Creation of a Framework that Integrates Technical Innovation and Learning in Engineering

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***Abstract*—This full research paper presents the development of the Innovation-Based Learning (IBL) Framework, the first framework to integrate innovation and learning within engineering classrooms. Engineering programs across the world are looking for ways to develop innovative engineering students. Work has been done in engineering education to develop qualitative frameworks and best practices for teaching, but these frameworks and practices do not align with many of the complexities of teaching innovation. Both the engineering education and research community could benefit from the creation of a framework that integrates technical innovation and learning in engineering because it would help drive development of best practices in teaching engineering innovation and lead to stronger research in this area. This work details the development of such a framework by using data from an Innovation-Based Learning course and the alternate templates strategy. The framework is simple enough that it includes only seven categories, generalizable enough that it can fit multiple students from multiple groups working on multiple projects, and accurate enough that there is sufficient interrater reliability. The final product is a framework that focuses on the divergent and convergent behaviors of innovation and learning. The IBL Framework has implications for both instructors teaching innovation and researchers studying innovation in educational settings. The framework gives instructors and students a unifying vocabulary about the process of learning innovation, and it allows researchers to sort student actions into illustrative categories. Ultimately, the framework can lead to unifying best practices when teaching and researching innovation in classroom settings.**

***Index Terms*—innovation, experiential learning, qualitative frameworks**

I. Introduction

The process of learning and the process of innovation are both highly complex, leading to challenges in understanding and researching how engineering students approach the innovation process. One of these challenges is a lack of a unifying framework that captures these complexities rather than simplifying them. If student behaviors can be grouped into the explanatory categories of a framework, the interactions and transitions between categories can be captured and compared to illustrate nonlinear and dynamic relationships. Therefore, the purpose of this study is to create a framework that integrates both the process of innovation and the process of learning in educational settings.

To create the framework, data from 2 cohorts of students in an Innovation-Based Learning (IBL) course were analyzed. IBL is an instructional model where students learn discipline-specific knowledge and demonstrate their learning by applying it to an innovation [1], [2]. Students in these two cohorts learned the fundamentals of cardiovascular engineering and applied them to innovation projects with the goal of creating value (whether that be for the scientific research community or for society). Throughout the semester, students progress from problem identification all the way to sharing their solutions with a broader audience. As they work through the course, they log their progress in an online platform, and the system keeps track of any additions, edits, or deletions [3]. This provides an illustrative process log for each student, and these logs can be used to find emerging themes across students, projects, and cohorts.

Using the alternate templates strategy, the IBL data was compared to existing models in five areas of literature: learning taxonomies, complex problem solving, self-regulated learning, the engineering design process, and diverging and converging behaviors. Although many of these models helped inspire the final framework that was created, no single model fully illustrates the interactions occurring as students are both learning course content and creating an innovation.

The final product is a model that integrates the learning process (e.g. surveying the problem, exploring the solution space, and drafting a message) and the innovation process (e.g. identifying a gap, solving a problem, and sharing the final impact). The model is general enough that it can represent the process of multiple students working on multiple projects, and it is simple enough that it can categorize student actions into seven components. The IBL framework benefits researchers by providing a qualitative coding scheme to categorize student actions and compare them at the event- and system-level. It also benefits instructors by giving them a unifying vocabulary, helping them better frame the innovation process for their students in an education-specific context.

II. Background

A. The Need for Innovators

The World Economic Forum published its most recent Future of Jobs report that explored what skills will be most important in the workplace in the year 2025. The most valuable skills included creativity, critical thinking, and complex problem solving, and the number one spot went to analytical thinking and innovation [4]. Similarly, the National Academy for Engineering [5], ABET [6], and hundreds of engineers in industry [7] have agreed that innovation is one of the most important skills that engineering students should be developing. As our society rapidly changes and has new societal, environmental, and technical challenges, the need increases for engineers who are able to integrate ideas to create innovations. Many leaders in engineering education are working towards finding new and creative strategies for teaching and learning innovation, but a remaining challenge is delivering these opportunities at scale [8]. This scaling up will require the development of best practices in teaching and researching innovation in classroom settings.

B. The Need for Qualitative Frameworks

Although there is no existing framework that integrates innovation and learning in the engineering classroom, there are other existing qualitative frameworks that strengthen both teaching and research. In education, learning frameworks can help instructors develop course goals, outcomes, and assessments. They also can give learners a unifying vocabulary and a way to practice metacognition and reflect on their own learning process. In research, frameworks can bridge the gap between illustrative qualitative work and objective quantitative work. This mixed methods approach can address the complexities of learning and individual students while still providing reliable measurements across groups and over time [9].

Previous work to explore innovation in engineering classrooms could also benefit from such a framework. Studies have been done using learning analytics to explore what differentiates successful students in the IBL model, but this work was not able to compare students at the system or process level [10]. With a unifying framework, students could be compared at specific stages of the innovation and learning processes. This could lead to earlier and more specific interventions for struggling students.

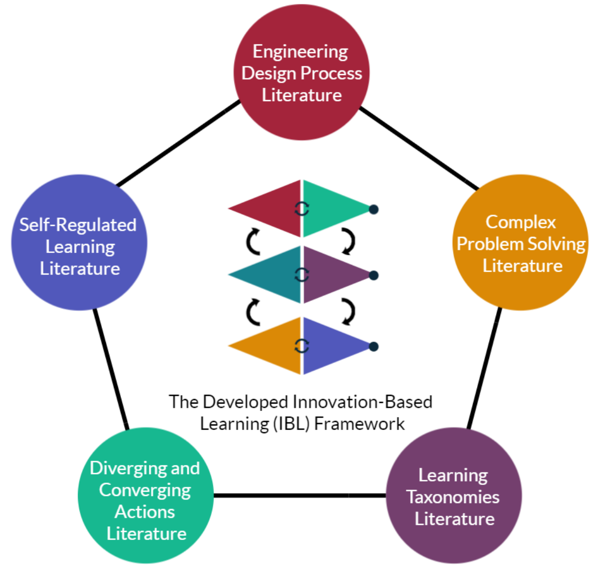

Fig. 1. In order to develop the Innovation-Based Learning framework, five areas of literature were explored. Existing frameworks from each of these areas were applied to the data in order to determine strengths and weaknesses, and these five areas were combined to create the final framework.

Creating and implementing a qualitative framework can complement learning analytics and educational data mining techniques by combining the benefits of each. The qualitative framework allows the researchers to keep the richness of their data without having to oversimplify it, and using the educational data mining and learning analytics techniques allows for scalability, consistency, and speed. Instructors and students can get feedback in real time without having to rely solely on simplistic quantitative measures [9].

C. Existing Templates

In order to create a framework that integrates innovation and learning, five areas of literature were explored: learning taxonomies, complex problem solving, self-regulated learning, the engineering design process, and divergent and convergent actions. Figure 1 illustrates each of these areas of literature coming together to create the final framework. Each of these areas has its own frameworks that group actions into categories. Information about existing frameworks in each of these areas is presented below. In addition, studies that have successfully used these frameworks are also presented, illustrating how qualitative frameworks can transform complex data into illustrative and meaningful results.

1) Learning Taxonomies: Learning taxonomies are frameworks created to scaffold various actions and behaviors in the learning process [11]. The most commonly known learning taxonomy is Bloom's Taxonomy, but other taxonomies include Webb's Depth of Knowledge, the Structure of Observed

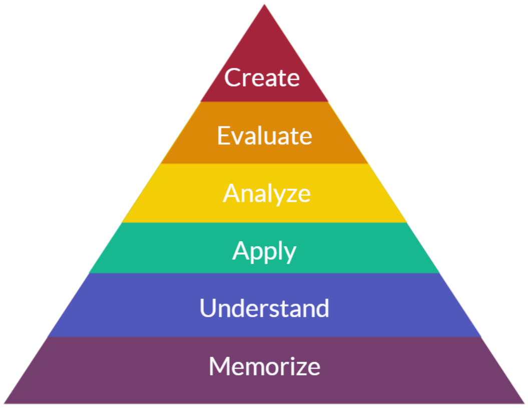

Fig. 2. Bloom's Revised Taxonomy from [12]

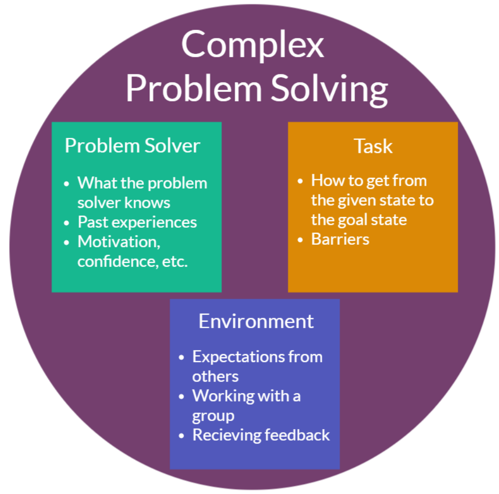

Fig. 3. Framework for complex problem solving from [16]

Learning Outcomes (SOLO) taxonomy, Fink's taxonomy, and a handful of variations of Bloom's Taxonomy (e.g. Bloom's Revised Taxonomy shown in Figure 2). The stages of each taxonomy vary, but most are presented as a hierarchy; lower level learning builds to higher level learning.

Learning taxonomies are helpful frameworks because they can be used to help instructors build course materials that are well scaffolded and assessments that properly align. For example, questions from exams in both Electronics [13] and Computer Science [14] were mapped to Bloom's Taxonomy in order to better understand what level of learning the exams were assessing. This research can help instructors develop more appropriate assessments based off of course goals.

Mapping student actions to learning taxonomies can also be done at a much larger scale by using learning analytics tools that use machine learning on educational data. For example, the Cognitive Operation Framework for Analytics (COPA) automatically maps the language used in course learning objectives, assessments, etc. to the various stages of Bloom's Revised Taxonomy. The results can then be shared with instructors in order to help them ensure that their goals, outcomes, and assessments are well aligned [15].

2) Complex Problem Solving: Although there are many definitions of complex problem solving, a general definition is the ability to overcome barriers between a given state and a goal state. The problem is considered complex because these barriers are usually unfamiliar to the problem solver and changing over time [16]. In order to better understand how problem solvers approach complex tasks, researchers have created a theoretical framework (Figure 3) to illustrate the components of complex problem solving. Not only does it include the task itself, but also the problem solver and the environment. The problem solver component considers prior knowledge, experience, and affect; the environment component considers any group interactions, feedback, or expectations from others [16]. Therefore, various studies in complex problem solving have focused not only on the completion of a task, but also the background of the problem solver, affect, and the environment [17], [18]. The use of this framework strengthens work in this area by encouraging the consideration of variables in all areas.

3) Self-Regulated Learning: Self-regulated learning is the act of monitoring and directing one's learning, including strategies, information, and self [19]. Multiple frameworks for self-regulated learning exist (see [20]), each with its own empirical evidence to support it. One of the most common frameworks for self-regulated learning consists of three components: forethought, performance, and self-regulation (shown in Figure 4). Forethought consists of planning out how the learner will approach the problem or take in information, performance consists of actually completing the task and maintaining focus and motivation, and self-regulation consists of reflecting on what was learned and assessing how well the task was completed and what strategies were successful [21].

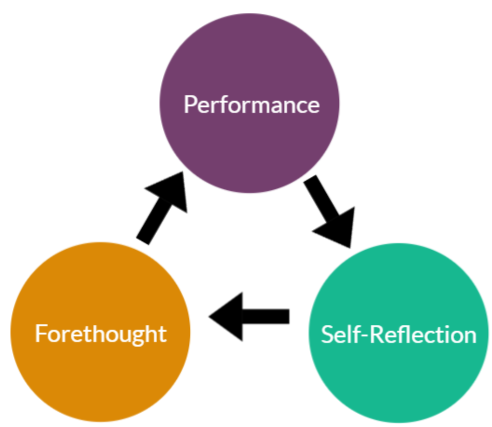

Fig. 4. Cyclical framework for self-regulated learning from [21]

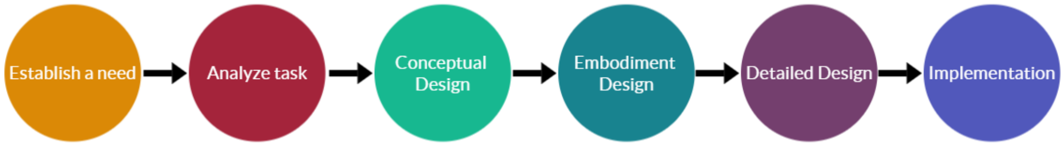

Fig. 5. One example of the engineering design process from [22]

By mapping student actions to the stages of self-regulated learning, information can be gained about how students guide and support their own learning. For example, this model has been used to explore how engineering students monitor behavior in design tasks in a 3D design and simulation platform by mapping clickstream data to the stages of the self-regulated learning framework. The clickstream data on its own is lacking the context needed to understand how students monitor their learning, but when context is introduced through the self-regulated learning homework, algorithms were then able to cluster students into illustrative categories: reflective-oriented, adaptive, and minimally self-regulated learners [23].

4) Engineering Design Process: The engineering design process has dozens of variations, but all consist of actions related to solving a problem. Although each of the variations has different names and stages, many consist of similar over-arching categories. One review found 23 different versions of the engineering design process and created six stages that best represent all models: establishing a need, analysis of task (which focuses on the function of the innovation), conceptual design (which focuses on the behavior of the innovation), embodiment design (which focuses on the structure of the innovation), detailed design, and implementation [22]. These steps are shown in Figure 5.

The engineering design process is a valuable framework for both assessment and research purposes. For assessment, understanding and applying the stages of the engineering design process has been a proposed metric when evaluating the quality of K-12 engineering education activities [24]. For research, the engineering design process has been used as a framework for a variety of learning analytics studies. The researchers map student actions (often from clickstream data) to the various stages of their chosen version of the engineering design process. Because there are countless combinations of clicks in these virtual environments, a qualitative framework allows researchers to simplify their data without losing the ability to illustrate student behavior. For example, [25] looks at clickstream data in a 3D design and simulation platform and maps strings of actions to stages of the engineering design process (e.g. adding a wall maps to the construction phase, and running an energy test maps to the testing phase). Similarly, [26] uses the same platform to explore how students conduct experiments when doing an engineering design task in a 3D design and simulation platform. By mapping the clickstream data to stages of the engineering design process, usable quantitative features are created that can be used as inputs for classification, clustering, sequence analysis, or other machine learning tasks.

5) Diverging and Converging Behaviors: The final area of literature is divergent and convergent behaviors. Divergent behaviors involve exploring multiple ideas, whereas convergent behaviors involve honing in on a specific problem or solution. Divergent and convergent behaviors appear in a variety of contexts. For example, one offshoot of the engineering design process, the Double Diamond Model for Design (shown in Figure 6) consists of two diamonds, both made up of a diverging action and a converging action. In order to create a solution, first a problem must be discovered and defined; then a solution must be developed and delivered. Discover and develop are considered diverging activities, meaning different options are being explored. Define and deliver are considered converging activities, meaning solutions are being chosen.

Similarly, one group that studies innovation in industry settings maps innovation as a cycle of divergent behavior, constraining factors, convergent behavior, and enabling factors. Ideas may arise which leads to divergent behavior (e.g. learning new things, building relationships, trying out new ideas) that then leads to constraining factors (i.e. realizing that there are obstacles that eliminate some of the options). This causes a need to shift to convergent behavior (e.g. conducting tests, narrowing ideas, and implementing specific strategies). These convergent behaviors can lead to enabling factors that lead to new ideas, cycling back to divergent behaviors. This model is called the Cycle of Divergent and Convergent Behavior in Innovation, and it is depicted in Figure 7 [27]. The creation of this framework for innovation allows the researchers to categorize their qualitative observations, leading to data that can then be analyzed quantitatively to better understand how

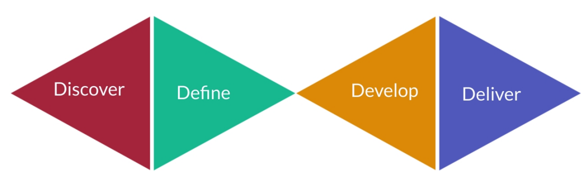

Fig. 6. The Double Diamond for Engineering Design

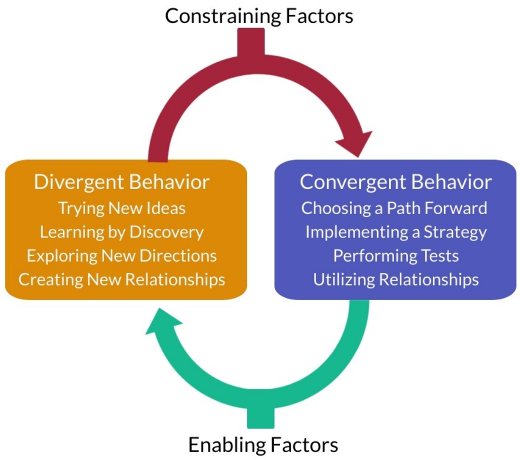

Fig. 7. The Cycle of Divergent and Convergent Behavior in Innovation from [27]

companies approach the innovation process. As seen in the other literature areas, the use of the qualitative framework translates complex data into features that can be analyzed and interpreted without losing its illustrative components, showing the need for development of strong frameworks.

III. Methods

A. Collection of Data

In order to assess how well each of the areas of literature illustrates how students innovate and learn in the engineering classroom, an illustrative dataset was needed. The data was collected in an upper level cardiovascular engineering course taught using Innovation-Based Learning. Students in the course learn the fundamentals of cardiovascular engineering and are assessed on their ability to apply those fundamentals to an innovation project. Students must identify an existing gap (either research or market), develop a solution, and create impact outside of the classroom (e.g. publishing a research paper, submitting an invention disclosure). Students keep track of their progress in a custom learning management system by logging tokens of learning. Each token has a title, description, and linked evidence. Anytime a student adds, edits, or deletes a token, a log file for that student is updated. The developed framework was designed so actions can be categorized at the token level. The dataset for this analysis was made up of students from two cohorts in the course and consisted of over 2000 tokens.

B. Alternate Templates Strategy

In order to identify an appropriate model for the data, the alternate templates strategy was used, which is common in qualitative research dealing with complex process data [28]. Alternate templates strategy consists of qualitatively reviewing the data and the literature, finding and/or creating appropriate models, assessing how well that model fits the data, and continuing to reiterate that process until a final framework is selected. Each of the five areas of literature mentioned in the background were explored: learning taxonomies, complex problem solving, self-regulated learning, engineering design process, and converging and diverging actions.The ways that each of these models do and do not fit the data are presented in the *Results* section.

C. Assessment of the Framework

A qualitative framework should balance simplicity, generalizability, and accuracy [28]. In order to assess the framework, the research team balanced the number of categories, how well it fit all students from both cohorts, and how well the data fit the framework. To quantitatively assess how well the framework fits the data at the token level, interrater reliability was measured. Two members of the instructional team categorized each token. Cohen's Kappa was then calculated to assess for interrater reliability. A confusion matrix was then created to determine where discrepancies were occurring. These discrepancies were then analyzed and grouped into categories to further refine the categories and make recommendations for future token creation.

IV. Results

In order to create the final framework, each of the existing areas of literature were explored. An explanation of how well each of these frameworks fit the data is presented, leading up to a description of the final iteration of the developed framework. Finally, interrater reliability is calculated, and discrepancies are explored.

A. Comparing Types of Models

1) Learning Taxonomies: Learning taxonomies can be a great introduction to what behaviors are incentivized in IBL because the taxonomies illustrate the difference between lower level learning (e.g. memorization and understanding) and higher level learning (e.g. analysis and synthesis). However, the hierarchical structure of most learning taxonomies does not lend itself well to our data. When trying to explain student learning in the context of any of the learning taxonomies, the taxonomies fail in being able to explain the nonlinear pathways that students take. For example, Bloom's taxonomy (which is commonly used in engineering fields to measure ABET requirements [29]) is set up in a way that suggests you are constantly moving up the pyramid from lower level learning to higher level learning. This hierarchy fails to illustrate that students who are creating and innovating must often return to the lower levels of the pyramid when ideas or prototypes do not work. This does not mean that students did not meet the objectives of the lower levels and were ill prepared to tackle the higher levels; it is simply part of the process.

2) Complex Problem Solving: Complex problem solving frameworks align nicely with the course because they include information about the problem solver, the task, and the environment – all of which play a role in both innovation and learning. In the IBL data, many tokens are related to the student being part of the class and of the group. Hence, the final IBL framework will include an "environment" category as inspired by the literature on complex problem solving. However, complex problem solving assumes that the problem has already been stated, so it does not account for the problem identification tasks that students complete in IBL.

3) Self-Regulated Learning: Students in the course clearly participate in self-regulated learning processes during the semester. Creating tokens aligns with forethought, completing tokens aligns with performance, and updating tokens aligns with self-reflection. However, the actions being defined by each token do not map to the categories in self-regulated learning frameworks. In addition, these frameworks fail to address the outcomes of the innovation and learning processes.

4) Engineering Design Process: Variations of the Engineering Design Process illustrate many of the actions that students are completing during IBL, but it misses out on the learning component. For example, it assumes that students know how to choose the best option and design it. In addition, most versions are presented with a specific order of steps. Even though some illustrate the cyclical nature of design, none fully illustrate the nonlinear processes that the data shows that the students took.

5) Diverging and Converging Behaviors: The Double Diamond for Design and the Cycle of Divergent and Convergent Behavior in Innovation both illustrate the idea of transitioning between divergence (e.g. trying new ideas, learning new things) and convergence (e.g. choosing a specific path, implementing a specific strategy). This idea of convergence and divergence appears in the IBL data; students write about content and skills that they are exploring, and they write about actions they are taking. However, both models do not directly address the creation of impact. In addition, the Double Diamond for Design model suggests that innovation is a linear process where you start at stage 1 and end at stage 4. The Cycle of Divergent and Convergent Behavior in Innovation eliminates this linear process model, but it does not focus on the outcomes of the process.

B. Description of Final Developed Framework

The developed IBL Framework (shown in Figure 8) implements the concept of convergent and divergent behaviors but extends it by creating three diamonds, each with a converging category, a diverging category, and an end product. The first diamond consists of survey and define, with the end product being the identification of a gap that needs to be filled (e.g. a question that still remains in the research or a space in the market that has not been filled). Surveying consists of learning about the problem space (including concepts learned in the course), and defining consists of narrowing the scope of the project to hone in on a specific project goal. The second diamond consists of explore and solve, with the ends product being the solution to the gap. Exploring consists of learning the tools or concepts that will be necessary to create a solution, and solving consists of making design choices and building a solution to the problem. The third diamond consists of draft and share, with the end product being the creation of impact. Students create impact by publishing their work, submitting invention disclosures, or sharing elsewhere. Drafting consists

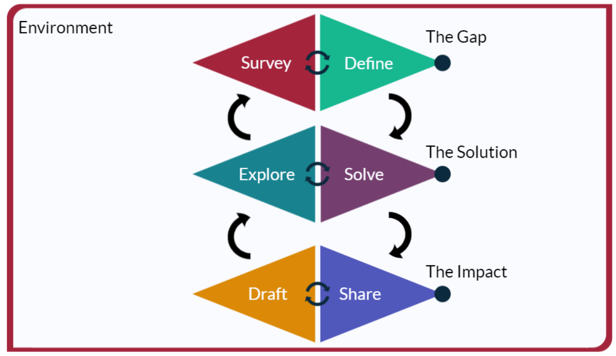

Fig. 8. The developed IBL framework integrates engineering innovation and learning in engineering education. The framework consists of three diamonds, each consisting of a diverging activity and a converging activity that produce an output. Diamond 1 consists of surveying and defining the problem to develop a gap. Diamond 2 consists of exploring and solving to create an innovative solution. Diamond 3 consists of drafting and sharing, leading to impact of the innovation. The final category is "Environment", and it covers any other activities related to being a member of a group or class.

of learning how to navigate this process and growing in their communication skills, and sharing consists of choosing an outlet and creating the impact. Finally, the environment covers any activity that does not directly lead to developing a gap, a solution, or impact. The environment can include activities like team meetings, completing activities for class, or doing any housekeeping items.

Table 1 shows the list of framework categories and an example token from the dataset that falls under each of the categories.

TABLE I
EXAMPLE TOKEN FOR EACH OF THE FRAMEWORK CATEGORIES

Category	Example
Survey	Understand the cardiovascular system and the applications of tissue engineering
Define	Narrow research topic to inform class
Explore	Learning about ECG signals and feature extraction
Solve	Apply preprocessing functions to data collected with team's hardware and revise functions as necessary
Draft	Obtain feedback from class for revisions of symposium poster
Share	Final paper to submit for provisional patent
Environment	Group meetings and presentations to evaluate progress and provide updates

Overall, the framework is built on three main tenets:

- An innovation consists of three components: an existing gap, a new and unique solution, and developed impact.
- The process of innovation consists of iterating between converging and diverging behaviors (explore options, make decisions, repeat).
- There is not a linear pathway from start to end; the problem gap, solution, and intended impact may be refined and adjusted over time.

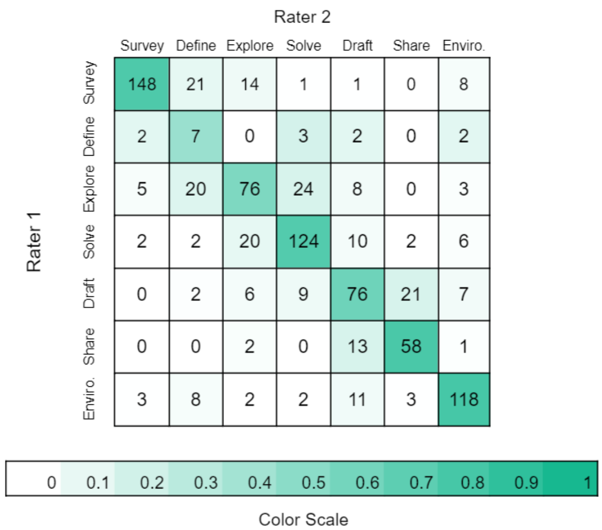

Fig. 9. Confusion matrix between the two independent raters. Boxes on the diagonal represent agreement between the two raters. The color relates to the ratio of tokens sorted into a certain category compared to the total number of tokens in that category (as determined by Rater 1). For example, Rater 1 put 193 tokens into the 'Survey' category, and Rater 2 agreed for 148 of those tokens, giving a recall value of 0.767. The matrix also identifies areas of discrepancy; these are the brighter green values that are not on the diagonal.

C. Assessment of the Framework and Takeaways

After two raters independently grouped the tokens, percent agreement and Cohen's Kappa were calculated. The raters had 71.2% agreement and a Cohens' Kappa of 0.664, which is considered moderate agreement [30]. This could be improved by exploring the discrepancies between the reviewers and refining category definitions. The decision matrix comparing the raters' categorizations is shown in Figure 9.

The discrepancies between the two raters were then analyzed and grouped into error categories: social learning, level of impact, practice vs. solution, content vs. solution, draft vs. submit, specific learning, unclear language, and websites. These error types, their descriptions, examples, and the number of occurrences of each type is shown in Table 2. Some errors could be reduced by more clearly defining the framework categories, but others are caused by the way that the specific token was written. These discrepancies led to takeaways for both token raters and token writers.

Takeaways for those categorizing tokens include:

- If a student is "just trying something", err on the "diverging" side. If students are not being specific about the content or skills they are developing, or if they use words like "practicing", or "looking into", they have not transitioned to the converging stage yet. This addresses the "Practice vs. solution" and "Specific Learning" error types.
- Teaching another student can be part of the learning process. For example, teaching a student about Simulink would still be considered part of learning about Simulink, putting the token into the "explore" category. This addresses the "Social Learning" error type.
- If students are learning about a process or skill, or if they are exploring the market space, "explore" is the most appropriate category. This addresses the "Content vs. Solution" error type.

Takeaways for those writing tokens include:

- Proofread your tokens to ensure that you are communicating clearly and that your title and description match. This addresses the "Unclear Language" error type.
- Clarify the purpose of your token. Are you learning more about the problem, or are you learning material in an attempt to assess possible solutions? This addresses the "Content vs. Solution" error type.
- Clarify the outcome of your token. Is it still in progress, or is it mostly finalized? This addresses the "Practice vs. Solution" and "Draft vs. Submit" error types.
- Carefully define your problem, solution, and form of impact. This addresses the "Level of Impact" and "Websites" error types.

Although many tokens nicely fall into one of the seven categories, these tips can help reduce the number of tokens that are unclear or fall into more than one category.

V. Discussion

A. Implications for Research

Those researching student innovation in classroom settings benefit from this framework because it groups student actions into illustrative categories. Categorizing student actions can be challenging because different students are working on different components of different projects, but this framework groups actions in a way that transcends project type, leading to multiple new research directions. For example, by combining this work with learning analytics methods, information can be gained about what top students are doing in each of the action categories, how they are moving in between convergent and divergent activities, and their overall process. It also leads to opportunities to see how teams work together on develop innovations (e.g. is one part of the team focused on the exploration and the over part of the team focused on action?) Ultimately, the IBL Framework opens the door to new quantitative analysis techniques that would not otherwise be possible.

B. Implications for Instruction

Having a framework for Innovation-Based Learning can help support both students and instructors in this model or other educational settings where students are solving emerging problems. This framework can help give instructors and students the words to describe their process when other frameworks don't fit. The structure of the diverging and converging diamonds can also help students identify road blocks. A common challenge in this instructional model is getting stuck in the diverging stage [31] and not converging in specific ideas or solutions. This model helps students visualize where

TABLE II
CATEGORIZATION ERRORS

Error Type	Error Description	Example	Occurrences
Social Learning	Social activities often fell under multiple categories. If someone is teaching a classmate about a tool they learned, the token could fall under "Explore", "Impact", or "Environment".	"Teach a lab coworker how to use iWorks hardware/software"	50
Level of Impact	Some tokens provide "secondary impact", meaning they are not the main impact deliverable. These tokens led to discrepancies between "solve" and "share" because they do solve a problem and create impact, but they are not part of the team's main solution or impact.	"Create public Jupyter notebook with tutorial on how to preprocess ECG signals."	33
Practice vs. Solution	The boundary between converging and diverging was sometimes unclear when it came to developing the solution. When using sample data or code, the student is still exploring possible options, but they have honed in on a more specific potential solution.	"Perform bivariate analysis with sample data."	33
Content vs. Solution	Some activities fell somewhere between learning content that is related to the problem and learning skills that are needed to develop a solution, leading to discrepancies between "Survey" and "Explore".	"Understand how genes play an important role in the cardiovascular system."	19
Draft vs. Submit	Some tokens combined both the drafting component and the submitting component of producing impact.	"Manuscript preparation/abstract submission"	25
Specific Learning	If students hone in on a specific thing they need to learn in order to refine the gap they are solving, the learning could arguably fall under "Survey" or "Define".	"Understand the cardiovascular system and the applications of tissue engineering."	23
Unclear Language	Unclear language occurred when token titles and descriptions did not match, or when the tokens were vaguely written.	"Gain access to data. Abstract development."	22
Websites	If the deliverable is a website, this led to confusion about how to classify components of the website. Because the website was designed to be both a "solution" and an "impact", it was hard to separate components of the website into categories.	"Create a working website."	19

they are at in the IBL process and encourages them to iterate between the diverging and converging behaviors.

C. Limitations and Future Work

Although this framework fits the overall pathway that students take, there is still some ambiguity when sorting student tokens into the categories. Therefore, future work could benefit from integrating learning analytics (see [9]). Using an algorithm to sort student text can lead to more consistency, and it serves as a scalable solution. This pairing of qualitative work empowered by learning analytics is becoming increasingly popular, and it could lead to new ways to support students and instructors in this model.

This work also could lead to a new way to have students document or sort their tokens. As seen in Table II, there were a variety of tokens where the gap, solution, or impact was unclear. By having students think about how their actions directly relate to the categories of the framework, they can more clearly explain their learning and better assess where their progress is lacking. Clearer tokens and outcomes could also improve interrater reliability of raters when looking at future data.

VI. CONCLUSION

This work presents a qualitative framework that is the first to integrate both innovation and learning. The IBL Framework supports educators and learners by illustrating the tasks and challenges related to creating innovations, and it gives classes a unifying vocabulary to talk about their processes. For researchers, the framework combines illustrative qualitative work with objective quantitative work, allowing for studies that identify best practices in teaching innovation. This mixed methods approach, along with learning analytics tools, can lead to scalable methods for exploring innovation in the classroom without oversimplifying the complexities of both the learning and innovation processes. The need for innovative engineers is growing, but so are the methods and tools that can help better support the development of these engineers. The creation of a framework that supports research and teaching in this area is the first step in building scalable, student-centered support.

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