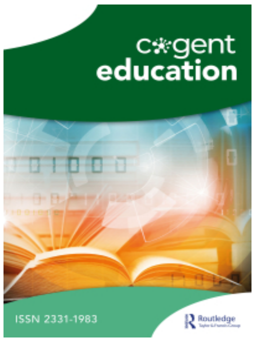

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PAtENT: a student-centered entrepreneurial pathway to the engineering doctorate

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ABSTRACT

Current structures of STEM graduate programs raise questions about addressing graduates' interest in multiple career paths, and how programs prepare graduates for positions increasingly available in varied occupations. This problem is addressed through an innovative doctoral program in engineering, Pathways to Entrepreneurship (PAtENT), which works to develop a scalable alternative student-centered framework. This research explores how this program responds to calls for graduate STEM education to address changes in science and engineering, the nature of the workforce, career goals, and how program components build an entrepreneurial mindset. A mixed-methods design includes a curriculum analysis showing alignment of program components to recommendations for Ph.D. STEM programs from the National Academy of Sciences, Engineering, and Medicine. Direct measures include surveys and interviews developed for current doctoral students and faculty to describe students' and faculty perspectives about program components, particularly entrepreneurship and the patent process. The curriculum analysis shows strong alignment of the PAtENT program components and activities to the ten elements of the National Academies' recommendations. A survey of graduate students in engineering, computing, and business show strong measures in engineering and entrepreneurial self-efficacy. Interviews of program participants and faculty demonstrate strong interest in patents and developing entrepreneurship. This innovative program in engineering focusing on obtaining a patent as a capstone shows potential to reform doctoral studies, so candidates are prepared not only for academic careers but a range of industry and government work environments. This work will lead to development of a model for other graduate STEM programs.

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1. Introduction

This study explores initial project outcomes for the **Pathways to Entrepreneurship** (**PAtENT**) doctoral program, implemented in multiple STEM departments (Mechanical Engineering, Civil Engineering, Physics and Optical Science, and Chemistry) across the University of North Carolina at Charlotte. This work addresses a paucity in graduate engineering literature which primarily focuses on faculty careers despite the fact that more than one-third of engineering students earning doctorates enter industry (Choe & Borrego, 2020). The majority of doctoral programs continue to have a research-based orientation that fits with the development of academic engineering researchers, but fails to address the wide

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range of skills and knowledge to succeed in industry such as leadership, communication, and teamwork skills (Martins et al., 2022) as well as development of an understanding of business, social, and ethical contexts within STEM (Hynes, Costin & Richardson, 2023). This is especially troubling given some estimates that only about 10% of doctoral graduates in STEM obtain a tenure-track position (Sauermann & Roach, 2016) with most doctoral scientists and engineers obtaining employment in the private sector rather than in education (Opsomer et al., 2021). One way to address these issues is through entrepreneurial connections that provide a broader skill set which addresses criticism of doctoral pathways that lack preparation and socialization for roles in industry, government and business (Gardner & Doore, 2020). Therefore, graduate programs in engineering should provide these broader career pathways given limitations for current doctoral education.

The overall project goal of the PAtENT program is to develop an alternate pathway for doctoral candidates in STEM programs to satisfy capstone degree requirements so they have the potential to modernize the STEM Ph.D., bringing it in greater alignment with recent rapid changes to the employment landscape. More specifically, this innovation involves providing as an alternative to the current practice (in Carnegie R1 and R2 institutions) of externally peer- reviewed publication(s), with an alternate capstone requirement: the development of a patentable technology. This alternative pathway allows the external peer-review aspect to be preserved, thus maintaining the academic rigor of the PhD programs. The PAtENT program has four overarching goals: 1) to develop an alternate roadmap for STEM Ph.D. students that is scalable and reflective of the evolving employment landscape and workforce needs; 2) develop an alternative roadmap for STEM doctoral students; 3) increase entrepreneurship rates among graduates; and 4) scale and propagate effective pedagogical strategies.

To achieve these goals, this research will focus on the following research questions:

1. How do program components address the core recommendations for STEM doctoral programs from the National Academies of Sciences, Engineering and Medicine:

    a. Develop Scientific and Technological Literacy and Conduct Original Research?
    b. Develop Leadership, Communication, and Professional Competencies?

2. How does the PAtENT program provide opportunities for entrepreneurial mindset development?

1.1 Theoretical framework

Doctoral programs in Science, Technology, Engineering and Mathematics (STEM) have traditionally been designed to provide pathways for graduates to conduct original research, and to join faculty ranks at institutions of higher education. Graduate programs that respond to a growing number of graduates interested in entrepreneurship are relatively non-existent. The current program landscape across universities typically took shape following the Second World War with few changes, both structural and philosophical. Despite changes in the number of STEM-related jobs and the range of STEM careers available for engineering graduates, the underlying structure of STEM Ph.D. programs, particularly in engineering, have remained unchanged.

Current paradigms for doctoral engineering students are aligned towards the research enterprise, and not necessarily on preparing students for a broader and dynamic set of skills for the modern engineering workforce (Del Río Fernández et al., 2022; Gardner & Doore, 2020; Zappe et al., 2023). This traditional model includes several components: discipline-specific coursework, guidance by a dissertation advisor and a dissertation committee, comprehensive exams related to subject matter, supervised engineering research resulting in peer-reviewed journal publications, and a final development and defense of a dissertation. Clearly, this trajectory prepares graduates with a deep grounding in their area of specialization; however, this paradigm lacks flexibility in the pathway lacking response to address changing needs of both employers and graduates.

Alternative pathways better meet the expectations of a more diverse student population allowing for focused and rigorous training to include transferable professional skills such as entrepreneurship. We argue that such changes provide a more student-centered emphasis. A focus away from the research enterprise to a student centered approach addresses diverse needs and challenges with opportunities to develop technical literacy in an area of interest, consider ethical issues associated with the field, explore a variety of points of view about the nature, scope and substance of the scientific enterprise, communicate results of their research to develop an understanding of the broader impacts, and create their own project-based learning opportunities (National Academies of Sciences, Engineering, and Medicine, 2018a). Sioukas (2022) reports that student-centered entrepreneurial classrooms include instructors and peers who are connected, participation in real-life activities, students taking responsibility for their learning, and reflective practice. Entrepreneurial education has been identified as important in transdisciplinary STEM programs (Rippa et al., 2022) affecting managerial skills, self-awareness and entrepreneurial skills of doctoral students. Of particular importance is the expertise from entrepreneurial development - problem solving, self-management, self-presentation, planning, teamwork and communication - responsive to calls from STEM industries. Researchers (Deveci & Seikkula-Leino, 2023; Kaya-Capocci & Ucar, 2023) argue that STEM fields and entrepreneurship are complementary resulting in higher social and individual benefits than when implemented independently. These characteristics provide a framework for the PAtENT program.

Student connections with instructors and peers is critical in providing growth opportunities for brainstorming ideas and sharing experiences and expertise which undergirds collaborative skill development (Sioukas, 2022). Engagement with peers builds networking communities that shapes experiences and is an effective learning pathway (Johnsson et al., 2016). Similarly, a study of a peer-led program, including engineering, at a US research university reported positive impact on participants' learning outcomes and retention (Drane, Micari & Light 2014), and also noted that participants benefited regardless of gender or ethnicity. Connections with faculty are central to effective student-centered graduate programs. Graduate students should have opportunities to develop relationships with their primary research advisors as well as additional advisor relationships which might include professionals in industry, government labs, and technical societies (National Academies of Sciences, Engineering, and Medicine, 2018a). Providing a pathway which includes work on a patent builds strong relationships between students and mentors. These connections foster relationships that extend to industries and networks such as business incubators (Fasi, 2022). This interdisciplinary nature of support allows students to pursue courses, workshops, and other opportunities for professional growth that are outside a research advisor's realm of expertise (National Academies of Sciences, Engineering, and Medicine, 2018b). Such teams favor linkages providing fertile environments for the emergence of entrepreneurial ideas (Barbini et al., 2021) and include broader experiences that expose both faculty and students to research that is applications oriented (Muscio & Ramaciotti, 2019) underscoring the importance of entrepreneurial skills in engineering.

Real life examples and activities are a primary motivator for students to construct knowledge as they engage in creating new information to resolve complicated problems (Jaiswal & Al-Hattami, 2020). Instructional models that focus on real-world problem engagement result in positive academic and related outcomes. For example, Matriano (2020) reported that using a model that involves exploration, research, interaction and creation (ERIC) enhanced student engagement resulting in more authentic learning, enjoyment, interest and confidence. Students showed a significant increase in performance and more positive attitudes toward topics, particularly real-life and real-world contexts. Students who have these types of learning experiences report more positive perceptions about the quality of their learning and report valuing opportunities to make a concrete contribution as they solve a real problem (Villarroel et al., 2020). The use of problem situations in engineering have similarly shown positive learning outcomes including skills in investigation, design, experimental design and advanced engineering skills (Zhang et al., 2022). Patent development provides students hands-on experiences that often involve multidisciplinary teams, an opportunity to understand issues around intellectual property, and the transformation of knowledge into invention (Plucker et al., 2023; Wang & Kleppe, 2001). Patents augment students' experiences through applied research involving university and industry collaborations focusing on real-life projects (Bekkers & Bombaerts, 2017; Latif & Zahraee, 2022). This process engages students in the entrepreneurial ecosystem through real-world case studies involving a range of stakeholders (Duval-Couetil, Ladisch, and Yi, 2021). The PAtENT program is centered on doctoral students' experiences in research and entrepreneurship as they go through the patent process.

In student centered classrooms, students take responsibility for their own learning. Universities are charged with developing this mindset with students through integrated partnerships between students, educational institutions, and workplaces that emphasize skills and knowledge of different disciplines, provide opportunities for reflective learning, and guidance in applying what they learn in autonomous situations (Bates, Bates & Bates, 2007). Wright (2011) identifies learner-centered approaches that promote students taking responsibility for learning as those where the student is actively involved in the process. engage in solving problems, develop higher cognitive abilities such as analysis, and apply investigative and research skills. Mejtoft & Vesterberg (2017) argue that students are motivated to take responsibility for their own learning process through integrated projects that develop not only disciplinary knowledge but also the generic skills to become professions which is vital for a future career within engineering. Work with patents, such as patent analysis, improve experiential learning and promote understanding of intellectual property rights (Aithal and Aithal, 2023). Entrepreneurial models reflect this problem-based approach where students learn to assess opportunities more critically (Bell, 2008) and original design work, such as patents, creates learning which is both student-centered and self-directed (Valenzuela-Valdés, & Aragón-Romero, 2012). Moore et al. (2022) argue that entrepreneurship promotes inventiveness through a student-centered approach that is inclusive.

Reflective practice has become a popular conception in education; however, it is sometimes unclear what is meant by the expression. Marshall (2019) conducted a systematic review of theoretical studies and proposed a working definition as a "careful examination and bringing together of ideas to create new insight through ongoing cycles of expression and re/evaluation" (p.411). Reflective practice, in engineering, might be characterized by a diverse range of knowledge and disciplines which are achieved through authentic engagement in engineering projects that are part of the process of becoming a professional (Mann et al., 2021). Reflective practice, like entrepreneurial mindsets, is deemed essential in engineering to promote deep learning and to address the nature of engineering problems and the scale of related issues (Riley et al., 2023). The process of invention, including the process of patenting, engages students as engineers in solving complicated and technical problems. Through this process engineers reflect on what they are learning and the work needed to solve the design project or engineering problem (Kelly, 2011). Patents and industry-based projects promote engineering innovation, design and leadership through reflective communities of practice (Jamieson & Shaw, 2020). PAtENT provides the environment to stimulate reflective thinking as the doctoral candidates engage in focused research and engineering design in creating a patentable solution to a problem.

1.2 National Academies recommendations for STEM graduate programs

Despite substantive changes in the sciences over the last century and data that show that over sixty percent of new doctorate program graduates do not go into academic research, graduate programs have not evolved (National Academies of Sciences, Engineering, and Medicine, 2018a). The Academies' project examines the current state of graduate STEM education in the United States with a focus on how evidence-based practices can respond to the needs of students and the broader society. This current study focuses on the recommendations of the Committee on Revitalizing Graduate STEM Education to assure that educational systems are dynamic in addressing current needs of students while anticipating future contexts in STEM graduate education. The Committee was charged with examining the state of graduate STEM education in the United States. In this study, we focus on recommendations from the Committee on revitalizing graduate STEM education for the 21st century. The spirit of these recommendations is an overarching theme of an increased focus on the needs of students - viewed as a call for a substantive cultural change in academia. In reviewing STEM doctoral education, the Committee called for core competencies that maintained the integrity of the degree while promoting possibilities for all students to develop these core competencies. These competencies provide a framework for a curriculum analysis of the PAtENT program.

1.3 Entrepreneurial mindset

The National Academies of Sciences, Engineering, and Medicine (2018a) report on transforming STEM graduate education includes preparation of innovators and entrepreneurs as perhaps the most important result of STEM graduate education. Entrepreneurship is among transferable professional skills along with science communication, leadership, management, outreach, and the ability to work as part of an interdisciplinary team. What is an entrepreneurial mindset? There are varied perspectives on an entrepreneurial mindset (EM) with nuances across areas such as the sciences and business. Naumann (2017) conducted a comprehensive synthetic literature review to explore the EM concept. While the review did not identify a commonly shared concept, the scholars depicted particular attributes of an entrepreneurial mindset which includes five core attributes. Cognitive tuning and goal orientation is the first attribute. This attribute changes over time depending on the activities in which an individual is engaged. The mindset ensures high effectiveness to solve the task at hand and differentiates between cautious and eager goal-setting and goal-striving. The second attribute is heuristic-based decision logic where decision making is based on heuristics and biases with effective and efficient results under conditions with high complexity and uncertainty. Alertness is the third attribute characterized by sudden insights of value and attentiveness. Fourth is prior knowledge when abstract knowledge combines and uses existing but disparate resources influenced by experiences, education and knowledge. The fifth core attribute is social interaction giving access to disparate information across the social network. Naumann also identified two metacognitive attributes that are less observable. The first is meta-cognition or reflection about one's own thinking processes along with flexibility to use different strategies to solve a task dependent on a situation. The second of the metacognitive attributes is cognitive adaptability characterized by flexibility to use different strategies to solve a situation dependent task. These five core attributes provide a comprehensive framework for thinking about entrepreneurship and the development of these soft skills through experiential student-centered learning experiences (Pihie & Sani, 2009). Describing these attributes provide a way of conceptualizing an entrepreneurial mindset given the elusiveness of a common definition. The core attributes described here reflect the integrated definition provided by Daspit et al. (2023, p. 17) "… a cognitive perspective that enables an individual to create value by recognizing and activating on opportunities, making decisions with limited information, and remaining adaptable and resilient in conditions that are often uncertain and complex."

2. Methods

The study used a mixed-methods design drawing from both qualitative and quantitative data and analyses (Creswell & Creswell, 2017). To respond to research question 1, curriculum coding was conducted to examine how the PAtENT program addresses the recommendations for doctoral programs as identified by the National Academies of Sciences, Engineering, and Medicine (2018). Coding followed an inductive, thematic and descriptive approach to align program components and activities to the 10 elements in the Academies' recommendations for STEM doctoral programs (see Table 1) (Franklin et al., 2022). The data for this question came from program documents including course syllabi, assignments, and initial patent application information. Through document analysis, curriculum expectations and program outcomes were identified and tagged to the elements in the recommendations. The goal was to identify which PAtENT features and activities were representative of a particular element. This analysis modified key processes from curriculum studies such as identification of desired outcomes (the Academies elements), determining what content and activities lead to those outcomes, and identifying experiences that are intended to result in the intended outcomes (Becker et al., 2022; Boehm, 1956). A dimensional core curriculum analysis (Mamaril et al., 2016; Wilson, Kickul, & Marlino, 2007) included a review of program information including documents, artifacts, and other data related to coursework, original research, student classroom experiences as well as laboratories and fieldwork. This analysis focused primarily on program documents, questionnaires, and other related records. Future work will expand the analysis to include focus group interviews, structured and semi-structured student interviews, performance assessments, observations, tests and other assessments and questionnaires (Levander & Mikkola, 2009). The

Table 1. Core recommendations for STEM doctoral programs.

ELEMENTS	KEY ACTIVITIES
1. Develop Scientific and Technological Literacy and Conduct Original Research	
a. Develop deep specialized expertise in at least one STEM discipline.	Progress in program requires acquiring deep specialized expertise and conducting original research; also emphasizes entrepreneurship.
b. Acquire sufficient transdisciplinary literacy to suggest multiple conceptual and methodological approaches to a complex problem.	Required to enroll in courses offered by College of Business on entrepreneurship and Innovation, in addition to engineering program.
c. Identify an important problem and articulate an original research question.	Patent planning which has a 4-step process.
d. Design a research strategy, including relevant quantitative, analytical, or theoretical approaches, to explore components of the problem and begin to address the question.	Committee evaluates the student's progress towards the research goals as outlined in the proposal for research.
e. Evaluate outcomes of each experiment or study component and select which outcomes to pursue and how to do so through an iterative process.	Support for progress toward filing a provisional patent, overseen by the entire committee, and supervised by faculty mentor.
f. Adopt rigorous standards of investigation and acquire mastery of the quantitative, analytical, technical, and technological skills required to conduct successful research in the field of study.	Viability of the patentable technology (as determined by the patent committee), and external peer review of the proposed technology.
g. Learn and apply professional norms and practices of the scientific or engineering enterprise, the ethical responsibilities of scientists and engineers within the profession and in relationship to the rest of society, as well as ethical standards that will lead to principled character and conduct.	Two required courses focusing on academic integrity and responsible conduct of research.
2. Develop Leadership, Communication, and Professional Competencies	
a. Develop the ability to work in collaborative and team settings involving colleagues with expertise in other disciplines and from diverse cultural and disciplinary backgrounds.	Management electives can lead to graduate certificate in Entrepreneurship and Innovation; candidates are required to take at least one management course.
b. Acquire the capacity to communicate, both orally and in written form, the significance and impact of a study or a body of work to all STEM professionals, other sectors that may utilize the results, and the public at large.	Students participate in Ventureprise (NSF I-Corps site) on-campus training modules and professional development programs for aspiring entrepreneurs, mentoring by commercialization experts, customer discovery.
c. Develop professional competencies, such as interpersonal communication, budgeting, project management, or pedagogical skills that are needed to plan and implement research projects.	Entrepreneurship courses (Business) focus on product and technology-specific strategies and case studies for market research, customer discovery, decision making, financing, team management, and product management.

descriptive content analysis uses a systematic process to allow for identifying attributes within documents and aligning identified components to program activities and structures (DeLuca & Bellara, 2013).

To respond to research question 2, a mixed methods approach was utilized to explore perspectives around entrepreneurship. First, a survey (Rorrer et al., 2021) was constructed to obtain measures of multiple constructs: engineering self-efficacy, entrepreneurial self-efficacy and innovation skills. A survey allowed for inclusion of items that were related to multiple constructs aligned with variables of interest and provided a tool for obtaining perceptions of respondents (Kent, 2020; Rahi, Alnaser & Abd Ghani, 2019). The survey was part of a larger administration which included all enrolled graduate students in Engineering, Computing and Informatics, and Business. A total of 737 students were invited to complete the survey. Of these, 46% or 339, were engineering program graduate students representing civil, electrical, mechanical, and infrastructure and environmental systems. For 2023 fall enrollment, there were 213 doctoral students in engineering. Approximately 27% of engineering doctoral students are female with 5.3% identifying as non-white. Approximately 73% of doctoral engineering students are male with 81% identifying as non-white. Non-resident alien enrollment was approximately 72%. Twenty-seven engineering students returned the survey, approximately 17% of enrolled doctoral engineering students. Response rates above 10% are considered viable (Nair et al., 2008); and email surveys are a viable method for data collection particularly when access is limited (Oppermann, 1995).

Qualitative data were collected through interviews with three student participants and one program faculty. The three students were two females (white and non-resident alien) and one male (white). The faculty member is a white male in nanoscale science. Additionally, an interview protocol was developed to collect more detailed data relative to participants' entrepreneurial perspectives and beliefs. Interviews as a research tool were selected to allow the collection of in-depth information and perspectives from students and faculty, and because the method allows for flexibility to elicit more robust data relative to the main objectives reflected in the protocols (Ruslin et al., 2022).

2.1 Measures and data collection

In response to the first research question, "How do program components address the core recommendations for STEM doctoral programs from the National Academies of Sciences, Engineering and Medicine?" recommendations from the National Academies of Sciences, Engineering, and Medicine (2018) call for STEM doctoral programs was used as a framework for a curriculum analysis. The National Academies called for programs that go beyond alignment to components of traditional degrees to expand experiences in the laboratory or fieldwork, workshops, internships and other opportunities that establish a critical mission that will "stimulate curiosity; develop the intellectual capacity to recognize, formulate, and communicate a complex problem; create multidimensional, analytical approaches toward solutions; and by creating opportunities for students to discover knowledge that advances their understanding of the world around them" (p. 150). The analysis drew from program documents including white papers, program proposals, syllabi, and related artifacts identifying activities and features of the program to map features to each of the core educational elements in the Academies recommendations (See Table 1). Table 1 lists each of the 10 elements from the recommendations and PAtENT key program activities that align to each of the elements.

In response to the second research question, the team sought to explore initial perceptions about entrepreneurship and the patent process. In order to establish a baseline for graduate students' beliefs about their academic and professional skill sets, a survey was designed which measured eight constructs including a self-efficacy scale which was developed specifically for engineering (Glazer & Peurach, 2012), measures for entrepreneurship efficacy (Preskill & Torres, 1999), and innovation scales that include measures for creativity, teamwork, initiative and networking (Clarke & Dede, 2009). The survey is implemented as a repeated measures design. Sample items for each construct are presented in Table 2. Interviews with program faculty and students in the program were also conducted to broaden understanding of how they viewed entrepreneurship in the program.

2.2 Data analysis

Curriculum coding was utilized in examining the relevance of the PAtENT program to the components of the recommendations for doctoral programs identified by the National Academies of Sciences, Engineering, and Medicine (2018a). An inductive, thematic and descriptive approach was used to code program components to 10 components in the Academies recommendations for STEM doctoral programs (see Table 1) (Franklin et al., 2022). Program features and learning outcomes were examined during the initial years of implementation. Document analysis identified curriculum expectations and program outcomes tagging them to the Academies elements. The aim was to identify key program activities with outcomes representative of a particular component. This process modified key considerations from curriculum studies such as identification of desired outcomes (the Academies elements),

Table 2. Graduate student entrepreneurship survey constructs and sample items.

Concept/Origin	Constructs	Sample Item
Engineering Efficacy (Glazer & Peurach, 2012)	Self Efficacy	I can master the content in the [graduate program]-related courses I am taking this semester
	Experimental Efficacy	I can perform experiments independently
Entrepreneurial Efficacy (Preskill & Torres, 1999)	Tinkering	I can work with tools and use them to build things
	Design	I can identify a design need
Innovation (Clarke & Dede, 2009)	Creativity	I can find new ways to implement ideas
	Teamwork	I can invite feedback and comments
	Innovation	Convince people to support an innovative idea
	Network	Build relationships outside the team/ organization

determining content that leads to these outcomes and identifying experiences and activities that develop the intended outcomes (Becker et al., 2022; Boehm, 1956).

Entrepreneurship. The survey instrument was deployed to current doctoral students in Engineering, Computing & Informatics, and Business programs in Fall of 2021 and Fall of 2022, as a means of capturing a description of entrepreneurial mindset among doctoral students. This paper presents the data from the 23 doctoral engineering students who returned the survey. The analysis will focus on the doctoral students in engineering. The survey measured constructs pertaining to confidence, entrepreneurial mindset and innovation: efficacy (general, experimental), entrepreneurship (tinkering, design), and innovation (creativity, teamwork, innovation, networking).

Qualitative data were collected through interviews with three student participants and one program faculty. These participants were part of a convenience sample of enrolled students and faculty members who were asked to volunteer for the interviews. Due to the Covid pandemic, there were only five students in the program. This small set of qualitative data provided perspectives from the students and program faculty about their views of the PAtENT pathway option. The interviews were audio recorded and transcribed for analysis. The protocol for the interviews was designed so that overall impressions with the program were explored. Interviews were audio recorded and transcribed for qualitative analysis. Protocols for the interviews were constructed to elicit perceptions on the initial experiences and ideas about the PAtENT program, based upon the five dimensions of scale (Clarke & Dede, 2009): depth, sustainability, spread, shift and evolution. These dimensions are important for a continuing evaluation of the program. Depth measures relate to the quality of the program. Sustainability measures focus on participation in the pilot track. Spread involves scale to other institutions. Shift centers on the evolution of the model with various departments and evolution measures learning across all components of the program across multiple contexts. The student and faculty responses were analyzed using a comprehensive process to identify evolving themes providing flexibility from both inductive and deductive processes to extract information and compare evidence (Braun et al., 2023; Alhojailan & Ibrahim, 2012). This approach was appropriate given the small sample size for this initial implementation phase. Respondent quotes are included to provide perspectives of individuals in their own voices.

2.3 Limitations

The PAtENT program is gaining traction after some set-backs during the virtual teaching and learning that were in place during the height of the Covid pandemic. A limitation of the curriculum analysis is the limited number of student artifacts to expand the curriculum analysis by providing data on critical experiences of students relative to the recommendations from the National Academies. As part of curriculum analysis processes, researchers report that student artifacts assist in showing alignment to benchmarks and other measures (DiPietro et al., 2022; West, 2021; Gathercoal et al., 2017). Such artifacts will be added to future research. The small number of students enrolled in the program limits the ability to compare entrepreneurial measures with a larger comparison group of STEM doctoral students who were not part of the PAtENT program. Additionally, due to the low survey response rate, the survey findings cannot be generalized to the graduate student populations overall.

The data collected to address an entrepreneurial mindset has several limitations. The number of doctoral students completing the survey measuring constructs pertaining to confidence, entrepreneurial mindset and innovation (self-efficacy, experimental efficacy, tinkering, design, creativity, teamwork, initiative and networking) was large enough to meet the assumptions for inferential statistical analysis, but does not currently have a large enough sample size to allow for generalization to the broader population of graduate students. This limits the ability to compare students across programs in engineering, business, and computing, and to compare PAtENT program participants to these groups of doctoral students. Interview data has been limited due to the small number of doctoral students in the program during the pilot and the complications to scheduling and conducting interviews due to constraints of the pandemic. However, this data provides a snapshot of the importance of entrepreneurial mindsets to the overall program, and enables evaluative application of findings. While these findings cannot be applied to the general graduate student population, a descriptive study from an evaluation lens provides insights into program context and to the student experiences so that informed decisions about program development can be gleaned and shared.

3. Results

3.1 Recommendations for STEM doctoral programs

To answer research question 1, a curriculum analysis (see Table 1) focused on the two components recommended by the National Academies and their related elements. For each element, the curriculum analysis identified key activities that were aligned to that specific element. The first component is "Develop Scientific and Technological Literacy and Conduct Original Research". This component contains seven elements. The first element is "Develop deep specialized expertise in at least one STEM discipline". Curriculum analysis found that program requirements for the Ph.D. require candidates to demonstrate specialized knowledge in their field. The PAtENT program provides an alternative pathway with entrepreneurship and technology development; however, the total academic load and technical rigor is maintained. The PAtENT program is a philosophical paradigm shift in the STEM Ph.D. model, where rigorous scientific research is the foundation for further research leading to commercialization of a technology. As presented in Figure 1, both the traditional and proposed Ph.D. roadmaps include formation of a Ph.D. committee with an advisor and qualifying exams and coursework which are foundational in developing specialized knowledge in a specified area.

The second element is "Acquire sufficient transdisciplinary literacy to suggest multiple conceptual and methodological approaches to a complex problem." Students in the program are required to enroll in courses offered by College of Business on entrepreneurship and innovation, in addition to engineering program coursework and research. The National Academies of Sciences, Engineering, and Medicine (2018a) envisions that such transdisciplinary studies will require addressing interconnected challenges that require convergent thinking. Both the coursework in the School of Business and summer work with Ventureprise provide candidates with experiences that include entrepreneurial topics such as design thinking for the purpose of identifying research projects based on industry needs and real-world problems, and development of a problem-solution fit of the research technology and customer discovery activities. These transdisciplinary experiences will support candidates' development of knowledge and skills necessary in identifying and tackling a complex problem. The Pathways to Entrepreneurship (PAtENT) program is currently being implemented in multiple STEM departments (Mechanical Engineering, Civil Engineering, Physics and Optical Science, and Chemistry) across the University.

The third element is "Identify an important problem and articulate an original research question." This maps onto the 4-step process of patent planning: understanding the invention, researching the invention, choosing the type of protection, and drafting the patent application. The alternative patent pathway is characterized by a capstone requirement: the development of a patentable technology as the

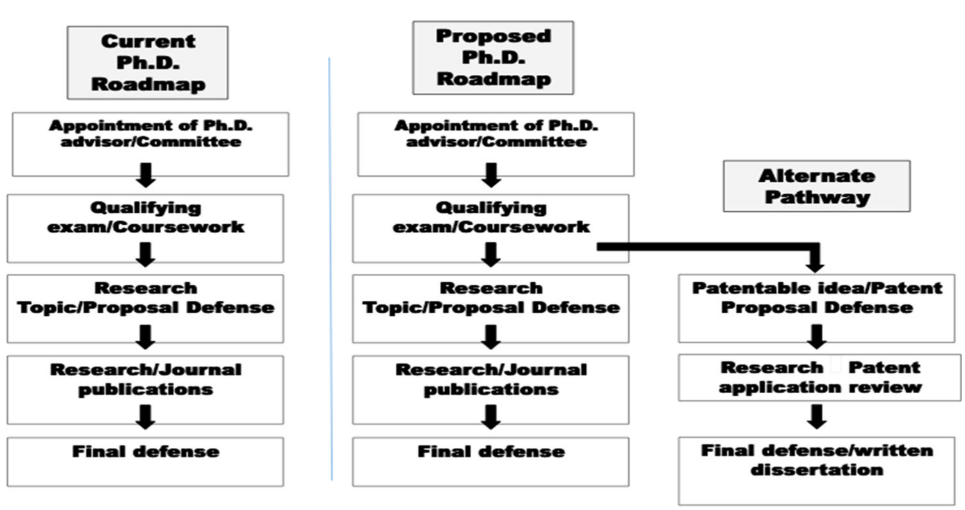

Figure 1. Roadmap of Progression towards Ph.D. Candidacy: Traditional versus PAtENT Program.

capstone event. This process preserves the external peer-review aspect found in research publication processes, thus maintaining the academic rigor of the Ph.D. program. Candidates have input from their dissertation committees and the University's patent review committee. Students receive feedback before submitting patent applications. Technical rigor is maintained through the external review committee which is appointed for each project, providing a single-blind review of the technical merits and commercialization viability of the patent application prepared by the candidate.

The fourth element is "Design a research strategy, including relevant quantitative, analytical, or theoretical approaches, to explore components of the problem and begin to address the question." The primary activity demonstrating this element is the doctoral student's evaluations provided by their committee relative to their progress toward the goals of their proposed research. The role of the student dissertation committee in the PAtENT program is similar to that of a traditional dissertation committee and includes the following responsibilities: (i) Advise the student on the suitability, originality, and promise of the proposed research topic; (ii) Evaluate the student's progress and performance towards the research goals (outlined in the student's proposal defense); and (iii) Provide technical consultation and strategic and technical advice to the student. The primary difference in the proposed PAtENT program, compared to the traditional pathway for PhD, is in evaluating the student's performance, the dissertation committee will consider the viability of the patentable technology (as determined by the patent committee), with input received from the external peer review of the proposed technology.

The fifth element is "Evaluate outcomes of each experiment or study component and select which outcomes to pursue and how to do so through an iterative process." Elements four through six are interrelated around students' conceptualization and progress in their research. Evaluation of each experiment or study component is based on the maturity of the research and technology development. Students might be staggered across cohorts for years 1 and 2, allowing faculty to implement a process of continuous improvement and iterative design. This allows a responsive evaluation practice which is characteristic of organizational learning (Ekundayo, 2022; Belinski et al., 2020). Students in year 1 will conduct research and product development based on preliminary results and finalize the patent proposal through the patent proposal defense which is presented to both the dissertation and the university patent committee.

The sixth element is "Adopt rigorous standards of investigation and acquire mastery of the quantitative, analytical, technical, and technological skills required to conduct successful research in the field of study." Progress toward filing a provisional patent is overseen by the entire committee and supervised by a faculty mentor. Students submit the patent proposal at the end of year 1 for peer-review by an external committee. In year 2, students respond to the external review comments. Based on the reviewer comments, a Go/No-Go decision will be undertaken by the student, in consultation with the dissertation committee. In year 3, the student will submit the final patent application including revisions based on reviewers' comments, produce a written dissertation and defend the final dissertation and research to the dissertation committee. In the event of a "No-go" decision, the student will consider multiple options including writing a journal paper based on the research results or proceeding to the dissertation defense stage directly. This process will maintain the same academic load as a traditional track and ensures comparable times-to-degree without sacrificing the technical rigor of research or diluting the core elements of the doctoral program.

The seventh element is "Learn and apply professional norms and practices of the scientific or engineering enterprise, the ethical responsibilities of scientists and engineers within the profession and in relationship to the rest of society, as well as ethical standards that will lead to principled character and conduct." Students are required to successfully complete two courses that address issues of academic integrity and professionalism. The course *Responsible Conduct of Research* focuses on research as part of a successful professional career. Students develop practical skills and knowledge around critical research focused on guidelines from the National Institutes of Health and the National Science Foundation. Students hear from experts from multiple areas related to professionalism and research ethics. A second requirement is *Academic Integrity* is an online training program which addresses issues related to academic integrity and reviews the University's policies and procedures related to the topic. These two courses reinforce values for sound and ethical conduct in pursuits that are both academic and professional.

The second component of the National Academies recommendations for STEM doctoral programs is "Develop Leadership, Communication, and Professional Competencies" which has three elements. The first element is "Develop the ability to work in collaborative and team settings involving colleagues with expertise in other disciplines and from diverse cultural and disciplinary backgrounds." Students are required to complete management electives which can lead to a graduate certificate in Entrepreneurship and Innovation. Candidates must complete at least one management course offered through the Belk College of Business. These courses include topics related to starting businesses, acquiring the right amount and type of capital, gender and race-related challenges, and tenacity and perseverance in overcoming setbacks. The courses also help students understand the rationale of entrepreneurs in decision making, develop perceptions about uniqueness of entrepreneurs, identity with the role of entrepreneur, and build entrepreneurial networks.

The second element for this component is "Acquire the capacity to communicate, both orally and in written form, the significance and impact of a study or a body of work to all STEM professionals, other sectors that may utilize the results, and the public at large. "A unique component of the program is students' participation in Ventureprise which is a NSF I-Corps program. Training modules and professional development programs focus on topics for aspiring entrepreneurs, mentoring by commercialization experts, and customer discovery. Ventureprise is part of the University's Innovation and Entrepreneurship Center which supports University innovation through commercialization advice, training and funding to identify customers and lab to market analysis. The program promotes diverse perspectives through an emphasis on inclusive leadership. Through these efforts, the graduate students develop critical thinking skills and creative problem solving as they advance their research.

The third element is "Develop professional competencies, such as interpersonal communication, budgeting, project management, or pedagogical skills that are needed to plan and implement research projects." Through management coursework and work with Ventureprise, candidates extend their skill set beyond engineering to focus on product and technology-specific strategies and case studies for market research, customer discovery, decision making, financing, team management, and product management. Ventureprise modules contain programming that advance participants in entrepreneurial thinking, customer discovery, and design thinking processes.

3.2 Entrepreneurial mindset

A survey was conducted to capture doctoral students' attitudes related to self-efficacy in engineering, entrepreneurship and innovation. The low number of responses limits interpretations; however, the data provides interesting insights about current students' beliefs about these related skills. Table 3 shows the means and standard deviation from the current sample (Rorrer et al., 2021).

The mean scores for the engineering students was near or above 5 (on a scale of 6) for all constructs, and comparable to students in business who did report higher levels of teamwork and innovation. This is an indication that the PAtENT program courses in the Business College are a positive direction for Engineering students seeking entrepreneurial engagement.

Interviews with two PAtENT students (mechanical engineering) were analyzed using a thematic approach with five overarching themes emerging from the analysis. The first theme provided students' initial understanding of the program. Relevant points included familiarity with the patent concept. One student noted interest in the financial support that would allow them to develop their idea for a patent. The entrepreneurial nature of the program was noted in the context of defending a patent and involvement with Ventureprise. "One of my friends already did Ventureprise, she went to the national NSFI core and started her own business and everything. So, I was a little familiar with everything. But I was

Table 3. Survey results by program for engineering self-efficacy, entrepreneurial efficacy, and innovation skills.

	Engineering Doctoral Students (n = 27)	
Construct	Mean	SD
Self-Efficacy	5.09	1.03
Experimental Efficacy	5.39	0.58
Tinkering	4.67	1.17
Design	4.99	1.10
Creativity	5.01	0.77
Teamwork	**4.88**	0.77
Innovation	**4.86**	0.73
Network	4.83	0.86

interested as well into maybe starting my own company and doing that kind of line. And also, I thought you know if it is available, it is good to have. Every experience is good." The second theme focused on the support from the program to sustain students' journeys. Students raised issues related to business classes and wanted information on which classes are good and why. One student shared "The Chemistry Department here is relaxed and informal, everyone is ready to help, can knock on someone's door for help, why I chose UNCC; a lot of collaboration in the dept between professor to professor. Students- yeah everybody is really friendly, if I have a question about an instrument I can get help." Theme 3 involved interdisciplinary collaborations and research, and access to entrepreneurs. One response highlights this synergy, "Research wise, the science side, we have a few collaborations with people, some of the dyes I'm trying to synthesize and use are being used elsewhere (U Chicago, UTK); Electrochromic Dyes how toxic they are to cells we collaborated with Bio, also for antibacterial levels, Architecture faculty my materials might go into building materials." The fourth theme centered on broad commercial applications of students' work. Views reinforced the critical nature of collaborating with multiple faculty and researchers. "I think so yeah, related to technologies measurement of surfaces related to scanning, geography; any kind of technology, for applications mostly maybe medical." The fifth theme advanced the role of students' incredible ideas and how hard work paid off. They saw the PAtENT program as a program for those with patentable ideas and entrepreneurial goals. "Filed provisional patent with the university back in March, so now we are trying to figure out how to get them to get a patent; we have one company that would license it, but I may start my own company."

An interview with a faculty advisor to a PAtENT student revealed four overarching themes. Theme 1 was the promise of PAtENT students used in program recruitment. The advisor observed that the opportunity to be involved in designing real-world applications was attractive to doctoral students and the ability to do this in terms of applying for a patent. "It's attractive to think about going through a PhD program and to try out [this] into a real working prototype which is pretty rare in [my field]. We could spend many years [doing traditional research in this field]." The second theme was the nature of interdisciplinary thinking as a catalyst for entrepreneurship. "Our program is interdisciplinary. Our students do a lot of different kinds of research, that model lends itself to real world applications. [In my field], we have to learn how to make a device, how to put it on a surface, and how to append it to something like a medical device. This program lends itself to an entrepreneurial mindset." A third theme was financial support for external partnerships and truly innovative research. "There needs to be more seed funding to support new pathways. And I think the university is already talking about this …. how do we keep it going, which will lead to more patents, new ventures, NSF centers … ? I feel like that is my biggest challenge- what do I have funding for? What is safer because I know this is going to work and I can get funding for it." The fourth theme was the ability of students to develop entrepreneurial skills through engagement with Ventureprise. "My experience working with students on this track, [the program] is learning about entrepreneurship, not about if you should license this technology, but interviewing scientists and engineers, they might not need our technology- it might be cool but not useful … …, So when we go to the patent committee we say it can do this and we talked to company x,y,z … and they need it, so it gives us structure and support, gives a lot of impact to the work my students are doing."

4. Discussion

The results of the curriculum analysis show that the Pathways to Entrepreneurship (PAtENT) Program maintains the National Academies of Sciences, Engineering, and Medicine (2018a) ideas of the mission of a STEM doctorate including core disciplinary coursework, original research, and other intensive experiences in the classroom and laboratory or during fieldwork, workshops, conferences, and internships. Programs that follow this mission "stimulate curiosity; develop the intellectual capacity to recognize, formulate, and communicate complex problems; create an iterative approach toward solutions, drawing from discipline-appropriate quantitative, theoretical, or mixed-methods tools; make original discoveries that advance understanding; and communicate the impact of the research beyond their discipline" (p. 106). Students in the PAtENT pathway develop the skills identified in the core elements providing rigorous and experiential learning that will provide graduates with the foundation for future success in multiple career paths. The National Academies report charged universities to verify that their graduate programs provide opportunities for graduates to develop them before completing their programs, and that programs should make public how programs align to these core competencies, and these competencies should be a core feature of student learning and career goals. The curriculum analysis undertaken as part of a review of the PAtENT program provides a description of how program activities and components align to these core competencies. Systematic consideration of these core elements for STEM doctoral programs is critical in stimulating the cultural changes necessary so that engineering doctoral students are prepared for the grand challenges of the 21st century.

The results of the entrepreneurial measures provide evidence of the central nature of these constructs to the alternative doctoral pathway in engineering. Survey data collection from the survey is ongoing with an intent to increase the number of responses to allow for comparative statistical analysis among students by program areas. The survey results, while showing notable differences between engineering, computing, and business doctoral students, indicate that the doctoral students across programs have solid foundations in self-efficacy and experimental efficacy with means above 5. It is worth noting that the means are below 5 for engineering students in tinkering, design, teamwork, innovation, and network. Only business doctoral students' mean scores were above five for teamwork, innovation, and network. The interviews of two doctoral students in the program and a faculty advisor provide initial snapshots of the importance of the pilot model with a patent as the outcome. The critical nature of entrepreneurship and its connection to patent design are evident in this interview data and reflected in the themes which emerged from the qualitative analysis.

4.1 Implications

The National Academies of Sciences, Engineering, and Medicine (2018a) recommendations for STEM doctoral programs provide a comprehensive framework for universities to review their programs and determine how they align to the competencies and skills identified through the Committee's work so that students are better prepared for the 21st century. The degree to which programs align with the identified elements reflects underlying rationales and goals for STEM graduate programs. Discourse around curriculum through the lens of these recommendations has larger implications for policy and the emphasis placed on the skills, values, and experiences in a learner-centered environment (Manyukhina & Wyse, 2019). Another implication for engineering education is the degree to which focus on the elements of these recommendations serve to change our understanding of the nature of engineering. A consideration of the cognitive and epistemic dimensions of the components can be central to a more holistic view of engineering (Barak, Ginzburg & Erduran, 2022) that defines engineering literacy in higher education.

The survey data indicates strong foundations for engineering students in engineering self-efficacy and experimental efficacy, design and creativity. This is a solid indicator that current programming supports these across programs. It also provides data showing a strong foundation for students to further build business and entrepreneurial mindsets through coursework in the College of Business and entrepreneurial work with Ventureprise. The survey data also indicates that students need additional support to strengthen their perspectives of teamwork, innovation and network. Both business coursework and entrepreneurial opportunities will provide these opportunities. The survey data, though limited in the number of participants, reinforces the role of entrepreneurship in the PAtENT program and offers glimpses into students' thinking around patents. There is limited feedback that students desire and may need more information to make decisions about which business courses best meet their needs.

4.2 Directions for Future work

Engineering education must respond to changes in scientific understanding and the societal changes of today. This requires a systematic review of the curricula in our universities. A robust curriculum analysis will look at all curricular aspects including the design of instruction, student projects and courses across interdisciplinary fields in ways that considers the nature of interactions both between engineering fields and between engineering fields and other STEM areas (Van den Beemt et al., 2020). The National

Academies of Sciences, Engineering, and Medicine (2018a) elements that frame recommendations for graduate education can provide a framework, but there is a need to extend beyond our initial curriculum analysis drawing from additional documentation and data to capture how program experiences and structures support these recommendations in ways that provide graduate students with authentic ways of engaging in engineering practice. Future curricular analysis will look at artifacts that provide snapshots of the experiences of PAtENT candidates as they engage within engineering fields and across STEM and non-STEM disciplines, and how those experiences continue to shape the culture of graduate education in the spirit of the recommendations of the National Academies.

The survey for measuring students' engineering efficacy, entrepreneurial experimental efficacy, and innovation will be administered to additional doctoral students in engineering, business, and computing. Additional data will allow for continued statistical analysis across and within groups of STEM doctoral students. The growth of the PAtENT program will hopefully provide a large enough subset of pilot participants to compare them among engineering doctoral students in other tracks and to doctoral students in computing and business. Interviews of students and faculty will continue allowing for thematic analysis to describe perspectives of students and faculty around key program activities and components. The larger data sets will enrich the descriptions of participant perspectives and provide opportunities to identify strengths and weaknesses in program implementation.

4.3 Conclusions

PAtENT (Pathways to Entrepreneurship) provides an alternate pathway for doctoral candidates in STEM programs at UNC Charlotte through which they meet degree requirements by applying for patents. The curriculum analysis showed that the program provides a better alignment between doctoral degrees and the rapidly changing employment landscape. Most current pathway models to a doctorate do not allow for differentiated backgrounds and interests of students. The PAtENT student-centered approach includes experiential opportunities that align to recommendations for transforming graduate STEM education. Through unique opportunities to engage in business and marketing coursework and programs, students extend their scientific research skills and knowledge in developing entrepreneurial mindsets. These key program components are evident in the initial, though limited interviews of students and faculty. These findings further highlight an entrepreneurial mindset as a key program component. The PAtENT model has the potential to modernize STEM doctoral programs so that graduates are better equipped to meet the needs of the country's future as a knowledge-based economy. Future research will expand the number of participants and support the refinement of program components for a scalable model for similar STEM doctoral programs.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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