



## Challenges to and Development of Innovation Discovery Behaviors among Engineering Students

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# Challenges to Innovation Discovery Behaviors among Engineering Students

## Abstract

Innovation is the process of developing novel and functional products, processes, and systems that appropriately address key user needs. As the role of innovation in engineering has grown, engineering educators have become increasingly focused on preparing engineering students to meet innovative challenges. Innovation discovery behaviors as described in *The Innovator's DNA* (questioning, experimenting, networking, and observing) represent four critical behavioral tendencies that can aid engineers during the innovation process, especially in identifying unmet needs and pursuing innovative solutions. In this study, we assessed the behavioral tendencies of 162 engineering students and compared them to an established sample of 382 professional innovative entrepreneurs. When compared to expert innovators, students scored lower on questioning and networking. Overall, students scored lower on networking compared to the three other behaviors. We also interviewed a sample of nine engineering students from the pool of survey respondents in order to gauge the challenges they face in employing these behaviors in an engineering setting. Results indicated that students face critical challenges in each discovery behavior along themes of educational context, individual mindset, lack of skill/expertise, and lack of perceived utility of the behavior. Implications of these findings for improving engineering students' innovative behaviors are explored.

## Introduction

Within the context of engineering, innovation is the process of developing novel and functional products, processes, or systems that appropriately address key user needs. Innovation has been described as the “lifeblood of all organizations”<sup>1</sup> and as the central factor contributing to the success of the United States in an increasingly global marketplace.<sup>2</sup> The innovation process is driven by people, and innovative solutions lead to projects or processes that are linked to tangible, real-world outcomes.<sup>1</sup> These outcomes of innovative design affect and must be adopted by stakeholders within a broad social context.<sup>3,4</sup>

As the recognized importance of innovation has grown both nationally and worldwide, engineering educators have become increasingly focused on preparing engineering students to become innovative.<sup>5-7</sup> Hence a common focus is on what skills or behavioral tendencies underlie innovation.<sup>3,8,9</sup> For example, one key skill for innovation within engineering design described by Salter and Gann was interpersonal collaboration, especially when working through complex design problems that had layers of uncertainty.<sup>10</sup>

Recent literature has suggested that engineering students do not value skills and mindsets essential for innovation. For example, reports have indicated that engineering students do not view creativity as an important aspect of the engineering design process<sup>11,12</sup>. Further, some studies suggest that engineering students tend to emphasize technical details over a more holistic understanding of a design problem<sup>6</sup> and are unable to identify design solutions that are both feasible and novel.<sup>13,14</sup> Engineering students may possess the skills and mindsets necessary for innovation, but the engineering identity they develop throughout their undergraduate education may limit their willingness or ability to demonstrate those skills and mindsets within an engineering context.<sup>11,15</sup>

In this study, we sought to understand how engineering students developed and utilized four behaviors (discovery behaviors) commonly linked to innovativeness. These behaviors include: questioning, experimenting, idea networking, and observing (as described by *The Innovator's DNA*).<sup>3</sup> More specifically, our research questions were::

- 1) How strong are engineering students behavioral tendencies on each of the four innovative discovery behaviors: questioning, networking, experimenting, and observing?
- 2) What do engineering students describe as challenges or supports to developing and demonstrating these behaviors?

## Literature Review

Within the Innovator's DNA, Dyer, Gregersen, and Christensen<sup>3</sup> identified a series of four behaviors linked to innovation, and built around the structure of associative thinking (hence the DNA reference). Associative thinking enables innovators to make connections across boundaries, disciplines, and knowledge domains based on the information and ideas they have recognized through four discovery behaviors, including:

- **Questioning**, or a passionate inquisitiveness of the surrounding world context
- **Observing**, or an everyday attentiveness to customers, products, and services
- **Networking**, or sharing and gathering ideas from a diverse group of individuals who may be part of an “internal” or “external” group
- **Experimenting**, or testing ideas by trying new experiences, disassembling artifacts, or piloting prototypes

The successful innovators Dyer, Gregersen, and Christensen studied exhibited these innovation skills to varying extents, suggesting that no single behavioral tendency was necessarily most important. In addition, while the innovators they identified may have been significantly more prolific at some subset of these skills than another, no single pattern of scoring was considered to be ideal. In other words, scoring extremely well in networking and questioning does not necessarily make one more innovative than scoring highly in observing and experimenting. The majority of the innovators in their sample at least scored in the 70<sup>th</sup> percentile of all respondents along questioning, and it was more likely that these individuals would be “innovative” if they thrived at two or more of the skills.

The innovators whom these authors used to identify these skills were primarily entrepreneurs and senior executives, which leads to the question, “Do these skills translate directly to an engineering context?” In Petre’s (2004) depiction of innovation within engineering teams, the answer would appear to be yes, as she described each innovative behavior as integral in some respect for the team’s ability to be innovative.<sup>16</sup> For example, questioning was key in allowing the team to identify gaps within the broader marketplace, whereas experimenting by ‘playing with toys’ allowed refinements of current innovation projects and development of promising new projects. In the following paragraphs, we briefly explore literature on each innovation behavior within engineering individually.

**Questioning** has been described as an integral component of the design process,<sup>17,18</sup> whereas intellectual courage has been described as the dispositional tendency to question anything, especially the most core and foundational beliefs surrounding an engineering design.<sup>19</sup> Questioning has been embedded or studied explicitly within a variety of engineering design tasks. For example, Winkleman and Hacker found that forced questioning enabled students to perform better at an engineering design task.<sup>20</sup> On the other hand, Eris (2004) explored the function of unprimed questioning within design teams and found that team members already spent a significant portion of their time asking and discussing questions related to the design tasks at hand. Notably, the function of these questions was highly variable. They may have been used to clarify/request information and perspectives, improve conceptual understanding, identify design concepts, organize team processes and interaction.<sup>18</sup>

**Observation** has been depicted as a key skill within engineering design, particularly in regards to its usefulness in meeting users’ needs.<sup>21,22</sup> According to Kolodner and Wills, observation is directly tied to perceptiveness which enables an engineer to have a meta-awareness of the context in which a problem is embedded, along with how that context formulates the problem at hand.<sup>23</sup> Observation seems particularly key to the growing body of knowledge on empathic design within engineering, where the direct focus may involve observing stakeholders in their real-world context.<sup>5,24</sup>

**Networking** has been captured by the broad range of literature on collaboration within engineering education research.<sup>25-29</sup> However, it should be noted that the impetus in much of this work tends to focus on *internal* networking within a design team, as opposed to how individual students might grow an external network of contacts to gather new insights within a domain. This type of external collaboration is probably best captured by literature on cross-disciplinary research, where the focus is on how working with individuals outside of one's engineering discipline can lead to novel perspectives and innovative solutions.<sup>30,31</sup>

**Experimenting** has historically been core to engineering and engineering education, as is evident by ABET's learning outcome specifying that students should be able to "design and conduct experiments".<sup>32</sup> As a result, laboratory instruction has long been a staple of engineering education. In Crismond and Adams' (2012) Informed Design Teaching and Learning matrix, the ability to conduct valid experiments was identified as a key design ability.<sup>33</sup> From the perspective of engineering students, experimenting has been depicted as supplemental to and reinforcing of the general theory learned from lecture or a textbook.<sup>34</sup> Therefore, the connection between experimenting and innovation within engineering seems direct and pervasive.

The literature compiled in this section identifies that each of the four discovery behaviors is valuable within engineering, and may be particularly impactful in the context of engineering innovation. This review has also revealed that little is known about whether and how engineering students translate these skills to their own engineering work. In this study, we aim to address that gap by identifying how well a sample of engineering students score on the Innovation Behavior Scales survey.<sup>9</sup> Further, we explore how students interpret these behaviors in their own curricular context, including challenges to their application of those behaviors.

## **Methods Overview**

This multi-phase study proceeded in two stages. The study began with a quantitative stage (phase 1) comparing engineering students' scores on the Innovation Behavior Scales to those of a previously collected sample of innovative entrepreneurs.<sup>9</sup> Differences in these scores represented a difference in self-reported behavior tendencies that indicate competency on the innovation discovery behaviors of questioning, experimenting, networking, and observing. The quantitative stage was followed by a qualitative stage (phase 2) of semi-structured interviews with a demographically representative sample of the surveyed student population. Thematic analysis was performed on the interview transcripts to understand the characteristics of engineering students, along with how their learning/work environments have supported or challenged development of the discovery behaviors.<sup>35</sup> The qualitative strand, thus, helped explain the survey scores and, more importantly, suggested ways educators may be able to help students develop stronger discovery behaviors within their own curriculum.<sup>36,37</sup>

## Phase 1: Comparing Engineers and Innovators using the Innovative Behavior Scales

### *Survey Implementation*

Students in all engineering majors at a large university in the United States were invited to complete the Innovation Behavior Scales through an electronic link sent to departmental listservs and posted on the daily announcements delivered to all College of Engineering network computers. Permission to use the survey was gathered by the authors from the survey designers via email. The respondents' completion of the survey was voluntary, but it was indicated that those who completed the survey would have the opportunity to volunteer to participate in a follow-up interview that carried a \$10 stipend.

A total of 162 engineering students completed the 19-item survey. Of these students, 92 identified themselves as male, 69 identified themselves as female, and one student preferred not to respond. The sample was also distributed across all grade levels and engineering majors at the school. Tables 1 and 2 provide an overview of the grade level and engineering major of respondents, respectively.

**Table 1:** Grade Level of Respondents

Grade Level	# of Respondents
First-Year	1
Sophomore	18
Junior	27
Senior	27
Master's Student	33
Doctoral Student	55
Other	1

**Table 2:** Engineering Major of Respondents

Engineering Major	# of Respondents
Aeronautics and Astronautics	19
Agricultural and Biological Engineering	6
Biomedical Engineering	1
Chemical Engineering	24
Civil Engineering	22
Construction Engineering and Management	3
Electrical and Computer Engineering	27

Engineering Education	13
Environmental and Ecological Engineering	3
Industrial Engineering	25
Interdisciplinary and Multidisciplinary Engineering	1
Materials Engineering	2
Mechanical Engineering	15
Nuclear Engineering	1

### Survey Analysis

The survey consisted of 19 items that individually mapped to one of the four discovery behaviors. Each survey taker was awarded a score on questioning, experimenting, networking, and observing based on the mean score on all the items that mapped to the skill. The potential range of these scores was 1 (strongly disagree) to 5 (strongly agree). Means of these scores were compared to means of a sample of 382 professionals described as “innovative entrepreneurs”.<sup>9</sup> The individuals in the professional sample represented a variety of individuals who have started businesses, and thus are not necessarily engineers. The scores of these individuals were originally on a 1 to 7 scale and were linearly mapped for this study to a 1 to 5 scale. Student scores were compared to innovative entrepreneurs’ scores with a series of independent samples t-tests. It should be noted that the authors of this paper were not affiliated with the study of innovative entrepreneurs. Interested readers are encouraged to read the full study by Dyer, Gregersen, and Christensen<sup>9</sup> for context on that sample and the development of the survey.

### Survey Outcomes

Of the innovative behaviors identified by Dyer, Gregersen, and Christensen,<sup>9</sup> the engineering students in our sample scored highest in experimenting followed by questioning, observing, and networking. Of these behaviors, students scored significantly lower along networking as compared to the other three behaviors.

When comparing our respondents with the innovative entrepreneurs surveyed by Dyer, Gregersen, and Christensen,<sup>9</sup> our participants reported significantly lower competency on two discovery behaviors: questioning ( $t(543) = -6.28, p < .05, d = -0.59$ ) and networking ( $t(543) = -3.67, p < .05, d = -0.34$ ). There were no significant differences on either experimenting ( $t(543) = 0.44, p = .66, d = .04$ ) or observing ( $t(543) = -0.68, p = .49, d = -0.06$ ). Table 3 provides an overview of these group comparisons.

**Table 3:** Engineering Students’ Discovery behaviors in Comparison to Innovative Entrepreneurs

Discovery Behavior	Innovative Entrepreneurs M(SD)	Engineering Students, M(SD)
Questioning*	3.99 (.59)	3.60 (.80)
Experimenting	3.62 (.67)	3.65 (.79)
Observing	3.62 (.75)	3.57 (.82)
Networking*	3.19 (.90)	2.88 (.92)

\*Engineering students scored significantly lower the innovative entrepreneurs at  $p < .05$

†Responses were along a 1-5 point Likert scale where 1 = Does not describe me well and 5 = Describes me very well

## Phase 2: Engineering Students' Challenges to Using Discovery Behaviors

### *Interview Implementation*

After completing the survey, twenty-five respondents indicated interest in participating in a follow-up interview, each of whom was invited via email to participate. Nine of these students consented to and eventually completed an interview during the same semester in which they completed the survey (Spring 2014). Interviews lasted from forty to ninety minutes in length, with the average time being a little over an hour. The first two authors co-conducted seven of the interviews. The first author conducted the remaining two interviews due to scheduling conflicts. Table 4 describes each interview participant by their self-identified academic discipline, gender, and pseudonym. Four participants opted not to select a specific pseudonym; in these cases the authors selected a pseudonym at random.

**Table 4:** Interview Participants

<b>Pseudonym</b>	<b>Academic Discipline</b>	<b>Grade Level</b>	<b>Gender</b>
Carl	Chemical Engineering	Junior	Male
Donovan	Biological Engineering	Junior	Male
Henrik	Computer Engineering	Masters	Male
Julie	Agricultural Engineering	Masters	Female
Luiz	Biological Engineering	Junior	Male
Marshall	Electrical Engineering	Sophomore	Male
Mike	Electrical Engineering	Doctoral	Male
Roxanne	Civil Engineering	Senior	Female
Terence	Electrical Engineering	Doctoral	Male

The interviews consisted of five stages, three of which were most relevant to the current study. The questions were semi-structured with a finite list of questions regarding participant perspectives on innovation, how they might use each skill in the context of engineering work, and their comments on the survey items, constructs, and scores. Each of these interview stages consisted of a limited set of structured questions in addition to follow-up questions utilized to request clarification of student responses, probe deeper into students' conceptions, and identify greater detail. A full interview protocol is included in Appendix A.

During the first stage of the interview, students discussed their perspectives and experiences related to innovation. The next stage focused on students' perspectives and experiences related to four discovery behaviors and the survey items that described these innovative behaviors. Students received a handout with the 19 survey items grouped into nameless dimensions representing the four discovery behaviors. Students were asked to describe these de-identified constructs. Next, students received the same handout but here with the dimensions identified, along with a brief summary paraphrased from an account of the larger Innovator's DNA study.<sup>9</sup> The interviewees reacted to this information and discussed how they would or would not utilize the skills and their applicability to engineering work. Finally, students were asked to predict and react to their survey scores, as well as mean scores of their academic major and all of engineering. The next two interview stages modeled the first two, but focused on a different



survey intended to measure empathy. Data from these stages did not focus on innovation or the discovery behaviors and thus these components were not analyzed in the current study. The final stage asked students to describe any potential connections between the four discovery behaviors and empathy in terms of innovative engineering design. The goal of including these stages in this order was to (a) address the survey constructs from a variety of lenses and (b) to vary the specificity with which they referred to the four discovery behaviors.

### *Thematic Analysis Procedure*

Thematic analysis<sup>35</sup> was performed on the nine interview transcripts in order to understand the challenges students faced in employing the four discovery behaviors within an engineering context or, conversely, factors that supported the utilization of the discovery behaviors. Thematic analysis is useful in uncovering the latent meaning among a group of participants, which is particularly helpful in this instance as many participants' responses were directly related to the survey. By focusing on latent meaning, we were able to extract meaning related to the utilization of four discovery behaviors beyond the specific examples provided by the students. Thematic analysis was performed independently for each discovery behavior with data from all interview phases given equal consideration and weight.

We utilized a seven-step process similar to that outlined by Braun and Clarke<sup>357</sup>, with an extra initial stage. During this first step, transcript data were parsed into four data sets. Each set included only excerpts in which the participant was directly discussing the given discovery behavior. This was determined by a combination of direct reference to the discovery behavior in the response, wording of the question preceding the response, and the judgment of the lead author. The next steps included: reading and re-reading the data, generating initial codes, collating codes and identifying themes, reviewing themes in light of coded extracts and the whole data set, defining and naming the themes, and crafting final theme descriptions and maps.

This process, while depicted as a series of steps, was iterative. During thematic analysis, we regularly shifted our focus between the steps as necessary. For example, if a coded extract revealed an issue with the current conceptualization of the theme, we would shift from framing themes to generating new themes. We would also return to previous steps after consulting with and receiving feedback from one another based on the current conceptualization of the themes. The process was completed when we believed the themes were stable, consistent, and accurately represented the participant responses as a whole.

During the thematic analysis process, it became apparent that similar challenges and supports were being identified across the four discovery behaviors; it was simply specific instantiations that differed. For example, one of the emerging themes represented the role engineering culture played in a student's willingness to utilize a specific skill. Many students referenced experimenting as "something engineers do," thus engineering culture as perceived by the respondents supported experimenting behavior. Others interpreted engineering culture as rewarding knowledge and punishing ignorance. As questioning was interpreted by some students as admitting ignorance, and as ignorance was seen as a general weakness within engineering, respondents reported they sometimes avoided questioning within the classroom. As a result of these overlapping across innovative behaviors, preliminary results from each analysis were

integrated into four meta-themes. The final thematic structure as represented in this paper represents factors that our respondents perceived as positively or negatively influencing their own utilization of the four discovery behaviors.

*Themes Representing Challenges to Innovation*

Thematic analysis across the four discovery behaviors revealed four themes that represented challenges the students faced employing the discovery behaviors, as framed by the Innovation Behaviors Scales survey, in an engineering or engineering education context. These themes included *individual mindset*, *lack of skill/expertise*, *lack of utility*, and *education context*. While certain challenges may be more applicable to one discovery behavior than the rest, excerpts from all discovery behaviors contributed to the overall formation of the challenge themes. We present specific instantiations of each of the themes across each discovery behavior in Table 5. The following section presents a thorough discussion of each. Supporting excerpts from student interviews are presented in this discussion to aid transparency and provide added context into the students’ worlds.

**Table 5:** Themes Representing Students’ Challenges to Innovation Discovery Behaviors

	<b>Generated Thematic Challenges</b>			
<b>Discovery Behaviors</b>	Individual Mindset	Lack of Skill/Expertise	Lack of Utility	Education Context
Questioning	<ul style="list-style-type: none"> <li>• Lack questioning mentality</li> <li>• Don’t want to challenge</li> <li>• Difficult to admit ignorance</li> </ul>	<ul style="list-style-type: none"> <li>• Lack knowledge to ask the right question</li> <li>• Don’t know the right people to ask</li> </ul>	<ul style="list-style-type: none"> <li>• Time consuming</li> <li>• Won’t lead to useful answer</li> </ul>	<ul style="list-style-type: none"> <li>• Instructor must create informal and open atmosphere</li> <li>• Grades inhibit true questioning</li> </ul>
Experimenting	<ul style="list-style-type: none"> <li>• Lack hands-on mindset</li> <li>• Need initiative</li> </ul>	<ul style="list-style-type: none"> <li>• Lack hands-on abilities</li> <li>• Difficult to think for self</li> </ul>	<ul style="list-style-type: none"> <li>• Time consuming</li> </ul>	<ul style="list-style-type: none"> <li>• Cookbook labs limit true experimentation</li> </ul>
Networking	<ul style="list-style-type: none"> <li>• Independence</li> <li>• Lack people orientation</li> <li>• Not enjoyable</li> </ul>	<ul style="list-style-type: none"> <li>• Lack social skills</li> </ul>	<ul style="list-style-type: none"> <li>• Irrelevant outcomes</li> <li>• People not useful</li> <li>• Not as efficient as other discovery behaviors</li> <li>• Did not realize benefits</li> </ul>	<ul style="list-style-type: none"> <li>• Need space for informal interaction</li> <li>• Need interesting and present peers</li> <li>• Need instructors to encourage collaboration</li> </ul>
Observing	<ul style="list-style-type: none"> <li>• Not reflective or attentive to everyday</li> <li>• Not oriented to think outside domain</li> </ul>	<ul style="list-style-type: none"> <li>• Lack ability to associate from everyday observation to specific engineering task</li> </ul>	<ul style="list-style-type: none"> <li>• Unstructured – benefits not guaranteed</li> <li>• Not relevant to all engineering work</li> </ul>	<ul style="list-style-type: none"> <li>• Not emphasized in many classes</li> </ul>

### *Individual Mindset*

Participants indicated that they and their peers did not always have the intrinsic motivation or orientation to pursue a discovery behavior, especially in light of the external difficulties (described in the subsequent sections). All four discovery behaviors were viewed by the students as requiring extra interest, drive, and effort. With questioning, students described a necessary tenacity to constantly think of and ask questions and feel comfortable with the challenging nature of asking certain questions. Students also described that individual (or team) initiative was often required to test ideas through experimenting. Luiz, for example, described an incident in which he took the initiative to experiment during a course design project while other students did not:

*Our topic was getting the thermal conductivity of animal organs. So we went and bought animal organs and then tested them and presented results and all that... My first thing was experimenting and like doing experiments in a lab and stuff. Others, or most of the class didn't even do any experiments. They just, for example, effects of like adding one chemical to food, and then they'd just do research online and then present those results.*

Julie added some clarity by suggesting some students were either not interested in or downright dreaded the results of testing their ideas. She described experimenting as,

*... not so much risk-taking, but you're willing to test out your ideas instead of just having an idea and wondering if it's right. Just not being afraid to confirm that or negate it.*

Similarly, networking and observing required orientations towards other people and, in turn, the external world.

Participants noted individual mindsets or preferences that naturally oriented them towards or against particular behaviors, regardless of willingness or initiative. With experimenting, it was an orientation towards mental rather than hands-on work. With networking, it was a desire to work alone – or as Carl called it, having “an independent streak.” Questioning was similarly challenged by a desire not to appear ignorant to peers, instructors, or supervisors. With observing, students felt they often did not think reflectively about their everyday observations, or, in Henrik’s case, did not think reflectively often enough:

*I'd like to do more of that. Maybe I do some of it, but I don't think I consciously do. Yeah. I may see it and may bring it up in conversations with people, but I don't know that I really critically sit there and churn on it.*

Collectively, students suggested their demonstration of discovery behaviors could be aided by the development of (a) a personal tenacity to overcome any social or physical challenges to demonstrating a discovery behavior or (b) a particular interest or lack of inhibition in utilizing the skill. Students did note, however, that they viewed many of these orientations as inherent traits, rather than learnable skills.

### *Lack of Skill or Experience*

Some students indicated they would not demonstrate the behaviors even if they possessed the mindset and opportunity because they did not feel they had the specialized skills or expertise to execute the behaviors effectively. Students described a lack of technical knowledge that may inhibit their ability to ask good questions, set up effective experiments, or link daily observations to their engineering work. For example, Mike felt he sometimes had insufficient knowledge to ask the *right* question, despite his general willingness to ask questions of other people or himself:

*I know with questioning my biggest problem would be, sometimes I don't know which questions to ask... Because, I wouldn't say that I have a problem with not asking questions. My biggest issue with questioning is when I don't have enough knowledge base trying to find out what questions to ask.*

Beyond technical expertise, tangentially related individual skills were also deemed necessary for displaying these discovery behaviors. Students felt they needed interpersonal skills for networking, hands-on ability for experimenting, and the ability to associate for observing. Likewise, perspective-taking was considered a key skill for interpreting experimental results, asking appropriate questions, interacting with others, and observing phenomena outside of the self. Students seemed to emphasize a lack of social skills (which could explain the lower survey scores on Idea Networking in Phase 1). For example, Roxanne noted that “a lot of engineers just aren’t very good at it and they find themselves uncomfortable in situations like that.” Similarly, Marshall indicated this discomfort may be especially significant when interacting with individuals from different academic background:

*I'm not a huge social person. I mean, I can talk to people, but I just don't—a lot of the times it's you have to find somebody who has the same mindset... If you went to an art school or something like that, they might not have any clue about how to talk to you, just because they don't have the same knowledge set that you do.*

### *Utility of Behavior*

Participants also indicated they may lack discovery behaviors because they did not see their outcomes as particularly useful for engineering work. Participants indicated this may be because the behavior did not appear to represent a result they desire, or they believed they could achieve a desired result through another behavior. In particular, observing and networking were described as less useful than experimenting and questioning.

Several participants noted that observing was not well structured and thus did not produce guaranteed results. Because of this, students often preferred other avenues which they felt could lead them to the desired results, such as experimenting. Students in electrical (Marshall and Terence) and biological engineering (Donovan), who dealt with micro-level phenomena, did not view external observations as having any use in their work. As Donovan noted:

*We wouldn't get any kind of ideas from just looking at a bird go to a tree or something. That wouldn't really help us that much in thinking of an idea, unless we go to the sheer*

*concept of something moving from some place to another. But the bird flapping its wings isn't really gonna help us in determining how molecules move or something like that. But in terms of ME [mechanical engineering] they can use something like that – the mechanism of flapping the wings – and then convert that into some sort of innovative ideas.*

Several students also limited their networking because they did not see the application of networking beyond receiving help for an immediate problem (such as a homework assignment) or the usefulness of networking with others outside their own academic discipline. Several of the graduate level students did note many of the potential benefits of specific networking opportunities (such as conferences), but noted that they were too time-consuming. As Carl indicated:

*Just personally my time is limited. I have a family and kids and, you know, to go on a week conference is a huge sacrifice for me. So I usually just would rather not, because I, again, I don't see as much benefit.*

It is interesting to note that questioning and experimenting were also seen as time-consuming, but this did not necessarily interfere with students utilizing these behaviors.

#### *Educational Context*

Finally, students identified external factors that may have limited their application of the four discovery behaviors. These included aspects of the contexts in which they learned and practiced engineering being less conducive to certain discovery behaviors. Students noted that some discovery behaviors were not encouraged by instructors, either explicitly through their verbalizations or implicitly through the learning environments they created. For example, the students often felt more comfortable asking questions when it was explicitly encouraged in class, or felt discouraged from networking by professors who did not allow group work on assignments. A collegial, open, and intimate atmosphere and shared informal workspace helped independent and experimentation-oriented students like Luiz ask questions of and network with instructors and peers. As Luiz explained:

*I also think we are encouraged to ask lots of questions in class. Because like our department is pretty small. And our classes we're like 50 students and we all have class, all of our classes are the same people so we get to know each other and it's not like in Mechanical where you have a lecture of 200 people. You're not going to ask questions there. In ABE when you're in a class and it's like you get to know the professor and he knows your name and you know everyone around you you're encouraged to ask lots of questions and all that. You find lots of study groups and stuff. And we have like lots of rooms and computer labs just for ABE students since we're a small department. That encourages us to go. It's not crowded and like there's lots of computers and stuff, and lots of space.*

Other students noted that typical engineering coursework devalued skills like observation, and in particular, experimenting. Several students noted cookbook laboratory approaches that stifled

true experimentation. This left students like Julie hoping for more fruitful experimentation opportunities.

*I don't know if I can really comment on experimenting. Even my favorite lab was fluid mechanics. And even that lab, everything was set up for us. You know. We always were told, like, exactly what we were looking for. So maybe this is a place where... [instructors] could ask more of us in this department.*

## **Closing Discussion**

The quantitative results of this study highlighted that, of the innovative behaviors identified within the Innovator's DNA (questioning, networking, observing, and experimenting)<sup>3</sup>, engineering students scored significantly lower in networking. In addition, when compared to innovative entrepreneurs, our respondents scored significantly lower along questioning and networking. This suggests that engineering curricula should emphasize questioning and networking skills to a greater extent if the broader goal is to inspire students to match the sample of innovative entrepreneurs. However, Dyer and colleagues<sup>3</sup> noted that not all four skills are required to contribute to innovation and there is no single ideal combination of skills that is most effective for innovation. Thus, engineering educators might focus more on helping students identify and expand upon their own unique talents.

The qualitative results added context to the quantitative results in two ways. First, while quantitative results indicated that students primarily struggled with networking, challenges to utilizing each of the other discovery behaviors were evident. These included challenges due to internal factors (e.g., a lack of motivation to perform the behavior or a lack of background expertise) and external factors (e.g., inhibiting educational contexts and limited perceived utility in engineering). Second, while each of these four challenges factored into each of the four discovery behaviors in some unique way, several of the individual challenges were often described in concert as limiting an individual's tendency to apply a particular discovery behavior. Collectively, these results demonstrate a complex ecosystem for understanding how and why engineering students demonstrate discovery behaviors, and how to best help students develop the tendencies that will be useful to them throughout their engineering education, and potentially their careers. As designers may not need to master each skill to be innovative, future research may wish to comparatively explore which behaviors are most essential for facilitating innovative expertise and behavior amongst their students.

We envision the challenges to innovation may be considered in light of the thematic challenges described in order to support instruction at the class and individual level. For example, those specific challenges listed under the *education context* theme represent aspects of course and departmental environments over which instructors and administrators may change to support student innovativeness. Challenges related to *individual mindset*, *lack of skill/expertise*, and *lack of utility* represent longer-term initiatives that might be pursued by educators and researchers. For example, instructors might begin to identify methods to incorporate activities that demonstrate the benefits of these behaviors to their students.

This study has also identified two additional research strands that may add additional depth to the topic investigated. First, preliminary versions of the thematic analysis revealed instances in which students demonstrated understandings of the behaviors that were slightly different than expert conceptions within *The Innovator's DNA*<sup>3</sup>. These instances were mostly attributed to the differences in context. For example, conceptions of the discovery behaviors were similar but may manifest themselves differently in an engineering environment as compared to a business environment. Further study of student conceptualizations of the four discovery behaviors could potentially suggest more deeply seeded challenges to engineering student innovativeness. Second, respondents indicated that engineering cultural norms may inhibit discovery behavior. Research on the potentially inhibiting role of engineering culture, mindsets, and identity in ought to be explored in future work.

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## **Appendix A: Interview Protocol**

### **Part 1: Innovation**

1. What does innovation mean to you?
  - a. How has innovation been portrayed in your courses or work experiences?
2. What role, if any, does innovation play in engineering?
3. In your experience, how does innovation occur?
  - a. Where do these views come from?
  - b. Do you have any experience working on innovation projects in engineering either through coursework, industry jobs or internships, or personal projects?
4. What does it take to be an innovative engineer?
  - a. Do you have any examples?
  - b. Are you innovative?

### **Part 2: Innovator's DNA Survey**

1. Part of the survey you took focused on four constructs linked to innovation. Here is a list of survey items linked to each construct. [Present the student with a list of Innovator's DNA survey items sorted into unlabeled categories]. How would you describe these categories?
  - a. Can you describe an example of each [preferably from an actual experience or engineering work]?
2. These survey items were originally designed to assess the following constructs: questioning, networking, experimenting, and observing. [Present the student with a sheet describing each of the four constructs and the related survey items]. Based on these descriptions, how do these constructs compare to what you previously described?
  - a. Do you see any survey items that do not fit their categories?
3. What role, if any, do you see these constructs playing in engineering work?
4. How do you think other engineers score in each of these categories?
5. How do you think you scored in each of these categories?
6. Here is a breakdown of your survey results [Explain scores and constructs]. What do you think about these scores?
7. What other skills, mindsets, and behaviors do you think are valuable for identifying needs, developing or refining design concepts, and expanding expertise in relation to engineering design?

### **Part 3: Empathy**

1. What does empathy mean to you?
2. What role, if any, does empathy play in engineering work?
  - a. How have you experienced or seen empathy your engineering courses?
  - b. How have you experienced or seen empathy in your engineering industry experiences?
3. How empathetic are you in general?
4. How empathetic are you in the context of your engineering work?
  - a. Can you describe an instance in which you applied empathy to an engineering project or problem?

- b. [If there are differences between general empathy and engineering-related empathy] What are the reasons for the differences you described between your general empathy and empathy in an engineering context?
5. How empathetic are engineers in general?
  - a. Can you think of examples of specific engineers? This could be instructors, fellow students, engineers you've known or worked with, family members, etc.

#### Part 4: Interpersonal Reactivity Index

1. Part of the survey you took focused on four constructs linked to empathy. Here is a list of survey items linked to each construct. [Present the student with a list of IRI survey items sorted into unlabeled categories]. How would you describe these categories?
  - a. Can you describe an example of each [preferably from an actual experience or engineering work]?
2. These survey items were originally designed to assess the following constructs: fantasy, perspective taking, empathic concern, and personal distress. [Present the student with a sheet describing each of the four constructs and the related survey items]. Based on these descriptions, how do these constructs compare to what you previously described?
  - a. Do you see any survey items that do not fit their categories?
3. What role, if any, do you see these components playing in engineering work?
4. How do you think other engineers score in each of these categories?
5. How do you think you scored in each of these categories?
6. Here is a breakdown of your survey results [Explain scores and constructs]. What do you think about these scores?
7. What other components of empathy do you think were not covered by the survey?

#### Part 5: Relationships between Empathy and Innovation

1. Do you see any connections between empathy and innovation?
  - a. What are some ways in which one may lead to the other?
  - b. Can you give any examples from your experience where you saw this relationship?
2. This table describes the correlations found from the survey. [Describe correlations and what they mean: effect sizes, negative/positive]
  - a. What do you think about these correlations?
  - b. Can you think of any specific examples of how these components are related or not related?