
Preparing Students for Research: Challenges and Some Results in Goal-Setting, Curricular Design, Assessment, and Program Coordination

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Tremendous strides have been made in undergraduate science and mathematics education, especially over the past 15 years. One can find many published examples of innovations in courses, teaching practices, and curricular design, all highlighted in the NSF CCLI conference *Invention and Impact*. Although these improvements are valuable, now numerous and widespread across institutions of all types, they have often been isolated to a single course or a portion of a curriculum and associated with individual or small groups of faculty members. In addition, on some campuses, similar innovations might appear in multiple departments and programs but remain disconnected.

All too often, the impacts of curriculum innovations and changes in practice have not been evaluated. We have seen little accompanying analysis of the impacts of the innovations on student learning or other desired outcomes. We might suspect there are improvements in student learning and very desirable outcomes from undergraduate research but have had relatively little information until recently to demonstrate the impacts of a particular approach. As a result, one might conclude from a scan across the U.S. that the science and mathematics education community has been very good at developing new approaches but less effective in implementing them across programs and not fully able to assess outcomes for student learning.

Challenges to Implementing Programs to Prepare Students for Research

For many reasons, these observations and the possible conclusion from them are not surprising nor should they be reason to fall backward or question whether progress has been made. First, we must realize that changes in institutions come slowly. Marginal changes produced by innovation might only spread across a curriculum over a period of years. The speed at which changes might occur depends on several factors, including size and diversity of a department's faculty, the rate of faculty turnover, and the ability of faculty to convince colleagues to support further change. Having the data necessary to demonstrate the impacts of a change in practice is essential.

One might expect that changes could occur more rapidly in smaller departments than in larger ones, but we find examples of very successful innovations in small departments that only involve one-third or one-half of the faculty members, with the remainder continuing their previous methods. Over time, hiring new faculty could help move curricular change forward, but this has not always occurred. The assumption that "newer" faculty might be more innovative than their more experienced or seasoned colleagues has not been universally valid.

Innovations tied to individuals may not persist. More importantly, they are difficult to scale up without buy-in from like-minded colleagues or ones who will protect and nurture such activities. Individual-based, bottom-up change is a very slow process unless coordinated across units and part of an organized process. Most campuses are structured in ways that unintentionally resist such efforts. Further, if funding opportunities for curricular innovations, equipment, and research involving undergraduates are to be pursued,

but only as disconnected entrepreneurial activities, they may not be easily coordinated or contribute in a common direction to changes on a campus.

For change to be sustainable, it must be organized consistent with a vision and mission for a department or campus. Incremental changes may occur in a department, college, or university, but organizing them in a coordinated way within a conceptual framework has not proven to be an easy task. But there are some circumstances in which broad-scale reform has been possible and systemic. One can cite examples of campuses that have become models for the incorporation of technology, for bringing students of diverse backgrounds into the sciences, and for providing research experiences. In these cases, a collective vision is an apparent and necessary requirement. How these situations develop and how to foster their development is consistent with building a collaborating team of faculty members with a common vision. It is thus incongruous to have individuals owning courses and determining their sole purpose and function within a curriculum without consideration of a broader context that is part of a student's experience in a major program or without full conversation and examination by colleagues across a department or program.

Bringing about change across a curriculum requires coherence and intentional decision-making at the level of a department, at a minimum. If we are interested in preparing students for research, that should be an explicit goal. It also depends on coordinated innovations and incremental changes organized within a broader framework. Throughout much of American higher education, curricula have been loosely organized and taught by assignment of particular faculty members to individual courses, often leading to the ownership referenced above. Examples of collective evaluation and decision-making about a curriculum in a broader context are relatively few. As a result, we have seen the appearance of many successful innovations, often tied to individuals, but not their persistence or spread across institutions, unless there is a broader, supportive campus climate. While change in one area of a program can be good, it is nonetheless a slow process if comprehensive reforms are desired and it is generally not sustainable. Complementary, incremental changes would be better, but better still would be coordinated, incremental changes that are part of a broader conceptual framework organized around student development and with attention to measuring outcomes.

Establishing Goals for an Undergraduate Research Program

We might begin with the premise that undergraduate research experiences result in important outcomes. These experiences could be offered by single faculty members or by a group. However, if a department engages in meaningful dialogue about its collective purpose in preparing students for research, the structure of the curriculum can be designed accordingly. For example, if we are interested in providing significant research experiences to all students in a major or to a significant number, it would require some rethinking of a curriculum in a broader context. If a previous mode involves emphasis on coverage of material and another purpose is preparation for research, some different questions need to be posed. Often, especially in highly structured and vertically integrated curricula, the tension between "coverage of topics" and gains in learning or development of skills could be profound. How a curriculum is then organized will depend on the primary purpose of instruction in the context of student development. If preparation of students for very meaningful and exciting research experiences is a desired outcome, then a curriculum can be organized accordingly.

One approach is to analyze a major program by required course and electives against the overall objectives, skills, and content to be addressed. This analysis could be done in a matrix or other format to see how well courses and objectives are aligned and whether enhancement of skills, refinement of knowledge, and application of knowledge are being accomplished across the full curriculum to prepare students for research. Such a matrix can be a most useful discussion piece for a department in organizing its curriculum. Importantly, this approach inherently recognizes the importance of student development as a result of courses and other experiences, which might also include some assessment of attitudes and skills, and challenges consideration of the full range of experiences necessary to prepare students. It should also be realized that students vary in their abilities to conduct research. Defining overall goals across a department and organizing a curriculum and other experiences, such as research or application in other settings, are essential to supporting a process of cognitive development of our students.

Some Efforts to Prepare Students for Research at James Madison University

While taking individual steps to improve preparation of students for research and teaching, the approaches are complementary and contribute to a larger, and mostly intentionally designed, framework across the sciences and mathematics. It does not assume that the overarching framework has been fully developed, that all faculty members in a department would agree on all aspects, or that all departments have tackled the difficult questions about their own majors. Nonetheless, it builds on some consistent themes of a keen interest in undergraduate education and in providing experiences that aid the development of our students. The topics mentioned represent a combination of activities supported by institutional funding and grants primarily from the NSF, of which some are in formative stages.

The assessment program at James Madison University provides an important framework for asking the right kinds of questions and reflects a culture of evaluating outcomes. The campus is unusual in having a richly developed assessment program that involves testing of all entering freshmen and institution-wide assessment days in the spring for sophomores and juniors (<http://www.jmu.edu/assessment/about.shtml>). Assessment of general education, for example, is based on established objectives for student learning in each of five "clusters." Instruments are selected and designed to measure student learning related to the objectives, information is collected and analyzed, and information is used to modify and improve the assessment instruments and to make changes in the program. Faculty members developed the questions for the assessment instruments, e.g., for quantitative reasoning and natural world (science), in conjunction with assessment specialists. Importantly, although not all would agree as to the best structure of general education, they can consider and debate what they see as desired outcomes for students and develop questions to assess these outcomes.

Assessment of major programs is done by means of a systematic and periodic academic review process (<http://www.jmu.edu/acadaffairs/acadreview.shtml>). As departments have worked through a self-study process, have been involved in conversations with external review teams, and have become even better at asking questions about learning outcomes within major programs, they have begun to ask questions that increasingly focus on gains in student

learning in the curriculum, from research experiences, and as a result of cognate requirements. The process is involved, complex, and frequently not straightforward. Questions are often raised and more data need to be collected to address them. For example, if our students have requirements for certain courses and then still struggle or perform less well than expected after completing such requirements, what should the response be? How do writing skills relate to performance on standardized exams or in developing papers on research? If writing is expected to be enhanced from a requirement, e.g., a course in technical writing, but writing skills in a departmental course do not seem apparent or adequate, should the requirement be changed? These questions relate to the benchmarks and expectations being set for student learning outcomes within departments. They also result in serious questions about the overall preparation of students and for what purposes—where students are going upon completion of the major and what experiences, including research, are most applicable.

The questions being asked about major programs can be related to a coordinated vision for a department and what kinds of skills and learning outcomes are valued. For example, we may be interested in performance of students in introductory courses but also their persistence in a program, and as such, the Department of Mathematics and Statistics is involved in a project with the Mathematical Association of America to assess a series of courses in mathematics. If the department has a goal of having students take more mathematics and statistics courses, this is enhanced by the key considerations of students being successful in the first course and continuing on to the second courses, where they would do well. If we then consider a department's overarching goals and mission, how will all of the goals be accomplished and with what priorities, especially recognizing the multiple demands on departments, including service roles, majors and minors, and specialized preparation for certain groups of students? Addressing quantitative literacy of all students, enhancing quantitative reasoning within disciplines, and preparing students for research or teaching can require different approaches. Multiple entry points into the curriculum given disparities in background preparation of entering students further complicate the solutions that might be developed. Further, quantitative skill development in support of research experiences is an important consideration.

At the Start of the Pipeline

Introductory courses in the sciences and mathematics have often been used as gatekeepers or filtering mechanisms for students wishing to enter certain programs. Being clear about our purpose and overall objectives in these courses is essential. If our goal is to improve performance and retention, we focus more on effective placement of students into courses where they can succeed and less on saying to a student that there is only one pathway or one set of courses for students of a particular major during their first semester in college. As a result, we have paid considerable attention to improving placement (and advising), especially in mathematics and general chemistry. All students are required to take an algebra-based mathematics placement exam on entering the university. The results of that exam are taken together with math and verbal SAT scores and writing exam scores to place students in appropriate courses. An advising matrix for freshman advisors has proven most helpful.

Departments have developed curricula (e.g., a new calculus sequence), paid special attention to alignment of instructors, and adopted pedagogical approaches designed to improve student comprehension and performance. An interest in longitudinal performance and persistence has resulted in improved success of students in introductory courses and more of them continuing on to subsequent courses or the completion of a minor in cognate areas such as mathematics and statistics.

Additional support for students in introductory courses was provided by the development of a Science and Mathematics Learning Center and through supplemental instruction made available in key courses. The learning center assists students in working through programs in basic science, mathematics, and statistics courses. The center is located in a visible campus facility and is staffed by two full-time professional faculty members, who are assisted by 10–12 students. Approximately 10,000 student visits are logged by the learning center during the academic year. The learning center and supplemental instruction both result in improved performance of students who take advantage of these opportunities. Paying attention to where students are entering an institution and providing supporting programs can improve performance and persistence without any change in standards. It represents important preparation but also results in improved persistence within majors.

Hiring Faculty to Meet the Needs of the Curriculum

We have sought to hire faculty members who are scholar teachers highly interested in undergraduate education and in research with undergraduates. The benefits of the research they conduct with students are seen as supportive of a vital faculty but also as a form of teaching and student learning. While benefits to students are important, so are the intellectual and other gains to faculty. Even though undergraduate research is an inefficient process if publications or grant activity are the goals, the research contributions of the faculty and benefits to them are significant. Mentoring of students in research is strongly valued in the evaluation process for faculty.

Faculty can benefit from mentoring in research and teaching, in learning departmental tasks and roles, and in discovering how to be part of a functioning team of good departmental citizens. The importance of hiring and mentoring cannot be overestimated, and yet it is often overlooked; hiring events may be disconnected with the broader vision for a department. Hiring good talent is a key step because such talent makes so many additional things possible—research possibilities, grant funding, and curricular innovation.

Preparing Students (and Faculty) for Research

In addition to improving performance in introductory courses, departments have designed courses and have used pedagogical approaches designed to improve persistence in majors and prepare students for research. For example, the biology core curriculum was recently revised with support from NSF CCLI (Monroe and Hurney, 2002). Four new courses were developed with companion laboratories to be completed over students' first two years. The labs are thematic, multi-week, and investigative in nature. They use model biological systems and processes that students see from different organizational perspectives and methodological approaches. Students test hypotheses and make project presentations, which represent early introductions to the process of research. The courses were intentionally designed to prepare students for research in several areas of biology. Assessment was built into the design and conduct of the courses, and analysis of the core is now underway because all courses have been taught at least once. In addition to

suggesting further revisions to the biology core, this assessment, along with results of seniors on the biology field-test, also inform revisions of upper-division biology requirements. In chemistry, students may elect a majors lab or majors section of organic chemistry as freshmen and sophomores. They then encounter an integrated inorganic-organic, project-based laboratory course in the spring semester of their sophomore year. Students work as part of a research group assigned to a peer mentor and to a faculty member. The emphasis is on data collection, use of instruments to characterize compounds, data analysis, and presentation of results (Amenta and Mosbo, 1994). The course provides exposure to a range of instrumentation and the process of research, resulting in students poised to conduct research.

Both of these examples were designed assuming undergraduate research is a developmental process and it requires preparation. Students learn how to approach research and to ask questions. While not for all students across all institutions or majors, research experiences can be important experiences with multiple outcomes (Brakke and Nelson, 2003). Further aspects of undergraduate research that suggest it is best viewed developmentally are the important ingredients of work ethic, tenacity, and persistence; modeling and observing mentors; asking questions about career pathways; and working with a mentor and often as part of a group. To bring such experiences into a curriculum, rather than having them added on or squeezed by ever-expanding content requirements, calls for the kind of careful attention to purpose within a department and balance in a curriculum mentioned above. It also requires analysis of how the preparation for research is best organized and how the additional benefits that might be expected to derive from research will be measured and assessed (Wenzel, 2004).

Organizing Programs in Research

Even though the benefits of undergraduate research experiences to students and faculty are not well documented (see Seymour et al., in press, and Lopatto, 2003), evidence is mounting on the importance of research experiences to student learning and development and for faculty members. Convinced of its effectiveness and importance to vitality of faculty members, especially in the sciences, we have attempted to expand and support student research programs through a variety of mechanisms. These approaches have included a combination of faculty members in several

departments working collaboratively or toward a common purpose of expanding undergraduate research experiences for the benefit of students. They have included the development of several successful proposals to the REU, RUI, UMEB, IRM, MRI, and CCLI programs at NSF, which have provided expanded support for students and faculty involved in research, support for necessary supplies, and several key pieces of instrumentation. Additional support has come from the National Institutes of Health, Jeffress Memorial Trust, and institutional support has come in the form of matching or seed money and travel for students and faculty to make presentations at professional meetings. Academic year research opportunities have been expanded, and a vibrant summer research community has been established in large part by the expansion of REU programs from one to four (Brakke et al., 2003).

A general model of undergraduate research developed in the Chemistry Department, and first supported by NSF-REU in 1990, has been elaborated within chemistry and expanded into other departments, each with their own particular emphases and pathways. First, the resulting connections within and across disciplines have been remarkable, suggesting that synergy among related programs and initiatives can be an important outcome of coordinated efforts and affect many aspects from efforts to obtain equipment to explore models of curricular structure. Second, the involvement of faculty and topics being addressed has extended well beyond that of single departments, indicating that multiple programs operating simultaneously can result in connections beyond those anticipated, for example, when pieces of major equipment contribute to more than one program. Third, one might assume that student learning through interdisciplinary experiences might require even further coordination and integration of complexity than what is found in a single discipline, but that may not be the case if the faculty coming from different disciplines are of similar mind and are focused on tackling the problem at hand.

Assessing the Outcomes of Research Experiences: A First Glance

Being clear in defining the objectives of academic year and summer research experiences has been important. Assessing the outcomes is necessary and has proven useful; however, the process extends well beyond the development of content knowledge in a discipline. We have collaborated with David

Lopatto of Grinnell College to assess the students' perceived gains as a result of summer research programs and their view of the importance of benefits to their careers. Similar to his results from a core group of four private liberal arts colleges reported elsewhere, we found mentoring by faculty crucial to a student's productivity and perspective on their experience. Our students also reported large gains in a number of benefits and high overall satisfaction. The long-term record of placement and persistence in graduate programs by REU program participants in chemistry has been very high, suggesting the experiences have been effective in training and preparing future scientists.

The many interconnections developing across departments and programs involving faculty and student research have set in motion other conversations and developing curricula that spun out. Hiring additional faculty who are working on questions at the interfaces of disciplines, whether in biological mathematics, computational science, molecular biology, or nanoscience, will likely result in further connections developing among departments but all related to an overarching purpose of providing the best possible experiences in undergraduate education and research. Whereas not the focus of this chapter, we have seen similar outcomes in collaborations designed to improve the preparation of science and mathematics teachers for middle schools, which were in part supported by NSF CCLI. In this case, a single project focused on mathematics course development, and has had impacts across three colleges, but additional funding, realignment, and additional position allocations from the institution have played important roles in that impact.

Conclusion

The process of institutional change is not simple and is most often slow. It can be jump-started by individuals and supported by funding of small projects. However, to spread most effectively, systemic change requires common purpose and vision across larger units, sometimes multiple sources and realignment of funding for equipment and other infrastructure, and an ability to organize incremental change into a coherent, intentional pathway to institutional change and improvement. None of these steps are easy or typical of most higher-education institutions.

Creating a culture of research and providing financial sup-

port and encouragement has resulted in numerous individual and joint awards for research, curricular innovation, and equipment that provide outstanding opportunities for undergraduate students in the sciences and mathematics at James Madison University and other campuses that provide an overall context and intentional decision-making and vision for undergraduate research. Building in an organized way from successful efforts and taking advantage of opportunities for funding and coordination across departments has resulted in an increasing number of opportunities for our students.

BIBLIOGRAPHY

- Amenta, D. S., and J. A. Mosbo. 1994. Attracting the new generation of chemistry majors to synthetic chemistry without using pheromones: a research-based, group approach to multistep synthesis at the college sophomore level. *J Chem Educ* 71: 661–664.
- Brakke, D. F., D. M. Downey, G. MacDonald, W. C. Hughes, L. A. VanEyck, and D. A. Wubah. 2003. Building a summer research community. *CUR Quarterly* 24: 22–25.
- Brakke, D. F., and M. Nelson. 2003. Practical limits to undergraduate research, with some possible solutions to enhancing quality and expanding capacity. *CUR Quarterly* 24: 88–93.
- Lopatto, D. 2003. Essential features of undergraduate research. *CUR Quarterly* 23: 139–142.
- Monroe, J. and C. Hurney. 2002. CCLI and curriculum change in biology. *CUR Quarterly* 22: 122–125.
- Seymour, E., A. B. Hunter, S. Laursen, and T. DeAntoni. 2004. Establishing the benefits of research experiences for undergraduates: first findings from a three-year study. *Science Education*. 88: 493–534.
- Wenzel, T. (Ed.). 2004. Enhancing research in the chemical sciences at predominantly undergraduate institutions. <http://abacus.bates.edu/acad/depts/chemistry/twenzel/summit.html>