institutions that provide undergraduate research in science, decided to explore the undergraduate research experience in some depth. In a series of inquiries, first involving colleges like his own, then extended to nearly 100 institutions of varying size and type, he concludes that it is not just more science that students take away from well-designed research projects but a hard-to-replicate encounter involving self-discovery and sometimes, for the first time, having to take responsibility for their own learning. Using the rubric of "personal development," against the findings of his own questionnaires, Lopatto concludes that, irrespective of the subject itself, much intellectual maturation occurs from designing an experiment, any experiment, and taking responsibility for the process.

There are, in addition, tangible benefits to the institution as a whole when ways are found to combine the presumably non-overlapping categories of teaching vs. research.

But undergraduate research projects cost more, much more, to design and staff than lecture and certainly online courses. Which raises another question: if the undergraduate research experience is so valuable in the small-college setting, how can it be transferred to larger, less well resourced institutions?

Here we learn that in 2005 a group of faculty came together to design a model for "research-like courses" in college science, ones that involved laboratory work or extended projects that would achieve at least some of the learning goals of a semester- or summer-long research experience. Other

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[1] Michael P. Doyle, *Academic Excellence,* Special Report of Research Corporation, Feb. 2002. Available online *http://www.rescorp.org/about-rcsa/publications/academic-excellence*

institutions are building research-equivalents into the interdisciplinary problem-centered courses that students flock to.

Lopatto is not naïve about the risks and challenges of reform. It's been more than 60 years since *Sputnik* and 25 years since Gerald Holton's *A Nation at Risk* reminded us of what's at stake if we do not attract more students, of both sexes, and all ethnicities to science. While undergraduate research has been fostered in somewhat elite institutions, without his quite saying so, Lopatto's findings leave this reader, at least, with a strong sense that an undergraduate research experience could be the cross-class leveler we've been searching for; one that provides the first-generation college student with some of the critical and self-critical habits of mind that more privileged young men and women bring with themselves to college.

Francis Bacon said it first. But it is no less true today than it ever was: "The scientific method allows ordinary people to do extraordinary things."

Sheila Tobias
Tucson, Arizona
December 2009

Introduction

For many years I was self-appointed inspector of snow-storms and rain-storms, and did my duty faithfully; surveyor, if not of highways, then of forest paths and all across-lot routes, keeping them open, and ravines bridged and passable at all seasons, where the public heel had testified to their utility.
H.D. Thoreau, *Walden*

About 10 years ago, the National Science Foundation announced a program called "Awards for the Integration of Research and Education at Baccalaureate Institutions" (AIRE). The proposal solicitation stated that the NSF had a "vision for enriching the Nation's future through research and education in science and engineering." This vision was "anchored in the process of discovery—discovery by researchers, teachers, professors, their students, and all citizens," and included as a core strategy integrating research and education in science and engineering. The AIRE program appeared a few years after Sheila Tobias' transformative report, *They're Not Dumb, They're Different*, which is one starting point for the work described in this book, and a few years before the current calls for interdisciplinary research and education and for scientific teaching. Although the AIRE program lasted for only one round of grants to baccalaureate institutions, and was criticized for providing funding to colleges that already had well-established and well-admired undergraduate programs in the sciences (an instance of the persistent "Matthew Effect" I will mention later) the original vision has, in my opinion, been vindicated.

In 1998 Grinnell College was proud to receive one of these AIRE awards to enhance our work as a model institution for undergraduate research and education. The award was followed by inquiries from faculty and administrators at other institutions. How did we at Grinnell account for our success, particularly at fostering undergraduate research? What were, to use a phrase coined by Dr. Elaine Seymour, the *essential features* of a good undergraduate research experience? For that matter, what *specifically* were the benefits?

These were surprisingly difficult questions to answer. We could, like other experienced educators, answer the questions with testimonials and anecdotes. But we were, after all, scientists, and scientists rely on systematic collection of data. We needed data if we were to move from simply being a role model for undergraduate research to constructing a conceptual model for undergraduate research.

Spurred by the AIRE, I began tentatively to probe the question of what might be the most effective process for doing undergraduate research. The early stage of this research involved creating interview protocols for students. I discovered a convenient and effective methodology for carrying out the protocols. I engaged talented psychology undergraduates as my co-researchers and asked them to interview other local undergraduate researchers, principally in the sciences, who were working on campus during a dedicated, 10-week summer research experience. The interviews yielded information about students' backgrounds, motives, professional intentions, and attitudes. This information then fed back into the creation of more specific research questions.

At about this time I attended a conference of AIRE directors at NSF headquarters, and in a meeting facilitated by Grinnell Professor of Chemistry Jim Swartz, met colleagues who were interested in the wider assessment of undergraduate research. Among the meeting attendees was Elaine Seymour, who catalyzed the group with straightforward research questions. Energized by the meeting, I asked faculty at several peer institutions to comment on her two questions about the essential features and benefits of undergraduate research. Faculty from Grinnell College, Harvey Mudd College, and Wellesley College responded, and I later published a summary of the results.[1]

Further conversations led to a plan for a grant proposal to the NSF program then called ROLE (Research on Learning and Education). Seymour and I were co-investigators in a fairly ambitious attempt to get credible data on the question of the benefits of undergraduate research. With the cooperation of four research sites, Grinnell College, Hope College, Harvey Mudd College, and Wellesley College, we were able to construct a mixed methodology approach to the problem. Seymour travelled to each research site and interviewed students, faculty, and administrators, yielding qualitative information that was carefully coded and described. Concurrently, I created a largely quantitative survey for the students that came to be called the ROLE survey. Students at the four research sites completed the survey for two summers (2001 and 2002). Most of the respondents were students working on 10-week research experiences in the natural sciences, but a few were from social sciences and humanities. Seymour and her colleagues have published the results of the student surveys in *Science Education*. I have disseminated the survey results, but some of the quantitative results appear here in print for the first time.

The outcome of the ROLE grant was a comparatively neat taxonomy of the benefits to students of the undergraduate research experience. The qualitative information and quantitative information provided a clear view of the benefits. There were also a few surprises, such as the large role of personal development among student-reported benefits. But the answer to the question, "What are the benefits of undergraduate research?" provoked further questions, most obviously having to do with the general nature of the findings. ROLE results were based on the experiences of students at four excellent liberal arts colleges. How relevant were these findings for other sorts of institutions?

As it happened, about the time that the NSF grant work ended, a distinguished Howard Hughes Medical Institute (HHMI) Professor, Sarah C. R. Elgin, of Washington University, proposed to HHMI a project to assess the learning outcomes for undergraduates whose summer research experiences were fueled by HHMI graduates. Elgin recruited me to construct the survey and analyze the data. This presented me with an opportunity to take the essential findings of the ROLE work and test them in the broader set of institutions affiliated with HHMI awards. The new survey, originally accessible on line at the Washington University web site, was called SURE (Summer Undergraduate Research Experience). We accumulated data over two years from 3,156 students at nearly 100 institutions, including liberal arts colleges, research universities, and comprehensive universities. We offered a 9-month follow-up survey that was completed by more than 1,000 of the original respondents. The results of this work were published in 2004.[2]

In terms of the research questions cogently posed by Elgin, the data supported three hypotheses: that the educational experience of the students was enhanced by the research, that undergraduate research experiences supported talented students interested in a science career, and that undergraduate research contributed to the retention of minority students on the pathway to science careers. Secondarily, the data demonstrated the wide generalizability of the original ROLE results. But again, answers led to more questions. Did the findings generalize from highly focused summer experiences to undergraduate work undertaken during the academic year? Was there any information to be gained about the experiences of undergraduates who served as peer mentors? Could classroom experiences approximate the benefit of dedicated research experiences?

With continuing support from the Howard Hughes Medical Institute, the SURE project was adapted and extended to pursue answers to these questions. The survey, now labeled SURE II, was modified to include a section of questions for students who had either served as peer mentors or who had been helped by peer mentors. The survey itself was moved to Grinnell College (hence the II in SURE II) and a parallel version was constructed that included a series of items about summer versus academic year research experiences (SURE AY, for Academic Year). Since 2005, more than 6,000 students at a wide variety of institutions have completed these online surveys.

A fascinating outgrowth of the surveys' widening reputation is the involvement of community colleges, coalitions of researchers dispersed across several institutions, and the National Laboratories. As the data are analyzed (and some are presented in this work), the bigger picture of the benefits of undergraduate research continues to develop. Empirical support grows for the benefits of research experiences for students across the science disciplines, for the benefits to younger students, and for the benefits of scientific communication in writing and speaking.

Even so, SURE II and SURE AY did not address the issue of classroom learning. To do so, the old ROLE collaborators were recruited for a new effort, supported by HHMI, to construct and test a survey instrument that could be used in the organized course curriculum. With the help and advice of colleagues at Wellesley, Hope, HMC and Grinnell, as well as the keen interest of faculty at other institutions, the CURE survey was created and field tested. The CURE (Classroom Undergraduate Research Experiences) survey permits comparison with the SURE survey research by employing similar survey items, as well as items relating to student experience, career intentions, science attitude, and learning style. The CURE approach is more elaborate than SURE. Summer research students participate in the SURE survey at the end of the summer or in the autumn, when they have completed their experience. CURE, on the other hand, examines three facets of the course experience. First, the course instructor provides information about the activities emphasized in the course. This information is crucial because it allows researchers to group courses, for example those that make use of pedagogic innovations that infuse a course with research-like attributes versus those that do not. Second, the students complete a pre-course survey, sharing information about their situation in science experience, attitude, and learning style before they are affected by the course experience. Finally, the students complete a post-course survey in which they report their learning gains and revisit their attitude toward science.

Use of the CURE survey has grown. We typically expect to have reports from approximately 950 students at 20 institutions for a single semester. Some of the findings are presented in the present work. The general finding is that students in a research-like science course report learning gains that resemble those reported by students in dedicated research experiences, with the magnitude of these gains falling between the higher ratings of undergraduate researchers and the lower ratings of students in more traditional courses. In a few cases of programs that strongly emphasize research activities in the course or courses, such as Prof. Elgin's Genomics Education Partnership centered at Washington University or Prof. Yi Lu's work at the University of Illinois, the student data match that of students in dedicated research experiences. These results support the exciting idea that the traditionally separate aspects of undergraduate science—classroom learning versus research experience—can be unified. This unification, for students and for faculty, is a theme of this book.

As the CURE data provide answers, they also provoke more questions. At the 2008 meeting of the Council on Undergraduate Research (CUR), I presented CURE findings to an audience that was too large to fit in the room. Among the questions posed by audience members were ones having to do with overall benefits of all undergraduate research experiences, not just in science or confined to disciplinary work. The latter task, finding some way to survey the benefits of interdisciplinary research and courses, occupies my attention at this writing.

My work with surveys, instruments often derided as yielding information a mile wide and an inch deep, has permitted me to experience a larger view of science education, something akin to what Thoreau meant when he wrote about that other kind of surveying, that it "seemed a noble employment" because it permitted him to observe nature. The nature I have observed is the nature of undergraduate research experiences. In its various forms and species, undergraduate research at its best interfaces with social, cognitive, and developmental dynamics to create a variety of benefits for student and faculty. Its most exalted promise is that the collaborative research of students and faculty "anchored in the process of discovery" challenges the convenient categories of teaching versus research and learning versus doing. Taken as a strategy for programmatic reform, undergraduate research may offer a solution to the challenges of producing the next generation of scientists, entrepreneurs, and the science-literate society that our leaders claim is essential for the future of our nation.

1

It was twenty years ago today…

To an uncertain adolescent, flailing about for something he or she might actually be able to do and do well, science offers not just a whole array of interesting and important careers, but a training that, to paraphrase Bacon, enables ordinary people to do extraordinary things. If physicists learned to regard every one of those 250,000 introductory physics students—most of them somewhat better than "ordinary"—as having something valuable to contribute and much to gain from science, there might be no science "crisis" at all.
Sheila Tobias, *They're Not Dumb, They're Different*

In 1990 Research Corporation for Science Advancement published a study by Sheila Tobias called *They're Not Dumb, They're Different: Stalking the Second Tier.* Tobias took on the question of how to stem the "science shortfall" at American colleges and universities. She wrote, "Everybody says it in one way or another, we need to teach more students more science."[3] One solution to the possible shortfall, Tobias suggested, was to recruit students from the "second tier," a loose category of students who were able to do science, but for reasons of learning style, expectations and experience, chose not to. The students of the second tier, Tobias wrote, "may have different learning styles, different expectations, different degrees of discipline, different 'kinds of minds' from students who traditionally like and do well at science."[4] To investigate the experiences of the second-tier student, Tobias recruited former college students to take introductory courses in physics and chemistry.

These participant-observers reflected on their learning experience, exposing the problems of introductory science teaching. The trouble with science, they suggested, was not the student's lack of ability; it was the traditional way in which introductory courses were taught. The courses were hierarchical, competitive, isolating, limited by the "tyranny of technique," and uninteresting to anyone who wanted to know the history of ideas or the bigger picture of the issues involved. The experience of Eric, a graduate with a degree in literature, was typical. Eric found his physics class dull, taught by an instructor who "was not particularly good at explaining why he did what he did to solve problems, nor did he have any real patience for people who wanted explanations."[5] Eric reflected that "the lack of community, together with the lack of interchange between the professor and the students combines to produce a totally passive classroom experience." Faculty assumed a pre-existing dedication to science and saw their role as "weeding out." Eric's course instructor stated his view as, "I assume that students...are pre-professionals who have already decided on a career in science and are in class to learn problem-solving techniques that will be required of them in their careers."[6]

Having demonstrated that reform was necessary, Tobias concluded her study with recommendations for reform, which were to occur at the level of the classroom and department. The recommendations included increasing the intellectual appeal of science courses, slowing the pace of content coverage in favor of depth, utilizing undergraduate support staff (peer mentors), reducing class size, enhancing mathematical competence, and significantly changing the way students are evaluated. Tobias concluded, "My hunch is that even students not yet demonstrably inclined to science will respond positively to special attention, curriculum enrichment, and personal opportunity."[7]

The impact of *They're Not Dumb, They're Different* is difficult to assess, but since its publication a number of reforms have been made in introductory science courses at colleges and universities.[8] Innovations include workshop science, problem-based learning, peer instruction, and research-embedded courses.[9] The publications of professional organizations such as the Council on Undergraduate Research (CUR) and Project Kaleidoscope (PKAL) are replete with reports of successful reforms of science and math curricula. Both governmental and private funding agencies have provided resources for reform and innovation. Committees of distinguished experts have outlined essential information about *How People Learn*,[10] how science curricula should be enhanced, and how interdisciplinary work may be undertaken. The recruitment of talent from traditionally underrepresented groups has been a feature of grant funding, curricular reform, and teacher training.

Yet the shortage of science students, science graduate students, and scientists has come to pass as predicted. A 2004 report from a RAND Corporation conference detailed the lack of growth in the number of Bachelor's degrees earned by U.S. citizens in science and engineering.[11] A report of the National Academy of Sciences entitled *Rising Above the Gathering Storm*[12] emphasized both the value of a strong science workforce and the decline of America's standing relative to the international community. In a more recent report, the Academic Competitiveness Council stated, "There is increasing concern about U.S. economic competitiveness, particularly the future ability of the nation's education institutions to produce citizens literate in STEM (Science, Technology, Engineering, and Mathematics) concepts and to produce future scientists, engineers, mathematicians, and technologists."[13] A report from the Business-Higher Education Forum stated "American students today have limited interest in studying mathematics and science, and academic achievement in these two foundational disciplines is demonstrably low….It is a national imperative… that we improve achievement… attract more individuals into [STEM] careers."[14] Science education reforms may be praised for increasing the proportion of science Ph.D.s awarded to women,[15] but overall science education has not been a growth industry. Twenty years have passed since Tobias' informants took their science courses. Despite the innovations that followed, the "second tier"—and maybe even the first tier—has not been recruited in enough numbers to change the trends in science education.

The lack of STEM workers is not the only penalty from our lack of growth in science education. A general education about science has been linked to our continued success as a democracy.[16] *Science and Engineering Indicators* (SEI), published by the National Science Foundation, stated that "Knowledge of basic scientific facts and concepts is necessary not only for an understanding of S&T (Science and Technology) related issues but also for good citizenship. Knowing how science works—how ideas are investigated and either accepted or rejected—can help people evaluate the validity of various claims they encounter in daily life." SEI reported survey results showing that science knowledge in the United States is not improving over time; that less than half the American population accepts the theory of evolution; that only 43% can answer a question about how an experiment is conducted; and that belief in pseudoscience has increased in the past decade.[17] Although Natalie Angier has pointed out that "The arguments for greater scientific awareness and a more comfortable relationship with scientific reasoning are legion, and many have been flogged so often they're beginning to wheeze,"[18] not much has changed for the better, and the reforms of science education since 1990 have not made a notable impact on the science literacy of the American public. Gerald Holton examined the implications of this illiteracy, and he observed that "in a democracy, no matter how poorly informed the citizens are, they do properly demand a place at the table where decisions are made, even when those decisions have a large scientific/technical component."[19] Such decision-making could be disastrous.

The second tier possesses no gender or ethnic markers. Rather, it seems to represent a kind of "cognitive diversity," the differences in thinking and in taking perspectives discussed by Page in his work on group problem solving.[20] It is composed of people who could contribute to science but who are discouraged by their experience with it. They are an "underrepresented group" in science, but unlike women or minorities, who may have faced institutional barriers to advancing in science, they choose to be underrepresented. As the opening quotation from Tobias suggests, if their experience had been different, they might have continued with science. Despite changes in pedagogy, the second tier has not shown up to announce a commitment to science careers. The shortfall is still with us.

Why has reform in the introductory courses failed to have an impact on the science shortfall? Maybe reform has not been widespread, leading Alberts in his 2003 address to the National Academy of Sciences to ask, "Why do we continue to treat our introductory laboratories in science courses as exercises in following directions, rather than challenging students to use inquiry to solve a problem with scientific tools?"[21] Maybe not enough time has passed since science education reform took shape. Maybe benefits will emerge in the next few years. Maybe it is too late, and the attractions of reformed introductory science courses fail to engage a student who has already been discouraged by suffocating science courses at the kindergarten through high-school level and by society's anti-science attitudes. Natalie Angier, in her book *The Canon*, relates the following conversation between two teenage girls:

> Girl A asked Girl B what her mother did for a living.
>
> "Oh, she works in Bethesda, at the NIH," said Girl B, referring to the National Institutes of Health. "She's a scientist."
>
> "Huh," said Girl A, "I hate science."
>
> "Yeah, well, you can't, like, pick your parents," said Girl B.[22]

Attributing the problems of science education to culture or to high-school education does not, however, relieve colleges and universities of the obligation to do their best to teach science. Such attributions are what Tobias described as the college educator seeing the problems as being "elsewhere" and so suggesting the reform happen elsewhere. However, judging by reported success of innovations in introductory college science courses, it is worthwhile to improve science education for undergraduates regardless of the problems occurring elsewhere.

But if innovative introductory courses ignite some interest in science and engender learning, why doesn't the success persist in the long run by producing more scientists? One reason may be that by itself, reform of the introductory science curriculum is insufficient. Students who succeed in innovative introductory courses find themselves in traditional courses at the second level. The innovations have not been extended up the curriculum. The weeding out has been postponed, but it has not been eliminated. Advanced courses—the canon of organic chemistry, cellular biology, advanced physics—may be difficult to make user-friendly. The negative characteristics of traditional introductory courses elaborated by Tobias (that the courses were hierarchical, competitive, isolating, limited by the "tyranny of technique") may still be there in the intermediate curriculum, robbing the students of the "creative and critical thinking that science also entails." Perhaps we need a pedagogy that restores the opportunities for this creative and critical thinking.

While science courses remain sharply focused on technique, the world flattens. Sobering forecasts about American science appear in *The World is Flat, Rising above the Gathering Storm*, as well as reports by the Academic Competitiveness Council and the Business-Higher Education Forum, and the *Test of*

Leadership, better known as the Spellings Commission Report.[23] The visions of these documents are, if not bleak, certainly anxious. In a world in which global competition is heating up, flattening, in Friedman's terms—and where the demand for those with science and engineering skills grows, the number of students gaining advanced degrees in science and engineering declines. In *Rising above the Gathering Storm*, a committee of the National Academies of Science sounded the alarm. The storm in the title is economic globalization. Historically, American economic success depends on technological innovations, and this level of technological innovation requires an educated workforce. But now, to quote the NAS committee:

> Thanks to globalization, driven by modern communications and other advances, workers in every sector must now face competitors who live just a mouse-click away in Ireland, Finland, China, India, or dozens of other nations whose economies are growing.[24]

Is the United States poised to meet this challenge? Apparently not. *Rising above the Gathering Storm* cites statistics revealing that half of Americans are dissatisfied with education; that performance of American teenagers compares unfavorably with that of their international peers; and that Americans are not as attracted to the engineering profession as are our international competitors. Worse, neither government nor industry is investing sufficiently in the kind of risky research that could produce huge discoveries. So what do the authors want? They want a future of economic well-being driven by the engine of invention and technological application. "Knowledge institutions" must produce innovations, what the National Science Foundation calls "transformative research," that will support American prosperity.

Finally, although its concerns are broader than science, the Spellings Commission report makes this observation regarding the shortcomings of American education:

> Fewer American students are earning degrees in the STEM fields [...] medicine, and other disciplines critical to global competitiveness, national security, and economic prosperity. Even as the Bureau of Labor Statistics projects that 16 of the 30 fastest-growing jobs in the next decade will be in the health professions, current and projected shortages of physicians, registered nurses and other medical specialists may affect the quality of care for the increasingly aging population of baby boomers.[25]

The connections between science education and economic well-being are well established. Changing introductory science courses, where that has happened at all, has not resulted in an adequate population of science-oriented students. What is a college or university to do?

Restraining forces

Institutions responding to the problems of science education use a common heuristic for reform. First, a committee is formed. Next, the local problem is identified. Solutions are proposed. Goals for reform are nominated and then opposed. The opposition appears to be unanswerable (no money, no personnel, no time), and so reform is postponed unless it is undertaken by a pioneer who tries to detour around the system. The process is reminiscent of a research demonstration by psychologist Kurt Lewin, who showed that young children separated from a desirable toy by a glass barrier pressed fruitlessly against the restraint in an attempt to get directly to their goal, then succeed by detouring around the barrier.[26] Lewin called the barrier a restraining force. The common restraining forces on reform are paralyzing dichotomies that may leave the institution in conflict. The list includes:

Educating the select vs. educating everyone. Are the pedagogies and programs that might cultivate an elite group of creative scientists and engineers (thus meeting the essential need for a STEM workforce) the same as those that may be employed to create a scientifically literate citizenry? Should we put our resources into cultivating undergraduate "all stars," hoping for a few outstanding scientists who meet the call for transformational research, or sacrifice resource-intensive pedagogies for general education?

Scientist shortage vs. scientist surplus. If science education is driven by the need for a supply of scientists and engineers in the job market, then reductions in the demand for scientists and engineers may undermine the effort to promote science education. Tobias noted that there may be pressures to limit the number of scientists. She wrote, "Mindful of the devastating effects of the oversupply of physicists in the 1970s, a situation which drove many good Ph.D.s permanently out of the field, many physicists tell me mournfully, 'there has never been a time when there were too few physicists.'"[27] *Rising above the Gathering Storm* included a contrarian opinion by R.J. Samuelson doubting the scientist shortage.[28] Should the job market even matter to undergraduates who show an interest in science, or is there significance to science education that goes beyond employment forecasts?

Creativity vs. accountability. Government committees contend we need to produce students who are unique, innovative, and creative, outcomes that are difficult to measure. Our government also tells us that accounting for student learning is essential, and best measured through standard tests emphasizing the homogeneity of education.

Too few vs. too many. There are too few students willing to go into science, either as undergraduate majors or as graduate students, but there are too many students in our introductory science courses for the instructors to employ innovative and time-consuming pedagogy. How do we increase the number of potential scientists in the pipeline while managing the scale of undergraduate science education?

Disciplinary vs. interdisciplinary. We need to teach more of the basic sciences, with required education in physics, chemistry, and biology. But the future of research and teaching may lie with the interdisciplinary, and with the interdisciplinary comes new tensions regarding the path of student education, the organized curriculum, and faculty evaluation.

Teaching vs. research. While university faculty, known for their research output, are admonished to spend more time teaching, college faculty, known for their teaching loads, are admonished to be more productive researchers. Teaching and research are treated as separate categories of professional activity, so more of one means less of the other.[29]

Most of the commission reports cited here are more detailed in their problem statements than in their suggested solutions. The theme of the solutions is to use money to push or pull harder at students so they continue to study science. In its recommendations for the “Best and Brightest,” *Rising above the Gathering Storm* suggests Undergraduate Scholar Awards of up to $20,000 annually to help students afford their STEM education (with the awards distributed based on test scores), and the creation of more graduate fellowships. This approach is time-honored; a committee appointed by Vannevar Bush to increase the number of students in science recommended in 1945 that the government provide 6,000 scholarships for undergraduates and 900 graduate fellowships in science.[30] The Academic Competitiveness Council recommendations include a call for more assessment of STEM education programs. The assessment of all education is taken up by the Spellings Commission, which highlights standardized tests that it recommends be given to college students to discern the “value added” of education.

None of these recommendations seems connected with what the various commissions and committees say they want: a cohort of creative, innovative, entrepreneurial scientists and engineers who will create or discover the next generation of scientific and technological products that will keep our country safe, bolster the economy, promote our health and well being, and transform our culture. The outcome of poor science teaching, according to Tobias, is that it undermines interest in the sciences and intrinsic motivation to pursue science. The second-tier population could succeed in science, but they are turned off. It is sobering to reflect that the two mechanisms proposed by government commissions for increasing motivation and interest in science, money and testing, are the very two mechanisms that some psychological research has shown to undermine intrinsic motivation.[31]

These six restraining forces stand in the way of reform, but is it possible to think of them in a different way, and find a means to resolve them? These restraining tensions co-exist in the same entities: universities, colleges, academic divisions, departments, and people. When opposing forces reside in the same place—when some department members wish to promote reform while others wish to conserve tradition, for example—it brings to mind the image of a battery, a device that simultaneously houses two poles of opposite charges. A question occurs. What sort of electrolyte, sometimes called an ionic solution, could be loaded into the battery to begin a flow of energy between the poles? One answer is promising: undergraduate students performing authentic scientific research are the ionic solution that releases the energy of science education.

Shifting the focus

It is time for a closer look at a common practice of undergraduate research in science education. Undergraduate research is challenging to define, appearing in many disciplines and in many flavors. We shall see that the benefits of an undergraduate research experience are complex and only recently enumerated. I also hypothesize benefits that go beyond students, that emanate from student activity, to faculty and to institutions. I will explore the argument that an undergraduate research experience contains the potential for a rich and multifaceted interaction between student scholar and faculty mentor. This interaction questions the traditional dichotomy between the professional roles of teaching and research and suggests ways in which academic institutions may be changed.

The underlying dynamic for this potential is development, the recognition that students are growing, becoming, engaged in self-discovery and self-authorship.[32] William Perry referred to such development as “students on the move.”[33] The developmental process powers student volition. This volition can make contact with undergraduate experience in science, setting the student in motion with energy that comes of their own interest in science. It goes by other names, including engagement, ownership, and involvement. It produces independence, creativity, and discovery.

What personal development does not produce in any direct way is an interest in joining a “workforce.” When we examine the benefits of undergraduate research, we need to set aside the purely vocational goal of producing STEM workers. When we think about the bigger picture—the future of the STEM workforce and the American way of life as portrayed in the numerous government and committee reports—we see that the active, developing student is not what the commissions and reports have in mind.

Consider the construct the government uses, “the STEM workforce.” The image of the “workforce” may be a residual concept, originating in Vannevar

Bush's report to President Truman on the future of science and technology after World War II. Bush appointed a committee headed by Dr. Henry Allen Moe to address the question, "Can an effective program be proposed for discovering and developing scientific talent in American youth so that the continuing future of scientific research in this country may be assured on a level comparable to what has been done during the war?"[34] The committee's response included exploiting the Selective Service law of the time. The committee recommended that soldiers who showed a talent for science "be ordered, by name, to duty in the United States as students for training in science and engineering of a grade and quality available to civilians in peacetime." The committee added, "It would not do to propose that such a plan should be done on a volunteer basis."[35] The original STEM workforce was a parallel to, and a subset of, the military force. A student's future in science was not to be discovered, it was to be conscripted.

Where is the appeal of such a construct to an undergraduate student? Young people are unlikely to desire to join an entity called "the STEM workforce." Indeed, adding "workforce" to any enterprise might dampen interest in joining. The very name undercuts the individuality that students feel and value as they journey toward their sense of identity. Consider also the values of entrepreneurship and discovery that are linked to this workforce in government reports. The heroes of modern technological entrepreneurship, such as Bill Gates or Steve Jobs, did not join the STEM workforce. The STEM workforce works for them.

The undergraduate research experience is considered the most direct path to a science career. A classic study of the personalities of eminent scientists was performed by psychologist Anne Roe.[36] Roe intensively studied biologists, physicists, and social scientists, noting that undergraduate research was a compelling influence on the scientist's career choice. "What decided him (almost invariably) was a college project in which he had occasion to do some independent research—to find out things for himself. Once he discovered the pleasures of this kind of work, he never turned back."[37]

But I suggest that the path is actually indirect. The goal society has in mind, the STEM workforce, appears to be straightforward but is really the refracted outcome. The direct outcome is personal development. Personal development, so thoroughly explored by Piaget, Perry, Chickering, and others, is the deep outcome of a research experience from which career choices stem.[38] We must characterize this development in the context of the undergraduate research experience. We must measure it and discern what it means. We must place it in the context of an organization where the mentoring faculty are also moving along a developmental path and where the subordinate institutions—departments—are evolving. In order to clear the way for the full benefits of undergraduate research, we must consider how undergraduate research helps faculty members develop as professionals and as mentors. We must consider how undergraduate research may be the glue that joins faculty collaborations across departments and the solvent that melts boundaries between departments. We need to see that if it is reasonable to accept the relation between undergraduate research and student learning, then it should be reasonable to accept the relation between research and teaching.

Undergraduate research in the sciences is a widespread practice, although just how widespread is not precisely known. Mervis[39] cites statistics indicating the number of students engaged in some type of research had risen 70% in the previous decade. Kuh, Chen, and Laird,[40] using data from the National Survey of Student Engagement, report that one in five seniors works on a research project with a faculty member outside of a course or program, with 39% of senior biological science majors and senior physics majors leading the way. Webb[41] reported NSF data indicating that 72% of chemistry majors have research experiences. Russell, Hancock, and McCullough[42] found survey respondents differed in their rates of research participation, from 34% in mathematics to 74% in environmental sciences. Just how many undergraduates have a research experience depends, of course, on the definitions used. Nevertheless, it is fair to say that undergraduate research is not a new idea. It is also fair to say that if undergraduate research is a powerful source of benefits to the student, there are not enough opportunities available.

Touting the benefits of undergraduate research is not a new idea, either. The National Conferences on Undergraduate Research (NCUR) and the Council on Undergraduate Research (CUR) collaboratively endorsed a statement supporting undergraduate research that included assertions of the benefits (Appendix 1).[43]

For all the work done to assess its benefits, there is still a sense that undergraduate research is a science department's window dressing, a vehicle for poster sessions and parents' weekend exhibitions. There is a perception that "undergraduate research takes place not in the designer's showroom of new ideas, but in the bargain basement of existing materials and methods."[44] Mentoring undergraduate research "places an extra burden on everyone involved," according to Chapman; or "many faculty members seem to view it as more of a burden than a benefit," according to Mervis. Undergraduate research is widely regarded as a student-centered experience, in the sense that students, rather than faculty or institutions, accrue the lion's share of the benefits. Because it is a "burden" and resource intensive, undergraduate research is rarely described as a significant part of a science curriculum. Rather, supporters of undergraduate research, such as PKAL, NCUR, and CUR, view undergraduate research as "reform."

Tobias, writing about two years after the second tier study, undertook to understand better the success of science education reform in *Revitalizing Undergraduate Science.*[45] Tobias reported on a series of case studies of science reform that did or did not last. Her criteria for success included successful recruitment of students, a high rate of retention, and high student and faculty morale. She concluded that successful programs were initiated through local commitment, usually through departments. Funding for the program made its way directly into instruction. The reward system favored improvement. She concluded, "The model for science education reform is not an experimental model, not even a research model, but a *process model* that focuses attention continuously on every aspect of the teaching-learning enterprise, locally and in depth."[46] Reform coming from a single individual with a strong belief in the ubiquity of his or her pedagogy, funded by external grants, and dependent on the dedication of a few volunteers in isolation from the larger community, did not survive.

How might undergraduate research help resolve the dyadic tensions I listed earlier in the chapter?

Educating the select vs. educating everyone. Because students from the second tier can successfully do undergraduate research and develop as scientists, undergraduate research blurs the distinction between the elite and the masses. Enlarging the scope of research opportunities, increasing the use of "research-like" experiences in course settings, or requiring a research experience for each student can expose every student to undergraduate research.

Scientist shortage vs. scientist surplus. The scientist shortage problem is under attack, recently by Lowell and Salzman[47] in their critique of *Rising above the Gathering Storm.* But the benefits of undergraduate research transcend arguments about too few or too many scientists and engineers. The benefits of undergraduate research are not strictly vocational. The personal development that results from an undergraduate research experience is broad enough to empower many career choices, enabling the student to become a member of what Richard Florida called the "creative class."[48]

Creativity vs. accountability. Undergraduate research, which sets the occasion for student creativity, invention, and problem solving, is more likely to meet the needs for an active STEM workforce than any passive pedagogy, even if it could be shown that the alternative promotes higher scores in standardized tests.

Too few vs. too many. The benefits of undergraduate research, which can be attained to some degree in groups that practice research within course settings, provide support for the argument in favor of allocating resources to smaller classes. Further, the undergraduate research experiences may occur at academic institutions, national laboratories, within international programs, or at industrial sites, and so increase the number and variety of research opportunities open to undergraduates.

Disciplinary vs. interdisciplinary. Undergraduate research can be the vehicle for explorations in interdisciplinary research and teaching. Undergraduate researchers, working with students from other disciplines and perhaps co-mentored by two or more faculty, may provide the leading edge of curricular change and community building. It may be in the arena of interdisciplinary research that students from the second tier rekindle their interest in science.

Teaching vs. research. Undergraduate research mentoring may be viewed as the "purest form of teaching"[49] with benefits to the mentor as a researcher and a developing teacher. The need for inductive teaching for researchers and the call for scientific teaching in the classroom induces a new opportunity for unity of the two forms of creative work.

We must investigate the benefits of undergraduate research to students, to faculty, and to institutions. We must fit the outcomes of undergraduate research with the goals set by government reports and commissions. As we explore this topic, it will be necessary to clarify related concepts such as student development and mentoring. First we turn to a description of the essential features of an undergraduate research experience.

2

The essential features of undergraduate research

I would rather discover a single fact, even a small one, than debate the great issues at length without discovering anything at all.
Attributed to Galileo

Defining undergraduate research

Because this book is about undergraduate research in the sciences, the term "research" is shorthand for scientific research, where the adjective "scientific" typically refers to the fields of biology, chemistry, physics, mathematics, engineering, and psychology. The National Science Foundation gives the following definition:

> Research means a systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge.[50]

This definition takes on more dimensions as we think about research at colleges and universities, which Boyer suggests could be divided into four categories. He points out in *Scholarship Reconsidered* that research can take the forms of discovery, integration, application, and teaching. The most familiar of these forms is the scholarship of discovery, which "comes closest to what is meant when academics speak of 'research.'" Boyer writes:

> The scholarship of discovery, at its best, contributes not only to the stock of human knowledge but also to the intellectual climate of a college or university. Not just the outcomes, but the process, and especially the passion, give meaning to the effort.[51]

This widens the NSF definition to include the effect that research has on the institution and on the people who undertake it. In a later essay, *The Student as Scholar,* Boyer commented that "the paradigm of scholarship might be appropriate not only for the professoriate but also for the students." He suggested a program in which professors "help undergraduates sort out their own intellectual interests" by involving students in research. "Further, every student, as a requirement for graduation, would complete a research project, working closely with a mentor."[52] Boyer, in short, invites collaboration between faculty and students. The Council on Undergraduate Research[53] makes collaboration central to its support of undergraduate students doing research. For CUR, undergraduate research is defined as "An inquiry or investigation conducted by an undergraduate student that makes an original intellectual or creative contribution to the discipline." More recently, Brakke asserted that "Undergraduate research is original work conducted by undergraduate students working in collaboration with a faculty mentor. As research, the intent is to provide new knowledge and requires the communication of results in written and oral formats."[54] Note that Brakke identifies "collaboration with a faculty mentor" and "communication of results" as essential features of undergraduate research.

These essential features were suggested by respondents to a short survey I undertook a few years ago. I posed this question to science faculty colleagues at three liberal arts colleges: "What are the essential features of undergraduate research projects?" The responses are given in Table 2-1.[55] The responses included references to collaboration and mentoring, as along with these other comments: "Students should strive to produce a significant finding" and "Students should have an opportunity for oral [or written] communication." The two elements are linked.

We can create an undergraduate research program that provides research mentors and requires a paper, talk, or poster at the end of the experience. But because many research projects, even those performed by professionals, fail to yield significant results, the element of producing a "significant finding" can only be made likely, not certain. And, to be meaningful, the paper, talk, or poster should have something significant to communicate. It might be argued that a more manageable approach to student learning would be to have the student reconstruct or rediscover a scientific finding that was already known. Indeed, some forms of inquiry-based learning follow this path. Fortenberry[56] suggests that "the only fundamental difference between research and inquiry-based learning is the prior state of knowledge of the broader community. In research it is unknown by all; in inquiry it is only unknown by the learner." In the constructivist approach to science education, the student is allowed to discover what the science community already knows—that some objects sink and some float, that pendulums behave in a certain way, and so on—with the intent that the construction of this knowledge will aid the student's learning. Constructivism is offered as an active learning strategy to promote retention and understanding of material. But authentic research includes the additional feature of contributing to generalizable knowledge or "knowledge production," and thus differs from other active learning strategies. The two goals of undergraduate research are student development and knowledge production. A few undergraduate courses or seminars have both these features, but undergraduate research should always have both.[57]

If producing new knowledge becomes one of the essential features of undergraduate research there is no need to differentiate between undergraduate research programs that focus on student development and those that focus on knowledge production. Student development in undergraduate research *depends* on knowledge production. Undergraduate research experiences set the occasion for discovery, and discovery sets the occasion for growth as the student researcher encounters the maturing process of communication, argument, and peer review. When the knowledge produced by research is truly new, not even a mentor can claim sole authority over it, and it can fall to the undergraduate to communicate, argue, and advocate for the discovery.[58] Veteran mentors of undergraduate researchers relate the moment when a student, having presented a paper or attended a conference, comes to the surprising conclusion that "I know more about my research than anybody else does."[59] Discovery as a feature of undergraduate research connects to self-confidence and creativity as benefits of undergraduate research. College students discover something about themselves: their competence or mastery of a domain.

Howard Bowen and his colleagues in their review of the value of higher education, *Investment in Learning,* present findings that personal self-discovery undergoes large increases in college, larger than increases in rationality or good citizenship.[60] Personal self-discovery about competence is private and is part of a continuous process that originates in childhood. Children are motivated to learn "in situations where there is no external pressure to improve and no feedback or reward other than pure satisfaction—sometimes called achievement or competence motivation."[61] In undergraduate research this intrinsic motivation is linked with the additional feature of producing new public knowledge. Now private satisfaction is complicated by encounters with external evaluators: mentors, peers, and the larger community. Piaget noted that after adolescents attain the level of formal reasoning, they begin sharing their self-discoveries publicly, forming opinions on music, film, politics, religion, and human nature.[62] They are moving from egocentricism to an awareness of community and are busy comparing what they know to what the community knows. They are ready for an intellectual challenge that moves beyond private belief to shared belief, and undergraduate research provides the opportunity for this kind of growth. The transition from private to public discovery implies that some features of undergraduate research—discussions with mentors and peers, effective presentations either spoken or written, reflective critique—are essential to this transition. By making a contribution to knowledge, undergraduates can advance their development toward independence. They are in a position to convince the science community of something new, rather than to conform to common knowledge.

To accomplish this task, they acquire the methodology of science. The methodological rules encourage the development of what King and Kitchener term reflective judgment, which includes the ability “to claim that the conclusions they are currently drawing are justifiable, believing that other reasonable people who consider the evidence would understand the basis for their conclusions.”[63] Children may be satisfied with a belief without reference to contradictory data, such as when they indicate that water poured from a short, wide container into a tall, narrow container has increased in amount.[64] Undergraduate researchers discover that they cannot support their hypotheses in the face of contradictory data. As Emerson once put it, “we must learn the language of facts,”[65] to communicate our discoveries to the world. The subject matter of the sciences includes precisely those worldly phenomena that defy our attempts to wish them away. Young children are egocentric, believing that the sky is blue because the child likes blue. The older adolescent’s encounter with science, where in the collision of fact and ego “the fact has the right of way”,[66] is a formative experience in maturation. The student learns to communicate new knowledge that is acquired within methodological constraints. So, both discovery and communication are essential features of undergraduate research, providing the discourse that Poincaré thought necessary for objectivity.[67]

Discovery in undergraduate research, already referring to private self-discovery and public discovery of scientific information, has another meaning: there is in science a *discovery process,* a creative but not entirely random approach to uncovering new knowledge.[68] Natalie Angier in *The Canon* quotes a number of prominent scientists who describe this process of discovery.[69] She writes, “I heard the earnest affidavit that science is not a body of facts, it is a way of thinking. I heard these lines so often they began to take on a bodily existence of their own.”[70] Some scientists have become reluctant to refer to this process as “the scientific method.”[71] Haack has compared the discovery process to solving a crossword puzzle. A new entry in the puzzle is both inspired and constrained by the context of previous entries. Wolpert, similarly, describes scientific creativity as “constrained by self-consistency, by trying to understand nature and by what is already known.”[72] Seymour and her colleagues see the adoption of the process as thinking and working like a scientist.[73] By whatever name, the process of guided discovery is an essential feature of undergraduate research.

Guidance is provided by the methodological rules of science and by the mentor, who models rule following and, on occasion, rule breaking. It is not surprising, then, that guidebooks for mentoring include advice about optimal undergraduate research projects. Mentoring would hardly apply to the supervision of a student whose only task was to wash dishes or clean cages. The selection of a project that involves discovery is essential to success. For example, to prepare faculty members and graduate students for their roles of mentor in undergraduate research, Handelsman and her colleagues have created a program for training research mentors. Advice about the research project is not separable from other advice about mentoring. Good research projects should:[74]

- have reasonable scope,
- be feasible,
- generate data that the student can present,
- not simply consist of cookbook experiments,
- have built-in difficulties that will be faced after the student has developed some confidence, and
- be multifaceted.

These elements get to the specific dynamics of the undergraduate research experience. While some of them, e.g., "built-in difficulties" may be challenging to plan, the list suggests that these essential features of undergraduate research optimize the learning experience for students. There is considerable overlap between the list in Table 2-1 and the elements listed by Handelsman, et al. Some essential elements are environmental (including adequate labs and instruments); some refer to the behavior of the research mentor; some to opportunities; some to student behavior.

None, however, refer to the qualifications of the student who will participate in undergraduate research. Although most undergraduate research programs have student application and selection procedures, it is not clear what kind of student will best profit from the experience. Reliance on previous course grades is risky; there are many anecdotes of students with modest grades blossoming in the research environment. Harold White related the story of two undergraduate research students who worked in his laboratory. One, an A student, "never did anything without my affirmation. He dreaded making a mistake and seemed incapable of exercising his own judgment on the data he collected." The other, a D student, "designed and modified his experiments, interpreted data, and functioned almost independently." Clearly, the grades of the students did not predict success in the research lab.[75]

Beyond grades, the issue of what a student needs to know before he or she attempts research is contested. It occurs in discussions of the advantage of working with younger students (who have not had the time to complete the curriculum) and of the challenges of interdisciplinary research (where some definitions of interdisciplinary expertise require prior disciplinary expertise). Willison and O'Regan provide one of the more thoughtful attempts to frame the issue.[76] They examine commonly known, commonly not known, and totally unknown kinds of knowledge, with the latter category including new contributions to knowledge, and suggest a systematic framework for scaffolding students to sophisticated research skills.

The varieties of undergraduate research experiences

In our earliest attempts to identify the essential features of undergraduate research, my student collaborators and I began by asking students to describe their routine work. Informally we found ourselves using three categories of experience—the employee, the apprentice, and the research fellow. The employee was a student hired to wash lab glassware, feed lab rats, or pull weeds in the greenhouse. The employee had no part in an actual research procedure. She read no literature, and authored no work. The apprentice was the most common kind of researcher, especially in the sciences. The apprentice earned a stipend and/or academic credit. She worked full-time in the summer, if possible, and participated fully in the research process. She read primary literature, discussed research with her faculty mentor and other members of the lab group, and collected and analyzed data. She was expected to present her findings publicly, as a poster or paper presentation.[77] The research fellow worked full time in the summer, communicating with a faculty mentor at regular periods. She most often worked in mathematics or in the humanities. The research fellow spent much time reading or thinking in solitude. The faculty member functioned as a counselor. Like the apprentice, the research fellow was expected to present findings, usually through a paper.

All three categories of experience have their uses and benefits, and over time a student might have all three. A work-study first-year student might become curious about research as a result of mere exposure to a science lab. A research fellow might benefit from the independence of his experience. It is the apprentices, however, that are most common in science undergraduate research. Apprentices work during the academic year, when they also do coursework, or during the summer when they do not. It is the summer apprenticeship that is perhaps the most dedicated and extended undergraduate research experience, and for that reason much of the assessment of undergraduate research is based on summer science apprentices.

Beyond distinguishing among these types of researchers, the models for implementation of undergraduate research programs are remarkably diverse. The Council on Undergraduate Research (CUR) has documented many models of them.[78] Every academic discipline has models to follow. Research is performed by first-year students and fourth-year students, by students in university labs and in industrial labs, in the United States and abroad.

A variable feature of undergraduate research is its duration. While summer may be the time for students to concentrate on their research, many programs either front-load the experience with prerequisite or preliminary work, while other programs provide follow-up experiences. Summer may be used for a period of active data collection, for example, when the researchers need to travel off-site to collect data, and the following fall term is used for analysis and communication. Sometimes a student participates in research for a summer, then returns for a second summer as a trained apprentice. The experienced apprentice is appreciated by faculty researchers; in addition, the trained apprentice may function as a group leader or a peer mentor. Recently, research programs have attempted to attract younger students and offer them extended research experiences over several years.

For anyone considering implementing an undergraduate research program, summer is an attractive option. For faculty at many institutions, summer is when teaching is discretionary. There is time to do research. Students have opinions about the summer as well. In recent years, I have offered students a survey that includes a comparison of summer and academic year research for those students who have done both.[79] Students completing the SURE AY (academic year) were asked if they had experience with both summer and academic year research. About a third of the students had both experiences. If they answered in the affirmative, they were presented with the series of statements shown in Figure 2-1. The students expressed their level of agreement with statements comparing their summer and academic year experiences. As can be seen, students find undergraduate research more interesting than courses, but they also report that academic year research is more stressful and difficult to balance with coursework. In numerous comments, students talked about having more time in summer to concentrate on research, while comments about academic year research referred to pressure, balance, and time-management challenges. Students also volunteered comparisons between research and coursework, often expressing greater interest in research and lamenting the lack of time for it. The student distinction between undergraduate research and coursework is reminiscent of a distinction that faculty make between research and teaching. Some faculty, as we will see, regard research and teaching as distinctly different activities competing for their time. Some students see research and coursework as distinctly different activities competing for their time. Only one student remarked, "My coursework was more interesting if I saw connections in my research (and vice versa)." It may be that undergraduate students are absorbing the faculty's fragmented view.

Another feature of undergraduate research has to do with the site of the research. Many science apprentices work on campus, but not all do. Science students may travel to other campuses to take part in a grant-funded opportunity, may work in industrial settings, or travel abroad.[80] The opportunity to travel to an exciting location can enhance the benefit of the experience. For students who travel to another university or college to do research, however, there may be a drawback. They are less likely to continue with the work when they return to their home campus.[81]

Procedural features of undergraduate research

As I mentioned in the introduction, the ROLE survey was undertaken to gather information about the essential features and benefits of undergraduate research. The following information is based on responses from a group of 384 science students, working at four liberal arts colleges for about 10 weeks in the summer, who answered questions about the features of their experience. Nearly all the students were in programs that assumed a full-time, 40-hour workweek. All students, working at primarily undergraduate institutions, worked directly with a faculty mentor and infrequently with graduate students or post-doctoral fellows. In addition, 73 undergraduates doing research in the social sciences or humanities completed surveys.

Contact and availability. In 2001 and 2002, I asked the students to report how many hours per week they spent in contact with their mentors. The results are summarized in Table 2-2. Chemistry students reported spending an average 15 hours per week in contact with their faculty mentors, although the data are skewed. Biology and physics students also reported spending considerable time with their mentors. Not shown in the table are the social science students, who reported about nine hours of contact time per week with mentors; and the humanities and fine arts students, who reported an average of about three hours. These differences are occasionally mistaken for an index of the work ethic of faculty. The chemist who spends the week rubbing elbows with student researchers in the lab mistrusts the literature professor who meets with a student one day a week. Of course, disciplines differ in their needs for contact time. One way of measuring the adequacy of contact time is to ask the student researchers if they are satisfied with how much time they have with mentors. Within two disciplines, biology and chemistry, student satisfaction moderately correlated with contact hours; however, for other disciplines there was no correlation between contact and satisfaction.[82] Contact time, to the disappointment of those who want all mentors to standardize their work, depends on the task. What's more, students occasionally complained about too much contact, writing comments such as, "I am frustrated to not have enough time on my own," and "I'm glad he is not around all the time. We can relax and just work."

One moderator variable in the contact time relationship is the availability of the mentor when he or she is not in contact with the student researcher. Availability, what Chickering and Reisser called "accessibility," signals an "institutional climate where talking with faculty members is legitimized."[83] Some research mentors make themselves available to students by inviting the students to call them, e-mail them, or to visit their office if the student needs help. Students tend to appreciate this availability, with more availability correlating with higher student satisfaction. Student appreciation for mentor availability was put nicely by a student's tribute to her mentor, an astronomer: "Even when he is asleep he is available."

Student input. There is a common perception that in order for a student to be fully invested in the research, he or she should design the project or have some input into its execution. One finding of the ROLE survey was that student-designed projects were relatively rare. About 57% of the science students reported that their research project was assigned by their mentor. Some 21% were given a choice of projects by the mentor. Only 5% of the students claimed to have designed the research project on their own.

The mentor's control of the research project makes sense. Imagine the chemist or physicist, working on a continuous research program with a specialized laboratory and expensive instrumentation, and the need to produce results to maintain funding (a professional obligation or their work). Such a scientist cannot allow student researchers to stray very far from the program's path. This is not to say, however, that mentors are authoritarian about choosing the student's project. Some student reports of how their research project was conceived are illustrated in Table 2-3. These roundabout attempts to balance the need for student input and the need to stay with the program reflect the mentor's understanding that student input is a significant element of undergraduate research. One faculty member told me that he gave undergraduate researchers a Hobson's choice, letting them think about various projects but gently guiding them to the one he wanted them to do. In many cases, however, student input is more genuine. Students do appreciate having input into a project. In the ROLE survey, students who had some form of input into the project reported greater satisfaction with their research experience than other students did.

Faculty-student interactions. A ROLE survey item attempted to characterize how faculty mentors worked with students. The five interactional styles are listed in Table 2-4. The most frequent style, learning by example, is consistent with the concept of apprenticeship. Disciplines that reported more contact time between students and faculty were also the most likely to report a learn-by-example style of interaction. Mathematics and Computer Science students, who had reported less contact time with faculty (Table 2-2), reported a "self-organized" style more than any other style of interaction.[84] Interactional style was not a diagnostic measure of student learning or satisfaction. Thus it seems, like contact time, to vary by discipline.

Working in groups. Many researchers feel that contemporary undergraduate researchers have an authentic experience if they work with peers, either as teammates or peer mentors. The variations in team structure are difficult to characterize. The student respondents in the ROLE survey were working together in the context of a single laboratory or under the supervision of a single mentor. If the study were to be replicated, it would need to take into account a wider variety of group work, including collaborations at a distance. The most interpretable response option is "I work alone." The ROLE survey found that only about 20% of undergraduate researchers worked alone. Student categorizations of working with peers are shown in Table 2-5. The SURE survey, undertaken after the ROLE project, posed a similar question to students working at over 100 institutions. About 25% of students reported that they work alone. Looking ahead to outcomes of undergraduate research, it is seldom the case that students assess their peers as a negative influence on the undergraduate research experience, although occasional problems such as "social loafing" and hostile peers are reported. Students completing the SURE survey have an opportunity to evaluate their student peers on a multiple-choice scale ranging from "one of the worst parts of the research experience" to "one of the best parts of the research experience." Reviewing over 5,200 cases collected over three years, I found that only 2.5% of the respondents characterized working with their peers as "one of the worst parts," while 37% characterized working with their peers as "one of best parts." Students who disliked their peers rated other aspects of their undergraduate research experience more modestly than other students. This discouraging result was largely independent of the way that students rated their mentors. Nevertheless, it raises the question of how a mentor supervises and interacts with an undergraduate research team. Mabrouk and Peters surveyed 126 undergraduate chemistry and biology students, many of whom reported working in teams. The results indicated that students working in small groups valued "nurturing" and "availability" in their research mentors.[85] Publications dedicated to mentoring seem to overlook the problem of mentoring groups.

Structural features. The term "structure" appears in various ways in the literatures of science, education, developmental psychology, and organizational psychology. In developmental psychology the term "life structure" was used by Levinson to characterize the efforts of an emerging adult to create a stable identity in work and life.[86] "Initiating structure" is a term used in some organizational theories to describe how a leader can create a framework for workers to become more productive. "Problem structure" or "task structure" is used both by researchers in cognitive development and organizational psychology to characterize a problem or task and its effects on human behavior. Structure influences the undergraduate research in at least two senses: Research mentors can shape the structure of the student experience, for example, by creating a work schedule; and the research problem itself can contribute to research progress and student development.

Initiating structure. Research in educational settings has examined structural issues such as course content, clarity of learning objectives, use of class time, and instructor preparedness. Structure items can be scheduled or programmed. Features of undergraduate research such as assigning tasks, setting a schedule, providing primary literature or requiring posters and papers can be built into the undergraduate research experience. They give the program its working structure. This sort of structure is the responsibility of the institution, usually through the research program director and the research mentor. It is correlated with what it means to be a mentor, and many "how-to" mentoring guides include structural items. In the ROLE survey I asked students to evaluate one aspect of structure, the work schedule. It was clear from preliminary conversations that research mentors employed more or less structured schedules during summer research. Table 2-6 illustrates how the students described the structure of their summer schedules. Of the five structures students reported, a schedule of research goals and meeting times was correlated with the highest student satisfaction; having no structured schedule was correlated with lowest student satisfaction.

Program activities, including learning opportunities for graduate school, for laboratory safety, for ethical conduct of research, are part of the structure of the undergraduate research experience. It has become more common for summer undergraduate research programs to have their own co-curricular features, helping to make explicit the behavior of scientists or the possibilities of a science career. In the SURE survey we routinely asked students about some of the more common of these activities or affordances such as housing or social events. Some recent data on student evaluations of these activities are given in Table 2-7.

The relation of these activities with student-reported learning gains is straightforward. The correlation between ethics instruction and student reported gain in learning about research ethics is about .45; final presentations of research, either written or oral, are correlated with gains in science writing and oral presentation skills at about .40. Learning community ratings correlate with a program of social activities (r = .35). Career path clarification ratings correlate with ratings for seminars at which local or visiting scientists discussed their research (r = .26).

Other components, such as housing and food, do not correlate with learning but do lead to student comments, especially comments of dissatisfaction. When students spend a summer doing research, housing and food, along with other problems of living, seem to function as what Herzberg termed "hygiene factors."[87] That is, the absence of convenient housing or good food can be dissatisfying, but their presence does not produce high satisfaction. Rather, they may be taken for granted.

A second sort of structure has to do with the research problem itself. Problem structure plays a role in critical thinking and reflective judgment. According to King and Kitchner, well-structured problems can be described fairly completely, can be solved with a high degree of certainty, and evoke high agreement on the correct solution. Unstructured (or ill-structured) problems cannot.[88] King and Kitchner believe that unstructured problems provide the occasion for student epistemological development. Mature reflective judgment requires the ability to make reasoned arguments in an uncertain world. Well-structured problems tend to reinforce the conception of the world as a place where there are clear answers, and so provide no catalyst for development. While King and Kitchner examined the structure of problems for their effect on student epistemological development, the organizational psychologist Frederick Fiedler made a similar distinction in the context of management. He defined a structured problem as possessing verifiability, good clarity, goal-path multiplicity, and solution specificity.[89] Unstructured problems do not. He wrote that a manager cannot force a group of workers to perform well on an unstructured task such as developing a new product or writing a good play. In selecting research problems for undergraduates there is a tension between choosing a problem unstructured enough to provoke student development and a problem structured enough to allow for a clear solution in a reasonable time. Research supervisors, who have schedules to keep, may prefer structured problems. The occasional observation that science students do not show evidence of improvement of reflective thinking may be a consequence of science research (and courses) too cut and dried for encounters with unstructured problems. Wieman observes that students in well structured physics courses have more novice-like beliefs after they complete the course than when they started.[90] In one of our on-campus research efforts, my student colleagues Kate Guica and Marie Liska found that about 75% of our science undergraduate researchers characterized their research problem as well-structured[91] while only about 25% of social science and humanities students characterized their research problems as such. Of course, not all research problems remain either unstructured or well-structured. One of the tasks of the research mentor is to help a student structure a problem sufficiently. As Kennedy writes, “Criticizing with respect and turning a poorly structured question into a good one are among the skills that good mentors are able to utilize regularly.”[92] The research mentor’s challenge in providing opportunities for undergraduates, then, includes selecting problems along the dimension of unstructured to well-structured. Structuring the research problem may become more significant in the future, when interdisciplinary problems become more common. Interdisciplinary research in science consists of problems that are less structured than disciplinary research, and so offer the potential of enhancing cognitive development.

Communication

As mentioned, effective presentation and reflective critique of scientific results are essential features of the undergraduate research experience. The most common form of presentation is the poster, usually presented on campus at a celebration or research meeting; the spoken paper is next most common, followed by the written paper. In our experience of surveying undergraduate research programs nationally, we have found that virtually all programs include some form of presentation. Professional presentation, meaning presentation at a professional meeting or publication in a peer-reviewed journal, is less common (about 8% of all presentation types) and more delayed. The probability of publication is related to the probability that the student was involved with finding a scientifically significant result. Results do not fall neatly into the time frame of a single research experience, and they often have to be shared among many researchers. Nevertheless, publication in a peer-reviewed journal benefits both the student and the faculty mentor. A publication is the return on the undergraduate research investment for a faculty mentor who is concerned about publications for tenure and promotion.

The essential features of a successful undergraduate research experience vary widely. Organizations such as the Council on Undergraduate Research, through their *Quarterly*, have highlighted many models of research programs appropriate for varied institutions. Implementation or adaptation of existing models means that the research program wheel no longer has to be reinvented. The value of the experience is in the benefits that may be observed. The variety of these benefits is examined next.

Table 2-1

Faculty responses to the question, "What are the essential features of undergraduate research projects?" Items are a composite of responses from three institutions. *Adapted from Lopatto, 2003.*

Students should read scientific literature.
Students should design some aspect of the project; students should have an opportunity to design and conduct the research; opportunities should exist for exploration of the student's ingenuity and creativity.
Students should work independently (of faculty) and have an opportunity to work on a team (of peers); establish a mentoring partnership between student and faculty.
Students should feel ownership of the project; there should be increased independence in the daily routine and problem solving.
Students should use careful and reproducible lab techniques; there should be a mastery of the techniques necessary to the research.
Students should have an opportunity for oral communication.
Students should have an opportunity for written communication.
Students should have a meaningful or focused research question.
Faculty should provide some structure to the experience.
Students should strive to produce a significant finding.
There should be a good (state-of-the-art) environment.
Students should have an opportunity for attendance at professional meetings.
Students should earn pay or credit.

Table 2-2

Mean and median weekly contact hours between student researchers and their faculty mentors.

Discipline	Mean	SD	Median
Biology	11.5	10.2	7.5
Chemistry	15.2	11.3	10.0
Physics	9.5	8.2	7.5
Mathematics	6.3	4.0	5.0
Computer Science	5.8	6.4	3.0
Engineering	5.8	2.9	5.0

Table 2-3

Sample student responses to the question, “Who conceived of the project?”

The professor found a problem in a math paper and gave it to me to do.
Professor had two projects and let me choose which one I wanted to do.
It’s not the professor’s continuing research. I came up with it on my own, but I had lots of help from my adviser and my group.
[The project] is the professor’s idea, but I decide how to do it.
It’s my own project, but it relates to the overall project.
We were told what we want to do but not the way to do it.

Table 2-4

The proportion of student respondents who characterized their interaction with their mentor in one of five ways.

Interaction	Proportion
Learn by example: My mentor showed me or my group) how to do the work and then I (or we) did it.	41.0%
Self-organized: I (or my group) did all of the work on my (our) own.	24.0%
Executive: My mentor gave written or oral directions and I (or we) did the tasks.	15.8%
Division of labor: My mentor and I or the group) allocated tasks and then worked on them concurrently.	11.8%
Collaboration: My mentor and I or our group) did all the work together.	7.0%

Table 2-5

Proportion of students working with other students or alone during summer undergraduate research.

Response	Proportion
I work alone or alone with my research mentor).	19.6%
I work alone on my project and I meet with other students regularly for general reporting or discussion.	30.7%
I work with other students in a shared laboratory or other space, but we work on different projects.	26.3%
I work with a group of students, all working on the same project.	11.9%
I work alone on a project that is closely connected with projects of other students I consider to be in my group.	11.4%

Table 2-6

The varieties of structure set by mentors and the proportion of students reporting experiencing each.

Structure	Proportion
The mentor did not set a structured schedule.	21.2%
The mentor set a rough schedule, for example, to meet research goals over the summer.	37.6%
The mentor set a schedule of research goals and meeting times over the summer.	24.3%
The mentor set a structured schedule, for example, including research goals, meeting times and work hours.	15.0%
The mentor set a very structured schedule, for example, including research goals, meeting times, work hours and make-up hours.	1.0%

Table 2-7

Students rated seven program components often found in summer undergraduate research programs. The scale provided ranged from 1 (not useful or enjoyable) to 5 (terrific). Resulting means and medians are reported. Sample size is reported as some students did not have the program component and could not evaluate.

Program Component	Number of responses (% of cohort)	Mean	Median
Preparing an application or writing a proposal at the start of the project.	1,459 (72%)	3.54	4
Seminars at which a local or visiting scientists talked about their research.	1,520 (75%)	3.82	4
Seminars on safety in the laboratory.	1,495 (74%)	2.73	3
Instruction and discussion in ethics.	1,196 (59%)	3.21	3
A program of social activities.	1,544 (76%)	3.71	4
Housing/food provided on campus.	1,400 (69%)	3.73	4
Final presentation of summer's work, either a written report, platform presentation, or poster presentation.	1,783 (88%)	4.12	4

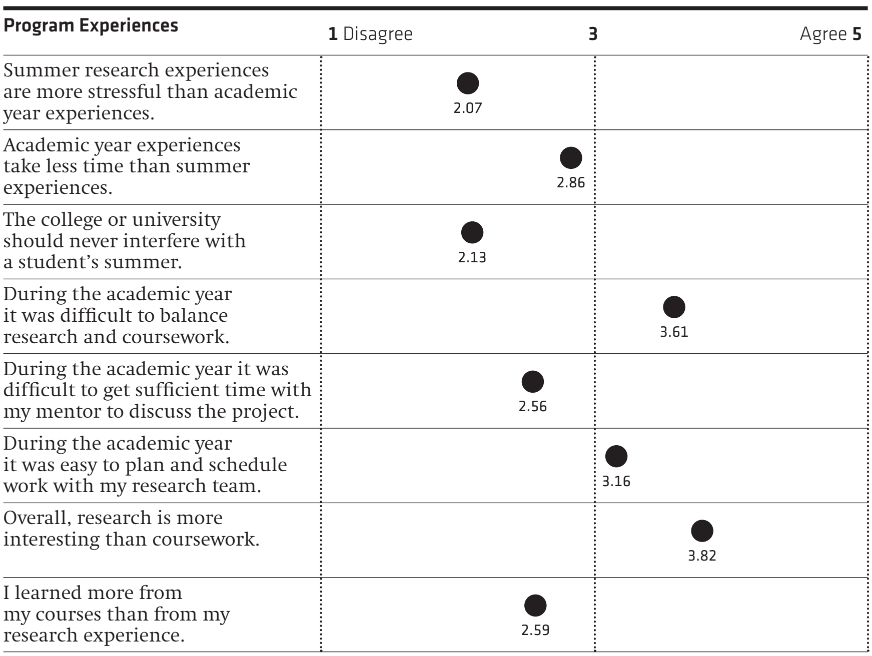


Figure 2-1

Student comparisons of summer and academic year research (1 = strongly disagree; 5 = strongly agree). Ninety students contributed data.

3

The benefits of undergraduate research

It is not so very important for a person to learn facts. For that he does not really need a college. He can learn them from books. The value of an education in a liberal arts college is not the learning of many facts but the training of the mind to think something that cannot be learned from textbooks.
Attributed to Albert Einstein

Consensus over the benefits

A student begins a 10-week summer undergraduate research program in biology. The first few weeks she is closely supervised as she reads primary literature related to the project and learns the appropriate staining techniques for cell cultures she will examine. As she becomes more adept at lab techniques, her mentor supervises her less. About four weeks into the project a shipment of cellular material ordered from a biological supply firm arrives spoiled; someone neglected to keep it frozen. The student endures this setback, as well as a failure of a cell staining technique and an unscheduled electrical blackout during some crucial lab work. Near the end of the 10 weeks she obtains some results, and with little time to spare, analyzes the data and prepares a poster for a college-wide poster session. The results make a new contribution to scientific knowledge. Although the summer program ends, the student resolves to contribute to a publication during the fall term. She also feels that she can do science, that she loves her work, and that she will apply to graduate school.

The challenge of naming the benefits of undergraduate research stems from the complexity of the experience. Undergraduate research, done well, engages multiple dimensions of a student's cognitive, behavioral, and attitudinal skills. Task-specific learning about instruments and methods cascades into active hypothesizing and procedural troubleshooting that result in the accumulation of self-confidence and independence that help shape the student's vision of her future. The whirlpool of outcomes mixes value added with value expressed, that is, mixes the guided acquisition of expertise with the discarding of the fear of expressing ideas and hypotheses. In an experience where assimilation and accommodation occur rapidly, it is significant that most undergraduate researchers enter their experience with a tentative scheme to make a career of science or medicine. Some observers deplore a state of affairs wherein most students applying for a science research experience have already tentatively identified themselves as scientists, physicians, or engineers. Indeed, my data from several thousand students indicate that only about 4% are first drawn to a science career by their undergraduate research experience. A similarly slim margin abandons this plan after doing research. No experience, however, can fully be assimilated without some prior scheme through which to interpret that experience; and what's more, it is unlikely that students who do not have a plan for a science career would invest their time in an experience they identify as unrelated to their vocation. The observation that a student will not enter into an undergraduate research experience unless she had a motive to do so is obvious, yet it leads to frustrations for program directors, who seek new ways to coax students into science, and for assessment researchers, who seek appropriate comparison groups for undergraduate researchers.

When we began to research the benefits of undergraduate research we turned to the experts who knew the most about it: the faculty. In an early attempt to triangulate ideas about student benefits, we asked science faculty at three liberal arts colleges to answer the question, "What are the benefits that students gain as a result of doing undergraduate research projects?" The responses are listed in Table 3-1.[93] Only one of the items addresses the possible career advantage of undergraduate research (Develop an orientation toward future work and education; clarify career plans). Twelve other benefits do not relate to careers. In fact, faculty comments about undergraduate research tend to be more about the cognitive and attitudinal gains that students might obtain, rather than professional or career gains. Scientists speak of their vocation with some emotion, as the professor who wrote:

> I hope that they will come to understand the joys of scientific research: dealing with a rational universe, the joy of discovery, the delight of challenging your intellectual abilities, the rewards of working with an international community of scholars and the satisfaction of coming to a solution to a long troubling intellectual problem.

That is what faculty members say. What do students say? When the ROLE research was undertaken, there were numerous testimonials to the value of the undergraduate research experience, especially in finding a science vocation, but there was little in the way carefully collected data on these benefits. Our approach was a mixed methodology designed to triangulate the benefits to students of undergraduate research experiences. We made some decisions to reduce the messiness of the problem. We studied summer research students in the sciences, concentrated largely on rising seniors, and collected qualitative and quantitative data at four institutions that had recently been acknowledged for their excellent undergraduate research. Seymour interviewed 76 undergraduates and carefully coded the statements they made about the benefits of undergraduate research. I drew from her first reports and from the literature to construct a survey with no fewer than 45 possible benefits, each to be quantitatively evaluated by the student. For two summers, dauntless undergraduate researchers completed the survey. Finally, we were in a position to look at the patterns of qualitative and quantitative results. My summary of Seymour's classification of the benefits of undergraduate research to students is given in Table 3-2.[94]

The order of the benefits in Table 3-2 reflects the frequency of the observations in the category. Personal/professional gains and "thinking like a scientist" were most frequently mentioned. The findings are robust. They triangulate well with both the quantitative measures of student-reported benefits and with parallel interviews that Seymour conducted with faculty.[95] The quantitative data were collected over two summers at the same four liberal arts colleges where Seymour had conducted her interviews, but with a different sample of students. A list of 45 possible benefits of undergraduate research was constructed, and students were asked to rate their gain on each item on a scale of 1 to 5. The data were then factor analyzed, with the result that appears in Table 3-3. It seemed to me that the items clustered in a way that resembled Seymour's categories, with the exception that the skills category had several subcategories. As an exercise in aligning the two sets of results, I drew the diagram in Figure 3-1. The categories from the qualitative analysis and the factors from the quantitative analysis align well.

A review of the benefits of undergraduate research exposes two interesting observations: first, that the benefits of the undergraduate research experience are rich and varied; second, that the relationship between undergraduate research experience and a STEM career is not as simple as one might suppose. In both the qualitative and quantitative results, preparing for a career in science is not identical to understanding the work of professionals. In addition, there is a dimension of personal development (including a sense of accomplishment and a gain in self-confidence) that conjoins with professional development toward science or liberates the student to take another life path. Undergraduate research has direct implications for the future of the STEM workforce, but the relationship between undergraduate research and the STEM workforce is complex.

Undergraduate research and the STEM workforce

It is firmly set in the collective minds of government and academia that an exposure to a good undergraduate science research experience will lead automatically to a career in the sciences. Government grants are predicated on this hypothesis; academic scientists, influenced by their own love affair with research, endorse it. The "mere exposure" view of undergraduate research goes back at least to the work of psychologist Ann Roe, who wrote of the scientists she studied, “What decided him (almost invariably) was a college project in which he had occasion to do some independent research—to find out things for himself. Once he discovered the pleasures of this kind of work, he never turned back.”[96] The “mere exposure” view has been reinforced by reports of the number of undergraduate researchers who go on to science graduate programs or into science-related work.

These numbers are impressive, but there is a confounding factor: selection. Undergraduate research opportunities have traditionally been offered to older students, juniors and seniors who already had declared a science major and who sought to enhance their credentials for graduate school applications. About 75% of the students who responded to my surveys were juniors or seniors. There is a second selection factor as well: most students beginning an undergraduate research experience already have the intention of going on in science. My survey data indicate that about 90% of students doing summer research have an existing plan to continue in science, and the plan did not change as a consequence of the experience. Relatively few students—about 4%—discovered a possible career plan as a result of undergraduate research. These recruits are offset by a similar percentage that became discouraged and did not continue in science. The 90% figure is not far from findings related by Tobias that 80% of Ph.D. scientists and engineers surveyed reported that they decided on a career in science or engineering before completing high school.[97] The intentionality of undergraduate researchers influences more than self-selection; there are program directors who believe that allocating a research position to a student who has not pledged to go on in science is a waste of resources.

Pre-existing intentions of students and faculty complicate the issue of how well undergraduate research compels a career in science. Seymour found no evidence that undergraduate research experiences led directly to choices for a particular career.[98] Russell and her colleagues, on the other hand, surveying students who participated in NSF programs, found a more optimistic result: 68% of her respondents reported an increased interest in a STEM career.[99]

Novice students

If older students have already decided to go on in science, then perhaps the needs of science and of the STEM workforce may be better met if younger students are involved with undergraduate research. The rationale is that younger students have not yet learned to avoid science or to make life decisions that exclude science. Perhaps there is a true yield of younger students to science, students who in the absence of a significant experience would have chosen the social sciences or humanities. Although offering undergraduate research opportunities to younger students (first-year students or even newly-admitted students) is becoming increasingly popular in undergraduate research, I have no evidence that the tactic is effective in increasing the number of students who go on in the sciences.

There are two complementary reasons for this null effect. First, some decisions are already made before college, as reported above. At my institution I routinely have asked undergraduate researchers when they first became interested in their field of study. The majority reply that they chose the field before they entered college. My most recent local survey resulted in 71% of the sample reporting they were interested in their field before college. Of these, 37% reported they were interested in their field before high school. So backing up the research experience to the first year does not necessarily capture students before they have made decisions regarding their interests.

Second, the further we regress the age of undergraduate researchers, the more likely we bump up against the "degrees of freedom" problem. That is, younger students are not ready to commit to a narrow academic or career path. They wish to engage in many diverse experiences, including exploring other disciplines, traveling abroad, and sampling extra-curricular activities; experiences that Tobias referred to as "discover other loves."[100] Furthermore, most institutions, through their commitment to liberal education and their structure for general education, promote a breadth of education that is incompatible with early specialization. The preservation of degrees of personal freedom has been identified as a fundamental process of development. As psychologist Daniel Levinson noted, a young person has "two primary yet antithetical tasks...to keep his options open, avoid strong commitments and maximize the alternatives" versus "to create a stable life structure... and make something of [his] life." [101]

If most students are already planning to go on in science, isn't a research experience a waste of resources with respect to encouraging a science career? I believe the answer is no. First, students who might provisionally think about a science career do not know the specific sub-disciplines and research areas of the sciences. Through research, students who initially thought they might go on in science learn that they are more attracted to developmental biology than genomics, to neuroscience than to chemistry, to biophysics than to astronomy. It is difficult to get a handle on the kind of career differentiation that goes on, but my experience is that such differentiation is part of the ethos of undergraduate research.

One clear finding stands out: students who initially thought of themselves as pre-medical students migrate toward science Ph.D. programs. My most recent data indicate that of the students who initially planned to go to medical school, about 15% change their plans in favor of a science Ph.D. Fewer than 4% migrate in the opposite direction. Second, undergraduate research has the benefit of adding to the student's credentials for being admitted to graduate school, so the experience has instrumental value in continuing the student's career trajectory.

There is one more benefit of early experience that may be simply put: a research experience helps one to be a better student. A majority of students report positive changes in their classroom behavior after a research experience.[102] The presence of undergraduate researchers in a science course after they have had research experience may enhance the course. The effect of experienced undergraduate researchers on subsequent science course behavior is one of many questions to be explored through assessment.

Experienced students

If most undergraduate students have made up their minds about a STEM career, or at least have made provisional decisions that are not changed by an undergraduate research experience, what is the value of recruiting the student for a second research experience? The answer to this question is often selfish. A faculty researcher, by having the student in the lab a second summer or throughout the year, gets a good (and cheap) worker. Needing less training, the worker becomes more productive and more research gets done. The undergraduate has already joined the STEM workforce.

What is the value of the continued experience to the student? When I asked students to complete the ROLE survey at four institutions, they identified themselves and their research mentors. In a two-year period, 28 students completed the survey in two consecutive summers. Among the survey items was a list of learning gains on which students could rate their perceived gain on a scale of 1 to 5. For some learning gains, the mean ratings did not differ much from the first year to the second. But those that did are suggestive of the differences in the experiences (see Figure 3-2). The learning gains rated higher in the first year seem consistent with a student's first experience of undergraduate research. These students were in science labs, and their gains were either related to their early training (lab techniques, instruments, safety, and ethics) or an assessment of their emotional maturity (more tolerant of obstacles and ready to do more research).

The learning gains rated higher in the second year also were reasonable. Second-experience students were more expert at finding and reading primary literature, had more opportunities for publication, and had more opportunities for presentations of research. They felt a greater sense of accomplishment (a sensible reaction to looking back at two summers of work) and had leadership experience.

Leadership experience comes with being the oldest or most experienced student in the lab. On occasion, the leadership role is formalized by designating the experienced student as a peer mentor with responsibility for training or supervising a less experienced student. The current SURE survey has a series of questions about peer mentoring. Over a 2-year period, 143 student researchers identified themselves as peer mentors. They answered a series of questions about their experience (Figure 3-3). Generally, peer mentors gained a greater appreciation of their own research, gained confidence, and enjoyed their responsibility. When these peer mentors evaluated their learning gains from undergraduate research, they typically scored higher than the average student, giving some credence to the old saying that the best way to learn is to teach (Figure 3-4).

Why undergraduate researchers leave the science path

Much has been written about why students leave the sciences. My research is focused more narrowly: why would a student who has experienced undergraduate research decide against continuing with science? There are two groups of students who discontinue their pursuit of a science career following an undergraduate research experience: students who are put off by it, and students who gain insight into themselves and see that scientific research is not for them.

Students put off by their undergraduate research experience occasionally allude to the monotony of the research, as one student put it,

> Most importantly, I gained understanding of the tediousness of research, and gained respect for the researchers who do it. I also reaffirmed my decision that I do not want to work in a lab my whole life, and that I do not want to be behind a desk my whole life. I do want to be challenged, as I was doing research, but I also want to have more contact with other people.

Another student wrote,

> I enjoyed my research experience immensely; however, experimental physics is not for me! Too much time alone in a dark lab! I'd rather be teaching.

But more often the student expressed disappointment with his or her mentors:

> I think my graduate student was too busy with his own project to assist me in any significant way. My research mentor was horrible, and showed no interest in my thoughts, ideas, or experiments.

> My professor seemed to forget how to relate to undergrads and even tended not to give us as much work. When deadlines didn't allow for even the slightest mistakes, I pretty much did menial tasks or just sat around reading papers and such while a grad student did the work.

Good mentoring is an essential element of undergraduate research, and the failure of the mentor is the most acute reason why dissatisfied students leave.

Other students leave, not from unhappiness, but from achieving insight:

> The most important part of the research experience was doing the research that I've never been able to do before. Before working in a research lab, I was sure that I wanted to obtain a doctorate in biology. Now, however, I see that this is not what I really want, and I thank the Howard Hughes program for saving me much time and money.

> The entire experience itself was most important. In my case it helped me realize that I do not want to pursue a postgraduate education in the natural sciences, which is an extremely important decision. The research experience was without a doubt, worthwhile.

> The greatest benefit that I derived from summer research was the knowledge that science research is not for me. Despite the fact that I disliked research, I found the experience very rewarding. Without such a comprehensive and accessible research program, I might have made the mistake of going on to grad school for science.

These students' personal development in self-confidence and independence resulted in both the insight about their compatibility with a science career and their courage to face this fact. Both self-confidence and independence are benefits of the undergraduate research experience. Despite their departure from a science career path, these students have accrued benefits of undergraduate research that may influence how they think about the world regardless of their career.

Personal development

Personal development benefits from undergraduate research experiences include the growth of self-confidence, independence, tolerance for obstacles, interest in a discipline, and sense of accomplishment—features of student maturation that are "seen out of the corner of the eye." Throughout the efforts to measure student benefits these outcomes have been reported by undergraduate researchers. Professors at liberal arts colleges, perhaps uneasy over the vocational nature of government reports on science education, should take comfort in the observation that the benefits of undergraduate research go beyond mere skill training. In fact, as we have seen, a high degree of independence and self-confidence may be necessary to face the decision to leave a science career path. Students comment on these gains:

> It was a great feeling moving from a relatively dependent stage to an independent one. I look forward to learning more and becoming more independent.

> My research experience fortified my self-confidence in the lab such that when I took laboratory courses in successive semesters and decided to move on to a higher level project in another lab, I was prepared, motivated and confident about working independently.

> My summer research helped me gain confidence in conducting independent work. I now feel like I know how to do research like "real scientists" do.

> This summer primarily involved trouble-shooting. It taught me tolerance for research and frustration and skills in research troubleshooting.

> More than any other experience in research, I learned that research needs patience and the ability to overcome obstacles.

> *The research challenged my determination, pushing me to new levels of creativity, comprehension.*

These personal benefits are the result of the essential features of a good research experience: projects that have built-in difficulties, independent work opportunities, and ownership of a project. As short-term outcomes of an undergraduate research experience, they may result in changes in student behavior as the student goes back into the classroom to continue the curriculum. Students who participated in undergraduate research reported nine months later that they were better able to think independently and formulate their own ideas, had become more intrinsically motivated to learn, and had become more active learners. These long-term changes in student behavior provide the precursors to the talents looked for in the future STEM workforce.

Precursors to professional success

Students graduate, and years may pass before they decide on their vocation. College and university faculty, eager to show that their programs produce successful graduates, are frustrated by their inability to tie undergraduate programs to a student's success in later life. The best they can do is measure the proximal outcomes of their programs, whether it be through exit tests, senior surveys, or student plans. When government commissions call for a successful STEM workforce, the university cannot guarantee that result. Experts call for creativity in science research, but other experts contend there is a "10-year rule" for experience and preparation to result in creative achievement.[103] So short-term assessment of distant goals is difficult to do. What can be done, however, is to examine what proximal outcomes might be a precursor of distal goals, and then to examine if current programs produce them. Recalling the various government reports from Chapter 1, it seems that the distal outcome is not just a STEM workforce, but a STEM workforce that produces innovation, invention, and entrepreneurship. The ideal STEM worker described there is a creative person capable of independent ideas and the self-confidence to express them. Respondents to my surveys reliably report gains in independence and self-confidence. The gains are similar to those found in successful scientists. In his study of Nobel Prize winners, sociologist Robert Merton noted that "the laureates exhibit a distinct self-confidence.... They exhibit a great capacity to tolerate frustration in their work."[104] Both gains in self-confidence and gains in tolerance for obstacles are routinely reported by undergraduate researchers. Reports of these gains are exhibited in quantitative surveys, qualitative interviews, and volunteered comments. Faculty commentators agree these benefits occur for students.

Three precursors are worth examining in greater detail: communication, creativity, and cognitive development.

Communication. One of the essential features of undergraduate research is the opportunity to communicate scientific findings and reflection to an audience, whether it be as a published paper, a presentation, or a poster. In an effort to understand how widespread the requirement for communication is, I offered a follow-up survey to students who had completed the SURE survey in 2003 and again in 2004. Of the original group of 2,021 respondents, 628 answered questions about their research nine months after the summer experience. The follow-up period allowed for students to complete papers, present posters, and write manuscripts for publication. The students reported all the communication activities they had completed. The frequencies of these activities are shown in Table 3-4. Presenting posters and giving talks on campus were the most frequent means of communication. Some students engaged in more than one activity. The number of communication activities seems to have a cumulative effect on student ratings of learning gains in science writing and oral communication (see Figure 3-5).

Creativity. We cannot measure creativity but we can set the occasion for it. Gardner and of Csikszentmihalyi describe creativity in terms very similar to my description of discovery in Chapter 2. One of Gardner's *Five Minds for the Future* is the creating mind, and he cautions against the risk posed by too narrow an education for cultivating creativity. "Options need to be kept open—a straight trajectory is less effective than one entailing numerous bypaths, and even a few disappointing but instructive cul-de-sacs."[105] Gardner worries that American education is becoming too conservative, relying on "uniform curricula, tests, and standards" that act against the cultivation of creativity. Undergraduate research experiences are not like that; they are certainly not uniform, and they permit or encourage creative thinking.

Csikszentmihalyi described creativity as occurring in a system that includes an idea that "must be couched in terms that are understandable to others, it must pass muster with experts in the field, and finally it must be included in the cultural domain to which it belongs."[106] The translation of these features into the process of undergraduate research is easy: undergraduate researchers need to learn how to communicate in their field; their ideas must be submitted to peer review; and their findings must make contributions to the field of science, mathematics, or engineering in which they do their work.

According to Csikszentmihalyi, it is not sufficient to be privately creative. "A child might possibly learn mathematics on his or her own by finding the right books and the right mentors, but cannot make a difference in the domain unless recognized by teachers and journal editors who will witness to the appropriateness of the contribution." The supporting characteristics that the environment provides to the creative person, described by Csikszentmihalyi, resemble the elements of an undergraduate research experience: training, expectations, resources, recognition, hope, opportunity, and reward.

Although creativity in later life is not predictable, I observe that good undergraduate research experiences produce high levels of satisfaction in students as well as gains in readiness for more research experiences. We might loosely interpret this result as "openness to experience," a construct used by psychologists in the measurement of personality.

Openness to experience, one of five quantitative factors employed to describe personality, is defined as "intellectual curiosity, aesthetic sensitivity, liberal values, and emotional differentiation" by McCrae.[107] The phrase openness to experience is attributed to psychologist Carl Rogers, who used it in his 1961 book *On Becoming a Person.* Rogers defines openness to experience as a "lack of rigidity and permeability of boundaries in concepts, beliefs, perceptions, and hypotheses."[108] It includes a tolerance for ambiguity and is an essential ingredient in creativity. Several researchers, including King, Walker, and Broyles have demonstrated correlations between measures of creativity and measures of openness to experience. While openness is often portrayed as a personality factor the reality may be that experiences such as undergraduate research lead to a readiness for more experiences, and thus provide occasions for creativity.[109] A similar line of research on positive emotions shows that positive emotions "broaden habitual modes of thinking."[110] It may be that the high degree of satisfaction or enthusiasm for the undergraduate research experience is a contributing factor to future creativity.

The precursors of creativity provided by the undergraduate research experience mean that science students not only qualify for the STEM workforce, but also qualify for Richard Florida's "creative class," which Florida asserts constitutes about 30% of the American workforce.[111] The creative class includes more than scientists and engineers, it includes any artist, designer, or knowledge-based professional who use their creativity in their work. As training in creativity, undergraduate research provides yet another benefit applicable to many careers.

Cognitive Development. The study of the development of student thinking skills has generated great interest, informed by works such as Perry's *Forms of Intellectual and Ethical Development in the College Years* and a variety of thoughtful theories on the development of critical thinking and reflective judgment.[112] The general idea is that young students arrive at an institution of higher learning with a mindset that is passive and accepting, expecting to hear experts tell them the answers to life's questions. As they encounter ambiguity or conflict among experts, the students are compelled to accommodate these conflicts with their views. In a healthy intellectual environment, students pass through a series of cognitive stages culminating in mature thinking, with students capable of arguing for a point of view by using the rules of evidence accepted in the discipline. In some theories, this mature view also initiates action or commitment.

Some of the more influential theories of epistemological development include those by King and Kitchner on reflective judgment[113] and by Baxter Magolda on self-authorship.[114] According to Baxter Magolda, student intellectual development follows a series of stages. These stages are summarized in Table 3-5. The table is a mere outline; it does not do justice to the richness of the theory. But it can be seen that each stage represents a more sophisticated level of understanding than the previous one. William Rauckhorst presented a paper at a 2001 PKAL conference based on Baxter Magolda's investigation of undergraduate research experiences.[115] Baxter Magolda had assessed summer research students with an instrument she devised called the MER (Measure of Epistemological Reflection). Rauckhorst reported that, based on MER scores, students who had a summer undergraduate research experience showed more frequent transitions up the stages than students in a control group. For example, 14 of 35 initial transitional knowers among research students shifted up to independent knowers at the end of the summer. In the control group, none of the 31 initial transitional knowers showed any shifting up the developmental ladder. This work is significant; it suggests that undergraduate research experiences produce measurable changes in student development, and it offers a measure of benefit that goes beyond skill learning or attitude change.

For several summers I have convened a group of student researchers to look at this research. Our attempts to convince ourselves of the usefulness of this approach began in the summer of 2003. Using information from Baxter Magolda supplemented by the work of King and Kitchner on reflective judgment, we prepared an interview protocol that provided respondents an opportunity to tell us something about their thinking on controversial issues. Forty-two students working on summer research projects for a 10-week period were interviewed early and late in the summer. We discovered that coding the student responses into categories of development is hard work; students often make a series of responses that cross categories. Nevertheless, we were able to form a consensus about placing each student respondent into a pretest category and a post-test category that roughly conformed to the Baxter Magolda levels. We placed 16 students into the absolute/transitional range, 20 students into the transitional/independent range, and six students into the independent/contextual range. Post-test classifications showed that 12 of the 16 students in the lower range on the pretest moved up the scale on the post-test; nine of the 20 mid-range students moved up; while none of the six students in the top range moved up. Twelve of the students were not doing research in the sciences; they showed the same patterns as the science students.

Since 2003 we have revisited this methodology, and despite small samples and uncertainties about scoring interviews for placement in stages, I have come to believe the following:

- Summer undergraduate researchers tend to begin their summers scoring in the transitional knowing range. Many, but not all, move up a stage at the end of the summer.
- Summer researchers as a group score statistically higher at the end of summer than members of a control group who did not do research. Our control group, consisting of college students who stayed in our town for the summer but did not participate in formal research or intellectual work, tended to stay at the "transitional knowing" stage.
- Older students tend to score higher than younger students.
- We occasionally employed standard questions used in this sort of research, which included questions about organic food, Shakespeare, and journalism. We found students indifferent to these standard questions, so we probed undergraduate research respondents for controversies in their own field of research. We found that students discussing their own research tend to score higher than when they were answering standard questions. Of course, the methodology was biased against control group students who did not have a research project.
- Some literature on epistemological development emphasizes the importance of the structure of the problems the student is thinking about. We asked students about the structure of their research problems and their preference for structured problems. Science students were more likely than other students to characterize their research as well structured. Science students also indicated they prefer structured problems. The high level of structure in science research problems may not incite epistemological development, since it is the ambiguity of the problem that incites development.

It seems that the undergraduate research experience ignited "a bright period of maturation." According to Baxter Magolda the goal of this maturation is "self-authorship," which includes reflection on epistemology, but also the discovery of self and the choosing of beliefs. Within the context of developmental theories like this one, expertise is not defined solely by cognitive capacity but includes self-knowledge and beliefs to which one becomes committed. Thus developmental theories attempt to describe not just how people learn but why people learn.

Of course, the quest for self-authorship is not limited to undergraduate students in the sciences. The same theme is echoed by Sharon Daloz Parks, whose interest is in the development of faith, an ostensibly unscientific concept.[116] Parks draws on the seminal work of Perry concerning the development of commitment. Parks suggests that young adults attempt a "probing commitment," a tentative attempt to discover truths that may be held in a contextual world. If successful, the young adult may grow to have a "confident inner-dependence;" meaning that one is able to "include the self within the arena of authority." Confident inner-dependence resembles the stage of "independent knowing," and both concepts suggest the development of a person who is actively engaged in searching for truth. This active engagement leads to decisions about vocation. So the gains in intellectual development may be instrumental in motivating a student to choose a science career.

Undergraduate research and other rubrics of educational success

Undergraduate research experiences provide a spectrum of benefits. How does this spectrum compare to authoritative statements of what college and university students in the 21st Century need to learn? One authority on this topic is the American Association of Colleges and Universities, which has been attempting to outline strategies for student learning across the disciplines. In 2006 the AAC&U issued the results of its Greater Expectations Forum in a monograph called *Purposeful pathways: Helping students achieve key learning outcomes.*[117] The authors describe "the powerful core of knowledge and capacities all students should acquire." Students, or "intentional learners," benefit from their college education by being empowered, informed, and responsible. The monograph emphasizes four categories of learning: integrative, inquiry, global, and civic. The contribution of an undergraduate research experience to global and civic learning would depend on the nature of the specific project, but the list of student outcomes for integrative and inquiry learning closely resembles the benefits of most undergraduate research experiences (Table 3-6). These outcomes are simply a different way to word the outcomes of undergraduate research that we have already reviewed. Undergraduate research experiences provide the occasion for progress on most, if not all, of these outcomes.

A different approach to describing the nature of a successful undergraduate education is the empirical approach taken by research programs such as the National Survey of Student Engagement, or NSSE.[118] Research with this survey, which focuses on student reports of activities and behaviors, has produced five "benchmarks of effective educational practices." These benchmarks include: level of academic challenge, active and collaborative learning, student-faculty interaction, enriching educational experiences, and supportive campus environment. These benchmarks are easily translatable into the elements of an undergraduate research experience. In 2007, Kuh elaborated on the NSSE findings regarding research with faculty. He reported that "students doing research with faculty are more likely to persist, gain more intellectually and personally, and choose a research-related field as a career."[119] Student researchers "more frequently used deep approaches to learning and report more learning and growth from their college years." Kuh further reported that "results show that the more time students spent on the project, the better they came to understand the research process and the more they gained overall." Clearly, undergraduate research provides the potential for a spectrum of benefits valued in higher education.

Table 3-1

Faculty responses to the question "What are the benefits that students gain as a result of doing undergraduate research projects"? Items are a composite of responses from three institutions. (Adapted from Lopatto, 2003.)

Learn a topic area in depth; have intensive exposure; learn subject matter in detail.
Construct meaningful problem; apply knowledge to a real situation.
Learn to use appropriate methodology; develop proficiency in laboratory practice and techniques.
Learn to work and think independently; foster independence.
Learn to design solutions to problems; learn to analyze data.
Improve oral communication skills.
Improve written communication skills.
Appreciate what scientists do; learn what scientific research actually entails.
Develop an orientation toward future work and education; clarify career plans.
Learn to use scientific literature.
Gain experience with contributions to a body of knowledge; learn how research ideas build on preceding studies.
Make connections to what was learned in courses.
Find a faculty mentor for continuing relationships.

Table 3-2

Summary of the seven benefit categories presented by Seymour et al. (2004).

Category	Observations
Personal/professional	Increased confidence in ability to do research and other tasks; feeling like a scientist; working relationships
Thinking and working like a scientist	Application of knowledge and skills; increased knowledge and understanding of science and research work
Skills	Improved communication, lab/field techniques, work organization, computer, reading, working collaboratively, information retrieval
Clarification, confirmation and refinement of career/education	Validation of disciplinary interests; graduate school intentions; increased interest for the field
Enhanced career/graduate school preparation	Authentic research experience; opportunities for collaboration/networking; résumé enhanced
Changes in attitudes toward learning and working as a researcher	Undertaking greater responsibility for project; increased independence; intrinsic interest in learning
Other benefits	A good summer job; access to good lab equipment

Table 3-3

Summary of the 10 factors resulting from survey data on benefits of undergraduate research experience.

Interaction and communication skills	Skill at oral, visual, and written communication; leadership; becoming part of a learning community; working independently; ability to collaborate with other researchers
Data collection and interpretation skills	Ability to collect data according to a plan; ability to analyze data; skill in interpretation of results; lab techniques; ability to solve technical or procedural problems
Professional development	Understanding professional behavior in your discipline; understanding personal demands of a career in your discipline; understanding the research process in your field; understanding how professionals work on real problems
Personal development	Sense of accomplishment; tolerance for obstacles; self-confidence; interest in a discipline
Design and hypothesis skills	Ability to employ appropriate design methods; ability to integrate theory and practice; critical evaluation of hypotheses and methods in the literature
Professional advancement	Opportunities for publication; sense of contributing to a body of knowledge; opportunities for networking; enhancement of your professional or academic credentials; developing a continuing relationship with a faculty member
Information literacy skills	Ability to read and understand primary literature; ability to locate and identify the relevant literature; ability to see connections to your college course work
Responsibility	Learning safety techniques; learning the ethical standards in your field
Knowledge synthesis	Learning a topic in depth; understanding how current research ideas build upon previous studies
Computer skills	Computer skills (either user or programmer)

Table 3-4

Proportions of students reporting communication or dissemination activities.

Communication activity	Proportion
A poster on campus.	61.0%
A talk or colloquium on campus.	51.9%
An academic paper read by your research mentor.	46.0%
A poster at a conference or professional meeting.	27.9%
A manuscript intended for a professional journal.	19.7%
A talk or colloquium at a conference or professional meeting.	12.9%
A performance or demonstration.	10.7%
A manuscript intended for a technical report.	4.9%
A manuscript intended for a student scientific journal.	4.2%
A web site or Internet presentation.	4.2%

Table 3-5

Stages of college student intellectual development (Baxter Magolda.)

Absolute knowing	Knowledge viewed as certain; authorities have the answers
Transitional knowing	Some knowledge is uncertain; find processes to search for truth
Independent knowing	Thinking rather than accepting views is important; individuals may have their own beliefs
Contextual knowing	The legitimacy of knowledge is contextual; perspectives require supporting evidence

Table 3-6

Student learning outcomes according to the Greater Expectations Forum.

Ask pertinent insightful questions about complex issues
Perceive relations and patterns
Recognize conflicting points of view and move beyond to a personal stance
Synthesize from different ways of knowing, bodies of knowledge, and tools for learning
Tolerate ambiguity and paradox
Reflect constructively on their experiences and knowledge
Employ a range of intellectual tools
Solve problems and work through situations
Connect in and out of classroom work
Apply theories to practice in the real world
Balance diverse perspectives in deciding whether to act
Distinguish multiple consequences of their actions
Go beyond facile answers to engage with the complexity of a situation
Readily identify ambiguities and unanswered questions
Understand the differences among analysis, synthesis, and comparison

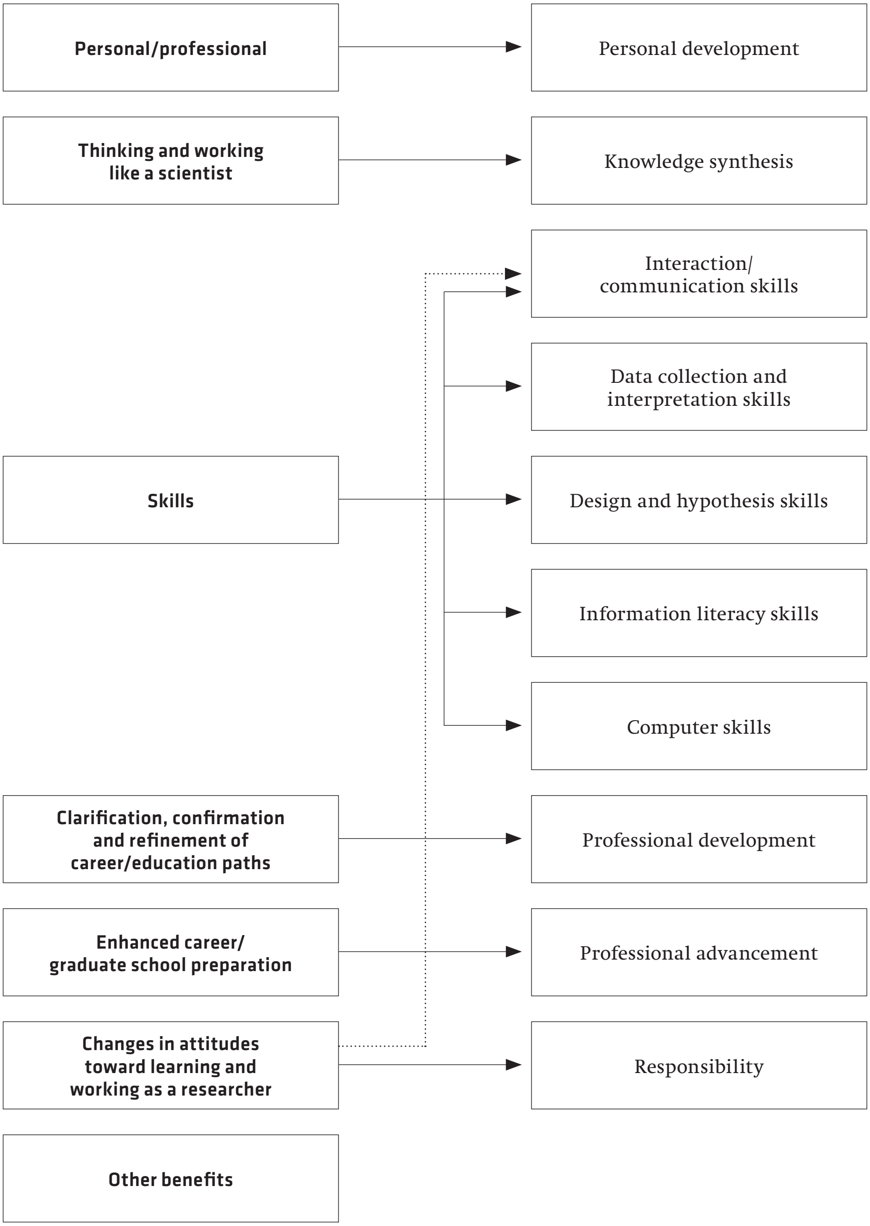


Figure 3-1

An attempt to align the seven parent categories of student benefits found by Seymour et al. *(left)* with a factor analysis of survey data on student benefits *(right)*.

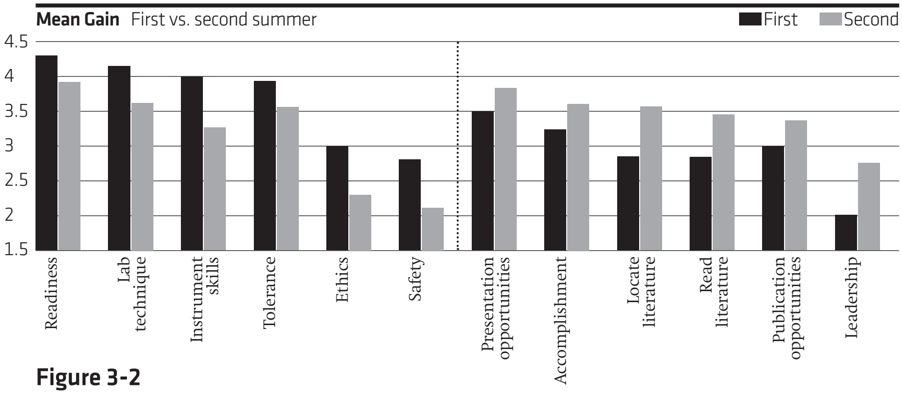


Figure 3-2

Mean learning gains for students who worked for two consecutive summers at research programs at four liberal arts colleges. The items on the left were rated higher in the first summer. The items on the right were rated higher in the second summer.

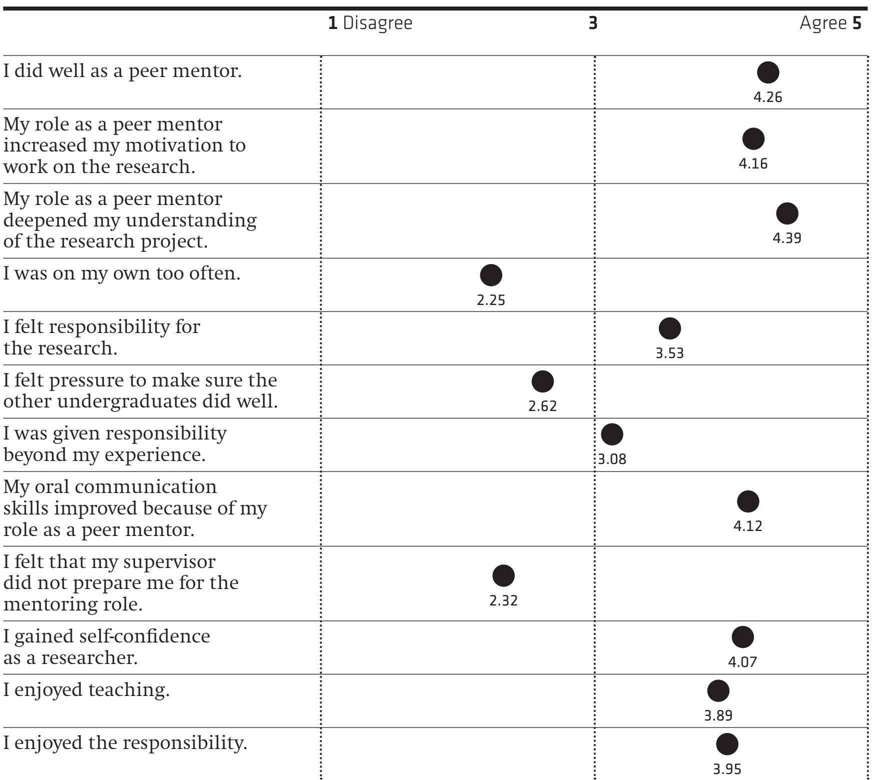


Figure 3-3

Peer mentors agreed or disagreed with a series of statements about their experience.

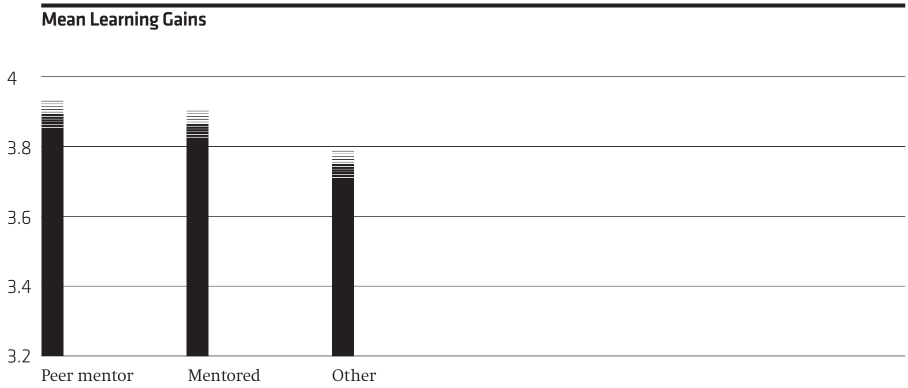


Figure 3-4

A comparison of mean learning gains from SURE survey data for three groups of undergraduate researchers. Peer mentors (n=143) reported serving as peer mentors; mentored (n=127) reported working with a peer mentor; other (n=1,242) did not report serving as or working with a peer mentor. Although the absolute difference in the group means is small, the two groups involved with mentoring are significantly higher than the "other" group. The gray bars represent two pooled standard errors.

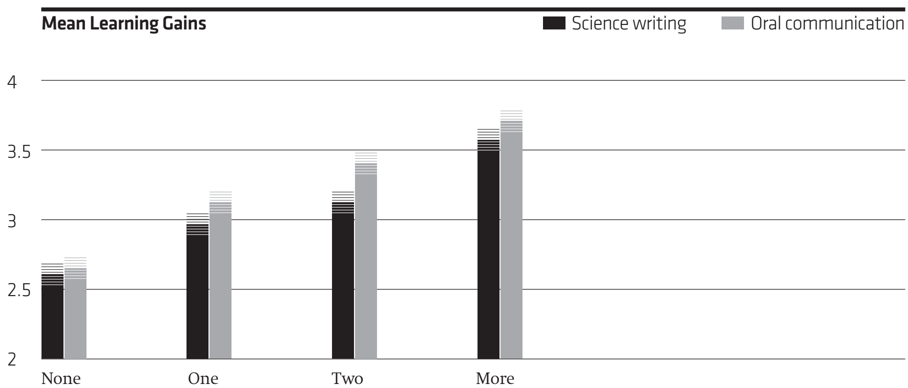


Figure 3-5

The relation of number of communication opportunities of all types on two types of learning gains, science writing (left) and oral communication (right). The error bars represent two pooled standard errors.

4

Disciplines

Jacques Loeb, when asked whether he was a neurologist, or a chemist, or a physicist, a psychologist or a philosopher, answered only, "I solve problems."
Abraham Maslow, *"Problem-centering vs. means-centering in science"*

In this chapter I wish to consider three aspects of undergraduate research. First, within the standard science curriculum, that is, within the regular courses and labs, is it possible for students to show some approximation of the benefits of undergraduate research, either because they completed coursework after becoming a researcher, or because they experienced courses that attempt to approach the benefits of undergraduate research? Second, what is the relationship between undergraduate research and interdisciplinary research? Third, what does diversity have to do with the success of the research?

Before answering these questions, however, it will help to note the role of scientific disciplines in education. It is common to identify the natural sciences as biology, chemistry, and physics; for no other disciplines, neither mathematics nor computer science nor psychology, is there such a high consensus that they are sciences. Biology, chemistry, and physics are labels with multiple functions on a college or university campus. They identify disciplines, departments, graduate degrees, and undergraduate majors. These superordinate sciences have seen both fission—splitting molecular biology from environmental biology—and fusion—biochemistry, neuroscience. Wedin describes the function of disciplines in this way: "The disciplines provide an effective structure for transmitting knowledge from one generation to the next—for passing along a body of information and for teaching students how to 'do science.'"[120]

Gibbons and his colleagues, in their study of knowledge production, write, "Disciplinary boundaries matter far more in education than in research. They are more important inside the university than outside."[121] According to Gibbons et al., disciplines provide individuals with a "competence card," but at the same time encourage conformity. The exciting prospect for undergraduate research is that it benefits students across the disciplines. Once we situate the undergraduate research experience in its discipline, allowing for norms of contact time between student and mentor, work in a lab or in a field, etc., the profile of benefits, professional and personal, reported by student researchers in the sciences is similar across the disciplines. In fact, there is no discipline in science and engineering that is unable to accommodate undergraduate research.

Back to the classroom

In a review of the literature on undergraduate research, Seymour and her colleagues found that some authors claimed that the benefits of the research experience included increased student interest in the discipline and a shift from passive to active learning.[122] During my research with the ROLE survey I developed a strategy that I hoped would clarify these claims. After the student participants finished their main survey at the end of a summer research experience, I waited about nine months and then asked the students to complete a follow-up survey. One section of the survey asked if the student had followed the summer research experience with taking more courses in the discipline. If the student responded in the affirmative, he or she was asked to think about their classroom behavior and evaluate the following three statements about positive changes:

- I feel that I have become better able to think independently and formulate my own ideas.
- I feel that I have become more intrinsically motivated to learn.
- I feel that I have become a more active learner.

More than 60% of the relatively small sample (120 students) reported positive changes on these three behaviors. When the opportunity to draw from a larger population occurred with the SURE survey, students were offered a similar follow-up survey in 2004 and 2005. The results are shown in Figure 4-1 for 614 students who responded to the three statements.[123] The trend is for students to report moderate to large gains in these three areas. A few students also volunteered some written comments on the connection between their summer research and subsequent course experiences:

> I became more driven to do well in my science classes, since I saw more meaning to them.
>
> Hands-on experience is the best possible way to absorb the copious amounts of information lectured to you in class. You cannot really understand science until you actively participate in it.
>
> The experience was extremely valuable because it demonstrated the differences between theory taught in the classroom and reality encountered in the field.

The evidence supports the hypothesis that an undergraduate researcher puts more thought and motivation into courses following a research experience. But what if the opportunity for research is not available? Are the benefits of an undergraduate research experience available in course work?

Research-like experiences

As mentioned briefly in the opening chapter, reforms in science education have included numerous variations on inquiry-based learning, problem-based learning, and research-embedded courses.[124] Some of these courses are intended to be "research-like," that is they include laboratory work or extended projects that mimic the features of research within the constraints of the course structure and duration. If these courses result in learning gains for students that resemble those of research, they dissolve the distinctions between classroom learning and research experience as well as make these learning gains available for a larger number of undergraduates. One example of the synergy between coursework and research work is the HHMI Science Education Alliance, which seeks to create a "nationwide genomics course that will involve first-year college students in authentic research."[125] Programs like the Science Education Alliance are the leading edge of the synergistic approach to science learning and research experience.

To investigate the influence of these courses on student-reported gains, a group of dedicated faculty and staff from several colleges convened in 2005 to develop a provisional description of the features of a research-like course in science.[126] It was challenging to create even a rough sketch of a research-like course that might be abstracted from courses across departments and institutions. The confounding variables are numerous. Courses differ in topic and discipline; they differ in level and prerequisites; they differ in class size; experience of instructor; group versus individual work; reading assignments; and so on. Nevertheless, the discussion resulted in a working definition of a "research-like" course. It contains some or all of these features in some amount:

1) it has a lab or project where no one, including the course instructor, knows the outcome;
2) it has a lab or project in which students have some input into the research process;
3) it has a project entirely of student design;
4) students become responsible for part of the project; and
5) students critique the work of other students.

There are, of course, many other elements to a course, and data have been collected on other elements. For research purposes, however, these five elements were isolated.

These features of a research-like course experience were embedded into a list of 25 elements for instructors to use to describe their science courses.

In the first research effort, instructors at participating colleges were asked to what degree these elements were to be emphasized in their course. They replied on a 0 to 3 scale. From these simple data I constructed a scale (0 to 15) and divided the scale at the median. Courses scoring low (0-8) were categorized as "low research-like" and courses scoring high (9-15) were categorized as "high research-like." Students in these courses, blind to the ratings of the instructors, completed a survey called CURE (Classroom Undergraduate Research Experiences). The CURE includes several kinds of questions, including a set that parallels the instructor descriptions, a set that matches the learning gain items used in the SURE research survey, and a set of attitude items.

If the instructor emphasizes the five items that characterize the research-like experience, does student data reflect the emphasis? Figure 4-2 shows how students rated their learning gains on the items used by instructors to describe research-like courses. Also included in Figure 4-2 are some items used in standard courses, such as listening to lectures. The means in Figure 4-2 suggest student learning reflects the emphasis of the course. How does this learning relate to the learning gains reported by students who participate in dedicated summer undergraduate research programs? Does the effort to create a research-like course lead to a result that resembles an undergraduate research experience?

To answer this question, we can look at the data from a list of learning gains that are embedded in both the SURE and CURE surveys. SURE student data was collected from 1,135 students who engaged in dedicated summer undergraduate research the summer of 2004. These results are typical of the summer survey. If SURE data can be taken as the benchmark of the benefits of a research experience, how would research-like courses measure up? The results from one fall term in 2005 are presented in Figure 4-3. The figure distinguishes between 115 students in high research-like courses and 220 students in low research-like courses. The figure shows an orderly relationship. Students in summer research have the highest average gain; students in high research-like courses have the second highest.

The learning gain items are shown individually in Figure 4-4. For each item, the summer researchers' mean gain is represented by a blue triangle. As might be expected, blue triangles dominate the figure as students participating in an authentic summer research experience assess their gains. Means from high research-like courses are represented by red triangles. These means fall into an orderly pattern of second highest, except for a few items. These items, including understanding that scientific assertions require supporting evidence, ability to analyze data, and reading primary literature, are plausibly as well done in courses as in summer research. Means from the low research-like courses are represented by green squares. These means fall into an orderly low pattern on the figure. Error bars representing two standard errors above and below these means give a sense of the distance between these means and the others. On only a few items do the students from low research-like courses rate their learning gains as high as other students do. Most telling of these items is science writing. This result may reflect the lack of writing instruction in any of these experiences. Generally, students in courses that have research-like features benefit in the same way, but to a lesser degree, than students involved in undergraduate research.

Interdisciplinary education and research

Current observers of science are urging the relaxation of disciplinary boundaries. The strongest reason for this change, from strictly disciplinary to interdisciplinary or integrated science, is the assertion that society's most pressing problems require interdisciplinary efforts to find solutions.[127] The National Academy of Sciences book, *Facilitating Interdisciplinary Research,* defines it as a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice.[128] *Facilitating Interdisciplinary Research* describes its drivers as:

1) The inherent complexity of nature and society;
2) The drive to explore basic research problems at the interfaces of disciplines;
3) The need to solve societal problems; and
4) Stimulus of generative technologies.

Randy Wedin, who interviewed a number of leading educators about interdisciplinary science, cites a correspondent who suggested that it is more authentic in reflecting nature: "Mother Nature doesn't know about chemistry, physics, mathematics, and molecular biology. It's all one glorious thing to Mother Nature."[129] Or, as the philosopher W. V. Quine once wrote, "Boundaries between disciplines are useful for deans and librarians, but let us not overstate them—the boundaries. When we abstract from them, we see all of science—physics, biology, economics, mathematics, logic, and the rest—as a single sprawling system, loosely connected in some portions but disconnected nowhere."[130]

A discussion of interdisciplinary science provokes many questions for researchers and administrators, but the focus here is on undergraduate researchers. Can they become meaningfully involved with interdisciplinary research? Are the benefits of interdisciplinary research similar to those of disciplinary experiences?

One problem imagining the undergraduate as an interdisciplinary researcher has to do with the most frequent description of how a researcher becomes interdisciplinary. Many descriptions of the process begin with the assumption that the researcher is already an expert in a discipline. Disciplinary background as a prerequisite for interdisciplinary understanding is asserted by Boix Mansilla, who writes that interdisciplinary understanding is "deeply informed by disciplinary expertise."[131] Simonton reviewed research on scientific creativity and asserted, "It has been estimated that it usually requires at least a decade of extensive study and practice to attain world-class expertise in any domain of achievement."[132] Malcolm Gladwell, in his recent book, *Outliers,* calls this "the 10,000 hour rule." According to some accounts, the disciplinary researcher then learns about or borrows from a second discipline on the way to developing emergent cognitive skills involving appreciation of multiple perspectives, enhanced problem-solving, and creativity. If prior disciplinary expertise is essential for interdisciplinary learning, then the undergraduate researcher, as a novice, would not contribute to, or benefit from, an involvement in interdisciplinary research. The student's lack of expertise, unfortunately, could also be used to argue that the student would not benefit from a disciplinary research experience. But, as we have seen, students claim a great number of benefits from their disciplinary undergraduate research experiences.

What seems to occur, however, is that if disciplinary knowledge is lacking, mentors use a variety of inductive teaching techniques, such as Just-In-Time Teaching, to give students the knowledge they need to contribute to research.[133] If the student is not working alone, and most do not, and has access to multiple mentors, then she has plenty of resources for learning as she experiences the research. The contribution of the student depends on the nature of the research problem. As Newell puts it, "If the problem can be illuminated adequately using a handful of introductory-level concepts and theories from each discipline, and modest information readily and simply acquired, then a solo interdisciplinary researcher or even a first-year undergraduate student can handle it."[134] Undergraduates are not normally relied upon to be the resident expert on any research problem, disciplinary or interdisciplinary. They are typically apprentices. Their role in interdisciplinary research should not differ significantly from their role in other research experiences.

For practical purposes it is useful to distinguish between interdisciplinary research and interdisciplinary education. Interdisciplinary research, performed by professionals, is seen as the desirable goal that will sustain the national economy and general well-being. The calls for interdisciplinary work, which can be reviewed in the National Research Council's *BIO 2010* and other reports, imply that interdisciplinary education of undergraduates leads to interdisciplinary research by professionals. For our purposes, which bear on science education, it is worthwhile considering what happens when interdisciplinary research (IDR) experiences are available to undergraduates.[135]

IDR is problem-driven. *Facilitating Interdisciplinary Research* defines it as:

> ...a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or

> more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice.[136]

IDR implies a finite timeline for its mission. Once progress is made on the problem in question, the IDR team may end its collaboration or reconfigure into new teams.

In contrast, programs created in the name of interdisciplinary education at colleges and universities have a continuous mission to educate successive generations of students. The creation of neuroscience or integrated biology-chemistry programs, for example, requires long-term changes in the college curriculum. Interdisciplinary education evolves into the organized curriculum, losing its fresh sense of transcending or transgressing disciplinary boundaries. Students may be unaware of interdisciplinary tags, or may come to think of interdisciplinary work as disciplinary.[137] The popular descriptive for interdisciplinary, “messy,” becomes less apt as time and repetition act on a program. People tend to process information by “chunking” it together in short-term memory and “clustering” it in long-term memory. This clustering, which accounts for the evolution from individual game moves of chess novices to the gambits and strategies of chess masters, inevitably sorts the messy interdisciplinary problem into a cleaner structure.[138] The interdisciplinary networking of two or more distinct sets of information with labels like biology and chemistry becomes one coherent structure in the memories of students who process and cluster the integrated information. When this clustering happens, it may change the way people look at the incumbent disciplines of science.

It may also, however, tidy up the ill-structured problems that catalyze student cognitive development and made the problem interesting. Interdisciplinary science needs periodic refreshing through reexamination and research or it too can become stale. As S.S. Stevens once wrote about operational definitions, interdisciplinary problems should not be allowed to congeal. There is a strong correlation in the literature on interdisciplinary education between an interdisciplinary approach and a problem-centered approach. Once one discipline is no longer at the core of the program, the research problem assumes the central focus. The growing popularity of interdisciplinary education, since it is problem-based, should result in more opportunities for undergraduate research.

The definition of interdisciplinary research cited above implies that the research team is recruited from within the sciences. Scientists tend to describe interdisciplinary work as a within-science phenomenon, calling for science “at the interface” to tackle problems in both basic and applied research. They also recognize, however, that the world’s problems—climate change, emerging pathogens, energy production—have obvious connections to disciplines in the social sciences and humanities. This recognition provides two models for creating undergraduate research opportunities. In the first, the inter-science disciplinary approach, the research remains within the sciences. In the second, the broader interdisciplinary approach, one or more science disciplines interface with the wider world. In the first model faculty (and post-doctoral fellows and graduate students) need to identify the research problem to be solved and the team of scientists needed to solve it. In the second model faculty may think about the broader implications of research they perform and find useful areas of interface, for example, with behavioral science, economics, or ethics. Here, the interested faculty member has more possibilities for creating a broader team of peer researchers and attracting diverse undergraduate researchers.

What additional features of undergraduate interdisciplinary research can be identified? The first new feature occurs when the research team includes more than one expert. It may be that the team of researchers includes two or more experts who serve as co-mentors to the undergraduates on the team. Bona, Rinehart and Volbrecht describe co-mentoring as a situation in which "supportive assistance" is provided by several connected individuals, who may be assisting each other even as they assist students.[139] The co-mentoring approach "assumes everyone has something to teach and something to learn." It may expose the student to meaningful dialogue and to peer education among experts that models how scientists think and work. Co-mentors give the student insight into different disciplinary perspectives. Co-mentoring may result in greater collegial treatment of the student, as no one mentor claims to be the sole authority.

The second new feature has to do with problem structure. By definition, interdisciplinary research problems are less structured than disciplinary research problems, because the "solutions are beyond the scope of a single discipline or field of research practice." Ill-structured problems provide a greater cognitive challenge than structured problems and provide an occasion for student epistemological development.

Interdisciplinary research adds new strains to mentoring. First, there is the problem of co-mentors. Do they get along? Can they communicate? Are they comfortable with sharing authority and with mentoring students? Daily management of the team may be a challenge, with no one person possessing the requisite knowledge to act in an authoritative manner. The team could become democratic and open to student ideas, managed through a kind of "soft control" that Richard Florida described in the management of creative people.[140] Soft control consists of recognizing that talented, achievement-oriented people work for "the challenge, the responsibility, for recognition and the respect it brings." Second is the lack of problem structure. As we have already seen, it is challenging for managers to supervise groups working on unstructured problems.

They're not dumb, they're interdisciplinary

Interdisciplinary research may add to the considerable benefits of undergraduate research experiences by enhancing creativity and strengthening, or enlarging, the learning community. For example, suppose a group of faculty and student researchers designed research on the problem of global warming, a complex problem with elements of physics, chemistry, and biology, but also of economics, politics and psychology. Even a limited effort to understand a specific piece of the larger problem would lead to discussions of the "bigger picture." It is this sort of research that might attract to science the untapped talents of the group of students identified by Sheila Tobias: the second-tier students discussed in *They're Not Dumb, They're Different*.

Recall that Tobias asked former college students to participate in college science courses. What did her respondents say about their experience? One wrote, "We were not required, at any time, to interrelate concepts or try to understand the 'bigger picture.'"[141] Another remarked, "I think the students around me are having the same sort of thought-provoking questions about the material that I put into my journal, but under time pressure they don't pursue them."[142] A third wrote, "I found myself craving some theory."[143] Tobias summarized the attitude of her respondents as, "They wanted more time to wrap their own intelligence and intuition (their 'creativity') around exploratory questions; to be given the formula or the explanation only later when they had exhausted their own imagination; and to learn the appropriate technique as a *means* toward solving problems; not as an *end* in itself."[144] It seems a reasonable hypothesis that students who have the attitude expressed by these respondents might be willing to become involved with science if they could think about the interrelated concepts, the thought-provoking questions, and the bigger picture that interdisciplinary research affords.

Interdisciplinary research, by bringing together students and mentors from diverse backgrounds, may have benefits beyond those I have enumerated. I have already claimed that undergraduate research provides a precursor to later creativity. Simonton asserts that the creative process includes an element of chance, that creativity is a "constrained stochastic process."[145] He describes creativity as containing an element of serendipity. In interdisciplinary research, it is not difficult to imagine that team members representing different disciplinary backgrounds will engage in dialogue rich in parallel terms, analogies, and metaphors that might inspire creative thinking in other group members. This dialogue may provide the serendipitous moment that affords a new idea about the research problem. Something one team member says may unexpectedly trigger a train of ideas.

One sort of contribution team members may make is analogical thinking, that is, communicating analogies to the team member's own experience, to common information, or to other disciplines. Dunbar studied four disciplinary laboratories that worked in the areas of developmental biology or biological pathogens.[146] He recorded the conversations of the scientists and later coded the conversations for content. He reported that scientists typically used analogies while discussing their work. The most frequently used analogies were local, that is, they referred to similar experiments or research techniques that helped the scientists understand a research problem. The effect on the lab scientists was that "new knowledge is added to their representation by making the analogy, and this drives the research forward." One lab was exceptional; no analogies were recorded. "The single laboratory that did not engage in analogical reasoning did not make any real gains in their understanding of the genes that they were working on." Dunbar interprets this finding:

> Why were the members of the laboratory not making use of analogy? One aspect of the laboratory appears critical to whether analogies will be used. It is the social structure of the laboratory. All the members of this laboratory had come from highly similar backgrounds, and consequently drew from a similar knowledge base....When all the members of the laboratory have the same knowledge at their disposal, then when a problem arises, a group of similar-minded individuals will not provide more information to make analogies than a single individual.

Using the technique of analogy, it is not difficult to see how an interdisciplinary research team might generate creative ideas by relating a current problem to the experience of each member. The group will not be composed of "similar-minded individuals;" it will be diverse. The opportunity for creative analogies will be enhanced.

Diversity and problem solving

The consideration of underrepresented groups begins with thinking about ethnicity and gender as input variables. The National Science Foundation recognizes students from specific ethnic groups as underrepresented, and attempts to ameliorate this underrepresentation by prioritizing the recruitment of students from underrepresented groups for grant activities. The need for diversity is also recognized in the published manuals for mentoring undergraduates. The motivation for this consideration may be idealistic—educational opportunity for all—or an attempt to recruit more talent to meet the needs for the STEM talent that so many commissions and reports predict will be needed. It is exciting, however, to discover that diversity may also be an important process variable that may benefit everyone in a research group and enhance the probability of success.

The benefits of interactions and relationships in the areas of social behavior and attitudes are well established.[147] Astin reports that diversity activities were associated with gains in cognitive and affective development, satisfaction with college, and desire to promote racial understanding.[148] More recently, economist Scott Page has developed a model of problem solving that indicates "diversity trumps ability."[149] Although his model is too complex to review here, it includes situations in which diverse groups of problem solvers contribute their individual perspectives and heuristics to reach a higher level of success than groups that might be talented (as measured, for example, by a standardized test) but have a more limited range of individual perspectives and heuristics. Although Page distinguishes between cognitive diversity and ethnic diversity, addressing his theory to "differences inside people's heads, not differences in skin color, gender, or ethnicity," it is nevertheless plausible that cognitive diversity correlates with other forms of diversity, because ethnicity and gender, among other variables, can stand as proxy for different experiences of the world.[150] If diversity trumps ability, it is advantageous to have a diverse research group. It is also challenging. Mannix and Neale in their study of diverse teams in the private sector, offer one bit of advice that should resonate with science mentors: "We believe that another way of obtaining the full benefits of a diverse team—and ultimately building trust and respect—is through bridges that connect team members in some way that is meaningful to the particular team."[151] In the case of the undergraduate research group, this bridge may be the excitement of scientific discovery, "the challenge, the responsibility, for recognition and the respect it brings" that Florida asserted was essential for "soft control." A common excitement about science, a shared engagement in the research experience, a feeling of common "ownership," may be the thread that connects the diverse undergraduate research group.

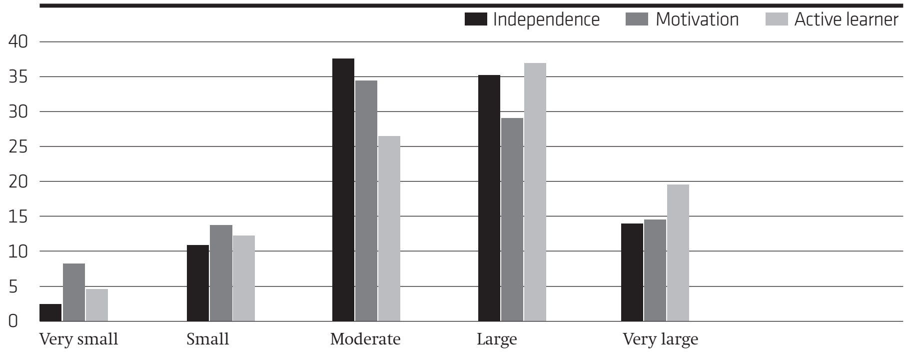
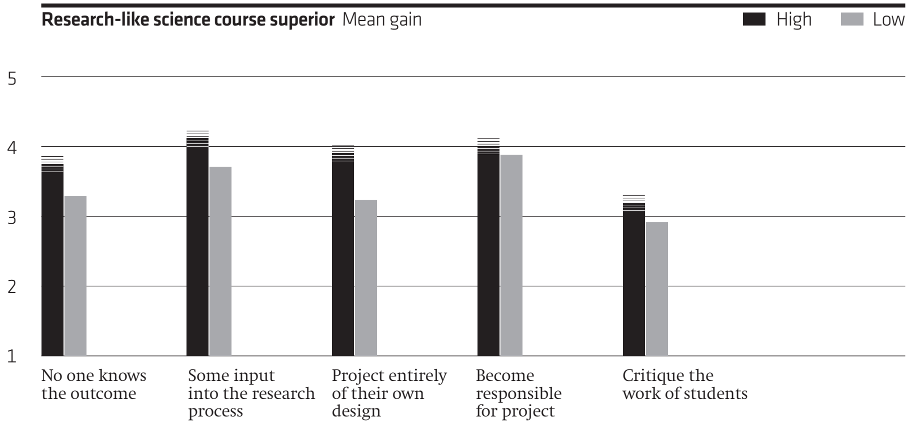


Figure 4-1

The figure shows the percentage of students who answered a follow-up survey regarding three aspects of their course behavior nine months after a summer undergraduate research experience. The data from two years are combined. The three items were, "I feel that I have become better able to think independently and formulate my own ideas;" "I feel that I have become more intrinsically motivated to learn;" and "I feel that I have become a more active learner."



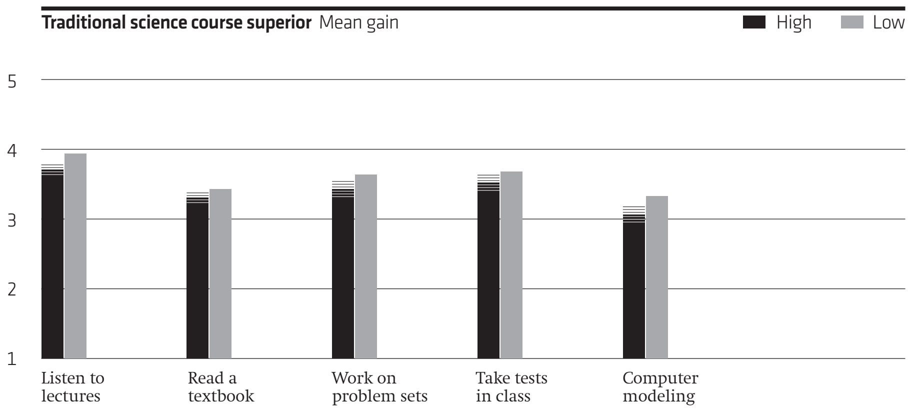


Figure 4-2

Mean student learning gains on items that describe research-like science course (top) and items that describe a traditional science course (bottom). The black bars represent data from students in high research-like courses. The error bars represent two standard errors. N=1,274.

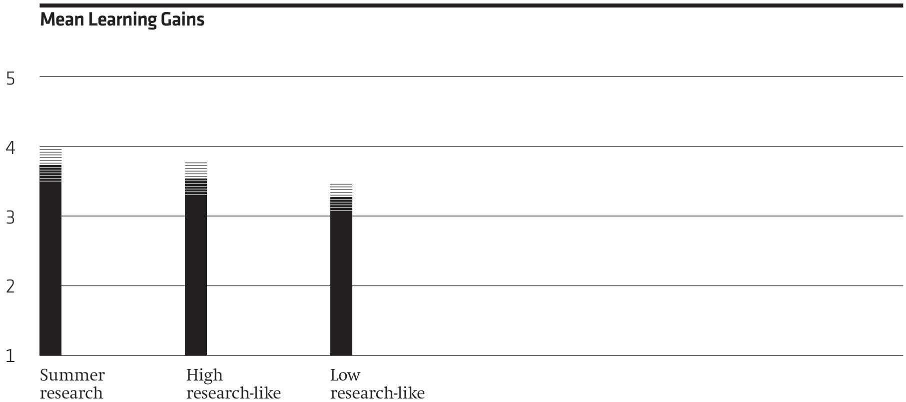


Figure 4-3

The graph shows the mean of 20 learning gains, each rated on a scale of to 5, by students from dedicated summer research, students from high research-like courses, and students from low research-like courses. On a few specific learning items, e.g., reading primary literature, students in high research-like courses scored as high or higher than summer research students, but students in the low research-like courses scored lowest on each item. The error bars represent one standard deviation about the mean.

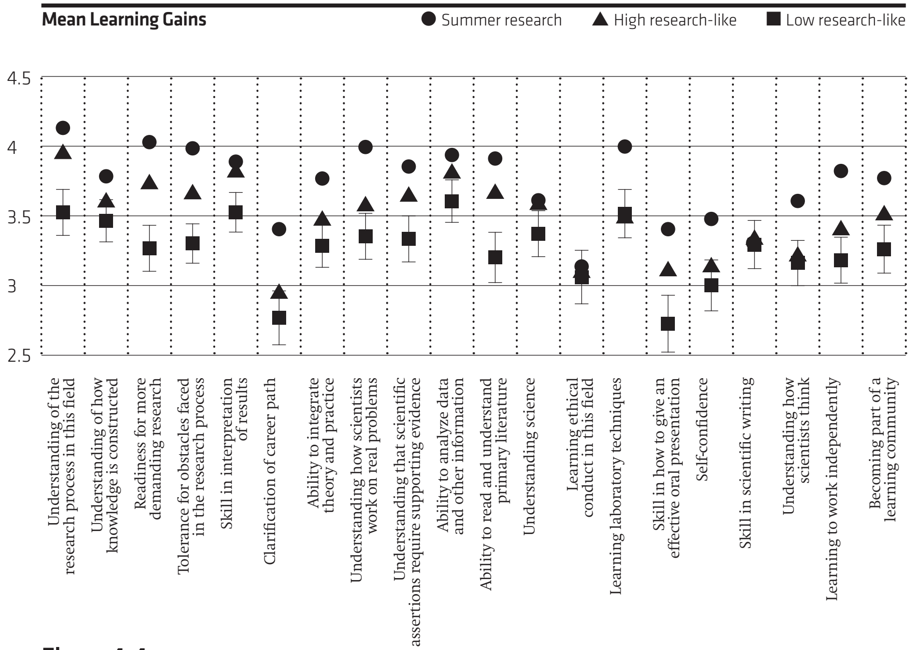


Figure 4-4

The figure shows the individual learning gain items evaluated by students in summer research programs, high research-like courses, or low research-like courses. Error bars representing two standard errors are shown for the low research-like courses. In general, students in high research-like courses rated their learning gains as higher than students in low research-like courses. For some gains students in high research-like courses rated their gains higher than students in summer research programs.

5

Mentoring

The duty to teach is transformed as the student becomes more advanced, as the venue shifts from the classroom to the laboratory, the library, and the office, and as the relationship becomes more singular and more personal. The one-on-one interaction that develops between experienced practitioner and aspirant is more like training than teaching; it resembles the journeyman-apprentice relationship that once characterized artisan guilds.
D. Kennedy, *Academic Duty*

It is challenging to find the appropriate title for the person or persons who oversee the student's undergraduate research experience. "Supervisor" seems too industrial; "professor" not always accurate, because in the research group graduate students, post-doctoral fellows, and industrial supervisors may be mentors. Undergraduate students may serve as peer mentors. The term mentor seems appropriate in undergraduate research because it describes the optimal relationship between supervisor and student researcher. In every undergraduate science research program there is optimism that the relationship between the student and supervisor will assume a more significant status than just supervision. As Sharon Daloz Parks wrote in describing a student's development of faith, "Mentors are those who are appropriately depended upon for authoritative guidance at the time of development of critical thought and the formation of an informed, adult, and committed faith."[152] Chickering describes the benefits of student-faculty relationships to student development. The benefits of a good relationship—the development of competence, sense of purpose, and autonomy—are found in a good research mentor relationship.[153] Astin, analyzing survey data, found that increased student-faculty contact had a positive effect on choosing a career as a research scientist. Working on a professor's research project was one way that this contact was maintained.[154]

What is mentoring?

In undergraduate research, the first candidate for mentor is the research supervisor or someone in the supervisory hierarchy.[155] Sometimes students become part of a research group through personal negotiation, but often they apply for a position with a supervisor they do not know. Mentoring emerges as the supervisor and student get to know each other, takes on characteristics beyond mere supervising, and may continue well beyond the conclusion of a research experience.[156] Merkel and Baker in their *How to Mentor Undergraduate Researchers,* wrote, “Mentors, whether faculty members or independent researchers, are pivotal in ensuring the success of the student’s experience. They teach a variety of applied skills, methods, and techniques.”[157] Mentors are teachers, but they are also coaches, gatekeepers to a community of scholars, and conduits for passing on the culture of science. Handelsman and her colleagues assert that a mentor is more than a faculty adviser. They write, “A fundamental difference between mentoring and advising is [that] mentoring is a personal as well as professional relationship.” They assert further that mentors are “good listeners, good observers, and good problem-solvers.”[158] The mentor is responsible for creating a good project, with essential features that we have already discussed. But a mentor also attempts to establish a relationship with the student. Many guides, including the National Research Council’s *Adviser, Teacher, Role Model, Friend*, emphasize the personal aspect of mentoring, suggesting that mentor tasks include asking the students about themselves, discussing their expectations for student work, and developing listening skills.[159] These guides are useful because they describe how mentoring influences the undergraduate research student, and they assert that mentoring can be learned. Handelsman and her colleagues have created a workshop for learning mentoring called the Wisconsin Mentoring Seminar. The participants “read articles and case studies, write biographies of their undergraduate students, compare their goals with those of their undergraduate researchers, explore time-management strategies, and write mentoring philosophies.” An evaluation of the seminar, published in Science, reported that graduates of the training seminar were more likely to engage in mentoring issues than control subjects.[160] These issues included discussing the student’s expectations of the mentor and considering issues of diversity. Despite the advantages of mentor training, some writers see good mentoring as a special talent. Kennedy writes, “There is no good formula for discharging the academic duties involved in being a good mentor. Knowing when to be demanding and when to be flexible and forgiving is a skill possessed by the best.”[161]

Mentoring training guides tend to be practical. Sharon Daloz Parks, in her book *Big Questions, Worthy Dreams,* took a more philosophical look at the role of mentoring in student development. Scientists may be inclined at first to shy away from Parks because she is concerned about the development of faith, but a great deal of her work on mentoring applies to the development of young scientists. Parks’ work is particularly valuable because she describes current work on intellectual and ethical development in college students. Parks observes that the term “mentor” is overused. “Popular usage has begun to use the mentor figure to evoke a sense of genuinely caring and educative relationships across the entire life span...where other terms may apply more appropriately: parent, teacher, sponsor, role model, hero or heroine, counselor, coach, companion, supervisor, guide, colleague, or helpful friend. The term mentor is best reserved for a distinctive role in the story of human becoming."[162] The phrase "story of human becoming" might seem esoteric, but Parks goes on to describe some recognizable characteristics of mentoring. The mentor is a person who recognizes the "promise and vulnerability" of the student. He or she supports the student by recognizing her continuing dependence, and at the same time championing competence and potential. The mentor provides the student with challenge and inspiration while understanding the conflicts the student may feel.

Much of the discourse on mentoring implies a personal relationship between one mentor and one student. When Kennedy wrote the lines about mentoring that head this chapter, he was thinking of the mentoring of graduate students, and he was thinking about one-on-one interactions between faculty and students. In undergraduate research the mentoring relationship is extended to all undergraduate participants, including first-year students. The mentoring relationship is also expanded to include the members of a working group of students. The mentoring of students of diverse ages and of groups of students may seem an overwhelming task. It is important for the mentor to rely on the community for help with mentoring.

Mentoring community

Parks points out that a single mentor cannot always encompass a young person's range of experience. She writes, "If one is going to be initiated into a profession, organization, or corporation and the societies they serve as they could become, then only a mentoring community will do." Young adults, according to Parks, need "a trustworthy network of belonging." Anticipating the formation of interdisciplinary teams of scientists and students, Parks discusses "co-mentoring," a term I mentioned earlier, in which "the leadership team members model mutual support and challenge among each other."[163] She goes on to assert, "This evokes comparable relationships among the students, creating a mentoring environment that is characterized by a heightened degree of trust and enhanced capacity for engaging and challenging everyone."

Parks addresses the issue of higher education as a mentoring community, calling it a community of imagination. "Every institution of higher education serves in at least some measure as a community of imagination in which every professor is potentially a spiritual guide and every syllabus a confession of faith."[164] Parks, with her interest in the development of faith, takes issue with higher education's attempt at objectivity, "the dispassionate presentation of value-neutral fact, or mere presentation of multiple points of view." In a characterization of faculty that calls to mind the experience of the students in

They're Not Dumb, They're Different, Parks writes, "professors are too often mere technicians of knowledge." Her discussion of meaning-making and spirituality may strike a scientist as beyond the scope of science education, but substitute passion for science or questing for a science vocation and her commentary seems relevant to mentoring in science. Her philosophical view may also be relevant as science mentors encounter more students interested in interdisciplinary education encompassing science and values.

The term "mentoring community" is less common in science education than "learning community" or "research community." Research communities, meaning the loose configuration of scientists working on more or less the same problem or in the same field, are also called "communities of practice."[165] Brown and Duguid describe communities of practice as "relatively tight-knit groups of people who know each other and work together directly. They are usually face-to-face communities that continually negotiate with, communicate with, and coordinate with each other directly in the course of work." They go on to write, "Coordination is tight. Ideas and knowledge may be distributed across the group, not held individually. These groups allow for highly productive and creative work to develop collaboratively."[166] Universities and colleges incorporate communities of practice: "Students get some sense, however implicit, of what it takes to join a particular community.... Teaching and education...are not simply matters of putting students in touch with information.... They are matters of putting students in touch with particular communities. The university's great advantage is that it can put learners in touch with communities that they don't know about...or that it would be hard to access in any other way."[167] Wenger states that "a well-functioning community of practice is a good context to explore radically new insights without becoming fools or stuck in some dead end. A history of mutual engagement around a joint enterprise is an ideal context for this kind of leading-edge learning, which requires a strong bond of communal competence along with a deep respect for the particularity of experience. When these conditions are in place, communities of practice are a privileged locus for the creation of knowledge."[168] It is the function of the mentor to guide the student into these communities.

Does mentoring matter?

Given all the significance placed on the mentoring relationship, and all the advice for becoming a good mentor, can we observe the effect of mentors on the experience of undergraduates doing science research? Individual scientists relate anecdotes about the influence of their mentors in undergraduate or graduate school, pointing to relationships that have lasted a lifetime. Data on the influence of mentors, however, is harder to come by. Handelsman and her colleagues, while reporting changes in the behavior of graduates of their mentoring seminars, did not find quantitative evidence that trained mentors were any more effective in enhancing the experience of undergraduate researchers than were untrained mentors, although they did relate that students supervised by trained mentors reported that those mentors were "more available to them, were more interested in them as individuals, and gave them more independence."[169] Susan Russell and her colleagues also found a lack of quantitative evidence for the effect of mentors on undergraduate research experiences. They concluded, "Neither involvement in decision-making nor perceived adequacy of mentor guidance was very strongly related to positive outcomes." However, qualitative responses by students led the authors to conclude that "mentors who are able to combine enthusiasm with interpersonal, organizational, and research skills play a large role in facilitating positive outcomes."[170]

Why is the influence of the mentor in undergraduate research difficult to capture with quantitative measures? Russell and her colleagues suggest that lack of result "reflects the complexity of the mentor's role rather than its unimportance."[171] The complexity seems manifest given all the traits the mentoring guides recommended. It is also true that large-scale studies (Russell was reporting on four surveys with almost 15,000 respondents) gloss over differences in the disciplinary areas. Mabrouk and Peters surveyed 126 undergraduates in biology and chemistry, asking the students to rate their agreement with characteristics that made for a good undergraduate research advisor. Students rated "knowledgeable," "enthusiastic," "available," and "patient" as the most desirable characteristics.[172] Seymour and her colleagues, interviewing students about their undergraduate research experience, noted that "the shift from a hierarchical and respectfully distanced relationship to one based on partnership in a common enterprise had a powerful effect on students."[173]

Research with the ROLE survey was successful in capturing data that reflect the relationship of mentoring to student perceptions of learning in undergraduate research experiences. When in 2001 and 2002 I collected data from four liberal arts colleges where students were spending their summers doing 10-week programs of undergraduate research, a group of 384 students responded to questions regarding their mentor's characteristics (see Table 5-1), as well as other questions about their experience. Figure 5-1 summarizes the mean responses. On the whole, faculty mentors (there were few other mentors in this primarily undergraduate institution group) rated highly in friendliness, respect, and collegiality. Ratings were more modest on the characteristics of reliability, clear communication, and organization. Several student-reported outcomes were related to these characteristics. Both overall satisfaction with the research experience and a sum of specific learning benefits (such as those previously discussed) correlated with these traits, with "treats you like a colleague" the best positive predictor of outcomes, and "unresponsive to your questions" the best negative predictor. The positive relation between collegiality and a good research experience was also noted by Hunter and her colleagues, who wrote that "faculty and students' accounts describe how treating students as collaborators and respecting their insights and contributions to faculty advisors' research affirmed their position as capable learners and encouraged a sense of self that they, too, could do science."[174]

The use of correlations for the quantitative data, while conventional, may be misleading about the role of the mentor in the undergraduate experience. The mentor and the research project are not easily separable. As Finkel and Monk wrote about teachers, the research mentor is the "very embodiment of the group's goal."[175] The intricate relationship between the student and mentor may be the reason why multiple choice or rating scale items don't show significant results in some studies, and why it might be better to describe the influence of mentors using plain English. One student wrote a supplementary comment about her mentor on her survey. Her comment (italics are mine) reads:

> Something that is very important for undergraduate research in my mind is the relationship between advisor and student. In my experience this summer I have not had the type of relationship that I would have wanted. I believe that I would have enjoyed the project more had I liked my mentor more as a person. I do get along very well with the other student in my lab as well as the other lab advisor. *These interpersonal relationships are just as important to me as the research itself.* Of course, these feelings affected my responses. In question 40, my feelings toward my advisor are the reason why I will not be continuing work in his lab. *This also helps explain why I am satisfied with very little contact with my advisor*—although I enjoy working by myself with little supervision no matter who my mentor is. My research experience has helped me in my plans for the future. I decided this summer that I do not want to pursue a degree in medicine but would rather go to graduate school. I am also planning on continuing to do research in biology during the school year, but I do not think I will be working in this same lab I am currently with. I'd like to say that although my experience this summer has been far from perfect, I'm very glad I took part in the program. I learned a lot about myself and scientific research.

This thoughtful comment untangles several aspects of the undergraduate research experience. On a superficial level, this student's experience is a success in that she plans to continue in a science career. Yet her experience with her mentor has repelled her from a specific research area. The relationships in the lab, not the research topic, drive her decisions.

The SURE survey expanded the coverage of student assessment of their mentors to over 100 institutions, including both colleges and universities. It includes one question about the research supervisor. The question is written this way:

Think about the person who was your most direct or primary supervisor. Evaluate the performance of your direct supervisor:

1. I feel that my supervisor was not a good teacher and mentor.
2. I feel that my supervisor was below average as a teacher and mentor.

3. I feel that my supervisor was about average as a teacher and mentor.
4. I feel that my supervisor was above average as a teacher and mentor.
5. I feel that my supervisor was an outstanding teacher and mentor.

The question, like many others, relies on the student's experience with teachers and mentors generally, and because all sorts of institutions are represented in the data, it is not necessarily the case that the primary supervisor is a fulltime faculty member. Nevertheless, this simple question yields some interesting results and triggers additional written comments from students. Over 6,000 students have addressed this question since 2003, and the results are very consistent from year to year. The good news is that slightly more than 50% of the student respondents evaluate their supervisor as an "outstanding teacher and mentor." The lower evaluations, including the "about average" with the other two, consistently stay at about 20% of the responses.

Analysis of student-reported learning gains on the same survey shows that learning gains are related to mentor evaluations. Figure 5-2 shows the relation of specific levels of evaluation to the average learning gains of undergraduate researchers. The relation is clear and orderly. Figure 5-3 shows that students who rate their research mentor highly rate all their individual learning gains higher than students who did not rate their research mentor highly. It might be argued that the students who rated their supervisors as outstanding did not really learn more than other students, but rather are displaying a sort of "halo effect" to represent their overall satisfaction. Maybe so, but the observation made by the student quoted earlier, *These interpersonal relationships are just as important to me as the research itself,* is relevant here. Can we really separate the overall experience of research from the student's experience with the mentor? The same survey asked the students if they had plans for graduate work in the sciences (the goal of recruiting for the STEM workforce) and how the research experience affected those plans. Every year a small group of students, about 4% of the total, report that they originally planned to go on in the sciences, but that the research experience discouraged their plans. While only 20% of the students overall report below average or average supervisors, about 30% of the students who leave report poor supervisors. The numbers are small but significant. Poor mentoring is related to discouraging a future in science. The poisonous nature of poor mentoring is revealed in the following quotation from a summer research student:

> I really enjoyed the lab work and learned a lot. My mentor was very mean, though, and therefore I avoided that person as much as possible. This meant that I didn't get all my grant money because getting my mentor to sign my timecard was an ordeal every time that I preferred to not go through. I felt afraid to go in and work if my mentor was there. I was blamed for things breaking etc. when I was not responsible. Even though I loved the actual work, my experience with my mentor has made me change my mind about graduate school. If getting a Ph.D. makes someone

> that mean and miserable, why would I do it? I would encourage future participants to CAREFULLY choose your mentor based on a positive/supportive attitude because it's hard to work when you feel degraded and intimidated.

Other written comments about the research mentors are found in Table 5-2.

Mentoring groups

As I reported, only about 20% to 25% of undergraduate researchers work alone. Unfortunately, surveys such as the ROLE or SURE are directed at individual students and so cannot capture group dynamics that affect the other 75% to 80%. There is a substantial literature, however, on groups and teams that can be tapped for advice on group mentoring. McIntyre and Salas studied team performance and decision making and formulated a series of 20 principles regarding team performance.[176] Among the principles most relevant to undergraduate research is that "teamwork and taskwork are distinct." True teamwork includes interactive behaviors, while taskwork is performed by an individual. When a group of undergraduate researchers is assigned to "additive tasks—tasks that people could do separately and then sum up,"[177] the group is not fully functioning as a research team. Rather, the group should become interdependent, by performing tasks that depend on the success of other team members' work and by becoming aware of the contribution of each member to the team. Teamwork includes communicating, monitoring, and providing feedback between group members. The mentor serves as a model for teamwork and provides performance feedback to team members. According to McIntyre and Salas, an authoritarian leadership style interferes with team effectiveness.[178] The authoritarian leader, who does not respond to feedback or treat students as colleagues, fares poorly in the mentoring literature.

Mentoring and leadership

Mentoring is a kind of leadership, and leadership has an extensive research literature. It is useful to borrow from the leadership literature to enhance our sense of what mentors can do. Leadership style is often described along a dimension of authoritarian to democratic. The authoritarian leader reserves decisions to himself or herself; a democratic leader allows his or her subordinates a voice in decisions. The leadership research has produced a variety of theories that treat leadership skill as a sort of meta-cognition. According to this view, the key to practicing good leadership is to size up decision-making situations that affect the organization and its members, or in the present context, research and researchers.

For example, power is a feature of leadership. In most undergraduate research programs faculty mentors have the power to grade, or to pay, or to provide a letter of recommendation for the undergraduate student. One consequence of power can be an authoritarian leadership style because the faculty member holds all the cards. But an authoritarian style is not best for the success of the research project or the development of the students, who, as we have seen, prefer a democratic style. On the other hand, an overly democratic style may lead to poor decision-making if the group is inclined to avoid hard work or if the group is not unified.

How does a mentor calibrate the best combination of leadership styles during a research project? A useful approach to this meta-cognitive decision is to contemplate the idea of structure, which was discussed earlier. Structure can refer to the framework of a research project, such as scheduling and the assignment of tasks. Structure also refers to the nature of the research problem, with well-structured problems being those that have a "high degree of specificity" that "can be solved with a high degree of certainty, and evoke high agreement on the correct solution." Highly structured problems permit an authoritarian leadership style. The leader knows what is to be done and assigns workers to do it. Ill-structured problems, in contrast, require a more democratic style. As Fiedler pointed out, "compliance with a task order can be enforced only if the task is relatively well structured. One cannot force a group to perform well on an unstructured task such as developing a new product or writing a good play."[179] Organizational psychologist Victor Vroom devised a decision tree for choosing among authoritarian, consulting, or democratic leadership styles based on a series of questions about the situation.[180] His decision tree is too complicated to reproduce here; however, one question for the leader to consider is whether the problem is adequately structured. If the answer is no, then all of the branches of the decision tree lead to group decision making or employing subordinates as consultants. Once it is recognized that the problem is ill-structured, no path leads to authoritarian leadership.

A mentor has an additional motive to consider leadership as a kind of meta-cognition. The mentor provides the undergraduate student with a role model for leadership. As we have seen, undergraduate researchers are sometimes placed in peer mentoring roles in which they learn to practice leadership. The kind of leaders students become depends on the kind of leaders from whom they learn.

Table 5-1

ROLE survey items on mentor traits. Scoring on some items was reflected during data analysis so that high scores were related to positive attributes.

Research on working environments indicates that different sorts of mentor characteristics may be effective in different work environments. For the pairs of words below, choose a number that best characterizes the behavior of your research mentor. Your choice of the appropriate number does not necessarily indicate approval or disapproval.

How would you rate your mentor according to these characteristics?						*Circle a number.*
Distant	1	2	3	4	5	Friendly
Reliable	1	2	3	4	5	Unreliable
Condescending	1	2	3	4	5	Respectful
Organized	1	2	3	4	5	Disorganized
Authoritarian	1	2	3	4	5	Democratic
Communication is clear	1	2	3	4	5	Communication is unclear
Responsive to your questions	1	2	3	4	5	Unresponsive to questions
Does not treat you like a colleague	1	2	3	4	5	Treats you like a colleague

Table 5-2

Comments from student researchers about their mentors.

The most important thing for me was that the mentors were down to earth and worked with me side by side, they treated me like I was a colleague.
The most important part of my summer research experience was my amazing mentor. She guided me through the planning, execution, and analysis of my work while allowing me enough space to work independently.
The summer research dispelled some ideas of what the research field is like, while confirming others. The direct and personal interaction with the professors also strengthened confidence in my own ability around the lab.
The most important thing was my mentor. A good mentor is essential to the entire experience.
Part of what made my summer research experience so wonderful was the relationship I developed with my research advisor. I found that she was not only a mentor for my scientific field, but also a friend. Also, I particularly enjoyed the idea that I was contributing to the field of science and that my discoveries or work may develop into something future students might study and learn from.
It was terrific to be a part of a learning and researching community. My mentor gave me help when I needed it, but also allowed me to do some independent thinking and experimentation. As well, the summer of research provided me with the skills and connections that will be imperative in my future educational goals.
I think one of the reasons why I enjoyed and learned from my summer research so much is that I had good mentors. They set high goals for me (while realizing that I still had limitations as an undergrad) so that I was an active participant in the research rather than a mere “worker.”

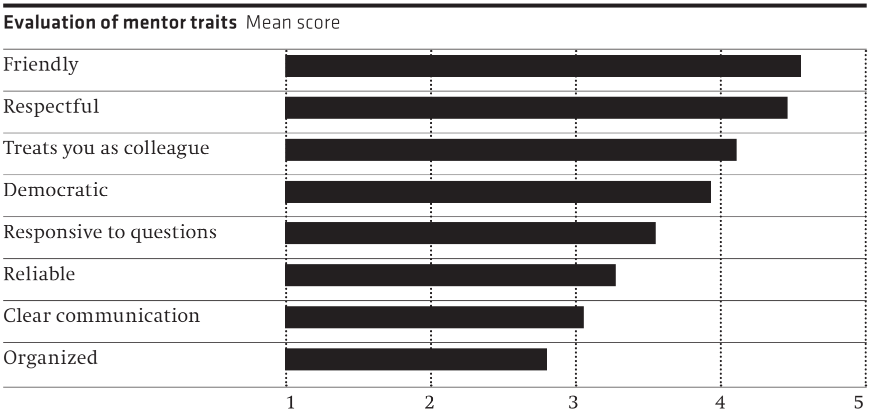


Figure 5-1

Mean evaluation of mentor traits by 384 undergraduate researchers on the ROLE survey. The results are presented such that the means are in the direction of the positive traits listed on the left. Friendliness received the highest evaluation, organization the lowest.

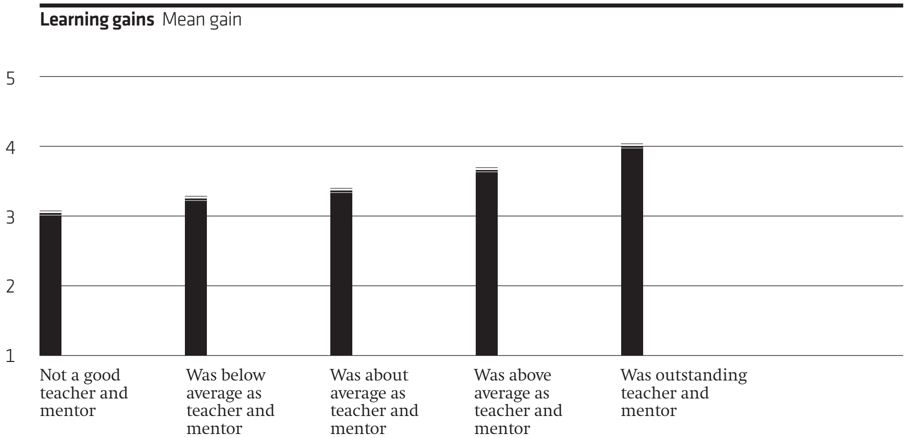


Figure 5-2

Mean of 21 learning gains reported by SURE survey participants over two years categorized by their evaluation of their research supervisor. Mean learning gains increments in statistically significant steps as the evaluation becomes more positive.

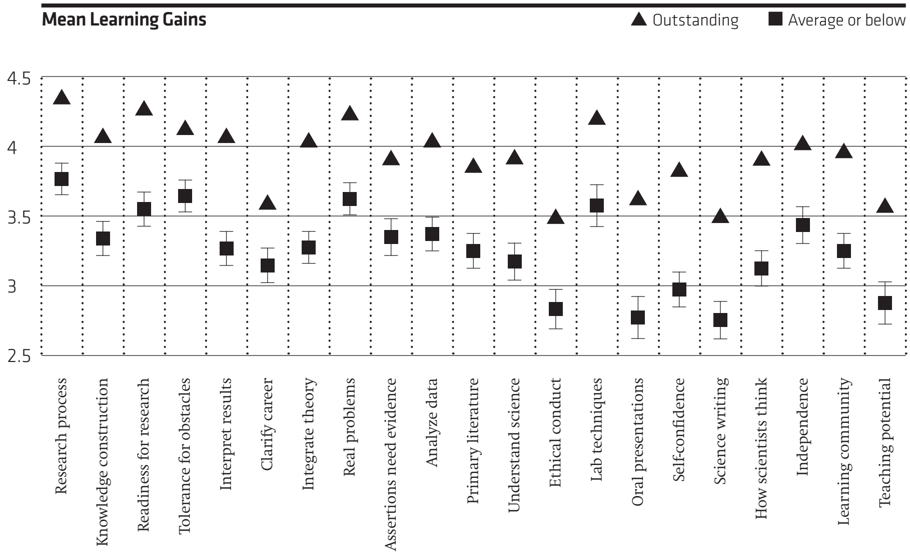


Figure 5-3

Mean learning gains for two groups of student researchers in the summer of 2007. The squares represent the means from 377 students who rated their supervisor as average or below average as a teacher and mentor. The vertical error bars represent two standard errors above and below the means. The triangles represent the means from 881 students who rated their supervisor as outstanding. Students report significantly higher learning gains with an outstanding mentor.

6

The teaching scholar

Learning and teaching are constantly interchanging activities. One learns by teaching; one cannot teach except by constant learning. A person properly concerned about education will come to grips with the practical realities of both teaching and learning.
K.E. Eble, *The Craft of Teaching*

Herman von Helmholtz, the 19th century researcher in the fields of physics, physiology, and psychology, wrote, "Anyone who desires to give his hearers a perfect conviction of the truth of his principles must, first of all, know from his own experience how conviction is acquired and how not. He must have known how to acquire conviction where no predecessor had been before him-that is, he must have worked at the confines of human knowledge, and have conquered for it new regions. A teacher who retails convictions which are foreign to him, is sufficient for those pupils who depend upon authority as the source of their knowledge, but not for such as require bases for their conviction which extend to the very bottom."[181] In other words, a good teacher ought to be an active scholar. Philosopher Alfred North Whitehead extended the idea to a reciprocal relation with students. He wrote, "Do you want your teachers to be imaginative? Then encourage them to research. Do you want your researchers to be imaginative? Then bring them into intellectual sympathy with the young at the most eager, imaginative period of life, when intellects are just entering upon their mature discipline."[182]

Ideally, a person of demonstrated scholarship forms a learning community with a group of aspiring student scholars. But instead of a community, we often see a hive of large lecture classes where teaching is disconnected from scholarship and students are barricaded from a source of interest in science. This hive has grown large over the years. The advantage of undergraduate research is that it restores the relation between scholar and student. It permits students access to the most valuable chambers in the hive. Undergraduate research induces coherence between the roles of teacher and scholar. James

Gentile asserts, "We operate on the principle that undergraduate research is not only the essential component of good teaching and effective learning, but also that research with undergraduate students is in itself the purest form of teaching."[183] Ernest Boyer quotes Aristotle, "Teaching is the highest form of understanding."[184] To synthesize: research with undergraduate students is the purest form of teaching, and teaching is the highest form of understanding. We are all learners, teacher and student alike, and we can function best as a community.

The unity of the teacher and scholar familiar to Helmholtz gave way to the dichotomy between teaching and scholarship. In the contemporary American educational system, career choice points occur that compel one career over another: teaching at primarily undergraduate institutions, research at universities. The Boyer Commission wrote, "At many universities, research faculty and undergraduate students do not expect to interact with each other, and both groups distinguish between teachers and researchers as though the two experiences are not inextricably linked."[185] The two sets of activities are seen as mutually exclusive; therefore, the more time spent on one, the less on the other. While some reformers advocate that "distinguished researchers engaged in education reforms should exhort faculty, staff, and administrators to unite in education reform and should dispel the notion that excellence in teaching is incompatible with first-rate research,"[186] James Luken observes that "More time spent on innovation in teaching typically means less time available for conducting research."[187] James Trefill, writing about science education, noted an example of a department chairman who advised a professor that "if you spend more than 10% of your time on teaching...you'll be hurting your chances for promotion to full professor."[188]

An argument for distinction

On what grounds do we consider teaching and research different? Barnett[189] examined the relationship between teaching and research and concluded they were distinctly different activities. He considered six differences between them:

Research is public; higher education is private. By this distinction Barnett means that research is "an attempt to produce objective knowledge" while education is "essentially a personal affair."

Research is a matter of outcome; higher education is a matter of process. For research, "outcome is all." The outcome of the research, a publication or patent, has to be significant. For education, "there is no outcome as such." Education is a "process of self-development, in which they [students] take responsibility for enlarging and deepening their own consciousness."

In research, learning is a by-product; in higher education, it is intended. If learning is defined as personal development, then no such development need occur as a result of research. Learning should occur in education.

Research is closed; higher education is open. In research, “the researcher starts off with a fairly hazy idea of what might emerge and ends with a precise formulation or conclusion.” In education, “The student starts off with a fairly definite hold on the world...but at the end of the course has grasped that very little of the intellectual world has enduring substance and that there are always more cognitive spectacles to put on.”

Research is a necessary but not sufficient ingredient for higher education. While higher education draws on research, “introducing research into the curriculum is justifiable provided it is used to expand the student’s intellectual horizons, and not because it propels the students toward becoming embryonic researchers.”

The academic community is directly related to research, but indirectly related to higher education. Academics are “locked into their own epistemic community, composed of others who are working in the same subject areas.” This community includes research institutes, industrial laboratories, and others. Students are “not (or only exceptionally) full members of the academic community. Occasionally, a student—perhaps in mathematics or logic—can be seen actually to make a contribution to the research literature, but that is so rare as to appear precocious.”

Barnett’s view is summed up by his observation that “knowledge in the context of discovery and knowledge in the context of transmission are entirely different enterprises.”

Barnett’s position is supported by some studies of the relationship between teaching and research in higher education. Chang and Astin[190] examined faculty survey data for the relationship between two aspects of institutional environment, student orientation and research orientation. They found a negative correlation between these two environmental variables. The few exceptions were among selective liberal arts colleges.[191] Thus, the roles of teacher and researcher would appear to be distinct.

An argument for interdependence

But are they? Findings regarding the independence or even inverse relation between teaching and research may simply reflect the behavior of faculty who are acting on the *assumption* that the activities are opposed. It has been pointed out, for example, by the Boyer Commission that institutional reward systems reinforce the distinction. Viewed through the experience of large lecture courses to undergraduates where general principles of the science are transmitted, the distinction between teaching and research seems obvious. Viewed, however, through the experience of undergraduate research, these distinctions do not hold up.

Let's go through Barnett's six assertions again while thinking about undergraduate researchers working with a mentor:

Research is public; higher education is private. In undergraduate research there is reciprocation between the public and the private. The public nature of research, in its aspects of communication and exposure to critique, is an essential element of the research experience and an essential element of the learning experience. At the same time, the research experience becomes private, in the sense of personal, as the student takes ownership of the research.

Research is a matter of outcome; higher education is a matter of process. Having an outcome makes the research process authentic, but the process of student development is a goal of undergraduate research. The research outcome of undergraduate research is essential to student learning.

In research, learning is a by-product; in higher education, it is intended. In undergraduate research, learning is intended.

Research is closed; higher education is open. Research problems may produce a sharpening of student critical thinking. Research problems need to be structured, and the exercise of structuring an ill-structured problem is formative in the development of reflective judgment.[192] Students achieving advances in epistemological development learn that assertions about the world are made in context rather than absolutely, and they learn the rules of evidence to support their assertions. The student of science also appreciates the observation that scientific findings always seem to raise more questions—that the work opens more avenues of inquiry than it closes.

Research is a necessary but not sufficient ingredient for higher education. In undergraduate research, the research question becomes the focus of the educational enterprise. Recalling the benefits of undergraduate research, one of which is the greater insight into career clarification that includes not continuing in a research career, students become not so much "embryonic researchers" as insightful thinkers.

The academic community is directly related to research, but indirectly related to higher education. By taking part in the research enterprise, students become members of the research community that Barnett describes. Attending professional meetings and co-authoring research publications are manifestations of this membership. Student contributions to new knowledge are increasing, in genomics, for example, where undergraduates contribute to the identification and annotation of genes.

The characterization of learning as a private experience with no outcome, as Barnett asserts, is not the case in undergraduate research, as the key developmental dynamic is the testing of the young researcher's ideas and skills by the research community, as discussed in Chapter 2. More generally, this student learning while doing research breaks down the dichotomy between learning and research and so breaks down the dichotomy between teaching and research.

The teacher as scholar can speak knowledgably about his or her research and is eager to join with students in the effort to move the research forward. This activity requires what developmental psychologists call "scaffolding," providing enough intellectual framework so that the students understand what they are doing. The extent of this scaffolding is a matter of debate.

Traditionalists believe that some core coursework must be completed before students are ready for undergraduate research. The alternative is sometimes called "inductive teaching," in which the course instructor presents students with problems or data related to a specific topic. Inductive teaching methods include inquiry-based learning, problem-based learning, and Just-In-Time teaching. They are approaches that teach less content while revealing the methodological basis of knowledge.

Undergraduate research experiences, especially those for younger students, are a form of inductive teaching and learning. This approach to education opposes the traditional wisdom that students need the complete transmission of disciplinary knowledge before they are capable of discovery.

The argument that teaching and research are fundamentally different activities, then, evaporates when looking specifically at undergraduate research. Perhaps there is a difference, however, in the personalities of teachers and researchers that causes difficulties for those who aspire to be both. Scientists are often described as introverted, stable, and dull. Feist and Gorman, in their overview of the psychology of science, report that "scientists, relative to nonscientists, do prefer to be alone and are somewhat less social."[193] Teachers, on the other hand, describe themselves as artists and may be extraverted and even theatrical. William James, offering advice to teachers based on psychological science, was aware that we conceive of teaching as an art. His first lecture was entitled "Psychology and Teaching Art," and his warning to his listeners was, "Psychology is a science, and teaching is an art; and sciences never generate arts directly out of themselves. An intermediary inventive mind must make the application, by using its originality."[194] More recently, Larry Cuban lamented, "Too often, teaching has been stripped of its artistic and human dimensions and made into a series of technical moves that can be swiftly learned and put into practice by anyone of average intelligence."[195]

The customs of traditional teaching, including performance and evaluation, typically do not recognize any effort by the teacher to investigate his or her own enterprise. Teaching is viewed as a kind of performance art undertaken by an intuitive actor.[196] The concept is so embedded in college teaching that I have had professors tell me that they don't know how they do what they do; that no instrument could measure the quality of their performance; or that to examine the phenomenon of their teaching would destroy it. If teaching is an art, and teachers are judged as artists, then it is understandable that even scientists might be reluctant to pursue teaching as a scientific enterprise. Just as scientists might be rewarded for their use of generally acceptable methodology, artists are rewarded by the seeming absence of generally acceptable methodology. Helmholtz noted, "If we do find that the artist has consciously worked after general rules and abstractions, we think his work poor and commonplace, and cease to admire."[197] Skinner observed that "the amount of credit a person receives is related in a curious way to the visibility of the causes of his behavior. We withhold credit when the causes are conspicuous."[198]

This is not simply a matter of ego; institutional evaluation is often dependent on the personal characteristics of the teacher. The most common instrument of teacher evaluation, the student end-of-course evaluation, is clearly influenced by personal traits. Every college professor is familiar with the stories of teachers who increased their student evaluation scores by smiling more, telling jokes, or serving the students chocolates. Gentile writes, "Sometimes student evaluations are like gauging theatrical performance. We ask, 'Did you like it?' 'Was your instructor on time?' and we find that most risk-takers often get sideswiped by evaluations."[199]

The performance aspect of teaching was familiar to Helmholtz in 1877, who attributed it to the French. "French teaching is confined to that which is clearly established...and does not excite doubt nor the necessity for deeper inquiry." Helmholtz preferred the approach of his German colleagues, who were scholars that taught. "It cannot also be doubted that many original men, who have done considerable scientific work, have often an uncouth, heavy, and hesitating delivery. Yet I have not infrequently seen that such teachers have crowded lecture-rooms, while empty-headed orators excited astonishment in the first lecture, fatigue in the second, and were deserted in the third."[200]

Scientific Teaching

We need not assume that because we are scholars who teach that we will be considered uncouth. There is considerable support, in the form of literature, teaching societies, and teaching and learning centers, for those who wish to polish their classroom manner. Of deeper significance is the need to understand the effect of our efforts on student learning.

An emerging model for the unity of teaching and research is "Scientific

Teaching."[201] That means "teaching is approached with the same rigor as science at its best." Scientific teaching advocates experimentation coupled with measurement of student learning. It incorporates all the variations of teaching, including lecture, problem-based learning, and so on. This "research applied to teaching" model does not rest on a routine collection of data for external stakeholders; it suggests that the teacher is an innovator in the same way that the researcher is an innovator. Scientific teaching challenges the insulated approach that some scientists use in teaching: "Why do outstanding scientists who demand rigorous proof for scientific assertions in their research continue to use, and indeed defend based on intuition alone, teaching methods that are not the most effective?"[202]

Scientific teaching includes both modeling the process of science and using data to learn about student learning. Assessing learning is guided by psychological science, recapturing the intent of William James but privileging student learning above faculty ego. An excellent overview of the approach, including reading the relevant literature, assessing the baseline situation, and collecting data on learning, is provided by Carl Wieman.[203]

The aim of scientific teaching is not scientific management, finding the "one best way" to teach science. To the contrary, a scientific approach to teaching might yield contextual variables that moderate the success of a pedagogical approach. For example, research may specify the conditions under which lecturing, the straw man of science reform, is the optimal way to facilitate learning. The scientist-teacher faces the same challenges as the scientific researcher: to abandon preconceptions of student learning if they are not corroborated by data; to sharpen the validity of measures; and to face the methodological challenges of this research. It is possible that the repeated assessment of student learning in a regularly taught course will lose some informational value, becoming more like the lesser valued replication research than the more valued novel research. But variations on the process of teaching, modifying an approach to take advantage of published results of other teachers or of changes in technology, for example, compel additional data collection and endow each iteration of the course with a certain freshness, a replication rather than a repetition. As a classroom technique, scientific teaching is a system of tinkering and fine tuning designed to improve the aggregate. The data from the measures of student learning will permit the researcher to know that learning, retention, and transfer of training are improving.

Scientific teaching does not dictate that a teacher's research program must be part of what he or she teaches. Imagine, though, if it were. When the teacher includes her research interests as teaching material, then the gap between teaching and research closes. When undergraduates become involved with the teacher's research, the gap between research and learning also closes. Recalling that "research with undergraduate students is in itself the purest form of teaching," we notice that the undergraduate research experience provides students with a more complete view of science and the scientist. The students see the scientist behave rather than talk about behaving.

The scholar as teacher provides the student with a unified role model. She provides the student with exemplars of teaching embedded in research and of research embedded in teaching. The role she models for the student includes behaviors that are called by various names, such as "thinking and working like a scientist"[204] and "scientific habits of mind."[205] These behaviors are more easily demonstrated than discussed. The philosopher Michael Polanyi once asserted that "we know more than we can tell," that we possess a wealth of tacit knowledge that we employ to perceive and process the world. He believed that the tacit knowledge required for scientific discovery could not be directly articulated. The excitement and hopefulness of the pursuit of discovery, however, can be shown to the student who participates in the scholar's research. The traditional approach to teaching and scholarship usually inhibits the scholar from revealing excitement and interest in the classroom. The traditional classroom lecture is an episode of information transmission in which every bit of information is articulated through words or pictures. But tacit knowledge involved in discovery, including how the researcher comes to identify a problem, how he or she incubates a hunch, and how undisclosed implications of research are sensed, are best witnessed in action.[206]

Earlier, I suggested that students doing authentic research are looking for knowledge previously unknown to everyone. This is contrasted to a second more common approach in which students discover knowledge that is already known to the course instructor. Scientific teaching suggests a third kind of knowledge: that which is known to the student but not to the instructor. Assessment of this knowledge may uncover student preconceptions about the material[207] or lack of retention of course material. In the context of undergraduate research, in which the relationship between the faculty and student is intense, the faculty mentor may find it necessary to extend this knowledge of what is known to the student to include personal preconceptions or misconceptions, feelings of self-efficacy or inadequacy, or other personal dispositions related to the student's success in research and planning for a science career. The assessment techniques of the classroom instructor are often geared to gathering information from a large group of students who presumably share a nearly identical experience. These techniques may include quantitative measures with each student treated as a replication of the educational experiment. The assessment techniques required by the mentor, on the other hand, are usually those of a case study. Even those students in a research group are, for the mentor, unique in their learning experience and their plans for the future. Using the techniques of a case study recalls the advice given by training manuals for mentors, such as asking the students about themselves and developing good listening skills.

Congruence

The unity of teacher and scholar provides the student with a role model whose life is relatively "congruent" or harmonious. Integrated science suggests an integrated scientist. There are two reasons to think about this aspect of unity.

First, there is a long literature in clinical psychology that claims that a successful professional needs to achieve congruence in his or her role. Carl Rogers wrote that we recognize congruence in other individuals. "We recognize that he not only means exactly what he says, but that his deepest feelings also match what he is expressing."[208] This perception aids in a "comfortable and secure" relationship. Science mentors are not therapists, and should not be, but the interpersonal dimension of mentoring, "good listeners, good observers, and good problem-solvers," suggests that mentors whose own identities are fragmented will not be fully successful as mentors.

Second, students observe the scientist for clues about the quality of working life. Science faculty whose teaching is superficial, rushed, and uninspired signal to students that the life they have chosen carries considerable strain.[209] Faculty who trade off proportions of their work life between teaching and research see their tasks as segmented and competing. It is far more attractive to the next generation of STEM workers to see the working life as congruent and complementary.

What would a congruent career look like? There is no single model, but we would look for teaching scholars who decline to structure their lives as a series of dichotomies: teaching versus research, family versus work, departmental versus interdisciplinary connections. These teaching scholars do not disconnect the present state of knowledge from its uncertain and creative genesis. They model the research process in the classroom, showing the connections between current knowledge and the means by which it was acquired, and also showing the intimate connections between their knowledge and the means by which they acquired it. They understand that collaboration with undergraduate researchers is a form of teaching. They do not use success at one activity to compensate for failure at another, taking comfort that they may be good researchers while continuing as poor teachers. Neither do they disconnect the components of their lives, but find that success at one is contingent in part on success in all.

The aspiration toward congruence uncovers a broader meaning in the observations of Helmholtz cited earlier. No teacher should retail convictions which are foreign to him or to her, and the range of our convictions includes those we model for students about the satisfaction derived from exploring scientific knowledge, research, and a life of science worth living.

7

Undergraduate research and institutional transformation

Universities are communities of learners, whether those learners are astrophysicists examining matter in the far reaches of space or freshmen new to an expanded universe of learning. The shared goals of investigation and discovery should bind together the disparate elements to create a sense of wholeness.
The Boyer Commission

Barriers to change

Undergraduate research yields many benefits for students. The potential gains have not yet been fully catalogued. New kinds of undergraduate research, such as those on interdisciplinary problems, may further enhance the attraction of this way of learning. Undergraduate research programs yield benefits for faculty, for departments, and for institutions. Undergraduate researchers energize departments, colleges, and universities. Students working on research may be seen buzzing like electrons down the windowed corridors of the science building. An optimal undergraduate research program produces benefits that connect with the demands for a new generation of scientists to meet the country's economic and technological needs. Yet attempts to realize an optimal program often meet resistance from the long-standing structures of the institution. In this chapter we look at some of the barriers to institutional change and look at some suggestions for overcoming them.

The catalysts for change and the barriers to change reside in the same familiar places, like two electrodes on a battery. Academic departments with their constituent leaders and senior members occupy the two poles: change agents or conservators of tradition. Students tend to polarize around these two mindsets. Tenure requirements, measures of success, and reward systems can facilitate change or preserve the status quo. A departmental battery has two electrodes with substantial stored energy connected by the wire of relationships. What is needed is an ionic solution to allow ions to flow between the electrodes, allowing electrons to flow through the wire and harness the stored energy in the battery. Undergraduate research is that ionic solution.

In the past century disciplines evolved toward more specialized and fractionalized departments. Faculty stopped being citizens of the college or university and became citizens of the academic department. As departments grew, they were entrusted with the tools of their own continuity. Typically, academic departments have the power to hire, renew, promote, and tenure faculty; to set curriculum; and to train undergraduate students. They became self-perpetuating.[210] For science departments, the on-going specialization was congruent with the overall strategy of science. Physicist Michio Kaku observed that the sciences proceeded largely by "reducing everything to its smallest components." Reductionism is consistent with specialization, as scientists "probed deeper and deeper into their subdisciplines smugly ignoring the developments in other fields."[211]

Wedin, in an insightful article on the future of science education, catalogues the barriers to reform. The first was inertia, observed in both individual faculty members and in academic departments. He writes, "The system of science education that's been in place for generations tends to stay in place."[212] The justification for the status quo is evocative of Lamarckism: the faculty pass on their acquired characteristics. Tobias remarks that "What we are left with… is the strong sense that scientists are born, not made. Unless they are unusually self-motivated, extraordinarily self-confident, virtually teacher- and curriculum-proof, indifferent to material outcomes, single-minded and single-track, in short, *unless they are younger versions of the science community itself,* many otherwise intelligent, curious, and ambitious young people have every reason to conclude there is no place for *them* in science."[213] Trefil concurs: "The attitude seems to be that unless science is taught with the goal of producing future scientists in mind–miniature copies of ourselves—it is somehow unworthy."[214] Wedin quotes William Wood remarking (critically) about status quo scientists, "I came up through the lecture system and I did fine. All my colleagues did, too, and they're all successful academics. So what's the problem?"[215]

This replication continues past undergraduate education into the early years of science careers, where senior scientists, acting as reviewers of grant proposals and scientific publications, favor "safe science" and avoid risk. Alberts writes, "This helps to explain why so many of our best young people are doing 'me too' science, working in areas where they compete head-to-head with other scientists who have gone before them—often their mentors or those who have trained in the same laboratory."[216] Veteran scientists have no strong motivation to make the effort to change the way they teach, and the existing structure of courses, majors, and textbooks reflects the fractionalized, discipline-based way of teaching students. Rowley and his colleagues note that, "If the faculty are senior, tenured, and not heavily engaged in creative activity or research, their resistance will be nearly impermeable."[217] They also observe that "faculty are, by role and ability, experts. Experts do not heed others well."

One drawback of inheriting the previous generation's modes of education and research is that the next generation engages in safe learning and safe science. This legacy is problematic in at least two ways: first, because it does not lead to the kind of risk taking, transformative science that experts call for; and second, because it does not facilitate recruitment and retention of scientists who are not copies of the older generation, i.e., it retards diversity.

Wedin points out that faculty are not the only conservatives in a science department. Students are the second barrier to reform, as they can oppose change that produces more challenging and effortful education. Teachers who try on a new role as a collegial researcher or course innovator sometimes feel the opposition of students, who worry about getting enough facts and vocabulary for a pre-professional test or just feel uncomfortable with any new mode of learning. In Tobias' report on the second-tier students, one correspondent, Eric, noticed the attitude of physics students. "The lack of community, together with the lack of interchange between the professor and the students, combines to produce a totally passive classroom experience."[218] Eric's fellow students "have had no training in working collectively. In fact, their experience will have taught them to fear cooperation, and that another person's intellectual achievement will be detrimental to their own."[219] Most teaching innovations such as teamwork, peer mentoring, or research groups, require that the teacher "step out of the middle" where she is the authority. As Finkel and Monk noted, "students are likely to resist the teacher's attempt to step out of the middle because they perceive this switch in roles as an attempt to abandon responsible leadership."[220] Teaching innovations tend to put more of the burden of active learning on the students, who may resist this challenge and voice displeasure in course evaluations. Wedin quotes Jack Wilson, president of the University of Massachusetts System, as saying, "We've created an education system where we pretend to teach them; they pretend to learn. Nobody asks too many questions; everybody is happy."[221]

The third barrier to reform, according to Wedin, is the tenure process.[222] As we have seen, assistant professors have occasionally been warned that they should not spend more than 10% of their time teaching. The pressure to sacrifice teaching for research can occur even earlier. One assessment of a career-awards grant program that helped post-doctoral recipients make the transition to tenure-track faculty positions not only noted that the grant stipulated that 80% of the recipient's time be spent on research, but reported that recipients in fact spent over 89% of their time on research.[223] Promotion, recontracting, and tenure still depend heavily at many institutions on research output, despite years of scathing criticism and promises for reform.[224] Because working with undergraduate researchers is viewed as a form of teaching that slows down research output, researchers often choose to sacrifice opportunities to collaborate with students in favor of producing publications.

Other barriers to reform, following Wedin, are lack of good measures of student learning and good communication about the successes teachers have had in improving student learning. There is no universally accepted measure of student learning in undergraduate research. Indeed, the term "learning" is overly general in this area, encompassing as it does cognitive, behavioral, and attitudinal changes. Some of the learning outcomes of undergraduate research are distant, occurring well after the experience is over. Delayed outcomes include attendance at graduate school, earning a graduate degree, and becoming a successful teacher and researcher. Becoming a co-author of a publication in a peer-reviewed journal or some other indicator of research creativity, even if based on the undergraduate experience, often happen months or years after the student graduates. Other outcomes, though proximal to the experience, are personal, including greater self-confidence, tolerance for obstacles, and independence. These are legitimately measured through student self-report and student behavior. Undergraduate research experiences may not affect scores on a standardized senior exam, or on any exam that assumes every student has had an identical learning experience, because undergraduate research does not produce identical learning experiences.

Research design problems in assessment abound, including the mostly fruitless search for the perfect control group and the tendency for undergraduate research programs to select their participants nonrandomly. Nevertheless, there is a literature of assessment of undergraduate research outcomes, not to mention the other active pedagogies of science education. Few scientists, however, are familiar with the literature. Publications by the Council of Undergraduate Research, by Project Kaleidoscope, by a growing number of journals, as well as sections on science education at national meetings of science organizations, make it possible for all of us to get sufficient information. But, as Wedin pointed out, that doesn't mean that scientists will talk about science education around the coffeepot.

Forecasting

The various government committees and learned groups cited in the first chapter have made their forecasts concerning America's need for a STEM workforce. Some sense of the future, however cloudy, helps guide planning. Gentile challenges his audience to think about what the world will look like in 25 years.[225] He sees tremendous changes in all aspects of science, including research, teaching, instruments and facilities. He sees the future of science as "problem-centered on issues that transcend disciplinary boundaries," with science becoming increasingly complex, collaborative, and costly. Sir John Maddox, former editor of the journal *Nature*, predicts a future for science driven by matter, life, and "our world." He writes, "Despite assertions to the contrary, the lode of discovery is far from worked out."[226] Kaku asserts that science is now driven by three revolutions, quantum, computer, and biomolecular. He writes, "The heyday of reductionism is probably past....This is heralding a new era, one of synergy."[227] The composite vision is one of problem-centered, interdisciplinary, collaborative science: what Gentile characterizes as "systems science."[228]

This evolution of science would be welcome to Abraham Maslow, the humanistic psychologist who wrote perceptively about problem-centering versus means-centering in science in 1946.[229] Maslow noticed that means-centering, a term anticipating Tobias' "tyranny of technique" observation, is the "tendency to consider that the essence of science lies in its instruments, techniques, procedures, apparatus and its methods rather than in its problems, questions, functions or goals." Means-centered science excludes the big picture, ignoring ethical and moral issues. According to Maslow, means-centering "tends to compartmentalize the sciences." Means-centered science had implications for science education: "The student is encouraged to identify science with directed manipulations of apparatus, and with rote procedures learned out of a cook book." Maslow, unfortunately, did not take the time to describe how science education will change as science moves from means-centering to problem-centering, but we can imagine the changes in the context of undergraduate research. Undergraduates will work in teams, probably co-mentored by several faculty or other experts who gather as a team to solve a problem. Students, taking advantage of their power to cross departments and divisions in pursuit of their education, will act to connect faculty who otherwise might not collaborate. Faculty will find they need more information about other disciplines, leading to conversations and tutorials among faculty peers. The interdisciplinary nature of the scientific problems may cause the network of community members to grow: the chemists and biologists working at the boundaries of their disciplines may seek additional collaboration from mathematicians and philosophers. Thus problem-centered research will "bind together the disparate elements to create a sense of wholeness." This holistic system is the future of science education.

An interdisciplinary, problem-centered, research-centered undergraduate science curriculum promises to change the role of students from a source of inertia to a driving force in creating new networks of collaborators. First-year students could be introduced to an interdisciplinary research problem. They may realize they need additional knowledge of the issues involved with the problem, and so see a consistency between general education and their own needs.[230] Biology students, for example, may find the motivation to take relevant courses in mathematics, physics, psychology, and philosophy. The current lack of enthusiasm with which most students undertake general education may be lessened by the congruence between this education and their own interests. Students would become intentional learners.[231]

An interdisciplinary, problem-centered, research-centered undergraduate science curriculum promises to change the focus of faculty members from the teaching-versus-research dichotomy to a more unified, fully-functioning approach to science education. This unity, in turn, may affect the faculty, who are currently concerned with the roles they play (teacher, researcher, community member, family member) and the role strain that occasions distress. Scientists have taken reductionism too personally. Roe, in her study of eminent scientists of the 1950s, described a typical case:

> He works hard and devotedly in his laboratory, often seven days a week. He says his work is his life, and he has few recreations.... He avoids social affairs and political activity, and religion plays no part in his life or thinking. Better than any other interest or activity, scientific research seems to meet the inner need of his nature.[232]

More recent observations of scientists come to similar conclusions. The scientist is introverted and not sociable. Her life has been reduced to that of a specialist. A transformation to a professional life in which the scientist sees research as linked to teaching, in which research is a social activity, with opportunities to mentor and be mentored, may lead to greater satisfaction and quality of working life.

Reward systems

The institutional system of rewards signifies its attitude toward teaching, signaling that teaching is antithetical to research success or that teaching is part of a holistic approach to science. Gentile lists the academic reward system among the problems that may impede reform, along with program evaluation, risk management, lengthy start-up times for young professionals, and budget strategies.[233] Many readers are familiar with the status quo, that young professionals are now taking longer to get a tenure-track position; that the grants system is stacked against them; that assessment or program evaluation plans are to be feared because they might reflect on the worth of the teacher or research mentor; that publications are prominent in the evaluation of professors, even at liberal arts colleges, because they are easy to count, while good teaching is difficult to measure; that researchers are encouraged by the system to conduct safe rather than risky transformational research; and that budgets are tight.

One does not have to look far to see that evaluation and reward account for a great deal of this culture. For example, most faculty report their annual professional activities to their institution by means of a faculty activity report or a revised professional vitae. Commonly, the form for reporting is divided into three distinct categories of activity: teaching, research (or scholarship), and service. The categorization reinforces the separation between teaching and research as independent activities. There is no format to convey the accomplishments of scientific teaching or mentoring undergraduate researchers, and so there is little opportunity for institutions to notice and reward innovation in teaching.

Things need not be so. Gentile contrasts the lack of reward for innovation in teaching with the attitude of grant reviewers, who are charged with looking for and rewarding innovation. Gentile's observation could be supplemented by another, that within a college or university non-funded grant proposals are often treated as an accomplishment. The reviews of a grant proposal may find merit in the author's ideas; fiscal limits, however, preclude funding. At some institutions the administration gives the grant proposer money for some or all of the items or activities requested on the externally rejected grant proposal. Taking the risk of writing the grant is thus rewarded by acknowledging the process rather than the product. The same tactic could be adopted to reward innovations in teaching by acknowledging the process of innovation and being more skeptical about negative evaluations from students who simply seem to prefer the status quo.

Managing risk

Focusing on the desirable processes in science education and on science education research might be a means to reward risk-taking and experimentation in those areas as well. How can institutions use rewards to encourage risk-taking and innovation while avoiding the paralyzing effect of failure? Gentile urges faculty members to "embrace failure as well as embrace success."[234] Failure is more common than success in scientific research. Gentile estimates that failure happens 80% of the time; Nobel Laureate Sir Harold Kroto has been quoted as saying, "Nine out of ten of my experiments fail, and that is considered a pretty good record amongst scientists."[235]

This failure rate may seem disturbing. Could it be that scientific teaching with its emphasis on experimentation will also be accompanied by a high failure rate? How could we tolerate this failure rate for teaching science? Of course, we might ask if a high failure rate, measured by student learning, already exists. Wieman, in his discussion of scientific teaching, tested student retention in physics:

> A number of times Kathy Perkins and I have presented some non-obvious fact in a lecture along with an illustration, and then quizzed the students 15 minutes later on the fact. About 10% usually remember it by then. To see whether we simply had mentally deficient students, I once repeated this experiment when I was giving a departmental colloquium at one of the leading physics departments in the United States. The audience was made up of physics faculty members and graduate students, but the result was about the same – around 10 percent.[236]

A 10% success rate—a 90% failure rate—may already be the case in some science courses. The promise of scientific teaching is that the success rate will improve as science educators discover and confirm empirically "what works." Sawyer examines the work of innovators like Samuel Morse and Charles Darwin, and notices that those great innovators also had many ideas that were not successful. Sawyer writes, "Successful innovators keep having ideas. They know that most of their ideas won't work out, and they're quick to cut their losses and pursue those few ideas that resonate with their collaborators."[237]

The question is, how can innovators be encouraged to take risks when the possibility of failure is high? How can institutions "embrace failure?" One tactic, observed by Merton among Nobel Prize winners, is to work with people who can "recognize an important problem when they encounter it."[238] These talented people will presumably have a higher rate of success in their endeavors than others. A second tactic for dealing with risk was observed by Dunbar in his study of the dynamics of four science laboratories. He notes that "most of the research scientists engaged in two or more research projects. The scientists tended to work on one high-risk and one low-risk project concurrently."[239] Nassim Nicholas Taleb recommends a "barbell" strategy toward risk: innovators should ignore medium risk, investing instead about 10% of their resources in high risk efforts and the rest in safe bets.[240]

The literature on rewarding productivity in the business world also has something to tell us about risk. In the classic business book *In Search of Excellence* Peters and Waterman describes their observations of the successful use of rewards.[241] They note that the judicious use of reward "nudges good things onto the agenda." They describe a company that rewarded risk taking by celebrating the "perfect failure." "The perfect failure concept arises from the simple recognition that all research and development is inherently risky, that the only way to succeed at all is through lots of tries…and that a good try that results in some learning is to be celebrated even when it fails."[242] The perfect failure concept reminds innovators to learn from their mistakes. This is the same wisdom that undergraduates acquire when they report learning to tolerate obstacles and persist in research.

Peters and Waterman also point out that the most effective rewards are immediate and intangible. Many of the regular rewards of research (like publication) are delayed, so an immediate, symbolic reward might be used as a substitute or conditioned reinforcer. Peters and Waterman relate the story of the company president who was so impressed with a scientist's idea that he felt the need to reward the scientist's behavior right away. The only reward he had was a banana, which he presented to the scientist. The immediate reward principle, which is well established in behavioral psychology, is in fact practiced at many institutions that reward faculty and students with recognition and praise.

Sheila Tobias noticed that successful science reforms came about where "Deans and department chairs have discovered the power of the 'little r'—the small reward for work well done, the enabling reward so that things can be done a little better each time."[243] Sheldon Wettack, emeritus dean of the faculty at Harvey Mudd College, wrote about "affirmational" rewards that a dean can provide to faculty. These rewards include the acknowledgement of faculty-student research collaborations through congratulatory notes, attendance at seminars or poster sessions, expressions of gratitude for grant submissions, and funds for faculty participation in organizations that promote undergraduate research.[244]

The business world also yields a literature on rewarding entrepreneurship and intrapreneurship;[245] universities and colleges could adapt the findings. Balkin and Logan examined reward policies in businesses that support entrepreneurship, and concluded that lump-sum salary increases supported entrepreneurship.[246] Kerr and Slocum, also looking at reward systems in business, find a distinction between “clan cultures” and “market cultures.”[247] Clan cultures emphasize relations among organization members, a sense of tradition, and a sense of interdependence, but also conformity and lack of risk taking. Market cultures emphasize contractual relations, a sense of self-interest, and individual initiative, but also short-term commitments and distance from others.

While Kerr and Slocum suggest that the market culture is more likely to support entrepreneurship, it seems that colleges and universities are more likely to maintain strong elements of the clan culture. The challenge is to adapt and implement rewards for risk-taking without losing our sense of community. The middle ground may be to reward interdependent coalitions of intrapreneurs for their ideas and experiments pertaining to undergraduate research and scientific teaching. Sawyer, in his study of group innovation, notes that group rewards are most effective for interdependent groups. This observation parallels the assertion that a key component of cooperative and problem-based learning in science is interdependence.[248]

Rewards have a significant effect on faculty early in their career; success breeds success. The sociologist Robert Merton dubs the phenomenon “The Matthew Effect,” after a passage from the New Testament: “For the man who has will always be given more....”[249] Merton’s study shows that scientists who were already well-known received the most credit for new work. Blackburn and Lawrence did a quantitative study of faculty productivity and found that “how prolific one has been predicts how prolific one will be” with regard to publications. They observe, “Early publishers become prolific publishers. As they publish, they get grants. As they get grants, they publish.”[250] We could speculate that the relation between early success and later success is based on personal talent or some other factor. If, however, the early rewards promote desirable behavior, then by extension we could apply the use of early reward to behaviors other than frequency of publication. For example, we could reward young faculty who work with and publish with undergraduate researchers. We could reward faculty who, instead of asking for teaching load reductions so that they may do more research, create research groups and seminars that permit the unification of undergraduate teaching and research experiences.

One difficulty with transforming science into the interdisciplinary, problem-driven enterprise where teaching and research merge and students learn to think like scientists is that traditional science departments are both the main initiators of change and main objects of change. Tobias, in her study of successful science reform, concludes that "change is not implemented by experts, but originates in local commitment and reallocation of resources at the midlevel of management—in the case of colleges and universities, the department."[251] Larry Cuban observes, "No viable alternative to the *department* and the university-college has been proposed, adopted, implemented, and institutionalized sufficiently to convince presidents and faculties that there is another, low-risk, economically efficient way of combining the teaching mission of building future citizens with the missions of increasing knowledge and maintaining high prestige."[252] Departments can be conservative, and yet are principal change agents, wielding influence over young faculty through tenure, promotion, and contracting.

While faculty at primarily undergraduate institutions may not feel the pressure that their university colleagues feel to devote 80% or more of their time to research, judgments made about the kind of research that will be supported can be helpful or harmful to reform. A progressive science professor's vitae will reveal a mix of research efforts: work co-authored with undergraduate collaborators, interdisciplinary work with various co-authors, and assessment of student learning performed in the context of scientific teaching. The conservative-minded department chair regards all three of these species of research with suspicion. Work with undergraduates is suspected of being less than rigorous; interdisciplinary work is seen as something soft and not clearly the scholarship of discovery; the scholarship of teaching is traditionally marginalized. A skeptical department chair could look at an assistant professor with accomplishments in all three of these research areas and ask, "Yes, but where is your real work?"

Finding the time

If teaching not a distinctly different activity than research, is it possible that time spent on one is not mutually exclusive of the other? Carol Colbeck visited physics and English department faculty at two universities.[253] She observed the activities of 12 professors for a total of 60 days, systematically recording teaching and research activities. She found that the faculty were able to integrate teaching and research—that is, allocate time in a way that was useful to both activities—between 8% and 34% of their time. Most of the integrated teaching time for the physicists was devoted to "empowering undergraduate and graduate students to pursue independent inquiry according to disciplinary standards." The physicists had difficulty with student understanding of the physics faculty's "frontier-level" research because the structure of physics required students to "master fundamental concepts and methods before progressing to the next level of understanding." Colbeck suggests that "high paradigm consensus" fields like physics face a greater challenge for integrated teaching than "low paradigm consensus" fields like English. She proposes that research and teaching are more likely to be integrated in programs that use a master [mentor]-apprentice model of research training, that have a broad definition of what counts as research, and that have faculty involved with departmental decisions about teaching assignments. Colbeck's work prompts us to believe that the adage that a university faculty member spends only 10% of his time on teaching may be usefully violated by one who becomes involved with undergraduate research. With the dissolution of the teaching/research dichotomy, deciding where to spend one's time may be an easier problem to solve.

Managing change

Most observers who advocate change at a college or university start at the top, demanding strong leadership from the president, provost or dean. Larry Cuban suggests that reform in university education would take "a president and a provost of uncommon political will, astuteness, and determination to persist for five to 10 years on this task." Cuban advocates an incremental approach to change, "short-term tinkering toward a defined long-term purpose of redesigning university structures, processes, and cultures. The kind of leaders I refer to are those who resist hunting boulders to crush the opposition and rather search for pebbles to make a path toward respecting and admiring teacher-scholars." Business writer Jim Collins suggested that great organizations take "Level 5 leadership."[254] Level 5 leaders are "modest and willful, humble and fearless." Collins suggests that an attempt to be a "larger-than-life, egocentric leader" in order to facilitate change is a mistake.

Certainly a leader should have a visible and affirmational presence, as Wettack suggests, but strength in the sense of authoritarian leadership may not be optimal for the goal of problem-centered, interdisciplinary undergraduate-oriented science. As science becomes more interdisciplinary, it will become more difficult for any one person to be in control. No single expert will have all the necessary information or ideas to make research successful. There may be multiple faculty members acting as co-mentors for students and peer tutors for each other. There may be multiple mentors for undergraduate researchers, whose own ideas may influence the outcome of the research. As we have seen, students prefer democratic and collegial mentors. We have also noted that industrial psychologists link lack of problem structure, a feature of interdisciplinary problems, with democratic leadership. In short, an authoritarian leader is not recommended.

Then how will this state of affairs be managed? Richard Florida, writing about *The Rise of the Creative Class,* uses the term "soft control" to describe the management of creative people. Soft control consists of recognizing that talented, achievement-oriented people work for "the challenge, the responsibility, for recognition and the respect it brings." His prescription for relying on the achievement motivation of the faculty and students rather than on a highly regulated, top-down leadership approach recalls the management research of industrial psychologist Douglas McGregor, whose interpretation of humanist psychology for the workplace rested on the assumption that "The motivation, the potential for development, the capacity for assuming responsibility, the readiness to direct behavior toward organizational goals are all present in people."[255] McGregor wrote, "The essential task of management is to arrange organizational conditions and methods of operation so that people can achieve their own goals *best* by directing *their own* efforts toward organizational objectives." He believed when people are acting on their own need to achieve and need to self-actualize, they do not need authoritarian management.

Still, leaders make decisions, and the decision-making theories of leadership described earlier indicate that the leader should understand the metacognitive aspects of each decision: whether the situation needs the authoritarian intervention of the leader to protect the quality of the decision; whether the problem is structured sufficiently for the leader to make a correct decision without consultation or group participation. On the first point, if it is the leader's obligation to protect the quality of the decision with respect to the college, division, or department, we would ask if the leader is protecting the status quo or striving for a new organizational configuration that has not yet fully developed: a vision.

Jeanne Narum, Director of Project Kaleidoscope, writes, "We are coming to recognize that a clear vision is a nonnegotiable commodity if efforts to transform the undergraduate STEM learning environment are to take root and flourish over the long term."[256] The vision is "where you want to get to" that indicates the way you "ought to go." Visions are created by the large community through communication and planning and then guide decision-making. Decisions based on a shared vision of the future permits the kind of management assumptions suggested by Florida and by McGregor. Without a shared vision, the leader is left "herding cats." [257]

Creating a vision has always been intimidating to some leaders, who admit they are not "into the vision thing;" it is also the case that what is retrospectively claimed as a vision by some campus leaders appears instead to be a slowly emerging story that becomes clear over time. Perhaps it would be useful to think of the exploration of a vision as a thought experiment.[258] According to Kuhn, "The function of a thought experiment is to assist in the elimination of prior confusion by forcing the scientist to recognize contradictions that had been inherent in his way of thinking from the start." The great thought experiments of Einstein and other scientists did not start with new information. Instead, they clarified the implications of known information. A leader could think through a new organizational configuration or program with the information available, striving to eliminate confusion or contradiction in the desirable outcomes.

What could organizational leaders do to build or improve a science curriculum centered on undergraduate research? Academic deans could:

- find long-term, stable sources of funding to replace or sustain the unstable extramural grants that often fund innovative research and education;
- work to count research with undergraduates as part of the faculty teaching load, thus reducing the dichotomy between teaching and research;
- reward faculty who engage in scientific teaching and assessment of student learning;

Department chairs have a significant role. They have a great influence on the organized curriculum of the department, and could:

- use their influence to create research seminars in which the faculty member leads an undergraduate research team;
- work to change the criterion for hiring, promotion, and tenure;
- ask job candidates a simple question: "Will you mentor undergraduate researchers?" and hire faculty members whose research programs are accessible to undergraduates;
- work to include undergraduate research mentoring, scientific teaching, attendance at meetings for science education, publications on interdisciplinary work or on the scholarship of teaching as significant contributions to the department and to the faculty member's career.

Collectively, the department and the broader academic community could recognize undergraduate research achievements through funding student attendance at professional meetings and through an occasion for celebration of research.[259]

Gentile has used a tugboat analogy to describe how change occurs in departments and institutions. He says, "Consider what you are trying to change as a super-tanker that turns very slowly.... You have to realize when you nudge a super-tanker to reposition it, much energy, a lot of effort, and more than one tug boat will possibly be needed."[260]

While thinking of this maritime analogy, it may be useful to contemplate a story regarding an actual ship in crisis. Sawyer related the findings of anthropologist Ed Hutchins, who happened to be observing crew members on a U.S. Navy helicopter carrier when it experienced power failures while docking in San Diego. Hutchins noted that the crew, deprived of electricity and a functioning rudder, nevertheless managed to function as a group to find a solution to the complex calculations that guided their navigation and anchoring. Hutchins concluded that "the solution was clearly discovered by the organization before it was discovered by any of the participants." Sawyer concludes that "when people improvise together, they develop innovative responses to unexpected events even though no one is consciously aware of exactly what the group is doing or why it works."[261]

We know more than we can tell, even when we work together, and working together can produce change. Change is often initiated by a lone pioneer. But we remember Tobias' observation that reform, coming from a single individual with a strong belief in the ubiquity of his or her pedagogy, funded by external grants, and dependent on the dedication of a few volunteers in isolation from the larger community, did not survive.

Transformation

Cuban, in the quotation above, suggested that leaders be prepared to work five to 10 years to enact reforms. In one example of the leisurely pace of change, *The Chronicle of Higher Education* reported the story of science teaching reform at California State University at Fullerton. The biology department began a curricular reform that took two years to discuss and seven years overall to implement.[262] And of course there is the time horizon created by grants: three or four years with some hope of renewal. While it is useful to have a time course for change included in a plan for change, it may be just as useful to press on with "short-term tinkering" until it becomes evident that a tipping point has been reached.

Richard Ogle posits the "law of tipping points" as an analogy to the concept of phase transition in physics. The law of tipping points is that "*more becomes different.* More change in lower-level elements prompts a self-organizing process that gives rise to a new, qualitatively different pattern."[263] In other words, by remaining committed to the tactics that encourage change, an institution may cause a transformation to emerge. An initiative begun by a coalition of a few faculty and supportive administrators leads to a pilot program or test of concept, and then to replication and extension, to growth through imitation and even rivalry, until the research and teaching landscape of the institution appear qualitatively different today than it did a few years ago.[264]

One aim of this transformation is to meet the challenges posed by the organizations and special committees reported in the first chapter, to increase the number of talented scientists and engineers who will in turn produce the transformational research needed to keep the United States competitive in the global economy. According to the National Science Foundation, transformative research is "a range of endeavors, which promise extraordinary outcomes such as revolutionizing entire disciplines, creating entirely new fields, or disrupting accepted theories and perspectives. In other words, these endeavors have the potential to change the way we address challenges in science and engineering and also provide grist for the innovation mill. Supporting transformative research is of critical importance in the fast-paced, science and technology-intensive world of the 21st Century."[265]

Transformative research is surprising, contributes to knowledge, and as a bonus increases employment opportunities for scientists.[266] The value of transformative research has been incorporated in the criteria for review of research grant proposals by the National Science Foundation, and is now part of the intellectual merit criterion. Given that transformative research includes the property of surprise, it remains to be seen how peer reviewers will be able to predict this quality in research proposals. The gain from doing so is immense. Transformative discoveries create a positive feedback loop. Whether the transformation be in the arts or in the sciences, it has a generative effect. The Beatles' Sergeant Pepper album, the discovery of stem cells, and creation of iPhones had this in common: they showed us that there was new work that had to be done and new work that we could do.

What implications does this ideal of transformative research have for science education? Creativity is implied by transformative research, and creativity is nurtured in undergraduate research experiences. Could we expect to see undergraduate scientists doing more creative research? Wieman writes, "I believe a successful science education transforms how students think, so that they can understand and use science like scientists do."[267] Undergraduate research opportunities provide the excitement and surprise that make a life in science compelling. Bertrand Russell once wrote that one of the merits of science "is hopefulness as to the future of human achievement, and in particular as to the useful work that may be accomplished by any intelligent student."[268] He concluded, "A life devoted to science is therefore a happy life, and its happiness is derived from the very best sources that are open to dwellers on this troubled and passionate planet."

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http://www.cur.org/postersession.html

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Science in Solution offers clear, empirical support for the value of undergraduate research. It also explores the effectiveness of research-like pedagogy in science courses, and assesses the impact of good and bad mentors.

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David Lopatto is a professor of psychology and Samuel R. and Marie-Louise Rosenthal Professor of Natural Sciences and Mathematics at Grinnell College.

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