Supporting Self-Directed Learning in a Project-Based Embedded Systems Design Course

James Larson, Shawn S. Jordan, Micah Lande, and Steven Weiner

***Abstract*—*Contribution:* This article shares the learning ecosystem of a project-based embedded systems course, identifying course elements that support self-directed learning and how assignments guide students toward becoming adaptive experts.**

***Background:* The technology advances while the fundamentals of electrical engineering remain static. Educators can increasingly prepare students to identify what they need to know to solve problems and avail themselves of resources to learn. This article seeks to further understand ways that a project-based learning approach in an undergraduate embedded systems course can facilitate students' self-directed learning.**

***Research Question:* In what ways can a project-based learning approach in an undergraduate embedded systems course facilitates the self-directed learning amongst students?**

***Methodology:* This article, conducted in the context of an existing embedded systems design (ESD) course, relied on interviews of students, teaching assistants, and faculty along with document analysis and a mixed inductive–deductive thematic analysis.**

***Findings:* A learning ecology of the course is presented. This includes descriptions of space and facilities that influence student motivation, means by which the pedagogical intent of the instructor impacts the student experience, how the course builds on project-based learning knowledge, how the content is distributed using knowledge sharing, how Making supported the ecosystem, how students and instructor occupy similar roles, how the curricular design process was conducted, and how the open ecology promotes student self-direction.**

***Index Terms*—Adaptive expertise, iterative prototyping, learning ecology, project-based learning, self-directed learning.**

I. Introduction and Context

THE FOCUS for many undergraduate engineering courses is specifically delivering technical content. However, there is an increasing pressure to sufficiently address the depth of engineering fundamentals; class time remains constant, but more and more material needs to be covered. Course topics then need to be pruned for educators to be able to cover areas with sufficient depth. Increasingly, new materials and experiences should be added to prepare students for the jobs of the future. With certain engineering knowledge becoming a commodity that can be easily accessed online or dispensed with more ubiquitous computing power, being able to solve problems and challenges at hand in novel and unique ways are becoming an ambition for engineering programs and a desirable outcome for employers. Procuring resources to support teaching capstone engineering courses and project-based learning courses can be a worry and concern for faculty and administrators alike. The purpose of this article is to share a study of a specific, project-based embedded systems design (ESD) course that supports students' development as self-directed learners. This course-based study illustrates the aspects and characteristics of its design and implementation that have allowed for the integration and contextualization of the traditional engineering content. Students are guided through their learning experiences to be better prepared to navigate the ambiguities of the project-based learning experience. The specific research question guiding this article is: In what ways can a project-based learning approach in an undergraduate embedded systems course facilitate the self-directed learning amongst students?

The course under examination is "Embedded Systems Design Project," a junior-level undergraduate course for electrical and robotics focus area students. It is part of a four year, project-based, ABET-accredited general engineering program at Arizona State University at the Polytechnic campus, where students have prior experiences through six semesters of project-based courses before their design capstone (semesters five and six are discussed in this article). Students gain exposure to the Arduino microcontroller platform in their freshman and sophomore years, which prepares them to work on professional microcontroller platforms in their junior and senior years. The learning goals for this course are designed to prepare students for industry employment by simulating an authentic design process that goes from problem definition all the way to the development of a fully functioning, high-fidelity prototype. The goal is realized through the design and fabrication of an embedded system to solve a themed design challenge. This design process rooted in iterative prototyping has students learning and practicing technical content related to sensors and actuators, and how one might create a system of physical components and software programming.

Manuscript received May 15, 2018; revised October 31, 2018, February 28, 2019, and November 1, 2019; accepted January 10, 2020. Date of publication March 25, 2020; date of current version May 5, 2020. This work was supported by the Fulton Undergraduate Research Initiative and Barrett, The Honors College at Arizona State University. *(Corresponding author: Shawn Jordan.)*

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Digital Object Identifier 10.1109/TE.2020.2975358

The ESD course also implements a progressive pedagogical approach to teach project-based learning at scale, including digital fabrication and prototyping techniques, maker-based learning [1], just-in-time learning, design reviews and industry practices, and flipped classroom. In addition, there are other unique elements of the characteristics around the course design, space, and community that make up a pedagogically rich learning environment. This course uniquely prepares students for their culminating capstone experience, serving as a foundational experience for students to draw from as they continue their education. The knowledge, skills, and dispositions learned help students adapt in their capstone experience and future projects, developing the fluid and agile mindset characteristic of the adaptive expert [2]. By investigating and understanding students' unique learning experiences within this environment, the curricular stimuli, and the pedagogical intent, a set of learnings can be generalized to additional contexts, classes, and programs to support learning.

II. Background

A. Learning Ecology

Barron's [3] learning ecology concept can holistically describe an informal learning environment. With this lens, the structure of a learning environment is not only limited to the teacher and students but can also encompass a broader array of categories. For our context, we borrow some of these categories to identify a larger possible consideration of influences at play, such as distributed resources and a larger set of stakeholders from work, school, home, and the community. The previous work has looked at a graduate mechatronics course [4] through this learning ecology lens to realize the wider set of influences at play in the classroom and in the students' learning experiences. Barron posits that fluency development in desired technological settings is derived from an agency in learning [3], implying that a student's self-direction requires types of informal support to be pursued at the discretion of the learner. This leaves researchers and educators with a responsibility to better understand how self-directed learners consolidate distributed resources for themselves, how they broker knowledge with peers, and how their learning can be supported at home, as all of these are fundamental components of a vibrant learning ecology, called motivating factors by Barron.

B. Authentic Control in Self-Directed Learning

Self-directed learning has been defined by Knowles as a process in which adults could diagnose what they needed to know and how to formulate learning goals and execute on them to achieve an outcome [5]. Project-based learning provides some similar opportunities for self-directed learning. Montessori education echoes some of this approach, though in a context of child learning. Montessori discusses the intrinsic learning in early cognitive development stating, "In childhood this force becomes partly conscious as soon as the child carries out a certain self-determined action and then this force is developed in children, but only through experience" [6]. While her definition cannot be directly applied to an upper division engineering course, it extends Knowles's process of self-determined and executed learning outcomes to lower levels of cognizance.

While the Knowles's initial definition [5] outlines a cognitive process in which a learner determines what to learn and how to learn it, another researcher has since developed a comprehensive theory for the motivating factors that facilitate self-directed learning, extending its application beyond adult education settings Knowles studied. Brookfield provides primary indicators of self-direction [7], including authentic control over learning through a range of available and appropriate resources as necessary for students to direct themselves in good faith [8]. This autonomy to pursue any available resources is at the heart of self-directed learning and maps to agency in learning as Barron describes. Appropriate resources can also be seen in the context of Barron's motivating factors. Students will have preferred methods of learning, more comfort learning from specific sources, and the freedom to pursue a classroom experience that more closely resembles professional settings. The achievement of learning outcomes now can be supported by the curation of the available resources and the facilitation of an environment that allows learner control over engagement with resources.

Progressive pedagogies like the flipped classrooms have been popularized with the advent of technologies that make it easy to present content to students outside of class hours. With content available online or in readings, class time can be made available for learner-centered activities [7]. While this structure is designed to promote active learning, it stops short of allowing complete self-direction or full authentic control over all learning decisions, as lectures or homework assignments are the primary vectors for conveying knowledge [8]. The affordance of ambiguous class time itself can be essential to fostering self-directed learning however. The classroom is a controlled environment, where resources can be introduced in a context that allows for self-directed learning and is supported by faculty.

C. Making and Self-Directed Learning

The Maker Movement also is a spur of inspiration for the ESD course's technical content and pedagogical approach and ethos. The Maker Movement is "a social phenomenon that combines the Do-It-Yourself ethos of the 1960s, the power of Internet-based knowledge-sharing platforms, and the democratization of digital fabrication technologies" [9]. In recent years, educators have identified the practices of grassroots Makers as a natural integration of 21st-century skills, such as collaboration, iteration, and grit [10]–[12] along with an active, inquiry-driven approach to technical knowledge [13].

There is a resonance between the theoretical foundations of Maker-based pedagogy and self-directed learning. Knowles' theory of adult learning is predicated on the assumptions that, for maturing learners, "a growing reservoir of experience… becomes an increasing resource for learning" and that their "orientation toward learning shifts from one of subject-centeredness to one of problem-centeredness (p. 55, 14)." Knowles goes further, suggesting that as an adult, the learner "begins to see his normal role in society as no longer being a full-time learner. He sees himself increasingly as a producer or doer" (p. 56, 14). Likewise, Maker-based educational pedagogies are deeply rooted in the theories of constructivism [15] and constructionism [16], which posit that authentic knowledge is made by the learner, not directly transmitted from an authority. It is due to these parallels between self-directed learning and Making that the authors started to think more explicitly about how the ESD course fosters self-direction among students.

D. Adaptive Design Thinking in Project-Based Learning

The undergraduate engineering program at Arizona State University's Polytechnic School is defined by a core set of classes in project-based learning [17], [18]. The curriculum is grounded in eight semesters of project-based design courses that support students' technical development through a succession of hands-on design challenges applied to authentic contexts, where the creation of prototypes and artifacts are probes to engage students in their own learning through a broad base of contexts, from expected engineering topics to exposure to humanitarian engineering, and entrepreneurship. Students have a regular practice in their studies to apply their engineering know-how through project-based learning experiences to solve problems. By the time students arrive at this junior-level course, they have had multiple, significant project experiences and cycles through an iterative design process. The *Engineer of 2020* [10] highlights characteristics, such as creativity, flexibility, and practical ingenuity that, for example, may be especially relevant to overarching goals about implementing and improving project-based learning. With a breadth of previous design experience to draw from, students in the ESD course are well equipped to apply their technical knowledge across a number of topical areas.

Students come to practice adaptive design thinking across these classes, as they think abstractively to make their artifact align with the theme, and actively to ensure its functionality [19]. These dimensions of metacognition that Neely codifies can be grounded in McKenna's existing adaptive expertise literature. The injection of entrepreneurship into engineering education has provided similar terms to be able to consider those aspects beyond technical content and pedagogical content knowledge. Locally, some of the authors are engaged in using a systems and entrepreneurship approach to better understand the broader educational system of engineering departments to understand how adaptive design thinking can be further stimulated. This is further explored here.

III. Research Design

A. Research Question

Seeing the effectiveness of self-directed learning in many informal learning environments, this article seeks to more deeply understand the effects of the pedagogical approach of project-based learning to promote self-directed learning amongst engineering students. The specific research question guiding this article is: In what ways can a project-based learning approach in an undergraduate embedded systems course facilitate self-directed learning amongst students?

By exploring the above question, we can more deeply understand the nuances of an existing project-based implementation in the context of a junior-level embedded systems course and how other courses might be designed to promote self-directed learning and adaptive expertise. Additionally, a greater understanding of self-directed learning approaches in a formal education context provides a foundation for future comparisons and improvements.

B. Methodology

In order to place the results in existing literature while remaining sensitive to the discovery of new knowledge, both inductive and deductive thematic analysis approaches [20] were selected.

Deductive *a priori* approaches to thematic analysis [21] rely upon the existing theory in the literature to develop a codebook, or list of themes expected to emerge, which is then applied to the data. This was based on Neely's framework of design thinking, with its three dimensions of active, abstractive, and adaptive design thinking [19]. Based on a positivistic epistemological perspective that the answers to the research questions already exist within the data and need to be discovered through a specific lens, this approach is useful for connecting directly to the existing theory. However, deductive approaches are subject to confirmation bias by not being sensitive to emergent themes. Inductive *posteriori* approaches to thematic analysis developed by Glaser and Strauss [22] and extended by Charmaz [23], [24] and Boyatzis [25] allow codes to be discovered in the data during the analysis process. An advantage of this approach is that it is not limited by existing theory, which in turn puts results at risk of the researchers' confirmation bias. Both the deductive and inductive approaches were used in this article to both confirm the existing theory and discover new themes in the data. By pairing these approaches (which each help address the weaknesses of the other), a stronger final theory was developed.

C. Participants and Sampling

Participants were students in a specific junior-level ESD course. Recruitment across multiple sections was done via e-mail sent to all current students. Participants received a gift card incentive and no students were required to participate in the study. In order to ensure that the sample represented a wide cross section of the class (e.g., not just the highly motivated, top-performing students), a stratified purposeful sampling approach [26] was used to select participants. A maximum of one participant was selected from each team that volunteered to participate with secondary sampling strata of underrepresented minorities and women.

This article had a total of 11 participants. Ten (10) students (seven males, three females, and three minority students) from ten different teams participated. Course instructor and co-author Jordan also participated in an interview but did not receive a monetary incentive. He was selected due to his extensive history as the designer of this course and a deep understanding of the intended learning outcomes.

D. Data Collection

Three primary sources of data were collected during this article: interviews, written student reflections, and course assignment descriptions. Semi-structured critical incident technique interviews [27] were conducted with all participants to elicit specific examples from participants' experiences course. This approach is appropriate because it relies upon "tell me about a time..." type questions that ask participants to recall specific examples in context, which better illuminate potential themes more specifically. Separate interview protocols (shared in the Appendix) were used for student and instructor participants.

The interview protocol was developed from both McKenna's design adaptive expertise [2] and Neely's engineering design thinking adaptive expertise [19] frameworks, which were appropriate given that self-directed learning is an outcome of adaptive expertise. The interview protocol had questions for students about 1) describing the project; 2) abstractive design thinking; 3) active design thinking; 4) adaptive design thinking; and 5) closing. For example, "How do you learn the knowledge and skills necessary to complete assignments and tasks for your project?" was asked to explore self-directed learning, but other questions around adaptive expertise were also asked to potentially discover other less direct ways that adaptive expertise can help promote self-directed learning. Additionally, several informal classroom observations were conducted during the semester to better understand the classroom environment and refine the questions. The full interview protocol is included in the Appendix. Pilot interviews were conducted with several students from prior semesters during the development of the interview protocol to help clarify and refine the questions. All ten student participants completed interviews of around 30 minutes each and conducted by the first author after the semester had concluded.

Course assignment descriptions (absent student responses) for all team assignments scaffolding the design process were collected. These assignments are described further in Section V. Additionally, biweekly individual guided written reflection assignment responses were also collected from all participants. The reflections typically consisted of four types of questions: 1) How did [specific assignment] inform the design of your project? 2) What obstacles did your team encounter over the past two weeks, and how did you individually contribute to their resolution? 3) How will you individually contribute to the project in the next two weeks? and 4) What resources do you need to be more productive? These were regular assignments for the entire class (though only participants' responses were analyzed).

The instructor interview protocol was developed based on the analysis of the student interviews, assignment descriptions, and reflection assignments to allow the instructor to expand upon and provide more context around themes discovered earlier in the research process. For example, the question "In what ways do you convey content knowledge with students?" was designed to triangulate student responses on how they learned content knowledge. Since the analysis of the student data had to be completed prior to the instructor interview, the interview took place eight months after the end of the Fall 2017 semester and lasted approximately 40 min. The full interview protocol is provided in the Appendix.

E. Data Analysis

All interviews were transcribed. The student reflection responses and assignments were already in digital form. The *a priori* codebook previously developed was used to conduct a deductive thematic analysis [21] on the student interview transcripts, while simultaneously conducting an inductive grounded theory analysis [22]–[25] to capture emergent themes absent in the *a priori* codebook. The deductive and inductive results were then merged to generate a combined hybrid codebook [20]. This codebook was then used to conduct a deductive thematic analysis [21] chronologically on both the assignment descriptions and student reflection responses. A deductive approach was chosen for the assignments and student reflection responses so that the results remained grounded in student experiences described in their research interviews. Additionally, this approach allowed for the triangulation of findings in other sources of data.

Following the analysis of the student interviews, assignment descriptions, and reflection responses, the instructor interview protocol was developed to support the triangulation of findings. The instructor interview was then transcribed and analyzed deductively using the same combined deductive and inductive coding scheme used to analyze the assignment descriptions and student reflection responses.

IV. Results: Creating Ecosystem for Self-Directed Learning

Considering the ecosystem associated with the course as a learning ecology broadens what items one might consider part of the learning experience, allowing educators more creative freedom in the curation of resources to support learning. The course is focused in a regularly, twice weekly meeting time but it also includes open access to resources like the resource-rich engineering studio classroom as well as the array of stakeholders who surround it. Literal and figurative aspects of the course were identified as essential to the learning ecology of the course. While some were not surprising to the research team, the totality of all parts as identified by students is useful to capture.

A. Course: Building on Project-Based Learning Knowledge

The ESD course serves as an instance across a curriculum (semesters five and six) that emphasizes and provides many project-based learning experiences. Students work in teams to solve themed design challenges, around an entrepreneurship idea, or to reinvent an interactive game experience inspired by a children's game. Themes change from year to year, providing a mission-based goal within each semester's course iteration. There is an increasing set of expectations for the application and implementation of their design projects. Students are accumulating knowledge and practicing applying it as they move from novice engineers initially to more competent intermediate

TABLE I
CLASSROOM LEARNING ECOLOGY (ADAPTED FROM BARRON)

Context	Description of Motivating Factors
Distributed Resources	Blog with posts accumulated throughout the course describing walkthroughs of complicated procedures in addition to conceptually focused video lectures
Work	Previous designs in earlier courses foster skills and dispositions in smaller scale projects
School	Shared content amongst classes happening simultaneously in addition to clear continuity from previous design courses
Home	Familiar physical space and process
Community	Culture of making in makerspaces on campus, open technology centers for tinkering and projects
Peers	Familiar peers in small program defined by working in teams on projects

engineering students. This course provides an inflection point from general engineering student to a student who now starts to have a specific concentration, for this class, of robotics or electrical systems within the general engineering program.

B. Space: Motivating Factors of the Learning Ecology

One factor present in the learning ecology of the course is the physical space in which it takes place. For example, student participant Samantha (all names pseudonyms) discussed how the facilities influenced her choice of university: "When I was coming to pick a college, this was definitely the project campus and that's why I picked it." After completing two years of project-based design and fabrication in the program, many students are already familiar both with the lab equipment and with each other. By virtue of the close-knit nature of the program, many have spent time working in the lab neighboring the classroom and that familiarity fosters self-efficacy. In this environment, all of Barron's contexts for fluency development are present with a low activation energy creating a space that fosters self-directed learning. A description of the motivating factors that foster fluency development are in Table I.

The artifact designed in this course is a high-fidelity prototype, an embedded system performing a specific function each team of students determine, leveled by a set of minimum requirements. With the implementation of required sensors and actuators after projects have been imagined and discussed, there is then the challenge of bringing a user-centered solution to fruition. Many projects frequently exceed the minimum requirements. Many students consider the functionality of their final prototype as a marker of success of their project. This is supported through the grading system that rewards both the completion of each stage of the design process as well as the functionality of the final product. As teams move forward in their design process, students learn on their own and from each other to achieve their individual and group milestones. One of the course instructors sees students succeeding on their own or with their teams and describes his teaching method in those cases saying, "My goal in the course is to not get in the way of [students teaching each other] happening naturally, but also to try and promote a community of where people are able to learn from each other." Data and observations support the successful implementation of his pedagogy, and the context he has created as a platform for a design process in this rich ecology produces engineers who will move on to tackle their capstone and other future efforts with confidence.

C. Facilities: Supporting Making and Doing

Engineering shop facilities support students and their activities in rapid prototyping. Local capabilities to design and fabricate printed circuit boards on site also serve to support electrical focused prototyping. With the ability to fabricate multiple prototypes, and the tools to reiterate a design during testing, students are able to fail fast and learn to remedy these failures with readily accessible curated content. Student teams can quickly and economically make high fidelity, functional prototypes locally, and iterate through multiple times. By being able to take conceptual understanding to a concrete functional prototype, the technology aids in this sort of learning. By bringing in current technology into the classroom, this type of artifact-based, project-based learning requires students to explore their resources, fostering cognitive engagement [17]. When learning through artifacts, student interest grows with a variety of technical challenges and social interactions that occur.

With the familiarity of project-based learning and executing the engineering design process, students in the ESD course, generally in their third year, are given access to more sophisticated resources. With the expectation of self-directed learning and the resources to succeed in doing that, students navigate the course as they choose, given some structure of milestones and deliverables. This allows for authentic control over their learning pathways. The open-ended context of a themed design challenge and the mission of building functional artifacts can motivate students to think about their projects in a broad way. Teams can then manipulate technology in abstractive ways that fosters decision making in ambiguous contexts [18]. This allows for another dimension of authentic control, as learning through making, and making clear design rationale, helps the student learn in a manner that can better transfer to the workplace once they graduate.

D. Content: Knowledge Sharing

To support learning, there is also an online repository of conceptual and practical knowledge consolidated over time and made readily available to students. Authored by instructors, teaching assistants, and past students, such an online collection helps students access required knowledge as it becomes applicable in their self-directed design process, in a just-in-time fashion. Aligned with a larger program goal of lifelong learning (in previous ABET language) and strategic learning (in current ABET language), being able to navigate this knowledge repository provides some initial practice at becoming a self-directed learner. Just what component to select or what information can be gleaned from a data sheet are two specific examples for this practice.

The repository of curated content available for students to access whenever, coupled with the rotating office hours of the instructor and TAs, ensures that students are able to learn ahead of the presentation of specific content during scheduled class time. The pedagogical intent of this presentation of content is so that students direct themselves to the content that they need, facilitating their growth as learners in addition to their mastery of content. This distinction from the traditional flipped classroom model allows the instructor to spend the majority of their time in class guiding students through problems that require true expertise. The buffer created by peers, TAs, and the online repository requires a higher activation energy for time with the instructor, prompting students to explore the learning ecology fully. Barron's motivating factors for fluency development categorize the other avenues students can pursue outside of presentation by the instructor [5]. The richness of these other areas in the ESD course is the result of the mindful design of the curriculum and classroom, as the instructor identifies the value of this course between what students are learning in other courses, past courses, and future courses.

E. Instructor Intent Is Triangulated With Student Experience

By triangulating instructor expectations with analysis of student interviews, there is a validation of the course pedagogy and its execution. This allows for elements of the course and the process used to design it to be duplicated across other programs and institutions. A maker-based pedagogy, along with techniques, such as the flipped classroom structures and industry practices, are foundational ideologies in this course. The instructor highlights that the integration of maker-based pedagogy into a project-based learning setup is a reason for its success rather than a weakness. "My goal in this class is for students to get experience designing a system and to learn not only from the successful design of that system, but to learn from their own failures so that way when they encounter things that they do not know how to do in a real industry setting, then they will know how to overcome those failures." This can be interpreted as evidence that designing a learning ecology where students can learn in a self-directed manner can result in successful outcomes, and that faculty do not need to be the direct source of all knowledge utilized by students in the classroom.

F. Students and Instructor Occupy Similar Roles

A compelling aspect of the course's learning ecology is that it predisposes students and instructors to play a variety of roles [28]. Any student is just as likely as the professor to be a "teacher" on a given day, meaning that if an individual is struggling overcome a challenge during a class work session, they will often find help in overcoming that challenge from a teammate or classmate on another team who has experience with that particular challenge before even asking an instructor or TA for help. Clayton describes this saying, "talking with teammates was generally a really good resource because somebody would be good at different parts." While this demonstrates the authentic control students have over learning decisions, it also indicates that the instructor has created an environment where students can learn from multiple sources—each other, TAs, instructors, and/or the blog.

This blurring of roles extends beyond just the notion of the teacher. With the sole exception of an evaluator, learning and teaching roles are practiced by instructors and students alike. Defined here as the archetypal professor, authority, and designer of the course, the evaluator provides the context for design and makes the ultimate decision regarding whether a group's efforts meet the minimum requirements. In every other case though, students and instructors swap roles with fluidity and agility. The instructor attests that "there will be some students who become experts in some area, and they help each other out." In his efforts as a curriculum designer, the instructor iterates his course frequently, monitoring current trends in the industry and soliciting critiques from students, practicing engineers, and faculty. Unafraid to make changes in approach in the midst of a semester or standalone session, the instructor ensures students have the time and resources to be successful.

G. Open Ecology Promotes Student Self-Direction

The learning ecology and design process that takes place in it affords students self-efficacy when facing challenges, authentic control in learning how to solve them, and the development of fluencies necessary to do it again in a future iteration. As students work through this design process that demands multiple prototypes, they develop their learning styles through iteration. Charles describes their starting point saying, "I'm thinking on my feet, and I know who to go to [for help]." With the freedom to engage with whichever components of the learning ecology they choose, at times directed by the passive elements of the ecology, students build self-efficacy as they teach themselves to learn.

This development of learning fluency in the ESD course is possible due to the motivation of self-directed learning through authentic control afforded to students. Without the direct presentation of content knowledge from a teacher on a regular basis, students exercise the learning modes with which they are the most comfortable. The development of fluency in specific engineering skills is present as well, as printed circuit board design, programming, soldering, and troubleshooting are all skills that become routine over iterations. With the call for these skills dependent upon the artifact design, and where students are in their design process, they also are able to practice just-in-time learning [29]. With the reality of digital repositories of knowledge, students are also gaining the valuable skill of recognizing legitimate knowledge by having to apply it to their wholly unique prototype.

V. Discussion

A. Creating Adaptive Learning Ecology

The continual iterations of this course, coupled with the diversity of perspectives that went into its conception have produced a space in which students grasp concepts, apply them in a unique fashion, and master a skill to the point where it becomes routine. While that sort of routine expertise exists in almost every industry setting [30], the course tints this process with the holistic, use-inspired design that is seen in the Maker Movement [31]. The abstractive nature of a creative Maker's design process is seen here in addition to the analytical design process of an engineer, with the innovative, and sometimes even fantastical, applications of technology. With this combination of abstractive learning through self-determination and user-centered design [32], [33], and active learning stimulated through project-based learning and peer-assisted learning [4], the ecology fosters adaptive learning according to Neeley's framework [19]. The development of adaptive expertise is the primary affordance of exercising self-directed learning which is more easily motivated in a space where project-based learning is supported.

The adaptive expert shares many similar character traits what is described in the *Engineer of 2020 report* [10], and frameworks for stimulating adaptive design thinking should be broadly disseminated so that educators can provide growth in adaptive expertise as a learning outcome at all levels of engineering education. The ESD course examined here is an example of the Polytechnic School's project-based program for developing adaptive expertise, as it best supports self-directed learning. From this course, grounded theory examined in this article, and more autonomy afforded to educators, frameworks for adaptive learning ecologies can be developed, applied, and reiterated to radically change the way that engineering students experience learning environments in a way that will allow them to become lifelong learners and innovate throughout their career. Brookfield recognizes self-directed learning as a component of lifelong learning [7], and we must recognize lifelong learning as a characteristic of the adaptive expert, which is a singularity that is reached through the lifelong stimulation of adaptive design thinking.

B. Hypothetical Path Through Ecology Develops Adaptive Expertise

As students autonomously navigate their way through this rich ecology, they end up being their own teacher, which Montessori would posit as an ideal circumstance for learning [6]. As students navigate their design process in this ecology, they practice abstractive design thinking [19]. While every student's project, process, and preferred modes of learning are unique, the simple fact that they have the authentic control to exercise them while still navigating the course and its learning outcomes leads to the growth of well-rounded engineers. Neeley understands that the presence of abstractive and active design thinking is the definition of adaptive design thinking, thus developing adaptive expertise [19]. Adaptive expertise is again found in this course through a framework for adaptive design expertise by [34]. It is based on a transfer through an examination of the course through, as McKenna posits, an optimal adaptability corridor [2]. Fig. 1 illustrates how specific motivating factors can be timed as guiding vectors for students to remain in the optimal adaptability corridor (OAC) with their self-directed learning.

As shown in Fig. 1, the invention pitch assignment asks students to give lightning pitches on their best ideas that meet the project requirements provided by the instructor. The students "judge" these ideas by voting for their favorites from each team. This assignment promotes the generation of innovative ideas while helping students pick from their ideas in

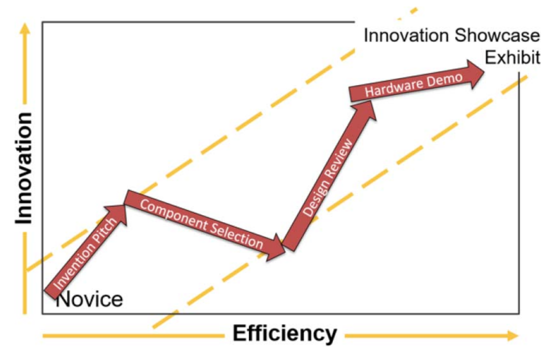

Fig. 1. McKenna's OAC with assignment vectors.

a time efficient manner. The component selection assignment asks students to research and identify possible technological solutions for each block in their block diagrams, and then make a rational pro/con-based argument for choosing one of the solutions to move forward with. This assignment encourages efficiency as it is preparing students to have a solid technological foundation from which to continue. The mid-point design review brings in current and former students, practicing engineers from industry, and faculty to help validate designs in table-top simultaneous design reviews. This process often uncovers the opportunity for additional growth in student learning and understanding through the identification of errors and better solutions to problems. 2/3 of the way through the semester, students participate in hardware demonstrations where they show what they have working (or not) to the class. This both encourages efficiency because students want to have something working to show to the class, but also encourages (sometimes undesired) innovation as students take shortcuts to optimize for a working product at the expense of a good design. Finally, students showcase their projects publicly at the end-of-semester public innovation showcase, where both their innovation and efficiency are on display.

The routine expert of the most efficient industry process, a product of the division of labor and countless repetitions of an unchanging task, sharply contrasts the Maker's comfort in the fluid and agile, almost entirely improvisational design process. But the differences in how these designer's ecologies shape their design thinking and ecology that incorporates the favorable motivating factors of both will likely propel students through the OAC. McKenna does recognize that the presence of both dimensions does not make growth toward adaptive expertise necessarily true as there must be a balance of innovation-based transfer and efficiency-based transfer. While this middle ground is not defined quantitatively, the analysis suggests that it is met by students designing in this ecosystem.

VI. Conclusion

The first author is a recent alumnus of the class and found this ESD course crucial in developing his competency as an engineer, enabling him to lead his own capstone team and determine their own project. This article extends from the first author's honors thesis to explore just how a student benefits from the range of experiences that make up the course. By taking a qualitative approach, grounded in students' experiences of the course, the authors hope to better describe these impactful elements. Students in this ESD course engage in practices one might expect in a capstone course and in industry. Through these measured efforts, the authors hope to illustrate useful transferrable insights that show how authentic control over design decisions fosters learning and personal development in students. This in-depth investigation into the underlying mechanisms and structural properties of the course is pertinent to this special issue as it enables student success in capstone courses and beyond.

Our students are placed in a curated learning ecology with a theme (e.g., wearable electronics and smart home devices) and a set of technical minimums (e.g., at least one sensor, at least one actuator, an 8-b microcontroller, and custom PCB), and are then given the freedom to generate a project of their own choosing. One risk of this approach is that students will make design choices that are beyond their current abilities to execute successfully. However, pedagogically the course is designed to support "fast failure" so that students can learn two things rather than one: what does not work, and what does. The ecology of this classroom affords students of all learning preferences the ability to navigate challenges they face in fabricating their project in unique, self-directed ways, that allows them to develop knowledge of ESD on their own terms.

Student action is guided by curated knowledge resources provided online to support just-in-time, self-directed learning. Instructors occupy a fluid post at the front of the classroom while students sit in teams at studio tables and workbenches, and instructors provide tailored just-in-time education to individuals and small groups. Often, questions are fielded by helping the student identify what they need to know in order to solve the problem as well as where they can learn it. Other times, deeper questions are asked that are situated in students' own conceptual (mis)understandings that can be resolved in an individualized manner. Students also learn from each other in the learning ecology of the course, transferring knowledge of their own expertise. Students begin to build areas of routine expertise themselves as the division of labor within teams leads to proficiencies in certain tasks, yet the structure of the course over two semesters along with assignments that hold individuals accountable assure that each student is still being exposed to the entirety of the course.

While no course (including this one) is perfect, it is the intent of this paper to help readers understand what specific characteristics of the course design support self-directed learning amongst students. Structuring for student self-direction creates the potential for students to develop outside of the OAC with the degree of autonomy they are afforded, which can only be constrained in future iterations of this course. This article itself has already caused reconsiderations of certain structures of the curricular learning ecology. Any wariness to incorporate practices with unproven ethos such as Making should be mitigated by the success of this program that exceeds accreditation standards. The key to success of this program should be understood as iteration, affording professors the room to prototype and reiterate curricula, the program director recognizes a need for innovative practices to offset the rigidity of structured knowledge and procedure in engineering design.

Appendix
Student Interview Protocol

1) What is your project in the embedded systems design project class?
   a) (probe) How did you describe it in your design review?
   b) (probe) How would you describe it to someone not familiar with the technology involved?
2) How did you come up with the idea for this?
   a) (probe) How did your teammates affect the conceptual design?
   b) (probe) What subsystem are you most excited about?
3) Since starting this project, how have you adjusted your own design process?
   a) Would you do anything differently now?
4) Were there any points where you had to change your initial idea?
   a) What sort of feedback did you get at the design review?
5) What sort of questions have you been unable to answer on your own?
6) How do you spend your time with teammates?
   a) How have your teammates shaped any ideas you've had?
   b) How have you shaped your teammates ideas?
7) How many prototypes of your subsystem have you made so far?
   a) Are there any changes you need to make to the current version?
8) What techniques have you learned to minimize the prototypes you have to make?
9) How have you altered your subsystem to mesh with the team project?
10) Have you gotten faster at drafting and testing PCBs?
11) Did you have a working prototype at innovation showcase?
12) What classroom equipment has been most helpful with fabrication and testing?
    a) Were you familiar with all of the lab equipment before this class?
    b) How did you learn to use equipment that you were unfamiliar with?
13) How much time do you spend in the classroom outside of class?
    a) (probe) How often do you work on your own in the lab?
    b) (probe) How often do you work with teammates in the lab?
    c) (probe) How often do you work with classmates that are not on your team?
    d) (probe) How often do you work with TAs during their office hours?
14) What knowledge have others shared with you that has helped you in your own design process?

   a) (probe) What skills did you learn from others that has helped you fabricate prototypes?
15) Can you tell me about a time when you helped any teammates or classmates through a challenge they were facing?
   a) How did you help?
16) How do you learn the knowledge and skills necessary to complete assignments and tasks for your project?
   a) (probe) What are your strengths compared to your teammates?
   b) (probe) What are your weaknesses compared to your teammates?
17) Have you encountered any challenges or failures in your project design or fabrication?
   a) (probe) What strategies did you use to overcome these challenges?
   b) (probe) How often is your first attempt at solving a problem successful?
18) What does success mean for you in terms of this project?
19) How will you approach next semesters project differently?
   a) (probe) What knowledge or skills will you carry forward into your next prototype/next project?
20) Can you think of some ways this class is preparing you for work you will do after graduation?
   a) (probe) How has this class changed your plans for after graduation?
   b) (probe) What are you most worried about in entering engineering industry?
21) Do you enjoy this class?
   a) (probe) Why or why not?
22) What advice would you give to a student that will take this class next year?
23) How long have you studied engineering?
   a) Did you start here at ASU Poly?
   b) Why did you come to ASU Poly?
24) How many engineering projects have you undertaken both through class or on your own?
   a) How did this project stand out?
25) Are there any classes [subjects] you wish you had before taking this course?
   a) (probe) What would you hope to learn from this?
26) Are there any activities in this class you wish you could do more of while at school?
   a) (probe) What about them seems like they would be useful?

Professor Interview Protocol

27) How often are you available to students?
   a) Can you describe how exchanges with students go?
   b) Where do they take place? (workbench, table, and office)
28) In what ways do you convey content knowledge with students?
   a) Can you describe an instance when you helped a team through a challenge?
   b) What additional people and resources are students able to benefit from?
29) Can you tell me about the pedagogical intent of this course?
   a) How does the structure reflect that?
30) How is the class designed to engage students?
31) How would you categorize your role in the classroom ecology?
   a) What are some of the other classroom archetypes students work with throughout the course?
32) Can you describe a typical assignment or milestone from the course?
33) What are differences in the student's learning between the first semester and the second semester?
   a) What are notable differences in their abilities?
34) How does the second semester structure change to accommodate students' fluency development?
35) What knowledge, skills, or dispositions do you think students are developing?

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