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Evolving Mindsets: A Case Study of Teacher Change in Engineering Education through the Lens of Biologically Inspired Design Integration (Fundamental Research)

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Abstract

In engineering education, professional learning (PL) is crucial for enhancing educators' capacity to deliver rigorous, relevant, and engaging instruction, especially for high school teachers without formal engineering training. PL initiatives focus on content knowledge, pedagogical strategies, and teacher self-efficacy, but their effectiveness depends on teachers' ability to translate new learning into sustained classroom practice. This is especially challenging when the content is novel and complex, as in integrating biologically inspired design into engineering curricula. This qualitative case study applies Clarke and Hollingsworth's Interconnected Model of Teacher Professional Growth to examine a high school engineering teacher's transformation during the implementation of a BID-integrated engineering curriculum. Data sources included semi-structured interviews, classroom observations, and enactment surveys. Thematic analysis mapped teacher growth across the model's four domains, highlighting the roles of reflection and enactment in professional learning and instructional change. Findings revealed a progression from initial uncertainty to confident implementation of engineering instruction, supported by scaffolded curriculum resources and immersive PL experiences. These experiences reshaped the teacher's beliefs and identity, leading to more flexible, student-centered instructional practices and increased student engagement in engineering design.

Keywords: Biologically inspired design; Engineering education; Professional learning; Teacher change, Qualitative, Case study

Introduction

In engineering education, teachers are increasingly expected to engage students in complex, interdisciplinary problem-solving that reflects real-world challenges [1; 2]. One such challenge is teaching engineering in novel and emerging contexts, such as biologically inspired design (BID), where solutions are modeled after principles and systems found in nature [3-6]. While these approaches foster creativity, sustainability, and systems thinking, they also introduce unfamiliar content and pedagogical demands for many educators, particularly those without formal training in biology or advanced engineering concepts [7]. Professional learning (PL) is essential for building educators' capacity to teach in these new domains [5; 8]. Effective PL provides more than just exposure to new content; it supports the development of pedagogical strategies, confidence, and the ability to translate complex ideas, such as BID, into engaging, classroom-ready instruction [5, 9, 10]. PL programs often take the form of workshops, summer institutes, or after-school sessions, aiming to strengthen content knowledge, instructional design, and integration within broader STEM curricula [11-12]. However, the impact of these opportunities depends on how well they prepare teachers to apply what they've learned in real classroom settings, via development of both content and pedagogical content knowledge [10].

This study examines the journey of a high school science teacher into an engineering teacher, focusing on their ability to implement a BID-integrated engineering curriculum following participation in a comprehensive engineering education PL program. The findings underscore the importance of sustained, context-rich PL that addresses both the technical and pedagogical challenges of teaching engineering in innovative and interdisciplinary ways.

Background and Literature Review

Biologically Inspired Design (BID) in Engineering Education

Biologically Inspired Design (BID) is an interdisciplinary analogy-based methodology that recognizes the structural, functional, and behavioral strategies that organisms have evolved to survive and thrive under diverse environmental conditions [13]. Many of these strategies parallel the challenges faced by modern engineers, such as developing lightweight yet durable materials, managing energy use, and improving mobility across complex or unstable terrains [14-15]. Beyond technical applications, BID serves as a powerful educational tool [14]. It engages students in systems thinking, fostering creativity, sustainability awareness, and integrative reasoning skills, all of which are essential for tackling complex, real-world problems [16-17]. Examining how nature addresses challenges through evolutionary processes enables students to engage with interdisciplinary perspectives that link biology, engineering, and design [15].

However, it also presents distinct challenges for educators [3-6]. Teachers must navigate the disciplinary divide between biology and engineering, often translating abstract biological principles into practical design strategies that students can apply [18-19]. This requires not only a deep understanding of both domains but also the ability to foster collaboration and guide students through the complexity of biomimetic thinking [4; 14; 18]. Research shows that teachers unfamiliar with biology or design often struggle to assist students in understanding biological mechanisms and applying them to engineering tasks [19]. Therefore, PL programs focusing on BID integration need to build conceptual understanding, pedagogical strategies, and confidence simultaneously [5; 8; 10]. Activities such as visits to biological research centers, hands-on design challenges, and collaborative reflection sessions can help teachers view BID as both a scientific and creative process [3-6; 11-12]. These needs align closely with broader findings in engineering education, where effective PL programs also emphasize deep engagement with both content and pedagogy [10].

Professional Learning in Engineering Education

In engineering education, PL programs aim to help teachers understand and apply the Engineering Design Process (EDP) and systems thinking in their classrooms [1; 10; 20-22]. Effective PL emphasizes authentic, sustained engagement that connects theory to practice through design-based activities, collaborative problem solving, and reflective dialogue [23-24]. Research shows that short-term or decontextualized PL rarely results in lasting instructional change; instead, teachers benefit most from iterative, long-term experiences that allow experimentation, feedback, and refinement [25-26]. Science and engineering teachers, especially those shifting from disciplines like biology, chemistry, or physics, face more than a subject change; they undergo epistemological and pedagogical shifts [27-29]. Unlike traditional science teaching, which focuses on established theories and controlled experiments, engineering education emphasizes open-ended problem-solving, iterative design, and real-world application [30-31]. Teachers must adopt new views of knowledge, recognizing that “failure” is a part of the design process [30-33], and implement methods such as design-based inquiry, creativity within limits, iterative prototyping, and authentic student collaboration [32-33]. Watkins et al. [34]

found that targeted training enhances teachers' pedagogical reasoning, helping them anticipate challenges and adapt instruction. However, initial confidence may be low due to the open-ended nature of engineering and limited resources, highlighting the need for ongoing support, collaboration, and accessible materials [1, 31]. Integrating engineering into science curricula also involves logistical challenges, such as time, resources, and standards alignment [35].

These studies show that shifting from science to engineering teaching requires not just new content but a fundamental change in how teachers understand knowledge, instructional approaches, and professional identity. Research suggests that successful transformation requires intentional support. PL experiences must address content and pedagogy [3-6; 25-27], blending conceptual engineering principles with hands-on design challenges and reflection on practice, challenges, and student views [24; 27]. When these elements are included, PL improves teacher confidence and skills in implementing the EDP, encouraging long-term instructional change toward more student-centered, inquiry-based teaching [20; 22]. To understand how PL fosters lasting change, we must examine the broader process of teacher learning and change.

Teacher Professional Learning and Change

Teacher change is a multidimensional, ongoing process shaped by beliefs, knowledge, context, and practice [36-37]. In engineering education, teachers are required not only to acquire new content knowledge but also to transform their instructional identities and pedagogical repertoires [1; 1; 26, 38]. PL serves as a key mechanism supporting this transformation, particularly when it emphasizes iterative cycles of enactment and reflection rather than a one-time exposure [39-40].

Several studies have explored the complex nature of teacher change, highlighting how shifts in instructional practice are closely linked to PL experiences, teacher agency, and school environments [41-42], especially in Math and Science. Penuel et al. [41] found that sustained PL grounded in collaborative design and local curriculum needs led to meaningful pedagogical shifts among science teachers. Luft and Hewson [42] demonstrated that science teachers' beliefs about teaching and learning evolved when PL was embedded in authentic classroom contexts and supported by ongoing mentoring. Witterholt et al. [43] applied the Clarke & Hollingsworth model to study teachers' practical knowledge in designing and supporting inquiry activities that develop over time. They discovered that cycles of professional experimentation and reflection, aided by peer collaboration, are essential for meaningful growth in teaching practice and practical content knowledge [43]. However, in engineering education, fewer studies have examined teacher change through the Clarke and Hollingsworth Interconnected Model of Professional Growth [36], particularly in pre-college contexts. Existing work documents increases in teacher self-efficacy and implementation of engineering practices following PL [44-45], but does not explicitly apply this framework, leaving a gap in understanding professional growth pathways for engineering teachers.

Furthermore, teacher identity, the evolving sense of self as a professional, is increasingly recognized as a central dimension of teacher change [46]. As teachers adopt new instructional approaches, they reconcile their prior beliefs with emerging practices, often navigating tensions between confidence and uncertainty [47-48]. Reflection plays a critical role in this identity work, as teachers engage in reflection-in-action and reflection-on-action [48] to make sense of successes, challenges, and their evolving roles. PL experiences that explicitly cultivate reflective practice can thus lead to deeper, more sustained transformation [49-50].

In engineering education, identity development is crucial as teachers shift from content conveyors to facilitators of design thinking [32, 51]. Studies show that gaining confidence in managing open-ended challenges increases ownership and self-efficacy [52]. These changes align with Clarke and Hollingsworth's model, emphasizing belief change and instructional experimentation. PL that integrates BID exemplifies this complex learning environment, requiring teachers to engage across domains, gain external supports, reshape beliefs, experiment with new methods, and reflect on student outcomes [41-51]. This interaction supports instructional changes and the development of teacher identity in interdisciplinary, design-focused learning.

These findings support Clarke and Hollingsworth's [36] Interconnected Model of Teacher Professional Growth, emphasizing the dynamic interactions among personal beliefs, external stimuli (e.g., professional learning), and classroom practice. Change, especially in engineering education, is complex and socially mediated, involving shifts in beliefs, identity, and instructional methods [1; 49-52]. It involves not just new strategies but reconstructing professional identities through supported, reflective, and contextually grounded experiences. The Interconnected Model offers a robust framework for understanding this complexity, particularly in BID integration. PL that emphasizes reflection, experiential participation, and relevance can help teachers develop adaptive expertise and confidence in innovative STEM curricula [3-5]. This study examines a science teacher's journey toward becoming an engineering teacher through multiple phases of PL and classroom applications.

Theoretical Framework: The Interconnected Model of Teacher Professional Growth

Teacher professional growth is a critical consideration in designing effective PL programs, particularly in complex, interdisciplinary fields such as BID-integrated engineering. Clarke and Hollingsworth's [36] Interconnected Model of Teacher Professional Growth provides a comprehensive framework for conceptualizing teacher learning as a dynamic, cyclical, and contextually situated process. This model identifies four primary domains where change may occur:

1. ***The External Domain***, which includes professional learning activities, curriculum materials, and other external supports;
2. ***The Personal Domain***, encompassing teachers' knowledge, beliefs, attitudes, and professional identity;
3. ***The Domain of Practice***, referring to classroom behaviors and instructional experimentation, and
4. ***The Domain of Consequence*** represents teaching outcomes, including student learning and teachers' reflections on those outcomes.

Central to the model is the interconnectedness of these domains, where changes in one domain often influence changes in others through reciprocal processes of enactment, the application or trial of new ideas in practice, and reflection, which involves the sense-making and evaluation of enacted practices and their outcomes. This cyclical interaction highlights that teacher growth is a complex, iterative process shaped by individual and contextual factors, rather than a linear progression [36]. See Figure 1.

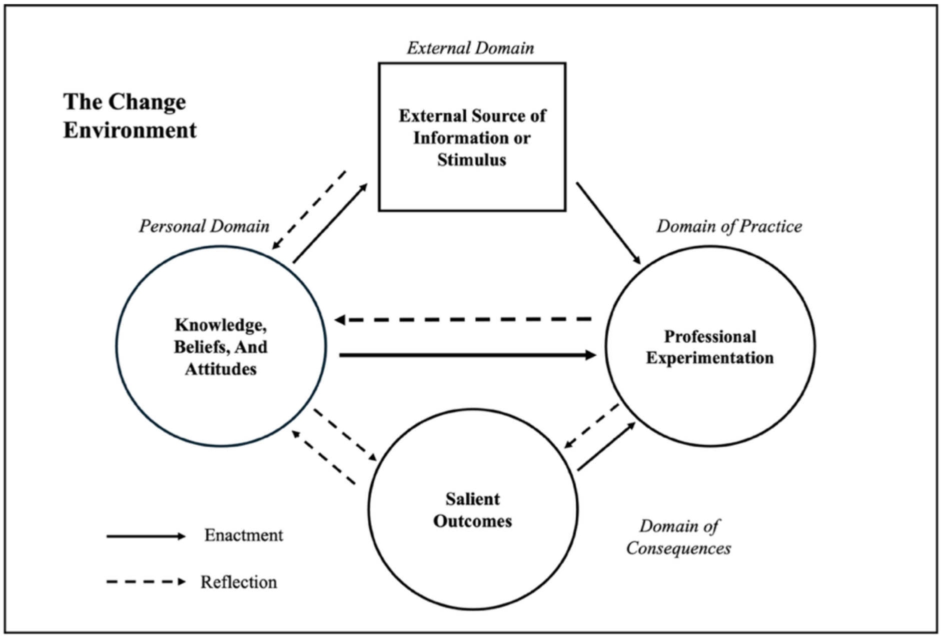

Figure 1. Teacher Change Model as cited in Clarke and Hollingsworth, 2002

Applying the Clarke and Hollingsworth Interconnected Model of Professional Growth [36] to engineering PL provides a valuable lens for understanding teacher change. Integrating BID into engineering design requires teachers to shift pedagogical beliefs and professional identities, engage in instructional experimentation, and interpret student responses to unfamiliar content and practices [32]. The model conceptualizes teacher learning as a non-linear, iterative process across four interconnected domains: **External** (e.g., PL and curricular supports), **Personal** (e.g., beliefs, knowledge, identity), **Practice** (e.g., instructional enactment), and **Consequence** (e.g., student outcomes) [36]. These domains are linked through cycles of enactment and reflection that mediate ongoing professional growth [36].

In the context of BID integration, this framework captures the complexity of teacher learning by tracing how and why changes occur across domains. It highlights reciprocal relationships among PL experiences, evolving beliefs, instructional practices, and interpretations of student learning, offering a holistic account of professional growth. In this study, the model is used to examine how external supports shape teachers' beliefs about engineering (Personal Domain), inform instructional experimentation (Practice Domain), and influence student engagement and outcomes (Consequence Domain) through iterative enactment–reflection cycles. This approach provides a nuanced understanding of how sustained, scaffolded PL supports teacher development, identity transformation, and effective engineering instruction.

Purpose and Research Question

This study builds upon a comprehensive examination of teachers' experiences throughout a three-year PL program and a multiple-case study that investigated the pilot implementation of the BID-integrated curriculum in classroom settings [3-5]. Although prior research has provided valuable insights into broad patterns of engagement and early implementation efforts, this study is novel in its examination of the ongoing need to closely monitor individual trajectories of teacher transformation, particularly as educators transition from teaching traditional science content to adopting engineering-focused, design-integrated pedagogies.

The purpose of this study is to investigate the transformation of a former high school science teacher as they navigate the transition to teaching engineering through the lens of a BID-integrated curriculum. By focusing on a single teacher's journey, this research provides a comprehensive examination of the intricate interplay between reflection, enactment, and professional learning. Specifically, grounded in Clarke and Hollingsworth's [36] teacher growth model, it explores how these elements influence shifts in instructional practice, personal beliefs, and the integration of external input. The guiding research question is: *How do reflection and enactment influence a former high school science teacher's professional learning across practice, personal beliefs, and external input when implementing a BID-integrated engineering curriculum in an engineering classroom?*

Methods

Research Design

To address the research questions, we employed a single-case qualitative design to investigate the impact of a comprehensive PL program on the instructional practices and professional growth of a high school engineering teacher. The study focuses on the teacher's participation in the program and its subsequent classroom implementation over a two-year academic period. This design enables a detailed, context-rich examination of teacher change in a real-world educational setting. According to Yin [53], a single case study is particularly useful when the case represents a critical or unique example, providing valuable insights into broader theoretical propositions about the role of professional development in teacher change.

Participants and Setting

The participant in the study was a first-year engineering teacher who identified as male and white. He was purposively chosen for the study because of his interest in participating. The teacher was formally certified to teach science in grades 6-12 and had 20 years of experience teaching high school science. His highest degree was a specialist in science.

This teacher participated in the study for one year, during which he attended a two-day PL session in early spring 2022 and subsequently participated in the pilot implementation of the BID integrated engineering curriculum. Following the pilot implementation, he attended a four-week PL program during the summer and then participated in the field study in the fall of 2022.

It is essential to note that, although multiple teachers participated in the research throughout the project, many subsequently retired, changed schools, or transitioned to new professions. Consequently, this study focuses on a single teacher, who not only participated in the study the longest but also exhibited significant growth and transformation throughout the study. This teacher's development aligns with Clark's Teacher Change Model, which emphasizes that sustained engagement, reflective practice, and contextual support are key drivers of meaningful and lasting change in teaching. His extended involvement in the project provided the time and conditions necessary for the iterative processes of experimentation, reflection, and adaptation outlined in the model (Figure 1 above), thereby making his journey a compelling case study of teacher change in action.

The study was conducted at a STEM-focused high school in a large school district located in the Southeastern United States. In the school, the majority of students were diverse, with 37% White students, while the rest were Asian (37%), Black (13%), Hispanic (8%), and Multiracial (5%).

Context: Professional Learning (PL)

The PL was grounded in experiential learning theory [54] and aimed to connect engineering educators with the natural world through engaging learning activities that enhanced their understanding of the integration of bio-inspired design into engineering. The teacher's first PL experience was a comprehensive two-day event (Spring 2022) designed to introduce participants to and immerse them in the principles and practices of BID. This occurred immediately following the COVID-19 shutdown. Given its timing immediately after winter break (i.e., Spring 2022), the session aimed to provide educators with a concise overview of BID and its integration into engineering curricula.

On the first day, the teachers were introduced to the foundational concepts of BID, including its purpose, key components, and its support for student-centered learning. They also participated in a BID warm-up activity designed to elicit prior knowledge and encourage reflective thinking. On the second day, the teacher participated in a detailed walkthrough of the BID-integrated curriculum. This session provided hands-on opportunities to explore how BID is integrated into engineering and how learning goals align with instructional activities. Following the PL, the teachers implemented the BID-integrated curriculum in their classrooms.

In the summer of 2022, the teachers were invited to participate in a PL program delivered in a hybrid format to support educator development. This program combined virtual and in-person learning experiences over four weeks. The structure was thoughtfully organized to maximize flexibility while maintaining the benefits of face-to-face collaboration [3-5].

The PL began with a week of virtual learning, during which participants engaged in online workshops, discussions, and self-paced modules from their own locations. This was followed by a full week of in-person sessions, where teachers gathered on-site for eight hours each day. These face-to-face interactions allowed for hands-on activities, peer collaboration, and direct engagement with facilitators. After this intensive week, participants were given a one-week break to rest, reflect, and process what they had learned so far. The third week resumed with another round of virtual learning, continuing the program’s emphasis on flexible, remote participation. Finally, the fourth and final week concluded with another in-person session, mirroring the earlier on-site experience. This alternating schedule, which included virtual and in-person components, provided a balanced approach that supported both independent learning and collaborative professional growth.

During the summer PL, the teachers underwent comprehensive BID training that covered specific curriculum activities and reintroduced Structure-Function-Mechanism (SFM) analyses. These analyses enabled teachers to gain a deeper understanding and to evaluate biological solutions. Additionally, the teachers and project team visited various locations, including the zoo, botanical gardens, and several bio-inspired research laboratories, to enhance their understanding of BID integration in engineering. Although multiple teachers attended the PL, this study focuses on a single teacher to examine his development and transformation throughout the project and his involvement in the PL during that period.

Data sources

To comprehensively assess the teacher's transformation throughout the two implementations, stemming from their participation in the PL experience and its impact on translating program knowledge into classroom practice, this study employed a diverse range of data sources. These encompassed semi-structured interviews (post-pilot implementation, post-summer PL learning, post-field study implementation), classroom observations, and weekly enactment surveys (See Figure 2). All of these are further detailed below.

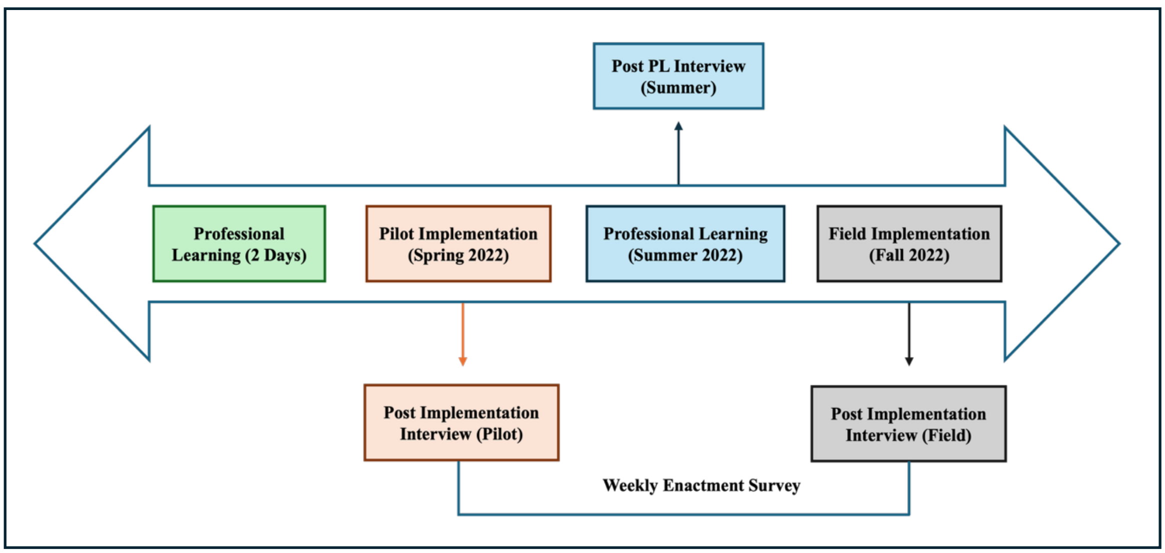

***Figure 2**. The various data points and sources*

Semi-structured teacher interviews were conducted at various intervals throughout the teacher's year-long implementation. The first interview was conducted at the end of the pilot study implementation in Spring 2022; the second at the end of the summer PL (2022); and the final after the field study implementation (Fall 2022).

The interviews aimed to elicit educators' perspectives on their experiences with implementation, PL, student learning, and engagement. The interviews specifically addressed several critical dimensions, including the overall structure of PL, the nature and effectiveness of learning activities, and the integration of BID concepts into engineering education. Additionally, the interviews explored the EDP and examined how the educators implemented the BID-integrated curriculum in their classrooms. To ensure accessibility and convenience, the research team conducted these interviews online via Zoom when necessary. Each interview was structured to last approximately 45 minutes, allowing for a deep exploration of the teacher's insights. Every session was recorded for accurate data collection and analysis.

Classroom observations: During the pilot and field study curriculum implementation, comprehensive, detailed classroom observations were conducted over seven weeks. These observations were designed to focus on various aspects of classroom dynamics, instructional effectiveness, and student engagement. Field notes were recorded during these observations, capturing not only the teacher's instructional methods but also the students' learning experiences and their interactions with one another and with the teacher. The observations aimed to document lesson delivery, the instructional strategies employed, and the teacher's pivotal role throughout curriculum implementation. Observations also focused on student interactions within teams and beyond, as well as their engagement with the teacher during unit activities. This aimed to understand student participation dynamics and their impact on learning. This multifaceted approach provided a richer understanding of the classroom, the teacher's translation of BID knowledge into practice, and its impact on student outcomes.

Enactment surveys were conducted throughout the pilot phase and during the subsequent field study implementation. After each lesson, the teacher completed weekly enactment surveys. These surveys aimed to gather insights into various aspects of the teaching process. Specifically, they were designed to evaluate which activities were carried out in each lesson, thus providing a detailed record of enacted lessons and instructional practices. Additionally, the surveys aimed to identify challenges encountered during lesson implementation, enabling analysis of potential barriers to successful teaching. The surveys also included sections on modifications made to lessons and activities, detailing any necessary adjustments to enhance the learning experience. Finally, the surveys placed significant emphasis on assessing student engagement from the teacher's perspective, a critical aspect of effective teaching and learning. Through this detailed information, we aimed to examine whether and how the teacher refined instructional strategies and whether and how this refinement improved overall student outcomes in subsequent lessons.

Data Analysis

The data were analyzed using a qualitative case study methodology, combined with thematic analysis [53, 55], by multiple researchers. This approach is effective at providing a deep understanding of individual experiences within the study [56]. By adapting this approach to the research context and objectives, this analysis aims to derive meaningful insights that reflect the participant's experiences. The analysis was conducted using an iterative model for examining qualitative data, as outlined by Huberman and Miles [57]. This model comprises three crucial stages: *data reduction, data display, and drawing conclusions and verifying them*.

In the initial stage, known as *data reduction*, the data was systematically organized and managed through various methods, including digital files. This structured approach facilitated easier access and manipulation of the data for subsequent analysis. Additionally, audio-recorded interviews were transcribed and subjected to a thorough review process. This comprehensive examination aimed to cultivate a deeper understanding of the content, ensuring that all key themes were effectively captured, as emphasized by Huberman and Miles [57]. By engaging in these detailed preparatory steps, the analysis established a solid foundation for the subsequent stages of display and conclusion, ultimately enriching the overall interpretations and findings.

Next, during the *data display* phase, the researchers categorized the data and identified connections across different data sources. To understand how the teacher participant integrated

PL content into their instruction, we conducted semi-structured interviews with the teacher. This was followed by a cross-case comparison to uncover common themes and instructional shifts across the various implementations [53]. To preserve the teacher's' unique perspectives, his experiences were documented as separate narrative accounts. These narratives, written in an accessible, reader-friendly manner, provided a concise, integrated summary of key findings [55].

Subsequently, the researchers engaged in collaborative data review, iteratively discussing and reaching consensus on the codes and interpretations across all data sources (i.e., field notes, semi-structured interviews, enactment surveys). A theory-driven thematic analysis [58] was conducted using Clarke and Hollingsworth's [36] Interconnected Model of Teacher Professional Growth as an analytic lens. Teacher growth was mapped across four thematic domains: External, Personal, Practice, and Consequence, highlighting how cycles of reflection and enactment supported professional learning and instructional change.

The analysis aimed to determine how the summer PL influenced teaching practices, particularly in the integration of BID into engineering curricula. This included: (a) demographic profile of the teacher, (b) strategies for integrating BID integrated engineering-related PL content into classroom instruction, (c) instructional changes post-summer PL, (d) indicators of success and challenges, and (e) illustrative teacher quotes reflecting the implementation, PL experiences, and their impact. The combination of narrative accounts and thematic analysis enabled a deeper understanding of the experiences, including those within the PL context [59].

The design of this case study is strengthened by triangulation, a widely recognized technique for enhancing internal validity, as highlighted by Merriam [60]. In this research, we employed multiple triangulation methods, drawing on data sources such as semi-structured interviews, enactment surveys, classroom observations, and contributions from multiple researchers. By combining diverse methods and analysts, we ensured the study's validity and reliability. The researchers engaged in collaborative data review, discussing and reaching consensus on the findings. The study maps the teacher's growth across the model's four domains: **External, Personal, Practice, and Consequence,** showing how reflection and enactment promote PL and instructional change. For privacy reasons, the teacher's name has been replaced with a pseudonym.

Additionally, the data sources in the findings are abbreviated as follows: Post-Pilot Interview (PPI), Professional Learning Interview (PLI), Post-Field Interview (PFI), Field Notes (FN), and Enactment Survey: Pilot or Field (ESP or ESF). Field Notes (FN), Pilot, Field, and PL refer to observations conducted during each session in the setting, such as classroom observations during pilot implementation or facilitation during professional learning (PL). All abbreviations are used consistently throughout the findings section.

Findings

These findings present the developmental trajectory of Josh, a former high school biology teacher, as he progressed through three stages of a comprehensive engineering education professional learning and implemented a BID integrated engineering curriculum. The findings are organized chronologically across themes, highlighting key shifts across Clarke and Hollingsworth's (2002) four domains of teacher change: the ***External Domain*** **(supports and**

resources), the ***Personal Domain* (beliefs, attitudes, and identity**), the ***Domain of Practice* (classroom experimentation)**, and the ***Domain of Consequence* (student learning outcomes)**. Each stage of Josh's experience demonstrates cycles of enactment and reflection that cumulatively supported his professional growth. Refer to the Table for the mapping of Josh's journey and the stages, which are further explained below.

Table 1: Teacher's Journey from science to engineering teaching

Domain	Findings from Josh's Journey	Stages
External Domain	- Initial exposure to BID curriculum and PL walkthroughs (Pilot). - Full summer PL with immersive experiences (zoo, botanical gardens) and detailed curriculum walkthroughs. - Continued curriculum resources and PL follow-ups (Field Study).	Pilot → Summer PL → Field Study
Personal Domain	- Early uncertainty about engineering teaching; saw EDP as similar to scientific method but prototype-focused (Pilot interview). - Beliefs shifted to understanding engineering as iterative and design focused (Filed Study). - Developed stronger identity as an engineering teacher, gaining confidence in teaching EDP and SFM Felt less stress, more clarity, and stronger belief in BID/SFM importance by the Field Study stage (Field)	Pilot → Summer PL → Field Study
Domain of Practice	- Careful lesson preparation initially, then more improvisation and adaptation (Pilot and Summer) - Experimented with BID warm-ups (white board integration of biology concepts into engineering challenges (Summer and Field) - Adapted lessons flexibly, skipped or shortened parts as needed (Field) - Used various strategies (SCAMPER, Morpho Matrix, Jitterbug) confidently (Field) - Guided students through problem statements and EDP stages effectively (Field)	Pilot → Summer PL → Field Study
Domain of Consequence	- Students engaged with initial activities but struggled to integrate biology, specifically SFM into design solutions (Pilot) - Recognized scaffolds (SFM, empathy prompts) as critical for learning (Summer) - Approx. 70% of students articulated SFM in presentations, showing improved problem framing and understanding of design (Field) - Student engagement strong by semester end (Field)	Pilot → Summer PL → Field Study

Enactment and Reflection Cycles

- **Enactment:** Josh's classroom experimentation with new strategies (warm-ups, integration of biology and engineering, scaffolded design processes) across all stages demonstrates active enactment of PD concepts into practice.
- **Reflection:** Through PD workshops, summer learning experiences, and observations of student outcomes, Josh reflected on what worked and what needed adaptation, deepening his understanding and beliefs about engineering teaching

Stage 1: Pilot Implementation (Spring 2022)

Josh's initial exposure to the BID curriculum occurred during a pilot implementation period. His initial experience with the BID curriculum exemplifies the intricacies of implementing a novel interdisciplinary teaching methodology. Initially, when encountering unfamiliar materials and grappling with the distinction between science and engineering, he experienced uncertainty in the early stages. Undeterred by these challenges, Josh embarked on a journey to explore novel instructional strategies and analyze their impact. This process provided him with valuable insights into student engagement and the importance of scaffolding, laying the groundwork for a more informed and effective teaching approach.

During the pilot implementation, Josh's professional growth was primarily externally initiated and exploratory, characterized by tentative enactment and emerging reflection. Interactions within Clarke and Hollingsworth's (2002) Interconnected Model of Teacher Professional Growth were asymmetrical, with strong influence from the External Domain and weak, developing connections across the Personal, Practice, and Consequence domains. Instructional decisions were largely driven by unfamiliar curriculum materials, resulting in inconsistent implementation and a surface-level understanding of engineering pedagogy. Reflection during this stage was reactive and localized, laying an initial foundation for sense-making but not yet producing cohesive or stable instructional change (see Figure 3 below).

In the **External Domain**, he received the first version of the BID curriculum binder and attended an introductory PL session. While the walkthrough offered a broad overview, Josh described the resources as "overwhelming," suggesting a lack of immediate clarity in how to apply the curriculum effectively. For instance, in the post-pilot interview, he stated,

> *Honestly, I think walking us through the first unit at first, when you see the text, binder, or even the online document, it can be pretty overwhelming because it is all combined in one. In hindsight, having that information available made the teaching part easier and helped me feel more comfortable about what was about to happen* (Josh, PPI).

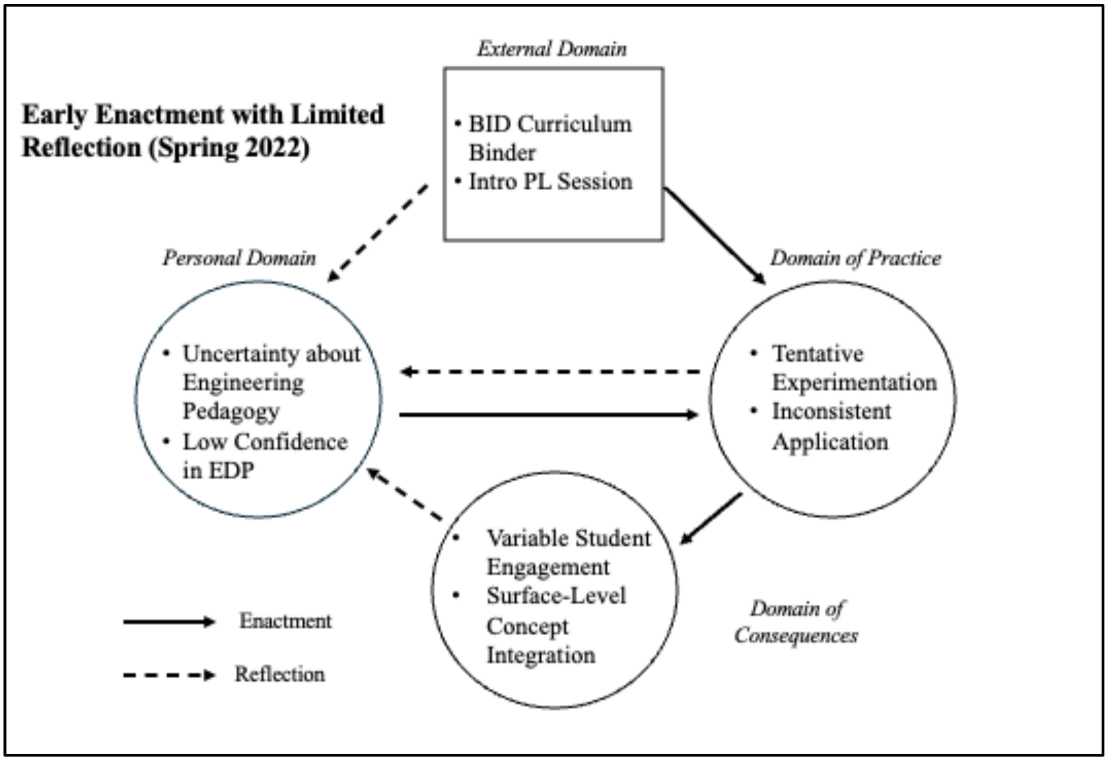

Figure 3. Stage 1: Pilot Implementation (Spring 2022)

In the classroom observation field notes, the teacher's overwhelming sense of stress was evident. This manifested in a recurring pattern of skipping lessons. Upon returning from spring break, the teacher realized that the class had inadvertently omitted a core instructional component, the design problem, resulting in student confusion. This instructional gap prompted the teacher to revisit lessons that were promptly reviewed as a whole-class activity to realign with the planned instructional sequence and transition into the subsequent topic. The enactment survey corroborated this, as the teacher indicated that he had *"skipped the design problem and had to go back"* (Josh, ESP) after recognizing that students were unable to comprehend the material.

In the **Personal Domain**, Josh expressed early uncertainty about his role in delivering engineering content. While confident in his biology knowledge, he noted "discomfort with engineering pedagogy", initially equating the "Engineering Design Process (EDP) with the scientific method", but recognizing its unique emphasis on prototyping and iteration. These reflections indicated an early, surface-level conceptualization of engineering as applied science rather than a distinct discipline. When asked specifically how he would describe the engineering design process, he stated,

> *"Well, it is just a blend of the scientific method, I guess. It is basically a science lab merged with making sure that all the kids have everything they need, or understand how it works, and how I get the data* (Josh, PPI).

This uncertainty was also evident when he discussed the EDP further; he claimed…

> *It was about understanding what the engineering design process lesson was supposed to be, or whether it was just a new way to demonstrate how the engineering design process*

> *would be taught, and what those things... I still did not fully understand until we started doing it, but at least it gave me an idea of how I would teach this part of the process* (Josh, PPI).

The observation underscored his explanation and implementation of the EDP, implying that he exhibited *"discomfort and a lack of a comprehensive understanding of the EDP process*" during implementation (FNP). Notably, he failed to establish a clear connection between the students' activities and any specific stage of the process until they commenced working on the prototype. This uncertainty, coupled with inconsistent application during implementation, suggested a superficial understanding of the framework and contributed to a general lack of confidence in his delivery of the engineering curriculum. Upon analyzing the weekly enactment survey, a clear, recurring pattern emerged, indicating that the EDP was consistently overlooked or applied insufficiently throughout the implementation.

Despite this uncertainty, Josh engaged in tentative experimentation in the **Domain of Practice**. He prepared thoroughly, using warm-ups as team-based activities on the big whiteboards and scaffolded activities to support student engagement. For instance, Josh noted that it was the

> "*content they presented on the whiteboard, how thoroughly they explained it, and how they tied it into the reverse engineering process. However, those handouts not only made it easier for me to follow along but also easier for me to review*" (Josh, PPI).

He also attempted to connect and elaborate on the biology content, such as thermoregulation and adaptations, which were the core science concepts covered in the engineering design challenge. His instruction varied by class period, which were long block periods, as he adjusted based-on student dynamics, indicating a developing awareness of instructional differentiation.

In reference to the comfort derived from science, he elaborated on certain lessons that primarily focused on those scientific aspects. He stated,

> *I was kind of planning and making sure I had everything, rereading everything. By the time we reached spring break, I was doing less of that because it was something I felt we could understand, such as thermoregulation, and diving deeper into what it means and how it relates. I was taking definitions and information from an AP biology class and adding it here, so the kids have a better understanding when they complete the Gallery Walk, or even with the lotus leaf, just providing more background* (Josh, PPI).

The interview data corroborated the classroom observations and his responses on the weekly enactment survey. In the field notes, the observer noted that Josh's implementation *was "driven by science"* (FNP). For instance, in one lesson, the teacher incorporated a *"Kahoot warm-up on biochemistry"* (FNP). The content covered in the Kahoot was unrelated to Bioinspired design and/or engineering; rather, it served as a review of biology concepts. The teacher documented these extensive modifications in the enactment survey, where he asserted that he incorporated an *"in-depth biology background into lessons related to thermoregulation"* (Josh, ESP).

Josh also reflected on how he adjusted his teaching between class periods through trial and error, as well as in response to his students' needs. For example, Josh claimed,

> *In the third block, I realized that due to the class size and the type of students, I understood what many of the students wanted to learn. They want to know and ensure that I have it right, so if I do not, I will hear about it; otherwise, they will get distracted and go somewhere else. The first block was basically a smooth walkthrough. Then the third block was implemented, adjusted, and added to as needed* (Josh, PPI).

In the **Domain of Consequence**, Josh observed that students were interested in hands-on activities, such as reverse engineering and SCAMPER. He claimed, "*Honestly, all of the hands-on stuff, the getting up and moving around, is something they all enjoyed, I think, from start to finish*" (Josh, PPI).

However, they struggled to integrate biology concepts into their designs meaningfully. He observed that students who engaged more deeply with scaffolded BID activities early on were better prepared for later stages of design. These observations prompted initial reflection on the value of scaffolds and the need for clearer connections between scientific and engineering thinking.

During the classroom observation, the observer documented the fluctuations in student engagement levels throughout the lesson in the field notes. The data indicated that student engagement varied from day to day, with some instances resulting from "confusion" and others due to a "lack of interaction" (FNP). The observer noted that the engagement was *significantly higher"* (FNP) during interactive activities", such as the Gallery walk and prototyping, as well as during collaborative warm-up activities.

Additionally, due to the teacher's inadvertent omission of the design challenge and subsequent return to it, the students were unable to effectively incorporate BID into their engineering design solutions. Conversely, the weekly enactment surveys exhibited a similar pattern, as indicated by the teacher, that *"engagement varied across lessons and block periods"* (Josh, ESP), necessitating adjustments to the lessons and constant redirection.

As presented, the first phase was characterized by early enactment and cautious experimentation. Josh's reflections demonstrated movement from uncertainty toward partial confidence. He began to recognize the potential of BID instruction but had not yet developed fluency in its implementation or a cohesive vision for integrating it into his engineering classroom.

Stage 2: Summer Professional Learning (Summer 2022)

The summer PL experience played a pivotal role in Josh's professional development, paving the way for significant transformations in both his external and personal spheres. The summer PL phase served as a reflective turning point in Josh's professional growth, marked by conceptual clarity and identity development. As illustrated in Clarke and Hollingsworth's (2002) model, growth during this stage was driven by intensive interactions between the External and Personal Domains, as immersive PL experiences supported a deeper understanding of engineering pedagogy and the BID framework. Although classroom enactment had not yet resumed, Josh demonstrated intentional planning within the Domain of Practice, informed by reflective consideration of prior student outcomes. This stage functioned as a bridging phase, strengthening connections across domains and preparing the conditions for more confident and reciprocal enactment (see Figure 4).

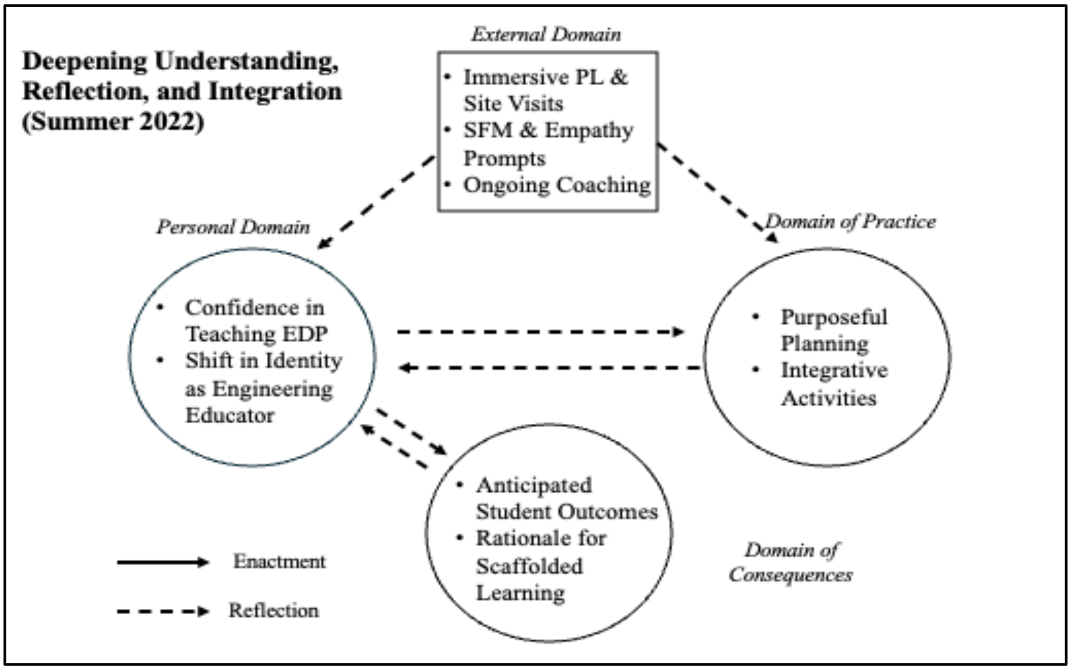

Figure 4. Stage 2: Summer Professional Learning (Summer 2022)

The **External Domain** expanded significantly with an immersive, content-rich PL program that included in-depth walkthroughs of the EDP, site visits to a zoo and botanical garden, and the introduction of tools such as the Structure-Function-Mechanism (SFM) framework and empathy prompts. These experiences provided both theoretical grounding and practical strategies, helping Josh see the relevance and purpose of previously overwhelming resources. When asked how he would describe his overall PL experience, he asserted,

> *I found walking through the EDP to be very helpful. I mean, I find it makes things a lot easier, even just walking through. I found that extremely helpful in understanding what we need to do, especially as we are doing it [referring to him engaging as a student]. For me, that was a valuable learning experience in understanding that this is where we go to the testing part—this is what it is asking for. So, walking through the EDP was now extremely important"* (Josh, PLI).

Josh also highlighted that the PL helped him understand the mindset behind the curriculum, as he claimed, "*The PL was very helpful and allowed me to understand the thought process that went into developing the curriculum"* (Josh, PLI).

The observation notes highlighted that during PL, Josh realized he had previously rushed through the EDP. The hands-on walkthrough clarified the intent behind each stage, helping him slow down to emphasize problem scoping and iteration. He stated during the debrief, "*Before, I just kind of ran through it… I need to take the time to go through developing the problem and what pieces of information are needed"* (FN-PL). These external supports served as both cognitive and structural scaffolds, providing Josh with new conceptual clarity and confidence through this collaborative engagement.

In the **Personal Domain**, Josh underwent a marked shift in beliefs and teacher identity. He reflected on the difference between scientific inquiry and engineering design, developing a clearer understanding of "engineering as iterative", purpose-driven, and solutions-oriented. These realizations began to reshape his self-concept, shifting from "a biology teacher teaching engineering" to someone who was beginning to embrace the identity of an engineering educator. He reported increased confidence in his understanding of the EDP and in integrating BID concepts into engineering instruction. He stated,

> *"What this curriculum has created is that it truly goes through the EDP… we are doing tests, prototyping, the research, and the empathy piece. It really teaches them how to do it. In science, whatever you do, you do one test. Here, we actually get to test, make a few changes, and test again…. Now it just gives me more of a tool to structure the class and connect concepts"* (Josh, PLI).

When asked if and how the PL aided in developing his engineering mindset, Josh indicated that the PL shifted his approach to teaching engineering and the EDP. He claimed,

> "*I guess just say how to teach the EDP, how to teach engineering, and how an engineering teacher should be teaching. Now I realize the biggest issue in science is trying to develop a correct hypothesis. In engineering, it is realizing what pieces of information you need to develop an accurate problem statement*" (Josh, PLI).

This shift in identity from a biology teacher to an engineering teacher was also observed in the PL field notes, where the observer noted changes in his "facial expression" and comments such as, "Oh, this is how you do this" (FN, PL), during the EDP presentation at the PL. In addition, when asked to redefine the EDP, he was quick to state, "it is an iterative process" (Josh, PLI), demonstrating the change in his thinking.

The **Domain of Practice** began to shift from tentative experimentation to intentional planning. Josh envisioned concrete classroom activities that connected biology content to engineering problems, such as incorporating physical "toys" for the reverse engineering activity, adding a dissection, or building in field-based experiences". He planned to modify existing lessons to allow for deeper exploration of prototyping, testing, and student collaboration. Josh stated during the PL interview,

> *I would probably depend on it if I were not following your step-by-step, day-by-day instructions. For example, for reverse engineering, I would add something like a small toy, which they would then reverse engineer, or a Grasshopper, by adding dissection. So, I would add or change things like that, allowing more time to do a deeper dive into it. Moreover, I think it is more than that; it is a better learning experience. Because not only are they reading it, but also the visual and kinesthetic pieces are involved, manipulating it and then trying to build it back together, and possibly adding an extra feature or something similar* (Josh, PLI).

The teacher also indicated that he would allow students to engage in field experience through field trips. Josh claimed,

> *Oh, yeah. Yeah. Many of the things we did or activities we participated in [Referring to his PL experience]. I probably plan out the trip to the Botanical Gardens and the trip to the Zoo. I took a bunch of notes, so it can help to plan a trip to the Botanical Gardens*

> *and the Zoo…. Like how we could do this, how to get it set up. Things like that* (Josh, PLI).

This shift in the domain of practice was also evident and documented in the PL observation field notes. The observer consistently noted that the "teacher asked questions about BID integration in engineering" (FN, PL). The observer also noted that the teacher was engaged during the field trip and discussed how this experience made learning authentic and "aided in BID integration in engineering" (FN, PL).

These examples illustrate a shift in Josh's Domain of Practice, moving from tentative experimentation to purposeful and strategic lesson planning. His growing confidence and intentionality in integrating biology, engineering, and design were evident through his suggested intentional curricular adjustments and enthusiastic incorporation of hands-on, experiential learning opportunities for students. This transformation, observed in both interviews and field notes, underscores an evolution in his teaching practice, one that reflects a more nuanced understanding of how to foster student engagement and interdisciplinary thinking through BID-integrated instruction.

In the **Domain of Consequence**, although Josh was not yet back in the classroom, his reflections on the prior semester helped him appreciate the impact of specific scaffolds, such as SFM diagrams and structured design prompts, on students' understanding. He reported a clearer rationale for how and why these tools supported rigorous and relevant learning, which he recognized due to his prior experience implementing and the PL experience.

Josh reflected on how repeatedly asking students to identify the structure**,** function**,** and mechanism (SFM) of their product components would help deepen students' understanding. Rather than presenting projects with surface-level explanations, "This will keep it cold" or "This is product A, students need to be able to explain *how* and *why* each part of their design contributed to the overall purpose" (Josh, PLI).

He also acknowledged that tools like SFM diagrams would make it easier for students to break down and articulate their thinking by parts, leading to more meaningful engagement, especially when they had to revisit and justify specific design choices. For instance, Josh noted that

> *The Structure-Function-Mechanism (SFM) framework is especially meaningful when introduced during the Understand and Ideate phases of the design process. While the problem statement provides a broad overview, the SFM scaffold helps students break down the problem into more specific parts, such as client needs, requirements, and the empathy piece* (Josh, PLI).

According to Josh, this is where students begin to deeply analyze what their design needs to do and how it should work. Thus, he expressed the need to incorporate this framework broadly in his other engineering design projects.

Additionally, Josh discussed the impact of his experiential learning experience in the PL, connecting this to teaching and plans for the next round of implementation. Josh emphasizes how real-world exposure, particularly through field trips, can spark creativity and foster a deeper understanding in students. For instance, he stated,

> *I think so, and yes, to a certain degree, the more we get out and view the world that way, the more students benefit. Taking a trip to the botanical gardens or the zoo really opened my eyes, and it would open their eyes. They will start to realize, 'Hey, there are more things out there than I thought* (Josh, PLI).

He elaborates on this, asserting that even something as simple as observing a plant or an animal can inspire innovative thinking:

> "*You might walk into the zoo and think, 'It is just a tree or a plant,' but then start wondering, 'What if I used this differently? How could this be manipulated to make something more accessible or more efficient?* (Josh-PL Interview).

For Josh, these experiences go beyond the moment; they stay with students: *"I think those kinds of experiences have a bigger impact on kids. They leave more of a lasting impression"* (Josh, PLI).

The observation field notes further revealed that, during PL activities and reflection, he explicitly articulated how he conducted the SFM analysis for the biological object he selected (i.e., philodendron), as well as how the plant's unique functions could inform his design decisions. His explanation demonstrated not only a conceptual understanding of the SFM framework but also an emerging ability to scaffold students' thinking by guiding them to make connections between biological systems and engineered solutions. This pedagogical move reflects a significant shift in his instructional approach, highlighting a growing fluency in integrating disciplinary knowledge with design-based thinking and reasoning, an essential skill in implementing the BID-integrated curriculum.

Stage 3: Full Implementation and Field Study (Spring 2023)

In the third phase of implementation, Josh's professional growth was most clearly demonstrated through his confident, adaptive enactment and robust bidirectional feedback loops, especially between the Domain of Practice and the Domain of Consequence, as depicted in Clarke and Hollingsworth's (2002) Interconnected Model. His transformation reflected the dynamic interactions highlighted in the model, where reflective practice, prompted by student outcomes and classroom experiences, continually informed his professional knowledge and beliefs. Josh's instructional decisions became increasingly grounded in an internalized theory of practice, with his beliefs, actions, and student outcomes mutually reinforcing one another. At this stage, reflection served to consolidate his professional identity and instructional fluency, rather than to initiate change. By this point, external supports functioned as background reinforcement, and Josh enacted the BID curriculum with fidelity, flexibility, and sustained confidence as an engineering educator (see Figure 5).

In the **External Domain**, ongoing curriculum resources and follow-up PL continued to support his classroom implementation. Josh highlighted how the PL impacted his teaching during the field study implementation as compared to the previous pilot study implementation. He asserted,

> *It was different for a couple of reasons. One, compared to last year, I was focused on implementing it while also ensuring it was being accounted for and meeting our*

components or standards that we were trying to teach. Last spring (2022), I primarily read and implemented (Josh, PFI).

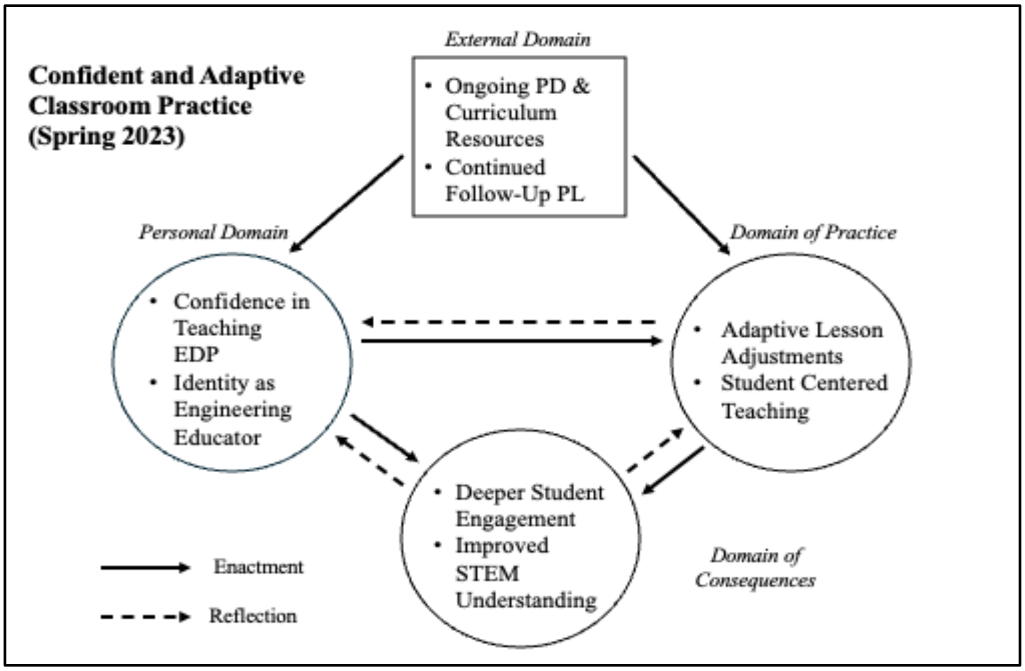

Figure 5. Stage 3: Full Implementation and Field Study (Spring 2023)

He further elaborated on how the PL activities, resources, and follow-up not only kept him on task but also deepened his understanding of the material, significantly enhancing his ability to grasp and teach the content effectively. As Josh stated during the post-field implementation interview,

> *It [[PL] helped explain the different components that I did not really understand or know. I had just been taking it as I read it, and wondering why it was so important. That part became much easier because I now understood where it was coming from, the reasoning behind it, and why that part was so important, as well as how to ensure I was teaching it correctly and explaining it properly* (Josh, PFI).

The observation field notes also revealed that the teacher was at ease during the implementation and was much more on task and organized. Josh implemented the curriculum exactly as designed, with only minor modifications to the lesson plans and worksheets. This contrasts with earlier implementations, in which changes were made, indicating increased confidence and familiarity with the materials. As the observer noted, *"Unlike the Spring 2022 implementation, the teacher followed the progression of each lesson as planned and did not make significant changes or modifications"* (FN, Field study).

The observation notes also revealed that the teacher made purposeful instructional adjustments to enhance student engagement, such as extending content discussions (e.g., properties of water), as noted: "*The teacher did extend the discussion about the lotus leaf and properties of water"* (FN, Field study). He ensured participation by consciously engaging students across all tables and encouraging group discourse, as noted in the field study: "*He makes a deliberate effort to engage students from each table…*" (FN, Field study).

These findings corroborated the results of the weekly enactment surveys. The teacher leveraged curriculum tools (e.g., BID WOW, BID Ideation) and credited PL for his improved instructional clarity and confidence. His responses on the survey revealed that PL helped him understand the curriculum's design intent, contributing to more effective implementation. Josh stated in the survey, "*The PL was very helpful and 'allowed him to understand the thought process that went into developing the curriculum"* (ES-Field study).

Josh's **Personal Domain** reflected further consolidation of his identity as an engineering teacher. He reported lower stress and greater clarity in his instructional decisions, noting that he now understood the purpose of each curriculum component. His belief in the importance of SFM and BID frameworks deepened, particularly in their role in supporting rigorous student explanations and design rationale.

Josh reflected on how repeated exposure to the material, both during the previous spring and over the summer, contributed to a reduction in stress and an increase in confidence in his understanding. Josh claimed,

> *It was much easier, and there was less stress about ensuring I had everything covered or understanding what the material was trying to convey or explain, or what I was trying to cover. All that worry and concern have kind of disappeared since I already did it last spring and went through the summer, which made it much simpler* (Josh, PFI)

This familiarity allowed him to engage more comfortably with the content, reducing the mental effort often involved in initial learning and teaching, as he claimed it was "*much easier to explain the mechanism and EDP this year (Fall 22) than last year (Spring 22)"*. Josh further added that the field trip experience also played a pivotal role in his conceptual understanding, which enabled him to connect the BID with engineering.

> *Yes, it did. The changes were more about when we walked through the zoo or botanical gardens. Now, I not only have had that physical interaction—I have seen it, touched it, and experienced it, so I understand more about what these things are, beyond just looking at pictures. This gives me either an experience to explain or discuss, or a different angle to approach that assignment or handout they were working on, and connecting back to SFM or BID* (Josh, PFI).

The observation field notes indicated a sense of comfort in the implementation, as the class felt like an *"engineering class"* rather than a *"science class"* (FN, Field study). The teacher demonstrated thoughtful sequencing and a comprehensive understanding of the curriculum's structure and objectives by deliberately selecting a review as the initial instructional approach. This deliberate choice underscores the instructor's recognition of the significance of reviewing prior learning in reinforcing understanding. For instance, the observer noted, "*The teacher began week three with a review Kahoot… Since there was a lapse in implementation from weeks one and two… the teacher felt it was necessary to review…"* (FN-Field study).

Josh also consistently integrated SFM into instruction and ensured students applied it in context. Even though he had to streamline BID Wow activities due to time constraints, he prioritized including at least one per class, signaling his belief in its instructional value. The observation notes revealed,

> *"He spent approximately 15 to 20 minutes reviewing SFM and SFM analysis of a screw within the same PPT... students completed the Analysis of a Nail as a group. Instead of not completing any of the BID-Wow for each lesson, he only completed one per class period for week three"* (FN, Field study).

Josh also extended the lotus leaf discussion, emphasizing how its structure and function informed the design of hydrophobic surfaces. This moment revealed his conceptual understanding of engineering through biology, a hallmark of his evolving pedagogical beliefs (FN, Field study).

Josh exhibited substantial improvement in his teaching practice, as evidenced by the weekly enactment survey. He reported greater clarity in his instructional decisions and a deeper understanding of the rationale behind each curriculum component. Furthermore, he observed a reduction in stress levels and a heightened sense of congruence with his identity as an engineering educator, indicating his growing confidence and the consolidation of his teaching identity.

These responses point to increased confidence and ease in managing lessons, as well as a more student-centered approach. Moreover, his reported adaptation of the curriculum, such as skipping certain BID components due to time constraints, demonstrates instructional ownership and the ability to exercise professional judgment.

The **Domain of Practice** showed significant changes. Josh became more flexible in adapting lessons to student needs, skipping or revising activities as appropriate. He continued to use and refine scaffolds such as SCAMPER, Morpho Matrix, and warm-ups. His confidence in guiding students through problem statements and EDP stages had notably increased.

Josh reflected on how his approach to teaching has evolved from feeling 'uncertain' at the start to now intentionally supporting student understanding through structured strategies. When asked how the implementation changed and how he sees himself continuing to teach engineering, specifically BID integrated engineering. He claimed, *"Yes, because I started out in engineering last fall, and I was just lost trying to figure out what we were doing or how we were doing it"* (Josh, PFI).

He further elaborated that this entire experience has not only changed his perspective but also his approach to teaching, particularly engineering.

> *This offers a completely different perspective; it is genuinely a new way of approaching a problem. I think writing out the actual problem statement made it easier for them to understand, as they were accustomed to writing much information or trying to cram everything into just one or three sentences. So, now that we have identified the problem, we begin to explore the understanding stage. As I mentioned earlier, I encouraged them to consider other options because we want them to be as creative as possible. Sometimes they do not, or they do not really go out, so I encouraged them to explore something other than Google to get them thinking* (Josh, PFI).

This shift highlights a commitment to fostering deeper student engagement and critical thinking in engineering contexts. He highlighted that activities such as SCAMPER, the BID warm-up, and the Gallery walk were essential in helping to understand the concept through research. For example, he claimed,

> *Well, I think honestly, so when we were doing the project and understanding, I think something as simple, or not simple, but something like that gallery walk where it gives them a little bit of a reading or a little background information, but also gives them that research that they do not have or they do not have to go out and sift through a bunch of websites with a ton of information, and sometimes maybe way over their head, if very helpful* (Josh, PFI).

The **Domain of Practice** showed substantial evolution as evidenced by the observations and weekly enactment surveys. Josh became more flexible in adapting lessons to student needs, skipping or revising activities as appropriate. He continued to use and refine scaffolds such as SCAMPER and BID warm-ups, as evident by the enactment surveys. He demonstrated significant instructional experimentation, testing, and adapting strategies while maintaining lesson coherence. His teaching showed both fidelity and innovation, reflecting iterative cycles of enactment and reflection. For instance, the observer noted in the field notes, *"He began each lesson with the BID Wow or BID Ideation… allowing students to record information graphically for deeper processing. Students drew products inspired by animals on the whiteboard* (FN-field study). This demonstrates his growing pedagogical agility; he actively tested new engagement structures, adapted lesson pacing, and leveraged visual, collaborative tools. His experimentation demonstrates enactment grounded in reflective refinement rather than trial and error.

In the **Domain of Consequence**, Josh observed stronger student engagement and learning outcomes. Students demonstrated improved problem framing and were more likely to view design as an iterative process rather than simply "building something". For example, Josh asserted,

> *I think, for the most part, students truly began to understand what they were doing in design as they walked through the engineering design process. They engaged more deeply with the 'understanding' component this time* (Josh, PFI).

He also noted that engagement was consistently higher in this round of implementation compared to the previous round, and many more students were able to articulate the SFM framework in their final presentations. However, some continued to struggle with explaining the mechanisms in depth. For instance, Josh pointed out that,

> *I think, for the most part, they were able to, and I would say about 70% managed to walk through and explain SFM. They may not have done a very good job on the mechanism part, but going through and identifying or listing each part and explaining its function for the lunch box was much better than what I did before or any other type of presentation. That is usually not something they need to explain; they just tend to explain whatever the teachers or the rubric asks for* (Josh, PFI).

Josh highlighted that students enjoyed many of the activities, some even ignited their appreciation for nature, as he claimed, *"I know many students talked about some of the activities here that required them to analyze biological systems, and one of the common activities that came up was the gallery walk* (Josh, PFI).

The observational fieldnotes also highlighted that Josh's evolving instruction produced clear and positive consequences in student engagement, collaboration, and understanding of engineering design. His facilitation fostered both cognitive and social learning gains, visible across the seven-week implementation. There were many instances across the weekly observations noted by the observer that highlight the positive consequences, such as,

- *Students really enjoyed the Natural Object activity and were captivated by how this relates to engineering".*
- *"Most students were able to identify how their design met the requirements and what their product was inspired by".*
- *"Students collaborated with group members and appeared much more comfortable with their group members as compared to before".*

These outcomes confirm a reciprocal growth loop as Josh's clarity and confidence improved, students' engagement and understanding deepened, reinforcing his belief in BID and SFM as effective pedagogical tools.

By this stage, Josh had internalized the curriculum and implemented it with confidence. His classroom practice was responsive and student-centered, and his reflections demonstrated a clear cycle of growth across all four domains. His identity as an engineering educator had solidified, and he was now better positioned to serve as a practitioner of BID curriculum integration in engineering education.

Discussion

The findings from Josh's journey illustrate a dynamic and iterative process of professional growth grounded in the four interrelated domains of the teacher change framework identified by Clarke and Hollingsworth [36]: the **External Domain**, the **Personal Domain**, the **Domain of Practice**, and the **Domain of Consequence**. Josh's trajectory across the three stages, Pilot Implementation, Summer Professional Learning, and Field Implementation, demonstrates the non-linear and cyclical nature of teacher learning and identity development. Importantly, his journey highlights that teacher change in interdisciplinary contexts, such as BID integration in engineering, involves challenges that extend beyond acquiring engineering knowledge or instructional strategies [36]. Rather, interdisciplinary PL requires teachers to reconcile differing disciplinary epistemologies, practices, and identities, a challenge increasingly recognized in engineering education research [22-23; 26; 38; 46, 61]. The teacher change framework enables a systematic understanding of how these challenges are navigated across domains.

Within the framework, the **External Domain** emphasizes how structured PL and scaffolded curriculum materials shape teacher understanding and practice. Josh's progression underscores the critical role of sustained and scaffolded PL, particularly when instructional innovations span disciplinary boundaries. Josh initially described the BID-integrated curriculum and introductory PL as overwhelming, reflecting challenges when teachers encounter engineering instruction without sufficient connections to their disciplinary expertise [22; 33]. However, the immersive summer PL, characterized by extended engagement, field-based learning, and in-depth curricular walkthroughs, supported Josh in developing both procedural clarity and an epistemic understanding of how BID integrates biological reasoning with engineering design processes and practices [5]. These findings align with previous research that highlights the role of sustained, authentic, and content-rich PL in promoting transfer to classroom practice [23, 54, 62].

The framework's **Personal Domain** captures transformations in professional identity. Josh's conception of engineering shifted from viewing it as an extension of science to recognizing it as a distinct, iterative, and solution-oriented discipline. His background in biology mediated this transformation, as he drew on structure–function reasoning to interpret engineering practices through the Structure–Function–Mechanism (SFM) framework [18]. By the final phase, Josh articulated a confident and coherent identity as an engineering teacher, consistent with literature emphasizing identity as central to teacher learning and sustained instructional change [46, 61]. Within the framework, these identity shifts illustrate how reflection-and-enactment cycles drive growth beyond exposure to PL experiences alone [36].

In the **Domain of Practice**, Josh's instructional strategies evolved from cautious adherence to curriculum guides to a more flexible, student-centered approach. His adaptations, including BID warm-up routines on the whiteboard, field experiences (e.g., walking around the school block), and the use of design scaffolds such as SCAMPER, the Morphological Matrix, and Gallery Walks, all part of the curriculum, demonstrated increasing pedagogical fluency in engineering instruction. These adaptations reflect increasing pedagogical fluency with engineering instruction, consistent with evidence that repeated engagement with engineering design practices enhances teacher confidence and adaptability [49; 62]. Josh's increasing instructional ownership further suggests that interdisciplinary PL can support durable changes in practice when teachers achieve epistemic coherence across disciplines [28; 36; 49]. Within the framework, this domain shows how epistemic alignment across disciplines facilitates durable changes in classroom practice [36].

Evidence from the **Domain of Consequence** further illustrates the interconnected nature of teacher change in interdisciplinary contexts. Josh observed improvements in student learning outcomes, particularly in students' ability to articulate design decisions using the SFM framework and to engage more deeply with the Engineering Design Process. Based on the field study, approximately 70% of students were able to explain their design decisions using SFM, representing a substantial improvement over the earlier pilot study. These outcomes align with prior findings that structured scaffolds can support student reasoning and bridge disciplinary gaps in integrated STEM and engineering learning environments [22]. At the same time, a slight decline in engagement toward the end of the semester highlights persistent challenges in maintaining momentum in extended interdisciplinary projects [62]. Within the teacher change framework, these consequences provide feedback that interacts with the other domains, reinforcing or reshaping teacher learning and identity development.

These findings highlight interdisciplinary PL as a teacher change process in which epistemic alignment across disciplines mediates movement across the domains of the teacher change framework [28, 36]. In Josh's case, his background in biology shaped how PL experiences were interpreted, how engineering practices were enacted, and how student outcomes were evaluated. Rather than operating solely within the Personal Domain, disciplinary epistemologies influenced interactions among the External Domain, Domain of Practice, and Domain of Consequence. This extends Clarke and Hollingsworth's [36] model by demonstrating that, in interdisciplinary PL, epistemic alignment between disciplines stabilizes instructional change and supports professional identity development [22]. By explicitly connecting teacher change to both domain interactions and epistemic alignment, the framework offers a systematic lens for analyzing how interdisciplinary PL, in general and specifically in engineering, leads to sustained teacher growth.

Limitation

Limitations of this study should be considered when interpreting the findings. First, the study focused on a single case (one teacher) within a specific PL context, limiting the generalizability of the results to other educational settings, grade levels, or engineering disciplines. Second, the study examined teacher change over a bounded time frame; longer-term investigations are needed to assess the durability of observed changes and whether instructional shifts are sustained. Finally, while the Clarke and Hollingsworth model provided a robust framework for analyzing teacher growth, interpreting change across domains necessarily involved researchers' judgment, which may influence how connections between domains were characterized. Future research should incorporate longitudinal designs and broader participant samples to further strengthen the understanding of teacher change in engineering education.

Conclusion

This study examined a science teacher's change towards becoming an engineering teacher within K–12 engineering education through the lens of a *teacher change framework* grounded in Clarke and Hollingsworth's Interconnected Model of Professional Growth [36]. The findings demonstrate that teacher change is neither linear nor immediate; rather, it emerges through iterative cycles of enactment and reflection as teachers negotiate new content, pedagogical approaches, and classroom realities in interdisciplinary contexts. Exposure to targeted PL fostered content knowledge, confidence, and instructional decision-making, especially when the teacher engaged with complex engineering concepts requiring disciplinary epistemological alignment. Sustained change required enacting new practices, reflecting on student outcomes, and reconciling existing beliefs with innovative instructional demands. This study emphasizes the dynamic, interconnected nature of teacher learning in K–12 engineering education, influenced by disciplinary identity, epistemic coherence, and contextual constraints.

Implications

These findings have implications for pre-college engineering education, especially for designing PL to support interdisciplinary instruction. Professional learning should be an ongoing, iterative process that supports enactment and reflection, not isolated workshops. In K–12 settings, where engineering is often integrated with science, effective PL must address both disciplinary content and pedagogical strategies. This is especially critical when introducing novel frameworks like BID, which require teachers to integrate knowledge across domains and reconcile epistemologies. Designing PL that prioritizes epistemic alignment can reduce cognitive overload, support instructional coherence, and promote sustained engagement with engineering practices.

From a theoretical and programmatic perspective, these findings suggest that adopting a *teacher change framework,* such as the one highlighted in this study, can support more effective design and analysis of PL in pre-college engineering contexts. Support structures, including collaborative reflection, access to instructional resources, and opportunities to examine student outcomes, appear critical for sustaining teacher change over time. More broadly, conceptualizing interdisciplinary PL as a change process mediated by disciplinary identity and epistemic coherence can help researchers and practitioners better understand how engineering instructional innovations take root and stabilize in K–12 classrooms. Attending to these mechanisms may lead to more coherent, effective, and meaningful engineering learning experiences for both teachers and students.

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