ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #37806

Addressing Convergent Problems with Entrepreneurially-Minded Learning

Stu Thompson (Dr.)

Stu is an associate professor and chair of the department of Electrical and Computer Engineering at Bucknell University, in Lewisburg, PA. While his teaching responsibilities typically include digital design, computer-related electives, and senior design, his focus

Alan Cheville (T. Jefferson Miers Chair in Electrical Engineering, Professor Department Chair)

Alan Cheville studied optoelectronics and ultrafast optics at Rice University before joining Oklahoma State University working on terahertz frequencies and engineering education. While at Oklahoma State he developed courses in photonics and engineering design. After serving for two and a half years as a program director in engineering education at the National Science Foundation, he became chair of the ECE Department at Bucknell University. He is currently interested in engineering design education, engineering education policy, and the philosophy of engineering education.

Jason Forsyth (Associate Professor of Engineering)

Jason Forsyth is an Associate Professor of Engineering at James Madison University. He received his PhD from Virginia Tech in May 2015. His major research interests are in wearable/ubiquitous computing and engineering education. Previously he was an Assistant Professor of Electrical and Computer Engineering at York College of Pennsylvania from 2015 – 2018. His wearable computing work develops safety systems that provide continuous monitoring and sensing to protect human life. Previous work examined the role of wearable pulse oximetry in protecting construction workers from carbon monoxide poisoning and developing a warning system for road-side workers and emergency personnel to estimate potential vehicle strikes. His current research interests focus on on-body human activity recognition and interactive machine learning for physical therapy patients and practitioners to increase exercise adherence and clinical evaluation.

Addressing Convergent Problems with Entrepreneurially-Minded Learning

Abstract
In this paper we explore the ability of educational frameworks focused on developing the entrepreneurial mindset to be used to develop students' abilities to approach convergent problems. While there is not a single widely accepted definition of convergence, there are some general aspects noted by the NSF including: socially relevant, multidisciplinary, complex, and not being adequately addressed by current methods and practices. Convergent problems require existing disciplines to collaborate to create new knowledge, skills, and approaches in order to be appropriately addressed. We believe that there are aspects of the entrepreneurial mindset and the learning of it that can support the development of knowledge, skills, and attitudes to approach convergent problems. This is relevant because most work on convergent problems happens at the graduate level and beyond and our interest is to create experiences for undergraduates that prepare them to embark on this work after graduation.

This study maps entrepreneurial mindset learning (EML) onto a framework based on prior work on convergence to identify the aspects of EML that directly support convergence work or preparation for convergence work. The existing dataset of KEEN cards is used as a proxy for existing work in this space, as well.

If existing work in EML can address some or all of the knowledge, skills, and attitudes needed for convergent problem solving then engineering educators have a set of tools and practices that can contribute towards creating engineers who are better prepared to work on the hard problems of tomorrow.

1. Introduction

This paper explores the connection between convergence and entrepreneurial minded learning. The term "convergence" emerged from work at the National Academies and the National Science Foundation. The goal of convergence work is to address problems that cannot be addressed by traditional disciplines or approaches by bringing together a variety of disparate disciplines, sectors, methods, and ideas to create new knowledge, tools, and modes of thinking [1]. While the idea of convergence emerged approximately 20 years ago, it is still evolving, and multiple reports have been published on the topic since that time [2]. The reports point to the inability of existing fields and methods to adequately address some of the global, systemic problems of today and tomorrow and the need for deep collaboration and integration of ideas and methods. The National Science Foundation recently began to explore the space of funding convergent research through two programs: The Convergence Accelerator (CA) program [3] and the Growing Convergent Research (GCR) program [4]. While these two programs both focus on convergence, they focus on different aspects of it.

Part of the framing of convergence is to address the perception that for a number of decades the academy has been exploring divergent paths. One way this is evident is the number and variety of college majors. Similarly, the last couple of decades have seen growth in the number of disciplines and subdisciplines leading to a view that the academy has been too focused on greater depth and understanding in specific areas. Roco et al. argues that in order to address the great challenges of now and the future, disciplines need to work together, now that we have extensive knowledge and methods to utilize, to solve problems that were previously inadequately addressed [5]. In other words, individual disciplines by themselves can only have limited impact on global-scale, inherently multidisciplinary problems.

In this paper the authors are interested in looking for connections between entrepreneurial minded learning (EML) and convergence because we believe that addressing convergent problems is a natural progression for engineering. Many convergent problems have arisen because of the successes of engineering lead to both positive and negative consequences. For example, one of the first CA cohorts was focused on "open knowledge networks" which are made possible by the massive computing capabilities of the world today. Additionally, a more recent CA cohort is focused on the "networked blue economy" which focuses on pollution of the world's oceans facilitated by our ability to produce and distribute massive amounts of plastic. In terms of EML, the mindsets and skills of entrepreneurship seem to have at least surface similarities with convergence. EML has gained prominence since a significant recent source of funding in engineering education has been through the Kern Family Foundation's KEEN EML programs [6]. These programs make awards to schools to integrate EML into the curriculum.

Both the Federal support of convergence and the private support of EML draw on similar, but not identical belief systems. Both center on technology as a major driver of solutions to issues facing society. Both have a distinctly neoliberal character - convergence, through activities designed to scale innovations beyond the traditional academic sphere into the free market, and EML's focus on entrepreneurship. Both imply the value of free market competition and emphasize sustained economic growth as a path to societal progress. There are, however, differences. Convergence is focused primarily on high level graduate students, post-graduate scholars, and researchers [7]. Meanwhile, KEEN's EML programs are focused on undergraduates. For this reason, it may be valuable to look for connections to leverage existing work in EML in order to better prepare undergraduates to address convergent problems throughout their careers.

On a more practical level, the authors' interests are to explore how we can better prepare students to work on convergent problems at the undergraduate level. We would like to leverage

EML where possible to accelerate that goal but we need to better understand where EML can support this and where we need to develop new experiences and material. This paper details the results of our exploration of this space.

2. The KEEN EML Framework and KEEN Cards

The Entrepreneurial Minded Learning educational framework has gained increased attention and popularity within undergraduate engineering education. The framework promotes both *skillsets* and *mindsets* for engineering students. Mindsets have become popularized as educators have become more aware of the work of psychologists on topics such as grit [8] that assume the importance of resilience in learning. Similarly Carol Dweck's growth mindset emphasizes how different forms of feedback impact the comfort level of students as they work on problems.

KEEN has published a list of skillsets and mindsets hypothesized to be important in EML. Each of the skillsets and mindsets within the EML framework are grouped into categories. Within mindsets, there are three major categories: Curiosity, Connections, and Creating Value. These items are commonly referred to as the "3C's" in EML literature. The high-level 3C's are broadly defined with specific language in EML framework in the following ways [9]:

- Curiosity - "In a world of accelerating change, today's solutions are often obsolete tomorrow. Since discoveries are made by the curious, we must empower our students to investigate a rapidly changing world with an insatiable curiosity."
- Connections - "Discoveries, however, are not enough. Information only yields insight when connected with other information. We must teach our students to habitually pursue knowledge and integrate it with their own discoveries to reveal innovative solutions."
- Creating Value - "Innovative solutions are most meaningful when they create extraordinary value for others. Therefore, students must be champions of value creation. As educators, we must train students to persistently anticipate and meet the needs of a changing world."

Table 1: EML Framework Mindsets with Categories

Curiosity	Connections	Creating Value
DEMONSTRATE constant curiosity about our changing world	INTEGRATE information from many sources to gain insight	IDENTIFY unexpected opportunities to create extraordinary value
EXPLORE a contrarian view of accepted solutions	ASSESS and MANAGE risk	PERSIST through and learn from failure

Table 2: EML Framework Skillsets with Categories

Opportunity	Design	Impact
Identify opportunity	Determine Design Requirements	Communicate solution in economic terms
Evaluate tech feasibility, customer value, societal benefits, and economic viability	Develop New Technologies	Develop partnerships and build team
Investigate market	Perform Technical Design	Communicate societal benefits
Test concepts via customer engagement	Create Model or Prototype	Identify supply chains and distribution methods
Create preliminary business model	Analyze Solutions	Validate market interest
Assess policy and regulatory issues	Validate Functions	Protect intellectual property

Each mindset category is provided further granularity with two mindsets describing that category such as “Explore a contrarian view of accepted solutions” for Curiosity, and “Integrate information from many sources to gain insights” for Connections as shown in Table 1.

Similar to the mindsets, the complementary engineering skillsets of the EML framework are described in three larger categories: Opportunity, Design, and Impact. Unlike the “3C’s” there are no definitions of these categories but each is divided into six specific skillsets for each such as “Test Concepts via customer engagement” for Opportunity and “Determine design requirements” for Design as shown in Table 2.

Several years ago, an online portal (www.engineeringunleashed.com) for entrepreneurial mindset (EM) activities was launched to provide an electronic community for the 50 KEEN partner schools to collaborate on research and curricular innovations. A key aspect of the site is a repository of “KEEN Cards" which are instructor-produced records of EM-related instructional artifacts such as assignments, modules, projects, or courses. Each card provides descriptions, learning outcomes, and instructional tips and materials to implement the module. Additionally, each card can be “tagged” with various engineering disciplines, EM skillsets, and EM mindsets to enable a fine-grained search. We drew upon these cards and tags as the basis for our analysis of mapping the EML framework to convergence. An example card is shown in Figure 1 with the “tagged” skillset and mindset attributes on the right-side.

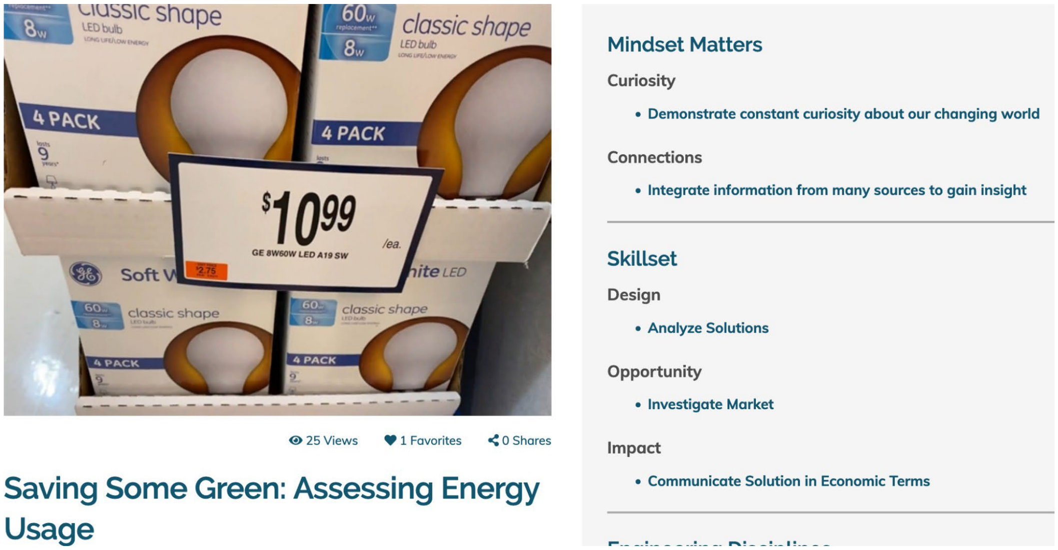

Figure 1: An example KEEN Cards with Mindset and Skillset elements "tagged". From KEEN card https://engineeringunleashed.com/card/1184

The KEEN framework for EML has undergone considerable evolution since the program was started, and the definitions above have changed over time. As is evident from the framework, it draws from two broad sets of skills. Those traditionally associated with engineering such as design, but others which are drawn from the entrepreneurial and business communities. Although stable and in relatively broad use, the EML framework is not without some tensions. One is that perhaps because of the entrepreneurial focus on growth and risk taking, some traditional engineering values such as caution and risk management are not included, an omission that seems to have led to critiques and pushback from faculty who are not affiliated with KEEN on some campuses. Another tension can be described as schismogenesis, the fact that cultures often define themselves in opposition to adjacent cultures. Despite the close relationship between engineering and business the integration of business and engineering cultures, particularly those which emphasize engineering science, may be problematic [10]. Third, it seems that the KEEN framework is not fully based on empirical research on how students learn, but rather desired traits of students that are assumed to benefit them in entrepreneurial endeavors. The extent to which these mindsets and skills do this is not yet clear since understanding the impact on students' careers requires difficult, long-term longitudinal studies

In summary, KEEN offers a re-envisioning of engineering education around entrepreneurship broadly defined. This ties to existing threads that have been in place for a long time. It is seeking not to really pave new ground but to re-center entrepreneurial and business-aligned engineering more towards the center of the curriculum.

3. The NSF Convergence Framework

While EML is defined as a set of skills and mindsets, the definition of convergence is more vague, often focusing more on the pathways to solution of a problem rather than skills useful for an individual. Although definitions of convergent skills are not tabulated in the same way as those for EML, the authors adopted Roco et al.'s five principles of convergence [11]. These are given as:

1. *Exploiting interdependence among domains: Convergence methods associated with this principle include integrating originally distinct domains and databases of science and technology; forming efficient science and production networks and ecosystems; changing local interactions and guided self-organization in systems to encourage, enable, and reward desired outcomes and governance improvements; supporting system science and team science; and advancing S&T dedicated social networking, holistic management, and interpersonal and intrapersonal education.*
2. *Improving the convergence–divergence evolutionary cycle: Convergence methods associated with this principle include balancing support for the creative, integration, innovation, and spin-off phases of the process; supporting the cross-domain spiral of innovation; facilitating open collaboration and innovation; combining knowledge and technology pushes from the convergence stage with societal pulls from the divergence stage; and scaling up knowledge and technology diffusion in the divergence stage.*
3. *System-logic deductive decision making and problem solving: Convergence methods associated with this principle include a holistic approach to problem solving in complex systems; combining deduction with induction, lateral, and time evolution approaches in decision making; balancing bottom-up research with top-down vision; and using knowledge mapping, network visualization, and fractal analysis to identify the relevant cause-and-effect system patterns.*
4. *Creating and applying high-level cross-domain languages to facilitate transfer of knowledge and new solutions: Convergence methods associated with this principle include using universal languages such as mathematical abstractization, music, and general system architectures and focusing on essential aspects through "simplicity"; promoting technology integrators and benchmarking to facilitate introduction of emerging technologies in multiple areas; and creating and sharing large multidomain databases and trading zones between areas of research and education in distinct areas.*
5. *Using "vision-inspired" basic research to address long-term challenges: Convergence methods associated with this principle include forecasting and scenario development; promoting a culture of convergence based on common goals; anticipatory measures for preparing people, tools, organizations, and infrastructure; and reverse mapping and planning.*

Because of the differences between the specific skillsets and mindsets of EML and the broader scope of the convergence principles it was difficult to directly compare the two. Because the convergence definitions are not broken down as cleanly into educational outcomes and mindsets relevant to undergraduates, one of the authors decomposed the five principles into a set of implied mindsets and skillsets. The initial list was then cross-checked and corrected by the other authors. In some cases, we identified a mindset or skillset that would lead to the desired outcome. In other cases, we related the principle to outcomes typically addressed in undergraduate engineering programs, for example through ABET outcomes 1-7 or engineering design. This list of our interpretation of the principles, henceforth called the "convergence framework," is shown in Table 3.

Table 3: Our "Convergence Framework": an interpretation of the 5 convergence principles from an undergraduate engineering perspective.

Convergence Principle	Related Undergraduate Outcomes
Exploiting interdependence among domains	Information Literacy Discover information from others Make connections between disciplines Effectively collaborate Expertise in one's domain Explain or teach others domain knowledge Desire to connect knowledge across domains Open to new knowledge and methods Seeks to build new connections Values expertise of others
Manage balance between discovery and innovation	Implement appropriate design methodologies Have a highly tuned crap filter Support and manage one's own creativity - metacognition Manage processes of diffusion and innovation
Practice systems thinking	Apply systems methodologies in problem definition/solving Effectively communicate with multiple stakeholders Effectively represent system dynamics Intellectual humility Knowing bounds of ability to change systems
Develop new grammars and representational methods	Fluency in the terminology of multiple disciplines Create problem-specific language Ability to craft effective explanations and insights. Ability to navigate and represent large datasets
Managing change	Know and implement effective change processes Mindset of emphasizing problem over process Ability to marshal resources Ability to manage resources

4. Questions and Methodology

There are three primary questions that we set out to answer:

- First, to what extent do the skills and mindsets identified with EML map onto the general ideas of convergence?
- Second, how does the work being done in the EML space align with the broad skills identified as needed in convergence?
- Third, what are the overall differences and similarities between the KEEN EML framework and convergence?

To address the first question, the Convergence Framework of Table 3 was compared to the EML mindsets and skillsets. A table was created with EML mindsets and skillsets as columns and our Convergence Framework items as rows. For each row-column combination we rated the "connection" of the two items using a rating value of 0 to 2. Ratings of 0 reflected no connection between column and row items. A rating of 1 indicated a weak, indirect, or supportive connection between the two. A rating of 2 indicates a strong connection between the two items; one is required for the other or a vital connection. Each of the three authors conducted their own independent evaluation of the entire table. The values for each cell in the three tables were added together to get a consensus value, with the highest rating possible, 6, indicating very strong alignment and the lowest rating is zero indicating no alignment among the authors. A significant limitation of the initial approach used in this study is the small number of raters size, n=3. In future work the authors hope to expand this analysis to include a larger number of raters from a broader audience beyond the authors' institutions, which are not necessarily representative of the US engineering education system.

A portion of the consensus score table is shown in Table 4; the full table is included in Appendix B, Table 9. This portion shows one macro-level EML concept (Curiosity) compared with one convergence principle, "exploiting interdependence". In the table convergence framework elements are listed in rows and EML mindsets and skillsets are listed in columns. Larger cell values indicate a stronger connection between the row and column elements. For example, the first column and row indicate a strong connection between "Demonstrate constant curiosity about our changing world" and "Information Literacy". Two authors rated the connection between these two a "2" and one author a "1". Overall the scores of the comparison between curiosity and interdependence are high as would be expected, since being curious can be thought of as necessary for working outside one's own domain of knowledge.

Table 4 - Example section of our mapping table connecting EML and Convergence frameworks.

		Curiosity	
		Demonstrate constant curiosity about our changing world	Explore a contrarian view of accepted solution
Exploiting interdependence among domains	Information Literacy	5	2
	Discover information from others	5	3
	Make connections between disciplines	5	2
	Effectively collaborate	2	2
	Expertise in one's domain	2	1
	Explain or teach others domain knowledge	3	4
	Desire to connect knowledge across domains	4	5
	Open to new knowledge and methods	4	6
	Seeks to build new connections	4	3
	Values expertise of others	4	4

To answer the second question, we analyzed the KEEN cards from the Engineering Unleashed website [12] using data obtained from KEEN by request. The Engineering Unleashed website defines a card as "an online template for faculty and staff to share lesson plans, activities, modules, projects, and more to help you bring the entrepreneurial mindset into your own classes, courses, and campus!" In our analysis we assumed that the KEEN cards are a valid proxy for the embodiment of EML work since the cards correspond to how users are interpreting and using the EML framework and what they are actually doing to cultivate learning in this space. We assume that users accurately self-tag their submitted cards in a way that represents how the activities build student competence in these mindsets and skills. We were given access to a subset of metadata for all published KEEN cards as of January 2022, comprising a collection of approximately 1900 cards. The various cards, skillset/mindset tags, and disciplines were analyzed using a custom Python program. The analysis for this paper relied on the card author-provided tag (skillset and mindset) information and focused on the frequency of tag use. We assume that more frequent use roughly corresponds with greater importance to the EML community and more frequent learning opportunities in classes. We note that because tagging is done by card authors without any form of external review there are limitations to this method.

To address the third question, we looked broadly across the results comparing the KEEN EML and our Convergence Framework and qualitatively analyzed the tags to identify areas of similarity and difference. This analysis was intended to identify underlying patterns or assumptions which might explain the more quantitative comparisons.

5. Mapping Between EML and Convergence

Overall, we found that EML aligns with, at least to some level, all aspects of convergence. Table 5 shows results for an aggregated analysis. Each value in this table shows the average value for all of the cells in this section of the larger table. For example, the top left cell matches the average of cells shown in Table 4. Given the uncertainties inherent in our approach at this high level we somewhat arbitrarily indicated strong alignment with scores of 2.5 or above, medium alignment to scores of 1.5 to 2.5, and weak alignment to scores of less than 1.5. Table 5 shows that there is a strong connection between the *curiosity*, *connections*, and *opportunity* aspects of EML and the transdisciplinarity of convergence. Additionally, there is a strong connection between the *connections* aspects of EML and the *systems thinking* aspects of the convergence; *design* in EML is almost a strong connection. In both of these cases a fairly strong common-sense argument emerges since *interdependence* would require students to be curious about other domains, make connections between them, and identify opportunities in the inter-domain space. Similarly, *systems thinking* requires making connections and this is a necessary skill in the divergent phase of design projects [13].

There are also areas in the mapping where there is a lack of alignment; for example, between the *impact* aspect of EML and most of the elements of the Convergence Framework. Given that the focus of convergent work is on addressing societally relevant problems, achieving *impact* seems related. This will be discussed subsequently when the third question is addressed.

Table 5: Aggregate mapping results of parent EML and Convergence frameworks (higher numbers mean a higher connection).

	Curiosity	Connections	Creating Value	Design	Opportunity	Impact
Exploiting interdependence among domains	3.50	2.55	1.80	1.55	2.63	1.82
Manage balance between discovery and innovation	1.88	2.13	1.88	1.63	1.33	0.96
Practice systems thinking	2.20	3.00	2.00	2.44	1.48	1.52
Develop new grammars and representational methods	1.75	1.75	0.88	1.83	1.38	1.21
Managing change	0.88	1.88	2.13	0.79	1.13	0.67

Based on this high-level analysis we see that EML conceptually does map onto areas of our Convergence Framework with some of the five principles significantly addressed through EML while others are addressed less so, but addressed nonetheless. What isn’t conveyed through our data is any sense of importance of the different parts of either framework; that is, are some of the aspects identified more useful or valued either in practice or by faculty who are responsible for designing and implementing curricula? To address these questions, we look into how faculty in the KEEN network are tagging the cards they submit as a proxy for what is valued and thus actually being taught.

As participants in the KEEN network submit cards they have the option to tag each KEEN Card with one or more engineering disciplines, EM skillsets, and EM mindsets; we generally refer to these attributes as "tags". The total list of available tags is found in Appendix A in Tables 7 and 8. There were 1911 KEEN cards with each card, on average, tagging 8.4 disciplines, 4.7 skillsets, and 3.2 mindsets. Note that to our knowledge there are no guidelines on tagging rules or policies that are shared across the KEEN network so that authors are free to add any number of tags. We assume, however, that with almost 2000 cards the dataset does accurately reflect, within some bounds of error, what KEEN faculty teach and, to second order, what they value.

Examining the tags for disciplines, all engineering-related disciplines were tagged on at least 25% of the cards with General Engineering and Mechanical Engineering being the most common tags, appearing on 52% and 49% of cards, respectively. With the average card tagging over eight disciplines, the conclusion is that many KEEN cards are independent of discipline to a large degree and thus focus on transferable skills. In terms of skillsets, card authors averaged almost five per card with *Identify Opportunity* and *Analyze Solutions* being the most popular tags represented on 52% and 48% of cards respectively. The least common tags were *Protect Intellectual Property* and *Identify Supply Chains and Distribution Methods* only tagged on 7% and 6% percent of cards, respectively. Finally, looking at mindset tags, all tags were represented in the cards with *Integrate information from many sources to gain insight* and *Demonstrate constant curiosity about our changing world* most commonly appearing on 80% and 74% of cards, respectively. *Explore a contrarian view of an accepted solution* and *Assess and manage risk* were least common, being found on only 32% and 30% of cards, respectively.

Overall, while some tags appeared more frequently than others, all skillset and mindset tags were sufficiently represented in the dataset so as to be used in our analysis.

6. Comparing the EML/Convergence Mapping and Distribution of KEEN Cards

Our earlier analysis of the mapping between EML and our Convergence Framework only shows that we see connections between the different frameworks. Further analysis is needed to determine how well work in EML can cover convergence in practice. We explored this by doing further analysis of the KEEN cards.

Although on detailed datasets like these it is easy to make comparisons and get far down in the weeds, such analyses are more informative if higher-level conclusions can be drawn. By eliminating the disciplinary tags there were 24 EML tags and 27 convergence tags that were used in this analysis. Looking across these two sets one difference that became clear was the EML tags generally focused on skills that were possessed by a student, that is the focus was on creating qualified individuals. While it is not possible to extract the reason for this emphasis from the dataset we had access to there we drew two hypotheses. First, since EML is targeted at undergraduate engineering students the tags may be designed to be read like student outcomes. Outcomes-based education has gained wide popularity in the last decades with ABET being one of the early adopters. It may be that thinking in terms of individual student outcomes has influenced engineering education culture to the extent that those who work in this space adopt the language and goals-focus inherent to outcomes-based education. Second, the KEEN program's focus on entrepreneurship has a distinctly neoliberal character. While what neoliberalism is at its core is hotly debated, there is a thread of individualism that runs throughout this diffuse set of thoughts and policies that set it apart from other systems of political thought that focus more on collectivism and the structural aspects of society. Thus, the focus on the individual may arise, in part, from the values upon which the KEEN program is built.

To look more broadly at the dataset, we also asked how does the popularity of the 24 EML tags (i.e. how often a term is used to tag a card) compare with the overall mapping to the 27 NSF convergence tags. The complete comparison between the use of KEEN tags on the x axis and mapping score (from 0 to 6) representing the level of alignment of our Convergence Framework with the KEEN tags on the y axis is included in Appendix B, Figure 9. As can be seen there is a positive correlation between the popularity of tags on the x-axis (that is how often they are used) with the mapping score on the y-axis. The correlation of $\rho = 0.60$ is reasonably high and is statistically significant ($p < 0.005$), however significance doesn't necessarily imply the correlation has any meaning.

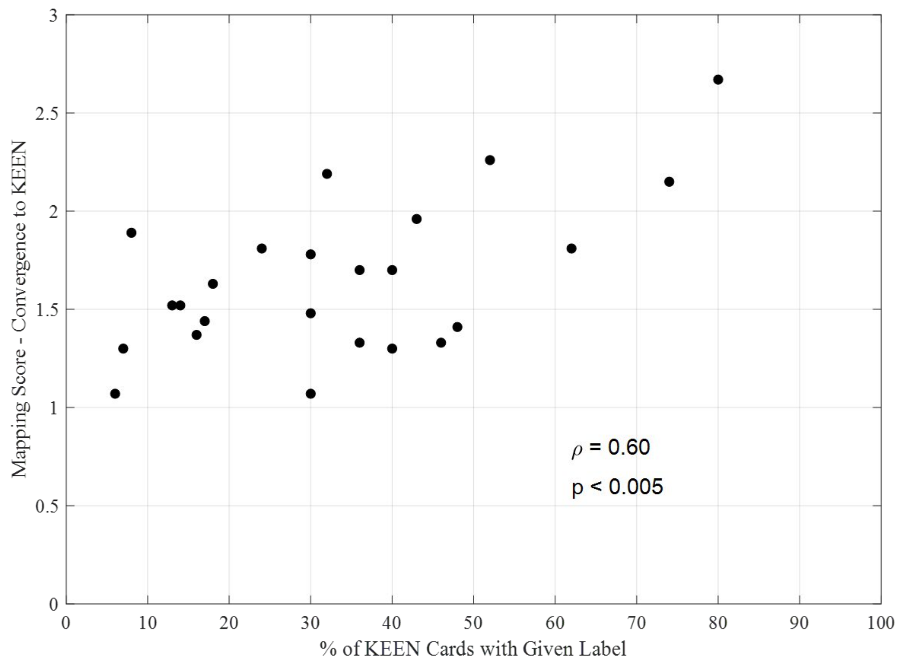

Figure 2: Mapping score vs. Frequency of Tag Use

From the point of view of alignment of KEEN's EML framework to our Convergence Framework goals in a large sense the positive correlation could mean that the more a KEEN skillset/mindset is related to convergence the more likely it is to be used to tag an activity. That is faculty use tags that better align with both frameworks. Given that universities have both research and teaching missions and the extent to which external funding influences the research activities at universities this is not a surprise. Alternatively, the relation for overlap score between the two frameworks and the popularity of tags could arise from the fact that some tags are simply more helpful or actionable—or alternatively less specific—than others regardless of how they are used. In this case the positive correlation arises simply due to the fact some KEEN tags are more descriptive or evince more meaning to faculty than others and thus are more likely to be used regardless of the specific application. For example, the tag *Identify Supply Chains & Distribution Methods* is used infrequently on cards so it may not be as descriptive, or in this case is much more specific, than the more popular tag *Analyze Solutions*. The positive correlation is likely due to both factors: first, it is easier to apply tags with broader meanings and second, the types of activities valued in universities likely align more with convergence so faculty are more likely to engage in such activities. Overall the authors see this relationship as a positive sign that the types of activities supported by KEEN and those promoted by convergence efforts do have synergy.

7. Concluding Remarks

The motivation for this paper was to determine if the existing work around EML could be used to help prepare students to approach and address large, complex convergent problems. Our analysis using the KEEN cards and Roco's five principles of convergence suggests that work focused on EML may help prepare students to address some aspects of convergent problems. The EML focus on *curiosity*, *connections*, and *design* strongly align with many of the goals of convergence work. Additionally, it could be argued that the collective set of work being done in EML covers a great deal of the elements of convergence based on our interpretation.

While there are several conclusions that can be tentatively drawn from this preliminary study the conclusions are not as robust as the authors would like because of some of the assumptions needed to undertake a first look at the overlap of convergence and EML as well as areas of this study that need further exploration. One conclusion is that EML's focus on the individual does not align with the team-based and transdisciplinary nature of convergence. Convergent work is almost always discussed in the context of a team and the EML framework has very limited discussion of teamwork. That a team is necessary in convergence is because a variety of expertise is necessary but also multiple aspects of diversity, including a variety of experience, is needed. Thus it is not possible for a single person to bring all of this to a problem. The NSF believes this is necessary and indicates that traditional preparation is insufficient by including Team Science training for all CA and GCR awardees. While most KEEN affiliated programs would clearly not claim that teamwork is unimportant, understanding the role of teamwork in EML was not clear from the material examined.

Second, selection of the problem–that is whether or not a problem being worked on is actually convergent–is not well addressed in the convergence framework. It is assumed that the rationale for the problem and the impact of the problem are appropriately chosen, but criteria for that selection are not clear from the literature reviewed. This lack of clarity in turn suggests that efforts to better define convergent problems and a set of methods to determine if a problem should be marked convergent or not may be valuable.

Finally there are many competing priorities for educational institutions, and limited resources for the long and difficult work of lasting change. The goal of this work was to broadly examine the overlap of two programs designed to support change- KEEN's entrepreneurial minded learning and NSF's convergence. While we identified areas of overlap our methodology of mapping and card analysis are limited. Greater participation from a diverse range of institutions needed to understand how EML and convergence are connected. Furthermore our card analysis assumes that each card author appropriately tags their respective card, and a logical next step in this work is to conduct an evaluation of how "correctly" cards are tagged. A first step in this analysis would be to create more specific definitions of each tag. The current level of vagueness allows space for interpretation but it complicates in depth analysis.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. ERC-2022271. The opinions, findings, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the view of the National Science Foundation. We would like to thank Michael Johnson of the KERN Family Foundation for his help getting us access to the KEEN card information.

References

[1] "Characteristics of Convergence Projects | NSF - National Science Foundation." https://www.nsf.gov/od/oia/convergence/characteristics.jsp (accessed Feb. 13, 2022).
[2] "Studies of Convergence | NSF - National Science Foundation." https://www.nsf.gov/od/oia/convergence/reports.jsp (accessed Feb. 13, 2022).
[3] "Convergence Accelerator | Beta site for NSF - National Science Foundation." https://beta.nsf.gov/funding/initiatives/convergence-accelerator (accessed Feb. 13, 2022).
[4] "NSF Growing Convergence Research | NSF – National Science Foundation." https://www.nsf.gov/od/oia/growing-convergence-research/index.jsp (accessed Feb. 13, 2022).
[5] M. Roco, W. S. Bainbridge, B. Tonn, and G. Whitesides, "CONVERGENCE OF KNOWLEDGE, TECHNOLOGY, AND SOCIETY: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies Editors Mihail," 2013. [Online]. Available: http://www.wilsoncenter.org/convergence.
[6] "What is KEEN? | Engineering Unleashed." https://engineeringunleashed.com/what-is-keen (accessed Feb. 13, 2022).
[7] J. S. Murday, "Global Perspectives in Convergence Education (November 2-3, 2017, Washington, D.C." Accessed: May 13, 2021. [Online]. Available: www.nsf.gov/nano/ConvergenceEducation
[8] A. Duckworth, *Grit:The Power of Passion and Perseverance*. Scribner, 2018.
[9] "The Handbook for EML." https://engineeringunleashed.com/keenzine5/ (accessed Feb. 13, 2022).
[10] S. Christiensen, B. Delahousse, C. Didier, M. Meganck, and M. Murphy, *The Engineering-Business Nexus : Symbiosis, Tension and Co-Evolution*. Springer, 2018.
[11] M. C. Roco, *Handbook of Convergence in Science and Technology*. Springer, 2016.
[12] "Cards | Engineering Unleashed." https://engineeringunleashed.com/card (accessed Feb. 13, 2022).
[13] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, "Engineering Design Thinking, Teaching, and Learning," *Journal of Engineering Education*, vol. 94, no. 1, pp. 103–120, Jan. 2005, doi: https://doi.org/10.1002/j.2168-9830.2005.tb00832.x.

Appendix A

Table 6: Number of disciplines tagged overall and as a percentage of KEEN cards

Discipline	Tags	Percentage of Cards with Tag
General Engineering	995	52%
Mechanical Engineering	937	49%
Electrical & Computer Engineering	763	40%
Biomedical Engineering	759	40%
Engineering Education	720	38%
Civil Engineering	707	37%
Aerospace Engineering	644	34%
Computer Science	639	33%
Chemical Engineering	637	33%
Environmental Engineering	623	33%
Industrial & Manufacturing Engineering	607	32%
Engineering Science/Physics	586	31%
Metallurgical & Materials Engineering	553	29%
Engineering Management	546	29%
Arts & Sciences	490	26%
Architectural Engineering	489	26%
Technical Communications	482	25%
Agricultural Engineering	478	25%
Health Sciences & Medical	476	25%
Petroleum Engineering	456	24%
Nuclear Engineering	451	24%
Business Economics & Law	447	23%
Mining Engineering	446	23%
Physics	445	23%
Chemistry	444	23%
Mathematics	437	23%
Engineering Technology	270	14%
Entrepreneurship	241	13%
Optics	124	6%
Comprehensive	97	5%
Biomolecular Engineering	72	4%
Biology	51	3%

Table 7: Number of engineering skillsets tagged overall and as a percentage of KEEN cards

Skillsets	Cards With Tag	Percentage of Cards With Tag
Identify Opportunity	994	52%
Analyze Solutions	910	48%
Determine Design Requirements	829	43%
Communicate Societal Benefits	762	40%
Evaluate Tech Feasibility Customer Value Societal Benefits & Economic Viability	758	40%
Develop Partnerships & Build Team	696	36%
Create Model or Prototype	694	36%
Perform Technical Design	571	30%
Communicate Solution in Economic Terms	568	30%
Investigate Market	454	24%
Develop New Technologies	341	18%
Test Concepts via Customer Engagement	325	17%
Validate Functions	301	16%
Assess Policy & Regulatory Issues	267	14%
Validate Market Interest	248	13%
Create Preliminary Business Model	162	8%
Protect Intellectual Property	127	7%
Identify Supply Chains & Distribution Methods	116	6%

Table 8: Number of engineering mindsets tagged overall and as a percentage of KEEN cards

Mindset	Cards With Tag	Percentage of Cards With Tag
Identify unexpected opportunities to create extraordinary value	1181	62%
Demonstrate constant curiosity about our changing world	1413	74%
Persist through and learn from failure	879	46%
Integrate information from many sources to gain insight	1520	80%
Explore a contrarian view of accepted solution	613	32%
Assess and manage risk	568	30%

Appendix B -- Table 9 Complete comparison of KEEN EML skill and mindset tags to skills drawn from NSF convergence framework

		Curio-sity		Connec-tions		Creating Value		Design						Opportunity						Impact					
		Demonstrate constant curiosity about our changing world	Explore a contrarian view of accepted solution	Integrate information from many sources to gain insight	Assess and manage risk	Identify unexpected opportunities to create extraordinary value	Persist through and learn from failure	Determine Design Requirements	Develop New Technologies	Perform Technical Design	Create Model or Prototype	Analyze Solutions	Validate Functions	Identify opportunity	Evaluate feasibility, value, societal benefits, and economic viability	Investigate market	Test concepts via customer engagement	Create preliminary business model	Assess policy and regulatory issues	Communicate solution in economic terms	Develop partnerships and build team	Communicate societal benefits	Identify supply chains and distribution methods	Validate market interest	Protect intellectual property
Exploiting interdependence among domains	Information Literacy	5	2	5	0	0	0	2	0	2	0	1	0	2	4	5	1	3	4	1	0	1	2	4	4
	Discover information from others	5	3	5	0	4	0	1	2	0	0	1	1	4	3	4	2	3	4	1	3	3	2	3	0
	Make connections between disciplines	5	2	5	1	4	0	3	2	0	1	1	0	5	1	1	2	3	3	2	4	1	1	2	0
	Effectively collaborate	2	2	3	2	3	1	0	2	3	3	0	0	4	1	1	2	2	0	1	5	1	1	2	1
	Expertise in one's domain	2	1	4	0	0	0	5	5	5	4	5	5	4	3	1	1	2	2	1	0	2	2	2	5
	Explain or teach others domain knowledge	3	4	3	0	1	0	1	2	2	2	2	2	3	2	1	1	1	1	2	2	2	0	1	1
	Desire to connect knowledge across domains	4	5	6	1	2	2	1	1	0	0	1	2	3	1	2	1	2	3	2	4	2	1	1	1
	Open to new knowledge and methods	4	6	3	1	4	2	1	1	1	2	2	2	5	2	3	3	4	0	1	4	2	0	1	2
	Seeks to build new connections	4	3	4	1	5	1	1	2	0	0	0	0	5	3	4	4	4	1	0	5	0	3	2	1
	Values expertise of others	4	4	4	3	5	2	3	2	2	2	2	0	4	2	4	4	4	4	1	5	0	1	3	2
Manage balance between discovery and innovation	Implement appropriate design methodologies	0	2	1	4	1	2	5	3	5	4	2	4	1	2	0	2	0	1	0	0	2	2	0	2
	Have a highly tuned crap filter	1	4	3	2	2	0	2	1	1	0	1	3	1	3	3	2	2	0	1	0	1	0	1	1
	Support and manage one's own creativity	2	2	3	0	2	3	1	2	3	0	0	0	4	1	2	1	0	0	1	0	1	0	1	2
	Manage processes of diffusion and innovation	2	2	2	2	3	2	0	2	0	0	0	0	0	2	2	0	3	0	1	0	2	2	1	2
Practice systems thinking	Apply systems methodologies	0	2	0	3	0	0	5	3	4	2	5	4	2	1	1	1	2	2	2	0	2	2	1	1
	Effectively communicate with multiple stakeholders	0	1	1	1	2	0	5	2	2	2	2	3	3	2	2	2	2	2	2	3	2	1	4	2
	Effectively represent system dynamics	1	0	0	2	0	0	4	0	4	4	3	3	0	1	1	1	2	1	1	0	2	2	3	1
	Intellectual humility	3	2	3	1	0	4	0	0	0	0	0	0	1	0	0	2	0	0	0	1	2	0	0	0
	Knowing bounds of ability to change systems	1	1	1	3	1	3	3	1	0	0	0	0	1	2	1	0	1	1	1	0	1	0	1	1
Develop new grammars and representational methods	Fluency in the terminology of multiple disciplines	3	5	6	1	1	0	3	2	2	3	2	2	2	3	3	2	2	4	3	1	2	1	2	2
	Create problem-specific language	1	0	2	0	1	1	4	4	4	3	4	2	1	0	0	0	0	1	0	1	0	0	0	1
	Ability to craft effective explanations and insights.	3	2	2	0	1	1	0	1	1	0	2	3	1	2	2	2	2	2	2	3	2	0	2	1
	Ability to navigate and represent large datasets	0	0	2	1	2	0	0	1	0	0	0	1	0	1	1	0	0	2	1	0	1	1	2	1
Managing change	Know and implement effective change processes	0	1	2	1	3	3	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0
	Mindset of emphasizing problem over process	3	3	2	2	0	1	2	1	1	0	2	0	4	2	2	2	0	0	0	1	1	0	0	0
	Ability to marshall resources	0	0	0	4	1	4	0	1	3	2	0	0	0	2	2	1	3	1	1	2	0	3	0	1
	Ability to manage resources	0	0	0	4	1	4	1	1	3	2	0	0	0	0	1	0	3	2	1	1	0	2	1	0