SEPTEMBER 01 2023

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Special Collection: Teaching about the environment, sustainability, and climate change

Mikkel Herholdt Jensen; Eliza J. Morris; M. W. Ray

American Journal of Physics 91, 696–700 (2023)
https://doi.org/10.1119/5.0137141

Implementing a course-based authentic learning experience with upper- and lower-division physics classes[a)]

Mikkel Herholdt Jensen,[b)] Eliza J. Morris,[c)] and M. W. Ray[d)]
Department of Physics and Astronomy, California State University, Sacramento, Sacramento, California 95819

(Received 30 November 2022; accepted 28 March 2023)

We describe a dual-class authentic learning experience (ALE) in which undergraduate upper-division physics students develop low-cost instruments, which are then used by students in a lower-division course to monitor water quality in rivers. The ALE bridges the experiences of lower- and upper-division physics majors by involving students across different stages of their college careers in a collaborative project. Lower-division physics students characterize, calibrate, and troubleshoot the instrument prototypes developed by their upper-division peers, and their work informs instrument modifications in future upper-division physics classes. This paper describes the first iteration of this project along with student perceptions. We find that lower-division students report an increase in their awareness of possible upper-division projects, an increased sense that their coursework has real-world applications, and a heightened understanding of how physicists can play a role in research on environmental issues.
https://doi.org/10.1119/5.0137141

I. INTRODUCTION

The implementation of course-based undergraduate research experiences (CUREs) in science, technology, engineering, and math (STEM) college education has been shown to convey multiple benefits, including increased student retention, growth in translational skills such as communication and teamwork, and a strengthening of the students' science identity.[1] Student retention is a particularly pressing issue in STEM with attrition disproportionately affecting persons excluded because of their ethnicity or race (PEERs).[2,3] Since it is implemented in a course, a CURE can be a more equitable tool for providing research experiences and, thus, improving retention rates among underrepresented groups in STEM.[4]

In this paper, we describe the implementation of a similar program called a course-based authentic learning experience (ALE). An ALE differs from a CURE in that it can include any project-based activity, including, but not limited to, research projects. ("Authentic" here refers to an activity that a professional in a particular discipline would do.) Our ALE bridges upper- and lower-division physics classes where students in an upper-division advanced electronics course build instruments capable of measuring temperature, depth, and turbidity of the American River, which runs by our campus. The students in this course are tasked with designing and building the instruments and the user interface. Students in a lower-division laboratory course will then use them to study the properties of the river. In this first iteration of the project, students developed and tested the instruments in the laboratory only. The feedback from the first iteration will then be used by the next set of students in the upper-division course to improve the instruments. In addition to providing students with authentic learning experiences as part of their coursework, this project also aims to provide a link between the lower- and upper-division experiences for our majors and seeks to integrate aspects of societal and environmental issues into the physics curriculum to heighten students' awareness of the role physics can play in these areas.

The American River is a rich natural resource in the Sacramento area that serves numerous stakeholders. It is home to hundreds of species and provides a breeding ground for numerous fish species, including the endangered Chinook salmon. At the same time, it serves as an area for human recreation, both in the river and in adjacent green spaces. It also supplies water to a large segment of the Sacramento population. Furthermore, Sacramento is historically a flood plain, and regular flooding was a part of life for those living along the river. Slightly upstream from Sacramento State are a series of dams that, together with the extensive levee structure, keep the water in the river. These dams not only suppress floods but also raise the water levels for navigation and generate hydroelectric power. They also substantially alter the ecology of the downstream river. Since their creation in the 1950s, there has been a need to balance the demands of all stakeholders, including the riparian wildlife, which has seen a marked reduction in habitat.[5] Part of maintaining this balance is a careful monitoring of the river and its properties such as flow and temperature. Indeed, the United States Geological Survey (USGS) monitors depth, flow, and temperature at multiple sites along the river. These sampling locations are often along bridge pylons near the middle of the river. To better understand the full hydrological picture of the river, the long-term goal of our project is to develop inexpensive instruments capable of measuring hydrological properties of the river at multiple transverse locations across the river. These instruments can capture not only temperature and flow but also turbidity, an important element in the consideration of the river's hydrology-sediment regime and, thus, the overall health of the river. Here, we report on the first phase of the project: The design, construction, and testing of the instruments, all of which was done by undergraduate students across two courses.

This project is one of numerous ongoing ALE projects that are part of the National Science Foundation-funded program Sustainable Interdisciplinary Research to Inspire Undergraduate Success (NSF SIRIUS-II). SIRIUS-II is a continuation of the original SIRIUS program,[6] which demonstrated that CURE projects result in an increase in student self-efficacy.[7] SIRIUS-II builds upon this program by (1) expanding the idea of a CURE to include any authentic, course-based project and (2) extending the project to include projects involving the nearby Los Rios Community College Campuses. SIRIUS-II projects focus on the American River and other Northern California waterways using ALEs to tie together research and societal issues that are right in the students' backyards.

II. THE COURSES

A. Physics 116

Physics 116 is an advanced undergraduate-level electronics and instrumentation course. Enrollment in this course is typically between five and ten students, and in the semester, this project was implemented, and five students were enrolled in the course. Students taking this course, all of whom are physics majors, have already completed Physics 115, an undergraduate, upper-division course that introduces students to basic electronics including both analog (DC, AC, semiconductors/op-amps) and digital circuits and analysis. In Physics 116, students learn advanced circuit analysis techniques such as Fourier analysis, along with digital signal processing and more advanced digital circuits (e.g., frequency counters, pulse width modulators, and phase-locked loops). In the lab portion of class, the focus is on learning instrumentation techniques that can be useful in a physics laboratory. This includes using LabVIEW, programming microcontrollers, and interfacing the two so that measurement data can be collected and processed on a computer. The course involves a student-driven project where students build an instrument that can perform a measurement of some physical quantity. Thus, this was an ideal class in which to implement the ALE.

B. Physics 11B

Physics 11B is our department's third and final physics course in our lower-division calculus-based series. Students taking the course have already completed lower-division mechanics and electricity and magnetism physics courses. The course covers the basics of thermodynamics and statistical mechanics, wave mechanics, light, sound, fluid dynamics, and an introduction to topics of modern physics. Typically, 15–20 students enroll in the course each semester. Most of the students taking the course are physics or chemistry majors, and typically, about half the students enrolled are physics majors.

Laboratory classes in Physics 11B traditionally include self-contained labs, in which students complete in the allotted lab time by following a lab manual outlining the procedure and analysis. The lab exercises are related to the topics of the lecture/discussion portion of the course, but also have overarching themes common to all the labs, such as analyzing experimental uncertainty, distinguishing between random and systematic uncertainty, laboratory conduct, and communication of results. Students in Physics 11B are completing their classical physics framework at the lower-division level, making the course a good candidate for an ALE. The course is also the final stepping stone into the more advanced and specialized upper-division courses, providing an opportunity to introduce students in Physics 11B to elements of upper-division coursework and help bridge the lower- and upper-division course experience, as well as to integrate the cohorts of physics students from the lower-division and upper-division courses through the ALE experience.

III. INSTRUMENT DEVELOPMENT

Five instruments were developed in Physics 116 during the Spring 2022 semester as part of the ALE: Two that measure temperature and one each that measure depth, turbidity, and flow speed. To build their instruments, students first selected a sensor, then developed a circuit to use the sensor, and finally determined a method for computing the value of the measurement. Though five instruments were developed, only the three instruments shown in the top of Fig. 1 were viable at the end of the semester and were used in the first iteration of the Physics 11B portion of the project.

To measure temperature, an LM335 sensor was used.[8] This sensor is a Zener diode with a reverse bias breakdown voltage that is dependent on temperature, $V_z \rightarrow V_z(T)$. A circuit that measures the temperature of the sensor is shown in Fig. 2(a). The diode is biased in the reverse direction with a voltage V_s along with a current-limiting resistor. As long as the supply voltage is larger than the reverse bias breakdown voltage, the voltage across the diode will measure the Zener voltage (or reverse bias breakdown voltage), $V_z(T)$. The sensitivity of the sensor is specified as 10 mV/°C, so all that is needed to determine the temperature is a single-point calibration of T_0 and V_0, and then the temperature can be found: $\mathrm{T} = T_0 + (V - V_0)(100\,^{\circ}\mathrm{C/V})$.

The turbidimeter is slightly more complicated using light scattering to make the measurements. The circuit diagram for this instrument is shown in Fig. 2(b). It consists of an LED and two photodiodes: One placed directly in front of the LED to measure transmitted light and the other placed 90° to the first photodiode to measure scattered light. In this

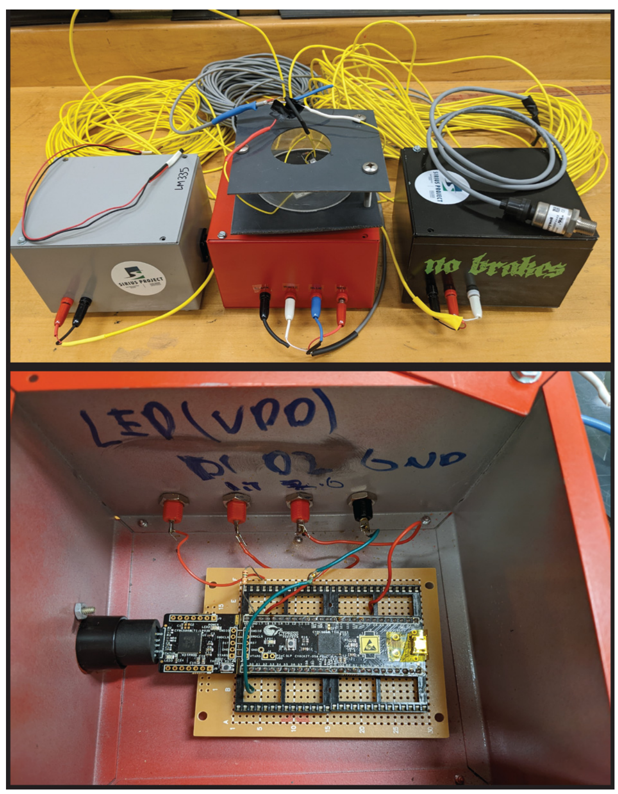

Fig. 1. Top: Instruments developed and used for the SIRIUS-II project that measure (from left to right) temperature, turbidity, and depth. Bottom: Inside of the interface box for the turbidimeter instrument showing the PSoC microcontroller.

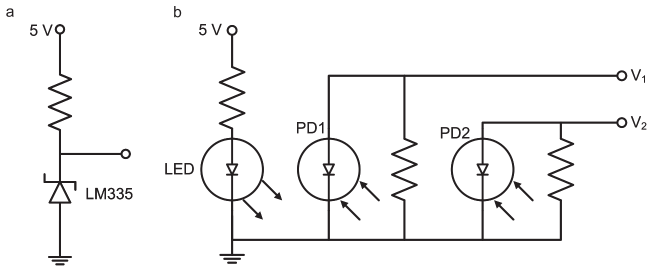

Fig. 2. Circuit diagrams for (a) temperature measurements showing the LM335 temperature sensor, which operates as a Zener diode where the Zener voltage is a function of temperature, and (b) the turbidimeter which consists of an LED and photodiodes PD1, which measures scattered light, and PD2, which measures the transmitted light.

first student design, no special care was taken to collimate the LED light. Turbidity is usually measured in Nephelometric Turbidity Ratio Units (NTRU), which is the ratio of the scattered light to transmitted light, $T = I_s/(dI_t)$, where I_s is the intensity of scattered light, I_t is the intensity of transmitted light, and d is a calibration constant, which is determined so that the turbidity of air is 1 NTRU.[9] Since the current produced by the photodiode is proportional to the intensity of light, the turbidity can be determined by taking the ratio of the voltages measured from the two photodiodes. The instrument works by first making measurements in air to determine d, before immersing the sensor in water and using the transmitted and scattered light signals to compute the turbidity.

Finally, a Honeywell PX2 pressure transducer was employed to measure depth.[10] This sensor outputs a voltage that is proportional to the absolute pressure. From this measurement, the hydrostatic pressure of a fluid column, $P = \rho g h$, is used to compute the height of the column of the water above the gauge (i.e., the depth). To determine the pressure, we use the fact that the ratio of the measured voltage, V_{out}, to the full-scale voltage, $V_{\max}$, is equal to the ratio of the pressure measurement, P, to the full-scale pressure, $P_{\max}$, so that $P = (V_{\text{out}}/V_{\max})P_{\max}$. As the sensor measures absolute pressure, we need to subtract the atmospheric pressure to obtain the hydrostatic pressure of the water, or gauge pressure, $P_W = P - P_{\text{atm}}$, which can then be used to determine the depth of the sensor. Thus, an initial pressure measurement in air is first made to determine P_{atm}, which is then used as a reference to determine the gauge pressure and depth in subsequent measurements.

All the instruments are run by a PSoC 5 microcontroller.[11] The advantage of this controller over others, such as the Arduino, is that (1) it contains on-chip analog and digital signal processing components, allowing students to more easily do some basic signal processing (e.g., amplification, filtering, etc.) without having to build extra circuitry into the instrument; and (2) these microcontrollers are relatively inexpensive and can sometimes even be obtained for free.[12] Programming of the microcontroller is done through PSoC Creator, which is a programming environment developed by the chip manufacturer, Infineon, and available for free. It uses a combination of graphical and C-based programming. Figure 3 shows an example of the graphical portion of the program: the signal routing for the turbidimeter. In this case, the signals from the two photodiodes are first sent through an amplifier before being digitized by a delta-sigma analog-to-digital converter (ADC).

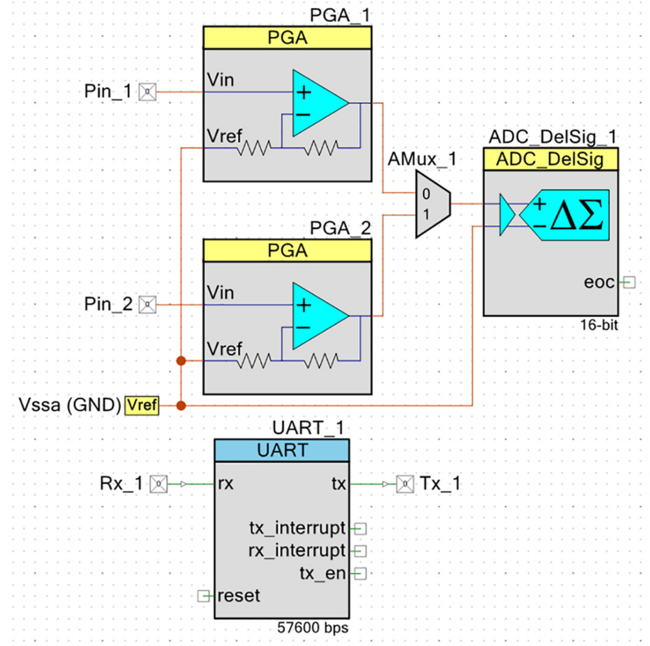

Fig. 3. Graphical portion of the microcontroller's programming for the turbidimeter. The two measured voltages (Pin_1 and Pin_2) first pass through non-inverting amplifiers PGA_1 and PGA_2, before going to a delta-sigma ADC. Once digitized, the data are sent via USB to a computer for processing.

Once digitized, a limited amount of processing can occur in the C-based code before the data are sent via USB to a computer that accompanies the instrument. Here, the data are collected by a LabVIEW program, written as part of the ALE, which applies the calibration. The LabVIEW program also serves as the main user interface for the instrument. Students in Physics 116 also wrote a "user manual" for their instrument, which detailed the methods and concepts relevant to the instrument, as well as basic operating instructions. This manual was provided to the Physics 11B students for their part of the ALE.

IV. INSTRUMENT CHARACTERIZATION AND IMPLEMENTATION

The ALE was implemented in Physics 11B lab during the subsequent semester of Fall 2022. Students were introduced to the project early in the semester, and their role in the project was described as testers for the prototype instruments developed by upper-division physics majors. Students worked in teams of five or six during two three-hour lab periods in the latter half of the semester to characterize and calibrate the instruments, develop standard operating procedures, and write a report summarizing the equipment capabilities and outlining future improvements and features needed to deploy the instruments in the river. In contrast to the more traditional lab exercises used in the course, the project description was purposefully kept open-ended. Along with the rationale and long-term goals of the project, students were told that the goal of their first project day was to develop a standard operating procedure (SOP) for the instrument with sufficient detail that another student in the class could use it, as well as a procedure for characterizing both the random and systematic error of the instrument. Students were instructed to include a schematic of their plan, a complete list of materials needed, a step-by-step plan for collecting any necessary data, and their plan for how to analyze and interpret the data, but the exact protocol development was left for the teams to decide upon with instructor input as needed.

Based on these instructions, the students developed protocols to characterize their team's instrument (see Fig. S1 in the supplementary material for examples of student data[13]). For example, to test the depth measurements, students used a column of water and a ruler and applied their knowledge of hydrostatic pressure to test the accuracy of the sensor. To test the turbidimeter, students used trays of water with a known concentration of dissolved milk powder. Unfortunately, a problem with one of the photodiodes prevented the students from computing the turbidity in NTRU, but they were able to show a clear relationship between the milk powder concentration and the amount of light the photodiode detected. Finally, students used a liquid-in-glass thermometer and a water bath to test the temperature measurements and were able to identify the functional range of the sensor based on their measurements. These data will be used in the next Physics 116 class to improve the accuracy of the instruments.

During the Physics 11B laboratory time, one physics major from the Spring 2022 Physics 116 class was hired as a department student assistant to aid students in the lab as they worked on the instruments. As part of this role, the former Physics 116 student also discussed their experience developing the instruments in the Spring 2022 upper-division class and their experience being part of the ALE in general.

To help scaffold the students' work on the project, all teams were provided a rubric to follow when writing their final report. The rubric items called for specific sections to be included in the report: (1) an abstract of the report summarizing their findings; (2) an introduction to the project; (3) a procedure, including their standard operating procedure; (4) analysis of random and systematic instrument uncertainty; (5) the results of their testing; and (6) a conclusion succinctly summarizing the outcomes of the work and outlining future work to improve and deploy the instruments in the river. The report was also graded on the quality and clarity of the writing.

V. DISCUSSION

The ALE aimed to achieve several goals. First, the implementation of an ALE is known to increase students' investment in the course. Furthermore, having students work on real-life problems helps them build science identity and develop a sense of belonging in science, especially for students traditionally underrepresented in science.[14] Through their work, students explored several concepts relevant to scientific experimentation, including random error, systematic error, instrument calibration, and the idea of a reference. They also practiced open-ended experimental problem solving not typically captured to an equal degree in more traditional labs, in which students are given specific instructions and procedures to arrive at a known result. Student work showed indications that these goals were being met. For example, the group of students characterizing the turbidity instrument determined an experimental relationship between the voltage and the concentration of milk powder in solution and proceeded to analyze the uncertainty inherent in their data, as well as systematic errors. The group also summarized a list of suggested improvements, including issues with one of the light diodes not responding as intended and ideas for how to deploy the instrument in the river in an actual experiment. This feedback, along with other similar feedback from the other groups, will be used by the next Physics 116 class to improve the functionality of the instruments.

When asked to share any additional comments about their experience working on the project, several Physics 11B students mentioned the satisfaction gained from a project with tangible applications, e.g.,: "I appreciated working on something with real-world value and doing something more in lab than repeating steps from the manual," and "I liked the involvement in a real-world issue." Several students also reported an increased appreciation for the complications associated with experimental research, especially the importance of understanding experimental uncertainty, e.g.,: "When it comes to working [on] the river instrument project, it made me realize just how much consideration and input needs to be [given to assigning] uncertainty to values."

Additionally, by having the ALE span a lower- and an upper-division physics course, we aimed to use the ALE experience to help lower-division students transition into the upper division by involving them in project work with advanced upper-division students. Finally, the ALE was designed to highlight the importance of the physical sciences in understanding today's environmental and societal issues. The goal was to both demonstrate to students one possible role physics can play in addressing environmental and societal problems and to heighten the sense of social responsibility borne by scientists, a topic often not given much weight in a traditional physics curriculum.

Students from the Fall 2022 Physics 11B class generally reported a heightened awareness of future upper-division physics projects, a better understanding of how their classwork could have real world impact, and a heightened appreciation of how physics might be involved in environmental research when surveyed at the end of the Fall 2022 semester (see Fig. S2 of the supplementary material for data[13]). Students were asked to respond on a 1-to-5 Likert scale on how they agreed with three statements: "My experience working on the river instruments in Physics 11B gave me a better idea of the types of projects available to me through upper-division coursework" (Question 1, average response 4.0/5), "My experience working on the river instruments in Physics 11B made me think the work I do in my classes can have direct, real-world applications outside the classroom setting" (Question 2, average response 4.5/5), and "My experience working on the river instruments in Physics 11B made me more aware of how physicists might be involved in research on environmental issues" (Question 3, average response 4.69/5).

Due to the small enrollment in Physics 116, we did not collect similar data about students' perception of the project. However, we can say that students in this class gained valuable experience in using low-cost sensors and electrical components to develop instrumentation that will be used by someone other than themselves. The autonomy that students had in designing, building, and testing their instruments has been linked to a sense of ownership in the project, which leads to an increase in engagement and better outcomes.[15,16] Though not as sophisticated as the commercially available counterparts, students in both classes gained an intimate knowledge of how the sensors are incorporated along with other electronic components to perform measurements. In future iterations of this project, we hope to begin collecting data that highlights these outcomes.

This dual-class ALE is designed to allow for sustainable future implementations in the Physics 11B and Physics 116 classes. The structure pairs the development in Physics 116 with the troubleshooting and development in Physics 11B. After Fall 2022, the project work in Physics 11B will inform future student work in Physics 116 to further develop the instruments, which will then be used in subsequent Physics 11B classes. What is particularly interesting in this project is that in the next iteration, some of the developers in the upper-division course will be from the class that originally used and characterized the instruments. This provides a unique opportunity for these students to see both sides of the process, and it will be particularly interesting to observe their perceptions of the project.

We also anticipate that the design will allow for a continuation of the ALE project without any substantial costs, as the same instruments will be utilized in future semesters. Finally, once fully developed, the instruments can continue to be used in classes in gathering temperature, turbidity, and depth measurements in the river to create a publicly available data set used by stakeholders and agencies monitoring river water quality.

VI. CONCLUSION

We have implemented a course-based authentic learning experience (ALE) spanning both upper- and lower-division physics classes that seeks to monitor the hydrology of the American River, a local river that runs by the campus of California State University, Sacramento. In this project, upper-division students developed and built instruments to measure the temperature, depth, and turbidity of the river, while students in the lower-division class characterized and tested the instruments. We stress that this paper describes the first implementation of an iterative process, and as such, our sample size of students is still quite small; however, we intend to continue collecting data on student perceptions of the project to help us gauge the outcomes. In addition, as the instrument design is finalized and the instruments are deployed in the river by students, the data collection and analysis could become part of a broader unit on environmental physics.

The project provides students with several positive outcomes: (1) it gives students experience applying their physics training to solving real-world problems, (2) it establishes a link between lower-division students and more senior upper-division students, and (3) it gives students a unique perspective on how their physics training can be used to study the environment. In all, this project provides students with opportunities to gain first-hand experience in designing, building, testing, and ultimately using instrumentation in an interdisciplinary setting.

ACKNOWLEDGMENTS

The authors would like to thank K. McDonald, E. Gonzalez-Orta, and C. Ishikawa for guiding us through this project and providing us with helpful feedback on this paper. Funding for this project was provided by the National Science Foundation under No. DUE 2012891.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

[a]**Note:** This paper is part of the special issue on Teaching about the environment, sustainability, and climate change.

[b]ORCID: 0000-0002-4821-3318.

[c]ORCID: 0000-0002-4658-502X.

[d]ORCID: 0000-0002-8829-1257.

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