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A Strategic Blueprint for the Alignment of Doctoral Competencies with Disciplinary Expectations*

CATHERINE G. P. BERDANIER
Pennsylvania State University, 206 Reber Building, University Park PA 16802, USA. E-mail: cgb9@psu.edu

ANNE TALLY
University of Chicago, 5828 South University Avenue, Pick Hall 301, Chicago, Illinois 60637, USA. E-mail: actally@uchicago.edu

SARA E. BRANCH
Hobart and William Smith Colleges, 219 Gulick Hall, Geneva NY 14456, USA. E-mail: branch@hws.edu

BENJAMIN AHN
Iowa State University, 2324 Howe Hall, 537 Bissell Road, Ames IA 50011, USA. E-mail: bahn@iastate.edu

MONICA F. COX
The Ohio State University, 244F Hitchcock Hall, 2070 Neil Ave, Columbus, OH 43210-1278, USA. E-mail: cox.1192@osu.edu

Improvement of doctoral education results from strong alignment of educational requirements with disciplinary expectations. This article reports on a qualitative study of 40 Ph.D. holding engineers working in academic and industry careers conducted through interview methods and constant comparative coding of transcripts, operationalizing Golde and Walker's Stewardship framework and making recommendations for doctoral engineering education. Findings indicate that engineering Ph.D. holders across both industry and academia participate in each of the three tenets of stewardship (i.e., generation, conservation, and transformation) in different ways. As such, we propose a new way to plan and to assess graduate student competencies that can be easily integrated into doctoral engineering programs.

Keywords: stewardship; engineering education; doctoral education

1. Introduction

The Ph.D. is often criticized for being antiquated, built on a legacy of apprenticeship for a privileged few scholars in the ivory tower of academia. Modern-day Ph.D. holders in all disciplines are lauded for their academic accomplishments, but the academy is facing dilemmas in terms of modernizing the purpose, enrollment, and methods for training disciplinary experts with doctoral degrees [1, 2].

Engineering as a discipline is fundamentally different than many other fields. Engineering doctoral students are not only seeking careers as professors and research faculty: Recent statistics indicate that 70–80% of engineering Ph.D. holders do not pursue academic careers [3, 4]. Additionally, engineers often move among academia, industry, and government, sometimes, as Dietz and Bozeman note, "changing sectors multiple times or working in multiple settings simultaneously" [5, p. 351].

Since the majority of engineering graduate students are not training for their mentors' careers as faculty, the current educational apprenticeship system develops skills in students that are misaligned with those expected by employers. This misalignment can result in lower employment placement rates and students' attrition from doctoral programs or the discipline after graduation [6, 7]. Furthermore, as universities, funding agencies, and graduate students' advisors invest large amounts of money and resources in graduate students, attrition has a significant financial impact on multiple stakeholders.

Although models for graduate education are slow to change, we propose that by understanding the practices and attributes of experts in engineering, the academy can better align education of disciplinary experts with future career paths. Our analysis of disciplinary alignment is guided by Golde and Walker's (2006) Stewardship framework, which posits that the activities of Ph.D. holders fall into three categories: (1) conservation of the discipline; (2) generation of knowledge; and (3) transformation of expertise to diverse settings [14]. Although prevalent in higher education literature, to date, the Stewardship framework has not been studied in engineering disciplines outside Cox's recent work [11, 15, 16].

As Stewardship theory is a relatively new framework in higher education research, and because we seek to propose new ways to think about and enhance doctoral education, our research questions are exploratory in nature:

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(1) What roles do Ph.D. engineers hold in their industry and academic careers (framed within the three tenets of Stewardship theory)?
(2) What recommendations can the operationalization of the Stewardship framework provide for Engineering department administrators and faculty?

Findings open a practical conversation about educational alignment with disciplinary expectations across engineering disciplines. The Competencies Blueprint unveiled in this work helps engineering students, faculty, and administrators align extracurricular activities (i.e., outside of regular research/teaching duties) with desired career trajectories.

2. Literature review

Most professional development literature in engineering education research focuses on the improvement of the problem-solving and technical abilities of undergraduate engineering students (for example, Dixon and Johnson [17]. Other studies [18–20] note the lack of explicit development of non-technical skills that are foundational to solving engineering problems, which include professional skills related to communication, engineering ethics, and teamwork. At the undergraduate level, these non-technical and global skills are vaguely required by ABET, and several large reports increasingly stress the need to teach these skills to novice engineers [8, 9].

Despite the focus on undergraduate skill development, literature focusing on graduate engineering education is sparse: Aside from stressing general technical proficiency [10] current research for Ph.D. holding engineers in industry and academia highlights a gap in non-technical competencies for doctoral engineering students, including the need for enhanced verbal and written communication skills [4, 10–11] and increased mentorship [12, 13, 15].

In groundbreaking research of engineering Ph.D. holders working in industrial environments, Watson and Lyons [4] found that over 25% of the sampled Ph.D. holding engineers employed in industry wished that had been better prepared in their doctoral program to understand the corporate environment and been trained in relevant skills, and over 40% lacked preparation in customer needs and identifying market products and processes. Overall findings indicated most industry-hired engineers, at the onset of their careers, lack familiarity with relevant business skills (e.g. marketing and entrepreneurship). They also had not developed adequate professional skills such as project management, communication, and most important, teamwork—that are critical to engineering success in industry. This work was one of the first and only comprehensive studies of Ph.D.-level engineers in industry explicitly, and the findings from that work have been used to propose skill set acquisition outside of technical skills for doctoral students. However, a skills-based proficiency model for graduate education is an extreme "one-size fits all" approach.

Further, even though graduate students are trained more explicitly for academic careers through traditional apprentice-based graduate programs, junior faculty are often still underprepared for the rigors of faculty life. Studies note that experience in interdisciplinary research, grant writing, and group management skills are critical for junior faculty success [21] yet these essential skills are rarely identified, deliberately practiced, or reflected upon during an engineering graduate student's doctoral career.

Because the engineering Ph.D. is so diverse, and since doctoral research is time-consuming, recommendations from literature stay at the surface level, calling out the needs for the acquisition of different skills and traits and for breadth in graduate education preparation. These skills and traits, however, are difficult to put into practice as time and resource constraints push most professional development programming into workshop form, where distinct skills are preached, often without time for practice and reflection.

In this study, we use the interviews of 40 Ph.D. holding engineers in academia and industry to identify several categories where progress is needed in doctoral engineering education. This research re-frames Stewardship theory and past recommendations for doctoral engineering education and professional development into a Competencies Blueprint that can be applied by individual students and faculty, or implemented program-wide by administrators.

2.1 Theoretical framework: Stewardship

Doctoral education has been studied using various broad educational and psychosocial theories. For example, cognitive apprenticeship theory [22, 23] reflects the advisor-student partnership that scaffolds the practices and learning of graduate students to become an expert researcher and eventually a productive Ph.D. holder in a given specialty. Academic literacies theory [24] proposes that in order to fully become a member of a disciplinary community, a student must adopt the normative discourse practices and expected behavioral patterns of a research community. Frameworks characterizing the activities of disciplinary communities post-doctorate are few: Community of Practice [25, 26] and Community of Inquiry theories [27] often are used to describe socialization into the norms and expectations within a field, discipline, institution, or department.

This work employs Golde and Walker's Stewardship framework [14] as a theoretical grounding for analysis and interpretation, which resulted from one of the most comprehensive and in-depth studies of the role of the Ph.D. The research grounding the framework studied Ph.D. holders in chemistry, education, English, history, mathematics, and neuroscience disciplines. The Stewardship framework posits that all Ph.D. holders act as *stewards* of their particular disciplines, and their *stewardship* activities can be sorted into three tenets: Conservation, Generation, and Transformation, as shown in Table 1.

Discipline **conservation**, or "conserving the most important ideas and findings that are a legacy of past and current work" [14, p. 10], is passed down to doctoral students through required coursework, readings, or seminars, in order to give students a wide and solid foundation in disciplinary norms. Through foundational work, students build a commitment to maintaining the rigor and standards of their discipline, while developing an understanding of a discipline's future and ethical issues. Each new generation of experts is responsible for maintaining the foundational disciplinary nature. Disciplinary **generation** is the idea that disciplinary stewards must be "capable of generating new knowledge and defending knowledge claims against challenges and criticism" [14, p. 10]. This is likely the most familiar role of a Ph.D. in the academic community, since the emphasis on generating information is present across all research-focused areas in higher education, translating to writing grants and obtaining funding, as well as conducting novel and transformative research. There is marked stress on doctoral students to participate in generating new ideas and furthering research [18, 28]. The third and final tenet within Stewardship is **transformation**, which proposes that expert stewards across disciplines transform knowledge "by explaining and connecting it to ideas from other fields" [14, p. 10]. Many prior studies [19, 21, 28, 30] find that graduate students must be trained to translate expertise to a variety of audiences, although the intricacies and ways in which transformation is enacted are often not addressed.

3. Methods and methodology

Data collection occurred through both purposive and snowball sampling methods [31] to contact Ph.D. holding engineers currently employed in the United States. After obtaining Institutional Review Board approval for the study, a recruitment email was sent to multiple division chairs within the American Society for Engineering Education (ASEE), which requested that the recruitment be forwarded to their division's members. In addition, we purposively contacted prior collaborators, which included university and institution deans, department chairs, faculty, researchers and administrators in education centers, and industry engineers. In order to expand participant samples, we asked contacts to identify people who met the study sample criteria (i.e., obtained engineering Ph.D. in U.S. and working in industry or academia).

The participants who responded to the recruitment were interviewed using a semi-structured protocol [32] which probed how each engineer demonstrated aspects of the Stewardship framework in their career. Before interviewing, the participants signed their consent and provided their curriculum vita (CV). Interviews were conducted through computer-based voice call or phone call, which are ideal methods for interviewing elites and technical experts [32]. After the initial recruitment and interviews, we noted that participants who had transferred at some point in their careers from industry to academia and academia to industry were underrepresented in our sample. We performed a second recruitment in an effort to increase the participants sample from the two transition groups by emailing contacts and colleagues, requesting them to identify engineers who had transitioned between sectors.

Table 1. Representation of Golde and Walker's (14) Stewardship Framework

Stewardship Framework	Tenet	Brief Definition
Ph.D. experts in a discipline are *Stewards* of their field, whose activities include these three tenets:	**Conservation**	**Preservation of disciplinary knowledge and history**
	Generation	**Producing new knowledge that contributes to the field**
	Transformation	**Translating expertise to a variety of audiences**

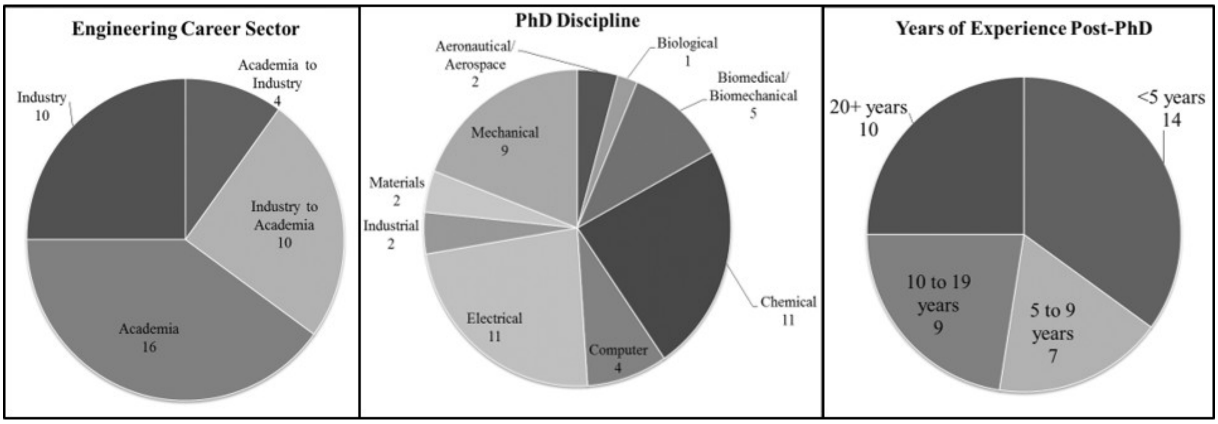


Fig. 1. Demographic data of participants.

The entire recruitment and interviewing processes took approximately one year and resulted in 40 hour-long interview transcripts and curricula vitae. All participants received a $25 gift card in exchange for their participation. The total participant demographics are shown in Fig. 1. Eleven of the 40 participants were female. Participants that explicitly noted holding Ph.D.s in multi- or interdisciplinary areas were categorized into both disciplines, which is why the discipline demographic count in Fig. 1 is higher than 40. Past research by the group mapped the career trajectories of these participants through Curriculum Vitae analysis methods, showing the variety of job titles and responsibilities that these participants have held, showing that even Ph.D. holding participants with "linear" career pathways hold multiple roles over the course of their careers [16].

The transcripts were coded at the idea unit of analysis using the Stewardship tenets as *a priori* codes. The data representing each tenet was then axially-coded using constant comparative methodologies through a post-positivist paradigm [33]. This paradigm is useful for understanding a definitive reality (the skills required for engineering careers) using participants' stories and experiences, understanding that each participant understands the world differently.

Data representing the three Stewardship tenets were coded into 12 secondary *themes*, which represented multiple tertiary *components* describing the activities, knowledge, skills, and attributes of Ph.D. holding engineers. This three-tiered coding structure is synthesized in Table 2, and concise component definitions are presented in Tables 3, 4, and 5.

For each tenet of Stewardship, we present findings through themes, components, and codebook definitions, followed by a brief discussion including relevant quotes from the interviews. Portions of quotes are boldface, showing which aspects of the quotation were most important in operationalizing Stewardship activities. All names presented are pseudonyms. Understanding that each participant has a unique story, the quotes selected represent common experiences among participants. We selected quotations to represent a breadth of participants working in both industry and academia, as well as those who moved throughout their careers from industry to academic (denoted as IN-AC), and from academia to industry (AC-IN). The quotations indicate the participant's sector to give context, but the purpose of this paper is to find the variation of skills required by engineering Ph.D. holders to better align doctoral education, not to contrast skills needed by broad employment sectors.

4. Results: Conservation

4.1 Definitions of themes within conservation

Three common themes emerged within the Conservation codes: (1) General Technical Skills, (2) Technical Leadership, and (3) Knowing the Field, as shown and defined in Table 3.

4.1.1 General technical skills

This theme includes three components: technical competency; mastery of engineering, science, and mathematical fundamentals; and technical expertise. Most participants discussed the importance of Ph.D.-holding engineers' ability to understand the first principles from which engineering decisions are made. This expectation is embodied George's words:

> *"I think [Engineering Ph.D.'s] absolutely need to have a very* ***sound appreciation of the foundational engineering things****. So by that I mean it's certainly a* ***deep understanding*** *and appreciation for the value of* ***mathematics in modeling, understanding of the physical nature of variability*** *and those things. Also the* ***foundational engineering***

Table 2. Codebook themes developed from interviews

Stewardship Framework	Conservation	Technical Skills (general)	Mathematical Fundamentals
			Engineering Fundamentals
			Expertise
			Scientific Method
			Data Analysis
			Technology
		Technical Leadership	Teaching
			Assessing Relevance to the Field
		Knowing the Field	Employ Literature
			Identify current Technology and Trends
			Synthesize Existing Information
			Use Multiple Resources from Diverse Sources
	Generation	Research	Improve on Prior Knowledge or Processes
			Employ Rigorous Research Methods
			Problem Analysis
			Data Analysis
		Contributions to the Field	Vision
			Impact
			Publications, Presentations, and Patents
		Characteristics	Personal Characteristics
			Professional Characteristics
			Ability to Teach Others to Generate Knowledge
		Knowing the Field	Knowing the Field
	Transformation	Teaching	Tailoring Communication to Audience
			Non-classroom Teaching
			Classroom Teaching
			Mentoring
			Administration
			Outreach
		Verbal Communication Skills	Presentation Skills
			Conferences
			Concise Communication
			Communicating appropriately for situations and audiences
		Written Communication Skills	Journal Publications
			Patents
			Concise Communication
			Appropriate Mode of Communication
			Research Proposals
		Communication (General)	Personal Attributes
			Break Down Complex Ideas
			Tailor Communication to Audience
		Application of Knowledge	Recognize Impact
			Commercialization
			Patents
			Broader Impacts

> ***components of just engineering analysis, problem recognition, problem statement, candidate solutions, and looking through those kinds of solution****s to select the best solution."*—George (Industry)

"General technical skills" also extend into competence with relevant data analysis programs, design skills, and instrumentation, pointing toward expertise in the sub-discipline in which the engineer is a leader.

4.1.2 Technical leadership

Participants in both academia and industry discussed aspects of this leadership, describing their roles in maintaining high academic standards for new engineers in combination with a commitment to service in order to maintain the integrity of the field. As Roger (IN-AC) demonstrates, assessing the quality of students and faculty, knowledge, or educational material is considered to be a very important quality for Ph.D.-holding engineers in his work in editing, reviewing, and sitting on academic committees:

> *"I do a lot of* ***professional service*** *which means I'm* ***editor of journals****, etcetera. I probably* ***review either as an editor, or as a reviewer****, I probably spend probably 10 hours a week on average doing that. So 10 to 15 hours a week. I'm on the* ***qualifier committee so I'm partially responsible for graduate student qualification exams****; you know, I'm on the committee that would* ***check the problems, proctor the exam****, that kind of thing."*—Roger (IN-AC)

Table 3. Codebook themes and definitions for Conservation tenet of Stewardship

Stewardship Tenet: Conservation Preservation of disciplinary knowledge and history		
Themes	**Components**	**Definitions**
Technical skills (general)	Mathematical fundamentals	Strong understanding of statistics; mathematical modeling
	Engineering fundamentals	Understanding the history of the field; knowledge of foundational engineering problem solving components (e.g. engineering analysis, problem recognition, application of science, math, and engineering principles, generate engineering solutions)
	Expertise	Depth of knowledge; being at the forefront of discipline
	Scientific Method	Apply scientific method, including generation of hypotheses, experimental design and execution, and data analysis
	Data Analysis	Analyze and interpret data generated through disciplinary research
	Technology	Identify and use relevant instrumentation or programs to achieve research objectives
Technical Leadership	Teaching	Build understanding or knowledge of the field in the classroom. Includes generating relevant examples, assessing level of learning
	Assessing Relevance to the Field	Guidance of discipline through gatekeeper roles (e.g. serving as an editor or journal reviewer, using knowledge to inform policy, service to the institution, creating new programs, serving on qualifying committees, or anticipating impact of policy on discipline)
Knowing the Field	Literature	Reading, analyzing, and utilizing published literature in the field
	Identify current technology and trends	Identify current topics/issues and current trends in a discipline's innovation, and be able to recognize state-of-the art technologies
	Synthesize existing information	Integrate information from different areas/sources to solve problems
	Use multiple resources from diverse sources	Find and use relevant information from a variety of online, physical, or human resources

Although many quotes in the technical leadership category were discussed in an academic context, industry-based engineers also were involved in technical leadership through their involvement in journal and/or review committees. Serving as an editor, reviewer, or qualifying committee member maintains the integrity of the field by ensuring new members demonstrate adequate understanding and mastery. Technical leadership was also discussed through participants' commitments to high-quality teaching such as making changes to engineering curricula that will best benefit future engineers.

4.1.3 Knowing the field

This theme is distinct from "General technical skills" because it implies a relationship with the field and its applications, rather than problem-solving and data analysis. Some participants emphasized that a Ph.D. level expert in a field should be intimately familiar with the discipline's literature. Others focused on the ability to keep up with current trends in a discipline's innovation, and to be able to recognize relevant technologies that may alter the state of the discipline. In addition, a Ph.D. engineer should be able to synthesize existing information, using multidisciplinary resources and innovative thinking to solve engineering problems, as indicated by Rob:

> *"I think there's a* ***balance that needs to be between discipline and freeform****. There* ***needs to be some discipline to know that there's an impasse that you're going toward and to keep a focus. But if everything's discipline, well, then nothing new ever happens. So there needs to be an explicit balance between the discipline*** *[. . .and. . .]* ***an ability to turn that discipline off at the appropriate times to go beyond the rigidity of those walls to build the new knowledge, to pull pieces of things together across traditional boundaries."***—Rob (AC-IN)

This theme completes the picture of Conservation: There is an intimate connection with understanding and being familiar with the history of a field and the technical expertise that comes from studying the fundamentals, but Ph.D. holders expand this expertise through their visions for the future.

4.2 Recommendations for alignment of graduate engineering education: Conservation

Elements of conservation showed that Ph.D. engineers incorporate leadership, judgment, and deep understanding of the history and future of one's discipline. Potential activities that may be helpful in developing Conservation competencies include:

- Help to review or critique manuscripts for conference or journal under the guidance of a mentor.
- Serve as a session moderator at a conference.
- Attend disciplinary conferences.
- Teach fundamental engineering courses to novice engineers.
- Attend seminars, dissertation defenses, and other presentations in one's own discipline and related disciplines.
- Visit relevant start-up companies to understand future commercialization opportunities.
- Actively discuss future grant or funding opportunities with advisors, funding agency representatives, and industry sponsors affiliated with one's discipline.

Conservation can be creatively applied depending on how a doctoral student wishes to apply their engineering expertise. The common theme in all these activities is the relationship with developing a vision of where the field has been and where it is going, and being able to identify innovation. This focus on the future is balanced by a firm understanding of engineering fundamentals: Opportunities like teaching undergraduate courses cement these foundational concepts for instructors, while helping students understand how equation derivations and underlying mathematical concepts apply to cutting-edge technologies.

5. Results: Generation

5.1 Definitions of themes within generation

The tenet of generation refers to the creation of new knowledge. We coded data within the tenet of generation into four themes: (1) Research, (2) Contributions to the field, (3) Characteristics, and (4) Teaching others to generate knowledge. These are presented in Table 4.

5.1.1 Research

The ability to plan and conduct research is an important factor that separates a Ph.D. level engineer from a bachelor's-level engineer. This theme described the research process broadly, including the day-to-day research methods, problem analysis, data analysis skills, and expert judgments required

Table 4. Codebook themes and definitions for Generation tenet of Stewardship

Stewardship Tenet: Generation **Producing new knowledge that contributes to the field**		
Themes	**Components**	**Definitions**
Research *(any element of the research process: not necessarily novel contributions)*	Improve on prior knowledge or processes	Improving products or processes (often in service of solving a problem), filling in gaps in competency or skill, and working to exceed the performance or efficiency of existing materials
	Employ rigorous research methods	Knowledge of scientific method, designing appropriate experiments to test well-developed hypotheses
	Problem Analysis	Assessing a problem and analyzing potential solutions; fully understanding a problem through direct experience
	Data Analysis	Knowing how to analyze data using appropriate statistical or qualitative techniques; interpreting and drawing relevant conclusions
Contributions to the Field *(specifically unique and novel contributions)*	Vision	Understanding how research fits into the broader field; recognizing boundaries and when boundaries can be pushed
	Impact	Conducting/publishing research that improves or advances knowledge or has practical impact; something that can elicit change
	Publications, Presentations, and Patents	Making viable, unique, and relevant contributions to the discipline through Intellectual Property, publication, or communication venues
Characteristics	Personal	Characteristics specific to the individual (and not to job training), (e.g. detail-orientation, strong work ethic, work style)
	Professional	Characteristics that reflect skills unique to job training (e.g. fundamental engineering knowledge, rigorous methods skills, critical assessment)
	Ability to teach others to generate knowledge	Mentoring or advising undergraduate or graduate students, specifically in regard to the development of research skills
Knowing the Field	Knowing the Field	Possessing deep disciplinary knowledge and experience which allows one to ask relevant and meaningful questions

to conduct discipline-leading research. Many participants emphasized the ability of Ph.D. engineers to use rigorous methods in order to analyze, ask questions about, and solve engineering problems. As Mitch describes, within this process, a Ph.D. is responsible for accurately interpreting the data:

> *"I would say that having a* ***very strong understanding of fundamental principles*** *is probably even more important because that's one of those things where you, what may appear just to be, one of these things* ***where something that may appear to be just sort of a normal occurrence, or kind of a random occurrence, or something like that, or some unexplained minor trend may really jump out to somebody that has a very strong understanding of physical principles,*** *at least in the work that I do. Understanding those principles really gives you a lot of insight to* ***interpret results correctly.*** *And to be able to* ***take further steps to expand things that work.***"—Mitch (Academia)

While engineers employed by academia focus on the acquisition of publishable data, engineers in industry may focus on other standards for their research, such as improvement on processes or prior knowledge in order to maintain competitive edge. As noted by several industry participants, "improvement" research for efficiency, cost-reduction, and resource-savings is highly valuable. Overall, although classifying "Research" as a theme seems obvious, separating the interpretations of research elicits a deeper understanding of the expectations for engineering Ph.D. holders.

5.1.2 Contributions to the field

This theme is separate from Research (the process) since developing novel technological advances is more rewarded and expected in certain career trajectories. However, whether or not a Ph.D. holding engineer publishes in their professional career, in order to achieve a doctorate degree, an engineer must have contributed significant findings in their dissertation research, so the skills associated with that contribution are expected. Some components associated with Contributions to the field are associated with professional visibility, usually communicated to the technical community through articles, presentations, or patents. Some participants reflected on their ideas of quantitative "standards" for how much new knowledge a scholar should produce, while others discussed the knowledge-generation component with a much broader idea of academic impact, such as Charles:

> *"I think one needs* ***vision****. So you have to* ***understand the broader field and how your work in particular fits into the broader field and why it's important****. And then [. . .] that tells you: Of the 50 different ways you can approach a research project,* ***which of the ways you should do it, and how you should use the results to push science forward****. That's where vision comes in."*—Charles (Academia)

Charles' thoughts were confirmed by other participants and consisted of elements belonging to both Conservation and Generation themes. Other participants blurred the line between Generation and Transformation, elaborating on solving relevant problems with societal impact, or explaining research goals in terms of changing methodologies, practices, or creating technology that affects underserved populations.

5.1.3 Characteristics

Participants described characteristics that impact an engineer's ability to generate knowledge. Some of these included being detail-oriented, having a strong work ethic and maintaining a discriminatory sense of creativity and innovation. Creativity, however, needs to be combined with sound engineering reasoning skills, as described by George, to combine fundamental engineering knowledge and thorough knowledge of experimental methodologies with the ability to critically assess findings and technologies:

> *"It's very important, and very critical that the person* ***be able to use, display, sound rational reasoning skills so that the research that's being conducted is sound and supportable.*** *[. . .T]he reasoning that supports the conclusions have to be sound and not wishy-washy. Depending on the research, I guess, the notion of properly conducted studies, and by that I mean the* ***understanding of sound experimental design and sound experimental results, interpretation skills*** *I think have to be there as well."*—George (Industry)

Some participants also included subscription to standards of professional ethics as another critical attribute of Ph.D. holding engineers, as many technological innovations require ethical considerations in means and ends, as well as professional ethics in teamwork and project management. These characteristics are personal, but directly impact the ability of an engineer to generate knowledge.

5.1.4 Teaching others to generate knowledge

The final Generation characteristic is the ability to teach others to generate knowledge. The quotes within this theme lend insight to the dynamics at the interfaces of generation, conservation, and transformation, indicating the importance of mentorship in the career of a Ph.D. holding expert. This finding aligns well with the apprenticeship model on which higher education is based. Some participants discussed their involvement in facilitating undergraduate research experiences, which fits into this category, while others, such as Roger, discuss their role as research advisors:

> *"When I meet with graduate students on research,* ***a very large fraction of that, probably at least 80% I'd say is really education rather than on really research****. What I mean by that is that a lot of it I'm just* ***teaching them how to think****, you know, I'm pointing them to different, you*

> *know, research areas, different fields that you can learn stuff about. I am, deriving models with them.* ***So a lot of that work is really just trying to educate them to a level that they can progress on the research.****"* —Roger (IN-AC)

Participants who discussed Generation in this way show how they work to generate knowledge through their own work and by fostering the work of a future cohort of engineers. These codes were double-coded in Generation and Transformation, and therefore show how activities of engineering Ph.D. holders can fall into more than one tenet of Stewardship.

5.2 Recommendations for alignment of graduate engineering education: Generation

Generation is the tenet that graduate engineering students are most familiar with, especially given the purpose of the Ph.D. research. However, our recommendations for better aligning Generation principles with an engineer's future career involve creatively harnessing opportunities across Stewardship tenets.

- Involve oneself with collaborative inter- or multidisciplinary research.
- Assist on projects that will be commercialized or patented.
- Seize opportunities to work closely with an industry-sponsored research project.
- If possible, intern at organizations that align with career goals: Industry, start-up companies, national laboratories, private R&D firms, or conduct research at collaborating institutions.
- Develop relationships with people who have complimentary research skills in order to develop the potential for future collaborations.
- Reflect on how dissertation research fits into the larger field, and how one's specific research skills will be valuable to various employment sectors.

Although all these activities are related to the generation of new knowledge, the venues for these generation educational opportunities may look different according to graduates' desired career trajectories, and new opportunities to further hone Generation skills will likely develop as students become more advanced and independent in their personal research.

6. Results: Transformation

6.1 Definitions of themes within transformation

Transformation is primarily concerned with the transfer of expertise to others and other applications. As shown in Table 5, over half of the themes in this tenet were related to communication; skills related to oral or written communication; and the ability to convey information to different audiences.

6.1.1 Teaching

Many participants spoke directly about teaching in their interviews; however, the mode of teaching, the audience, and the setting for teaching varied widely among the interviews. Components within the theme of teaching included Tailoring Communication, Non-Classroom Settings, Classroom Settings, Mentoring, Administrative Duties, and Outreach Opportunities. Each of these presents a different facet of teaching, yet all fulfill the definition of teaching and the definition of transformation.

Samantha discusses the role that strong communication skills play in effectively transferring knowledge to novice engineers:

> *"I think that engineering Ph.D.s need to understand* ***students do not have the same technical background*** *as their peers. [. . .] So you're* ***teaching [students] the technical terms, but you use non-technical terms to bring them there.****"*—Samantha (Academia)

Similarly, Miles discusses the importance communicating relevance in order to motivate engineering students:

> *"I think that by* ***tying everything we do for the students to a long-term goal that directly benefits society, benefits not only the students in their education process but it also helps society*** *because their needs are being directly seen by the students as they do the work. It further* ***motivates the students to perform at a higher level.****"*—Miles (Academia)

Service learning, mentoring, and outreach were also described as Transformation activities, especially as teachers could transform their disciplinary knowledge both to motivate students and to apply their expertise in real-world applications to benefit the community.

Non-classroom teaching experiences were most often mentioned by industry-employed participants: Some discussed their duties as doctoral-level engineers to teach their colleagues through internal engineering courses within their organizations, as well as training programs for new employees and interns. The re-framing of the role of "teaching" to be a necessary skill within *both* academic and industry careers is a significant finding. Many graduate engineering students, even those pursuing academic careers, do not get practical teaching experience, and those pursuing careers in industry may engage in teaching responsibilities irrelevant to their careers. However, these data point to the fact that teaching as an element of Transformation is important for Ph.D. engineers, regardless of career choice.

Table 5. Codebook themes and definitions for Transformation tenet of Stewardship

Stewardship Tenet: Transformation **Translating expertise to a variety of audiences**		
Themes	**Components**	**Definitions**
Teaching	Tailoring communication to audience	Recognizing audience's level of knowledge, perspective, break down complex technical problems to basic principles
	Non-classroom teaching	Teaching, training, or education of audiences outside a classroom setting
	Classroom Teaching	Teaching within a traditional engineering higher education classroom
	Mentoring	Formal or informal guidance of younger or less-experienced engineers
	Administration	Program direction and leadership related to education
	Outreach	Informal education with the intent to expose outside groups to engineering and/or science principles
Verbal Communication Skills (Public and Private)	Presentation Skills	Characteristics related to public communication in presentations: (e.g. Articulateness, eye-contact, use of media, content, etc.)
	Conferences	Willingness to engage with disciplinary community in conference settings
	Concise communication	Judgment of what information is relevant and necessary
	Communicating appropriately for situations and audiences	Management of professional discourse among colleagues and collaborators, including method and mode of communication, roles in business or research meetings, interactions with customers
Written Communication Skills (Public and Private)	Journal Publications	Ability to write for scholarly audience by publishing new knowledge in scholarly journals
	Patents	Ability to file patents in order to protecting intellectual property
	Concise communication	Ability to write in a succinct and clear manner
	Appropriate mode of communication	Understanding appropriate situations in which to use different modes of communication (e.g. face-to-face communication, phone, email, videoconference, written report)
	Research proposals	Ability to write research proposals to obtain research funding
Communication (General)	Personal Attributes	Skills related to overall personal presentation during communication (e.g. voice, poise, confidence, articulateness, conciseness and non-verbal communication employed during any form of communication)
	Break down complex ideas	Ability to dissect ideas into most basic components
	Tailor communication to audience	Communicate effectively with audiences of different needs and knowledge levels (e.g. management, customers, colleagues, students, public)
Application of Knowledge	Recognize impact	Understand the impact of engineering decisions on stakeholders' interests (e.g. profitability, innovation)
	Commercialization	Translate research findings to business application
	Patents	Protect generated knowledge through patent
	Broader Impacts	Understand impacts of technology beyond immediate benefits to stakeholders

6.1.2 General communication

This theme encompassed the most general mention of good communication skills, where participants did not specify particular modes or venues for such communication. Components include personal attributes; the ability to break down complex ideas; and the ability to tailor communication to the audience. Personal attributes were usually discussed in terms of characteristics, such as the ability to be articulate, have positive non-verbal skills, or convey confidence. Peter emphasized the need for current and future Ph.D. holding engineers to learn to maintain poise and control under pressure while communicating with confidence:

> *"You know, frequently Ph.D. students [. . .]really need some experience* ***presenting in front of audiences, or giving talks in front of—I don't want to say hostile–but a committee or a group that may doubt their results.*** *You know, that may be looking for something wrong. So, you know, I characterize that as* ***poise, you know, being forceful, and articulate, and being confident in your own results****."*—Peter (AC-IN)

Many of the communication (general) themes discussed knowing the audience across a variety of environments and media of communication. Participants discussed various methods and venues for communication, but the findings converged on the idea that all Ph.D. engineers are responsible for communicating their expertise across multiple populations and venues. As a result, Ph.D. engineers need to be eloquent and discriminant in their communication in order to best tailor communication to their audiences.

6.1.3 Application of knowledge

Many participants directly described how participants *apply* their knowledge to various applications. The four components of this theme include Impact for company/organization, Commercialization of products, Patents, and Broader impacts. The commercialization and patents themes are self-explanatory, offering application of knowledge to benefit intellectual property. Ryan (IN-AC) notes his commitment to being oriented toward "***how do I make it better? How do I improve upon it? How is it applicable?****' [. . .] 'How do we explain it to engineering students?'"* Additionally, Sandra notes the calling of an engineer to harness physical principles to benefit society:

> *"In my particular field,* ***applying the knowledge that we gain from materials to help with sustainable environments, applying those materials to alternative energy sources, you know applying different materials to understanding biological and bioengineering devices.*** *And so all of these things are* ***directly related back to the community*** *and how* ***with engineers we of course are—are here to serve the community and to make life better*** *at least that's the way I see it,* ***for not only the national, but the international community****."*—Sandra (IN-AC)

In these excerpts, elements of Transformation also incorporate aspects of Conservation and Generation—only by being a Steward in the other areas are these participants able to best translate their findings, passion, vision, and technical leadership to better the future of engineers and engineering.

6.2 Recommendations for alignment of graduate engineering education: Transformation

Some of the aspects of Transformation are common in calls for improvement of engineering education as a whole, especially the communication aspects. However, Transformation goes beyond pure communication skills and posits that Ph.D. holders apply their expertise (usually through communication) in broad applications. Development of the Transformation skills may need to be explicitly sought, since they require practice. However, in educating well-rounded doctoral engineers that will be able to succeed in multiple venues, these activities are valuable.

- Present research at conferences, both within one's discipline and at interdisciplinary conferences.
- Pursue teaching opportunities, recognizing that "Teaching" skills are useful within both industry and academic careers.
- Apply research expertise to projects which have broad societal impact.
- Practice disciplinary writing in a variety of venues: Grant writing, fellowship applications, journal/conference paper publication.
- Practice disciplinary communication: Seek opportunities to present at departmental seminars; substitute teach undergraduate courses; practice appropriate communication, grammar, and spelling in all communication (including email).
- Explicitly network with leaders in the field at conferences in order to practice verbal communication about your research and interpersonal skills.
- Seek advice and mentorship with disciplinary leaders outside one's institution to build strong relationships and future collaborations that span disciplines.

Transformation opportunities may be viewed as superfluous or irrelevant in the short term to students and advisors, or seen as skills to develop at some time in the future. However, these skills are important to graduate education and may aid in job placement and advancement.

7. Introduction to the competencies blueprint model for doctoral education

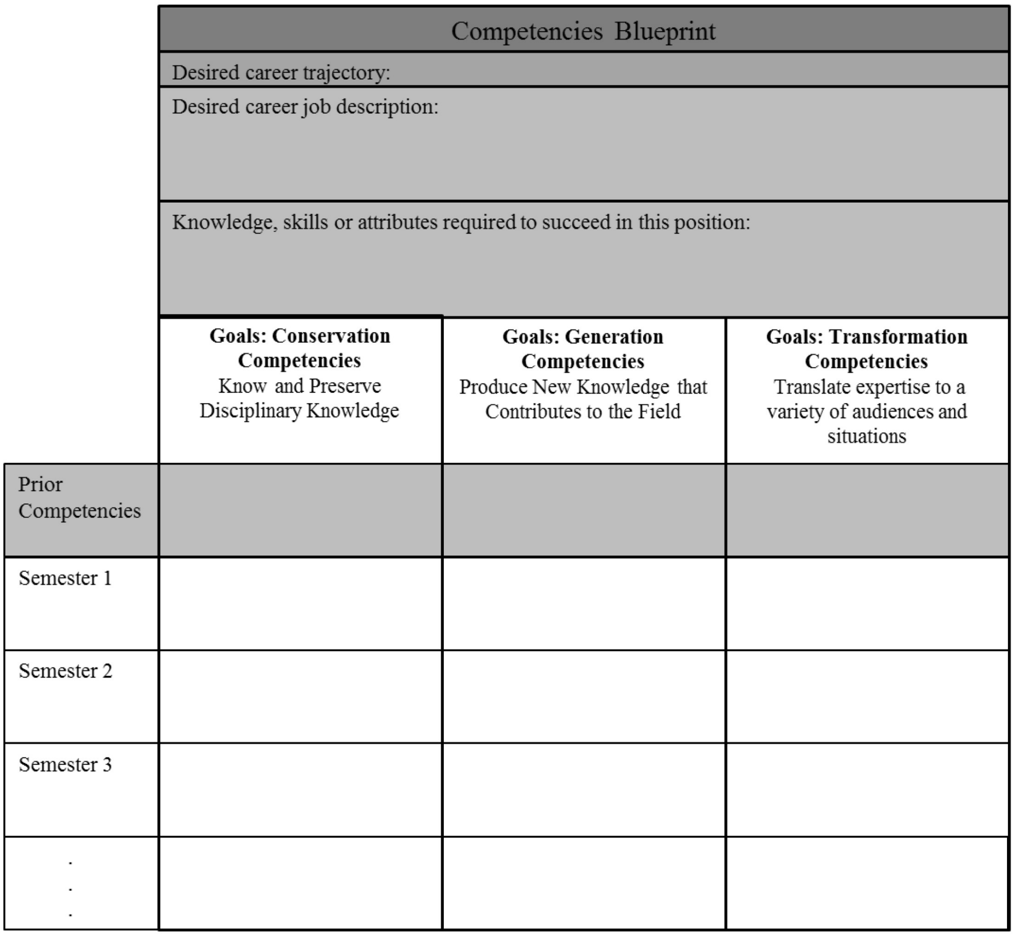
The recommendations within each of the tenets of Stewardship based on the findings from our study can be compiled into a useful tool for doctoral students, advising faculty guiding student professional development, or engineering administrators seeking to align and assess competencies in an entire engineering program. Here, we unveil the Competencies Blueprint, which is based on Stewardship and helps align skills learned through traditional engineering research and teaching education and extracurricular opportunities with students' desired career paths.

Figure 2 shows a sample Competencies Blueprint template. Students should spend some time individually reflecting on their career goals and researching job descriptions for types of institutions or organizations in which they would like to work, in order to best complete a personal Competencies Blueprint before consulting with their advisors or mentors. Programs or faculty might offer a finite list of competencies that could be selected to be fulfilled and could align with Conservation, Generation, and Transformation, or they could leave it to the student to creatively plan professional development opportunities. We fully expect users of the Blueprint to adapt the representation or template based on preference or use. Ultimately, the goal competencies chosen should strongly align with the knowledge, skills and attributes and job description/qualifications within the chart. Filling out the chart may be an iterative process. The flexibility of the Blueprint permits change as career opportunities or goals evolve and allows students to monitor their own progress.

The Competencies Blueprint model for professional development is not intended to disturb or disrupt the traditional advisor-advisee relationship; teaching, research, and publication requirements; or coursework standards. The activities would be completed in addition to the expectations required by a doctoral program: Students should not use their future career goals to refuse to participate in some element of program or advisor requirements. Rather, a student should deliberately choose outside activities (within their control) that develop auxiliary professional skills, to increase hirability after graduation. Faculty and administrators might employ this flexible and robust Competencies Blueprint within their research groups or across an entire graduate program in order to better align graduate education with the needs of engineering careers and assess student competencies.

8. Discussion

The tenets of Stewardship seek to inform educators of three large ideas that Ph.D. holders across disciplines exemplify through their activities, whether or not they identify these distinct components in their own lives. By operationalizing Stewardship and providing engineering-specific examples, it becomes clear to educators how practicing engineers think about their world and what it *means practically* to be an engineer. This research adds to the body of knowledge characterizing the engineering Ph.D., extending work that Watson and Lyons conducted focusing on engineering Ph.D. holders in industry [4], as well as extending the utilization of Golde and Walker's Stewardship framework into the discipline of engineering [14]. Lastly, this is one



	Competencies Blueprint		
	Desired career trajectory:		
	Desired career job description:		
	Knowledge, skills or attributes required to succeed in this position:		
	Goals: Conservation Competencies Know and Preserve Disciplinary Knowledge	**Goals: Generation Competencies** Produce New Knowledge that Contributes to the Field	**Goals: Transformation Competencies** Translate expertise to a variety of audiences and situations
Prior Competencies			
Semester 1			
Semester 2			
Semester 3			
. . .			

Fig. 2. Competencies Blueprint.

of the only works in engineering education that proposes a concrete research-to-practice mechanism for doctoral-level preparation and professional competencies.

The sample recommendations for competency development in each tenet of Stewardship and the Competencies Blueprint are not novel: Many are proposed in prior reports [2, 34]. However, as a "to-do list" for professional development, (e.g. as the survey studied by Bieschke, Bishop, and Garcia [35] may be interpreted), the tasks overwhelm the goals, which is to socialize students as leaders of a disciplinary community. Grouping activities by Stewardship tenets can help students and faculty deliberately plan activities so that over the course of a semester, year, or program, a graduate student has developed skills within all three tenets of Stewardship, as they apply to a desired career. Our operationalization of Stewardship and the examples mentioned are lists of opportunities that can develop specific skill sets required in engineering. Using the tenets, themes, and components as competencies within the Competencies Blueprint to guide learning opportunities will help align the (formal and informal) doctoral engineering curriculum with disciplinary career expectations.

This approach for graduate education aligns well with adult educational theory, which centers on the idea that adults need to be personally motivated: Achievement in adult learners is linked to intrinsic motivation, senses of agency, and ideas on self-authorship [36, 37]. Within the traditional requirements of an engineering Ph.D. program, students can be asked by faculty advisors to develop and fulfill their individual professional goals, potentially motivating milestone and degree completion, and perhaps boost placement rates for Ph.D. engineers. Using the Stewardship framework to guide these activities simplifies the opportunities and helps students to align their goals with future engineering employers' expectations.

9. Role of the researchers, limitations of the study and future work

The research data were collected by seven research team members holding degrees in engineering and currently involved in engineering education research. This positionality allowed the researchers to recognize particularly interesting aspects of engineering careers, and a deeper understanding of disciplinary terms or jargon. The coding and analysis of the data for this publication was conducted collaboratively by one researcher with an engineering background and another researcher with a social psychology background. This pairing was conducive to creating clear codes and definitions that outline the roles and responsibilities of the Ph.D. engineer.

One limitation of the study involves the sampling methods, which only targeted Ph.D. engineers currently working in the United States. It would be interesting to take a look at the engineering Ph.D. more globally, looking across cultures to understand the way in which Stewardship is either upheld or disproven in the roles of Ph.D. engineers around the world. Additionally, as engineering disciplines are expanding rapidly, it may be interesting to examine the expectations of Ph.D. holders in some of the traditional engineering disciplines (e.g. civil engineering or mechanical engineering) with the newer disciplines (e.g. biomedical engineering or ecological and environmental engineering).

Future work with the Competencies Blueprint will involve implementation, assessment, and adaptation of the model to work in various applications (individual use, in a research group, department-wide). Users of the Blueprint or any variation of our model or findings are encouraged to contact us with their experiences and findings.

10. Conclusion

Through this study, we offer insight into the roles of Ph.D. engineers in academia and industry using Golde and Walker's Stewardship framework, which divides the tasks that Ph.D. holders perform into the three categories of Conservation, Generation, and Transformation. In this study, we expanded prior work studying other professions by interviewing 40 Ph.D. engineers in a variety of engineering disciplines holding careers in industry and academia. This study contributes to the body of knowledge in engineering education by offering interpretations of how engineering experts operationalize Stewardship. We found that engineers in both industry and academia enact elements of Conservation, Generation, and Transformation in different ways, and these activities and the skills they represent might be better aligned with doctoral engineering education opportunities. While previous studies have examined some of the knowledge, skills, and attributes that Ph.D. students need going forward, this research frames the needed skills through Stewardship theory, and extends the theory into an easily applied mechanism for competency planning. As a result of this qualitative study, we unveil a flexible and robust Competencies Blueprint based on this research that can align doctoral engineering education with students' career trajectories. The Competencies Blueprint will be useful for students, faculty, and administrators seeking to reform graduate competencies achievement and assessment.

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Catherine G. P. Berdanier is a Research Associate in the Department of Mechanical and Nuclear Engineering at Pennsylvania State University. She holds a holds a Ph.D. in Engineering Education from Purdue University. She earned her B.S. in Chemistry from The University of South Dakota and her M.S. in Aeronautical and Astronautical Engineering from Purdue University. Her current research interests include graduate-level engineering education, including inter- and multidisciplinary graduate education, innovative and novel graduate education experiences, global learning, preparation of graduate students for future careers, and engineering writing

Anne Tally is pursuing a Master of Arts in Social Science at the University of Chicago. Her research focuses on sociolinguistics applied to online communities and the use of hashtags for political activism.

Sara E. Branch is an assistant professor of psychology at Hobart and William Smith Colleges. Her research focuses on individual differences and motivation with a focus on the association between environmental orientations and career selection and persistence.

Benjamin Ahn is an Assistant Professor in the Department of Aerospace Engineering at Iowa State University. He obtained a B.E. in Aerospace from the University of New South Wales (Australia), a M.S. in Aeronautics and Astronautics from Purdue University, and a Ph.D. in Engineering Education, also from Purdue University. His research interests include implementing and assessing active learning pedagogy in engineering mechanic courses, identifying effective mentoring skills in undergraduate research settings, and creating assessment tools to measure engineering students' professional skills.

Monica F. Cox is a full professor and department chair of the Department of Engineering Education at The Ohio State University. She obtained a B.S. in mathematics from Spelman College, a M.S. in industrial engineering from the University of Alabama, and a Ph.D. in Leadership and Policy Studies from Peabody College of Vanderbilt University. Teaching interests relate to the professional development of graduate engineering students and to leadership, policy, and change in science, technology, engineering, and mathematics education. Primary research projects explore the preparation of engineering doctoral students for careers in academia and industry and the development of engineering education assessment tools. She is a National Science Foundation Faculty Early Career (CAREER) award winner and is a recipient of a Presidential Early Career Award for Scientists and Engineers (PECASE).