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Article

A Writing-Intensive, Methods-Based Laboratory Course for Undergraduates[S]

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Keri L. Colabroy‡

From the Department of Chemistry, Muhlenberg College, Allentown, PA 18104

Engaging undergraduate students in designing and executing original research should not only be accompanied by technique training but also intentional instruction in the critical analysis and writing of scientific literature. The course described here takes a rigorous approach to scientific reading and writing using primary literature as the model while simultaneously integrating laboratory instruction on basic enzyme purification and characterization, followed by 6 weeks of laboratory dedicated to student-designed original research projects. In the preparation and execution of their original projects, students engage in analysis of the primary literature, proposal writing, peer review, manuscript preparation, and oral presentation. The result is a comprehensive and challenging course that teaches third- and fourth-year undergraduates what it means to "think and work like a scientist."

Keywords: Writing, laboratory, research, literature.

Over 20 years ago, the value of undergraduate research was articulated to the academic community by a report from the National Science Foundation [1]. Since this idea of a research-friendly undergraduate curriculum was first introduced, education in biochemistry and related disciplines has benefited enormously from the realization that students learn more and learn more willingly when they are personally intellectually engaged and curious about the subject matter. Undergraduates engaged in research experiences demonstrate an increase in "understanding, confidence, and awareness" [2] and in their ability to "think and work like a scientist" [3]. To this end, some authors have described involving students in planning laboratory exercises [4, 5], incorporating original research projects into semester-long laboratory courses [6–8], performing faculty research as part of a course curriculum [9, 10], using cooperative-style learning and student peer mentors to conduct undergraduate research across multiple semesters [11] and advocating for installation of institutional undergraduate research programs at small colleges and large universities alike [12–14]. At the root of all these objectives is the acknowledgment that students are more motivated to learn a technique or solve a particular problem when the answer is unknown—when they are actually engaged in doing science rather than simply repeating it.

Although the motivation created by performing original research is necessary, alone it is not sufficient for successful learning. Professional scientists would readily acknowledge that analyzing, understanding, and writing scientific literature is just as inseparable from the process of doing original research as is the mastery of basic experimental technique. The value of original research in the undergraduate science curriculum is undisputed, and although many have argued that scientific literacy is a necessary part of the undergraduate curriculum [15–17], the practical connection between scientific reading, writing, and undergraduate research remains somewhat less explored. Future scientists are instructed at length on the process of writing about science in texts such as "Writing in the Biological Sciences" or "A Short Guide to Writing about Chemistry." While these texts, by their very nature, are divorced from any particular scientific content, they all begin with similar instruction and exhortation on reading the scientific literature to understand why you are writing. "Write like a Chemist" is a textbook that overtly educates the student writer on using genre analysis to understand both the broad and fine organizational structure within different types of disciplinary writing used in chemistry [18]. This "read-analyze-write" approach is presented in the context of disciplinary writing provided within the text. However, despite the emphasis, the scientific community has placed on the relationship between scientific reading and writing, the graduate school transition from textbook-based instruction to primary literature-based learning is often navigated with difficulty [19, 20]. Instructors of biochemistry report using writing to help students understand scientific literature as part of seminar and laboratory courses [7, 16, 21, 22], and as a way of assessing stu-

[S]Additional supporting Information may be found in the online version of this article.

‡To whom correspondence should be addressed. 2400 Chew St, Allentown, PA 18104. Tel.: 484-664-3665.
E-mail: colabroy@muhlenberg.edu.

dent learning in group and laboratory projects [23]. Through the development of a rigorous seminar course for first-year graduate students, Carey and Colicelli used the presentation and analysis of scientific journal articles along with student research to teach effective scientific communication, experimental design skills, and promote critical thinking, ultimately preparing students for graduate level research. Here, Carey and Colicelli acknowledge what others have implied, that the literature-based learning necessary for effective scientific experimentation and writing—in essence, reading to write—is most effectively mastered when embedded within the context of original research. Therefore, it must follow that mastering the discovery-oriented process of original research cannot be fully realized apart from the habits of mind cultivated from the writing and critical analysis of scientific literature.

As a school of the liberal arts, we at Muhlenberg College are passionately committed to educating the whole student. In keeping with that philosophy, there is a strong and active undergraduate scientific research community on the campus. An average of 40 students per semester is engaged in original faculty sponsored research in biochemistry, biology, chemistry, computer science, environmental science, neuroscience, mathematics, and physics [24]. But when one considers that an average of 215 students are declared science majors each academic year [24], less than 20% of our students engage in original research at the college. Another 20% do go outside the college for academic, industrial, and clinical internships, but these may or may not contain an original research component [24]. Even with five to ten biochemistry majors per class and the small faculty student teaching ratios of a liberal arts college, the teaching loads leave insufficient time to engage every major in a meaningful collaborative and original research experience with a faculty member. It was with these limitations in mind that BCM 341: Experimental biochemistry was created. Experimental biochemistry tries to meet three distinct needs within our biochemistry curriculum and in the larger community of science majors: 1) to instruct students theoretically and practically in basic biochemical experimental technique; 2) to guide students in the process of analyzing and writing about scientific research; and 3) to engage students in the process of original research. These three overarching goals are inexorably intertwined, and, therefore, the course described here not only addresses experimental technique and original research but also the role of scientific reading and writing in the mastery of both.

COURSE PLANNING

A course of this design could be taught in many different disciplines. The author chose to focus this course on biochemistry, specifically using a bacterial enzyme, because it capitalized on departmental expertise and experience, as well as complemented existing course offerings in the Biology and Chemistry departments, but the intent is that the course model could be extended to other systems and even other disciplines, indeed others have reported laboratory courses with a similar original research component in molecular [8] and cell biology [7]. Apart from just an original research component, this course also fills an important gap in the deliberate and integrated instruction of scientific writing using the context of student driven experimentation. The accumulation of reports, a proposal, and an original research article totals over 15 pages of writing, making Experimental Biochemistry the course that fulfills the writing intensive graduation requirement for all biochemistry majors. Scientific writing is inseparable from literature-based learning, and the scientific reading and writing addressed within the course are not only necessary for advanced study in biochemistry but also particularly applicable to students who pursue additional original research by way of an honors thesis or postgraduate work.

Bacillus subtilis glycine oxidase, the enzyme chosen as the subject of the semester-long investigation, is a flavoprotein that overexpresses in high yield from *E. coli*, withstands the brutality of inexperienced hands with little to no effects on its activity, and can be frozen indefinitely at -80°C. The flavoprotein cofactor gives glycine oxidase its yellow color and provides the opportunity for UV–visible and fluorescence spectroscopy, and several published crystal structures allow for an *in silico* study of structure. Many proteins would meet these criteria, and, therefore, a course of this type could be designed around almost any protein of interest.

The course is divided conceptually into 30% basic technique (experimental skills that are performed as part of basic research in most laboratories asking biochemical questions), 30% modern techniques (experimental specialties that require prerequisite knowledge of basic technique), and 40% scientific reading and writing, but in practice, these three topics are integrated throughout. On completion of the course, it is expected that students should be able to (i) propose and conduct experiments to illuminate a biochemical problem or answer a specific biochemical question, (ii) critically evaluate published experiments used to understand a biochemical problem, (iii) read and understand the components of biochemical scientific literature with confidence, and (iv) develop and improve writing skills in the proposal and reporting of scientific research. These objectives could be summarized in the three overarching areas of experimental technique, scientific literature, and original research.

COURSE ORGANIZATION AND CONTENT

The three overarching goals of the course were addressed by splitting the course into two modules, each with lecture and lab components. In the first module, students learned the theory and practice of basic biochemical techniques, how to deconstruct and analyze a scientific paper and perform a guided set of laboratory exercises to isolate and study *Bacillus subtilis* glycine oxidase. This knowledge of basic technique and development of skills to understanding published scientific work prepares the students to design and write their own original research proposal. In module II, the lecture component of the course deals with modern techniques, and

TABLE I
Lecture topics

	Lecture no.	Topics
Module I	1	Introduction to course, classes of biological molecules, central dogma, why study proteins
	2	Studying specific proteins—before and after the genomic revolution (classical purification, cloning, recombinant protein expression), prokaryotic DNA sources, and expression hosts
	3	Eukaryotic DNA sources and expression hosts and protein extraction and purification
	4	Site-directed mutagenesis, buffers, and protein stability
	5	Protein detection: UV, visible (colorimetric), fluorescence
	6	Immunological methods for protein detection (immunoblot, ELISA, and immunocytochemistry)
	7, 8	Detecting (yeast two-hybrid, far western, pull down, and crosslinking) and quantifying (gel filtration, surface plasmon resonance, UV–visible and fluorescence spectroscopy, and isothermal titration calorimetry) noncovalent binding interactions between proteins
	9	Steady-state enzyme kinetics
	10	Enzyme assay (UV–visible or fluorescence spectroscopy, radioactivity, and oxygen consumption)
Proposals	11	How to write a proposal, and literature searching
	12–16	Student–instructor conferences on proposal ideas
	17	Study sections for proposal review
Module II	18	Protein sequence and structure and homology
	19	Protein structure determination by X-ray diffraction and NMR
	20	Journal club on protein structure and homology
	21–22	Protein mass spectrometry
	22–23	Proteomics (2D gel, MudPIT, and shotgun)
	24	Journal club on protein MS and proteomics
	25	Rapid kinetics (quench and stopped flow)
	26	Journal club on rapid kinetics

the 6 weeks of laboratory time are dedicated to the student-designed original projects.

Instructional Resources

Developing this course was challenging because no specific text addressed all of the course goals. As a reference, the students are assigned "Biochemistry Laboratory" by Rodney Boyer as a required text. For laboratory handouts in module I, original research articles on glycine oxidase and manufacturer protocols (*e.g.* Pierce, Bio-Rad, Qiagen) were used to write lab handouts specific to the course (see Supplementary Information). The primary literature serves as the main text, and in keeping with college library access, the ACS journal *Biochemistry* and ASBMB's *Journal of Biological Chemistry* were the sources of nearly all research articles used.

Course Prerequisites

Experimental Biochemistry is part of the core biochemistry major curriculum, and yet Organic Chemistry I and II are the only course prerequisites. The decision to offer Experimental Biochemistry without general biology or introductory biochemistry as prerequisites derives from the fact that Experimental Biochemistry is not about biochemistry *per se*, it is about doing biochemistry—perhaps a fine but still a necessary distinction. The content of the biochemical discipline has and will continue to evolve. And although content is essential for any course, this course is about learning the skills necessary to navigate a complex and exclusive world of scientific literature, experimentation, and discovery. In practice, this philosophy impacts pedagogy in several ways: 1) it is assumed that all students have a working knowledge of small molecule structure from organic chemistry but no previous knowledge of the macromolecules of biochemistry. 2) Rodney Boyer's "Concepts in Biochemistry" is a source of material for lecture slides, and the text is recommended to any student that rosters the course with no previous biology or biochemistry. Boyer's text is written for chemists and, therefore, assumes only a working knowledge of Organic Chemistry, and finally, 3) students may have no knowledge of pipetman use or sterile technique—therefore, these techniques are addressed in the first lab period. The relaxed prerequisite structure has made the course accessible to not only biochemistry majors but also chemistry, natural science, neuroscience, and biology majors. Thus, far, two chemistry majors have performed successfully in the course with no college biology background. Students most often roster the course in their third year, but approximately 20% of every class are seniors.

Lecture Topics

In module I, the two 50-minute lectures per week are used to discuss and analyze methods of biochemical experimentation from published research articles; a summary of lecture topics is provided in Table I. The first few lectures are used to establish a foundation and fill in any existing gaps between students' previous knowledge of biochemistry. These lectures are followed by a historical perspective on how proteins were studied before the genomic revolution and after the advent of DNA technology. Although classical techniques of protein purification are nearly obsolete in current practice, a goal of the course is to understand scientific literature past and present, which makes the classical purification of proteins from biological sources relevant. Recombinant DNA

TABLE II
Student evaluation

Components	Number	Percentage of grade
Take home exams	4	25
Laboratory progress reports	3	20
Special project proposal (Two drafts)	1	20
Special project final paper and 15-minute presentation	1	20
Lab notebook	1	5
Class participation	–	10

technology as a means of overexpressing and purifying proteins and site-directed mutagenesis are followed by methods of protein detection, methods for studying protein–protein and small molecule–protein binding, and finally, the measurement of enzyme activity.

The lecture component of module II is dedicated to modern techniques. With the training of module I, students are now prepared to analyze full research articles. Each topic (Table I) is presented from a practical standpoint with a full research article taken from the recent literature that the students analyze and prepare for class. The theory behind each technique is addressed briefly, but theory as content is not the focus. These techniques are not practically available at a small liberal arts institution, so presenting them without a practical lab component is reasonable. Even at a larger research institution, undergraduate courses would not likely have access to mass spectrometry, NMR, or stopped flow, as these instruments are costly and often only one or two is available within a department.

In both lecture modules, primary literature is used throughout. It may seem challenging to teach from primary literature when the students could be starting with a very limited knowledge of biochemistry in content. This difficulty is avoided by taking a methods-based approach to each article. The instructor focuses on what was accomplished experimentally in the paper—for example, simply the collection of experiments in the methods section is enough to determine if the authors were investigating binding, kinetics, structure, or some combination thereof. Furthermore, the instructor mediates gaps in understanding by providing limited context on the objectives of a given article. As the students progress in their understanding of scientific article assembly through genre analysis [18], they are able to identify goals, results, and data analysis simply by their placement and manner of discussion within the paper. They might not readily understand the full context and implications of the results, but they are able to evaluate to what extent the paper's authors find the context and implications relevant and important to the field. This process is facilitated by choosing original research articles that are not jargon and acronym heavy, as well as defining jargon when it appears.

Student learning was evaluated by four take-home exams (two per module). The take-home exams were very simply the guided analysis of a recent journal article from the literature. The article was selected based on its use of techniques relevant to that series of lectures. The students were asked to evaluate the methods, the data (in figures or tables), and as the semester progressed, they were asked to solve a separate hypothetical research problem (based on the primary literature) by proposing reasonable experiments. The process of analyzing methods and data from research articles and proposing experiments to solve problems was modeled in almost every lecture. In addition, class participation was measured by student preparation for journal article discussions and interaction in the classroom. Table II describes the evaluation categories and the percentage of the grade applied to each category.

Module I Laboratory: Basic Technique and the Elements of Scientific Writing

The laboratory component of module I is found in Table III and surrounds a guided investigation of *Bacillus subtilis* glycine oxidase using the published article by

TABLE III
Laboratory topics

	Lab period	Topics	
Module I	1	Lab #1: Transformation Scientific writing exercise #1 Sterile technique, autoclaving, and buffers	
	2	Lab #2a: Overexpression, pour Ni-NTA columns Lab #2b: Bradford assay calibration curve Scientific writing exercise #2	
	3	Lab #3a: Protein extraction Lab #3b,c: Protein purification and concentration determination	
	4	Lab #4a: UV–visible spectroscopy Lab #4b: Fluorescence spectroscopy Lab #8a: Bioinformatics	
	5*	Lab #5a: SDS-PAGE and blot Lab #8b: 3D protein structure	Lab #6: Activity assay Lab #8b: 3D protein structure
	6	Lab #5b: Immunoblot detection Lab #8b: 3D protein structure	Lab #7: Michaelis–Menten kinetics Lab #8b: 3D protein structure
	7	Lab #6: Activity assay	Lab #5a: SDS-PAGE and blot
	8	Lab #7: Michaelis–Menten kinetics	Lab #5b: Immunoblot detection
	9	Usually module I has a lab period lost to fall break	
Module II	10–15	Student projects	

* Lab periods 5–9 are comprised of two groups of students rotating through different lab exercises—this is due to limitations in instrument access.

Settembre *et al.* [25] as a reference point (see laboratory handouts in Supplementary Information). Starting with an ampicillin resistant plasmid containing a polyhistidine-tagged *thiO/yjbR*[1] gene under the control of an isopropyl β-D-1-thiogalactopyranoside inducible promoter, the students transform *E. coli*, then overexpress, purify, quantify, and characterize the protein. The activity of the enzyme is measured by oxygen consumption with an oxygen electrode, and by coupled assay with UV–visible detection. Students also determine Michaelis–Menten kinetic constants, which they can compare to the literature as a means of evaluating their experimental technique. Sequence and structure are explored through guided bioinformatics exercises and an *in silico* investigation of the PDB file 1NG3 using the freeware Swiss-PDB viewer (available from http://www.expasy.org/spdbv/download.html). PCR and gene cloning are notably absent from the list of techniques in Table III. The author chose not to cover PCR and gene cloning, because they are covered in another core course within the biochemistry major. Should students wish to perform PCR as part of a special project, for example, in a site-directed mutagenesis project, that instruction is handled on a one-on-one basis.

In tandem with the experimentation in module I, some laboratory time is devoted to scientific writing exercises. In these exercises, two articles are used as examples: one from the ACS journal *Biochemistry* and one from the ASBMB journal *The Journal of Biological Chemistry*. The students work individually and in small groups to analyze each section from each article for its goals, specific style (words, phrases, and types of sentences), and particular formatting rules both at the sentence and paragraph level (*i.e.* use of personal pronouns, references, use of figures and tables, and specific types of paragraphs) [26]. The sections are addressed in the following order: exercise #1—introduction, materials and methods, abstract, and exercise #2—results, discussion, results and discussion combined, and conclusion. This reductive approach to technical literature can be applied to any specific discipline when analyzing technical writing or professional presentations [18, 21, 27]. The point is in the process. For example, an abstract from one subdiscipline does not always resemble in shape or form the abstract from another subdiscipline—this is confusing and frustrating to students when they are not instructed to expect and navigate such differences. When using a reductive approach, the students can count and determine that the introduction and discussion contain the most references to the primary literature. When seen in context, they are able to reason that the introduction is placing the reported work in its scientific context, whereas the discussion is comparing and negotiating differences between the reported work and similar or related data from the literature. This analysis has profound effects on their ability to successfully write comparable sections of their own scientific paper, and their ability to target their own reading and critically analyze scientific articles. To this end, during the laboratory component of module I, students are evaluated with laboratory progress reports. The report is modeled on a scientific paper and allows students to practice the style and syntax of scientific writing while still learning technique.

Student-Designed Original Projects

The transition between the two halves of the course (module I and module II) is made with a lecture on proposal writing and literature searching, and several class sessions devoted to individual instructor–student interviews on crafting a proposal to investigate glycine oxidase (Table I). As newcomers to the field, the students are guided in the process of reading the literature to generate multiple potential ideas, then refining and developing one or two of those multiple ideas into a proposal. The instructor involvement in this process via individual student conferences (see syllabus, Supplementary Information) ensures that students do not duplicate ideas or spend too long researching an idea that is unoriginal or impractical. The students are instructed that a good proposal tries to solve a problem, and in doing so, the proposal must: 1) explain why solving the problem is important and valuable by considering short-term and long-term impact, 2) explain how the proposed work is feasible by including references on similar work that was successfully performed and explaining the technology and techniques, which exist to solve the problem, and 3) lower the "risk" for the funding agency investing in the work by illustrating what potential problems could be encountered and how those problems could be solved. The total proposal is 2,000–2,500 words broken into two sections: 1) statement of the problem and scientific significance and 2) project description. The proposal itself is written over at least two drafts, and the instructor reads and comments on an intermediate draft.

Every student writes a proposal, but only half of the proposals are "funded." The "funded" proposals are chosen by the students themselves in an anonymous peer review. One lecture period between modules I and II is devoted to study sections. The students are divided into two groups and each group reads and ranks proposals from the other group. The top two to three proposals from each group are "funded," and the remaining students become the lab partners of the proposal competition winners. After the winners are chosen, the instructor attempts to match the students along lines of research interest, so both members of the research team can be equally engaged in the process. In practice, this proposal exercise has generated excitement and healthy competition among students in the class. The proposals are unique, and the product of individual effort. Furthermore, this exercise is fundamentally different from a semester-long proposal assignment in which the students must propose an original research idea without taking into account the limitation of research facilities, funding, and time [22]. Having to craft a proposal that is significantly original and experimentally tractable in 6 weeks requires that students engage with the primary literature as scientists. They must read and understand not only the pur-

[1]A generous gift from Tadhg Begley (formerly of Cornell University). KLC will make the plasmid available upon request for educational use only (colabroy@muhlenberg.edu).

Table IV
A sample of student designed original proposals from 2006 to 2009[a]

Cellular localization of ThiO using immunofluorescence
Site-directed mutagenesis of Tyrosine 246 in *Bacillus subtilis* glycine oxidase
Exploration of subunit interactions of the homotetramic glycine oxidase by point mutation at an interior positively charged pocket
Reevaluating ThiO's active site residues through competitive inhibition and site directed mutagenesis: A structural study.
Comparative kinetic study of mutant (Ile15Met) glycine oxidase to sarcosine oxidase in *Bacillus subtilis.*
Identifying binding proteins of *Bacillus subtilis* glycine oxidase that prevent hydrolysis of dehydroglycine
Steady-state kinetics investigation of *B. Subtilis* glycine oxidase with several substrates utilizing both a direct continuous and a coupled continuous enzyme assay

[a] These proposals were "funded" in the class competition.

pose and impact of an article but also the means by which the experiments were conducted. Focusing the proposal to a single enzyme, with which they are already familiar, keeps this assignment from becoming too difficult for the time allotted. A short list of funded student proposals can be found in Table IV. Over the 4 years, the course has been offered, site-directed mutagenesis proposals have been most popular, as proposals to investigate binding interactions and kinetics of the enzyme. Intellectual honesty is enforced by requiring two drafts of the proposal in addition to student–instructor conferences. The nature of the focused topic (*i.e.* all proposals are on *B. subtilis* glycine oxidase) results in proposal ideas repeating over the years; however, as long as the students arrive at these ideas on their own, the repetition is advantageous to the instructor in advising students of potential problems and so forth. As part of their project proposal, students must generate a proposed timeline and list of necessary instrumentation, chemicals and supplies with vendors, and prices as appropriate. Students are advised to keep their project budget below $200 when writing their proposal. The instructor acquires the necessary chemicals and supplies such that work can begin on Week 9 or 10 of the semester.

Module II Laboratory: Original Research and Writing the Scientific Paper

The laboratory component of module II is dedicated to the student-designed original projects. Because the students are responsible for organizing their time in module II, the instructor serves as a resource for troubleshooting experiments and interpreting results. Experimentation in module II culminates with each student team writing a formal research article to report their findings from their 6 weeks of original research and presenting that work in a course symposium during the final exam period. By this point in the semester, the class is proficient in reading original research articles. They understand the purpose and content of each section, and their knowledge of technique makes reporting on their methods both reasonable and intelligible. Students write an intermediate laboratory progress report halfway through module II, which forces them think about and write the final paper in stages. The final paper is more a compilation than an entirely new piece of writing. The collaboration between the members of each lab group to write the final paper is also an accurate reflection of how most published scientific papers are written. Although many student projects do not progress to completion, this has not discouraged students from enthusiastically reporting and presenting what they have learned. In practice, the motivation of pursuing their own research projects has often resulted in effort over and above the expectations of the course. Students are determined to solve their problem even if it requires additional hours of experimentation.

CONCLUSIONS

The course presented here instructs students in current biochemical technique while teaching them to become independent scientific thinkers and writers. It teaches not only the fundamentals of experimentation but also how to use those fundamentals to ask and answer real research questions. Whether the course is offered at a small college or a larger research university, the basic infrastructure could be adapted to complement the available resources. Basic instrumentation used included floor and table shaking incubators capable of holding at least four 2–4L Erlenmeyer flasks, cell lysis equipment (sonicator, beadbeater, or French press—even lysozyme could be used in the absence of mechanical methods of cell lysis), a high speed centrifuge capable of pelleting cell debris, three double beam UV–visible spectrometers, one scanning fluorometer, three rigs for SDS-PAGE and blot, a ChemiDoc for immunoblot imaging (blots could be imaged colorimetrically if other imaging instrumentation is unavailable), a controlled temperature water bath, and freezer ($-20°C$ or $-80°C$) and refrigerator ($4°C$) storage. All column chromatography was done by gravity on the bench top, but a chromatography system could certainly be used were one available. Kinetic data were analyzed via nonlinear least squares fitting software (*e.g.* Origin, Grafit, Kaleidagraph); however, if such software is unavailable, Lineweaver–Burk analysis of Michaelis–Menten kinetics is possible, although not preferable. As glycine oxidase uses molecular oxygen as a substrate, a Clark polarographic oxygen electrode was also used for a direct continuous assay of enzyme activity, but many methods are available for continuous measurement of enzyme activity, and another method could certainly be substituted if a different enzyme were the subject of investigation. While in the laboratory, students work in groups of two, with a maximum of six groups (12 students). The course was run without the aid of teaching assistants, but a laboratory assistant was employed three to five hours a week to prepare buffers, wash glassware, autoclave and so forth.

Student perception of the course was measured using the 10 categories of SIR II [28] standard 5-point scale questions (45 questions total) and anonymous written evaluations. The SIR II assessment results from the two

TABLE V
Average of SIR II results from 2008 to 2009[a]

Experimental Biochemistry lecture and lab	Fall 2008	Fall 2009
Course organization and planning	4.65	4.85
Communication	4.76	4.83
Faculty/student interaction	4.47	4.63
Assignments, exams, grading	4.18	4.67
Course outcomes	4.45	4.81
Student effort and involvement	4.52	4.85
Overall evaluation of instruction	4.55	4.78
Number of students evaluating	10	7

[a] The scale was as follows: 1 = ineffective, 2 = somewhat ineffective, 3 = moderately effective, 4 = effective, and 5 = very effective.

most recent years are summarized in Tables V and VI. Student evaluation of course outcomes and their effort and involvement is perhaps most revealing. Every student enrolled in Experimental Biochemistry lecture in 2008 and 2009 indicated that their learning increased "more" or "much more than most courses," whereas all but one student indicated that Experimental Biochemistry helped them to "think independently about the subject matter" and it did so "much more than most courses." Results from anonymous written evaluations also indicate that students feel more "confident" especially with their analysis of original research articles, which is consistent with the feelings of "independence" that they indicated on SIR II evaluations. SIR II reports also indicate student anxiety over the clarity of exam questions, grading, and the quality of the textbook. The reservations about the textbook are to be expected, because no published textbook adequately addressed all course content and objectives. To mitigate anxiety over exams and assignments additional effort was put into generating detailed grading rubrics for assignments and in modeling how to answer exam questions during in class journal article analysis. This is reflected in an increase in rating within the assignments, exams, and grading section between 2008 and 2009 (Table V). This qualitative reporting of student perception is preparation for an upcoming systematic and quantitative assessment of student writing within this course and across our biochemistry curriculum.

Course goals addressed three overarching areas: experimental technique, scientific literature, and original research, which were integrated across the course objectives. Each student mastered the course objectives to different degrees, but all reported an increase in the level of confidence and independence with which they approach the course material. In 2008 and 2009, each student enrolling the course met the objectives by earning a grade of 80% or higher: they could demonstrate competence in navigating original scientific literature, they could propose reasonably plausible experiments to analyze a problem, and they demonstrated an improved capacity to think creatively and originally about their research. Since Experimental Biochemistry was launched for the first time in the fall of 2006, 33 students have taken the course, and in senior exit interviews, it is frequently ranked as the most valuable course taken by graduating biochemistry majors. Some students used Experimental Biochemistry as their singular research experience in preparation for graduate or professional school, whereas others were motivated by the course to pursue research at Muhlenberg, still others used the skills learned to craft, investigate, and defend successful honors thesis projects. Of those 33, 26 have graduated, and most are currently engaged in graduate (chemistry, biochemistry, molecular biology, and biomedical science) or professional (MD, DO, DDS, DMD, DVM and pharmacy) programs, whereas $\sim$ 20% entered the workforce (biomedical sales, laboratory assistant, research associate).

The idea of performing original research in the teaching laboratory is not new [7, 9, 10], but letting students develop and execute their own research ideas is not something typically attempted at the undergraduate level [8]. Evidence presented here would argue that coupling research with writing not only allows students to assert ownership over the material and, therefore, over their learning, but also cultivates within the students confidence and independence that develops in spite of experimental failure and actually persists beyond the course. Graduating seniors remarked: "I like the way the lab work was split up in Experimental—first half, the labs are set up for you and you are learning by answering questions, then the second half going out on our own and doing experiments, and failing—that was important....," "The research proposal from Experimental was a really valuable—I know I'm going to have to publish in residency, and write grant proposals...," and "...(after Experimental), you can talk about research with real scientists (getting

TABLE VI
Summary of SIR II results from 2008 to 2009

SIRII questions	5 Much more than most courses	4 More than most courses	3 About the same as others	2 Less than most courses	1 Much less than most courses
Course outcomes[a]					
My learning increased in this course...	82.5	17.5	0	0	0
I made progress toward achieving course objectives...	57	38	5	0	0
This course helped me think independently about the subject matter...	75	20	5	0	0
Student effort and involvement[a]					
I studied and put effort into this course...	82.5	17.5	0	0	0
I was challenged by this course...	90	7.5	2.5	0	0

[a] Percentage of response in course outcomes and student effort and involvement for both lecture and laboratory components.

internships, etc.), it shows you what research outside the classroom is like..." As we prepare the next generation of scientists, an integrated approach to technique, writing, and research may be just what we need.

REFERENCES

[1] NSF (1996) Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering and Technology vol. NSF publication No. 96-139, National Science Foundation, Arlington, VA.

[2] S. H. Russell, M. P. Hancock, J. McCullough (2007) THE PIPELINE: Benefits of undergraduate research experiences. *Science* **316**, 548–549.

[3] A. -B. Hunter, S. L. Laursen, E. Seymour (2007) Becoming a scientist: The role of undergraduate research in students' cognitive, personal, and professional development. *Sci. Educ.* **91**, 36–74.

[4] M. V. Merritt, M. J. Schneider, J. A. Darlington (1993) Experimental design in the general chemistry laboratory. *J. Chem. Educ.* **70**, 660–663.

[5] J. G. Dunn, D. N. Phillips (1998) Introducing second-year chemistry students to research work through mini-projects. *J. Chem. Educ.* **75**, 866–869.

[6] V. Demczylo, J. Martinez, A. Rivero, E. Scoseria, J. L. Serra (1990) Research projects for undergraduate students: A more rewarding approach to analytical chemistry courses. *J. Chem. Educ.* **67**, 948–950.

[7] A. E. Gammie, N. Erdeniz (2004) Characterization of pathogenic human MSH2 missense mutations using yeast as model system: A laboratory course in molecular biology. *Cell Biol. Educ.* **3**, 031–048.

[8] S. Zhang (2008) A research project-based and self-determined teaching system of molecular biology techniques for undergraduates. *Biochem. Mol. Biol. Educ.* **36**, 181–188.

[9] M. S. Reagan (2004) Integrating research and teaching labs with the module evolution approach. *Council on Undergraduate Research Quarterly* **24**, 165.

[10] K. J. Parra, M. P. Osgood, D. L. Pappas Jr., (2010) A research-based laboratory course designed to strengthen the research-teaching nexus. *Biochem. Mol. Biol. Educ.* **38**, 172–179.

[11] L. Henderson, C. Buising, P. Wall (2008) Teaching undergraduate research: The one-room schoolhouse model. *Biochem. Mol. Biol. Educ.* **36**, 28–33.

[12] M. Malachowski, M. E. Nelson (1999) CUR Institutes on institutionalizing undergraduate research: A success story. *Council on Undergraduate Research Quarterly* **20**, 36–39.

[13] A. Harris (2007) Institutionalizing undergraduate research. *Academic Leader* **23**, 5–7.

[14] R. G. Winningham, J. H. Templeton, B. E. Dutton, S. H. Scheck (2009) A Grassroots, faculty-driven initiative to institutionalize undergraduate research: The ins and outs of cultivating administrative support. *Council on Undergraduate Research Quarterly* **30**, 29–34.

[15] A. R. Burkett, S. B. Dunkle (1983) Technical writing in the undergraduate curriculum. *J. Chem. Educ.* **60**, 469.

[16] P. J. De Ávila, B. B. Torres (2010) Introducing undergraduate students to science. *Biochem. Mol. Biol. Educ.* **38**, 70–78.

[17] D. W. Sherwood (1999) Writing in chemistry: An effective learning tool. *J. Chem. Educ.* **76**, 1399–1403.

[18] M. S. Robinson, F. L. Stoller, M. S. Costanza-Robinson, J. K. Jones (2008) Write Like a Chemist. Oxford University Press, New York.

[19] M. Carey, J. Colicelli (2005) Primary Literature-Based Learning Complements and Enhances Research Experience: The Howard Hughes Undergraduate Research Program (HHURP) at UCLA. *Council on Undergraduate Research Quarterly* **25**, 114–117.

[20] C. A. Kozeracki, M. F. Carey, J. Colicelli, M. Levis-Fitzgerald (2006) An intensive primary-literature-based teaching program directly benefits undergraduate science majors and facilitates their transition to doctoral programs. *CBE Life Sci. Educ.* **5**, 340–347.

[21] P. Higgins (2008) Investigational writing exercises for undergraduate biochemistry experiments. *Am. Chem. Soc. Natl. Conf.*

[22] A. M. Rammelsberg (1999) Biochemistry idea papers: Teaching proposal writing. *Chem. Educ.* **4**, 125–127.

[23] H. B. White (2002) Writing and individual accountability in problem-based learning. *Biochem. Mol. Biol. Educ.* **30**, 196.

[24] N. Hammel, Ed. (2009) Muhlenberg College Source Book, Muhlenberg College Press: Allentown, PA.

[25] E. C. Settembre, P. C. Dorrestein, J. -H. Park, A. M. Augustine, T. P. Begley, S. E. Ealick (2003) Structural and mechanistic studies on ThiO, a glycine oxidase essential for thiamin biosynthesis in *Bacillus subtilis*. *Biochemistry* **42**, 2971–2981.

[26] D. Rosenwasser, J. Stephen (2009) Writing Analytically. Thompson Wadsworth, Boston, MA.

[27] I. E. Clark, R. Romero-Calderón, J. M. Olson, L. Jaworski, D. Lopatto, U. Banerjee (2009) "Deconstructing" scientific research: A practical and scalable pedagogical tool to provide evidence-based science instruction. *PLoS Biol.* **7**, e1000264.

[28] J. A. Centra (2006) The Student Instructional Report II: Its Development, Uses and Supporting Research. An Issue paper from ETS (Educational Testing Service).