INTEGRATING AUTHENTIC RESEARCH AS INTELLECTUAL MERIT AND BROADER IMPACTS

in an Undergraduate Bioenergy Course

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Integrating teaching and research can benefit both instructors and students by providing an enriching, stimulating experience that combines the instructors' interests with topics that are relevant and motivating to students.[1,2] Funding agencies—faced with increasing demand and decreasing resources—have developed rigorous peer-review systems to allocate funds; the best known example in chemical engineering is the National Science Foundation (NSF) review system based on "intellectual merit" and "broader impacts," requirements that are technically well defined, yet remain sufficiently open to interpretation to cause confusion among both new and experienced researchers. Lastly, on the university level, the emergence and increasing popularity of new ways to deliver post-secondary education, including massive open online courses and online learning in general, place pressure to provide students with education experiences that differentiate the traditional university from online competitors.[3,4]

From the faculty perspective, integration of teaching and research can help resolve potentially conflicting priorities since activities in one area can be leveraged to reinforce the other. For example, background research to prepare for teaching a course can be repurposed for writing the background and motivation sections of new research proposals or manuscripts. Moreover, evidence of integrating education and research can be valuable in many grant applications, especially with the NSF. From the university perspective, integrating teaching and research can be marketable to prospective students while improving faculty fund-raising effectiveness.[5,6] From the student perspective, research-oriented classes can foster development of many higher-level and highly transferrable skills often reserved for Ph.D. studies,[7] including: facilitating group discussions or conducting meetings; collaborating on projects; forming and defending independent conclusions; and designing an experiment, plan, or model that defines a problem.[8] Integration of teaching and research can help students connect their studies with the solution of tangible problems.

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TABLE 1
Bioenergy Course Data

Cycle #	Enrollment	Research integration	Focused activities	Content	Assessment methods
1 Spring 2013	42	Research and education both based on bioenergy; students were encouraged to attend regular departmental research seminars	Guest lectures Lab tour	Bioethanol and gasification	2 exams 6 problem sets
2 Spring 2015	30	Specific connections based on common problems appearing in a series of problem sets	Guest lectures Problem sets Lab tour	Bioethanol	6 weekly quizzes
3 Fall 2016	33	Tightly integrated with the entire focus of the course embracing societal impacts and technological aspects of research	Guest lectures Group discussions Labs	Bioethanol and butanol, gasification	2 quizzes 1 problem set 2 labs 2 group activities

Participation in research projects is a proven method to improve student retention and interest.[9] Moreover, opportunities exist to address specifically the goals of funding agencies. For example, intellectual merit may be represented by the theory required to understand a basic area in engineering (*e.g.*, bioreactor design) and broader impacts as the application of this theory to problems of societal importance (*e.g.*, production of cancer therapy drugs).

This paper describes intertwining of research and education in a bioenergy-focused course that embraces intellectual merit and broader impacts by adoption of a suite of techniques including: (1) lab visits, (2) lab activities, (3) guest lectures, and (4) group discussions. All of these techniques are well-known in chemical engineering education and are easily harnessed for the purpose of instilling research-flavored intellectual merit and broader impacts in an undergraduate course.[10] The use of these techniques is described along with some suggestions on how they might be modified for courses focused on topics other than bioenergy, especially in elective courses on topics such as nanotechnology, biomanufacturing, or drug delivery. Student responses are summarized and recommended future work is outlined. This contribution may be useful to new faculty members who are seeking to craft new courses, especially in their area of research specialization, or for established faculty who would like to break down artificial barriers between their research and education activities.

DESCRIPTION OF BIOENERGY RESEARCH

The bioenergy course has drawn on several aspects of bioenergy research in the instructor's lab, with specific emphasis on one project in particular: development of a new biofuel production technology based on fermentation in the presence of supercritical carbon dioxide ($scCO_2$). The main source of inspiration originated when environmental microbiologists discovered organisms that were able to grow in an aqueous phase contacted by $scCO_2$.[11] Prior to this discovery, $scCO_2$ was considered a sterilizing agent, especially useful for thermally labile components.[12,13] Of several candidate organisms, *B. megaterium* showed the most promising and robust growth characteristics. Biochemical engineers then began inserting new pathways into the organism to produce bio-butanol. Butanol was a natural choice for the end product as it has superior fuel properties compared to ethanol and, as with many polar organic molecules, butanol partitions favorably into $scCO_2$,[14] affording the opportunity to extract the cytotoxic product as it formed. The interdisciplinary research team includes the microbiologists who discovered the organism, the biotechnology engineers who manipulated its genetics, and the author of this article.[15] Accordingly, this particular project was selected to highlight the interdisciplinary nature of research to craft a class that includes microbial metabolism and growth dynamics, microbial production of useful chemicals, mass transfer, and many other relevant topics.

OVERALL COURSE DESCRIPTION

The bioenergy course was taught in three cycles, offered in 2013, 2015, and 2016. In each case, the course was 7 weeks and met for 28 total contact hours. Table 1 provides some of the most important course data. The average course enrollment was 35 students, and these students consisted of seniors (approximately 50%), juniors (30%), and sophomores (20%). Because of Worcester Polytechnic Institute (WPI) policies, the course has no formal pre-requisites; instructors who can establish pre-requisites might consider reactor design and thermodynamics. The course demographics were similar to those in WPI's Chemical Engineering Department, with approximately 50% female enrollment. Lastly, course resources consisted primarily of instructor notes. In the first cycle, the instructor provided a "book" assembled from chapters of several texts; however, the cost of the custom-made book was approximately $100 and student reviews of this approach were unfavorable due both to its cost and the difficulty in navigating between different sources.

TABLE 2
Topics covered by week in three cycles of the bioenergy course

Week #	Cycle #1	Cycle #2	Cycle #3
1	Climate change, energy, and biofuels	Climate change, energy, and biofuels	Climate change, energy, and biofuels
2	Properties of biomass and fuels, combustion First- and second-generation ethanol	Cellulosic fuels Types of biofuels	Corn and cellulosic ethanol Types of fuels
3	Reactor design Biochemical reactors	Enzyme kinetics	Microbes/microbial growth
4	Enzyme reactions	Microbes and microbial growth	Metabolism and product yield
5	Separations	Metabolism and product yield	Microbial growth lab
6	Thermochemical biofuel platform	Bioreactor design	Thermochemical biofuels platform
7	Catalytic reactions	Bioreactor design	Catalytic reactions

In all three cycles, the main learning outcome was that students should be able to use fundamental chemical engineering concepts and tools to solve problems on bioenergy. The specifics of the tools that were emphasized varied, but included the use of material and energy balances to design bioenergy production processes; the use of thermochemistry and thermodynamics for technological selection of biofuels; and the use of chemical and biochemical reaction engineering to design biofuel production reactors. The secondary objective that was a common theme in all versions of the course was for students to understand the connection between chemical engineering and current small-scale research and development on bioenergy. As the class evolved from cycle to cycle, additional outcomes on entrepreneurial mindset learning, societal impacts, and working on interdisciplinary teams were added.

Table 2 summarizes the course schedules used in the three versions of the class. As with other aspects of the course, the course schedule changed incrementally as the content became more deeply and explicitly integrated with the instructor's research. In each case, the course began with an introduction of bioenergy in general and biofuels specifically, with some discussion of petroleum-based energy and the leading competitor technologies for renewable energy. The objective of the introductory period was to motivate the remainder of the class, explain the energy options for reducing CO_2 emissions, and make a case for the importance of bioenergy. In all cases, the importance of chemical engineering for biofuels research and development was stressed, including high-level descriptions of new projects in the field and potential career opportunities. After this introductory period, content focused on various technical aspects of bioenergy, with emphasis on fermenter and reactor design.

Evaluation in the first cycle consisted of several exams and a series of homework assignments. In the second cycle, evaluation was based on weekly in-class quizzes, with no graded homework assignments. Finally, in the third cycle, grades were based on reports from in-class discussions and laboratories as well as two in-class quizzes. As an elective course, grades were mainly A's and B's and the overall trend was an increasing percentage of A's. In particular, student performance on reports and quizzes was excellent in the third cycle, and 90% of the students received A's in that term.

INTELLECTUAL MERIT

In the most general terms, incorporating intellectual merit into undergraduate engineering courses is completely natural since all courses necessarily consist of some intellectual merit—without intellectual merit, the course is pointless. Connecting research-based intellectual merit with educational intellectual merit is less obvious, and may be difficult to accomplish if research content, learning objectives, and content are not well aligned. In this specific case study, the instructor's bioenergy research was well-aligned with the bioenergy content of the course—meaning that connecting the intellectual merit of the research with that of the course was straightforward. In general, elective courses will be more easily crafted to align with intellectual merit, since instructors have more leeway when developing elective courses compared to core courses. Specific approaches included classroom lectures and homework problems to highlight aspects of the research, for example giving a lecture on microbial growth through the lens of *Bacillus megaterium SR7*. The richness of both the research and learning objectives provided scope for developing more innovative connections. By the third cycle of the course, instructor confidence was sufficient to test new learning activities, including introduction of two lab activities.

WPI's curriculum stresses hands-on learning, making lab activities especially relevant. Despite the emphasis on hands-on learning, much of these experiences are back-loaded into the final year of the chemical engineering curriculum. Inclusion of lab activities in the sophomore and junior years is therefore a way to bridge between student expectations and actual practice. Naturally, incorporating lab components in classes traditionally consisting strictly of lectures requires allocation of appropriate resources, identification of which was not straightforward at WPI and might be impossible elsewhere. Strategies to overcome this challenge included: (1) touring existing WPI laboratories as part of the curriculum,

(2) implementing a take-home lab that did not require new facilities or class time to execute, and (3) utilization of existing laboratory facilities available at WPI that are not typically scheduled for undergraduate training.

Lab tours

The first two course cycles included visits to existing labs at WPI focused on biochemical engineering: WPI's Bioprocess Laboratory, a contract research facility focused on bio-production activities to support small biotech companies; and the Biomanufacturing Education & Training Center, a lab facility specializing in delivering professional training opportunities to local biotech companies. In both cases, the visits gave students a first-hand look at the fermentation equipment used in small-scale bioprocess R&D, greatly enhancing the experience provided in class. Laboratory staff described the design and operation of the equipment and its scale, methods of agitation, control, and monitoring. Students were then better able to connect lecture content with actual process equipment. Homework and quiz questions helped focus student attention. The lab-tour strategy can easily be transferred to other universities, by touring either on-site labs or local companies. The author acknowledges that courses that feature factory tours have long been part of the chemical engineering curricula at many universities; the suggestion here is to include lab tours in classes that are not dedicated specifically to "plant trips," a suggestion also made by Wankat and Oreovicz.[10]

Take-home yeast growth experiment

A take-home lab, based on published documents from the Institute of Food Technologies (IFT),[16] was assigned for students to measure the CO_2 production of *Saccharomyces cerevisiae* (Baker's yeast) when provided several different substrates, including glucose (an aldose form of $C_6H_{12}O_6$), fructose (a ketose form of $C_6H_{12}O_6$ and isomer of glucose), xylose (a pentose found in hemicellulose with the formula $C_5H_{10}O_5$), cellobiose (a glucose dimer with $\beta 1 \rightarrow 4$ bonding similar to that found in cellulose, $C_{12}H_{22}O_{11}$), and maltose (a glucose dimer with $\alpha 1 \rightarrow 4$ bonding, $C_{12}H_{22}O_{11}$). Students were required to grow the organism in homemade "fermenters," constructed from plastic water bottles. CO_2 production was quantified by recording the diameter of a balloon secured to the mouth of the water bottle at regular intervals.

By completing the lab activity, students found that CO_2 production followed the trend fructose ~ glucose ~ maltose (with a short time delay) >> xylose ~ cellobiose. Students were then required to complete a short lab report describing their observations. During completion of the lab report and an ensuing instructor-led discussion, students learned that the edible carbohydrates (*e.g.*, glucose, fructose, and maltose) are more readily fermented than the non-edible ones (*e.g.*, xylose and cellobiose), pointing out the need for additional enzymatic pathways to produce bioenergy from non-edible components of biomass. The lag observed in CO_2 production from maltose was associated with the additional enzyme step required to hydrolyze its $\alpha 1 \rightarrow 4$ glycosidic bond to generate fermentable simple sugars. In contrast, students learned that *Saccharomyces cerevisiae* cannot hydrolyze cellobiose due to a lack of the appropriate enzyme required for $\beta 1 \rightarrow 4$ glycosidic bond hydrolysis. The contrast between maltose and cellobiose helps students learn by experience the specificity of enzyme catalysts and the differences in carbohydrate binding, and is especially relevant since the abundant biopolymer cellulose consists of $\beta 1 \rightarrow 4$ bonds.

In practical terms, take-home labs are easily implemented at other universities as they do not require dedicated space or staffing. The cost of this lab was approximately $50 per team of two students, mostly due to the cost of some of the more expensive carbohydrates (cellobiose and xylose). Excluding the expensive reactants would decrease costs accordingly. Scope remains for further innovation in future deployments of the lab, for example, allowing students to study: co-fermentation of multiple carbohydrates; effects of inhibitory compounds (*e.g.*, acetate); inclusion of different carbohydrates; or co-addition of enzymes for required fermentation pathways (*e.g.*, lactase to convert lactose into fermentable sugars).

Weeklong microbial growth lab

The take-home lab gave students basic experience in microbial growth and data collection—preparation for a more intense weeklong lab to investigate the growth protocol of *Bacillus megaterium SR7*. As a newly identified organism, *Bacillus megaterium SR7* had not yet had optimal growth conditions established, giving the students an opportunity to learn research skills through participation in an authentic experience.

The weeklong laboratory was introduced to the class over the course of several weeks to provide students an opportunity to absorb new aspects of it concurrently with relevant course material. In the first weeks of class, the students learned about the organism and early attempts to grow it. From these data, they were coached to arrive at the conclusion that its growth was not yet optimized and that a key limiting nutrient had not been added to its fermentation media. Then, as the students learned about microbial growth, the students and instructor collectively developed hypotheses to test. In the week prior to the lab, the experiments were divided into sets that could be addressed by groups of students. Specific group assignments included examining the effects of nitrogen content, glucose content, and pH buffering. Students also helped devise control tests.

Students were organized into teams of six and training was administered to the teams at the beginning of the week during regular class hours. Teams then organized into pairs, with the pairs of students taking turns to return to the lab at regular time intervals over a 3-day period to record optical density and solution pH and to collect samples for subsequent analysis. The course teaching assistant and technical staff in the Bioprocess Lab managed training and supervised all laboratory activities. To organize their data and simulate actual practice, students completed batch records as part of sample collection. Once all of the samples were collected, the course teaching assistant analyzed them for glucose and ammonium content. The collection-and-analysis approach was adopted as a compromise solution as students were granted direct access to the Bioprocess Lab, but not the Biomanufacturing Training & Education Center, which housed the immunoanalyzer used to measure glucose and ammonium concentrations. During this week, the course teaching assistant was committed nearly full-time to the project. To minimize the impact on his other research and education activities, requests on his time were minimized for the remainder of the term.

On completion of the lab, students "crowd sourced" the data and used it to determine growth parameters using standard graphical methods that had been covered previously in class, albeit for more highly idealized data sets. By plotting concentrations of glucose and ammonia over time, students were able to determine that both nutrients limited growth. The results of this part of the project afforded an opportunity for students to identify new avenues for future work that would permit determination of substrate limitations, an activity that simulated the basic elements of the research process. Because the bacterial strain had not been engineered to produce fuels at the time of the project, students were given simulated yield coefficients to combine with microbial growth parameters for process scale-up. Given basic economic data, students projected the economic feasibility of using the optimized growth procedure to produce a biofuel product. The entire project culminated in a final report including the economic analysis and recommendations for future work.

Implementing an intensive laboratory may not be practical in many courses, especially if it disrupts an otherwise well-established flow. Lab space might be appropriated several ways, for example by using existing dedicated undergraduate lab space during a time when it would otherwise not be in use. Here, the Bioprocess Lab and Biomanufacturing Education & Training Center were available for student use during the week of the lab. Resources such as these are not available at all universities; however, most chemical engineering departments have some under-utilized laboratory space, for example unit operations lab space that is used only part of the year or part of the day. Human resources are equally important. In this case, both the course teaching assistant and the staff of the Bioprocess Lab were available to supervise and manage the laboratory. Not all elective courses have assigned teaching assistants and the availability (and willingness) of staff such as those at the Bioprocess Lab cannot be taken for granted.

Student response to the weeklong growth lab and associated activities was overwhelmingly positive. Some representative comments include: "The course was engaging and stimulated my interest.... I think that the dynamic of the traditional learning and lab experiments helped in doing so," and "The lab growth experiment was amazing...do this project every year."

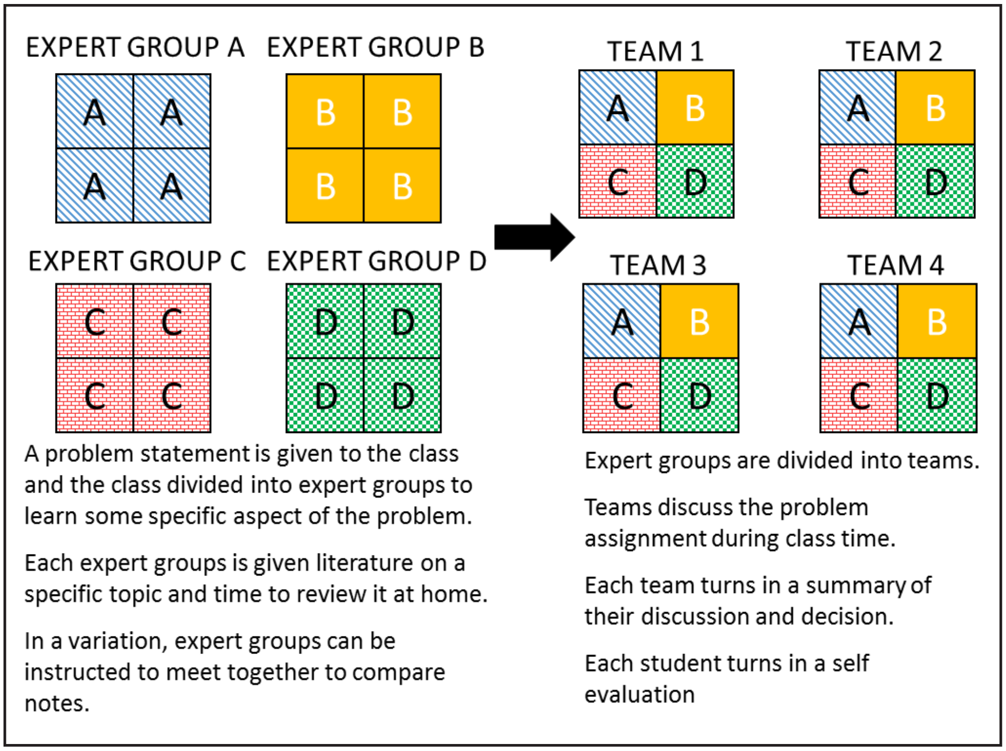
BROADER IMPACTS

Incorporating broader impacts into undergraduate engineering curriculum may be less obvious than intellectual merit. However, all engineering activities have societal impacts and the challenge is mainly one of emphasis. Many, if not most, engineering courses explicitly or implicitly incorporate some type of broader impacts; for example, content on reaction rates might be coupled with environmental chemistry, reactor design to produce useful chemicals, or some other societally impactful application. In the case of bioenergy, incorporation of broader impacts is more straightforward than it might be for some chemical engineering courses, for example a course on heat transfer or control theory. Here, this section describes some of the strategies used to incorporate broader impacts within the bioenergy course; none of them are time intensive for the instructor to develop and most of them can be adapted for other courses.

Guest speakers

Dissemination of results is a major component of broader impacts. Moreover, 21st century research advances rapidly, and many books that attempt to cover research fields are obsolete by the time of printing. Experienced researchers know this, and find that attending research conferences is the most effective way to stay on top of the latest developments in their field. But how can research dissemination and conference attendance be simulated in an undergraduate class? One solution is to invite guest lecturers to the class. In some cases, in-house experts served as substitute lecturers. In others, students were encouraged to attend seminars on relevant topics hosted as part of the department's regular seminar series. In both cases, student experience was enriched, and many instructors could easily adopt a similar approach.

Selection of guest lectures was guided in part by personal relationships, but was sometimes admittedly *ad hoc*. Whenever possible, experts with a reputation or known ability to deliver effective lectures were selected. When possible, experts who proved themselves to be especially effective at delivering content while inspiring student interest—as indicated by speaking directly with students or from reviewing their course evaluations (*vide infra*)—were invited to return. Specific guest lectures by WPI experts included Prof. Frank Hoy (Business Department) to discuss entrepreneurial aspects of bioenergy; Prof. Reeta Rao (Biology Department) to highlight genetic engineering of organisms to produce biofuels; Dr. Alexander Chirkov (HDS International) to describe algae biofuels; and Prof. Steve Kmiotek (Chemical Engineering Department) to explain design aspects of ethanol-water distillation. National experts included Prof. Phil Savage (Michigan), Prof.



A problem statement is given to the class and the class divided into expert groups to learn some specific aspect of the problem.

Each expert groups is given literature on a specific topic and time to review it at home.

In a variation, expert groups can be instructed to meet together to compare notes.

Expert groups are divided into teams.

Teams discuss the problem assignment during class time.

Each team turns in a summary of their discussion and decision.

Each student turns in a self evaluation

Figure 1. *Schematic of the jigsaw pedagogical technique.*

Russ Chianelli (UTEP), and Prof. Paul Dauenhauer (UMass Amherst). In all cases, the external speakers graciously provided their presentation materials for the instructor to post on Blackboard (or Canvas), allowing students to attend the lecture and then review the material afterward, in a process designed to stimulate natural curiosity. To address the gap in experience level between the students and the experts, class lectures would often reprise some of the main points of previous lectures, connecting them to material students learned (or would learn) in class. Including guest lectures was a very successful strategy, and positive comments for guest lectures have been one of the most consistent pieces of feedback I have received over the years. Specific comments include: "…loved what was added by guest lectures"; "I also enjoyed the guest speakers and ties to entrepreneurship."

In-class jigsaw discussions

Cycle 3 included two in-class discussion activities using the "jigsaw" method to provide students opportunities to learn specifics of technical and non-technical aspects of bioenergy. Slavin[17] introduced the jigsaw teaching method, in which students become local experts in their technology niche, and then are asked to contribute their specific knowledge to solve a common problem alongside peers who have different expertise.

In brief, the jigsaw method divides the class into teams, ideally with each team consisting of four to six students. The class was also divided into "groups," with each group assigned a specific area of expertise. Students were given materials to become experts in their areas, then convened as a class to discuss as teams. Each team was balanced to consist of at least one person from each expert group. Figure 1 is a conceptual schematic showing a hypothetical class consisting of 16 students divided into four expert groups and four teams; in practice, scale-up of the jigsaw method is straightforward. Teams were then given an entire class period (50 minutes) to discuss an open-ended question on biofuels. The focal points of the jigsaw discussions were: (1) selection of an "optimal" fuel for the future (the "Future Fuel Jigsaw"); and (2) selection of a fuel policy for an indigenous community (the "Tribal Fuel Jigsaw").

The jigsaw method is especially relevant for research-integrated courses, since it simulates many aspects of the dynamic of research, in particular interdisciplinary research. Most obviously, the process of becoming experts mimics that which occurs during acclimation to a new research field, and can embrace many aspects of a literature search.[18] Based on the literature review process, students formulate a position on the topic, and prepare to defend it, similar to an activity recommended by Graham, et al.[19] for helping students learn how to perform a literature review. During subsequent team discussions, the experts must then explain their field to their peers, while learning from each other in turn.

Jigsaw methods can be easily adopted in engineering courses, regardless of content. Using them to introduce broader impacts of engineering may be less intuitive, but still easily implemented. For example, a project on some technical objective (distillation column design, for example), might assign both technical and nontechnical roles for team members. Using distillation as an example, student assignments might include technical tasks such as developing the vapor-liquid equilibria requirements or calculating stages and completing mass/energy balances, as well as nontechnical ones such as performing a market analysis of the product or developing environmental impact or safety plans for the factory and/or surrounding community.

TABLE 3
Summary of key course evaluation metrics

Metric*	Cycle 1	Cycle 2	Cycle 3
My overall rating of the quality of this course is	4.24	4.22	4.44
My overall rating of the instructor's teaching is	4.19	4.35	4.70
The instructor's organization of the course was	4.19	4.13	4.30
The instructor's clarity in communicating course objectives was	4.50	4.30	4.56
The instructor stimulated my interest in the subject matter	4.42	4.13	4.59
The amount I learned from this course was	4.22	3.96	4.08

* on a 5-point scale, with 1 being the least supportive, and 5 being the most supportive; based on standard deviations, uncertainty is approximately ±0.1.

STUDENT FEEDBACK

Table 3 summarizes student feedback to the course. Course reports indicated that the students generally appreciated the course, in particular as shown by rating of the course (4.24-4.44) and instructor's teaching (4.19-4.70). In comparison, the university-wide averages to these questions were both 4.14 over the same time frame as the course was offered. Averages within the Chemical Engineering Department were 4.06 and 3.97, respectively, again during the same time period. Overall, the trend in student course evaluations is positive, with the third cycle representing the most favorable ratings. Interestingly, the rating of instructor teaching improved more than the rating of the course itself, as shown in Table 3. The difference may be due to greater instructor enthusiasm for teaching the integrated course rather than a perception of an improved course per se, as students may be more sympathetic to an instructor than the course, especially one who gives the appearance of enjoying the topic being taught.[10]

Aside from these two main metrics, some other minor trends emerged in the student course reports. After decreasing between the first and second cycles, the student evaluation of the clarity of course objectives improved in the third cycle. Student response to the instructor's ability to stimulate interest followed a similar trend. Student self-reporting of the effort put into the course decreased with each cycle, from approximately 10 hours per week to less than 5 hours per week. The greatest difference was between the second and third cycles. In the third cycle, the course emphasized open-ended literature searches, in-class discussions, and lab activities that either may have been less time consuming than completion of problem sets, perceived by students to be less time consuming, or (possibly more realistically) easier for students to minimize their effort. Here, additional guidance on the part of the instructor might be necessary to ensure that students understand the expectations; for example, students might be required to write a short document describing their literature search prior to in-class discussions. Interestingly, student assessment of their own learning decreased from the first to the second cycle and then improved slightly in the third; inclusion of the jigsaw and lab activities may have improved student assessment of their learning without increasing the real or perceived student workload.

In addition to the quantitative data, student open responses provide additional feedback that suggests greater student motivation and provided some evidence of deeper learning than might have been accomplished in a traditional course. Positive comments outweighed negative ones by a factor of about 2 to 1 and a representative sampling is presented here:

- *"The course was engaging and stimulated my interest…. I think that the dynamic of the traditional learning and lab experiments helped in doing so."*
- *"Overall, the course broke the 'going through the motions' experience I get sometimes accompanying engineering courses."*
- *"It definitely sparked my interest in the field."*
- *"I learned a lot without being forced to simply memorize it for an exam and forget it the next day."*
- *"[The] jigsaw activity was great. I think its [sic] a better way to learn about different technologies than just lecture."*
- *"Great use of scholarly journal articles rather than textbook."*

On the other hand, adding research activities may have led to shortchanging of other learning activities:

- *"Some materials weren't presented fully" – several students made similar comments after the second class cycle.*
- *"Short quizzes do not allow time for critical thinking" – again, this comment was made after the second cycle in response to the weekly quiz format, which the instructor dropped in the third cycle.*
- *"Cover membranes" – this comment was made in response to a change in the announced coverage. The change was necessary as the instructor scheduled insufficient time for covering other topics.*
- *"(The class should) have graded homework" – a common comment in both the second and third cycles.*

These comments point out the usual challenges that instructors face when prioritizing class time and devising evaluation tools. Although they are not exclusive to the design of courses integrating teaching and research, preparing schedules for newly designed classes or re-designed classes will necessarily require strategies for handling uncertainties in the amount of time required to adequately cover topics. New instructors especially should consider including buffer zones and review days in the schedule, as suggested by Wankat and Oreovicz, [10] to allow for overruns. In addition to these written comments, informal conversations with students after the third cycle indicated that a subset of students perceived the emphasis on classroom discussions as a lack of technical rigor. This sentiment can be difficult to avoid in a class with enrollment of students with different backgrounds, as was the case for this class. Several approaches might satisfy this concern, the simplest of which is framing. Student expectations could be managed early in the class by explicitly stating that a primary objective of the class is to develop some of the nontechnical skills that the graduated engineer will need to round out the technical skills developed in his or her other classes. A second option would be to include one or more highly mathematically rigorous activities, possibly making them group activities to encourage peer-directed learning. A third option would be to prevent or discourage less advanced students from taking the class, an option which may be feasible at some universities but impractical at others.

FUTURE DEVELOPMENT

The bioenergy course offers ample opportunity for future development and improvement. In fact, an incremental approach was adopted by the instructor, to build his confidence with each cycle and limit his sense of being overburdened. Thus, the first cycle used primarily traditional lecture and homework methods. Only by the third cycle were lab activities and jigsaw discussions incorporated. For new instructors—or for experienced instructors who are seeking to incorporate new methods in their teaching—incremental implementation of research-oriented activities may be a way to overcome the "activation energy" associated with adopting unfamiliar techniques.

In an elective course, the instructor can be reasonably flexible in the content delivered during the course. Thanks to this flexibility, new advances in the field of bioenergy can easily be incorporated into future versions of the bioenergy class. On the other hand, significant scope exists for improving and refining the existing methods: new invited speakers can be included, the microbial growth labs can be modified to include new objectives, etc. In particular, the *Bacillus megaterium* growth lab can evolve in parallel with advances in research, for example by growth of the engineered organism and concomitant monitoring of biofuel under selected conditions.

A specific area for future improvement of the course is to incorporate more-targeted student evaluation tools. To date, the author has exclusively used the evaluation sheet provided by the university, which consists of 31 questions with quantitative responses (some of which are summarized in Table 3) and four open-ended questions. Future cycles would benefit from targeted assessments to obtain quantitative and qualitative data on the effectiveness of labs, discussions, and similar activities. At present, the only data available in these specific areas is from responses to open questions, which means that the data are less complete than might be desired. Future versions of the class can benefit from responses to tailored questions that can be used to assess student learning benefits. Pre- and post-tests are another option for assessing student learning.

CONCLUSIONS

Integrating research and teaching can be a useful strategy for increasing both instructor and student enthusiasm, either for junior faculty seeking to balance research and education objectives or for experienced, research-active faculty seeking ways to reinvigorate their teaching. The case study of the bioenergy course highlights one approach to the incorporation of intellectual merits and broader impacts in undergraduate education. A similar approach might be applied to many other areas of chemical engineering education, from nanotechnology to bioprocessing. A wide range of activities is available to the instructor—here, lab tours, guest lectures, jigsaw discussions, and hands-on laboratory experiences were highlighted. Student response was positive, suggesting that incorporation of research concepts in the class helped motivate students and may have promoted deeper learning of the material than would have been possible in a traditional course.

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REFERENCES

1. Eagan Jr MK, Sharkness J, Hurtado S, Mosqueda CM, & Chang MJ (2011) Engaging undergraduates in science research: not just about faculty willingness. Research in Higher Education 52(2):151-177.
2. Brew A (2010) Imperatives and challenges in integrating teaching and research. Higher Education Research & Development 29(2):139-150.
3. Ingolfsdottir K (2016) Winds of Change in Higher Education. Trends in Pharmacological Sciences 37(12):990-992.
4. Surratt CK, Kamal KM, & Wildfong PL (2011) Research funding expectations as a function of faculty teaching/administrative workload. Research in Social and Administrative Pharmacy 7(2):192-201.
5. Durham SA & Marshall W (2011) Tips for Succeeding as a New En-

gineering Assistant Professor. *Proceedings of the American Society for Engineering Education Conference*, Vancouver.

6. Schrader C, et al. (2011) How Can We Help Faculty Balance Between Teaching and Scholarly Activities? *Proceedings of the American Society for Engineering Education Conference*, Vancouver.
7. Fletcher AJ, Sharif AWA, & Haw MD (2017) Using the perceptions of chemical engineering students and graduates to develop employability skills. *Education for Chemical Engineers* 18:11-25.
8. Anonymous <https://careercenter.umich.edu/article/phd-transferable-skills>, accessed October 2017.
9. Gregerman SR, Lerner JS, von Hippel W, Jonides J, & Nagda BA (1998) Undergraduate student-faculty research partnerships affect student retention. The Review of Higher Education 22(1):55-72.
10. Wankat PC & Oreovicz FS (2015) *Teaching Engineering* (Purdue University Press, West Lafayette, IN) 2nd Ed.
11. Freedman AJ, Tan B, & Thompson JR (2017) Microbial potential for carbon and nutrient cycling in a geogenic supercritical carbon dioxide reservoir. *Environmental Microbiology*.
12. White A, Burns D, & Christensen TW (2006) Effective terminal sterilization using supercritical carbon dioxide. *J. Biotechnology* 123(4):504-515.
13. Zhang J, et al. (2006) Sterilizing Bacillus pumilus spores using supercritical carbon dioxide. *J. Microbiological Methods* 66(3):479-485.
14. Timko MT, Nicholson BF, Steinfeld JI, Smith KA, & Tester JW (2004) Partition coefficients of organic solutes between supercritical carbon dioxide and water: experimental measurements and empirical correlations. Journal of Chemical & Engineering Data 49(4):768-778.
15. Boock JT, et al. (2016) Engineering an Environmentally-Isolated Bacterium for Continuous Biofuel Production and Recovery Under Supercritical CO2. National Meeting of the AIChE.
16. Anonymous (2017) Experiment 1: What Affects Yeast Growth? (IFT Experiences in Food Science Series).
17. Slavin RE (1990) Research on cooperative learning: Consensus and controversy. *Educational Leadership* 47(4):52-54.
18. Jensen Jr D, Narske R, & Ghinazzi C (2010) Beyond chemical literature: Developing skills for chemical research literacy. *J. Chemical Education* 87(7):700-702.
19. Graham KJ, Schaller CP, & Jones TN (2014) An Exercise To Coach Students on Literature Searching. *J. Chemical Education* 92(1):124-126. ❐