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High-Impact Practices in Materials Science Education: Student Research Internships Leading to Pedagogical Innovation in STEM Laboratory Learning Activities

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ABSTRACT

Traditional lecture-centered approaches alone are inadequate for preparing students for the challenges of creative problem solving in the STEM disciplines. As an alternative, learner-centered and other high-impact pedagogies are gaining prominence. The Wabash College 3D Printing and Fabrication Center (3D-PFC) supports several initiatives on campus, but one of the most successful is a computer-aided design (CAD) and fabrication-based undergraduate research internship program. The first cohort of four students participated in an eight-week program during the summer of 2015. A second group of the four students was successfully recruited to participate the following summer. This intensive materials science research experience challenged students to employ digital design and fabrication in the design, testing, and construction of inexpensive scientific instrumentation for use in introductory STEM courses at Wabash College. The student research interns ultimately produced a variety of successful new designs that could be produced for less than $25 per device and successfully detect analytes of interest down to concentrations in the parts per million (ppm) range. These student-produced instruments have enabled innovations in the way introductory instrumental analysis is taught on campus. Beyond summer work, the 3D-PFC staffed student interns during the academic year, where they collaborated on various cross-disciplinary projects with students and faculty from departments such as mathematics, physics, biology, rhetoric, history, classics, and English. Thus far, the student work has led to three campus presentations, four presentations at national professional conferences, and three peer-reviewed publications. The following report highlights initial progress as well as preliminary assessment findings.

INTRODUCTION

Digital modelling, coupled with 3D fabrication continues to provide unique and exciting opportunities for the development of innovative new educational tools. Consumer-grade 3D printers, computer numerical control (CNC) tools, and laser engravers are advanced tools for the fabrication of custom prototypes via the precision offered through digital design [1]. Technological advances offer enhanced capabilities, while increased market competition drives prices lower to expand access to these exciting instruments for educational research labs and community makerspaces. Realizing the significant potential for engaging STEM students, the Wabash College 3D Printing and Fabrication Center (3D-PFC) was established to provide the infrastructure and technical expertise required to enable the exploration of diverse, learner-centered initiatives on campus. The 3D-PFC currently houses a diverse range of 3D printers, digital scanning equipment, laser engraver/cutter, vacuum forming instrument, computer numerical control (CNC) router, and several CAD workstations. These resources have been critical in providing the instrumentation required for the exploration of new student research internships focused on promoting student engagement, critical thinking, and creative problem solving across the disciplines most central to materials science [2]. Moreover, the work produced from these experiential learning opportunities was leveraged to promote innovative new laboratory learning activities deployed in introductory STEM courses offered at Wabash College.

THEORY

High-impact, learner-centered pedagogies continue to gain prominence due to their association with enhanced student engagement, learning, and retention. Reports, such as those compiled by George Kuh and others, cite compelling evidence from the National Survey of Student Engagement (NSSE) to support the success of these practices [3]. As opposed to more passive, lecture-centered approaches, these learning opportunities most often focus on developing meaningful interactions with faculty, encouraging collaborative experiences, and providing frequent and substantive feedback within a supportive environment [4]. Experiential learning, via an internship or field experience, is often one of the most effective high-impact practices associated with the STEM disciplines [5]. These immersive experiences are usually related to career interests and provide students with mentoring from accredited professionals. Undergraduate research is a valuable means for developing important skills, such as empirical observation, experimental design, mathematical modelling, utilizing the primary literature, and drawing meaningful conclusions via data analysis, all within a relevant and meaningful context. Simultaneously, the associated student gains in engagement, confidence, and communication are significant. The literature continues to provide evidence that these opportunities serve as a powerful motivation in a students' decision to pursue a graduate degree. In this work, we report initial progress toward introducing digital design, 3D printing, and fabrication in support of undergraduate research internships. Here, we highlight an early success demonstrated by an intensive materials science research experience that challenged students to use digital modelling and fabrication to design, test, and produce inexpensive scientific instrumentation for use in introductory STEM courses at Wabash College.

DISCUSSION

Wabash College is a four-year liberal arts college with an enrollment of approximately 900 students. The institution is fortunate to support multiple internships, entrepreneurial experiences, and undergraduate research programs. In the STEM disciplines most closely linked to materials education, both summer and academic year undergraduate research opportunities are made available. The goal of these programs is to involve students with actively contested questions, empirical observation, cutting-edge technologies, and the sense of excitement that comes from working to answer important questions. By engaging in original research with faculty, supported by state-of-the-art instrumentation and facilities, Wabash students are continually challenged to become investigators and independent thinkers.

Substantial instrumentation and facilities support for STEM focused undergraduate research was one of the primary themes contained in the successful grant proposal leading to the establishment of the 3D-PFC. An initial cohort of four summer research students were selected for an eight week summer research internship. The four chemistry majors recruited included a freshman, two sophomores, and a junior. Applications were competitive and judged based on personal essays and faculty recommendations. The students worked approximately forty hours a week under direct guidance of a faculty mentor. Campus housing was provided that integrated research students from various academic departments and both social and professional development programming was coordinated by faculty across campus. Students were assigned small working groups that focused on specific research projects and worked closely with their faculty mentor in every aspect of their projects. For example, students were guided in reviewing the primary literature, digital modelling and 3D fabrication, analytical instrumentation operation, experimental design and data collection, proper maintenance of laboratory notebooks, formal report preparation, and poster presentation skills. Following the experience, both written and oral research presentation skills were emphasized via opportunities to contribute posters to both local and national symposia and contributions toward the preparation of manuscripts submitted to peer-reviewed journals. Internship evaluations were obtained through various survey instruments, including a slightly modified version of the SURE (Survey of Undergraduate Research Experiences) [6]. The following summer, an additional four interns were recruited for the program. Beyond summer work, the 3D-PFC staffed student interns during the academic year, where they collaborated on various cross-disciplinary projects with students and faculty from departments such as mathematics, physics, biology, rhetoric, history, classics, and English. Thus far, the student work has led to three campus presentations, four presentations at national professional conferences, and three peer-reviewed publications.

Survey Item	Mean
The experience helped me to develop skills required to integrate theory and practice.	5.0
The experience helped me to understand that scientific assertions require supporting evidence.	4.8
The experience helped me develop data analysis skills.	4.9
The experience helped with my learning of ethical conduct.	4.3
The experience helped with my learning of laboratory techniques.	4.8
The experience helped with my ability to read primary literature.	4.4
The experience helped with my ability to give an effective oral/poster presentation.	4.5
The experience helped with my ability to write about scientific research.	4.6
The experience helped me learn how to work as part of a team.	4.8
The experience helped improve my understanding of chemical analysis.	4.9
The experience helped improve my digital design (CAD) skills.	4.5
The experience helped improve my 3D printing skills.	4.9
I would recommend the experience to future students.	5.0

Table 1. Representative survey items with preliminary responses related to learning gains. The scale provided ranged from 1 (strongly disagree) to 5 (strongly agree). Resulting means are reported (N = 9; a pilot student from 2014 and four from each subsequent summer program).

When the undergraduate research interns were asked to evaluate their summer internship experiences, both qualitative and quantitative survey responses revealed that the students' overall attitudes toward the opportunity were very positive (Table 1). Without exception, the interns noted that they would recommend the internship opportunity to future students. The author certainly recognizes that the institution size, program scope, and limited respondent pool restrict any meaningful statistical power related to the quantitative responses. However, the SURE data, when coupled with qualitative responses, provided important feedback signifying preliminary successes of the internship program. For example, student intern survey answers indicated that the summer opportunity enhanced their educational experience, reporting gains in both technical and personal skills. When reflecting upon traditional STEM technical skill development, the most highly rated gains connected to "integrating theory and practice," "developing data analysis skills," "learning of laboratory techniques," and "understanding of chemical analysis." Unsurprisingly, skills related to digital design, 3D printing, and rapid prototyping were also very highly rated. The summer interns reported personal gains in terms of learning to work as a collaborative team, critical thinking, and creative problems solving. Open responses revealed mutual observations of gains in appreciating the cross-disciplinary nature of modern research and a realization of how modern research is conducted. Finally, the student interns valued the internship experience as a significant and positive impact on their motivations for pursing postgraduate work in STEM. Half of the students classified the influence as confirmatory in terms of reinforcing their desire to take on postgraduate research. The remaining responses rated the impact as "helping to change my postgraduate plans" toward a STEM related program.

The survey data and qualitative responses also revealed several areas where more deliberate instruction and supplemental programming might be developed for future cohorts. While still rated as positive responses, gains associated with, "learning of ethical conduct," "ability to read primary literature," and "effective oral presentation" did not receive rankings as high as those previously discussed. Ethical reasoning and awareness related to STEM research has gained prominence with granting agencies, such as the National Science Foundation (NSF). In response to grant requirements, greater resources have become available to educators. Given that Wabash College is a liberal arts institution, this aim provides an excellent opportunity to engage faculty across campus via interdisciplinary connections to ethics. A summer intern discussion group or workshop, including faculty from philosophy, education, and psychology, will be explored. Engaging students with the primary literature remains a challenge, especially for younger interns. The technical voice and jargon that dominate research publications often prove intimidating for undergraduate students. In response, research mentors must take on significant and active role as supportive guides in deciphering how to search for and identify the most relevant articles through standard tools, such as SciFinder and Web of Science. Once quality sources are retrieved, students require assistance in learning to identify the larger points of a paper, methods employed to explore the significant questions pursued, and the analysis of data presented in support of key findings. These represent significant tasks given how central primary literature is to research and how little it is incorporated into typical introductory STEM coursework. Finally, communication tutorials related to both written and oral presentation of research results is a priority. In the future, more time must be set aside for deliberate instruction related to technical writing and poster presentation. Student observations note that the internship period was almost exclusively devoted to the pursuit of laboratory results and greater time should be reserved for writing, poster design, and tutorials related to speaking about one's work to a variety of audiences.

The most significant research effort pursued by the summer interns involved harnessing digital design and 3D printing to produce an inexpensive, yet high-performance colorimeter instrument (Figure 1) [7-8]. This analytical instrument is less sophisticated than the research-grade spectrophotometers typically used in STEM laboratory activities to determine the concentration of analytes in solution. Commercial devices of this type typically cost hundreds or thousands of dollars, yet the 3D printed colorimeter version costs under $25 to produce per device. Digital models were constructed by students using simple computer-aided design (CAD) programs, such as Tinkercad and Inventor Professional. These software packages are simple to use and are available to students and educators. The instrument is powered by 9 volt ac to dc adapters or batteries and is compatible with a variety of commercially available light-emitting diode sources (LEDs) and solid-state detectors. The 3D printed colorimeter performs well when compared to commercially available spectrophotometers and the digital design is easily modified in order to incorporate lenses, more advanced electronics and microcontrollers, or explore a variety of configurations inaccessible to more conventional instruments. In contrast to commercial instruments, the student-produced models are open source, customizable for a variety of applications, and easily assembled by students in activities that directly confront the "black box" perception of analytical instrumentation. The inexpensive nature of the instrument design provides the opportunity for each student laboratory partnership or group to utilize a 3D printed filter colorimeter for the entire activity period. This is in contrast to typical models of student engagement with instrumentation, where one instrument must often serve an entire class of students. These devices are also appropriate for outreach projects involving local middle and high schools, thereby introducing a service learning component to the internship experience.

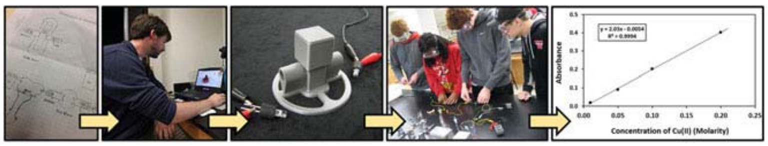

Figure 1. Undergraduate summer research interns drafted paper schematics for colorimeter instruments, which were translated into computer-aided design (CAD) files using accessible software packages. The digital models were fabricated into novice-friendly instrument kits for use in STEM laboratory learning activities at the introductory level.

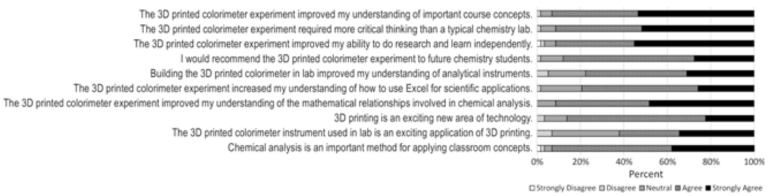

Figure 2. Postlab feedback survey results related to general chemistry student perceptions of the 3D printed colorimeter laboratory activity. Relative percentages of response are presented above for each question. Increased darkness of bar shading corresponds to a positive (agree or strongly agree) while decreased bar shading reflects a negative (agree or strongly agree) responses to each question (N = 58; 2015 fall general chemistry course, CHE111).

The student-produced colorimeter devices were piloted in small laboratory groups for several semesters in a variety of Wabash College STEM course. In the fall of 2015, however, a large scale trial was undertaken at the introductory level when the devices were used in every general chemistry (CHE1111) laboratory section. The 3D printed colorimeters were employed in a new laboratory experiment aimed at exploring spectroscopic principles, fundamental quantitative analysis, and mathematical relationships involved in data examination. A regular three-hour laboratory meeting was devoted to the activity. Student laboratory groups were provided with the 3D printed instruments in the form of an unassembled kit. At the conclusion of the laboratory period, fifty-eight students completed a feedback survey (Figure 2) inspired by Wang et al. [9]. The student survey responses revealed that the students' overall attitudes toward the activity were very positive (Figure 2). In particular, the students indicated that they were engaged by the inclusion of the 3D printed instrument in the experiment. In particular, they cited the activity as important in helping to improve their understanding of "important course concepts," "analytical instruments," and "mathematical relationships involved in chemical analysis." The majority of the students reflected that the activity challenged them to think critically, yet they enjoyed the experience and would recommend the activity remain in the CHE111 laboratory program. The same 3D printed colorimeter experiment was utilized once again during the fall 2016 semester and the additional survey data is being compiled.

CONCLUSIONS

Initial progress toward introducing digital design, 3D printing, and fabrication in support of undergraduate research internships was reported. Preliminary data indicates both technical and personal learning gains. In addition, student-produced scientific instrumentation was successfully used in introductory STEM courses at Wabash College. Future efforts will focus on more deliberate program revisions, assessment, and dissemination work.

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