The ‘Structured’ Engineering Design Notebook: A New Tool for Design Thinking within a Studio Design Course

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Introduction

The foundation of engineering itself is design [1], as design “has been widely considered to be the central or distinguishing activity of engineering” [2]. Design thinking—which is applicable across all design fields—can provide engineering students with a useful set of tools to help them develop a designerly mindset and to support the complex work of engineering design. Design thinking “refers to how designers see and how they consequently think” [2]. Organizations like the Stanford d.school have their own conceptions of design thinking and offer design thinking resources in the form of activities, tools, videos, how-to guides, crash courses, and classes. Like the scaffold around a brick wall that allows the bricklayer to build it higher and more robust, design thinking tools act as scaffolds that help engineering students develop a designerly mindset. Thinking like a designer, and leveraging the tools of design thinking, can benefit engineering students as they prepare for their professional practice. At present, however, the engineering education research community does not know enough about how to support engineering students to develop a design thinking mindset and to know how and when to apply the scaffolds of design thinking. Specifically, the engineering education community needs to develop tools to support this work.

An engineering design notebook holds promise as a tool to support student learning about design and design thinking. A blank notebook or electronic log is a tool of professional engineers; it is also a tool that engineering students need to gain expertise with as they prepare for their future professions. Blank notebooks have been studied as a space for design work and documentation [3], [4], however learning how to use a blank notebook in this way can be daunting to engineering students. In this paper, a new type of engineering design notebook—a structured—notebook is described. The notebook was specifically developed as a tool for scaffolding the design processes for university-level engineering students enrolled in a studio design course. Whereas a blank notebook is just that, completely blank, the structured engineering design notebook is comprised of prompts, tasks, and spaces for writing and sketching that help to illuminate the process of engineering design and provide design thinking scaffolds. Interestingly, although these types of more structured design notebooks are a tool seen in K-12 science classrooms where there is a clear need to scaffold the design process for young designers [5], [6], they are largely absent at the undergraduate level.

The purpose of this qualitative case study is to understand students’ experiences using the structured engineering design notebook as part of a bioengineering studio design course offered at a large, urban research university. In this course, teams comprised of both undergraduate and graduate students designed, prototyped, and presented innovative neural engineering devices in a competitive environment. This study is guided by the research question: How does a new type of engineering design notebook—structured with prompts, tasks, and scaffolds—support college students as they engage in design thinking within an engineering studio design course?
Framing Literature

*Design Thinking in an Engineering Context*

The skills involved in developing expertise in design thinking and engineering design are different, though an understanding of one can support an understanding of the other. Design thinking is a process or creative approach to problem solving and solution creating. It is an “iterative, exploratory, and sometimes a chaotic process” [2]. Organizations such as Stanford d.school and IDEO offer their own definitions and tools for design thinking, many of which take a human-centered or user-centered approach to design. This study was grounded by the Stanford d.school’s conception of design thinking, which includes the modes of Empathize, Define, Ideate, Prototype, and Test [7].

The engineering design process is a “decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet” [8] a specific set of criteria and in which “designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve client’s objectives or users’ needs while satisfying a specified set of constraints” [1], (see [4] for a process diagram). While there is not consensus within the engineering field about how to best represent this process [5], [9], for the purpose of this paper, the engineering design process was conceived as an iterative approach to solving authentic problems that includes: *identifying a problem; developing possible solutions; constructing prototypes; testing and optimizing prototypes; and communicating the solution*. When an engineer engages in the engineering design process to find a solution to a problem or meet a stated need, she can apply the tools and mindset of design thinking to her work.

In the design studio, engineering students are challenged to both learn and apply the components of design thinking as they work to design and build. Scholars have argued that preparing engineering majors to develop a design thinking mindset is a promising approach to address better preparation of engineering students for their future professions and call for all engineering faculty to “incorporate those habits of mind and the tools of design thinking into all parts of the engineering curriculum” [1]. Razzouk claimed that “helping students to think like designers may better prepare them to deal with difficult situations and to solve complex problems” [2]. However, this is not a simple task. The structured engineering design notebook featured in this paper provides a tool for engineering students to use while engaging in design thinking, perhaps for their very first time.

*Epistemic Practices of Engineering*

Although engineers work across fields, there are epistemic practices that are critical to engineering as a discipline and which engineering students need to develop in order to prepare for their future professions. Cunningham and Kelly describe epistemic practices as having four characteristics: they are interactional, contextual, intertextual, and consequential [10]. From their review of the literature of engineering in practice, Cunningham and Kelly developed a set of epistemic practices of engineering. Their goal was to identify the practices that would help
educators understand “what counts as engineering knowledge” and to identify differences between propositional knowledge carried over from other fields of study like science and math, the procedural knowledge needed to engage in engineering design, and the extant knowledge embodied in tools used for design work [10]. Though their focus was on K-12 engineering education, Cunningham and Kelly’s list of sixteen epistemic practices of engineering are also relevant to undergraduate education, as they “capture important aspects of doing engineering and learning about and how to be an engineer” [10]. These epistemic practices are classified into four categories: engineering in social contexts; use of data and evidence to make decisions; tools and strategies for problem solving; and finding solutions through creativity and innovation. As engineering students at the university level learn about engineering, gain experience in engineering design, and discover how to be and think like an engineer, they develop facility with these epistemic practices of engineering. The structured design notebook described in this paper helped to structure and support students’ engagement in these practices.

Design Notebooks: A Tool of the Engineering Trade

Professional engineers commonly use blank bound books, often called engineering journals, portfolios, or logs, as a place for logging data, sketching, recording intellectual property, and other purposes [5], [11]. In some contexts, electronic logs or online portfolios may be used instead of a physical notebook [11], [12]. In academic and industry laboratories, these notebooks are permanent, legal documents that have strict protocols for use in order to clearly document procedures, establish intellectual property, and protect research subjects [12], [13]. These blank books are a tool of the engineering profession, but are also viewed as pedagogical tools, recommended as a best practice for undergraduate engineering faculty to use for both instructional and assessment purposes [3], [5], [11].

While it has been shown that a blank notebook offers some benefits for engineering students [5], [11], for a student engaging in the complex work of design for the first time, knowing how to plan and carry out a design project specific to their discipline, how to document the process, and how to make their invisible design thinking processes visible in a blank book can be a challenging task. Moore et al. reported on some of the challenges that students and instructors encounter when using blank engineering notebooks, including confusion about what should go in the notebook, uncertainty about the purpose for keeping a design notebook, not seeing the value in careful documentation of design work, and a reluctance to engage in reflection of their design process [5]. The structured engineering design notebook described in this paper can help support students as they build expertise in this complex work. This notebook offered prompts, tasks, and scaffolds that were specifically cited by students as helpful in structuring their design process as they learned how to engage in and document their design work.

Documentation in the Design Notebook

Much of design work can be invisible; it is through documentation that designers can communicate and collaborate with others. These invisible components of design include both the cognitive, physical, and social aspects of design work that engineering students engage in both inside and outside of class time, and conducted both individually and in their teams. Nigel Cross
[14] described the often hidden, private processes of design and offered the designer’s (blank) notebook as an artifact for uncovering these complex processes of problem solving and creativity through documentation. Drawing, sketching, and diagramming are key components of design thinking across disciplines and “serve as a primary vehicle for thinking and solving problems” [1], [2]. Beyond sketches, Asunda and Hill wrote that documentation in a (blank) engineering notebook also includes a “collection of notes, mathematical equations, graphical drawings, records of constraints imposed, description of the steps that were carried out to construct the product, documented criteria that were developed to analyze and compare each solution generated, and how a decision was reached regarding the best solution” [4]. Therefore, within the setting of a studio design course, a notebook is a tool for the student’s use as they document and make visible the cognitive process of design work, but also a way to share ideas with others. However, researchers and educators have discovered that there is a reluctance among engineering students to see the value in careful documentation of their design processes [5], [14].

**Study Design & Methods**

This qualitative research study presents a case study of one team, consisting of three college students, in an engineering studio design course. Case study, while a long-established methodology of the social sciences [15], is considered as an “emerging methodology” in engineering education research that is “not yet well represented” [16]. Quantitative methods dominant in a research community that “has tended to give preferentiality to one epistemology over the others” [15]. However, by accepting “diverse ways of knowing” [15], engineering education researchers can employ qualitative methodologies to ask different kinds of questions and to develop understandings of “key engineering education challenges, such as students’ responses to innovative pedagogies, diversity issues in engineering, and the changing requirements for engineering graduates in the twenty-first century” [16]. Case study, with its “concrete, context-dependent nature,” is an appropriate methodology for this study, as it can be used to address questions “concerned with the specific application of initiatives or innovations to improve or enhance learning and teaching” [16]. This approach allowed for an in-depth, single case analysis of how these particular students used an innovative pedagogical tool for design thinking. In order to understand other students’ experiences with the notebook, data was also collected from other students in the class who were members of the other teams.

In this section, I present information about the setting, participants, and timeframe followed by an overview of data sources, data collection, and methods of analysis. I also describe the featured design notebook in detail. In the Finding sections, a set of design principles that emerged from this analysis is shared.

**Setting**

The setting for this study is a ten-week long, bioengineering studio design course offered to upper-level undergraduate and graduate students which ran during Winter 2017. This setting provided the opportunity to study how the structured design notebook, which was being used for the first time, functioned as a tool for design thinking. Classes met for weekly two-hour sessions, with the expectation that design work would extend outside of class hours. During the ten-week course, students were placed into teams comprised of two or three undergraduate students and
one graduate student, who was positioned as the team leader. They worked to design, prototype, and present an innovative neural engineering device to a panel of industry judges. The winning teams were offered seed funding and incubator space at a neural engineering research center if they wished to pursue the commercial viability of their product ideas. Though the competitive element of the course rewarded students based on the quality of their design product and presentation, the course itself, along with the grading structure, privileged students’ engagement with the design process and use of the design notebook over the designed product.

Participants

The course enrolled students from engineering departments, as well as computer science, biochemistry, neurobiology, and physics. Thirteen students enrolled in the course, and were placed by instructors into four teams. Eight of those students (three female and five male; five undergraduate and three graduate) consented to participate in this research study, representing all members of two teams, as well as three other students from the other two teams. Data was collected from all eight of these students, but some data collection activities were focused specifically on the two teams in which all members had agreed to participate in the study. Data analysis focused one of these teams, known as NeuroGrip. This team was chosen as the focal team for the case study because it was the only team in which both an undergraduate student and a graduate student team leader agreed to be interviewed, which offered two important perspectives. Also, the three members of NeuroGrip had received a range of grades on their engineering design notebooks, (100%, 95%, and 90%, out of a class range of 85-100%), which could imply different levels of embracing the spirit of the notebook. Finally, NeuroGrip placed first in the judging competition of their designed product at the end of the course.

The members of Team NeuroGrip included Gavin, Ash, and Luke, as shown in Figure 1. Gavin, self-described as the “mechanic” of the team, was a doctoral student in a mechanical engineering program who had worked as a graduate research assistant in a university lab focused on human mobility. As the graduate student on the team, he was positioned as team leader. Luke, the team “doctor,” was an undergraduate student majoring in bioengineering, who worked as a research assistant in the same lab as Gavin. Ash, acting as the team’s “computer nerd,” was an undergraduate student majoring in computer science who had an interest in neural engineering. Gavin’s motivation for enrolling in the course were of a personal nature. He was friends with a man who had experienced partial paralysis as a result of a spinal cord injury eighteen years previous. Gavin was therefore driven by a desire to design and build a device that would aid his friend with daily activities involving the use of his hand. The motivating factor of this relationship and of having the specific needs of a real end-user in mind drove Gavin and his team’s user-centered design approach.

\[^1\] Team name is a pseudonym.
\[^2\] All student names are pseudonyms.
A New Type of Engineering Design Notebook

I was invited in Fall 2017 by the course instructor, Dr. Lise Johnson, to collaborate with her and a teaching assistant on the re-design of her neural engineering studio design course, which had been offered for the three years prior in a different form. During the re-design of the course, we identified a need for a tool that could scaffold students’ development of a design thinking mindset and support them through the stages of planning and carrying out the complex design process. Previously, design thinking had not been explicitly mentioned in the course, but both I and the instructor felt that providing design thinking scaffolds would be a beneficial addition to students’ experience and learning outcomes with the course. In response to these identified needs, a structured engineering design notebook was developed to serve as the course text and which would account for a major portion of students’ grades. In the re-design of the course, we blended our conceptions of the engineering design process with the Stanford d.school’s conceptions of design thinking, organizing the design notebook and the course itself into the phases of: Exploring, Planning, Understanding, Prototyping, Pitching, and Reflecting. The engineering design notebook was organized chronologically with a section dedicated to each of these phases. A spiral-bound, physical copy of the 137-page notebook was provided to each student during the first class meeting (see Figure 2). In addition, students were also required to purchase a supplementary bound, blank notebook to provide additional space for documentation, particularly during the Prototyping phase. The instructor’s reasoning for requiring the supplemental notebook was to reduce printing costs, as the design notebook was provided to students at no charge. She also wanted students to gain some experience in the use of a blank notebook, a tool they were likely to use in the future as professional engineers. Therefore, the Prototyping and Appendix sections in the notebook included only a limited number of blank pages, with the supplemental notebook providing ample space for documentation during the Prototyping phase.
Data Collection

Key data collection activities included semi-structured interviews with students and instructors, and photocopies of students’ completed/graded engineering design notebooks. Supporting data included class observations and post-class debriefs with instructors. Data was originally collected as part of a graduate school class project. An Institutional Review Board determined that the analysis of the previously collected data for research purposes qualified for exempt status.

Semi-structured interviews with students.

Semi-structured interviews were held in-person with six of the eight participating students, one week after the final class, each lasting approximately one hour. Data was collected via video recordings and jottings, with field notes became the source of data for analysis. Two students did not respond to requests for interviews; it is possible that the timing of the interviews during finals week and the subsequent spring break may had impacted students’ availability. Ash and Gavin from the focal team, NeuroGrip, were interviewed, however, their team mate Luke did not respond to interview requests. Interviews were guided by a protocol that focused on students’ motivations for enrolling in the course, general course reflections and learning outcomes, thoughts on design thinking, and reflections on the design notebook. Retrospective questions asked students to consider the ways in which they used the notebooks, including with whom and for what purposes, along with the affordances and challenges of the design notebooks, and their suggestions for improvement. Photo elicitation [15], [18] was used by asking each student to use sticky notes to flag the pages of their design notebook that were the “most helpful” and “least helpful.” I encouraged students to share aloud their reasoning as they flagged the notebook pages.

Semi-structured interviews with instructors.

Semi-structured interviews were held in-person with the instructor (pre- and post-) and teaching assistant (post-). Data included video and audio recordings and jottings. Interviews were guided by a protocol, with post-interviews focusing on reflecting on the course re-design, perceived and observed uses of the design notebook, and the benefits and challenges of using the
notebook. The teaching assistant, who had formerly been a student in an earlier iteration of the class, was also asked to reflect on his own student experience.

**Artifacts.**

The engineering design notebook functioned as a physical tool within the system of the class, and therefore was considered as an “artifact” [18]. Photocopies were made of the completed notebooks for all eight participating students, including all members of Team NeuroGrip.

**Class observations.**

I observed each of the ten weekly class sessions. Video or audio recordings were made of whole class activities and of activities specific to the focal team, providing about 20 hours of video/audio data. During class, I took jottings, which I later elaborated on in the process of writing up my field notes.

**Post-class debriefs with instructors.**

At the conclusion of each class, when possible, I met with the instructor and teaching assistant for an informal debrief. Data included audio recordings and jottings. These conversations served as a way to triangulate my own observations of design thinking and notebook use during the class sessions with the insights of the instructor and teaching assistant.

**Data Analysis**

This research study is designed as a qualitative case study [16], [19] of Team NeuroGrip, with a deep analysis focused on two of the three team members, Ash and Gavin. The findings of this case study are further explored and triangulated through comparison of data from other students representing the three other teams in the class. While video and audio recordings were made, field notes were the key data source for analysis, with recordings available as needed for accuracy checks. Qualitative methods were employed for analysis of field notes and students’ engineering design notebook artifacts; analytical memos were written for each data source at each phase in the data analysis process. Data analysis occurred through three phases, beginning with analysis of all data, followed by a deep analysis of the case study team, and then going broad again by consulting data across all teams for triangulation purposes. Table 1 provides a summary of the three phases of data analysis.
<table>
<thead>
<tr>
<th><strong>Data Source</strong></th>
<th><strong>Data Source</strong></th>
<th><strong>Data Analysis</strong></th>
<th><strong>Insights</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase One: Analysis across teams for code development</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interviews with all students and instructors</td>
<td>Field notes</td>
<td>Open coding</td>
<td>Developed code book with <em>in vivo</em> and <em>a priori</em> codes. Organized into categories.</td>
</tr>
<tr>
<td>Class observations</td>
<td>Field notes</td>
<td>Analytical Memos</td>
<td>Theoretical sampling for identification of key moments in interviews and key episodes in class for two focal teams for further analysis.</td>
</tr>
<tr>
<td>Post-class debriefs with instructors</td>
<td>Photocopies of submitted notebooks</td>
<td>Content analysis</td>
<td>Notebook pages flagged as (un)helpful for insight into students’ perceptions of the pages and sections.</td>
</tr>
<tr>
<td>Notebook artifacts of all students</td>
<td>Photocopies of submitted notebooks</td>
<td>Content analysis</td>
<td>Notebook pages left blank/unused for insight into notebook use.</td>
</tr>
<tr>
<td><strong>Phase Two: Developing a Case Study of Team NeuroGrip</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interviews with Ash and Gavin of Team NeuroGrip</td>
<td>Field notes</td>
<td>Constant comparative method</td>
<td>Insights into the ways they thought about design thinking, their perceptions of the notebook, and examples of how they engaged in design thinking.</td>
</tr>
<tr>
<td>Key class episodes featuring Team NeuroGrip</td>
<td>Photocopies of submitted notebooks</td>
<td>Re-analysis using code book, Analytical Memos</td>
<td>Insights into when and how students used their notebooks and engaged in design thinking during class.</td>
</tr>
<tr>
<td>Notebook artifacts of Team NeuroGrip</td>
<td>Photocopies of submitted notebooks</td>
<td>Content analysis</td>
<td>Insights into physical traces with a focus on accretion in the notebooks.</td>
</tr>
<tr>
<td><strong>Phase Three: Analysis Across Teams for Triangulation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data associated with each code category across all students</td>
<td>Coded field notes</td>
<td>Constant comparative method, Analytical Meta-memos</td>
<td>Triangulation of findings from Team NeuroGrip across data from all students and instructors. Developing “thick description” for case study</td>
</tr>
</tbody>
</table>
Phase one: Analysis across teams for code development.

With my first pass at the data from all eight students and instructors (field notes of interviews, class observations, and debriefs), I open coded using a grounded theory approach, identifying in vivo codes which emerged from the data. A second pass at the field notes was taken using focused coding, a more fine-grained analysis coding for a priori concepts that made up the conceptual framework [20], [21]. Codes were then organized into categories (see Table 2 for the final coding scheme for this study; sub-codes are not included). By coding the field notes from all six students’ post-interviews, which represented students from across all four teams in the class, I was able to orient to students’ own definitions and examples of design thinking, their thoughts on how the notebook supported and constrained their learning, and the differences in notebook use among students and teams. This in turn led to theoretical sampling [21], which allowed me to identify the most salient moments in the interviews with all six students and key episodes from specific class sessions when design thinking and notebook use were most evident among the two focal teams. Content analysis [18] of all six students’ engineering design notebooks was approached by cataloging the notebook pages that the students (including Ash and Gavin) had flagged as being particularly helpful or unhelpful during their post-interviews, and counting any blank, unused pages.

Phase two: Developing a case study of team NeuroGrip.

After the data from students across all four teams were examined, I chose to focus my analysis on a case study of Ash, Gavin, and Luke from team NeuroGrip. Field notes of the post-interviews from Ash and Gavin as well as field notes of key episodes from class sessions were re-analyzed using and adding to the coding scheme developed in the first phase. I engaged in qualitative content analysis [18] to understand the ways in which the focal students Gavin, Ash, and Luke used their design notebooks by triangulating class observations and interview data with the students’ completed notebooks. Physical traces of these students’ notebooks were also analyzed as a source of data. Physical trace materials are “changes in the physical setting brought about by the activities of people in that setting” [18]. The focus was on the accretion, or “the degree of accumulation,” [18] of the physical traces of the design notebooks, looking for how students changed the notebooks through their use of it. This analysis specifically looked for what students added to their notebooks, such as written text, diagrams, sketches, CAD drawings, and code.

Phase three: Analysis across teams for triangulation.

Triangulation of data is a key strategy to increase internal validity in qualitative research [18]. In the third phase of analysis, insights from analysis of Team NeuroGrip’s data were compared across multiple data sources and participants outside of the focal team. Meta-memos were written during this phase. In addition, all data sources were consulted as relevant in order to develop a thick description of the case study [18].

Researcher Positionality

At the time of this study, I was employed as a member of the education team by the Engineering Research Center that hosted the course. Dr. J, her teaching assistant, and I met weekly for several months to re-design the course. During these meetings, my positionality was as a collaborator, co-designer, and colleague. During data collection, I took on the role of an
observer as participant with a peripheral membership role during class sessions, and as participant-observer during post-class debriefs with the instructors [18].

Table 2. Final Coding Scheme.

<table>
<thead>
<tr>
<th>Category</th>
<th>Code</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Thinking (DT)</strong></td>
<td>Sources of Knowledge about DT</td>
<td>Indication of prior experiences with DT.</td>
</tr>
<tr>
<td></td>
<td>Definition of DT</td>
<td>Students’ definitions of DT.</td>
</tr>
<tr>
<td></td>
<td>Examples of DT</td>
<td>Examples students provided of how they engaged in DT during the course.</td>
</tr>
<tr>
<td><strong>Design Notebook</strong></td>
<td>Positioning by Students</td>
<td>Instances in which students or the instructor commented or reflected on the notebook, its contents, and purpose.</td>
</tr>
<tr>
<td></td>
<td>Benefits</td>
<td>General references to benefits of using the notebook.</td>
</tr>
<tr>
<td></td>
<td>Challenges</td>
<td>General references to challenges of using the notebook, including instances in which participants discussed barriers to their use of the notebook.</td>
</tr>
<tr>
<td></td>
<td>Project Documentation</td>
<td>Instances in which the notebook was described, positioned, or used as a tool for documenting projects and design processes.</td>
</tr>
<tr>
<td></td>
<td>Examples and Types of Use</td>
<td>Examples of notebook use. Instances in which different approaches or typologies were evident in the ways that students talked about or how they were using the design notebook. Instances in which there was talk about the role of sketching in design work.</td>
</tr>
<tr>
<td></td>
<td>Importance of Notebooks as Physical Objects</td>
<td>Instances in which participants talked about there being something important about having the notebook as a physical, rather than digital, object.</td>
</tr>
<tr>
<td></td>
<td>Tools Other than Notebook</td>
<td>Instances in which the required supplementary lab book or other preferred tools were talked about.</td>
</tr>
</tbody>
</table>

Findings

In this section, findings are presented about how the design notebook supported, with some exceptions, students’ engagement with design thinking within the engineering design studio course. First, I share how students’ across teams held varied conceptions of design thinking, reported different views of the value of the design notebook, and approached their use of the notebook in different ways. I then present examples of how the design notebook supported
students’ engagement in design thinking, using the case of Team NeuroGrip. I also share the challenges that students encountered in their use of the notebook and barriers that kept some students from taking up the spirit of the notebook.

Students’ Varied Conceptions of Design Thinking

Students in the studio course thought about design thinking in different ways, and they provided differently nuanced definitions of it when asked during their post-interviews. Design thinking was never explicitly defined or taught by the course instructor. It was only briefly described in the front matter of the notebook, as influenced by the Stanford d.school model, but it is uncertain if all students read this text as it was not part of a task associated with their use of the notebook. However, the processes and tools of design thinking were implicitly provided in the design notebook, serving to scaffold students’ engagement in design thinking. None of the six students who were interviewed indicated that they had received prior formal instruction in design thinking, but they picked up some understanding of design thinking through the course itself, or through previous educational, professional, or social experiences.

During the post-interviews, each of the six students were asked to define design thinking. Students’ definitions of design thinking were varied, showing that they had each developed different conceptions of this way of approaching design work. Gavin provided a user-centered definition of design thinking. His definition was aligned to the Empathize and Define modes of design thinking and matched the user-centered approach taken by Team NeuroGrip throughout the course. Gavin described design thinking as a combination of communication, keeping the customer at the center of the design, and having user feedback drive the design. Gavin differentiated between the “engineering bits of design” like having a criteria, identifying needs, and developing a design to fulfill that, and his own user-centered approach to thinking about design. Ash provided a problem-solving definition of design thinking, more in line with Gavin’s idea of the “engineering bits of design,” with a focus on problem solving that included complex, multiple considerations at play. She viewed design thinking as a formulaic approach to addressing a problem, but also described design thinking as going beyond just the engineering, so that the designer has to consider many things, from ideas and feasibility to values, customers, and pricing. She asserted that design thinking supports the engineering design process. Dex, a graduate student, provided a perspectives focused definition, describing design thinking as a many spoked wheel with design at the center and many perspectives as the spokes. In his example, everyone pushes and pulls to optimize the design. Emma and Summer, both undergraduates, provided a product-focused definition of design thinking. Emma focused on the steps of production, offering a definition more in line with the engineering design process than design thinking. Whereas Summer talked about the importance of form and function in the designed product, identifying design thinking as both a practical and creative process. The students’ definitions of design thinking were mostly in alignment with the Empathize (Exploring phase) and Define (Understanding phase) modes of design thinking. None of the students’ definitions clearly articulated the Prototyping and Testing modes of design thinking, with Alan’s definition mentioning iteration without specifically calling out the building and testing of prototypes.
Interestingly, when asked to provide examples of how they had engaged in design thinking during the course, these same six students provided examples that were traced to the Exploring (Weeks 1-2; Empathize mode), Understanding (Week 4; Define mode) and Prototyping (Weeks 5-8; Prototyping and Testing modes) phases of the course. This corresponded with my own observations of design thinking occurring during class mostly in these same three phases. No students provided an example specific to the Planning, Pitching, and Reflecting phases. These responses provide insight into how students were thinking about the ways in which they engaged in design thinking within the context of the course.

Ash and Gavin from Team NeuroGrip provided examples of how they engaged in design thinking, which were traced to the Understanding phase of the course. Ash talked about the user-centered design approach taken by her team and how having that as her mindset impacted all of their design decisions. Ash remarked that bringing design thinking into the course was “so powerful” and that “this needs to be integral to how we all think and work; it’s the real world.” Gavin said that the reason that their team chose their project idea—a neuromechanical hand orthosis—is that they had a user at the center of it, an idea of the parts of a successful design, the needed skillsets, and confidence in their abilities to go the mile. Gavin explained that their meetings with their customer helped instill ownership in the project for the other team members (“intangibles”) while it also helped them understand the technical challenge (“tangibles”) they would encounter as they designed their orthosis. Considering how the students defined design thinking and identified examples of when they engaged in it provides insights into how they were thinking about it.

Student Perspectives of the Notebook across Teams

The design notebook supported and facilitated opportunities for students across the four teams to engage in design thinking. However, students had different perspectives on the notebook as a tool for design thinking and engineering design.

Overall reviews of the design notebook.

Of the six students interviewed, reviews of the notebook were mostly positive. In their post-interviews, three of the students provided an overall positive review of the notebook, describing it as: “Blew my mind,” “beautifully designed,” and a “pleasant surprise.” One student had a mixed review as he felt the work demand and size of the notebook was a bit daunting, but was mostly positive in his review. Two students, Dex and Emma, had a less enthusiastic view of the notebook as a tool for design work, viewing it as “more of a hassle than it was worth” and “more of a hindrance to the project”.

However, while Dex and Emma might not have valued the notebook as a way to support their design process in the ways the instructor had hoped, Emma did see value in the notebook as a tool for assessment and grading, and Dex as a tool for team leaders. It should be also noted that both Emma and Dex did not fully take up the spirit of the notebook as a tool to use during the process of design; rather they engaged in significant retroactive backfilling of their notebook pages in order to submit it for grading at the end of the course.
The teaching assistant, who had been a student in a previous iteration of the course that did not make use of a tool like the design notebook, shared in his post-interview that he felt that the notebook provided students with a more formalized thought process to follow, “even if they didn’t like it.” He felt that hindsight bias came into play with the students, so that after you read something—like a scaffold in the design notebook—it becomes obvious, causing students to not “fully appreciate” what the notebook scaffolds provided. Also, much of the students’ negative feedback on the notebook centered on their preference for digital tools.

“Most helpful” notebook sections identified across student teams.

Students from across all four teams reflected in their post-interviews that the structured engineering design notebook was most beneficial during the Understanding, Planning, Pitching, and Reflection phases of the course. Similarly, when asked to flag the pages of their notebooks that were the most and least helpful to them, the pages in the Exploring, Understanding, Planning, and Pitching sections, in that order, emerged as the ones containing the most helpful scaffolds for student learning. Students talked about how the notebook illuminated and provided a framework to help them structure the complex, sometimes nebulous process of design. In post-interviews, Gavin explained that the notebook formed an initial structure for his team’s design process. Ash remarked that the notebook illuminated the design process for her, stating that it “leads you along a path that initially seems obscure” and that it “makes it seem like there is a process to help you tackle a problem.” She said, “That’s really powerful.” Alan described how the phase-structure of the notebook helped him stay on track and in the right part of the design process throughout the course. It also helped him “stay on the rails” in regard to his team’s vision for their project. Similarly, Summer felt that the chronological order and layout of the notebook guided her through the design process. Dex, a graduate student positioned as the leader of his team, felt that the notebook helped take the burden off of the leader to figure out the next steps, the best strategy, or the stages of design, because it was all provided within the pages of the notebook.

Process-oriented vs. retrospective approaches across student teams.

For students from across the four teams, analysis of post-interviews and the notebook artifacts revealed that students took process-oriented or retrospective approaches to their use of the notebook. The process-oriented students viewed their notebook as a tool for design work and it was used as working space for doing their design work, as a space for raw thoughts and sketches, and as a non-static, growing document. The students who took a retrospective approach viewed the notebook as a way to report on the design work. They viewed it as a polished product to be mostly completed at the end of the course in order to turn in for grading purposes; these students engaged in significant retroactive backfilling prior to submitting their notebooks for grading. Ash, who used her notebook extensively throughout the course, described the notebook as being “more powerful the more you use it,” which may help to explain why the students, like Emma and Dex, who did not take a process-oriented approach of using their notebooks during their design process may not have realized the same benefits as those who did. Emma and Dex were also students who gave the notebook a cooler review during their post-interviews. Whether their review of the notebook was overwhelming positive or somewhat lackluster, all students reported on ways in which the notebook both expanded and constrained their learning and design processes during the course.
Team NeuroGrip’s members took a more process-oriented approach to their use of the notebooks. Their design notebooks were used as a tool for design work, as it helped to both synthesize the processes and provide scaffolds for engagement in design thinking and engineering design. In this way, the notebook supported students’ development of epistemic practices of engineering. In this section, I begin with examples of how the design notebook supported Team NeuroGrip through the use of design thinking scaffolds in the Exploring and Understanding phases. I also report on how the Prototyping section of the notebook was not as successful in supporting students in engaging in design thinking and learning how to document the processes of engineering design.

**Exploring phase: Design thinking across student teams.**

Exploring was the first phase of the studio course and represented students’ initial encounters with the notebook as a tool for design thinking. The Exploring section of the notebook maps onto the design thinking modes of Define and Ideate. The Stanford d.school explains the Define mode as being about sensemaking and “bringing clarity and focus to the design space” [22]. The goal of this mode is to “craft a meaningful and actionable problem statement” [22]. The Ideate mode is described as the think big, idea generation stage where the designer transitions from identifying problems to creating possible solutions [22]. The Exploring section of the notebook included a variety of tools to support students in engaging in the Define and Ideate modes of design thinking. These included: Initial Personal Interest and Skills Analysis; Problem Exploration; Round Robin Expert Consultation—Prep & Notes; Team Skills Assessment—Part 1; and Choose Your Project.

In post-interviews, Ash and Gavin specifically called out the Exploring section of the notebook as being particular helpful for them. However, they weren’t the only ones who found this section to be a beneficial resource. Looking at data from across all four teams, when students were asked during their post-interviews and during the Reflection section of the notebook to mark pages of their design notebooks that were most helpful and least helpful to them, the Exploring section received the most helpful flags by far of all the sections. This illustrates that the Exploring section of the notebook was especially helpful as students engaged in the initial work of problem exploration and selection.

In the first two weeks as students engaged with the Exploring phase, class observations documented that design thinking was evident as students engaged in the processes of: considering different problems and project ideas; communicating their ideas with each other, consulting experts, and instructors; considering pros and cons of their ideas; considering the market, competition, costs, and end-user; exploring different solutions to a chosen problem; and choosing their project idea to move forward with for the rest of the quarter. These align with the epistemic practices of envisioning multiple solutions, communicating effectively, and considering problems in context [10]. However, these class observations only tell part of their story. The students’ notebooks help to illuminate the processes and strategies they used when identifying the problem, ideating on possible solutions, and selecting the project idea that would be their focus.
Exploring phase: Design thinking in Team NeuroGrip.

The move from project exploration to choosing a problem and potential solutions can be a difficult one, especially given that this was an initial task of newly formed teams who were just starting to get to know each other. Due to the course timeline, they needed to move through this process swiftly. In Team NeuroGrip’s notebooks, the teammates engaged in design thinking to surface ideas, considering skills and priorities, and choose the problem space and project idea they would pursue for the rest of the course. Their notebooks document how Gavin, Ash, and Larry initially surfaced five project ideas in the Ideate mode of brainstorming and then in a principled manner suggested by the notebook—which is known as considered selection in design thinking—winnowed this down to three and then to two competing ideas: a sleep tracking device and a finger extension/flexion orthosis for people with spinal cord injuries. In the Exploring phase, they were provided with multiple tools to scaffold this process of project selection. For example, on their Problem Exploration notebook page, students were prompted to first discuss their areas of interest and project ideas and then to draw a visual representation to assist them with identifying areas of intersection between interests and project ideas. In his notebook, Gavin sketched Venn diagrams to identify areas of overlap between the three teammates’ aspirations and skills, while identifying the specific problem that each project idea aimed to solve (See Figure 3).

Figure 3. Problem exploration in Gavin’s design notebook.

When preparing for an Expert Round Robin activity slotted for the second week of class, the notebook prompted students to frame the problems they had surfaced in different ways, as shown in Figure 4, including writing a problem statement, flipping it into an opportunity for design by asking “How might we…” (a technique for moving from the Mode to Ideate mode), identifying the end-users, making a sketch or diagram, and thinking about their questions and concerns about each project idea (components of a considered selection process). Gavin and Ash’s notebook pages are covered in text and sketches for these initial exercises, while Larry’s is
more sparsely documented. Gavin described the problem statement and design opportunity as, “No reliable active orthosis available to our friend with a cervical SCI [spinal cord injury] to support hand function. How might we design an orthosis to support powered extension or flexion for our individual with hand impairment due to SCI?” During the second week of class, Team NeuroGrip pitched their nascent ideas to four experts during the Expert Round Robin activity and recorded their reflections in their notebooks on a page that specifically prompted them to reflect on this consultation (see Figure 5 for a sample of Gavin’s reflections).

Figure 4. Problem exploration and selection using the tools in Gavin’s design notebook.
As shown in this example, students in Team NeuroGrip were actively engaged in the Define and Ideate modes of design thinking, including the process of considered selection. To engage in this work, they leveraged the design thinking scaffolds provided in the notebook’s Exploring section. In this way, they were also engaged in the epistemic practices of considering problems in context and envisioning multiple solutions [10]. As noted through analysis of class observations and design notebooks, this active engagement in the design thinking processes of project exploration and definition were evident for students across the other three teams as well.

**Understanding phase: Design thinking across student teams.**

Like the Exploring phase, the Understanding phase of the course was aligned to the Define and Ideate modes of design thinking. The Understanding phase, however, also included the Empathize mode. The Stanford d.school describes the Empathize mode as being about the “human-centered design process” in order to “understand people within the context of your design challenge” [22]. The goal of this mode is to gain an understanding of the beliefs, values, and needs of the user through interviews and observations, and then to synthesize that understanding [22].

The Understanding section of the notebook provided a series of tools to help students engage in the Empathize, Define, and Ideate modes of design thinking. These included: Market Analysis; Ethical Considerations; Refined Value Statement and Project Plan; Sketch Your Concept; Reflection on Gallery Walk Feedback. In addition, the Appendix included three
optional Build a Question resources for students to use during the Understanding phase to help them prepare for consultations with experts or end-users. These focused on preparing for interviews, observations, and online research. The Understanding notebook section was viewed as beneficial to students across all four teams. When flagging the notebooks during their post-interviews, across six students from all four teams, the Understanding section was cited by students as the second most helpful section.

**Understanding phase: Design thinking in Team NeuroGrip.**

More than any other team, NeuroGrip took a user-centered approach to their design process. It therefore is no surprise that the team deeply engaged with the tools provided in the Understanding section of the notebook that aligned to the design thinking mode of Empathize. Team NeuroGrip’s user-centered approach to their design work stemmed from the fact that their project idea was driven by the need of an actual user, Craig, who Gavin knew personally. Craig had experienced a spinal cord injury that caused partial paralysis, including affecting his ability to open and close and to receive sensory feedback from his hands. In their final presentation at the end of the course, the three members of Team NeuroGrip introduced Craig and his service dog as team members number four and five, illustrating their framing of Craig as not just a client, but as a co-designer.

The scaffolds in the Understanding section of the notebook supported Team NeuroGrip in their efforts to co-design their product with Craig’s regular input. In the example shown in *Figure 6*, in order to prepare for their initial meeting with Craig, Luke used a design thinking tool provided in the notebook Appendix, Build a Question Guide: Interview, to brainstorm and prepare the questions they would ask of Craig. Ash then took notes (on paper that were later added to her design notebooks) from their initial meeting with Craig. In this meeting, the students then engaged in problem framing and empathizing as they learned more about Craig’s injury, his needs and desires, and how that framed the criteria and constraints for their design. Gavin’s notebook shows the user profile that he developed directly from their meetings with Craig, as prompted by the Market Analysis prompts in the notebook. Together, the scaffolds offered in the Understanding section of the design notebook supported Team NeuroGrip as they prepared for their meetings and testing sessions with Craig and documented the outcomes in their notebooks. The notebook supported these students as they engaged in the epistemic engineering practices of considering problems in context, envisioning multiple solutions, making trade-offs between criteria and constraints, and assessing implications of solutions [10].
Figure 6. Team NeuroGrip engaged deeply in the Empathize mode of design thinking as they prepared questions for their initial consultation with their co-designer (Luke, left), took notes on that meeting that shaped their future design decisions (Ash, right), and created a user profile (Gavin, center).

Prototyping phase: Design thinking across student teams.

Of the six phases, Prototyping was the longest phase of the course, spanning four to five weeks depending on the team. Due to the intensity of this stage and the importance of having a working prototype for the final presentations, prototyping was positioned by Dr. J during the first class meeting as “all the work of the quarter.” The Prototyping phase is an example of where the prototype-test-optimize steps in the engineering design process come together with the Prototype and Test modes of design thinking. The Stanford d.school explains the Prototype mode as “the iterative generation of artifacts intended to answer questions that get you closer to your final solution” [22]. Prototyping can be useful for ideating; it occurs in a recursive process in tandem with testing. The Test mode provides a way to refine prototypes and is also another way of empathizing and better understanding the needs and desires of users [22]. The prototyping and testing process engages students in the epistemic practices of constructing models and prototypes and persisting and learning from failure [10].

Unlike the other sections, the notebook was not intended to function as a tool to support students in learning how to build, test, and iterate on prototypes; rather it was positioned as a
space for students to use when documenting that process. The Prototyping section of the notebook did not provide specific prompts or scaffolds; this section instead provided pages for planning for and reflecting on team meetings during prototyping, and beyond that, eight pages of blank graph paper. Due to the limited amount of blank pages provided in the notebook (to reduce printing costs since it was provided to the students at no charge), students were not required to use the Prototyping section of the notebook for documentation. They were told by the instructor that they could choose instead to use a supplemental blank notebook which they purchased on their own. Students took up both of these options.

Unlike the Exploring and Understanding sections that received high marks from the students for their helpfulness, the Prototyping section of the notebook received the lowest number of helpful flags. This should not be interpreted as the Prototyping phase itself as being unhelpful for students. The notebook was intentionally designed to be open-ended during this phase (to be used in tandem with each student’s supplemental blank notebook) as a space for documentation rather than as a set of scaffolds to support the work of prototyping and testing. Perhaps for the very reason that the notebook did not provide scaffolds for how to document their prototyping process, students struggled with documentation during this phase.

Physical accretion was observed in the notebooks, both structured and blank, when students taped and tucked papers into their notebooks that were generated in other places during the Prototyping phase. In these ways, students documented their work through CAD drawings, sketches, photographs, storyboards, flow charts, data graphs, screenshots from app or game design software, and annotated computer code.

Prototyping phase: Design thinking in Team NeuroGrip.

While documentation of the Prototyping phase may have met with some uncertainty and resistance by students in the class, the pages of Team NeuroGrip’s notebooks provide examples of how these students were engaged in the design thinking modes of Prototype and Test. Ash’s documentation of the Prototyping phase focuses on notes that capture what happened during the team’s design meetings and testing sessions with their co-designer Craig. Her documentation is dependent on written text, with only a few sketches and diagrams. Conversely, Gavin’s notebook is heavily pictorial. His notebook shows evidence of accretion, as he has tucked many sheets of paper between the pages of his notebook’s Prototyping section. These pages include hand-drawn sketches, many CAD drawings, several photographs, and a computer-generated graph. Luke approached documentation through a combination of written text and hand-drawn sketches and diagrams. Like Ash, Luke also included notes on the team’s design meetings.

As documented in their design notebooks and supplemental blank books, we see Team NeuroGrip engage in the design thinking modes of Prototyping and Testing through brainstorming, sketching, building different types of prototypes, and testing them with their end-user/co-designer. The notebook pages also tracked their user-centered approach to design, including weekly consultations and testing sessions with their co-designer Craig. In these ways, the process of documentation in the notebook supported students during the Prototyping phase as they engaged in the epistemic practices of constructing models and prototypes, persisting and learning from failure, and assessing implications of solutions [10]. The design notebook functioned as a space for documentation during the Prototyping phase, as did the supplemental
blank notebook, but it did not provide scaffolds specifically designed to help students learn how to document their design work.

Challenges of the Engineering Design Notebook across Student Teams

There were instances in which the design notebook presented specific challenges to learning for some students. As we have seen, some students took a retrospective documentation approach to their use of the notebook, rather than the process-oriented approach that was intended and for which it had been designed. In addition, in post-interviews, students across the four teams talked about writing as a barrier, their desire for a digital component to the notebook, and the time constraints they encountered. Dr. J and several students also reflected on how the process of documentation was particularly challenging during the Prototyping phase. In addition, some students encountered the tension between using the notebook as a tool for their design work and feeling the pressure of its use as a tool for assessment.

Writing as a barrier.

For Ash, Emma, and Dex, having to write by hand in their design notebook presented a challenge. Ash, a computer science major, clarified that this preference came from her perspective as a “digital person.” Similarly, Emma explained that typing is easier for people of her generation. These same students felt that projects with digital components, such as game and app design, were particularly difficult to document in a physical notebook. Several students (Emma, Dex, and Gavin) stated that they would have either preferred a digital version of the notebook or some kind of digital supplement that allowed for them to upload digital artifacts, rather than having to print them out and add to their physical design notebooks. Emma joked that the notebook needed to have a USB drive attached to it. Dr. J revealed in her post-interview that she too was considering how to develop a digital option to complement the physical design notebook, as she noticed that it “was clearly frustrating” for students to have to write things down.

However, there was value in the materiality of the notebook. Dr. J remarked that “the physical nature of the notebook was important.” Ash echoed this thought when she noted that, though she felt that writing by hand was a barrier to using the notebook and that she struggled with how to best document her coding work, she admitted that “there was something powerful” about having a physical notebook, that “it’s awesome to have something tangible,” and that “it becomes more important when you have it in a physical form.” One possible reason for why a physical artifact is important as a tool for design work is the space that the notebook provided for drawing, sketching, and diagramming by hand. Dex commented that though he would have preferred an online version of the notebook—and requested it several times in class—he admitted that a digital version would not work as well for his sketches.

The need for additional scaffolds for documentation of prototyping work.

Another challenge that emerged was students’ difficulty with knowing how to document their process during prototyping. Whereas other sections of the notebook provided scaffolds for students to engage in the design work associated with that phase of the course, as mentioned previously, the Prototyping section of the notebook was deliberately designed only as a space for project documentation, and did not function as a scaffold for learning how to document. In their
post-interviews, Ash, Emma, and Dex all talked about acknowledging the importance of project documentation, while acknowledging that documentation can be difficult. It was especially challenging for students to figure out how to document digital projects that involved computer coding. Alan noted that having to document the prototyping process “felt like a task more than a help.” In her post-interview, Ash, who regularly used her design notebook throughout the course, noted an exception during the Prototyping phase. She didn’t put things in her notebook “while doing the engineering work,” but rather, documentation during that phase was “an afterthought.” However, Ash reflected that she had realized that “this wasn’t the right approach,” demonstrating that she thought there was a better way to engage in this work.

Sketching and diagramming are critical components of design thinking and are one way that invisible design processes are made visible. The notebooks from all eight students included a range of drawings, sketches, and diagrams made by hand, some more than others. These included concept sketches, process and flow block diagrams, app and game storyboards, team logo sketches, skill assessment diagrams, sketches of components and their placements, and looks-like prototype drawings. Figure 7 provides examples from students’ different notebook pages.

Figure 7. Examples of sketching in the design notebooks include Dex’s user interface flow diagram for an app (top left); Emma’s storyboard for a video game (top right); Gavin’s concept sketch of the mechanical components of a hand orthosis (bottom left); and Summer’s concept sketches of a team logo (bottom right).

In her post-interview, Dr. J shared her disappointment that students did not engage in the type of documentation she had hoped for, calling good documentation a “lost art”. Dr. J
explained that when working on computer coding, documenting one’s code (e.g. taping a print-out of a section of code onto a notebook page) is different from documenting one’s thinking process and logic while building and iterating on that code (e.g. making linear notations about how the code functions, how decisions were made, and how the code was iterated upon). She reflected that “people don’t want to write down their thoughts, plans, flow charts,” the type of documentation practice she thought are useful in the design process. Documentation is useful both for novice engineers in developing their own practice but also as one of the critical ways for Dr. J, as the course instructor, to assess student work. Therefore, poor documentation presented a barrier to assessment.

However, the process of muddling through different approaches to documentation was beneficial for at least one student. Ash from Team NeuroGrip felt that having to document the prototyping process, which for her was mostly computer coding, was “challenging in a good way” that pushed her to “think about how to document processes moving forward”. This experience was one that she would take back to the computer science classes in her major. Ash admitted that she struggles with how to document her code in her other classes, in which instructors evaluate her purely on the how well her code works and not on the process of building and iterating on it, but “it needs to change; the notebook is helping me with that.” However, the notebook could have included more scaffolds to support students in the process of documenting the Prototyping phase. This finding will drive future iterations of the design notebook.

**The tension between documentation for design and for assessment.**

Some students reported that one of the greatest challenges of using the notebook was time constraints, given all they had to accomplish in just ten weeks. They struggled with knowing how to split their time between working on their design project and working through the prompts in the notebook; these students seemed to identify these two practices as disparate, rather than overlapping tasks. For example, Ash talked about how she struggled to keep up with her notebook throughout the quarter, and that she often viewed project documentation as “an afterthought”, as something she did after engaging in prototyping work or after she knew that her code worked, rather than documenting throughout these processes. Gavin described the difficulty he experienced in distancing himself from the notebook when attention was needed elsewhere in the project.

All six of the interviewed students commented in their post-interviews about feeling the pressure of needing to turn in their design notebooks for grading purposes, since a significant portion of their grade was comprised of their use of the notebook. This grading pressure may offer an explanation for why those students who did not embrace the use of the notebook throughout the course took the approach of backfilling. In her post-interview, Emma, who did significant retroactive backfilling of her notebook just prior to submitting it for grading, talked about feeling like she needed to put something on every page, knowing that her notebook was going to be graded. This tension highlights how knowing that the design notebook was going to be graded, for some students, may have made it more difficult for them to use the notebook as a tool to engage in the authentic practices of design thinking and documentation.
Though some students felt a tension between time constraints and needing to adequately complete their notebooks for grading purposes, these students also offered suggestions on slight tweaks to the notebook that will be considered for future iterations. Additionally, it must be considered that most if not all graded courses will have some components that are submitted for grading, be it a course paper, oral presentation, or design notebook. While some students may have felt that the size of the notebook and their unfamiliarity with how to best approach was a heavier lift, as Dex noted, “it’s a class; there’s always something you have to do for a grade.”

**Design Principles & Conclusion**

In this studio course, a novel engineering design notebook provided resources that synthesized and scaffolded the process of design thinking for students. The notebook was the tool by which the students in the course learned about and engaged with design thinking modes and resources. Students, with some exceptions, reported that the notebook expanded and supported their learning and were observed engaging in some of the design-related epistemic practices of engineering. Students and their instructors both spoke about the value of bringing design thinking concepts into an engineering design studio course. The course instructor felt that the notebook made a positive impact to the course and to students’ experiences in the course, as compared to previous iterations of the class.

**Design Principles for Structured Engineering Design Notebooks**

Three design principles for the design and implementation of structured engineering design notebooks in engineering studio design courses have emerged from this analysis.

**Design Principle #1: Provide scaffolds for design thinking, the engineering design process, and project management.** Engineering studio design courses could benefit by including student scaffolds for learning and engaging with the engineering design process, project management, and design thinking and to support students in developing epistemic practices of engineering. This amalgam can be thought of as the phases of Exploring, Understanding, Planning, Prototyping, Pitching, and Reflecting. Project management is not specifically included as a part of the engineering design process, nor viewed as a component of design thinking, but is a critical skillset for engineering students to take to their future workplaces. At the student or professional level, good ideas and designs are difficult to take to fruition without adequate skills in project management. These scaffolds have the potential to create more equitable learning opportunities, especially for students who have not previously taken an engineering studio design course or been previously introduced to design thinking.

**Design Principle #2: Offer both physical and digital formats.** When appropriate, physical notebooks may be introduced in partnership with online portals for submitting digital samples of student work. The materiality of the design notebook provides value, especially as a space for raw thoughts and sketches, however students also desire a way to submit digital artifacts for grading.
**Design Principle #3: Provide supports to help students learn documentation practices.** Documentation during prototyping, testing, and optimization is particularly challenging for students. Scaffolds should be developed to assist students in understanding what and how to document this phase of design work. In particular, scaffolds are needed to support students in understanding how to document the logic behind the process of iterative computer coding for digital projects. In addition, students need explicit support in understanding that engaging in design work and documenting their process are overlapping and complementary, not disparate, practices.

**Limitations of the Study Design**

One limitation of this study is that since complete data for all four teams was not available, it was difficult to be purposeful in choosing which teams to focus for data collection. Therefore, it was not possible to analyze the notebook use across the teams or to understand the role the notebook may play among teams with different dynamics and leadership styles and those pursuing different types of design projects than Team NeuroGrip. Secondly, as a qualitative case study, the purpose of this research was to engage in a deep analysis of students’ experiences using the engineering design notebook as a tool for design thinking. This does not offer insights into how students might have engaged in design thinking in the same course while using a blank notebook. A third limitation of this study is that Luke, one of the members of the Team NeuroGrip, did not respond to interview requests. A close analysis of the Reflection section of this student’s notebook, however, was informative as there was overlap between some of the interview questions and those posed in the Individual Reflection pages. A fourth limitation is related to the fact that there is no consensus on how to describe the process of engineering design [5], [9] or how to characterize or define design thinking [2]. Both the design of the design notebook and the analysis of data were aligned to the Stanford d.school’s conception of design thinking modes. While it was necessary to choose from among the many perspectives on design thinking, this choice limits analysis to one particular perspective.

**Future Research**

Several unanswered questions remain that could be investigated through future studies. I plan to apply a lens of sociocultural learning to an analysis of the ways that students employed their notebooks within teams, across teams, with course instructors, and with end-users, which could provide valuable insights into the way that the design notebook functioned as a tool for communication and collaboration practices across people in different roles. Second, given that assessment of students’ design processes is known to be significant challenge for instructors of studio design courses [4], a potential contribution to the larger engineering education field would be to examine how the notebook functioned as a tool for assessment for the course instructor [12]. Third, the research literature has shown the importance of including scaffolds for reflection in engineering education [3], [12], [23]. A future analysis will examine how the notebook supported students and instructors as they engaged in reflection-in-action during design meetings and reflection-on-action at the end of the course. Finally, as the goal of the notebook’s creators is to eventually make it widely available to other educators, the role of the notebook for both students and instructors could be studied across different settings and engineering disciplines as the notebook is adopted and adapted in other contexts.
Scholarly Significance

This work speaks to the value in bringing design thinking concepts into an engineering design studio course. This analysis showed that offering design thinking scaffolds in the structured engineering design notebook is one way to help develop students’ develop the design-related epistemic practices of an engineer and the mindset of a designer. The engineering design notebook at the focus of this research study has the potential to be used in other settings both inside and outside of engineering studio design courses. Indeed, this was our intention from the beginning; the notebook will eventually be published and made available for other engineering educators and students to use. One student saw value in using the design notebook in other settings, reporting in her post-interview that she “would totally buy one” if she had an idea for a new product that she wanted to pursue.

The notebook is already being locally adapted for use in other learning contexts. First, Ash, a student on Team NeuroGrip, asked permission to remix the notebook for use with a business-technology weekend hackathon event. Her adapted version trimmed the notebook down to the 18 pages she thought were most salient for teams of engineering and business students. Secondly, Dr. J revised the notebook for use as a tool to guide undergraduate students in research projects for use in a summer research experience program at an engineering research center, and idea that was supported by Dex in his post-interview reflections. Third, the results of this study were shared with Dr. J and informed our second iteration of the engineering design notebook. For example, one revision to Version 2.0 of the notebook was to include a page on Documenting the Prototyping Phase that provided information on why documentation was important, what kinds of things should be documented, and provided specific instructions on how to document computer code. One major difference with the revised notebook is that Dr. J chose to provide the notebook in both physical and digital formats, and allowed students to submit their work digitally through the course website, rather than requiring that all components be integrated into the physical notebook, allowing students who are digital natives to interact with the design notebook in multiple ways.

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