Approaching Convergence from an Undergraduate Engineering Perspective

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***Abstract*—This research-to-practice full paper presents and approach to bringing convergence to the undergraduate engineering context. Convergence is the process of integrating a variety of ideas, skills, and methods to create new ideas, skills, and methods in order to address complex, socially relevant challenges like the UN Sustainable Development Goals [1] and the National Academy of Engineering's (NAE) Grand Challenges [2]. In the US, the National Science Foundation (NSF) has been a major driver of convergence related research and has focused on work primarily at the graduate level and beyond. To explore how convergence concepts translate to an undergraduate engineering context this research to practice paper describes a taxonomy that translates convergent knowledge, skills, and mindsets into the domain of undergraduate engineering education. While we do not believe it is reasonable to expect undergraduates to engage with convergence in the same way as graduate students or postdoctoral scholars, we believe that they can develop in areas that will allow them to engage in convergent work later in their careers.**

This paper first defines convergence and then examines the challenges and opportunities related to developing a student's ability to do convergent work in an undergraduate context. The developed taxonomy outlines the knowledge, skills, mindsets, and structures that support convergent work from the larger research literature, and adapts these to an undergraduate context. The taxonomy is then used to conduct a gap analysis of an undergraduate electrical and computer engineering degree program. This analysis is based on the syllabi. This work was conducted in the context of an electrical and computer engineering department situated in a medium-sized primarily undergraduate liberal arts institution in the mid-Atlantic region. As the challenges and opportunities are similar to but also unique to this institution this work forms a rich case study that can inform similar efforts in other institutions and contexts where a similar gap analysis may be beneficial. The goal of this work is to enable others to analyze an their existing student experience to see what aspects of convergence are currently included.

***Index Terms*—convergence, complexity, systems engineering, grand challenges, transdisciplinary**

I. Introduction

In this paper, we will explore how the aspects of convergence[1] translate to the undergraduate context. Our long-term goal is to embed convergent thinking into an undergraduate electrical and computer engineering department because we believe that this will help prepare our students to face the problems of the future. The value of this has been extolled by many groups and is well-captured in [3] and [4]. Convergence is typically applied in the context of graduate and post-graduate research groups. Moving it into the undergraduate context requires that it be redefined for that particular context. This paper begins by reviewing the current state of convergence from multiple perspectives. Next, we identify specific challenges and opportunities in moving these ideas into an undergraduate context. An undergraduate specific model of convergence follows along with a gap analysis of an undergraduate ECE program to illustrate how the taxonomy can be used to analyze what aspects of convergence are covered in the existing program. Taxonomy allows one to identify the aspects of convergence but this alone is not something that can be operationalized. We are working to understand how these elements connect together to help students develop convergent related abilities as well as how to evaluate those abilities.

II. What is Convergence?

The goal of convergent work is to address complex, global-scale, socially-relevant problems like the UN Sustainable Development Goals and the NAE Grand Challenges [5]. It is argued that problems of this scale and complexity are not well addressed by current disciplinary approaches and methods. An initial challenge is that simply defining the term "convergence" is challenging as these types of problems are not easily categorized beyond saying "big, giant problems". Additionally, existing definitions tend to emphasize the design tools and techniques needed to solve complex problems, rather than seeking to elucidate what kinds of problems might qualify as "convergent". Our analysis of convergence focuses on four different areas and attempts to integrate them.

First, we leverage the work of Bainbridge and Roco in [3] that comes primarily from work done within the US National Academies and the NSF which represent the view of the US and of the scientific community. These authors introduce five principles of convergence: (1) *Exploiting interdependence among domains*: sociotechnical systems are highly

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[1] We will use the terms "convergent," "convergence," and "transdisciplinary" interchangeably in this paper.

inter- and intra-connected; (2) *Improving the convergence-divergence evolutionary cycle*:there should be a constant cycle of exploration of ideas that is followed by decision making; (3) *System-logic deductive decision making and problem solving*: multiple problem solving approaches are needed in convergent work and systems thinking is a must; (4) *Creating and applying high-level cross-domain languages to facilitate transfer of knowledge and new solutions*: representation of ideas is important in convergent work. Existing representations should be leveraged when possible and new representations and languages should be created as needed; and (5) *Using "vision-inspired" research to address long-term challenges*: the focus should be in higher-level goals to maintain focus that will have a positive impact on society.

Second, we leverage work from Pohl et al. which comes from work done by the STEM community in Europe [6], [7]. These authors focus heavily on a process for transdisciplinary research that includes the following steps: (1) problem identification and structuring, (2) problem analysis, and (3) bringing results to fruition. This process is more high level than Bainbridge and Roco's and notes that the approaches and processes need to be determined by those doing the work. It places a great deal of focus on understanding the problem and connecting with numerous perspectives.

Third, we adopt principles of *Team Science* [8], [9] which is specifically called out by Bainbridge, Roco, and the NSF as being an appropriate approach to teamwork in the convergent space. As the name suggests, Team Science is the study of teams and builds on many years of work on how teams operate.

Finally, we build upon the ideas of the Cynefin framework from researchers at IBM who provide a way to think about the space of complex problems [10]. This work categorizes problems into four types: simple, complicated, complex, and chaotic. Convergent problems often defy simple categorization and may move between the categories. Engineering students are accustomed to working in the simple ("known"), complicated ("knowable") realms where problems can be simplified and "solved" using existing methods. In the complex, chaotic world of convergent problems, multiple interconnected variables cannot be ignored and existing methods cannot be applied. In the case of complex problems, patterns can be identified looking backwards. In the chaotic space there are not discernible patterns and defining causality is not possible.

Convergence contains similarities to many other design processes that are common in engineering, including "traditional" engineering design, human-centered design, and systems thinking. Several co-authors of this paper have previously compared the convergence with KEEN's 3 C's [11] and with humanitarian engineering [12]. While a systematic comparison is outside the scope of this paper, we will briefly mention some similarities and differences to help readers position convergence in relation to these other popular frameworks. Convergence differs most significantly from "traditional" engineering design, which typically involves narrowing the project context so that the problem becomes more easily "solvable". Traditional design projects typically do not involve disciplines outside engineering or interactions with communities who are impacted until after the design process is complete. Convergence has more in common with human-centered design and systems thinking, both of which have been incorporated into the convergence taxonomy. As in human-centered design, convergence advocates involving users in all steps of the design process to provide regular feedback on the progress and direction of the project. Similarly, systems thinking is a critical component of convergence, which requires a full accounting of the non-technical context, an analysis of the impacts of the new technology on existing systems, and critical thinking around the outcomes. However, convergence differs in its insistence on multidisciplinary teams that cultivate deep understandings of other team members' perspectives. One convergence expert described convergent teams as "smoothies", where everything is blended, rather than "fruit salads", where ingredients remain separated. This is facilitated through a new design element of convergence-divergence cycles (explained below). Convergence also often involves collaborations between multiple sectors, including academia, industry and government organizations. Furthermore, the product of convergence is expected to be something entirely new - the creation of new products and processes that generate new areas of knowledge, spanning multiple disciplines. To continue to draw on the smoothie analogy, in this case the product is no longer fruit salad, it is something transformed - a smoothie.

III. Undergraduate-specific Challenges and Opportunities

There have been multiple, national level reports and "handbooks" motivating convergence and providing ideas of how to operationalize it [3], [6], [13]–[17]. A majority of these have focused on doing convergent work at the graduate level and beyond. While this *informs* doing work at the undergraduate level, the same expectations cannot be applied because of the differences in the students' backgrounds and experiences and the institutional structures and goals. In this section, we will explore the differences and the challenges and opportunities that arise from them.

Challenge: Convergent work takes time. Convergent teams are multidisciplinary and also be multi-domain including education, industry, government, etc. Learning how to communicate not only the highly specific details of the work takes time but basic day to day conversations will be different and culture norms will vary based on who people are and space they are coming from. Additionally, convergent projects themselves take a large amount of time because teams are typically creating new ideas and they must be explored and tested. It is likely that convergent projects run continuously for multiple years. In the undergraduate context, experiences typically run for short periods of time (quarter / trimester / semester) and include summer breaks when most students leave for a time. The calendar of the undergraduate programs is more broken up than that of graduate programs or post-education research labs that run continuously. Most undergraduate students take multiple classes which may span a diversity of topics in a given academic year which divide their attention across multiple things at any given point in time. Additionally, their attention is not only focused on academics but social and co-curricular activities. This limits the amount of time that they can spend on any single activity in a given day and may mean that it is challenging to find a large chunk of time, multiple contiguous hours, to focus on a given task.

Challenge: Limited knowledge and experience. Undergraduates, especially those of traditional age (18-22), have limited life experience. This limits what they can connect new learning to and what they have to leverage in problem solving. Their space of the things they *don't know they don't know* is larger than graduate students or graduated researchers. Additionally, undergraduate curricula tend to be a mix of breadth across a wide range of general education topics and depth in a particular area of study. When trying to do convergence-building work as an undergraduate, students are building up their base knowledge while being asked to leverage it. This is a challenge because transfer related work, typically relies on conceptual understanding that is built and honed over time.

Challenge: A Focus on Individuals. The focus of credentialing at universities is on individuals. Institutions grant degrees to individual persons, not teams. The ABET student outcomes are vague with regard to this particular challenge but we assume that it is interpreted on an individual student level. This focus on evaluating an individual is challenging in the convergence space because ideation and project development are closely shared by the group. This is mirrors the challenges identified about evaluating faculty for convergent work, as well [13], [18].

Opportunity: Learning in context. Traditionally, convergent work is taken on by those who have undergone a traditional path of schooling where is it likely that learning happened in silos: engineering courses typically focused on engineering topics, humanities courses focused on humanities topics, and so forth. If we are rethinking how students learn, we can create interdisciplinary learning opportunities where courses connect across areas. In this case, we can get students thinking about how the various disciplines connect with each otheras they are learing about them initially. We believe this approach may help undergraduates develop convergence abilities faster than helping graduate students re-learn to think. Finally, because undergraduate students typically take multiple courses at the same time, the structure inherently supports this type of model.

A. A Note About Disciplines and Silos

Convergence experts suggest that there is a base or foundational set of knowledge that students need in order to do convergent work [13], [14]. For example, engineering students should also be exposed to the literature, history, sociology, and psychology in addition to their engineering discipline. We value a breadth of knowledge but argue that there is no universal knowledge set. If there was a universal set of knowledge or experiences, we believe that every accreditation body would include it and/or university curricula would all have some universal overlap. Additionally, we also believe that the variation in disciplinary boundaries across institutions and countries supports the ideas that there aren't necessarily universal aspects of knowing. Instead, we think of convergence much like engineering design where a mindset and general approach can be applied by an individual and team in order to do work. Each team brings a unique set of knowledge and experiences to the table and learns whatever is needed along the way. Each individual brings in a unique set of academic and life knowledge, as well. Some breadth of knowledge and experiences combined with the ability to connect those across an individual's set and the team's set can be applied in nearly any situation by any group. Helping students to learn to do these things with what they have *and* helping them learn to learn is our focus because we believe that once a students has those skills they can apply them to what they know now and what they will learn in the future.

IV. An Undergraduate Convergence Taxonomy

The goal of this paper is to introduce the aspects of convergence, adjusted appropriately to the undergraduate space. We have broken down the space into six categories which were derived heavily from Roco's Principles of Convergence [3] combined aspects of Team Science [9], and ideas from Pohl et al. [7], and ideas from a National Research Council report [13]. The collection was developed by one of the authors in collaboration with another. The collection was further detailed and explained in a separate document and then discussed by the team together to identify areas of redundancy and areas that required additional clarity. We note that this is not a process and it is not prescriptive. We are still working on how to operationalize the taxonomy. Just introducing these things will not necessarily help students develop the abilities to do the work of interest. We will now explore each of the categories of the taxonomy.

A. Inspiration and Context

The goal of convergent work is to help people in a non-trivial way. In order to do that, the desired value or specific problem needs to be clear in terms of who is impacted, how they are impacted, and the systems in which those things are embedded. The who, where, and what are important aspects of the work. It is important to remember that undergraduate students have limited exposure. One approach is to encourage students to operate in spaces that are familiar to them, where they already have personal knowledge and experience. This can increase motivation but it may also put them in a position where they can't appropriately understand the values of those they are trying to help [17], [19]. This approach, however, may reduce the cognitive load, aiding in learning, because while the work being done may be new, the context is familiar. Too many new aspects can limit learning. Moving to an unfamiliar context could happen after they develop appropriate skills to do the work but care should be taken to help them understand and explore the context correctly.

Students need to determine the social relevance and impact of their work, which should be informed by an understanding of the sociotechnical systems involved [13]. We define sociotechnical as the bidirectional impact of technology on society and vice versa; both directions are needed. This distinction is important because our interpretation of the 2024-25 ABET Student Outcomes is uni-directional: "4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts" [20]. Understanding the complexity of the problem and taking into account what is currently known about the space from a variety of perspectives, and focusing on the common good are key aspects of the process [6].

Major aspects of this category are supported by the ability do the following:

- Identify who they wish to help and understand their history and values [7]
- Identify the problem or the new opportunity desired and the value proposition
- Describe a subset of the relevant sociotechnical systems involved and the bidirectional impacts
- Capture quantitative and qualitative data about the problem or context from multiple perspectives [10]

B. Learn

Even though students may be working in a familiar area, it is likley that they will need a deeper understanding of the particular problem and context. The students will need to acquire and integrate new knowledge and skills in order to carry out their vision. Because the space of "you don't know what you don't know" is quite large, they need to be adept at exploratory research to identify new domains and disciplines that they did not know existed; this is in comparison to graduate students and older who have a larger body of knowledge of what actually exists even if they don't know much about a given topic. Once new avenues of information are available more traditional methods of learning be employed to go in depth. Another challenge is their limited ability to identify the importance of information and having less existing knowledge to connect to new knowledge, making conceptualization and transfer, key aspects of the convergence-divergence process, more difficult. In summary, at the undergraduate level, the focus is two-fold: developing the skills to find new, unknown information and having the skills to learn about and connect those spaces.

Major aspects of doing work relevant to this category include:

- Developing and using discovery techniques to find new, relevant domains and disciplines
- Developing and using techniques to explore known domains and disciplines to learn conceptual and procedural knowledge
- Finding and learning from individuals who have knowledge and experience of value
- Learning and developing high-quality skills

C. Convergence, Translation, Integration

There are a number of similarities between more traditional engineering design and convergent work. This area is a major exception. The idea of what we are calling *convergence*, but also been termed *translation* and *integration*, is at the heart of what we are doing. It is a focus on not only bringing together different disciplines and domains but creating new knowledge, methods, language, and so forth. Hadorn et al. [6] talk about the need to "transgress boundaries between different academic cultures" and the need for researchers to "step into problem fields and engage in mutual learning with people in the life-world." The same authors note that "Transdisciplinary orientations in research, education and institutions try to overcome the mismatch between knowledge production in academia, on the one hand, and knowledge requests for solving societal problems, on the other." Bainbridge and Roco describe the essence of convergence as "the escalating and transformative interaction of seemingly different disciplines, technologies, and communities to (a) achieve mutual compatibility, synergism, and integration, and (b) create added value (generate new things, with faster outcomes), to meet shared goals" [3]. Since no two people, even experts in the same domain, have the exact same set of knowledge and life experiences, we generalize this *as the need to work together closely throughout the process of generating ideas*. We are emphasizing this specific point because the primary sources for this paper focus on disciplines, domains, knowledge, and experiences which all are held by people. So, our interpretation is that this is about people working with people. Helping students to understand the spectra of how teams can work together and what is appropriate at various points in the process is important. Scaffolding this appropriately and intentionally, because this will likely be new to most undergraduate students, is important. Our interpretation of convergence is that it requires more "all hands" work than traditional engineering design, where teammates work *collaboratively* because they are being prepared to possibly scale to larger, corporate contexts where hundreds or thousands of people work together.

According to the Cynefin framework, convergence-type problems defy known categorization and, in the case of chaotic problems, lack patterns to even attempt to categorize them [10]. In all cases, there is a need to create something new by leveraging what exists broadly and looking for new ways to connect unconnected areas.

The application of knowledge in different contexts is known in the learning literature as *transfer* [21]. This is typically understood as the ability of an individual to apply existing knowledge in new contexts which requires a deep conceptual understanding. Our interpretation of convergence is similar, but this re-application of concepts happens within the team. We believe this is a combination of *individual transfer* and something we are calling *group transfer*. The basic questions is: How do you take knowledge from individuals, collectively share and learn, and apply it in different ways and in a different contexts? Individual transfer is difficult and not necessarily well understood. We are working to understand this idea and the existing work in this space. Undergraduate students are rarely educated on transfer and we assume that undergraduate students should not be expected to achieve group transfer. We are thinking more about the prerequisite knowledge, skills, and experiences that are needed in order to build a foundation from which individual and group transfer can be supported. Intentionally informing students about learning and transfer so they can understand the individual process seems necessary. We hypothesize that being able to support their own individual transfer process is necessary in order to be able to support group transfer.

Bainbridge and Roco include creating new "languages" as needed to represent new ideas and methods [3]. In this context, we interpret this to mean that ideas are communicated using a variety of, likely, abstract representations that are appropriate to the context. Students should be comfortable communicating and interpreting ideas in ways that are appropriate for the context. We rely heavily on block and flow diagrams in our own design courses, for example. Bainbridge and Roco specifically call out mathematical modeling as another example.

We have identified the following knowledge and abilities as being relevant to developing in this category.

- Understanding how people learn with the goal of fostering individual and group transfer
- Teach others with different backgrounds and knowledge
- Persuade others, listen to the ideas of others, and negotiate
- Follow a basic convergence-divergence cycle to develop and choose ideas
- Use and interpret multiple types of representations to capture and communicate ideas
- Use common archetypes of problems or solutions within the discipline(s) and being able to map aspects of a problem or solution to those known archetypes

D. Intervention

This category of convergence is about how to change a system, which is typically focused on moving from an idea to an implemented solution. In an engineering context, this solution would likely leverage technology and consume resources to accomplish a set of goals. However, since convergence should go beyond technology alone, solutions might include policy, education, and other non-technical aspects. Another aspect that differentiates convergence from traditional engineering design is the category of the problems addressed. Convergent problems are much larger and occupy the complex and chaotic spaces of the Cynefin framework while typical design problems at the undergraduate level tend to be complicated or simple [10].

We see problem solving skills from a variety of domains being needed for *full convergence*. We assume that collectively, a team has a set of knowledge and experience to draw from which includes engineering design abilities. We see engineering design as a required aspect of doing convergent work because the application of and creation of technology is crucial to addressing some portion of convergent problems. Teams require much broader expertise and need to bring other knowledge and problem solving approaches to the team. A question that we continually ask ourselves is "how does convergent work differ from traditional engineering design work?" Our answer is that: (1) the problems are different, typically occupying the complex and sometimes chaotic space of the Cynefin framework; (2) solutions are not solely technological interventions and they cross multiple domains and disciplines; (3) evaluating the impact of a solution is difficult because specific causes are not necessarily known or easily measured; (4) causality is complex and not often fully understandable and this evolves continuously; and 5) problems and systems are highly people-focused and people are not necessarily rationale or predictable and may respond differently to the same intervention. Traditional engineering design processes assume that problems and results are repeatable, allowing for consistent measurement and evaluation which is not the case for convergence work. In order to attain this prerequisite, engineering often limits the scope of work which reduces the impact of the overall solution. At this point, we believe we are doing our job correctly if readers who are engineers are actively dismissing these ideas and mumbling something about impossibility. In the end, convergent problem solving cannot follow a defined process because the problems defy traditional approaches and thinking, leaving the team to build the process as they address the challenge [6]. Again, these ideas are for *full convergence* work.

In the undergraduate engineering education context, at some level students need a constrained and straightforward way to create technology to apply to the larger project even if the larger project is more chaotic. We believe a traditional foundation in engineering design is appropriate with some changes around it to capture some of the aspects of convergent work and to start building a foundation for later work. First, students should be working with convergent problems so they are aware of them and begin building an understanding of them. Second, students should start to think about non-technical aspects of solutions and how technical solutions play a role but need to be integrated with a suite non-technical aspects. Third, a good deal of time needs to be placed on analyzing the intended and unintended impact of their work. Monitoring the unintended impact of their work is challenging and likely requires more perspective than undergraduate students have. To address this, students should continually engage with people in and around the impacted community as well as users and other stakeholders to get feedback on their ideas [6].

We have identified the following knowledge and abilities as being relevant to developing in this category.

- Proposing a "solution" to the convergent problem (i.e. a process, system, or object) that meets a set of desired goals
- Engaging in a process focused on rapid creation and feedback from those impacted by the work with a goal of continual improvement

- Integrating simple and non-technical solutions or parts of solutions with equal weight as innovative, technical solutions
- Looking for intended and unintended effects of the work
- Creating a desired system, process, or item using appropriated knowledge, skills, and judgement
- Engaging stakeholders in the design process, seeking continuous feedback about goals and ideas
- Applying knowledge and skills to create limited-complexity solutions in a known context

E. System Analysis

The last category of our taxonomy is the ability to deploy one's work into the world. The focus is to think about the solution at the appropriate scale and in a sustainable way. To do this, one must not only understand the systems that need to be modified but know how to modify them appropriately and convince those with authority to allow them to be modified. This is a challenging aspect because these solutions are multi-modal in nature and may involve a number of disparate entities including government, non-profit, education, and industry. Again, the expectations for undergraduates in this space should be different those later on in their careers. We believe the focus at the undergraduate level should be awareness of the scale needed and the challenges of getting there and not to necessarily deploy a system. Within our own institutions, undergraduate student projects do not reach a technology readiness level high enough to consider real-world deployment [22].

We have identified the following knowledge and abilities as being relevant to developing in this category.

- Explain the desired scale and discuss the resource needs and time needed to deploy the intervention
- Connect with previously identified, impacted entities to understand the challenges of integrating to the desired systems
- Define value for all those impacted by the project in some fashion
- Evaluate potential negative impacts on local populations, historically disadvantaged communities, and environmental resources
- Define qualitative and quantitative metrics by which the impact of the solution can be evaluated and the timescale for observation

F. Mindsets

In addition to the categories of convergent work, we have identified two other things that support convergent work. The first of the two is mindset. In the convergence community, there is a universal realization that convergence requires a level of teamwork that goes beyond other types of multidisciplinary work. Key aspects to support this are a constant focus on the vision of the project [3] and supporting the team [9], [23]. With regard to vision it is about keeping the high-level goals of the work in focus: *who are you trying to help and why?* Regarding the team, one must work to build and maintain trust and psychological safety in the team in order to allow the highly integrated aspects of the convergence process to happen. It suffices to say that any and all of the aspects of good teamwork are needed in convergent groups - clear and open communication, being reflective, seek and be open to feedback, build and maintain trust, and have a positive attitude are just a few from the list. Finally, a team needs to recognize the individual and collective efforts of those involved and value their contributions from the perspective of the larger project. In our experience, it seems completely reasonable for undergraduate students to develop and practice, but it is also assumed that developing this aspect of mindset will need to also be intentionally scaffolded and is built through many real team experiences.

A final aspect of mindset is curiosity. There is always more space to explore and convergent problems are always changing, thus there is a continuous need to think about how new knowledge and experiences can be leveraged to help improve the life of others. The curiosity to explore, learn and connect plays an important role in the larger goal of improving society.

Below are the desired mindsets to support convergence.

- Be vision focused - have shared, high-level goals
- Be team focused including communication, trust, recognition of effort and results of others, and psychological safety
- Continuously engage in development related to the team, the project, and one's self which should include being curious, seeking feedback, and having a growth mindset

G. Institutional Support

The second element of support is institutional support which covers an array of external influences on a team and project. All of these are important to varying levels depending on the task at hand. We recommend having designated spaces to support different parts of the design process: technical work, meeting space, team building, and individual work. These should support effective and efficient work as well as individual and team development space.

In addition to space, groups need appropriate time to get work done. In the context of undergraduate students who typically have a lot of competing priorities, dedicated time to work together is crucial to allow teams to prosper. In our experience, one-hour blocks are less effective than larger chunks of time. Care should be taken when scheduling course times and project meetings to ensure consistent, dedicated time periods for work. If students from different departments or colleges are expected to work together, collaborative approaches to scheduling are needed to ensure students aren't put in a situation that leads to failure. Additionally, the project schedule should reflect the values of those involved. A specific example is having a project schedule that is adapted to the religious obligations of those on the team, including religious holidays and prayer times throughout the day.

Technology plays a large role in enabling teams to communicate internally and externally. It also can support or hinder discussion, ideation, and other parts of the design process. Proper technology tools and infrastructure are necessary to support all team processes throughout the life of the project. In our experience, more tools does not equal better. A small set of complementary tools that provide communication, storage and organization, and ideation work well. Overlap in functionality should be minimized.

Finally, recognition and reward structures by the supporting organization, which is typically a class in the undergraduate context, should meet the needs and values of those who are engaged in the work. Reward structures constructed around the values of engineering may not work well for those outside of engineering. At the undergraduate level, this might manifest itself as co-taught, interdisciplinary courses with alternative evaluation efforts and alternative types of assignments. In any case, the evaluation process should support the desired learning in the course or experience. This section was heavily informed by a report from the National Research Council [13] and Hall et al. [23].

Below is a summary of the major aspects of institutional support.

- Facilities to support team and project development (e.g. discussion, design, fabrication, team building)
- Time to meet and time to work that align with the institution norms and teams values
- Technology appropriate to support team and project development (e.g. communication, ideation, fabrication, organization)
- Evaluation, reward, and recognition processes that promote the desired outcomes

V. Gap Analysis of an Existing ECE Program

Our taxonomy was created to capture the aspects of convergence but it does not capture how these can be connected in order to support students development. This is an area of future work. However, we believe that it can be used to identify what aspects of convergence development that are present in a curriculum. Our assumption is that if these aren't present then development is hindered. If they are present then it is a matter of connecting them appropriately to support development. In the remainder of this paper we will conduct a gap analysis of an existing undergraduate ECE program housed in a small, liberal arts institution to determine what elements are convergence are currently included, what areas could be integrated without major changes, and what areas might require major changes.

A. Methods

This particular program is organized around subgroups of courses call "threads" that each have a particular focus, programming or design for example. Our analysis reviewed the syllabi of 14 courses and rated how well each on included the desired knowledge and skills of the different taxonomy categories. There were four possible ratings: (3) this part is a significant part of the course, (2) this subcategory appears some in the course, (1) this subcategory *could* be integrated without significantly changing the course, and 0) it is unlikely that this subcategory could be integrated without significantly changing the course. Two of the authors, one engineer and one anthropologist, reviewed the set of courses and discussed their ratings of each subcategory in order to find consensus. While this was a subjective process, consensus-building is often recommended to reduce bias in qualitative research [24], [25], and the different disciplinary backgrounds of the authors offered two distinct viewpoints in assessing the presence and potential for integrating convergence components.

	Inspire / Context	Learn	convergence	Intervention	System Analysis	Mindset
Full Curriculum	28%	60%	30%	25%	27%	38%
Design Thread	62%	81%	68%	44%	68%	80%
Elec Sys Thread	13%	54%	17%	5%	7%	11%
Info Syst Thread	13%	63%	21%	18%	5%	42%
Prof Skills Thread	13%	25%	8%	0%	20%	33%

TABLE I
How well the program is *currently* addressing the major categories of the taxonomy. The percentage of 2s (some inclusion) and 3s (a great deal of inclusion) in each category.

The analysis of this program is focused on answering the following questions.

1) Which aspects of convergence are *currently* well-supported and which are minimally supported?
2) What areas of the taxonomy *could potentially* be better supported without substantial changes to the course at the curricular and thread levels?

Our full dataset includes a course by course analysis, however, we found that there were strong similarities between courses within each of the threads. While we don't expect every course to contribute to all aspects of the taxonomy we are able to show that each course does contribute to some categories. Furthermore, this analysis indicates several areas of improvement for classes of many different types to contribute to convergence goals. We did not include the "support" category because most syllabi do not have specific information about those topics and we found it difficult to make judgements in this area about the ability of what was noted on syllabi to fulfill the needs of a course. In addition much of the "support" infrastructure is supplied at the department or university levels, making it out of the scope of this paper.

B. Data and Analysis

Table I shows how well the entire curriculum and each individual thread *currently* address the major categories of the taxonomy. Table II shows the same information as Table I but for the "possible", current and potential combined. The percentages shown are the count of the number of 2s (some) and 3s (a lot) divided by the total number of rankings. This

	Inspire / Context	Learn	convergence	Intervention	System Analysis	Mindset
Full Curriculum	82%	92%	67%	55%	51%	71%
Design Thread	95%	95%	97%	67%	100%	100%
Elec Sys Thread	75%	96%	64%	36%	27%	50%
Info Syst Thread	81%	100%	50%	61%	25%	67%
Prof Skills Thread	75%	50%	58%	36%	100%	100%

TABLE II
HOW WELL THE PROGRAM *could* ADDRESS THE MAJOR CATEGORIES OF THE TAXONOMY. THE PERCENTAGE OF 2S (SOME INCLUSION) AND 3S (A GREAT DEAL OF INCLUSION) IN EACH CATEGORY.

data shows that the Design thread includes multiple areas of convergence while the Electronics Systems and Information Systems threads, which are more "traditional" in approach, address fewer areas of convergence. The Professional Skills thread is also limited. Across all of the threads we see that the curriculum as a whole has a strong focus on the "Learn" category of convergence.

The general trend shown by this data meets our expectations: the Design Thread of this program was created to address synthesis and application of knowledge and skills from across the curriculum. The data also shows that all of the major categories of the taxonomy are addressed to some level across the curriculum but to a low level. We further explored the data by counting how many times each category was addressed at the curricular level. This data is shown in Table III. This table includes a column for the number of times that the subcategories are currently addressed ("Current") and the potential for how well they could be addressed without significant course changes ("Current + Pontential"). The rows are ordered by the counts in the "Current" column. The maximum count for this table is 15.

Table III shows that a majority of the subcategories are currently only included in about a third of the courses in the curriculum. The table shows that, with some effort, about half of the subcategories could be addressed in about half of the courses. We also note that ABET Student Outcomes do not have specified levels of priority and it is up to departments to determine this individually. Further work is needed to determine if minimum levels are needed and what those levels are.

The data in Table II shows room for further inclusion of all of the major categories of the taxonomy across all of the threads. The Design Thread continues to be a place where convergence can be embedded, which matches our understanding of the thread's goals. Additionally, the program, as a whole, has strength in the category of learning which matches our expectations of an academic program with almost a dozen engineering science courses.

Our analysis has identified the areas within convergence that are well addressed, those towards the top of Table III

Subcategory	Current	Current + Pontential
Learn from known domains / disciplines	13	13
Learn and develop high-quality skills	13	13
Continuous engage in development	8	15
Use diverse representations	8	12
Create a desired system, process, or item	7	9
Develop metacognition	6	15
Who they wish to help with context	6	14
Be team focused	6	10
Apply knowledge and skills to create in context	5	14
Learn from learned people	5	15
Develop discovery techniques	5	14
List sociotechnical systems and impact	5	15
Define value for all	5	7
Define qualitative and quantitative metrics	5	8
Map to common archetypes	4	12
Identify intended and unintended effects	4	10
Teach others with different backgrounds	4	8
Identify integration challenges	4	7
Engage in rapid iteration and feedback cycles	4	5
Identify problem or opportunity, value proposition	3	13
Persuade others, be pursuaded, and negotiate	3	8
Propose a solution	3	8
Be vision focused	3	7
Capture quantitative and qualitative data	3	7
Explain scale / resource needs / timescale	3	8
Evaluate negative impacts on people, places, and things	3	8
Follow a convergence / divergence cycle	2	5
Engage stakeholders and community continually	2	7
Leverage simple and non-tech aspects	1	5

TABLE III
THE COUNTS FOR HOW OFTEN EACH SUBCATEGORY WAS NOTED ACROSS COURSES IN THE CURRICULUM. CURRENT COUNTS ARE VALUES OF 2 OR 3 AND POTENTIAL COUNTS ARE 1, 2, AND 3. CONDITIONAL FORMATTING HAS BEEN APPLIED TO EACH COLUMN INDEPENDENTLY. ROWS ARE ORDERED BY THE "CURRENT" COLUMN. THE MAXIMUM POSSIBLE VALUE FOR A CELL IS 15.

and those that are less addressed, towards the bottom of the table. It has also identified which parts of the curriculum are already supporting student development in relevant areas of convergent thinking. Further discussions are needed with the program to identify which courses they want to change and how. At this time, we do not have specific ways to develop different aspects of the taxonomy but this is an area of future work. Our initial interest is to evaluate how well proven experiences like the AAC&U's High Impact Practices are at supporting convergence [26]. Regarding the frequency of experiences to develop convergent thinking in particular areas, our general guidance is to expose students multiple times over their time in the program. Our own experience has been that intentional, coordinated and connected experiences work best. These experiences are a lot of work to create and maintain and so a small number of them is better than trying to do a lot. However, we do not have specific targets for these values at this time.

VI. Limitations and Future Work

The interpretation of the categories of the taxonomy can vary which we encountered during our own analysis and later discussion even between paper drafts. We have worked to clarify them within the team but ongoing work is needed.

We attempted to make the review as systematic as possible by using the syllabi of the courses in the program. The program under review does not have a specific syllabus template so the information included about each course is varies, even those taught by the same instructor. The information available to us was limited as not every course included an in depth list of topics or experiences which is what most of our analysis used. Because we are familiar with the program under review we could identify points where the syllabus did not provide enough information for something that we knew was included in the course. For consistency, we did not rank by our knowledge, only by the information provided in the syllabus. A more in depth evaluation could be done through interviews or review of additional course material like assignments and lecture notes and we would encourage interested programs to go into greater depth.

More broadly what has been presented is not an actionable plan nor do we suggest that by doing these things students will develop useful convergent abilities. We are working on a way to operationlize this work. We believe that we must first better understand how the different knowledge, skills, and mindsets connect to each other but more work is needed. We are also working on creating scoring rubrics for the categories in the taxonomy.

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