A major change in higher education in the past three decades has been the increasing emphasis on the process of learning as opposed to strategies for teaching (Barr and Tagg, 1995; Boyer, 1990). More recently, the emphasis on learning has been described as transformative pedagogy. Such forms of learning are characterized by disciplinary integration, experiential learning, and problem-based learning. These active, engaged approaches to learning are often connected to service learning, civic engagement and/or leadership development.

The Council on Undergraduate Research (CUR) has long recognized that undergraduate research experiences provide many of the elements that exemplify transformative learning such as a deeper understanding of the discipline and its research methodology, critical and analytical thinking, and a quest for knowledge. Since its founding in 1978, CUR has been joined by many campuses and other higher education organizations in recognizing the value of the undergraduate research experience as a form of pedagogy -- not just in the sciences but across the entire spectrum of disciplines and types of institutions in higher education. Undergraduate research has also expanded to all types of institutions from community colleges to research universities, and there is a growing international interest in this model as well. The belief in the value of this endeavor is not just demonstrated by the increase of campus undergraduate research programs or through anecdotal evidence; it is also demonstrated by the accomplishments of students who have been involved in undergraduate research. Student engagement data from the National Survey of Student Engagement (NSSE), reports from the Association of American Colleges and Universities (AAC&U) and Project Kaleidoscope (PKAL), and assessment studies such as those headed up by Elaine Seymour and David Lopatto all provide evidence of the educational value of undergraduate research.

CUR was founded by chemists from private liberal arts colleges who believed passionately in the ability of undergraduate students to engage in original research. The founders advocated for recognition of the quality of research that students and faculty at predominantly undergraduate institutions (PUIs) were doing. CUR continues to believe that when students engage in authentic research under the guidance of a faculty mentor, their learning process is significantly enhanced and students develop skills and attitudes that will be used throughout their lifetime no matter what career they may choose.

What has all of this meant for STEM education?

A number of disciplinary societies such as the American Chemical Society now have strong statements about the importance of engaging students in research as a part of their undergraduate education. The American Society of Biochemistry and Molecular Biology (ASBMB) includes research skills in their list of important outcomes that a student should have by the time they finish their undergraduate program. With support from the Teagle Foundation, ASBMB conducted a study of how the recommended curriculum in biochemistry and molecular biology is implemented at a range of institutions, and “examined the relationship of a hierarchical, interdisciplinary science major to broad educational goals”.

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The survey data and recommendations in the report from this study speak to the importance of undergraduate research as a means of introducing significant concepts (such as ethics) and developing higher order skills – many of which are not taught in the classroom or only in select advanced courses for majors.

Similar support of undergraduate research is typical of most other STEM disciplinary organizations. But none have gone as far as the physics community, including the American Physics Society Committee of Education, American Association of Physics Teachers, Society of Physics Students, American Astronomical Society and the Physics Division of CUR, all of who have endorsed statements in the past year calling for every physics and astronomy department to provide, as an element of best practice, opportunities for all undergraduate physics and astronomy majors to engage in a significant research experience.

The importance of undergraduate research and its connection to transformative learning is expressed well in this excerpt from a 2007 white paper of the Teagle Foundation – an organization that focuses on strengthening liberal education:

*Faculty who involve students in their own research projects not only sharpen students’ expertise in a specific area but foster discipline, independent thought, creativity, and responsibility in those students. When students are given the opportunity to work in the field alongside a biology professor, participate in an archeological dig with an art history professor, or analyze data and coauthor a paper with an economist, they learn to take their own ideas seriously and see their own intellectual work as valuable. Perhaps most importantly, students who witness the ongoing production of knowledge learn to understand how it is arrived at, how it evolves over time, and what its consequences are for social and political choices.*

Undergraduate student participation in research is now also seen by many as a way of developing leaders in the science.

Undergraduate student participation in research is now also seen by many as a way of developing leaders in the sciences. It is well recognized that research experience develops confidence, critical thinking and problem solving skills. Increasingly, these student researchers are presenting their work to campus-wide audiences, to peers at national conferences such as the National Conferences on Undergraduate Research (NCUR), to scientists at disciplinary society meetings, and to legislators at the state and national level. These different audiences require the students to be able to communicate at a variety of levels – including to “non-expert” audiences (in terms of scientific literacy). Because a growing number of research projects have significance to the local community, there is also often a chance for these researchers to interact directly with the public and use the projects as an opportunity to educate a general audience about science. Besides enhancing a student’s communication skills, all of these dissemination activities also enhance public understanding of science and allow our students to become ambassadors for illustrating the importance of science in society. It is our impression that this “bringing the knowledge out of the ivory tower and to the people” is a relatively new role for STEM education and research that has evolved over the past decade.

So given this focus on transformative pedagogies and the integration of teaching, learning and scholarship, what changes have been observed or required on campuses? We see two major trends: first, the revision of the curriculum to include undergraduate student research and, second, as a consequence of the curricular changes, changes in the expectations for faculty as teacher-scholars. In addition to these two interrelated trends, we also see several ongoing and new challenges that are confronting those who are or want to be engaged in faculty-student collaborative research. These topics are addressed briefly below.

**Shifting to a research rich curriculum**

The value of faculty-student collaborative research has long been recognized in the laboratory and field-based sciences as a way for students to put into practice what they have learned in the classroom. But within the STEM disciplines undergraduate research is no longer solely viewed as a capstone experience; there are many programs that introduce students to research as early as their first year on campus. The tighter link between research and learning is also evident by the fact that it is now
common for the research experience to be complemented by an entire departmental curriculum that develops an investigative spirit and research orientation.

According to Husic and Elgren (2003), a research-rich curriculum enables a student to:

- Search, read and evaluate the scientific literature;
- Articulate a concise, approachable research question and its context;
- Design and execute experimental approaches to a research question employing appropriate instrumentation and techniques;
- Appreciate ethical, environmental and safety issues associated with laboratory (and field) experimentation;
- Collect, assess, and communicate experimental data and scientific information; and
- Communicate clearly the nature of the research and its significance.

Students are now often exposed to scientific literature earlier and more frequently. This has been enabled by the rise in online databases, making the literature more accessible, especially to smaller institutions with limited library budgets. Laboratory experiments are being revised from cookbook-like procedures with known (at least to the faculty) outcomes to ones characterized by open-endedness, including inquiry-based and authentic research experiences. More and more laboratories are dependent on instrumentation and technology. Weekly lab reports are often replaced by manuscripts more closely resembling scientific journal articles and representing multi-week experiments where students or groups often have tested different hypotheses or worked with different variables from others in the class. There is a focus on “next steps” or identifying the “next research question” and sometimes, students are asked to write grant proposals prior to starting a project. Laboratory experiments might be followed by discussions on responsible research and the ethical implications of research in a particular field. And it is not uncommon for courses to end the semester with poster sessions – modeling professional scientific conferences.

The synergy between teaching, learning and research is evidenced in what students report as outcomes of participating in research (Seymour, et al., 2004; Hunter, et al., 2007; Russell, et al., 2007). Adding research-enriching experiences throughout the curriculum presumably develops students who are better prepared for independent research projects, honors thesis projects, and participation in Research Experiences for Undergraduates (REU) or other summer research experience. In addition, according to Husic and Elgren (2003), the establishment of a research-rich curriculum also helps to cultivate a research culture for the students and the department as a whole.

The teacher-scholar model

With the increased importance that has been placed on undergraduate research, so too have there been greater expectations for the faculty to be collaborators in this enterprise – both as mentors and as role models for the students. While faculty research has been the norm at numerous institutions for a long time, the teacher-scholar model has gained greater significance at essentially all types of predominantly undergraduate institutions including community colleges. And, of course, the expectation is that teacher-scholars work collaboratively with undergraduate students in the laboratory or field (in the STEM disciplines) and that the research will inform the faculty members’ teaching.

As noted by the authors of the above mentioned Teagle Foundation white paper:

“We believe, however, that student learning outcomes are also powerfully and positively affected by repeated encounters with teachers who are active scholars. Indeed, student learning flourishes precisely in the synergy between teaching and scholarship. We believe as well that although faculty satisfaction and job performance relate closely to such conditions as a sense of independence and adequate compensation, faculty are most likely to do their best work when they can regularly connect their expertise to their work as teachers. As a result, there is good reason to think that faculty will achieve most when their teaching has lively connections with their role as expert scholars, and that they will perform better when their understanding of student learning outcomes feeds back into curriculum design and teaching strategies.”

Thus, over the past few decades, a model has been evolving where faculty and students are partners in the learning and discovery enterprises.
When new faculty members are hired, they are often mentored by other faculty or participate in formal orientation programs. There are multiple and good resources to promote excellent teaching, to learn about assessment, etc., but, in our view, campuses have placed less emphasis on mentoring faculty to get started in their research program (at least at smaller schools) or how to be a mentor to research students than is needed to offer an effective and comprehensive undergraduate research program. Given the above described focus on undergraduate research in STEM and other disciplines, this should be an important focus in faculty development.

Through a variety of programs, CUR has played an important role in this form of professional development through its conferences, institutes and mentoring programs. Many of these programs focus on how to:

- Initiate and sustain active high quality research programs;
- Network with other teacher-scholars; and
- Identify relevant funding sources and write quality proposals.

As important as these efforts have been, we still believe that such faculty development with an emphasis on faculty-student collaborative research should occur on the campus level. New faculty need the orientation, but professional development and support for faculty at all stages of their career is also important. In addition to developing faculty in terms of the scholarship, we must also be developing leaders who will serve as campus and national voices advocating for the infrastructure and other resources needed to do collaborative research with students and to develop the research-rich curricula and campus cultures that support and reward faculty-student collaborative scholarship.

...a model has been evolving where faculty and students are partners in the learning and discovery enterprises.

Challenges: The widened gap between the “haves” and “have-nots”

As exciting as the gains in acceptance of the importance of undergraduate research and the value of the faculty-scholar model have been, there are still departments and campuses that haven’t embraced these concepts and institutions that haven’t committed the resources to allow this to happen at a high level of quality. In the last set of PKAL essays from a decade ago, Jeanne Narum noted that “transforming the undergraduate STEM learning environment has not yet reached a credible ‘tipping point’”. The same is now true for institutionalizing undergraduate research – within the STEM disciplines and beyond.

There are a number of reasons for this. Many institutions haven’t invested resources into undergraduate research (or even faculty scholarship) and there are places where, historically, research has not been a part of the culture. There are science facilities at a number of institutions that are outdated and even unsafe, and the boom in science building renovations and new buildings over the past decade has been slowed with the current economic recession.

The resource of time is an issue at many institutions. For the sciences, there remains uneven recognition of how much work and time faculty must invest in the science laboratory portions of classes that often aren’t even credited or counted the same as other forms of teaching. With teaching loads of 12 to 15 contact hours per semester at many undergraduate institutions, faculty members have difficulty finding time for their own professional scholarly development and thus, see it as impossible to also find time to mentor students except in the summer. They also need time and support for grant writing and fear that if they were to get a grant, they may not have the time to properly implement it.

Many departments have insufficient equipment funds, much less replacement cycles, and, without a successful research track record within the department, it is difficult to be competitive in grant programs such as the NSF-MRI program. Even where there is instrumentation, often faculty, rather than support staff, are responsible for lab prep and breakdown, and instrument repairs and maintenance – all of which cut down on time that faculty could be using to engage in meaningful research with their students.

In the last PKAL essay series ten years ago, Margaret A. Miller, then President of the American Association for Higher Education, wrote in her essay entitled Looking Backwards: The 1990s about “the machine in the garden”. She was speaking about the rapid adoption of the computer into
the classroom as a major story of the decade. This trend has continued at an unbelievable pace with all sorts of new applications of technology in the classroom and in research. We have witnessed the increase in portability of technology, social networking, sharing of massive databases and other forms of rapid access to information, and increased computing capacity and speed on smaller and smaller machines.

The same is true with equipment required for STEM fields – for both research and teaching. Today’s instrumentation has high-throughput capacity, smaller footprints, increased capacity and capability, and, of course, is all interfaced with computers. This makes it more adaptable to work with undergraduates – both in the classroom and research settings. However, departments with insufficient equipment budgets are falling farther and farther behind. They lack the technology to carry out meaningful, relevant research or to use in teaching. Even for departments with large equipment budgets, the rapid rate of redesign and turnover (as with computers) makes it difficult to keep up with the latest advances and, thus, most undergraduate institutions lag significantly behind industry in terms of the equipment being used.

As was the case when CUR was founded over 30 years ago, the need for external funding to support high-quality scientific research conducted in collaboration between faculty and undergraduate students is high. As more and more science departments across the country have seen the value of undergraduate research and the teacher-scholar model, an increasing number of faculty and administrators have come to realize how crucial external funding is for sustaining quality research programs. Unfortunately, it has also become apparent that it can be very difficult to compete for grants. Poor success in securing grant funding can be due to internal factors (insufficient time or institutional infrastructure to enable high-quality research, a poor track record of research success, poor mentoring for new faculty, etc.). Additionally, declining foundation endowments and shifting national research priorities can limit opportunities for many researchers and institutions – especially those just beginning to develop a culture of research. An important lesson is that regardless of how valuable research is as a form of pedagogy, external funding rewards success as measured by sound scientific ideas and a demonstrated record of published data.

Considering the purpose and outcomes of research with undergraduates

The educational and personal/professional development outcomes of participating in research as an undergraduate student are now well documented. The benefits to faculty who are active researchers have also been acknowledged in CUR publications, and the findings presented in the 2007 Teagle Foundation white paper should put to rest the teaching vs. research debate. But, ultimately, scientific research is of primary importance for the generation of new knowledge and the contributions that it can make to the STEM disciplines and to society at large.

Following on the announcement by NSF’s National Science Board in 2007 to increase its agency’s support for “research that has the capacity to revolutionize existing fields, create new subfields, cause paradigm shifts, support discovery, and lead to radically new technologies”, CUR hosted a summit on transformative research in June 2009. Twenty-four active researchers from predominately undergraduate institutions gathered to discuss whether or not students at PUIs could engage in high level potentially transformative research. Several questions about the purposes of research were raised. Summit participants saw the value for undergraduate students of engaging in basic research that has the possibility of leading to innovation and discovery, but also research that is user-inspired by needs of the industry, the research, or the community at large. Basic research, applied research, user-inspired research and high risk research should all be considered as potentially part of the undergraduate research experience.

It is likely that, in the future, we will see an even stronger emphasis on research that can serve the “greater good” -- be it research that benefits our local communities or work that might help to address global issues for now and future generations. The value of government-funded research will need to be clearly articulated to a public that is growing increasingly skeptical of science (consider the high percentage of people who still don’t believe in evolution or who don’t accept the scientific evidence of climate change). A number of grand challenges have been identified for science and engineering by the National Academy of Engineers, the National Research Council, and the Bill and Melinda Gates Foundation.
These challenges range from the need to develop a better understanding of biological diversity, ecosystem functioning, climate variability, and hydrologic forecasting to finding renewable, clean energy solutions or “greener” materials that lessen our dependence on diminishing natural resources to the global health issues including the development of new vaccines or novel ways to control infectious disease. The United Nations Millennium Development Goals (such as ending hunger, improving maternal and child health, combating HIV/AIDS, and environmental sustainability) will also require great advances from the scientific community working closely with our colleagues in other disciplines. There will be a tendency to lose sight of the importance of basic research – understanding the fundamental questions of the physical and natural world. The significance of answers to such questions may not always be immediately obvious, and thus, such research may be viewed as a luxury or even frivolous.

Those of us involved in STEM education must realize the importance of preparing the next generation of scientists who can work across disciplines, consider the big questions or grand challenges, conduct research in a responsible manner, be cognizant of the social impact of the use of science-based technologies, and be able to clearly articulate the significance of their work to diverse audiences. Building on the foundation of the now well-documented value of undergraduate research as a form of pedagogy in the sciences, we must show how this model can both enhance and diversify the STEM pipeline for future researchers and a science-literate public and help address the need for innovation and technology leadership in this country.

The theme of the 2010 CUR National Conference seems particularly timely: “Undergraduate Research as Transformative Practice: Developing Leaders and Solutions for a Better Society.” The planning committee produced a description for the meeting that really can’t be improved upon and ties in nicely with the challenge for STEM education and research in the 21st century:

“We live in a moment of radical change... in order for change to be positive—to be transformative— we must be intentional, grounding our work in our visions for better lives and a better society.

Developing Leaders and Solutions for a Better Society.” The planning committee produced a description for the meeting that really can’t be improved upon and ties in nicely with the challenge for STEM education and research in the 21st century:

“We live in a moment of radical change... in order for change to be positive—to be transformative— we must be intentional, grounding our work in our visions for better lives and a better society. We must challenge what others take for granted, look at our work in new ways and consider the future possibilities of our work.

The practice of undergraduate research opens transformative possibilities: possibilities of knowledge and of action, possibilities for students to learn the power of their own thinking, possibilities of futures that would otherwise not have been open to us.”

**Literature Cited**


FROM TRANSFORMING THE CURRICULUM TO TACKLING GLOBAL GRAND CHALLENGES – THE ROLE OF UNDERGRADUATE RESEARCH IN THE 21ST CENTURY


