# Supporting Design Capabilities Across the ECE Curriculum, the Role of DAMNED Projects

This paper reports on the development of a second-year design course intended to support student design capabilities in a coherent four-year design thread across an Electrical and Computer Engineering (ECE) curriculum. At Bucknell University students take four years of design starting by building an Internet of Things (IoT) sensor module in first year, a robust IoT product in the second year, using the product to address societal challenges in the third year, followed by a culminating capstone experience in the fourth year. While the first year introduces students broadly to the ECE curriculum, the second-year course reported here is designed to provide students' abilities in electronic device fabrication and test and measurement, areas students at Bucknell have had little previous exposure to. This course is designed to anchor the remainder of the design sequence by giving all students the capability to independently fabricate and test robust electronic devices.

The second-year course has students individually build an IoT appliance—the Digital / Analog Modular Neopixel-based Electronic Display, or DAMNED project—by going through twelve sequential steps of design from simulation through PCB layout, device and enclosure fabrication, to application development. Because this course is most students' first encounter with electronic fabrication and test and measurement techniques, the course has students build the project in twelve steps. Each weekly step is heavily scaffolded to allow students to work independently out of class. The paper discusses how such scaffolding is supported through design representations such as block diagrams, pre-class preparation, rapid feedback, and the use of campus makerspaces and educational software tools. The paper also shares results of making iterative improvement to the course structure using action research, and early indications that students are able transfer skills into subsequent design courses.

## Introduction

Smith, Wankat, and Froyd [1] point out in their analysis of historical trends in engineering education, that while design has been important since the turn of the last century [2], the emphasis on teaching design has been increasing in engineering degree programs. In part this is due to ABET's requirement of a culminating design experience following the shift to EC-2000 about two decades ago [3]. The resurgence of design is also due to: a recognition that design courses can address a broad range of transferable skills thought important for graduates [4], design and problem solving align with the epistemological stance of engineers [5], the products of design drive innovation which is valued in our current neoliberal economic system to which engineering education is coupled, and a subset of faculty simply like to teach design courses.

This paper reports on early stage results of a second year course design course within an electrical and computer engineering curriculum. The course is part of a significant curriculum reform which has been in place for two years in the ECE Department at Bucknell University. The curriculum implemented a "design thread" to ensure design taught at least once in each year as shown in Figure 1. In part the curricular change was due to the importance engineering students reported design play in their own development in a decade of responses to surveys done as part of ABET evaluation. Prior to the curricular change the program had design in the first and final years, or a "bookend" curricula [6], and the move to a four year design thread was intended to address the loss of learning associated with such a structure. The course sequence (thread) shown in Figure 1 consists of six courses—two in the first year, one each in the second and third, and two in the final year for a total of five credits (equivalent to 20 credit hours or 15% of the curriculum).

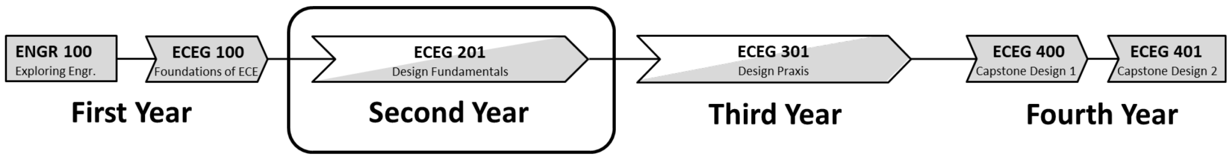


**Figure 1: Four-year ECE design sequence at Bucknell University. The course discussed is the third in the sequence and taken in the students' second year.**

In the first year a course for all engineering students is taught in the first semester (ENGR 100) that broadly introduces design in engineering followed by an ECE specific design course in the second semester (ECEG 100) that introduces students to various sub-areas in the discipline and which is supported by a basic Internet of Things (IoT) project. There is a half credit course in each of the second and third years. The second-year course, described in detail in this paper, emphasizes providing students practical skills in design while the third year course introduces team projects contextualized in larger social issues. The design thread concludes with a two-course capstone sequence in the fourth year in which students undertake client-sponsored projects.

The concept of a design "thread" in the curriculum purposely evokes continuity, that courses build on each other using a common framework rather than serve as standalone experiences. To create continuity, the department adopted a common design framework, Figure 2, consisting of eight different perspectives that inform design. The eight perspectives on the outer perimeter the framework guide the types of attitudes and skills students are expected to develop as designers and inform learning objectives for courses across the curriculum. These perspectives can be thought of "design lenses" that are intended to give different views of the aspects of doing design in electrical and computer engineering. The interior of the figure emphasizes the role of representations and negotiation in the design process. The sequence of design courses teach students to formally represent ideas as part of the design process, and each of the eight perspectives has a set of representations students learn throughout the sequence. Drawing from studies of the process of design [7]–[10], Figure 2 places negotiation as central to the conception of design to remind faculty that while drawing from necessity, design is a contingent activity that is dynamically negotiated with team members and stakeholders in real time. The goal of adopting this framework is to cultivate a more flexible stance in contrast to more well-known "design cycles" taught in many first year courses thereby avoiding teaching the process of design as sequential or formulaic since that does not align with the work of expert designers [11].

In terms of the framework of Figure 2, the first year introduces students to the multiple aspects of design by having them do projects – first in a team of engineers from different majors and then creating a simple IoT device with other electrical and computer engineering students. The second year focuses on providing students practical skills in implementation and performance while the third year focuses on teaching representation that address value, people, context, function, and design. The capstone sequence has students integrate all the perspectives [12]. Communication is emphasized throughout as is learning to represent ideas formally through engineering diagrams, and how to work with ideas in an iterative manner. This paper describes a recent revision of the second course in this sequence to help prepare students to obtain practical skills in electrical and computer engineering project implementation and testing performance.

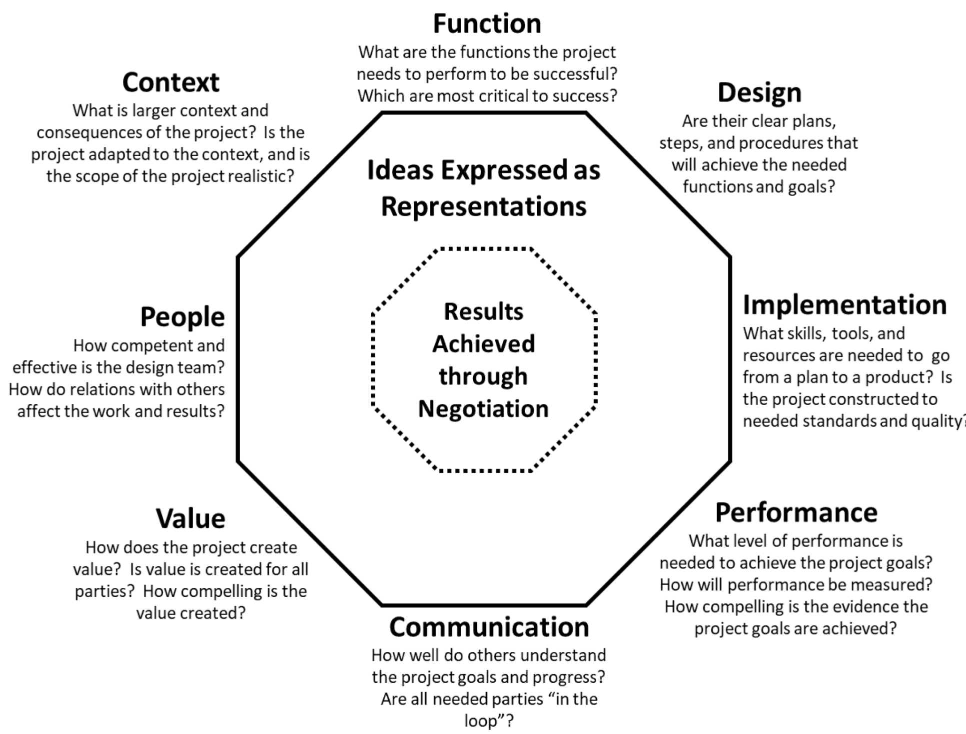


**Figure 2: Representation of eight "design lenses" used to frame design activities across the curriculum. The course described focuses on implementation, performance, and communication**.

A group of three faculty and the department lab manager met over one summer to redesign the course. Discussions were informed by the overall vision of the design thread to lead students from understanding the role of design in ECE in the first year to independently undertaking a project for a client as part of a large team in their final year. In-depth assessment of design abilities in the capstone course showed that students consistently had difficulty defining and measuring performance of hardware and software systems as well as being able to rapidly prototype and iteratively develop such systems. As the team met over the summer reflecting on areas the existing second year design course was seeing successes, areas where it could be improved, and thinking through how to make the overall design thread more coherent for students five course learning objectives were developed:

1) learn to create electronic devices that perform functions,

2) learn system design and problem abstraction,
3) learn to debug and test electronic devices in hardware and software,
4) acquire, analyze, and professionally present data, and
5) independently acquire information needed to complete technical work.

The focus on systems, devices, and practical skills suggested a project-based course. The default in the department has been to assign projects to small student teams, perhaps because historically space restrictions in labs required multiple students per bench. However recently the department has required students to purchase the Analog Discovery 2 measurement pod from Digilent instead of a textbook in the first design course to facilitate learning the basics of electronic measurements. Additionally, in the past the department has noted that students seem not to benefit equally from lab instruction, and we hypothesized part of the reason may be unequal distribution of effort (and thus learning) on team projects and labs. Given students' ability to independently do test and measurement anywhere and the desire to ensure the course equally benefitted all students, the decision was made to have students work individually.

**The Digital / Analog Modular Neopixel-based Electronic Display (DAMNED) Project**

Given the choice to structure the course in a project-based format the team debated various formats including multiple small projects focused on different topical areas within ECE but eventually decided on a single IoT-based project that stretched over the whole semester. The rationale for this format was it enable students to undertake a project that went from circuit simulation through a completed product, thereby gaining a broader view of product development. It was also noted in discussions that constructing a robust product could teach students to better understand the difference between prototyping methods such as breadboards they were familiar with from labs and what was required at the higher technological readiness level such as robustness, user interfaces, and overall system functionality. The choice to base the project on IoT was based the fact that IoT integrates many areas of electrical and computer engineering so students can both get insights into specialty areas as well as see practical implications of topics they are learning in more engineering science focused courses.

IoT projects that have been previously been offered at the undergraduate level, many reported in special journal issues [13]. Some other example include integrating IoT technologies into core undergraduate courses that increased student interest in ECE [14] and the use of IoT projects in ECE labs [15]. Beyond traditional undergraduate engineering education, Internet of Things projects have also been aimed at community college and K-12 students [16]. IoT technologies are also integrated into emerging forms of educational technologies such as wearables – for a review see [17]. The team decided to design an IoT device that could both sense and display data so as to enable bidirectional data flow to and from the cloud. We hypothesized that a built-in display function would both engage students and simplify real-time monitoring and debugging of any sensors attached to the project. Based on examples from the Maker community several iterations of a device that could read sensor data, display the data through both a physical dial and ring of programmable LEDs, and send and receive data from cloud services was developed.

A block diagram of the most recent version of this project, the Digital/Analog Modular Neopixel-based Electronic Display (DAMNED) is shown in Figure 3 below.

The most recent version of the DAMNED project is based on Adafruit's Feather M4 board running CircuitPython which is a reduced-function version of Python designed for embedded processors; Python is the programming language learned early in the degree program. Sensor input can come in via analog or an I2C bus and wifi connectivity enables connection to the cloud-based IoT service ThinkSpeak which is supported by Matlab, another software package familiar to students. While the system runs from 5 VDC, a 12V to 5V buck converter was added to provide students experience with power supply circuits as described in the next section. Display functions are accomplished, as previously mentioned, through both a 24 element ring of neopixel LEDs and a physical dial driven by a stepper motor. The motor driver incorporates an I2C to digital decoder and H-bridge adapted from a motor controller board with a CircuitPython driver.

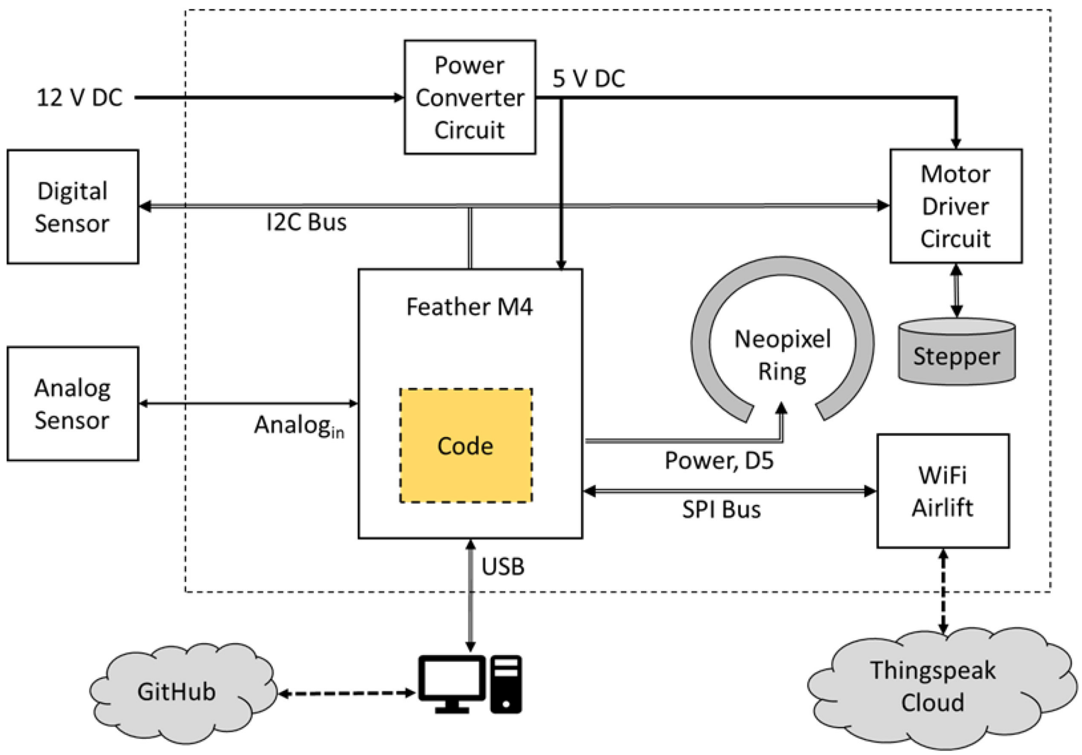


**Figure 3: Simplified block diagram of the DAMNED project. This project representation is used repeatedly in the course to focus on the project as a system and to teach abstraction.**

The DAMNED project is built on a custom printed circuit board using both through hole and surface mount soldering with a custom case designed using SolidWorks with elements that are both 3D printed and laser cut. An assembled DAMNED project is shown in Figure 4(a), showing the lighted ring of neopixels, stepper-motor driven dial, and the 3D printed case with laser cut faceplate. The printed circuit board is shown in Figure 4(b) with the Feather M4 attached to header pins; a wifi board sits on top of the Feather. The DAMNED project has undergone several iterations during the two academic years the course has been offered. Initially linear regulators were used rather than a buck converter, a low-cost ESP wifi board was connected via a serial RS-232 bus, and the Feather M0 was used as the embedded processor. The number of input ports has also increased to support additional sensors. It is worth reiterating that every student in the course independently constructs and tests the DAMNED project shown in Figure 4 over the duration of the design course as described in the next section.

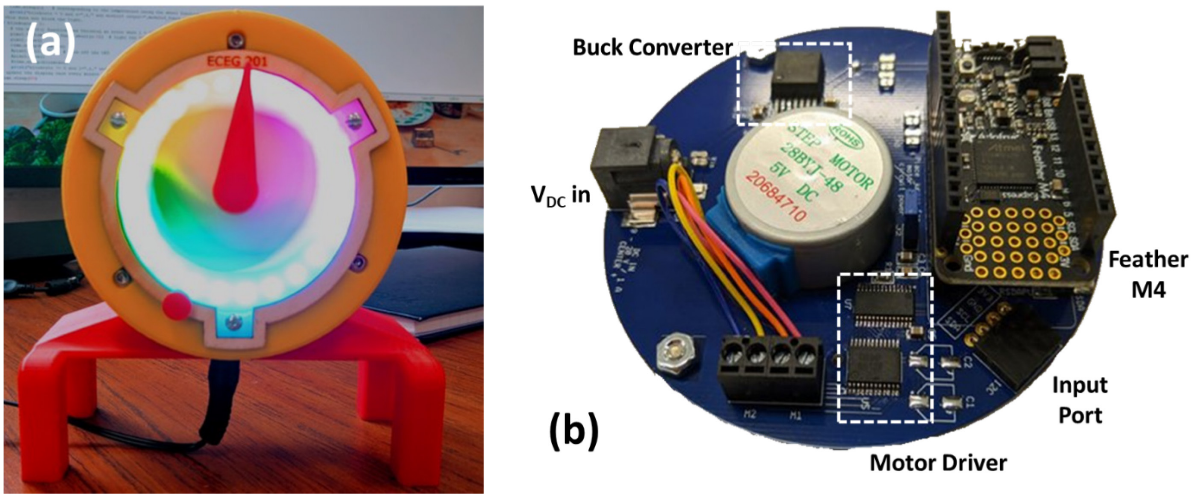


**Figure 4 (a): a completed DAMNED project showing the lighted neopixel ring and stepper-motor controlled dial. Part (b) shows the printed circuit board internal to the DAMNED project. Students lay out parts of the board and solder on components as well as test board functionality across multiple design assignments.**

## Course Implementation

As described previously the course has each student individually construct the DAMNED project in a series of weekly steps, each of which is heavily scaffolded by supporting assignments. Each week is organized as an independent module that covers consecutive steps in the fabrication process as well as different content related to that step. The course, equivalent to two credit hours, meets three times per week with much of the work done outside of the regular class hours. Assignments are due Friday, but students are able to request a "no-cost extension" (i.e. does not impact the grade) until Monday if they show up to class in-person on Friday. The extension was implemented when we learned that students who need to hold down a part-time jobs to support themselves in college often catch up on work over weekends. Weeks are structured similarly throughout the semester as shown in Table 1. The goal was to set up a highly structured course which provided for learning background material, being able to test one's self knowledge, completing a design task in a reasonable time frame, then reflecting and documenting the work performed.

As mentioned above, the DAMNED project is built over one semester, fourteen weeks, in a series of discrete steps. Each step of the project has four broad learning goals that are framed as pairs of goals that are in tension with each other. One tension between learning goals can be described as between learning necessary knowledge and contingent knowledge. This classification of truth dates back as least to the ancient Greeks – some things are true all the time, e.g. they are necessarily true, while other the truth of other things depends on values, perspectives, or prior choices. These latter are contingent truths. While engineering science focuses on necessity, in engineering design choices build on assumptions, user needs, and prior choices so reasoning is highly contingent. A second tension relates to abstracted knowledge that is broadly applicable and transferable, and knowledge and skills that are specific to a particular device or task. For example, to complete the first module of the DAMNED project students need to model a Texas Instrument LMZ12001TZ-ADJ switching power module which requires specific knowledge of this component. However, this particular integrated circuit is a specific example of the broad class of switching regulators, which in turn is a subset of voltage regulators. We wanted students to be able to gain conceptual knowledge about abstracted classes of components, systems, instruments, and software while effectively utilizing specific items in that class in fabrication, for example by reference to a datasheet.

**Table 1: Weekly In-Class Activities / How Learning is Scaffolded**

| **Day** | **Activities in Class** | **Scaffolding** |
|---|---|---|
| **Mon.** | Discuss the week's design assignment consisting of some steps in the overall fabrication of DAMNED. Discuss concepts related to the fabrication step. | Assign relevant readings or videos on Perusall (a group annotation platform) that are due the following Monday. Students read about the topic the week before it is introduced in class. |
| **Wed.** | Student submit "muddiest point" questions before class which are answered by instructor during class. | Online formative quiz over material covered in readings is due. The quiz serves as a "highlighter" reinforcing important or relevant topics from the reading. |
| **Fri.** | Work day for the week's assignment in the Makerspace and design assignment due. By showing up to class students can get an extension until Monday. | Design assignments provide detailed guidance on DAMNED fabrication. A short report, graded using a rubric, over the work done on the DAMNED project is due weekly. |

The fabrication and measurement of the DAMNED project over the course of the semester through a series of design assignments that scaffold those tasks through application of specific and contingent knowledge is described first. The more abstracted and necessary knowledge that supports broader understanding and the ways it was scaffolded is described subsequently.

For each weekly step of the DAMNED fabrication students are guided by a written design assignment that provides necessary information and links to code, resources, etc. The design assignment is not a "cookie cutter" set of instructions, but it is sufficiently comprehensive to guide students through the design task. Given the aggressive schedule and the fact that the course was a half credit, corresponding to about six hours per week of work, a high level of scaffolding was necessary. Table 2 briefly lays out how different topics and construction steps were organized for students' sequential fabrication of the DAMNED project. Each design assignment also contained a "bonus task" for a small number of extra points which extended the concepts further; typically 15% - 25% of students completed the bonus task.

**Table 2: Learning Outcomes by Week, Separated into Specific and Abstracted Assignments**

| Week | DAMNED Project Step (specific & contingent) | Learning Outcomes & Related Concepts (abstracted and necessary) |
|---|---|---|
| **1** | Model and simulate DC-DC converter in Electronic Workbench. | Systems, abstraction, and limitations of circuit models. |
| **2** | Layout buck converter on PCB | Fundamentals of electronic CAD |
| **3** | Populate a PCB – through hold and SMT | Electronics manufacturing and soldering |
| **4** | Test and debug buck converter | Test and measurement – DMMs and power supplies |
| **5** | Characterize buck converter operation | Test and measurement – oscilloscopes and function generators |
| **6** | Analyze and display measured data in Matlab | How to format and display test data |
| **7** | Design an enclosure | Advanced manufacturing – mechanical CAD |
| **8** | Construct an enclosure | Advanced manufacturing – 3D printing and laser cutting |
| **9** | Catch up week | NA |
| **10** | Choose, integrate, and calibrate temperature and humidity sensors | Sensing and data communications |
| **11** | Program a heat index application | Team programming using tools – GitHub |
| **12** | Propose a custom application | Define value to an external audience |
| **13** | Develop custom application | Python programming and API interfaces |
| **14** | Live demonstration and create project datasheet | Proper documentation of design process and results |

Each design assignment has students summarize their work and findings in a short written report. Reports followed a common structure throughout the semester to minimize extra cognitive effort. Each report asked students to briefly define the problem; describe the work they did supported by diagrams or photographs; provide specified results, findings, or data; reflect on and interpret the work done in the context of their own pathway towards becoming an engineer; submit 'muddiest point' questions [18] on aspects they would like to have clarified (these were answered in class); and summarize the results of the efforts. The report was supplemented with either a live demonstration of their work in Friday's class, or a short video submitted electronically. Reports were scored using a rubric on seven factors: the degree to which the work contributed to the students growth as an engineer, the extent to which the student gained or used knowledge and concepts, the extent to which engineering skills were developed and practiced, the degree to which engineering work was abstracted or related to larger contexts, the effectiveness of communicating that knowledge, the degree to which the student demonstrated collaboration and professionalism, and degree to which the effort was complete with work of high quality. The analysis of student work and reporting is discussed subsequently.

In the final weeks of the course after each student built a working DAMNED project and demonstrated functionality by building a heat index monitor by building from example code provided on GitHub, then they used this as a springboard to develop a custom application. This final assignment stretched over two weeks and students were given considerable latitude on what they developed, but were expected to sense some data, push the data to Thingspeak, analyze and display data, and analyze the cloud data to show the system performed as intended. Optionally students could connect multiple sensors or pull and display data from public APIs. Each student did a short, public demonstration of their project at the end of the course. Each student also submitted a final, comprehensive datasheet for their DAMNED project modeled after the datasheet for the buck converter used in the first design assignment. Students had measured required data over the course of the semester so this aspect of the course was designed to have them curate and integrate knowledge from previous design assignments.

The supporting assignments that focused on necessary and more abstracted knowledge were similarly heavily scaffolded using existing software platforms. Readings and videos were posted on Perusall [19] a platform designed to allow group annotations and questions to build comprehension. Perusall algorithmically scores students on reading based on time spent, coverage, quality of comments, and other factors. Faculty were able to go into Perusall readings and answer questions or make comments as well. To emphasize key points in the reading assignment a formative online quiz was given in conjunction with the reading; students were allowed three attempts. The quiz focused on aspects of the readings faculty thought were most important or most relevant to the design assignment. Finally in student's design assignment reports they were required to ask open-ended questions about aspects of the DAMNED project they did not understand. While faculty initially expected these questions to be narrowly focused on aspects of the DAMNED fabrication, they tended to focus more on abstraction or broader application. One day a week (Wednesday) faculty grouped questions into categories and engaged in-depth discussion during class.

## Results and Lessons Learned

The intent of revising the second-year course in the four-year ECE design thread was for students to learn how to implement and measure the performance of an embedded system with both hardware and software elements. The course focused on both the specifics of design tasks, i.e. having students do the detail work needed for actual fabrication and testing, as well as abstracting the tasks so the knowledge gained could (hopefully) be transferred to future projects. The material was taught as described in the previous section, introducing overall system design in a series of heavily scaffolded weekly steps which were supported by readings, formative quizzes, and question sessions intended to abstract specific tasks in the process. To achieve the desired learning outcomes an action research approach was taken over the four semesters the course has been offered in the current format. This section explores both the extent to which these learning goals were achieved and the changes that were made to better achieve the desired outcomes, drawing lessons for others who may want to strengthen design similar courses or programs in ECE.

The most important learning goal of the course was to provide skills in creating and being able to measure the performance of electronic systems, in this case a functioning IoT system. The first time the revised course was taught, in Fall 2020 when classes oscillated between in-person and remote modes due to COVID, approximately 75% of students individually completed the project. Changes were then made to the course structure (discussed subsequently) that have raised the completion rate to nearly 100% of students completing a functional DAMNED project. The course was designed, however, to have a high success rate by making significant help available for students. Class sizes at Bucknell University tend to be small and this course is offered twice a year, with enrollment averaging around 12 students per semester, and significant individual help is available. Despite the availability of support, most students were able to complete the work independently with a smaller number, typically about 25%, needing considerable assistance.

An in-depth analysis of rubric scores for design assignments across the semester for the second iteration of the course provides insights into differentials of progress on the topics evaluation. Evaluation of these elements was performed on student self-reports responding to prompts in the writing assignment. Prompts for self-reported behaviors included describing collaborations with others, attributing work, maintaining a professional attitude, connecting to personal interests and experiences, and connecting work to personal goals. Because of the scaffolded nature of the assignments, scores were consistently high across the data set and differences are not statistically significant. However the findings do corroborate instructor observations. Of the elements on the rubric students performed best on 'gaining knowledge and concepts' as well as 'developing engineering skills', likely because these were generally the most heavily scaffolded learning outcomes on design assignments. Students performed least well on more abstract elements such as 'collaboration and professionalism' and 'becoming an engineer' which was more ontological/attitudinal and sought to capture how student perspectives of design changed during the course. The lower performance was mainly because many students were not particularly metacognitive in the way they reported their results and efforts.

A similar examination of rubric scores on the project datasheet, which summarized work throughout the semester as well as student demonstrations of the custom application they developed using the DAMNED project, corroborates the above results. While most students performed extremely well, there were the largest variations in performance in using figures and tables to present data, and citing prior work. These are areas which may need to be emphasized in the future if trends continue.

The rubric for final project datasheets focused on specific elements of student reports related to overall development of engineering attitude and skills, but did not capture the overall effort and originality of student projects. Because the final customization of the DAMNED project was significantly less structured than the series of design assignments used during fabrication and test & measurement these are used as a proxy for student motivation and engagement. Note that confounding factors such as the time students were able to put into the project and prior knowledge of electronic fabrication and comfort level of Python coding were unable to be accounted for. Over multiple semesters approximately one third of students submitted a basic project that is not too dissimilar from the required heat index monitor, thus putting in a minimal level of effort. Approximately half of the students integrated additional sensors, customized the display significantly, or pulled data from APIs. The remaining students, about 20%, put in significant additional effort to create highly customized applications, undertook sensor fusion, or significantly modified the case design.

In terms of the weekly assignments to get students to abstract generalizable knowledge from the design assignments—readings on Perusall, formative quizzes, and muddiest point questions—the results were not as positive. There were a small number of students, on the order of 10% to 20%, who got behind on readings or showed continual lack of engagement, did not seek to improve grades on the formative quizzes, and submitted few or simple questions to the muddiest point prompt that could be addressed with yes/no answers. The majority of students kept up with the work but did not show a great deal of engagement while approximate a third or quarter of students were highly engaged. In particular the muddiest point questions often showed that while students did not suffer from major misconceptions, they also did not make as many connections with other areas of electrical and computer engineering as desired.

Another goal of the course pertains to students' ability to transfer what they learned in this course to subsequent design courses. There has been little opportunity to measure this since the revised course has only run for two years so there is one year of preliminary data from the third design course (ECEG 301 in Figure 1). What data is available indicates that students are able transfer knowledge and skills. Briefly, in ECEG 301 small teams of students are taught how to contextualize design in human and social problems then must independently design a device to address an engineering grand challenge [20] or United Nations Sustainable Development Goal [21]. The third year course does not teach the implementation and performance aspects of design, Figure 2, requiring students to apply what was learned in ECEG 201. To gauge the degree of transfer, we classified student projects in the follow-on course. Of the projects attempted over half chose to create an IoT device and integrated new sensors in addressing a societal challenge. Students were able to construct and test these devices independently, thereby providing some evidence for transfer.

As discussed previously an action research approach [22] was used to iteratively make improvements in ECEG 201. This section discusses heuristics [23] learned in this process that might be helpful to others who wish to create or adapt some of these ideas.

In terms of the hardware and software used in the DAMNED project there have been a considerable number of modifications made over time. These include providing more input and output functionality, moving to a more powerful embedded controller, better wireless access, increasing power capacity by moving from linear to switching regulators, and improving connectorization. While initially it was attempted to keep costs down by using a variety of vendors, over time the instructors transitioned to the Adafruit CircuitPython design environment due to the available support resources, wide compatibility of components, and ready access to source code. The heuristic learned is to anticipate expansion of capabilities, overbuild, and invest in a well-supported design environment.

Initially the course was less heavily scaffolded, with the DAMNED fabrication divided into two week, rather than one week, long modules. Over time it became clear that many second year students were not able to judge the requisite effort required in two week modules, and often waited until just before the due date to begin work. Increasing the scaffolding by having weekly assignments, setting due dates on Friday with "no cost" extensions to Monday to encourage students to come to the open lab hours, and being more explicit with the instructions provided in design assignments all served helped to keep students on track. Additionally this reorganization allowed the addition of a "catch-up" week midway through the semester that allowed those students who had gotten behind to get back on track. The heuristic learned is that for fabrication and test and measurement second year students need both the task and scheduling of time to be structured. Anticipate that students will not manage their time well and provide opportunities for them to catch up if needed.

As mentioned previously the course was designed to both teach specific knowledge that is contingent to the particulars of the DAMNED project and also to help students abstract the project-specific knowledge in order to draw transferable design skills. In early iterations of the course we hoped that 'muddiest point' questions and the ensuing class discussion would help such abstract assisted by the readings and formative quizzes. This approach had mixed success, with many students having difficulty both abstracting information from the project and "reversing the vector of abstraction" [24] in understanding how the readings informed the specific tasks of the design assignments. Over time more information about abstraction was moved into the design assignments to better connect specific tasks with generalized engineering knowledge. An example from a design assignment is:

> Above we used an analog temperature sensor to light the LED ring when the analog input detected a preset voltage. Sensors also communicate by sending data digitally rather than as an analog voltage. [Note that a sensor measures some property of the environment and converts that measurement into an output that can be read by electronics. Historically this was an analog voltage or current since most electronics were analog. However it has become easier and easier to build sensors that put out digital data, and today most new sensors are digital.]

The above quote is verbatim from the assignment with the comment focusing on abstraction highlighted and in square brackets. The heuristic learned is that students need regular prompts and multiple pedagogical approaches to connect abstracted and specific knowledge.

Building on the above, it was observed that students entering the course had a very wide range of preparation for the tasks of implementing an electronic project and measuring its performance. Some students had considerable prior experience due to hobbies or participation in robotic clubs, while others had no experience fabricating devices. To better support students with little experience the instructors added additional tutorial materials to support fabrication and test and measurement activities. Tutorials were created using the Dozuki platform which supports access using both computers and mobile devices. Having a weekly workday (Friday) was found to be helpful as was the fact that fabrication took place in the department makerspace where makerspace technicians were available in evening hours to help students. The learned heuristic is that successful fabrication at the level of the DAMNED project is possible for all students to undertake independently, but needs multi-faceted support and external resources to achieve high success rates.

## Conclusions and Future Work

This paper has reported on a second year, project-based course in a curricular "design thread" that was revised to teach students basics of electronic fabrication and test and measurement. In the course students developed a working IoT device—the DAMNED project—that was built to robust standards through a series of weekly design assignments. After making modifications to the course over time currently almost all students complete the project and develop a functioning IoT application. To achieve this success rate in a course where students work independently outside of class time, the instructors developed assignments that were heavily scaffolded and focused both on specific and contextualized, and well as knowledge that was necessary and abstract. These assignments consisted both of specific steps related to construction of the DAMNED project as well as weekly readings and formative quizzes designed to help students abstract the specific and highly contextualized fabrication and test and measurement tasks.

Currently the revised course is on its fourth iteration, and the format of the course and assignments have reached a point where major changes are no longer required and so learning outcomes are becoming stable. The development focus is now shifting to the third-year course in which students are expected to transfer their knowledge and skills on implementation, performance, and communication (see Figure 2) to design in larger, socially relevant contexts. Early indications from the third year design course show students are able to transfer knowledge from the second year course to closely related contexts, indicating that at least some success is being achieved in having students abstract their learning.

While an old joke in engineering education is that the plural of anecdote is not anecdata, there are some indications that fabrication of the DAMNED project is having unexpected positive impacts on students. Several students have reported they took their DAMNED project to job interviews, and the project served as a center of conversation with the interviewer, leading to positive outcomes in finding summer internships. Similarly the DAMNED project is prominently featured at recruiting events since it allows a very visual indicator of projects that students undertake in the curriculum.

The authors are happy to share information, assignments, and detailed fabrication files on the DAMNED project with interested faculty members. Please contact us using the information in the title block of the article. This material is based upon work supported by the National Science Foundation under Grant No. EEC-2022271. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

## Citations


[1] J. E. Froyd, P. C. Wankat, and K. A. Smith, "Five Major Shifts in 100 Years of Engineering Education," *Proc. IEEE*, vol. 100, pp. 1344–1360, 2012.

[2] C. R. Mann and M. Press, "A Study of Engineering Education," Carnegie Foundation for the Advancement of Teaching, Boston, 1918.

[3] M. Besterfield-Sacre *et al.*, "Defining the Outcomes: A framework for EC-2000," *IEEE Trans. Educ*, vol. 40, no. 2, pp. 100–110, 2000.

[4] J. Heywood, "The response of higher and technological education to changing patterns of employment," in *ASEE Annual Conference and Exposition, Conference Proceedings*, 2012.

[5] A. L. Pawley, "Universalized Narratives: Patterns in How Faculty Members Define 'Engineering,'" *J. Eng. Educ.*, vol. 98, pp. 309–319, 2009.

[6] D. Kotys-Schwartz, D. Knight, and G. Pawlas, "First-Year and Capstone Design Projects: Is the Bookend Curriculum Approach Effective for Skill Gain," in *American Society for Engineering Education Annual Conference & Exposition*, 2010.

[7] L. Bucciarelli, *Designing Engineers*. Cambridge, MA: The MIT Press, 1996.

[8] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, "Engineering Design Thinking, Teaching, and Learning," *J. Eng. Educ.*, vol. 94, p. 103, 2005.

[9] B. J. Kallenberg, *By Design: Ethics, Theology, and the Practice of Engineering*. Eugene, Oregon: Cascade Books, 2013.

[10] N. Cross, *Designerly Ways of Knowing*. Basel: Birkhauser, 2006.

[11] M. Besterfield-Sacre, C. J. Atman, and L. J. Shuman, "Engineering Student Attitudes Assessment," *J. Eng. Educ.*, vol. 87, pp. 133–141, 1998.

[12] R. A. Cheville and M. S. Thompson, "Navigating Process-Product Tensions using a Design Canvas," in *ASEE Annual Conference and Exposition, Conference Proceedings*, 2018.

[13] M. J. W. Lee, "Guest Editorial: Special Section on Learning through Wearable Technologies and the Internet of Things," *IEEE Trans. Learn. Technol.*, vol. 9, no. 4, pp. 301–303, Oct. 2016.

[14] S. Abraham and A. Miguel, "Creation of an Internet of Things (IoT)-Based Innovation Lab," *ASEE Annu. Conf. Expo. Conf. Proc.*, vol. 2017-June, Jun. 2017.

[15] J. P. Agrawal, O. Farook, Z. J. Anderson, and D. G. Walker, "Internet of Things (IoT) Laboratory," *ASEE Annu. Conf. Expo. Conf. Proc.*, Jun. 2019.

[16] G. J. Mullett, "Internet of Things Education Project (IoTEP)." 26-Jul-2021.

[17] M. Bower and D. Sturman, "What are the educational affordances of wearable technologies?," *Comput. Educ.*, vol. 88, pp. 343–353, Aug. 2015.

[18] T. A. Angelo and K. P. Cross, *Classroom Assessment Techniques: A Handbook for College Teachers*, 2nd ed. San Francisco: Jossey-Bass, 1993.

[19] C. Suhre, K. Winnips, V. De Boer, P. Valdivia, and H. Beldhuis, "Students' experiences with the use of a social annotation tool to improve learning in flipped classrooms," in *5th International Conference on Higher Education Advances*, 2019.

[20] Grand Challenges for Engineering Committee, "Grand Challenges for Engineering," National Academy of Engineering, Washington, DC, 2008.

[21] "United National Sustainable Development Goals," 2021. [Online]. Available: https://sdgs.un.org/goals.

[22] G. M. Bodner and M. Orgill, *Theoretical Frameworks for Research in Chemistry/Science Education*. New York: Prentice-Hall, 2007.
[23] B. V Koen, *Discussion of the Method: Conducting the Engineer's Approach to Problem Solving*. Oxford: Oxford University Press, 2003.
[24] G. Bassett and J. Krupczak Jr., "Abstract Thought in Engineering and Science: Theory and Design," in *Philosophy and Engineering Education: New Perspectives*, San Rafael: Morgan & Claypool, 2019.