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Educating the Whole Engineer at Wake Forest Engineering: Using Cognitive Apprenticeship as an Effective Pedagogical Approach to Cultivate Design Learning, Team Effectiveness, Entrepreneurial Mindset and Character in Capstone Design*

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To better serve the evolving needs of society through responsible design, we must better educate the next generation of engineers to continue innovating and advancing technological solutions for the betterment of humanity. Wake Forest Engineering was built on the mission to Educate the Whole Engineer with a vision for our graduates to make positive societal impact (For Humanity). In educating the whole engineer, we must recognize that the complexities of engineering practice involve not only technical domains of learning (e.g., technical engineering knowledge, processes and thinking, fundamental principles, advanced technological methods and tools, prototyping, testing) but also non-technical domains of learning (e.g., collaboration and teamwork, engagement with stakeholders, effective communication, project management, ethical decision making, entrepreneurial mindset, professionalism, character development, etc.). The closest we come to engineering practice within undergraduate education is capstone design project experiences typically found in the senior year. Like engineering practice, engineering design involves not only technical domains of learning (e.g., design process and thinking, design principles, design methods and tools, prototyping, testing) but also non-technical domains of learning (e.g., collaboration and teamwork, engagement with stakeholders, effective communication, project management, ethical decision making, entrepreneurial mindset, etc.). It is thus imperative for engineering educators to use appropriate pedagogical approaches to prepare engineering graduates for the complexities associated with real-world engineering practice and this can happen during capstone design experiences. Because both technical and non-technical domains of learning involve cognitive development for the learner, this paper connects engineering design, in the context of capstone design experiences, with a cognitive learning theory that is appropriate for engineering practice and engineering education – cognitive apprenticeship. The purpose of this paper is to reflect on the appropriateness of cognitive apprenticeship as a model to support pedagogical approaches and innovations in engineering design education via capstone design experiences. Applied to both technical and non-technical domains of learning within capstone design at Wake Forest University, we have discovered that cognitive apprenticeship can offer a meaningful way to develop and reflect on pedagogical features that can support engineering student development. Cognitive apprenticeship is grounded on six phases of learning – modeling, coaching, scaffolding, articulation, reflection, and exploration – and all these phases are important to the learning complexities of engineering design. While capstone design faculty may be better at scaffolding and articulation, we found that improvements could be made in regard to modeling, coaching, reflection, and exploration so that students can better cultivate engineering design competencies as well as entrepreneurial mindset and character development. We also found that while capstone design faculty may be more innately prepared to cultivate engineering design competencies and team effectiveness, more intentionality is needed with competencies like entrepreneurial mindset and character development. Knowledge gains at Wake Forest Engineering have significant potential for transferability to other engineering programs. Many opportunities for future work (research, pedagogy, and assessment) exist.

Keywords: capstone design; cognitive apprenticeship; coaching; engineering design; character; entrepreneurial mindset; educate the whole engineer

1. Introduction

Engineering design is required in the education of engineering students and the engineering design mindset (i.e. multiple viable solutions and multiple paths to a viable solution, collaborative approach to developing technical solutions), in contrast to the more traditional 'one correct solution and individualistic' approach of engineering science courses, is essential to professional engineering practice. In fact, engineering design is distinctly defining of the engineering profession and distinctly defining in the work of engineers. It is thus not a surprise that ABET accreditation requires all

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Engineering design is a process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade- offs, for the purpose of obtaining a high-quality solution under the given circumstances. For illustrative purposes only, examples of possible constraints include accessibility, aesthetics, codes, constructability, cost, ergonomics, extensibility, functionality, interoperability, legal considerations, maintainability, manufacturability, marketability, policy, regulations, schedule, standards, sustainability, or usability.

Fig. 1. ABET'S Definition of Engineering Design [1].

engineering programs to prepare engineering graduates with knowledge and skills pertinent to engineering design. Fig. 1 provides the definition of engineering design according to ABET [1]. In addition to engineering graduates being able "to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" (ABET Student Outcome 2) [1], all ABET accredited engineering programs are required to offer culminating design experiences within their undergraduate education. Most often, these culminating engineering design experiences, also known as capstone design experiences, are offered as one or two semester experiences during the senior year of undergraduate education. These culminating engineering design experiences are required by ABET to be project-driven, team-based, design focused, culminating (in terms of supporting the translation of knowledge gained in years one to four) and helping engineering programs bridge the gaps between classroom learning and professional practice. As an example, students are expected to identify and apply engineering codes, standards, and regulations that are appropriate for their design to ensure its relevance within a real-world context. In addition to technical constraints and requirements, students are also expected to take into consideration social, environmental, economic, and legal matters. The value and importance of capstone design experiences are well-documented in the engineering education literature [2, 3].

The complexity of learning associated with capstone design experiences are also documented because such learning is atypical to the more traditional one-correct solution problems often seen in engineering classrooms [4–8]. Real-world or workplace engineering problems are ill-structured and complex because there are conflicting goals from stakeholders, there are multiple correct solutions and even multiple solution paths, there are both engineering and non-engineering standards and constraints, there are collaborative experiences, and even multiple forms of problem representation [4]. Thus, from a cognitive perspective, engineering design is a problem-solving experience that requires constraints, requirements, and stakeholder needs to be well understood before making critical decisions that will be embodied in an engineering solution that is not dictated by one correct solution nor one correct path to get to a solution. The complexity associated with engineering design continues to be a focus of investigation for engineering education and educational psychology researchers. Because of this complexity, which brings both technical and social factors and constraints, we broaden ABET's definition of engineering design – Fig. 2.

Engineering design is a process of devising an engineering system, product, or process to **ethically meet desired human needs and technical specifications within constraints. Human needs are derived from engagement with relevant stakeholders and consider human flourishing domains (e.g., accessibility, equity, usability). Technical specifications are derived from standards, codes, and other technical requirements (e.g., environmental, sustainability, failure analysis, functionality, manufacturability). Constraints that inform the human needs** and technical specifications involve ethical, legal, policy, and economic considerations. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, making trade-offs, **and creating positive value for the people that will be impacted by the engineering solution.**

Fig. 2. Wake Forest Engineering's Definition of Engineering Design. This definition is inspired by both ABET definition (Fig. 1) and the WFU Mission of Pro Humanitate (for humanity). The lighter wording makes visible the humanistic elements added.

Because capstone design experiences innately and most often represent the most complex projects and problem solving in undergraduate engineering student experiences, it is vitally important that engineering educators use appropriate pedagogies to support project-based, design-focused, team-based learning that adheres to the highest engineering and ethical standards of practice. We do believe that the project-based, cognitive-rich nature of capstone design is conducive to cognitive apprenticeship. This paper thus represents an investigation on the use of cognitive apprenticeship theory and pedagogical strategies to teach capstone design within a brand-new engineering program at Wake Forest University. To the best of our knowledge, this is the first publication that bridges cognitive apprenticeship to capstone design education within engineering. Conceptually, others have pointed to the value of cognitive apprenticeship within engineering design [9, 10 p. 12], but this is the first in depth publication showing use of the learning theory as a pedagogical framework within capstone design. The findings herein have the potential to inform engineering educators worldwide. The added value of this paper is that it offers insights into the use of cognitive apprenticeship theory across both technical and non-technical domains of learning associated with engineering education and engineering design..

2. Cognitive Apprenticeship Theory

The term cognitive apprenticeship describes both a theoretical model and pedagogical approach that experts can use to aid in the instruction of novice learners. First coined by Collins, Brown, and Newman in 1987 [11], cognitive apprenticeship has been applied across various professions and trades to support teaching and learning. Whereas traditional apprenticeship learning is an on-site, reality-based training that involves an expert demonstrating and observing a less-skilled person or learner to achieve specific tasks or goals, cognitive apprenticeship learning places greater focus on developing mental models and metacognitive skills while recognizing that many cognitive skills learners must acquire are not fully observable.

Cognitive apprenticeship learning theory consists of four dimensions – *content*, *methods*, *sequencing*, and *sociology* [11, 12]. *Content* refers to the different types of knowledge necessary for expertise and mastery over a specific topic or domain. *Methods* refer to the different teaching methods that are the core of cognitive apprenticeship designed to aid students in the acquisition of the skills necessary to learn effectively [12]. *Methods* also refer to designed learning experiences that provide opportunities to observe and engage learning strategies. *Sequencing* involves structuring materials and assignments appropriately to ensure the student novice feels supported during skill acquisition [12]. *Sociology* refers to the environment in which the novice learns from the expert(s) [12]. During an apprenticeship, this often entails peer learning and active community participation. Often underappreciated but critical to success, focusing on *sociology* can increase student learning, confidence, and motivation. These four dimensions can be segmented into six pedagogical stages: *modeling*, *coaching*, *scaffolding*, *articulation*, *reflection*, and *exploration* (Fig. 3). *Modeling*,

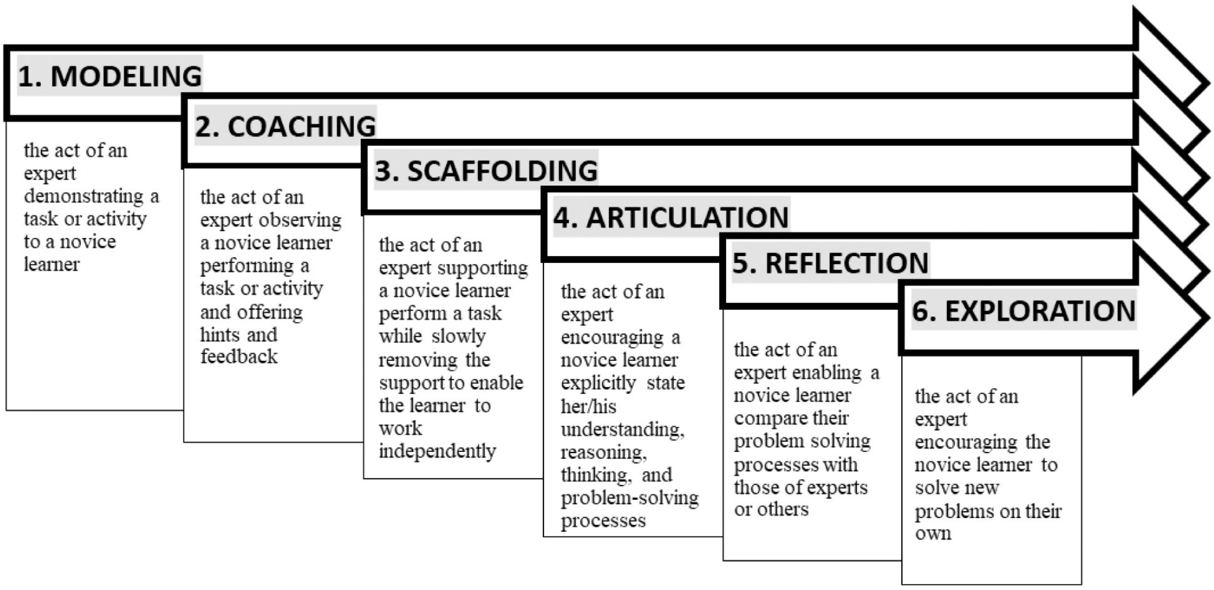

Fig. 3. The six stages of cognitive apprenticeship theory. Adopted from [11].

coaching, and *scaffolding* are often associated with traditional apprenticeship learning, while a*rticulation*, *reflection*, and *exploration* are linked to higher-order cognitive learning processes. All six phases are relevant to engineering practice, engineering education, and capstone design learning goals.

The six stages of apprenticeship learning, Fig. 3, track a novice learner's progression from observer to proficiency [11, 12]. The use of *modeling* allows an expert to explicitly demonstrate tasks. For example, an expert may work through the derivation of a solution to demonstrate procedural knowledge. *Coaching* allows the expert to provide constructive feedback both during and after a learning experience or assignment. *Scaffolding* provides both experts and novice a structured environment in which to teach and learn. *Articulation* enables the novice to articulate their reasoning and decision-making processes within specific domains. *Reflection* enables the novice to compare their own solutions and decision-making processes with those of peers and, eventually, the expert. *Exploration* is arguably the most crucial strategy as it encourages the novice to set and pursue independent subgoals within their own area(s) of interest. Collectively, these strategies enable the novice to apply their learned skills and experiences to realistic problems [11–13].

Prior academic studies have showcased the effectiveness of cognitive apprenticeship as a theoretical foundation for learning models and as a practical foundation for growth [13–22]. Woolley et al. demonstrated that the cognitive apprenticeship model provides a useful framework for cultivating problem-solving skills, while noting that the model requires significant resource investment [20]. Robust assessment is essential for gauging faculty and student expertise as well as student performance during the apprenticeship learning experience [18].

Cognitive apprenticeship has previously been applied to engineering education and medical education [20–24]. One such study concluded that, compared to traditional teaching methods, the applied cognitive apprenticeship model is more likely to equip civil engineering students with applicable professional skills that are relevant to authentic work environments. The students in this study were receptive to the course design and found the approach useful for learning, with some students requesting the design be applied to other courses. A notable challenge that the study designers faced was getting students to actively engage in classroom work as traditional courses often involved a lecturer and passive participation from the students instead of the active learning inherent in the cognitive apprenticeship model. The study concluded that the applied cognitive apprenticeship model is more likely to leave students with long term skills relevant to workplace environments. A study of STEM doctoral students who used the cognitive apprenticeship framework to improve their technical skills found it was generally effective but required earnest participation and deliberate action from novice and expert alike [22]. Similarly, another research team developed a study to analyze the effectiveness of the cognitive apprenticeship approach for a mathematical modeling and problem-solving course [24]. The student response was positive, with some study participants calling the experience the most important of their educational career. The cognitive apprenticeship approach has also been found to increase both long-term content retention and short-term student satisfaction, as instructor and student interactions are often more personal and stimulating [25].

Cognitive apprenticeships allow novice learners to frame interesting problems and take initiative to explore independently. By applying the theory and framework to capstone senior design, the benefits and shortcomings of the theory can be examined to provide a greater understanding of the model as it applies to engineering students. The outcomes of this study can be broadly applied to similar engineering programs.

3. Capstone Design at Wake Forest Engineering

Wake Forest Engineering welcomed its inaugural class in August 2017 and launched its capstone design experience during the 2020–2021 academic year [26]. With a program mission to Educate the Whole Engineer and committed to the university mission of Pro Humanitate (For Humanity), Wake Forest Engineering provides an interdisciplinary and integrated engineering education (BS Engineering degree) focused on technical breadth and depth as well as personal and professional development. A commitment to project-based and experiential learning in every course enables ethical reasoning, social responsibility, inclusive and collaborative learning, technical communication, entrepreneurial thinking, team and project management, self-discovery, and self-development. Capstone design represents the embodiment of all these learning domains and the third run of capstone design is the primary context for this paper. More details about Wake Forest Engineering and the integrated curriculum are provided in previous publications [27].

The capstone design experience at Wake Forest Engineering includes a three-course sequence that totals 9 credit hours: Capstone Design I (*EGR 313*, 1 credit), Capstone Design II (*EGR 314*, 4 credits), and Capstone Design III (*EGR 315*, 4 credits). Learning outcomes for each of these courses are mapped to ABET Student Outcomes 1 through 7, which build upon prior design learning and prior design projects starting in year one of the engineering curriculum and spanning all four years. Learning goals for capstone courses are culminating and developmental offering students an opportunity to apply what they have learned prior but also challenging them to advance their design knowledge and thinking, communication skills, project and team management, reasoning and decision-making skills, engage with more diverse stakeholders, connect design thinking to personal and professional growth, etc. In capstone, as compared to design projects earlier in the curriculum, the expectations are higher because the design projects are more complex and more ill-structured. Some of the overarching learning outcomes include:

1. Understand the engineering design process and apply it iteratively to a real-world challenge in understanding decisions that engineers make across various phases of the design process.
2. Demonstrate customization of the engineering design process to meet the needs of one's capstone design project and one's capstone design team.
3. Demonstrate effective application of diverse engineering knowledge, methods, and tools to support and justify decisions within the capstone design project.
4. Apply design thinking towards self-discovery of one's personal and professional goals and planning of one's future.
5. Identify capstone design project ideas informed by self-discovery and design thinking principles.
6. Demonstrate an ability to summarize and communicate project progress in various formats.
7. Demonstrate ethical reasoning and virtuous decision making towards engineering practice.
8. Demonstrate effectiveness as a team member and agility in learning (and seeking new knowledge) to supporting the needs of one's capstone design project and one's capstone design team.
9. Demonstrate effectiveness in oral presentations and soliciting feedback from external stakeholders (e.g., Design Review Panel) in support of one's capstone design project and one's capstone team.
10. Demonstrate effectiveness in project management and team management.
11. Demonstrate individual professional development toward career readiness.

Our pedagogical vision in teaching these engineering design courses is to enable mastery learning through directed and non-directed, group-based and independent, simple and complex, structured and unstructured, problem-based learning experiences to incrementally expose and reiterate the design process. Our overarching goal is to teach our students to be effective, adaptive, and ethical problem solvers.

In our three capstone design courses (EGR 313, 314, 315), there are several topics that are covered to advance students' engineering design knowledge and skills which also apply to diverse problem-solving contexts and experiences (i.e. workplace, team management, project management, etc.). Topics that are developmentally integrated in the upper-level design courses include:

(a) *Engineering Design Process and Advanced Design Methods* (related primarily to ABET Student Outcomes 1, 2, and 6) – To advance students' engineering design knowledge, we introduce them to principles and methods such as Design for X, Embodiment Design and Evaluation, the Theory of Inventive Problem Solving (TRIZ), Failure Modes and Effects Analysis, User-centered Design, and Intellectual Property & Patents. Other topics and assignments include configuration design, mathematical modeling, prototyping, testing, economic analysis, environmental impact analysis, social impact analysis.

(b) *Technical Communication Skills* (related primarily to ABET Student Outcome 3) – To advance students' written and oral communications skills, we cover several relevant topics including technical writing style and form, presentation delivery, personal communication styles, presentation slide design, project progress reporting, resume updates, cover letters, and personal statements, design report writing, and design presentations.

(c) *Team and Project Management* (related primarily to ABET Student Outcome 5) – To prepare students to enter the workforce as effective teammates and team leaders, we target team building, collaborative excellence through shared leadership, self and peer evaluation, Agile project management, and conflict engagement.

(d) *Personal Values and Purpose, Ethical Character and Leadership* (related primarily to ABET Student Outcomes 4 and 7) – To advance students' ethical awareness and understanding, we expose them to learning topics and case studies with ethical implications and ask them to complete assignments related to ethics in a virtuous or legal perspective.

During the first semester (EGR 313 – spring of junior year), students learn fundamental concepts related to the four-phase design process they will be utilizing senior year. Students gain hands-on experience by applying the four-phase design process (Fig. 4) to a real-world challenge, practicing critical tasks such as defining and scoping problems, developing system requirements, generating concepts, evaluating, and selecting concepts, and effectively rendering their work.

During their senior year in EGR 314 and EGR 315, students work in groups of four to five with one or more faculty coaches. Students build upon previous design courses while integrating knowledge and skills gained across the curriculum. At the beginning of the fall semester (EGR 314), each student conducts a series of feasibility analyses and selects the top four projects of interest. The capstone instructors finalize projects and form student teams. From that point, the students work through a four-phase design process (Fig. 4), which includes (1) Discovery Design (aka problem discovery), (2) Conceptual Design, (3) Embodiment Design and (4) Detailed Design. Although there are many engineering design processes used across diverse sectors of engineering practice, we employed this four-phase design process at Wake Forest Engineering to facilitate the learning in the capstone design course sequence (EGR 313, EGR 314, and EGR 315). Students learn this 4-phase process in EGR 313 and proceed to put it to use in EGR 314 and EGR 315. Discovery Design (phase 1) and Conceptual Design (phase 2) are of focus in EGR 314, and Embodiment Design (phase 3) and Detailed Design (phase 4) are of focus in EGR 315. This 4-phase Design Process is iterative and serves as a roadmap for capstone teams, who are able to customize the steps within each phase to support project progress. One team may spend two weeks to progress through Discovery Design, while another four weeks. This flexibility enables a team to plan within each phase to determine the strategies and methods to employ in best supporting the project goals. As teams progress through the 4-phase Design Process, they consult the faculty coaches to develop a detailed plan of progressing through each design phase. As students begin work on their projects, the instructional team devotes 30–75 minutes each week to provide students with essential design concepts, methods, and tools. Teams in time progress to a more independent work schedule and coordination with the capstone instructors and faculty coaches on a periodic basis.

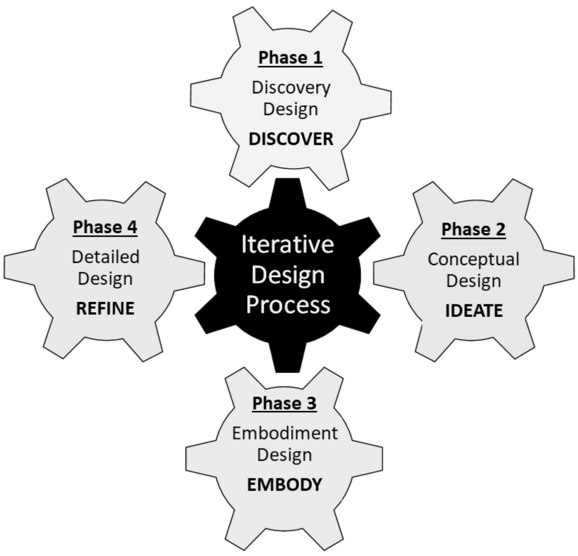

Fig. 4. Four phase design process followed within the Wake Forest Engineering capstone experience. This four-phase design process was developed by the lead author who served as the lead capstone coordinator of the inaugural years of capstone design at Wake Forest Engineering.

Various models of experts (e.g., faculty, industry experts, graduate students, peers) have been used with the Wake Forest Engineering capstone model and more will be discussed in later sections. We also utilize a collaborative "Design Review" process wherein students can interact with technical experts in fields related to their specific projects. Students work on capstone projects collaboratively with the faculty instructors, as well as their faculty coaches and technical experts. Each of these groups plays a key supporting role for the projects, as described herein and are essential for the modeling, coaching, and scaffolding stages of the cognitive apprenticeship model.

Faculty Instructors serve many roles throughout the design process. One of the main roles is to deliver content to students that supplement and supports student learning throughout the capstone design course sequence. Regarding the design project itself, capstone instructors serve as the main point of contact for project process details, and they are available to discuss various aspects of the project and to provide feedback to teams.

Faculty Lead Technical Coaches serve as the closest faculty technical expert for an individual team. The students meet weekly or biweekly with their lead faculty technical coach as a source of information when making design decisions and determining directions for their projects. Frequent meetings between faculty coaches and project teams will ensure that more meaningful insights can be offered to the team. Faculty coaches also periodically provide feedback to the instructors on the overall progress of their teams.

Technical Experts may include faculty instructors, other faculty coaches, clients, or external experts with knowledge of the project's subject area. The primary role of the technical experts is to participate in design reviews where they will offer feedback on current progress, provide critical perspectives on engineering practice within their area of expertise, and suggest future directions for the team. Depending upon the availability of the technical experts, they may be open to additional conversations in the time between the design reviews.

The integration of the four-phase design process mapped to the six stages of cognitive apprenticeship is illustrated in Fig. 5. This is an overarching visual illustrating how students are guided iteratively through the design process and the six stages of cognitive development. Students receive formative feedback at checkpoints for each design phase that require students to conduct design reviews, write design reports, and perform teaming assessments. The faculty instructors provide design resources, regularly check-in with teams, and administer additional assignments to guide students through each design phase. Students receive periodic feedback from technical experts, faculty technical coaches, and faculty instructors through design reviews, design reports, and teaming assessments, completed at the conclusion of each design phase. The instructors also carefully assess all deliverables and determine grades. Technical experts and lead faculty coaches attend all four design reviews and provide feedback and follow-on technical support. Students are expected to ask their panelists targeted questions that will advance their project and implement the panelists' feedback. All teams submit the most current version of their design report on pre-determined dates, but teams can emphasize the phases that are most relevant to them and are expected to revisit and revise earlier work as needed.

During EGR 314, students are focused on the first two stages of the design process: Problem Discovery and Conceptual Design. Throughout the Problem Discovery phase, teams focus on understanding the problem and defining requirements that will guide them to a successful design. Understanding the problem involves tasks such as literature reviews, interviewing stakeholders, observing users, benchmarking current solutions, and analyzing relevant codes and standards. All these factors are combined to generate targeted system requirements that can be used throughout the remainder of the design process. At this point, students have their first of four design reviews. This information sharing session involves a short (~15-minute presentation) delivered by the student team, followed by a longer (~45 minute) question and feedback session between the students, faculty coaches, and technical experts.

Once the problem discovery phase is completed,

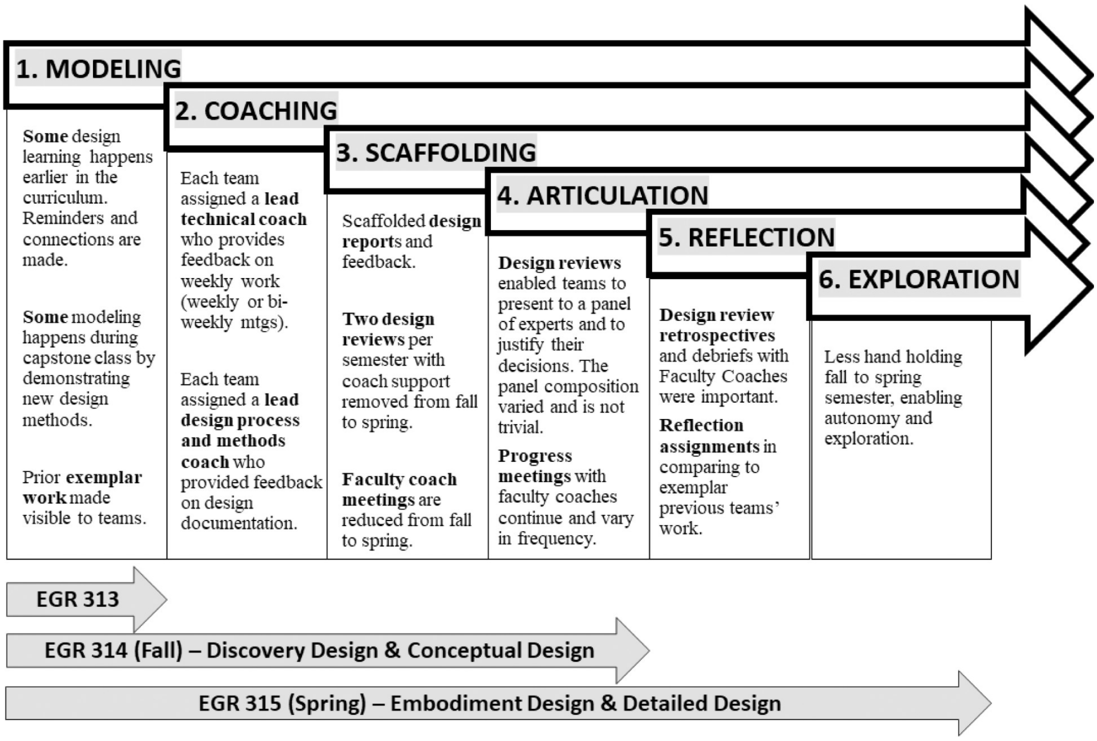

Fig. 5. The four-phase design process of the Wake Forest Engineering capstone courses (EGR 313, 314, 315) are mapped to the six stages of cognitive apprenticeship.

students move on to the Conceptual Design phase (EGR 314), where they spend time generating numerous concepts using a variety of methods, such as concept maps, functional modeling, morphological matrices, benchmarking, etc. Teams then systematically evaluate and select the most viable concepts using tools such as Pugh charts, weighted decisions matrices and proof of concept prototyping. Students can systematically generate and evaluate concepts by considering the system requirements that were generated within the Problem Discovery phase. Once again, students partake in a design review at the end of this phase to ensure that they have made appropriate decisions during the conceptualization process. This also allows teams to ensure that their chosen concept aligns with the desires of their client before moving to the embodiment design phase in EGR 315.

Within the embodiment design phase (EGR 315), students focus on translating rough concepts into preliminary prototypes. This process requires students to rely on their engineering fundamentals when making decisions about factors such as component selection, material selection, dimensioning, etc. To make these decisions, students utilize a combination of engineering calculations, numerical simulations, material property tables, CAD software and more. Once critical decisions have been made, students move on to preliminary prototyping and testing. At this stage, teams are focused on validating the performance of their system relative to their system requirements and determining areas for improvement. The iterative nature of this testing, evaluating, and refinement process leads directly into the Detailed Design phase. During the Detailed Design phase (EGR 315), students are focused on improving the quality of their prototypes and moving towards a finalized version of their design. This process involves several stages of testing and refinement, consideration of commercialization potential and overall validation of the design. This stage of the process again relies on the system requirements, wherein teams can base their testing and evaluation on the requirements that were established back in the Problem Discovery Phase. In the end, we look for teams to thoroughly document the performance of their designs and provide a summary of project progress and what future steps could look like.

It is important to note that iteration is the central tenet of this framework, as it is with many design frameworks. While the stages are presented linearly in the context of the capstone course sequence, this does not imply that they cannot be revisited as the design evolves. This iteration and reflection is expected and is intentionally built into the scaffolding of the design reviews.

Via design process content, rubrics, report templates, etc., there are clear expectations and requirements for our students to document and justify the design process and the steps used in completing their capstone projects. In preparing students for the workplace and engineering practice, this is a standard in which we strongly believe. We also encourage our students, where applicable, to apply engineering standards in executing their capstone projects. Towards this goal, a section in the final design report specifically requires that capstone teams identify engineering standards that apply to their project and describe how these standards were utilized to govern their design process.

Design Reviews are critical in real-world engineering practice and critical to capstone design as well. Design Reviews serve as key opportunities for the capstone design student team to showcase their progress and solicit feedback from experts and key project stakeholders. Each capstone team has 3 to 5 Design Review Panelists, comprised of subject-matter experts and key stakeholders (e.g., clients, users, etc.). At least one Capstone Coach (Capstone Instructors) is a member of this panel. Each semester, in EGR 314 and EGR 315, a minimum of two Design Reviews must be conducted by each capstone team. The design review process is essential to the articulation stage of cognitive apprenticeship. This is also a reflective process and provides an authentic opportunity for coaching from the design review panel. The composition of the Design Review Panel can evolve as the project needs to evolve in order to ensure that student teams are receiving relevant feedback regarding aspects of their project (e.g., concept generation, prototyping, etc.). The Design Review Panel serves as a "sounding board" for students to ask questions and get technical expertise on the direction of their projects and help identify knowledge gaps and areas of improvement for future Design Reviews.

Over the course of envisioning and delivering the WFU Engineering capstone design experience three times, we have adjusted each year informed by our own observations as faculty coaches, student feedback, and evaluating students' work products. It is important to note that the first cohort launched into capstone design amid the Covid pandemic. For the first cohort, EGR 314 (fall 2020) was fully remote and back in person for EGR 315 (spring 2021).

4. Cognitive Apprenticeship: Engineering Design Process, Methods, and Tools

In this section, we reflect on the Wake Forest Engineering capstone design experience leveraging the six phases of cognitive apprenticeship. We support the narrative with observations and student assessments.

4.1 MODELING: Engineering Design Process, Methods, and Tools

A variety of experts and strategies were used to model for students learning that is relevant to capstone design projects. Related to cognitive activities like the use of design methods, instructors provided examples of using specific design methods to guide students through the design process. As one example, students were asked to use morphological matrices to generate concepts that aligned with system requirements. Thus, this was a design method to support ideation, concept generation, and eventually concept selection. Other examples of faculty modeling design methods involved mathematical and computational modeling using subject-specific tools, failure modes analysis, stakeholder analysis, system requirement generation, etc. Using examples generated by experts (in this case faculty), students could witness and experience how key design activities and methods can support the iterative design process and engineering decisions. During year one, capstone instructors modeled the use of many design methods during class sessions, pre-recorded videos made available to students, and within assignments. From year one to year two to year three, this level of modeling (capstone instructors modeling the appropriate use of design methods) decreased because students wanted more autonomy to work on the capstone project. By year three, very little modeling was done by capstone instructors during class time and pre-recorded videos and resources were made available to students. As a result, we observed a decrease in student performance pertinent to the appropriate use of design methods and evidenced in their design decisions (Table 1). The challenge that students faced in this stage of the cognitive apprenticeship model is taking a worked-out example and translating the method or tool to their specific capstone project. We discovered that not all capstone teams effectively used such methods to support their project progress. Some teams struggled to connect elements of the design methods to their specific project, and this disconnect was further exacerbated by not having faculty fully aligned with understanding the design methods and the value such methods have to structure design decisions for novice learning.

4.2 COACHING: Engineering Design Process, Methods, and Tools

Coaching, which is the process of experts making observations of novices and offering feedback, has been critical for the WFU Engineering capstone design experience. As described previously, we have used an elaborate coaching model within WFU Engineering capstone design to support learning and offer capstone teams considerable feedback. During year one, one *capstone faculty coach* was assigned to each team to support them in navigating the design process. During year two and three, one lead technical faculty coach was assigned to each team to do this same role. The challenge that arose is that although the *lead technical faculty coaches* had subject-matter expertise with the technical aspects of the project, many of them lacked knowledge and experience with the intricacies of mentoring teams through customized design processes, using design methods appropriately, and helping students build connections between design process, tools, and application. The frequency of meeting with the lead technical coaches has varied over the years. During year one, it was a requirement that the capstone teams meet with their lead technical coach weekly or biweekly to provide a progress update, discuss the upcoming priorities, and discuss hurdles the team is facing. During year two and three, these regular meetings with coaches changed to becoming check-in and check-out sessions at the start and end of each of the four design phases. This resulted in capstone teams having more autonomy and less frequent meetings with some coaches happening. During year two, an attempt was made to designate *"area" coaches*. As an example, we have one coach that served as the "documentation coach" and who met with every team to provide them feedback on their documentation. Another example being a "prototyping coach" who met with each team prior to starting prototyping to ensure that each team had a prototyping plan in place, understood safety requirements, had adequate access and training to facilities and equipment, and had a clear purpose to the prototyping and testing work. These "area" coaches supported all the capstone teams in a systematic manner, and we saw good performance amongst the students. The one challenge with "area" coaches is that a disconnect could often arise between the feedback provided by the "area" coach and the lead technical faculty coach. Coordination would be essential amongst the coaches. Coaching has also played a critical role during the four design reviews (two per semester) during the senior year. We have learned that it is not trivial who is part of the design review process. During year one, we intentionally invited engineering faculty, subject-matter experts, industry engineers, and even "users" to be part of the design review process. This level of expert diversity and depth of expertise was immensely impactful to the capstone teams and the diverse feedback students received forced them to consider many perspectives that they would not have naturally been aware of. During year two and three, the *design review panels* were comprised of mostly engineering faculty and very few external experts. The impact of this change had both positive and negative effects. It was certainly easier to manage a smaller team of design review panelists and this was a positive, but it also removed essential expertise that external experts offered. As an example, an industry or practicing engineer often identified other areas of feedback compared to the engineering faculty. How this impacted student teams is that the feedback they received was now less diverse and less inclusive of industry practices.

4.3 SCAFFOLDING: Engineering Design Process, Methods, and Tools

Scaffolding involves experts supporting novices (i.e., students) with slowly removing support so as to allow students to work more independently. Scaffolding within WFU Engineering took place with *design reports*, *design reviews*, and *prototyping* each semester. Design report submissions within the capstone curriculum are scaffolded such that students slowly work through a complete template of sections to be completed, receiving feedback repeatedly on their drafts as they go through their project. Formal design review presentations are conducted twice per semester to provide thorough updates to their coaches, ask targeted questions of technical coaches, and receive feedback on their progress and project decisions. Prototypes are gradually built up with repeated technical feedback starting with a proof-of-concept model and building up through Alpha and Beta phases, providing structure at each step for students to demonstrate prototype function before refinement is conducted. Scaffolding is also taking place with adding formal and informal checkpoints throughout the semester and across the span of the year. Feedback and learning is supporting through scaffolding by all coaches involved. Scaffolding is also promoted by making course deliverables and deadlines visible to students at the beginning of each semester to provide a transparent pathway. *Tiered scaffolding* is also happening in a developmental nature. As an example, the fall semester (EGR 314) has tended to include more assignments and checkpoints compared to spring semester (where less scaffolding is provided). This intentional scaffolding offers students an opportunity to fully understand expectations and new content in the fall semester and operate more independently in the spring semester. While coaches still meet with their capstone teams in the spring semester, the teams start to operate with more autonomy.

4.4 ARTICULATION: Engineering Design Process, Methods, and Tools

Articulation involves the process of an expert(s) promoting the novice learner to articulate her/his understanding, reasoning, decision making, etc. Within WFU Engineering, articulation happens most prominently during progress meetings with coaches, during design reviews (two per semester), and in critical reviews of design documentation (e.g., progress meetings, demo sessions, etc.). While *progress meetings* with coaches have varied over the course of the past three years at WFU Engineering, effective progress meetings with coaches are an informal mechanism to observe students articulate their reasoning and justification of decisions. During year one, capstone coaches were required to have progress meetings weekly in the fall semester and biweekly in the spring semester. Student teams were expected to follow a consistent framework to share progress, upcoming priorities and deadlines, as well as dealing with obstacles. Year two and three, teams were given more autonomy in determining the frequency of progress meetings with coaches and this autonomy did not always benefit the project and team (and reflected in the performance results of Table 1). In general, and independent of the frequency of these progress meetings, technical coaches aim to understand how students are reasoning through the decisions they are making and focus on pointing students in the right direction without explicitly directing them. During these meetings, students articulate their progress and plans in some technical detail, including technical diagrams or testing plans. Such informal and ungraded documentation supports capstone teams' cognitive learning and development. Regarding *design reviews*, articulation of reasoning, understanding, and decision making was made visible to a broader panel of experts (beyond just the faculty coach) when students presented their project progress. This broader panel of experts often validated the observations and feedback of the faculty coach and served as a significant accountability step to empower the capstone teams to address the shortcomings that they were noticing for themselves and the shortcomings that the experts made visible to the teams. Design reviews have been a mainstay of the WFU Engineering capstone experience since year one and continue to be a significant learning activity. The design reviews are ideally suited to make visible to capstone coaches how the team is progressing through the project, how the team is making decisions, how well they can justify the decisions, how they are managing the team and project, etc. The practice of students developing and delivering these design reviews and reports allows students to step back and consider the bigger picture of their project and may prevent them from getting caught in the minutia of their project. Feedback during design reviews becomes an opportunity for capstone teams to refocus, rescope, rethink decisions, and reset priorities (as evidenced by the iterative approach illustrated in Fig. 5). Critical review of *design reports* also offers an opportunity to assess the cognitive reasoning of capstone teams. During year one, both capstone faculty coaches and the lead technical coach reviewed the design reports, but the amount of coordination became cumbersome and the misalignment of feedback from these two coaches became frustrating for students. During year two and year three, one capstone faculty coach reviewed all the design reports to offer teams consistent feedback. There are pros and cons to each of these models, but one thing is clear: technical documentation can reveal misconceptions, inappropriate reasoning, and unclear justifications in ways that oral presentations (e.g., design reviews and progress meetings) cannot always capture. Thus, it is advisable to have experts review diverse forms of communication (oral, written, prototypes) to effectively support students with articulation.

4.5 REFLECTION: Engineering Design Process, Methods, and Tools

Reflection allows the novice learner to compare their processes with those of experts. Design reviews which have been described previously offer an opportunity for students to hear from diverse experts how they are reasoning through the project and hear advise on other strategies to use in delivering a solution. Year one of WFU Engineering capstone design brought together a diverse team of experts to serve on the design review panels. As noted above, faculty experts combined with subject-matter experts, industry engineers, and other relevant stakeholders diversified the perspective and the feedback that student teams received. During year one, several reflection assignments supported students in reflecting on the feedback they received. As an example, during year one, teams were expected to document and summarize feedback received by experts on their design review panels and document meetings with relevant stakeholders. This type of reflection not only built accountability for the team, but it also enabled deeper reflection and synthesis of expert advice. Teams and faculty coaches could come back to this documented synthesis and reflection to determine project priorities, leverage new strategies and methods to make project progress, and use new resources or knowledge to make decisions. During years two and three, this level of reflection was not required (in the form of a course assignment), but some capstone faculty coaches continued the practice informally. We believe that there are more opportunities to support this cognitive phase within capstone design. Demonstrating more explicitly how experts problem solve effectively and allowing students to reflect on such processes is significant. What can be difficult in a typical engineering undergraduate department is having faculty who have practiced engineering and who themselves have experience with design processes, design methods, and design tools. Such experiences are essential.

4.6 EXPLORATION: Engineering Design Process, Methods, and Tools

Exploration involves the experts encouraging the novice learners to solve problems on their own. In fact, we have intentionally built in more exploration within capstone design from year one to year two and three. Students, in course evaluation surveys, voiced a desire to have more autonomy and thus we adjusted coaching and scaffolding to support exploration. From fall to spring semester, many faculty coaches shift their coaching style to further support exploration and to enable teams to solve their own problems. This is exemplified by teams initiating prototyping and testing plans, refining system requirements and prioritizing them, realigning on design decisions, etc. There are some areas (e.g., codes and standards, testing techniques, etc.) that are inherently difficult for students to know and be aware of and this requires coaching and scaffolding. Teams are asked to make their work visible and to show drafts of their work before getting formal sign-off to proceed to the next step. This is an important procedure for teams to grasp and a process that challenges many teams, especially those ones who are not comfortable and lack confidence to showcase their draft work to receive feedback. Teams engage with their faculty coaches and technical experts throughout the prototyping stages of their project, gaining experience prototyping through physical models and/or software in line with their project needs. Project groups who require physical models are trained on the necessary equipment at the Wake Forest Engineering Innovation Studio or relate to a local partner with the appropriate expertise. Lectures throughout the latter two design phases, embodiment, and detailed design, include prototyping thinking and considerations, where students learn design considerations such as rapid prototyping tools, workflow, tolerancing, and tool kerf. Student teams are encouraged to share their early models and prototypes to faculty and engage in conversations with faculty and technical experts about how they are considering solving their design challenges, with the goal of shaping student design thinking to more effectively and elegantly problem solve. Special consideration must be provided to teams with software components being part of prototypes.

4.7 OTHER OBSERVATIONS: Engineering Design Process, Methods, and Tools

From course evaluation results, we discovered that students highly valued (1) interactions with faculty coaches over any classroom lecture or pre-recorded video, (2) interactions with technical experts and relevant stakeholders, (3) design reviews with a diverse set of experts, and (4) appreciated detailed feedback on design reports, design reviews, and one-on-one meetings with coaches. Similarly, we discovered that students wanted more customized coaching that was project specific over generic lectures and methods. The challenge this presented though was that not all faculty coaches were familiar with the design tools and methods of the class so disconnect and misalignment became visible and this even impacted student performance.

Although not inclusive of all areas of student learning and student performance, Table 1 showcases how students performed across key areas of problem solving, design process, design methods, prototyping, stakeholder engagement, decision making impacts, and testing. As many capstone design experiences are integral to ABET accreditation procedures, the performance metrics (column 1) map to the ABET Student Outcomes 1, 2, 4, and 6. The shaded cells reflect areas where performance decreased from year one to year two. In part, even while more rigorous study design and assessment would be needed, we can attribute some of these performance changes to the changes we made to the structure of the experience from year one to year two. As an example, because expert modeling as a cognitive phase decreased from year one to year two, as did the number of scaffolded assignments to support design methods, we observed that student performance across performance areas of Student Outcomes 1, 2, and 6 also decreased. In some cases, the performance changes were not high or significant, but overall, a general pattern is important to note. In other learning areas, because the coaching model was enhanced, we saw areas of increased performance (e.g., stakeholder engagement and understanding the impacts of decisions). Future work to connect student learning and the cognitive

Table 1. Student performance over the first two runs of WFU Engineering across key areas of learning. Percentages are associated with the number of teams who attained the performance indicator. Shaded cells reflect decreased performance from year one to two

Performance Indicators	**Year 1 (10 Teams)**	**Year 2 (11 Teams)**
Effective Use of Engineering, Science, and Math Principles (ABET SO1 related)		
Identify appropriate engineering, science, and math principles	100%	100%
Formulate appropriate engineering, science, and math formulas or models	100%	91%
Apply appropriate engineering, science, and math principles, calculations, & models	100%	73%
Effective Use of Engineering Design Process, Principles, Considerations (ABET SO2 related)		
Effective use of the engineering design process	100%	82%
Consider alternative solutions to meet design specifications	100%	91%
Select concepts to embody the design specifications	100%	91%
Consider appropriate technical factors	90%	73%
Consider appropriate sociocultural factors	100%	100%
Consider appropriate economic factors	100%	91%
Consider appropriate environmental factors	100%	100%
Use appropriate methods and tools to produce an alpha or beta prototype	90%	91%
Appropriate use of codes and standards	90%	82%
Effective Engagement with Stakeholders and Impacts of Decisions (ABET SO4 related)		
Identify and engage with relevant stakeholders	100%	100%
Understand ethical implications of design decisions to stakeholders	100%	100%
Recognize appropriate *sociocultural* impacts to inform decision making	100%	100%
Recognize appropriate *economic* impacts to inform decision making	80%	82%
Recognize appropriate *environmental* impacts to inform decision making	100%	100%
Effective Testing, Experimentation, Analysis, and Conclusions (ABET SO6 related)		
Develop appropriate testing plans and procedures to evaluate system performance	90%	64%
Conduct appropriate testing plans and procedures to evaluate system performance	90%	82%
Analyze data from testing and interpret appropriately to inform design decisions	90%	91%
Use engineering judgment to draw conclusions that inform next steps	90%	82%

phase of the apprentice model would be needed to make stronger conclusions.

5. Cognitive Apprenticeship: Team Effectiveness and Project Management

Capstone design programs typically emphasize technical and design knowledge and skills, but professional success is enabled by effective teamwork and communication, interpersonal fluency, cultural competence, self-mastery, and a learning orientation. Cognitive apprenticeship supports deep engagement of non-technical learning goals by challenging team members to surface their thinking for collaborative analysis, articulation, and/or reflection. During the past three years of capstone design at Wake Forest, the instructional team designated a *Team Strength Coach* who, with input from the instructional team, designed, implemented, and iterated on instructional content and pedagogical strategies to support learning domains associated with team effectiveness and project management. Agile project management training and strategies were offered to the capstone teams as were strategies for team effectiveness. Importantly, development and application processes are intentionally aligned with the design and character aspects of the course to provide a coherent experience for student teams as they gain expertise and independence across two semesters of immersive capstone project work and learning. The progressively empowering mentor-apprentice learning exchanges that characterize cognitive apprenticeship have demonstrated value across individual and team contexts.

Because strength-based approaches have demonstrated efficacy for higher education [28], professional development applications [29], and even engineering education [30–31], Wake Forest Engineering has adopted a strength-based framework for teaching team effectiveness and project management that we call *GRIP Strength* due to foci on goals, roles, interactions, and planning (GRIP). The term *Team Strength* is used here, as it is in our courses, to encapsulate learning related to effective teamwork and project management. Wake Forest Engineering's *GRIP Strength Framework* is adapted from established industry practices and designed to enable collaborative strength, motivate prosocial action, and encourage creative exploration [32]. General Electric (GE) provided the "source code" for our approach based on its long-term emphasis on collaborative productivity, employee character, and its engagement of apprenticeship training. Indeed, GE was one of the first large engineering companies to embrace apprenticeships. In the early 1990's, CEO Jack Walsh ushered in the Change Acceleration Process (CAP), which GE and many subsequent adopters use to this day. Numerous high quality educational tools have emerged from CAP over the years, including a multipurpose rubric based on the GRIP Model of Team Effectiveness [33] which GE has continued to use for team assessment and improvement across the company [34].

5.1 MODELING: Team Effectiveness and Project Management

During first semester of capstone, the *Team Strength Coach* regularly used modeling as a demonstrative tool. The short classroom lectures that framed essential collaborative practices stemmed from industry standards, faculty experience, and feedback from previous students. Successful teamwork and project management are enabled by productive communication, expectation setting, mutual accountability, and conflict engagement. For instance, good communication is modeled through active listening, questioning, and immediate feedback in team coaching sessions. Expectation setting and accountability are modeled through faculty conscientiousness as well as clear and consistent team expectations adherent to the *GRIP Strength* Framework (Table 2). The importance and innovative potential of conflict engagement is modeled by prioritizing and establishing norms of trust and transparency in faculty-student and faculty-team communication. Engineering faculty and external technical experts also played critical roles in modeling effective teamwork and communication. The collaborative co-teaching model allowed students to experience a diversity of expertise presented in a cooperative format.

5.2 COACHING: Team Effectiveness and Project Management

Coaching strategies characterized by instructor observation and formative feedback have demonstrated utility across many higher education contexts [35, 36]. As noted earlier, instructional coaching is a core driver of the WFU Engineering capstone design experience. Rather than providing direct answers, instructors often use open-ended questions, hints, and feedback to encourage teams to think critically and find their own solutions. This approach empowers students to take ownership of their work while developing problem-solving skills. Teams are encouraged to adopt a growth mindset by embracing the learning process and perceiving challenges as opportunities for creative innovation. This approach helped students develop resilience and perseverance when faced with setbacks. To facilitate self-awareness and encourage teams to take responsibility for their own learning, coaches employed Agile tools that compelled teams to periodically reflect on their progress and identify areas for improvement. Twice per semester, the Team Strength coach conducted a rubric-based assessment of team performance across the eight GRIP Strength domains in Table 2. Teammates had ample time to review their feedback internally prior to sharing reactions and development goals with the Team Strength coach in scheduled sessions. In the interest of cultivating trust and engagement, both written and oral feedback targeted accessible improvement goals and highlighted strengths as well as development opportunities. Teams were advised early and often that interpersonal conflict is inevitable and can often catalyze creativity and innovation when engaged earnestly and openly. Team working agreements were recognized for their ability to render shared expectations and recognized standards for collaboration, accountability, communication, and conflict. Although such activities were not favored by the students and for some regarded as a distraction from more important project work, most teams discovered that the quality of their working agreements depended on the quality of their interactive process. Coaches provided feedback to these working agreements and could also provide one-on-one feedback to individual students as appropriate and as needed.

5.3 SCAFFOLDING: Team Effectiveness and Project Management

Scaffolding was important to support team effectiveness and project management. A year-long design project can feel complex and overwhelming, and preparing a detailed task backlog at the beginning of each design phase (Fig. 4) helped teams break down project goals into manageable tasks. When managed effectively, backlogs enable detailed task tracking, reprioritization, and work assignments. Such a practice was designed to help team members feel less overwhelmed and maintain confidence in their ability to complete the project successfully. What was observed over the years is that capstone teams would not consistently present their backlogs to their Lead Technical Coach for feedback. While some teams might present these backlogs to the Team Strength Coach, their Lead Technical Coach would not have seen their backlog. Such disconnects demonstrated how easily student teams can skip important feedback and communication steps with technical experts who can inform project management timelines. As the teams progressed from semester one to semester two, particularly for teams who were meeting project goals and deadlines, coaches scaffolded project management oversight and allowed teams to work more independently. From the perspective of team effectiveness, we discovered that while most conflicts were resolved internally, a significant minority required faculty facilitation to manage disagreements resolve misalignments and relieve tension. In most such cases, coaches scaffolded support over a matter of weeks until teams were able to (re)take ownership. In rare cases, teams needed regular support for the duration of the project to maintain functionality.

5.4 ARTICULATION: Team Effectiveness and Project Management

A team's ability to successfully articulate progress toward GRIP Strength learning goals (see Table 2) represented a critical competency on the journey toward independent exploration and innovation.

Table 2. Team GRIP Strength Framework used by Wake Forest Engineering for capstone design

Team GRIP Strength Framework **G**oals, **R**oles, **I**nteractions & **P**lanning	
G	**Common Purpose:** Team is aligned on project goals & shares a vision of the path to success. Core Strengths: Empathy, Honesty
	Pro Humanitate: Team activities are characterized by efforts to better the lives of others. Core Strengths: Compassion, Service
R	**Equity & Shared Leadership:** Responsibilities are delegated equitably & engaged responsibly. Core Strengths: Cooperation, Autonomy
	Team Agility: Team can adapt to change and meet emergent challenges (functional flexibility). Core Strengths: Judgement, Creativity
I	**Interpersonal Dynamics:** Team demonstrates effective communication & collaboration. Core Strengths: Trust, Authenticity
	Decision Making: Team decision-making processes are cooperative, thoughtful, and prosocial when possible**.** Core Strengths: Practical Wisdom, Humility
P	**Short-Term Planning:** Team maintains effective short-term planning practices & a detailed weekly schedule**.** Core Strengths: Diligence, Persistence
	Long-Term Planning: Team maintains a long-term schedule including known deadlines, events & milestones. Core Strengths: Purpose, Perspective

From a Team Strength perspective, articulation is primarily demonstrated through scheduled coaching sessions, Agile retrospectives, and periodic self and peer evaluations. During face-to-face meetings, the Team Strength Coach challenged teams to reflect on experience and illustrate specific processes or experiences they associate with good practice. These sessions also provided regular opportunities for teammates to share formative feedback with one other, a daunting task for some that takes both time and trust to establish. Teams also completed periodic retrospectives framed by Agile best-practices [37]. The points of reflection offered numerous opportunities for each team and each student to articulate their own learning and performance in service of developing a clear action plan to support continued development. Finally, the CATME (Comprehensive Assessment of Team Member Effectiveness) peer and self-assessment [38, 39] was deployed at three points across the capstone experience to compel meaningful engagement and articulation of feedback processes essential to building team strength. While students did not want CATME ratings to be used for performance grading, we discovered that many students appreciated the tool as a means of self and peer evaluation. When faculty coaches were able to debrief with teams, either in a one-on-one setting or in a group setting, about team effectiveness, it was well received.

5.5 REFLECTION: Team Effectiveness and Project Management

Reflection allows students to compare their processes with those of experts. While such comparisons are not generally explicit, team strength exemplars are embedded throughout the capstone experience in the form of best-practices (as noted in the previous section), exemplary work from previous capstone teams, and engagement with professional practices through readings and videos. One particularly popular comparative methodology does exist, however. The recently established tradition of gathering team strength advice from each graduating class and passing it on to the next class. Peer advice has been shown to be a potent motivator among university students [40], and based on our early returns, it appears that engineering design is no exception.

5.6 EXPLORATION: Team Effectiveness and Project Management

Although our coaching model is specifically designed to encourage teams to resolve internal challenges independently through mutual trust and transparency, such autonomy is not truly expected until the second semester, and teams always have a straightforward path to faculty support. Because team effectiveness and project management are not typically top of mind for engineering students who tend to prioritize technical rather than humanistic content [41], independent exploration is encouraged through value propositions that illuminate the importance of collaborative communication and project management skills to professional engineering practice [42]. As demonstrated in the next section, capstone coaches also target team-specific opportunities to demonstrate the professional value of personal strengths like honesty, compassion, and practical wisdom.

5.7 OTHER OBSERVATIONS: Team Effectiveness and Project Management

Among the most important lessons we learned across three years of team strength coaching is the importance of cultivating student motivation. During year one, team effectiveness and project management topics were taught with the expectation that teams would engage these non-technical topics with the same vigor applied to technical and design challenges. In relatively short form, and despite the fact that collaboration and communication skills are valued by industry as much as technical competencies [42, 43], student behavior demonstrated that team-focused course content was typically regarded as less important, "necessary-but-boring," or even superfluous. For this reason, targeted motivational strategies were developed and increasingly embedded in apprenticeship practices during years two and three. Research on socioemotional aspects of student learning during cognitive apprenticeships have highlighted the motivational importance of contextual factors [44] and student goals [45]. The motivational potential of specific learning contexts was leveraged by drawing on the students' common intrinsic desires for ownership, self-assurance, and professional success. For instance, teams were granted higher degrees of independent control regarding development and maintenance of project management processes. Anecdotal evidence suggests that higher degrees of ownership and trust do motivate teams to independently maintain detailed project backlogs, however, the *quality* of the project management strategies suffered in comparison to teams who were subjected to more faculty oversight. So, there may be a trade-off between effort (i.e.. quantity) and effectiveness (i.e. quality). A more successful method of motivating students to engage non-technical team strength content entailed regular value-propositions (i.e. pitches) delivered by the Team Strength Coach. When students understand the professional desirability and practical value of soft skills, the shift in perspective typically leads to increased engagement and effort.

6. Cognitive Apprenticeship: Character Cultivation & Entrepreneurial Mindset

In 2018, Wake Forest Engineering joined the Kern Entrepreneurial Engineering Network (KEEN) as an institutional partner with a commitment to integrate an entrepreneurial mindset across the engineering curriculum. Additionally, in 2019, Wake Forest Engineering received multi-year funding to support character education across the engineering curriculum. This unique combination of entrepreneurial mindset with character education may seem as two distinct areas of learning, but that is not how the Wake Forest Engineering capstone design team saw things. In fact, we believed that capstone design experiences serve as fertile ground for both an entrepreneurial mindset and character development to be embodied. We broadly define entrepreneurial mindset as learning that supports positive value creation through curiosity and building connections [46]. We also broadly define character development as the process to continuously advance one's dispositions towards moral, civic, performance, and intellectual virtues. Some of our prior work serves to offer context to our approach in linking engineering ethics to character education and the importance of character education within capstone design [47–50]. In this section, we reflect on students' entrepreneurial and ethical development leveraging the six phases of cognitive apprenticeship. Virtues that our team has identified to be important to engineering practice, capstone design, and in developing an entrepreneurial mindset are listed in Table 3. This list of virtues is informed by the Jubilee Center Framework which categories virtues across four categories – performance virtues, intellectual virtues, moral virtues, and civic virtues [51]. All these virtues culminate into one integrated virtue – practical wisdom. From this list, one can imagine that the process of designing an engineering solution for human flourishing requires (a) *purpose* to understand the potential impact to people, (b) *empathy* to understand the needs and perspectives of others, (c) *curiosity* to explore new ideas, new knowledge, new perspectives, (d) *creativity* to transcend the existing solutions that might not fully meet the needs of those most impacted, (e) *humility* to understand the limits of one's knowledge and recognize the importance of seeking new knowledge and seeking expertise from others, (f) *teamwork* to bring diverse expertise in tackling a problem collaboratively, (g) *honesty* to communicate openly and with integrity, (h) *courage* to stand up for visible or invisible injustice or to stand up for values that will benefit others even when it goes against the traditional norms, etc. We do not suggest that this list of virtues is all exhaustive, certainly there are other virtues that are important to character development and entrepreneurial mindset. This is simply a start for us.

6.1 MODELING: Character Development and Entrepreneurial Mindset

The act of modeling entrepreneurial mindset and character is built into the ethos of Wake Forest

Table 3. Virtues relevant to the capstone design at Wake Forest Engineering and enabling us to embody character development and entrepreneurial mindset [52]

Virtues	Type [51]	Definitions We Adopted
Resilience	Performance	The capacity to recover quickly from difficulties.
Critical Thinking	Intellectual	Being analytical and approaching challenges from multiple perspectives
Teamwork	Performance	Being collaborative and participative as a group or team member
Curiosity	Intellectual	Being interested in new ideas, experiences, and people
Creativity	Intellectual	Thinking of unique ways to solve problems and create new opportunities or products
Purpose	Civic	Having a sense of meaning beyond oneself
Practical Wisdom	Integrated	Knowing what the good, right, or best thing is to do given a particular set of circumstances
Humility	Intellectual and Moral	Having an accurate understanding and acceptance of one's own intellectual strengths and limitations
Honesty	Moral	Telling the truth
Service	Civic	Working to benefit others
Courage	Moral	Being willing to engage challenges that are difficult or dangerous
Empathy	Moral	Putting oneself in other people's shoes and understanding other points of view
Zest	Performance	Being enthusiastic
Authenticity	Moral	Understanding and embracing one's identity and values in how one lives
Justice	Civic	Valuing and working for fairness and equality

Engineering. Students witness early in the curriculum engagement with the community and engagement with a wide array of stakeholders that inform and support professional engineering practice via a project-based learning curriculum. In the context of capstone design, authentic projects are sourced from students, faculty, staff, community partners, and industry partners. Such action demonstrates to students the *responsibility* engineers have to society and the sense of *purpose* and *service* that accompanies engineering work. In fact, engagement with relevant stakeholders is a requirement for all capstone projects and is something that teams are expected to do throughout the project duration. Stakeholders include clients, users, subject matter experts within and beyond engineering, regulatory experts, context experts, etc. Some stakeholders might play a role at the onset of the project, while other stakeholders may be meeting with teams monthly. The frequency and cadence of stakeholder engagement is determined by the capstone student teams and their faculty coaches. Stakeholder engagement is not only important for the technical aspects of the design projects, but also important in promoting an entrepreneurial mindset that is achieved through *curiosity*, *critical thinking*, *empathy*, *creativity*, *justice*, etc. Stakeholder engagement also promotes students' focus on identifying and working on the design requirements that will offer the most value for those that will be impacted by their engineering solutions. The capstone faculty coaches also model entrepreneurial mindset in their day-to-day interactions with student teams and model character in the ways that they promote effective communication, teamwork, and decision-making. This intentional integration shows itself in various ways: (1) faculty coaches facilitating meetings with stakeholders (e.g., clients, users, technical experts, etc.) to ensure appropriate questions are asked and appropriate understanding of context, (2) faculty coaches demonstrating to teams techniques that can support value creation (e.g., existing solutions, benchmarking, finding appropriate stakeholders, etc.), (3) experts presenting to the capstone teams to model new methods and approaches that can inform project work (e.g., engineer entrepreneurs, legal experts, IP experts, PE licensure requirements, etc.).

6.2 COACHING: Character Development and Entrepreneurial Mindset

The diverse team of faculty, staff, and experts that are integrally involved in the Wake Forest Engineering capstone design experience serve as coaches for the student teams. These experts challenge the students teams to think out of the box in ensuring they have engaged with stakeholders adequately, understand the problems and identify design requirements, deliver creative solutions, recognize misconceptions, etc. Engineering faculty have consistently engaged with the KEEN network, developed character modules throughout the curriculum, and have made character education the focal point of several department meetings. All capstone faculty coaches are therefore familiar with these character virtues and committed to integrating them into the engineering curriculum. Although coaches do not catch all the issues that a student team will face, there are opportunities during weekly faculty coach meetings, design reviews, informal interactions, and meetings with stakeholders for the experts to provide guidance, feedback, and insights. As an example, coaches will point to conceptual designs lacking *creativity*, stakeholder needs not fully being addressed, expert feedback from design reviews not fully being addressed, or *teamwork* not being transparent and effective. Coaches truly play a critical role as evidenced by these examples: (1) faculty coaches debriefing with the student teams after critical meetings with stakeholders, (2) faculty coaches providing feedback and critiques on design decisions and providing feedback to student teams running meetings with relevant stakeholders.

6.3 SCAFFOLDING: Character Development and Entrepreneurial Mindset

In line with what has been shared previously, faculty coaches and other experts support student teams with some tasks and slowly remove the support to allow independent work. This is evidenced when faculty coaches step away from the meetings with stakeholders and allow the student teams to facilitate the meetings and communication. Scaffolding is also evident when faculty coaches invite student teams to find additional relevant stakeholders and potential users for feedback and invite teams to rethink the prioritizing of project goals. By the second semester of capstone design, many faculty coaches step back and allow more autonomy for the student teams even at a cost of impacting project performance. Such intentionality truly supports the development of *practical wisdom*, *humility*, *critical thinking*, and *resilience*.

6.4 ARTICULATION: Character Development and Entrepreneurial Mindset

It is a powerful moment to see student teams justify their decisions with strong reasoning and we often observe such moments during design reviews and meetings with faculty coaches. Justifying decisions and articulating how a team made a decision is not an inherently easy process for student teams and does require prompting from the faculty coaches. It is a critical step though that reveals gaps and misconceptions of student teams and even coaches. Questioning and inquiry are powerful ways to promote articulation. Effective coaches are doing this in every interaction with the student team and effective coaches are also open to learning and challenging their own misconceptions. These back-and-forth exchanges are supporting *honesty*, *humility*, and *authenticity*.

6.5 REFLECTION: Character Development and Entrepreneurial Mindset

Reaching this phase of cognitive development is not trivial for capstone teams. Because most teams are tackling projects that have not been completed before (i.e. these are novel projects), it is not easy to create opportunities where students teams can compare their processes with those of experts. What we have evolved to do better over the years, but still developing, is to enable student teams to make their work and processes visible to other teams. Not only does this promote camaraderie, but it also allows teams to see methods, tools, resources, and experts that one team used over another. This opens up opportunities for teams to learn from each other. One strategy that was piloted this past year is to allow junior engineering students to observe the senior engineering students during design reviews and presentations and in some cases to have junior engineering students support in a small way tasks that the senior capstone teams need. Regarding the entrepreneurial mindset, assignments in the first two years enabled the student teams to develop commercialization plans and compare such plans with those of experts. This past year, faculty from the business and law schools were invited to present to the teams and showcase business thinking and legal matters. Students valued these non-technical perspectives and reflecting on their projects from the lens of business and law, supporting their *critical thinking* and *empathy*. All in all, this phase thus continues to be a work in progress.

6.6 EXPLORATION: Character Development and Entrepreneurial Mindset

This phase of cognitive development can be reached by some capstone teams. While faculty coaches promote exploration and students tackling new problems on their own, many teams do not feel prepared to do this early in the project. We see more evidence of this in the second semester of capstone when teams begin to demonstrate more ownership and independent thinking with project work. Such exploration takes *courage* because it is perceived as taking risk with a new idea that might cost the team time and loss of progress in other areas, *practical wisdom* to start making decisions that will impact other design decisions and over project progress, and *creativity* to recognize that novelty with a new direction or a new design feature or a new stakeholder engagement will impact the performance of the entire system. The teams that we have observed reach this phase of cognitive development are the ones that feel empowered by their lead technical coach, that have made adequate progress in other areas of the project, and are innately interested to explore new directions and ideas.

6.7 OTHER OBSERVATIONS: Character Development and Entrepreneurial Mindset

As is evident from the examples provided above, faculty coaches and experts with entrepreneurial mindset and who model virtuous character are essential. While steps have been taken to deliver relevant content, bring relevant experts, and promote virtuous character and entrepreneurial mindset to capstone design, we believe that the lead technical coaches must model such attributes for the student teams. Regarding entrepreneurial efforts, our team is limited by the fact that only a few engineering faculty have extensive expertise with commercialization of engineering innovations and expertise to move technical ideas to commercial use. So, while entrepreneurial mindset is promoted, the coach expertise does not fully exist. It is also important to note that a one-year capstone experience is not conducive to making progress with commercialization.

In regard to character development, Fig. 6 points to student self-perceptions of growth. Administered within the second semester course evaluation and with a high response rate (~90%), students rated the extent to which they perceived growth across the specified virtues. The highest rated growth were performance and intellectual virtues – *resilience*, *critical thinking*, *teamwork*, *curiosity*, and *creativity*. The second tier of perceived growth were civic and moral virtues (plus the integrated virtue of *practical wisdom*) – *purpose*, *humility*, *honesty*, *service*, *courage*, *empathy*. *Justice* was the lowest rated growth area. Such results are in line with other parts of our curriculum [51] and may not seem surprising to see that intellectual and performance virtues are prioritized over civic and moral virtues for our novice learners.

7. Discussion

Applied to both technical and non-technical domains of learning within capstone design at Wake Forest University, we have discovered that cognitive apprenticeship can offer a meaningful way to develop and reflect on pedagogical features that can support engineering student development.

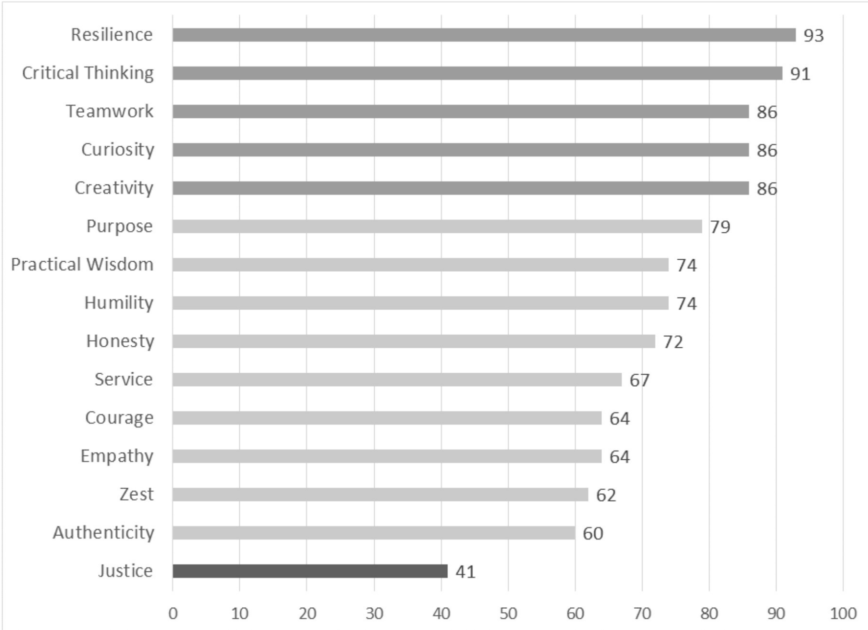

Fig. 6. Percentages of students that perceived growth across the specified virtues during capstone design.

Accompanied with appropriate learning assessments, which was not the focus of this paper, we believe that a cognitive apprenticeship model to capstone design can transform how we educate and prepare our engineering graduates for the complexities of real-world engineering practice. Fig. 7 illustrates how a cognitive apprenticeship approach can guide teaching teams and educators at many levels to rethink how cognitive learning across technical and non-technical domains can be guided by intentionality. Recognizing the cognitive stages that need improvement is fundamental for all bettering ourselves as educators and bettering our students.

Cognitive apprenticeship is grounded on six phases of learning – modeling, coaching, scaffolding, articulation, reflection, exploration – and we discovered that all these phases are important to the learning complexities of engineering design. Learning does start with clear understanding and articulation of the learning goals. As a new engineering program, learning outcomes continue to be a work in progress, but we are proud of the commitment of the faculty team to support technical and non-technical domains of learning in every course. As evidenced from this paper, our capstone design experience intentionally bridges engineering design and engineering science content knowledge with personal and professional development (e.g., teamwork, communication, ethics and character, project management, entrepreneurial mindset, etc.). At a high level, Fig. 7 points out that capstone design faculty may be better at scaffolding and articulation. Phases of improvement include modeling, coaching, reflection, and exploration so that students can better cultivate engineering design competencies as well as entrepreneurial mindset and character development. We also observe that while capstone design faculty may be more innately prepared to cultivate engineering design competencies and team effectiveness, more intentionality is needed with competencies like entrepreneurial mindset and character development. These kind of knowledge gains at Wake Forest Engineering have significant potential for transferability to other engineering programs. Many opportunities for future work (research, pedagogy, and assessment) exist to Educate the Whole Engineer across technical and non-technical competency areas [53]. This is a form of integrative learning [53] that requires intentionality. The following paragraphs highlight major take-aways from each of the six phases of cognitive apprenticeship.

Modeling allows an expert, which in our case were engineering faculty and external experts, to demonstrate effective use of tasks, activities, and decisions. We discovered by engaging a diverse set of engineering faculty experts and external experts (e.g., subject-matter, industry, community partners) that it truly takes a village of experts to effectively model to students both technical and non-technical domains of learning. While many engineering programs are not ideally setup to support such a diversity of engineering and non-engineering experts to support this phase of learning development, we encourage experts to be sourced from other units of the university and the community. Student teams truly need to see a diversity of

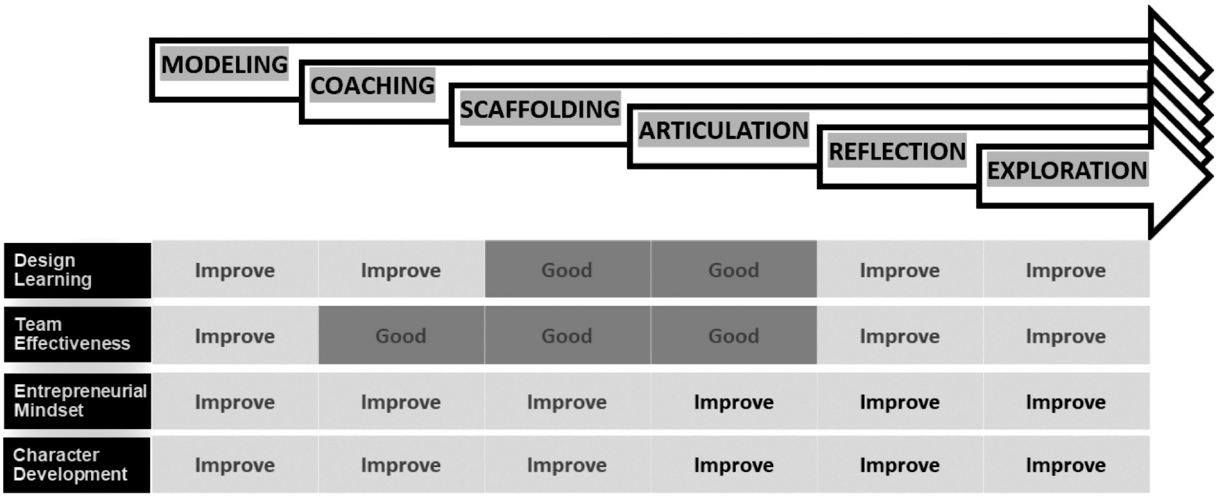

Fig. 7. Summative reflection of areas to improve capstone design at Wake Forest Engineering across the six cognitive apprenticeship stages.

experts coming together to support the complexity of learning associated with engineering design. How the modeling takes place is also not trivial and requires iteration to determine the appropriate content, the appropriate methods, the appropriate sequencing, and the appropriate coaching approach.

Coaching enables an expert to observe a novice learner perform a task and to offer feedback and hints for improvement. Through iteration with various faculty coaching models, we have discovered that effective coaches use every moment of interaction with a student team and diverse activities to offer feedback and support learning development. Regular progress meetings, design reviews, debrief sessions from meetings with stakeholders, debriefs from design reviews, and review of design artifacts all serve as powerful opportunities for faculty experts to provide feedback to teams on both technical and non-technical domains of learning and growth. Design reviews which often involve external experts (engineers and non-engineers, industry perspectives and stakeholder perspectives) further serve as opportunities for learning and feedback as well. Coaching moments are thus everywhere, and intentionality is needed to effectively provide student teams feedback. The progressively empowering mentor-apprentice learning exchanges that characterize cognitive apprenticeship have truly demonstrated value across individual and team contexts. Because engineering faculty may come lacking experience with formal training and professional experience in engineering design, we have discovered that professional development can support effective coaching.

Scaffolding is another critical component of cognitive apprenticeship where experts must find the right balance between providing structure and autonomy for different phases of the design project. We discovered that scaffolding supported mastery of learning and even promoted learning through failure. Whereas at the beginning, experts provided instruction and coaching, by second semester, most of that support was removed to allow student teams to work more independently. Reduced structure allowed students to spend more time working on the project and more flexibility to apply specific design tools that are most relevant to their project. With flexibility and autonomy came failure too and with that at times less developed prototypes and final products. This flexibility though was essential as our team valued process just as much as (if not more than) the final product. In our approach to teaching capstone design, we carefully integrated activities and assessments that emphasized process-centered learning (e.g., two design reviews per semester, mid-term reports along with end-of-semester reports, prototyping checkpoints, backlogs at the start of each design phase, etc.). We preferred students to develop a product that represented a careful and reflective design process as opposed to one that superficially impressed an outside audience with a perfectly functioning prototype that did not effectively meet the user needs. Thus, via scaffolding, which continues to be a work in progress, we made trade-offs with adding and removing learning activities and assessments to ensure students are not only digging into the technical aspects of their projects, but holistically growing as individuals and teams through failures too.

Articulation of technical and non-technical learning within capstone design involved opportunities where student teams could explicitly share their understanding, reasoning, and decision making.

This was most evident during design reviews, which occurred twice per semester and involved faculty and external experts, and during meetings with the coaches. Design reviews were more formal sessions and meetings with coaches less formal. Whereas the technical faculty coaches may have targeted students' articulation and reasoning on design decisions (e.g., concept selection, prototyping decisions, testing protocols, etc.), the team strength coach supported non-technical domains of learning and articulation like team effectiveness (e.g., conflicts arising, clarity of roles and responsibilities, effective communication) and project management (e.g., meeting deadlines as a team, keeping backlogs or schedules updated, aligning on priorities, etc.). Synergy amongst the coaches was important. Ideally, the faculty coaches would be equipped to support both the technical and non-technical aspects of the capstone design learning experience, but this has taken a few years to achieve and we are more intentionally ensuring such integration and synergy is happening.

Reflection is the act of an expert enabling the novice learner to compare their processes with other experts. Some reflection happened via coaching, extensive research being built-in to the process, and some peer-to-peer comparisons, but as a brand-new engineering program, reflection may have been the hardest cognitive learning phase. Because most of the faculty coaches were inexperienced with capstone design and engineering design experience, reflection was not easy. Howe et al. [2, 3] have extensively surveyed engineering capstone design programs and emphasized the importance of engaging faculty that have industry experience and who pursue continuing education related to design practices. We would support this claim on all fronts for both technical and non-technical domains of learning. It can indeed be difficult in a typical engineering undergraduate department to have faculty who have practiced engineering and who themselves have experience with design processes, methods, and tools in an industry setting. While many engineering faculty work on translational research, practicing engineers operate under different constraints and more often consider the diverse and complex needs of stakeholders. Reflection thus can look different under the mentorship of engineering faculty who do research than practicing engineers in industry. When faculty instructors and coaches have these knowledge and experience gaps, incentives should be provided to encourage continuous learning and professional development. Junior faculty might feel stretched thin to pursue such opportunities and one way we mitigated this was the recruitment and involvement of external technical mentors (many from industry or more senior faculty) who have the capacity, knowledge, and experience to guide students in targeted areas.

Exploration being the final phase of cognitive development is the act of an expert encouraging the novice learner to solve problems on their own. For most of our student teams, this took place in the second semester, but some teams were able to demonstrate exploration from the start of the project. Because stakeholder engagement happens in our engineering program from year one, many of our capstone teams felt confident to engage with diverse stakeholders early and explore diverse perspectives in scoping the projects. Prototyping, on the other hand, required most teams to work with coaches and fabrication experts before exploration could take place. Thus, we observed that exploration varied for each team and varied depending on the expertise of the team and the complexity of the project. Team performance benefitted from faculty trust and independence.

8. Conclusions

To Educate the Whole Engineer holistically, engineering educators must recognize that both technical and non-technical domains of learning are needed within every engineering class to support the cognitive development of the engineering student as the learner or apprentice. This is a must to prepare them for the complexity of professional engineering practice. Engineering design plays a most critical role during undergraduate engineering education for the authenticity of learning that most closely mimics professional engineering practice. Considering the importance of engineering design to the practice of engineering, it is thus imperative for engineering educators to use appropriate pedagogical approaches to prepare engineering graduates for the complexities associated with engineering design projects and ultimately with the complexities of professional engineering practice. The complexities of engineering design involve not only technical domains of learning (e.g., design process and thinking, design principles, design methods and tools) but also non-technical domains of learning (e.g., collaboration and teamwork, engagement with stakeholders, effective communication, project management, ethical decision making, entrepreneurial mindset, professionalism, character development, etc.). This paper connects engineering design, in the context of capstone design experiences, with a cognitive learning theory that is appropriate for engineering practice and engineering education – cognitive apprenticeship. The purpose of this paper is to reflect on the appropriateness of cognitive apprenticeship as a model to support pedagogical approaches and innovations in engineering design education via capstone design experiences, which are required of all ABET accredited engineering programs in the US.

We have learned that a cognitive apprenticeship approach to pedagogically guiding capstone design experiences in engineering can be fruitful and valuable. While some capstone design programs may measure success based on students' technical and design skills, we have found immense value in supporting students' personal and professional success as well. Just as important as the technical aspects are to engineering design, so are the non-technical aspects of interpersonal communication, ethical reasoning and character development, entrepreneurial mindset, self-awareness and self-mastery, project and team management, etc. Cognitive apprenticeship emphasizes deep engagement of both technical and non-technical learning goals by challenging team members to surface their thinking for collaborative impact. Such a framework elucidates the need to value and measure cognitive skills across technical and non-technical domains. Instructors should use the cognitive apprenticeship framework for capstone design course improvement. Also, non-technical learning should be well-integrated with technical learning throughout capstone design as that is inherent in professional practice and will help us graduate well-functioning engineering graduates. Within capstone design contexts, cognitive apprenticeship may be especially useful as an organizational tool with capacity to enhance individual and team learning trajectories while simultaneously providing broad coherence to instructional challenges. As a professional undergraduate degree where most graduates end up in the workplace, we encourage future work by engineering educators and educational scholars within cognitive apprenticeship in engineering education learning contexts.

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Olga Pierrakos, PhD is a Program Director in the Division of Undergraduate Education at the National Science Foundation and a Founding Professor at Wake Forest Engineering. Olga served as the Founding Chair (2017–2022) of Wake Forest Engineering from launch to accreditation and led transformational change to position the program as the 14th Best Undergraduate Engineering Program (US News Report) and achieving unprecedented student and faculty diversity via inclusive innovation (e.g., cultural, curricular, pedagogical, institutional, etc.). Olga also served as the lead Capstone Design Coordinator (2020–2022) and led the launch of Wake Forest Engineering being a project-based learning curriculum. Olga has a PhD in Biomedical Engineering and a MS and BS in Engineering Mechanics from Virginia Tech. She has been founding faculty of two brand new U.S. engineering undergraduate programs – Wake Forest University and James Madison University – and leveraged education and social science research to transform engineering education. She led the vision and development of capstone design at both of these engineering programs. She brings vision, inclusion, innovative partnerships, and pedagogical innovation to the classroom and capstone design. She believes in the integration of engineering science (theory) and engineering design (practice) across the curriculum as well as in the mission and vision she set at Wake Forest University to Educate the Whole Engineer with a deep commitment to Human Flourishing via integrative learning. Olga is a national thought leader in STEM and higher education and innovation ecosystems.

Jesse Pappas, PhD is currently an Assistant Professor in the Department of Science Technology and Society at the University of Virginia. From 2019–2022, Jesse served as Research Scientist and Capstone Design Instructor in the Department of Engineering at Wake Forest University. When he is not synthesizing engineering and social science in the classroom, he studies identity development, situational aspects of character, and the organizational culture of engineering education. He received a PhD in Social Psychology from the University of Virginia, an MA in Psychological Science from James Madison University, and a BS in Psychology from Virginia Tech. Jesse has taught in Central and South America, India, and Europe, and his work has been published in journals such as Social Psychology Quarterly, Journal of Personality, and the Journal of Cleaner Production. He is also a part-time entrepreneur, serving as Cofounder and Chief Data Officer at The Lupulin Exchange, the leading hops marketplace in the craft brewing industry.

William Crowe, PhD is a Visiting Assistant Professor and the Faculty Director of the Innovation Studio at Wake Forest Engineering. William is currently the co-coordinator for Wake Forest Engineering capstone design. After graduating from the Virginia Tech Wake Forest School of Biomedical Engineering and Sciences in 2021 with his PhD in Biomedical Engineering he joined Wake Forest Engineering. He brings broad expertise in design thinking, innovative pedagogy, and prototyping. As an educator, he is focused on helping students to convert technical skills into problem solving skills using an iterative design pedagogy, using rapid prototyping and rapid prototype assessment strategies to reinforce and refine design choices in capstone, and team building. In capstone, Dr. Crowe works closely with students to help them build successful prototypes, refine presentation skills, and produce externally-facing media to showcase their work. He strives for teams to develop the skills necessary to succeed in a rapidly changing technological landscape.

Ty Holcomb is a fourth-year biomedical engineering PhD student at the Wake Forest University School of Medicine. He received a Master of Science in Biomedical Engineering from the Wake Forest University School of Medicine in 2022 and a Bachelor of Science in Mechanical Engineering from North Carolina State University in 2020. He is interested in head impact exposure in youth sports and is currently working to better understand the relationship between athlete head impact exposure and tackling form in youth football. Outside of his research, Ty has been a teaching assistant and faculty coach within the Wake Forest University Engineering Department for nearly four years and supported capstone design for several years.

Courtney Di Vittorio, PhD is an Assistant Professor at Wake Forest University (WFU) in the Engineering Department and a founding faculty member. Courtney is currently the co-coordinator for Wake Forest Engineering capstone design. She earned her Ph.D. in Civil Engineering with a focus on Water Resources from the Georgia Institute of Technology. As a licensed Professional Engineer and an educator, she is an advocate of project-based learning and the importance of connecting theory and practice. Within the context of WFU's capstone design course, she has recruited industry sponsors and technical mentors that work with student groups. She has mentored several design teams that have engaged in local and service-oriented civil engineering projects.

Kyle Luthy, PhD is an Assistant Professor and founding faculty member in the Department of Engineering at Wake Forest University. Kyle has taught across the engineering curriculum and supports undergraduate student projects in capstone as well as his own research. His research focus is on unattended systems for environmental sensing as well as the integration of the virtue of humility in engineering education. Kyle holds a PhD and a MS in Computer Engineering from North Carolina State University, as well as BS degrees in Electrical Engineering, Computer Engineering, and Computer Science from Louisiana State University. As an educator, he brings professional experience as an engineer and project manager from industry and government settings.