Curricular Structures to Support Undergraduate Research

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The independent research project has become widely embraced and broadly implemented as a capstone experience for the science major. The widespread incorporation of these experiences into the undergraduate curriculum is testimony to the pedagogical merit of engaging undergraduates in hands-on, open-ended investigations. However, a capstone research opportunity (as well as the quality of the entire undergraduate science education) would be significantly enhanced if students could be exposed earlier in the curriculum to experiences directed at developing critical research skills that both include and go beyond the technical laboratory experience. Inclusion of such curricular components enables students to achieve the following objectives.

- Search, read and evaluate the chemical 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 experimentation;
- Collect, assess and communicate experimental data and scientific information; and
- Communicate clearly the nature of the research and its significance.

Adding research-enriching experiences throughout the curriculum also helps to cultivate a research culture for the students and the department as a whole.

The American Chemical Society's Committee on Professional Training (ACS-CPT) enthusiastically endorses the profound impact that independent research can play in the development of young scientists and recommends that research be part of an ACS-certified chemistry degree. The ACS-CPT describes the benefits of an undergraduate research experiences and some guidelines for implementation as follows:[1]

Undergraduate research can integrate the components of the core curriculum into a unified picture and help undergraduates acquire a spirit of inquiry, independence, sound judgment, and persistence. By doing research, undergraduates develop the ability to use the chemical literature and report effectively in spoken and written presentations. Also, supervision of research helps the faculty maintain enthusiasm, professional competence, and scholarly productivity.

The Committee strongly endorses undergraduate research as one of the potentially most rewarding aspects of the undergraduate experience. A successful project requires proper and careful attention by the faculty advisor. It places heavy demands on the faculty, the students, and the institution. The ideal research project is well-defined, stands a reasonable chance of completion in the time available, avoids excessively repetitive work, requires the student to use advanced concepts as well as a variety of experimental techniques and instruments, and develops chemical information that might be publishable. It brings the student into active contact with the research literature. Though reality frequently falls short of the ideal set of goals, the experience can nevertheless be extremely valuable.

This description is a tremendous endorsement of the pedagogical merit of undergraduate research and an attempt to alert the reader to some of the demands required for a successful research experience. The laudable goal of "integrating the core curriculum into a unified picture" does not occur by simply bringing students into our research activities towards the end of their undergraduate education. In fact, it is the purposeful integration of the specific components and activities associated with successful independent research throughout their undergraduate experience that can help cultivate the skills and attitudes necessary to prepare students for successful research experiences. Lecture and laboratory courses should be designed to introduce, refine, and reinforce a range of skills required for research.

Important curricular discussions related to pedagogical strategies and the on-going struggle to balance process and content in the curriculum continue to be invigorating and innovative. A rich and exciting literature exists that details creative pedagogical strategies and objectives for problem-based learning and inquiry-based labs; such teaching and learning methods can be included at both the individual course level as well as throughout a curricular program. While pedagogical strategies are not the focus of this paper, the movement to broadly adopt these methods is worthy of mention. These initiatives enable motivated educators to move beyond a teaching model which has students a) passively listen and watch lectures and b) execute laboratory exercises – a model better characterized as self-demonstration than actual experimentation. A common benefit associated with the newer teaching strategies is that they afford students and faculty the opportunity to engage in the lively discourse that illustrates the vitality and dynamic nature of our discipline and the type of discourse they will likely encounter in the research lab.

Unfortunately, the chemistry curriculum is among the most vertical and restrictive of academic programs at most institutions. In spite of this, institutions that support successful research programs have adopted a variety of strategies for creating research space within the seemingly rigid chemical curriculum. For instance, many have eliminated the laboratory components of all senior level courses enabling seniors to focus on their capstone research project. Others have combined the upper-level lab experiences into a joint laboratory that focuses on advanced techniques, instrumentation, and experimental design, typically offered in the junior year. In many instances, these intensive laboratory-based courses serve as "gateways" to research. In some instances, departments have formally separated the laboratory components from all individual courses to emphasize the critical and distinct role that experimentation and laboratory work plays in science.[2]

Recommendations for Curricular Structures to Support Undergraduate Research:

Chemical Literature: Students who can confidently search and read the primary literature and chemical database information are at a tremendous advantage when they enter the research laboratory. Primary literature should be introduced into normal coursework as early as possible in the curriculum. Early introduction to the chemical literature conveys the integral role that communicating science plays in the progress of science. In addition to reading the literature, students need to know how to search for information in the literature and in databases. Through guided exercises and report writing, students should develop the ability to read the text, figures and tables critically, extract essential experimental details and concisely summarize the content. These activities can begin by using the primary literature to introduce topics and creating laboratory opportunities that require students to consult the primary literature from which they extract critical experimental details or background information. Inclusion of articles not directly related to the immediate research topic can help students appreciate the benefit of reading broadly about a topic. Even exercises where students peruse non-technical web sites to critique the science provide valuable experience in learning to objectively evaluate scientific content. In advanced courses, students should be reading classic and recent seminal papers in the field. By this point, they should be able to critically analyze and critique the scientific quality and impact of the work. Such exercises provide both a historical context for science students and helps them begin to understand how scientific knowledge is developed.

Experimental Design: Central to scientific inquiry is the iterative process of articulating questions and seeking answers. Intellectual experiments can be as helpful as physical ones for students developing this skill. Exercises can be readily tied with reading the chemical literature – by having students identify the questions asked by the authors, how and why they approached the experimental testing and how the experiments tie to the questions being asked. Inviting students to engage in open-ended questions allows them to exert some of their own control and creativity in the solution of the problem. Framing an experimentally approachable research question should become a regular exercise for undergraduate chemists. Have students craft mock grant proposals is one way to reinforce this skill. These are the intellectual skills that encourage and promote integration of the core content of the curriculum. In fact, these are often the rationale behind the acquisition of new equipment through programs such as the NSF-Curriculum and Laboratory Improvement and the Camille and Henry Dreyfus Special Grant Program in Chemical Sciences.

Instructional laboratories can also be designed to dovetail with research. For example, at Colgate University an instructional laboratory in recombinant DNA methods was turned into a mini-research laboratory to identify and catalog the exact mutation sites of a series of BRCA1 (breast cancer gene) genes catalogued by the NIH. The NIH lab involved in this project did not have the resources to clone and sequence the hundreds of genes, but it made an excellent project for an army of undergraduates in the teaching lab. Not only did the students learn all the techniques they would have anyway, but they also did so in a format that was scientifically useful and eventually resulted in the submission of a paper for publication. This type of laboratory exercise creates interested student stakeholders without sacrificing instructional quality, and is well worth pursuing whenever practical.

Focus on Data: Students need to see data to begin to appreciate and experience the dynamic nature of our discipline. Exercises can be designed around a data set that allows students to reflect on the conditions and assumptions employed during data collection, consider the quality of the data with respect to the hypothesis being tested, propose follow-up that could bolster the data. Data used for these discussions can originate from their own experiments, the literature, or other sources.

Communicating Science: Many of us emphasize written reports and a variety of supporting materials are available to assist students in the development of this skill.[3] Unfortunately, less attention is given to helping students develop oral presentation skills that will help them cogently deliver the results of their research efforts. These skills can be developed and refined as part of a departmental and/or divisional seminar series, as well as during class presentations. Oral presentations can also be incorporated as a part of regular coursework, especially in small classes. Attending seminars given by departmental faculty or invited guest speakers allows students to see how others organize material and present it to an audience not acquainted with their field of research. Structuring the content of a report or presentation is a skill that will serve our students well regardless if they continue in chemistry.

For a multitude of reasons, it is really helpful for students to hear about the kinds of research questions that have piqued a faculty member's interest. The natural passion faculty have for research and learning will be conveyed when they describe their topics, approaches, and results. Individual research interests, experiences, and methods can be introduced in the class or lab setting and through periodic departmental presentations (either formal seminars or during brown-bag lunch talks). Department-wide research group meetings allow faculty and their students to communicate what they are learning across sub-fields. All of this serves to build research momentum.

Poster presentations have become the most common form of disseminating information at scientific meetings. Student poster sessions held within a class, or for a department or college-wide event encourage students to communicate in a concise manner and allows for two-way dialog with other students and faculty about the content of their poster. If the quality is high, these can be placed in a public location in the department or in a high-traffic area on campus – again to foster the culture of research by making science visible and promoting discussions among students from other courses and majors. In addition to communicating science to other scientists, students should appreciate the value and necessity of communicating science to the public.

Ethics: Inviting students to consider ethical and moral implications of the research being undertaken can often surprise and startle students who have been consumed with "getting up to speed" on the project. Incorporating these issues into laboratory and course work earlier in their careers emphasizes the central role that the ethical conduct of scientists plays in the integrity of the work and public trust in the results. Case studies, class debates, and assignments where students are asked to identify the ethical issues associated with a particular research area are also ways to introduce students to the ethical dimensions of scientific research.

Safety: Largely dictated by law, safety issues (environmental, health and personal) must be at the forefront of faculty and student minds prior to entering any laboratory. Laboratory independence requires that students become proactive advocates of safe laboratory conduct, so by the time a student reaches the independent research project they should be in a position to watch over the less-seasoned lab co-workers. Safe habits must be developed early and reinforced at all stages of a student's education. Safety can be discussed not only during instructional laboratory sessions, but also in conjunction with assignments for other classes. For instance, when reading primary literature, students can be asked to identify the safety issues that the researchers had to consider (e.g. toxicity of reagents used, safe handling of radioisotopes, etc.).

Conclusion

Addressing some or all of these issues early and often in the curriculum can help better prepare students for the capstone research experience and for a career in science. There are many skills that are needed that complement the content learned in class and the technical and instrumentation experience gained in laboratory courses. The better prepared a student is by being groomed throughout their undergraduate experience, the more valuable the collaborative research experience will be between the student and faculty mentor in the all too-short capstone project. In addition, if research-related opportunities are embedded throughout the undergraduate curriculum, and not limited to a capstone event, students will more clearly see that research is *how* scientists learn and is what many scientists actually *do* in their careers.

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1. "Undergraduate Professional Education in Chemistry: Guidelines and Evaluation Procedures" Spring 2003 American Chemical Society Committee on Professional Training. www.chemistry.org/portal/a/c/s/1/general.html?DOC=education\cpt\guidelines.html
2. Rice University and East Stroudsburg University.
3. "The ACS Style Guide", Dodd, J.S.; American Chemical Society, Washington, D.C. 1997.